Atomic Energy in India:
Achievements since Independence

A. K. Tyagi
P. R. Vasudeva Rao

HOMI BHABHA NATIONAL INSTITUTE

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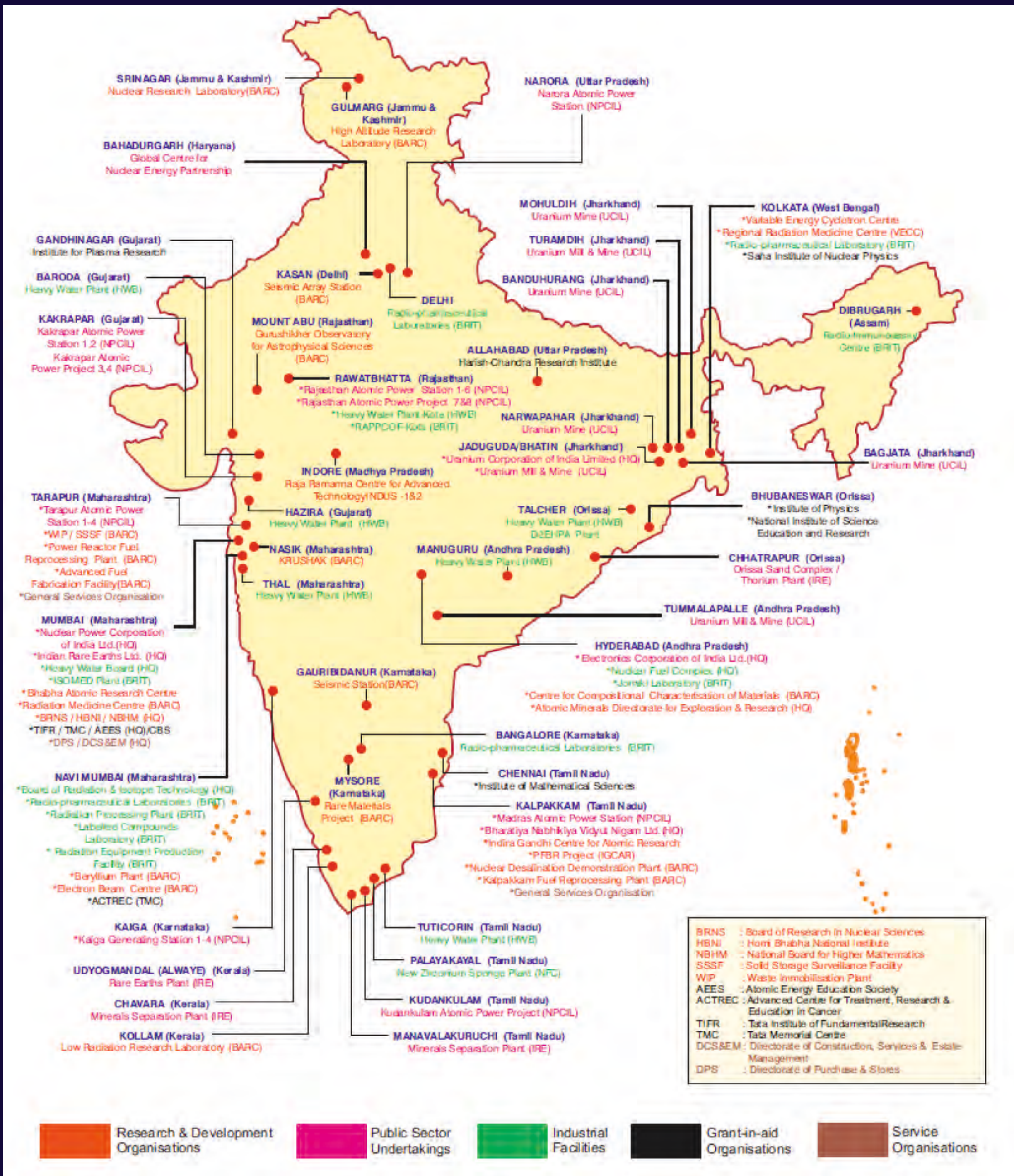
Department of Atomic Energy



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K. N. Vyas

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Government of India

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व
सचिव, परमाणु ऊर्जा विभाग
Chairman, Atomic Energy Commission
&
Secretary, Department of Atomic Energy

FOREWORD

Nuclear energy is a clean source of power enabling significant reduction in $C0_2$ emission. Government of India is committed to growing its nuclear power capacity as part of its overall infrastructure development programme. Department of Atomic Energy, India is actively involved in development and deployment of nuclear technologies to further the cause of national development. India's nuclear energy self-sufficiency extends from uranium exploration and mining through fuel fabrication, heavy water production, reactor design and construction, to reprocessing and waste management. It has a small fast breeder reactor and is building a larger one. It is also developing technology to utilize its abundant resources of thorium as a nuclear fuel.

We all are aware that Government of India has initiated "Azadi Ka Amrit Mahotsav" to celebrate 75 years of India's Independence. The development of the mostly homegrown Indian nuclear energy program has played a crucial role in enforcing the energy independence and security needs of the country. The release of this book is a befitting tribute to such a monumental occasion.

The various chapters in this book are an excellent collection of all the significant milestones of nuclear technology achieved indigenously by our scientists and engineers since independence. I am sure that the lucid presentation would make it an informative and interesting read for a broad and diverse readership. I must compliment the editors of the book, Dr. A. K. Tyagi, Director, Chemistry Group, BARC and Dr. P. R. Vasudeva Rao, Vice Chancellor, HBNI for putting-in efforts to assimilate such an extensive amount of research and development in a compact format.

I wish all the readers an enjoyable and enlightening journey through this book.

(K. N. Vyas)

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PREFACE

Atomic Energy in India: Achievements since Independence

India gained freedom in 1947 and in the very next year, the country made a formal beginning of its programme on nuclear energy development and deployment by establishing the Atomic Energy Commission (AEC) under the inspiring leadership of father of Indian Nuclear Programme, Dr. Homi Jehangir Bhabha. Within eight years of the constitution of AEC, India took a great leap when Apsara, India's first nuclear reactor, became critical in 1956 wherein entire reactor system including control instrumentation was indigenously designed, fabricated and commissioned (fuel was provided by UK). This landmark achievement paved the way for several other equally important milestones such as commissioning of a 40 MW natural uranium heavy water moderated reactor (CIRUS) in 1960, uranium extraction and purification, fuel fabrication, reactor instrumentation, radioisotopes separation, setting up of accelerators and related technologies, just to name a few. These achievements placed India in the league of a few developed nations who have indigenously developed, demonstrated and deployed nuclear reactors as well as associated fuel cycle facilities for electricity generation, as well as applications of radiation and radioisotopes.

The present book intends to provide an account of some of the important achievements of India in the area of atomic energy. The first chapter is dedicated to Dr. Homi Jehangir Bhabha, the architect of India's nuclear programme. The second chapter of the book is about life and contribution of Dr. Vikram Sarabhai who provided impetus to a number of programmes. These are followed by chapters dedicated to the journey of atomic mineral exploration, uranium mining and processing, success story of India's heavy water production from shortage to surplus production, fuel fabrication, development of research and power reactors. The nuclear energy programme of India was designed to recycle nuclear fuel towards effective utilization of its resources and as the result India is one of the few countries in the world having mastered all aspects of nuclear fuel cycle technology including fuel reprocessing and waste management. A detailed chapter on the back end of the nuclear fuel cycle lucidly explains this aspect. Over a period of time, in addition to providing power, the atomic energy programme has significantly contributed to health, agriculture and industrial sectors. These aspects are covered in chapters detailing the major achievements in application of radiation processing and radio-isotopes for societal benefits. The book also contains a broad discussion about research carried out in the allied fields of Nuclear Physics, Structural Materials, Laser Based technologies, Accelerator, Fusion and Plasma Research which also contribute to the success of the Atomic Energy Programme and its impact on society and industry in particular and the country in general. A dedicated chapter on Homi Bhabha National Institute, academic wing of Department of Atomic Energy, India, would be a great read for those aspiring for a career in nuclear energy.

We would like to express our sincere gratitude to Dr. Anil Kakodkar, Chancellor, HBNI, Shri K. N. Vyas, Chairman, Atomic Energy Commission and Secretary, Department of Atomic Energy and Dr. A. K. Mohanty, Director, Bhabha Atomic Research Centre for their support to the book. We are thankful to all the authors for their contributions. Dr. S. Adhikari, Head, Scientific Information Resources Division, BARC and his colleagues Shri Manoj Singh, Smt. Leena Kanal, Shri Bhushan Chavan and Shri Sanjay Singh are thanked for taking efforts for publication of the book. Dr. Kruti Halankar is thanked for her assistance at various stages.

Attempts have been made to strike a balance in the contents of the book to make it appealing to a wide spectrum of readers comprising of science professionals and non-professionals. Although, due care has been taken to make the book as error-free as possible, some errors may have crept in by oversight. We shall be thankful to the readers for bringing such unintentional errors to our notice.

A. K. Tyagi
P. R. Vasudeva Rao

Homi J. Bhabha
(1948-1966)

Vikram Sarabhai
(1966-1971)

H. N. Sethna
(1972-1983)

Raja Ramanna
(1983-1987)

M. R. Srinivasan
(1987-1990)

P. K. Iyengar
(1990-1993)

R. Chidambaram
(1993-2000)

Anil Kakodkar
(2000-2009)

Srikumar Banerjee
(2009-2012)

R.K. Sinha
(2012-2015)

Sekhar Basu
(2015-2018)

K.N. Vyas
(2018-)

Leaders of the Indian Atomic Energy Programme

About the Editors

Dr. A. K. Tyagi joined Chemistry Division, Bhabha Atomic Research Centre (BARC), Mumbai in 1986 through BARC Training School (1985-86 batch). Presently, he is Director, Chemistry Group, BARC, and a Senior Professor of Chemistry at Homi Bhabha National Institute (HBNI), Mumbai. His research interests are in the field chemistry of materials, which includes nuclear materials, functional materials, nanomaterials, energy materials, metastable materials, hybrid materials and structure-property correlation.

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Dr. P.R. Vasudeva Rao is currently the Vice Chancellor of Homi Bhabha National Institute, Mumbai, which is a Deemed-to-be University under Department of Atomic Energy (DAE). He joined DAE in 1973 through the BARC Training School (1972-73 batch). He worked in Radiochemistry Division, BARC until 1978 when he shifted to Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. He was the Director of IGCAR at the time of his superannuation in 2015. He is a specialist in the chemistry aspects of nuclear fuel cycle and particularly actinide separations.

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Homi Jehangir Bhabha and the Atomic Energy Programme

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Preamble

Homi Jehangir Bhabha was a man of many parts: a scientist of distinction; the visionary founder of the Tata Institute of Fundamental Research; a lover of art, music and gardens; and the person who single-handedly conceptualized and actualized the atomic energy programme of the country.

This article tries to give a sense of Bhabha's remarkable vision and how he succeeded in transforming the scientific and technological landscape of the country in the short span of two and a half decades.

Homi Bhabha was just seventeen when he left India to study in Cambridge in England. The year was 1927 and the plan was for young Homi to get a degree in Engineering, which would enable him to make a career in industry on his return to India. His father J. H. Bhabha was well-connected to many of the Tata enterprises in the country, so Homi's path seemed well laid out. But rather than maintaining a steady course which would have guaranteed a safe voyage through life, Homi Bhabha changed course and took on a new challenge.

This pattern – a bold decision to chart a new course -- was to be repeated at different junctures of his life. The result was that in 27 short years after his return to India, he successfully spearheaded the effort to bring modern science to India by taking two decisive steps with far-reaching consequences: founding the Tata Institute of Fundamental Research (TIFR), and establishing the Atomic Energy programme in India. These separate, but closely linked, initiatives allowed the country to forge ahead into the nuclear age. He also played an important part in laying the base for India's space programme and the country's involvement with electronics. How this happened makes a fascinating story, which is brought out in the pages that follow.

Homi Bhabha (right) with his father Jehangir Bhabha, mother Meherbai Bhabha and brother Jamshed Bhabha

Cambridge

While at Cambridge, Bhabha carried on a lively and detailed correspondence with his parents. From his letters, we learn that he immersed himself in the student life at the University, and took part in dramatics, rowing and athletics. But more importantly, he was drawn strongly towards the epoch-making discoveries in experimental and theoretical physics that accompanied the dawn of quantum mechanics in the 1920s and 30s. Bhabha was deeply attracted to these developments and felt strongly that he must be part of the new enterprise, and contribute to it. This is recorded in a memorable passage in a letter to his father.

"I seriously say to you that business or job as an engineer is not the thing for me. It is totally foreign to my nature and radically opposed to my temperament and opinions. Physics is my line. I know I shall do great things here. For each man can do best and excel only in that thing of which he is passionately fond, in which he believes as I do, that he has the ability to do it, that he is born and destined to do it. My success will not depend on what A or B thinks of me. My success will be what I make of my work. Besides, India is not a land where science cannot be carried on."

His father relented, and agreed to finance his son's stay in Cambridge for two more years, provided Homi first completed his Mechanical Tripos in Cambridge with a first class. Bhabha obliged, with firsts in the Mechanical Engineering and in the Mathematics tripos, two years later, although he held the view that "no exam was ever a test of original or creative ability in anybody".

He made the most of his years at Cambridge where he was deeply influenced by Dirac. He was awarded a travel fellowship which allowed him to visit Pauli in Zurich, Fermi in Rome and Kramers in Utrecht. Bhabha was excited by the beauty of the underlying theory of elementary particles, and equally by new experimental studies of cosmic rays which vastly extended the range of available energies. He did his Ph. D. with R. H. Fowler, who incidentally was also the supervisor of the Indian astrophysicist Subrahmanyan Chandrasekhar.

Bhabha's research results from his Cambridge days remain relevant and important to this day. A few highlights follow.

- He was the first to perform the calculation that pertains to the interaction between an electron and a positron when they scatter from each other. Importantly, he included the crucial element of exchange, a quantum effect arising from the indistinguishability of identical particles. It was almost two decades later that these theoretical predictions were verified by experiment. Today, the Bhabha scattering formulae are used routinely to calibrate particle beams at high energy accelerators.
- Bhabha did pioneering work on the physics of cosmic rays, which are comprised of particles moving at very high energies, reaching the earth from outer space. Along with Heitler, Bhabha explained the occurrence showers of particles observed on earth as arising from a cascade of electron-positron pair creation events, as a very high energy cosmic particle passes through the atmosphere.
- A couple of related works, to which he contributed: Bhabha worked on the heavy-particle component of cosmic rays, and was led to invent the word “meson” to describe these particles. There was a debate on the best name for the particle, and Bhabha's proposal won out. Further, he was the first to offer a clear and succinct explanation of why “the time of disintegration (of mesons) is longer when the particle is in motion”. The explanation rests on the phenomenon of time dilatation, which is familiar from the special theory of relativity.

Homi Bhabha at Cambridge

Bhabha's achievements in physics at Cambridge earned him a strong international reputation at the time. Both from his own research and by imbibing the stream of new results from others at Cambridge and elsewhere in Europe, Bhabha also discerned the importance of fundamental research as well as its applications. Yet it must be noted that beyond his grounding in physics, it was his earlier training in engineering that was a critical element in his later successes, while planning and executing major projects for the country, after his return to India. Equally important were the friendships he formed in his years at Cambridge, with colleagues like John Cockroft and W. B. Lewis. These stood him in good stead when he embarked on the atomic energy programme in India, many years later.

A Larger Purpose

While in the prime of his research career at Cambridge, Bhabha came to Bombay on vacation in 1939. The outbreak of World War II in September 1939 prevented his return to England, and Bhabha moved from Bombay to Bangalore to join the Indian Institute of Science. He was appointed Reader in charge of the Cosmic Ray Research unit, in which capacity he started experimentation with the aid of balloons launched to measure the fluxes of cosmic ray particles and their derivatives, at different heights. At IISc, C. V. Raman thought highly of Bhabha and nominated him for the Fellowship of the Royal Society, London. He was appointed FRS in 1941, and was awarded the 1942 Adams Prize by the University of Cambridge for “The theory of elementary particles and their interactions”.

Bhabha with C.V. Raman and others at the Indian Institute of Science in Bangalore

The period 1940-45 was a crucial period in the development of Bhabha's ideas. It was then that he first had inklings of a larger purpose, which saw him transform from a scientific researcher of distinction to a scientific thinker and planner, whose extraordinary vision was to transform the scientific landscape of the country. In the words of B. M. Udgaonkar “he reestablished an identity between himself and his country, and became aware of the role he could play in the development of India….He discovered his mission in life". In a letter to J. R. D. Tata in 1943, Bhabha wrote: *"The lack of proper conditions and intelligent financial support hampers the development of science in India at the pace the talent in the country would warrant"*. He was encouraged to apply to the Tata Trusts, and in an oft-quoted letter he wrote in 1944 to Sir Sorab Saklatvala, Chairman of the Sir Dorabji Tata Trust, Bhabha requested the Tatas to seed a new institute of fundamental research. He says, *"The scheme I am now submitting to you is but an embryo from which I hope to build up in the course of time a school of physics comparable to the best anywhere*". But it is not to be an end in itself, for *"It is absolutely in the interest of India to have a vigorous school of research in fundamental physics, for such a school forms the spearhead of research not only in less advanced branches of physics but also in problems of immediate practical application in industry."* He cites the example of Britain where pure research workers of the standing of Lord Rutherford, W. L. Bragg, R. H. Fowler, Lord Raleigh, James Jeans and A. V. Hill played a crucial role as members of the advisory council of the Department of Scientific and Industrial Research. He adds *"Moreover, when nuclear energy has been successfully applied for production in say a couple of decades from now, India will not have to look abroad for experts but will find them ready at hand. I do not think that anybody acquainted with scientific development in other countries would deny the need in India for such a school as I propose."*

From the very start, Bhabha emphasized the need to strive for and achieve true excellence in an absolute sense. In an address on "Atomic Energy" before the Bombay Branch of the Indian Council of World Affairs in August 1945, he said *"It should no longer be enough for us to say to-day that some scientific or industrial effort in this country is as good or almost as good as that in some other country. We should aim at doing things which are in advance of what has been done elsewhere. Given proper education and facilities for work, the Indian mind is perfectly capable of this, as has indeed been demonstrated by Ramanujan, perhaps the greatest mathematical genius the world has produced in this century."*

The Tata Institute of Fundamental Research

The first step in the realization of Bhabha's vision was enabled by the Sir Dorabji Tata Trust, which accepted his proposal; the Government of Bombay too was a co-founder of the Institute. But even before it had a proper location, the Institute began functioning in June 1945 in a laboratory at IISc in Bangalore. It moved to Bombay in December and occupied a part of "Kenilworth", a spacious bungalow on Peddar Road which belonged to Bhabha's aunt, Ms. Coover Panday. The initial areas of research at the fledgling institute included mathematics, theoretical physics and cosmic ray physics; indeed, by the time TIFR was formally inaugurated in December 1945, eight research papers had been published already, true to Bhabha's dictum that scientists and scientific work matter the most, and must come first; buildings can come up later.

Bhabha's speech at the formal inauguration on December 19, 1945 is a masterly exposition of the state of research in the world for a lay audience, ranging from elementary particle and cosmic ray physics, to the theory of relativity and quantum mechanics. Underlining the fact that scientific knowledge provides the key to control nature and ultimately influence history, he said: *"In the nineteenth century, fundamental research was a curiosity pursued by men with deep interest in nature and looked upon as cranks by the rest. Today we all know of the great importance of fundamental research and the recent release of atomic energy for practical purposes has brought forcibly before the public how new avenues may be opened up by fundamental research, namely the study of nature itself unhampered by preconceived practical* *ends ... As Marx said, "Man's power over nature lies at the root of history", and we have in our own times seen the history of the world shaped by those countries which have made the greatest scientific progress."*

In a few years, both the faculty and student population increased, and in 1948 the Institute began a move to more spacious quarters in the Old Yacht Club which is located close to the Gateway of India in Bombay. As the years progressed, the quality and diversity of research grew and the Institute needed more space once more. Bhabha identified a beautiful site to locate the new Institute, close to the southern tip of Bombay, overlooking the Arabian Sea. The foundation stone was laid in 1954 by Prime Minister Jawaharlal Nehru. It took eight years to design and make the new buildings, and it was in 1962 that they were inaugurated by the Prime Minister. The pace of research grew strongly in the intervening years, and by the time of inauguration, the new buildings already housed many laboratories that were practically complete. As Bhabha noted in his speech at the inauguration, *"The building is only a shell to make possible the work inside it. It is by the quality and volume of its scientific work that an institute like this must be judged, by the extent to which it has helped to explore and push back the frontiers of knowledge.*

Prime Minister Jawaharlal Nehru laying the foundation stone of the buildings of the Tata Institute of Fundamental Research at Colaba, Bombay (1954).

The scientific work in the institute began with mathematics, theoretical physics and experimental work in high energy physics and cosmic ray physics. A cloud chamber, made already in the days at IISc, was brought to Bombay, and two larger chambers were designed and made soon thereafter, with the idea of installing them at high altitudes, to track cosmic rays. As the years passed, research activities were initiated in nuclear physics, condensed matter physics and computer science. The first full-scale electronic digital computer to be designed and built in India, the TIFR Automatic Calculator or TIFRAC, was commissioned in 1960.

The setting up of these programmes illustrates two important components of Bhabha's thinking and way of going about things. First, he felt it was critically important to take up research in modern experimental areas, not only to strike a balance with theoretical activities, but also to generate confidence in the design, fabrication and use of sophisticated equipment. This was crucial as TIFR was to go on to seed the atomic energy programme of the country, as envisaged by Bhabha. The other point, equally important, is to note is how he went about it. The Bhabha formula is simple to state: Identify a talented individual who is capable of leading the effort, and give him or her complete freedom, with full backing. Of course, it is not so easy in practice, as such individuals are rare, and it is not always easy to identify and attract them. Bhabha's special gift lay precisely in this direction --- he was able to recruit and retain such people, to inspire them and get the best from them, and build lasting programmes around them.

Perhaps this is best illustrated by two later hires he made, which have had considerable impact. In the last lecture he gave a couple of days before his tragic death, to the International Council of Scientific Unions (ICSU), he recalled: *"It may be of interest to give two more examples of building projects and development around people. As early as June 1944, Sir A. V. Hill had written to me that biophysics is a neglected subject in India and that it should be taken up under the wing of the Institute. While I agreed with his suggestions, I did not think it would be wise to embark along these lines till someone was found mature enough to be able to work on his own and build up a group. When however in 1962 my attention was drawn by the late Dr. Leo Szilard to a very promising Indian molecular biologist, it was decided to start work in microbiology which has since then been growing very satisfactorily."* The young molecular biologist in question was Obaid Siddiqi, who went on to build a vibrant group at TIFR which encompassed several branches of modern biology, and later headed TIFR's National Centre for Biological Sciences (NCBS-TIFR), Bangalore. The other instance of a new programme built around people was the radio astronomy programme of TIFR, which was started when four young

Bhabha speaking at the inauguration of the buildings of the Tata Institute of Fundamental Research at Colaba, Bombay. On the dais are Prime Minister Jawaharlal Nehru, Chief Minister of Maharashtra Y.B. Chavan, Governor Sri Prakash and J.R.D. Tata (1962).

Indian radio astronomers proposed to return to India to establish radio astronomy in India. Bhabha recognized the worth of their proposal, and supported it. As he recounted, in his address to ICSU: *"A project has been developed for a large cylindrical radio telescope for studying quasars and other radio sources and locating them accurately by lunar occultation. The telescope, which will have four to five times the collecting area of Jodrell Bank will be designed and built entirely by Indian scientists and engineers..."* This radio telescope, located in Ooty, was built by Govind Swarup, who went on to build the Giant Metrewave Radio Telescope (GMRT) and head TIFR's National Centre for Radio Astrophysics (NCRA-TIFR).

Bhabha knew that building an institution and nurturing it in its many aspects was a process that required patience and care. He likened it to growing a tree. In his Presidential Address to the National Institute of Sciences of India (now INSA), Bhabha said: *"A scientific institution be it a laboratory or an academy has to be grown with great care, like a tree. Its growth in terms of quality and achievement can only be accelerated to a very limited extent. This is a field in which a large number of mediocre or second rate workers cannot make up for a few outstanding ones, and a few outstanding ones always take 10 to 15 years to grow."*

Niels Bohr with Homi Bhabha, J.R.D.Tata and Jamshed Bhabha during the International Colloquium on Function Theory (1960)

Besides establishing vigorous research programmes at TIFR, Bhabha was keenly aware of the importance of exposing students and young scientists to developments at the frontiers of research. To this end, he developed a twin strategy: first, he sent youngsters from TIFR to the best universities in the West, to imbibe knowledge, witness research in the making, and above all, develop the confidence to excel in research themselves. The second leg of the strategy was to invite leading scientists from other countries to visit the Institute and give extended lecture courses. These lecturers, who included P. A.M. Dirac, W. Heitler, B. R. Mottelson, L. Schwartz and C. L. Siegel spent extensive time at TIFR and interacted with students both in and out of the classroom. Beyond this, TIFR hosted important international meetings and symposia in physics and mathematics. These too gave younger scientists an unparalleled opportunity to get to know internationally established scientists, and equally important, for the international visitors to get to know our young scientists.

Bhabha showing Epstein's bust of Einstein at TIFR to M. C. Chagla, Minister of Education. On the extreme left is M. G. K. Menon.

As envisaged at the time of founding the Institute and under Bhabha's guidance, TIFR provided all possible help, in terms of training scientists and building capacity, to assist in the founding of the atomic energy programme of the country, a step of major importance in the history of independent India. We now turn to an account of this phase.

The Atomic Energy Programme

Already in the 1940s, Bhabha envisaged that the country would need nuclear power to fill the gap between demand and supply of power based on traditional sources. Thus in his letter of 1944 to the Sir Dorabji Tata Trust where he proposed the foundation of an institute of fundamental research, he wrote: *"Moreover, when nuclear energy has been successfully applied for production in say a couple of decades from now, India will not have to look abroad for experts but will find them ready at hand"*. It is remarkable that he was thinking in this direction a year before the Hiroshima and Nagasaki explosions showed the world the raw power of nuclear energy unleashed for destructive purposes.

Bhabha advocated the development of peaceful uses of atomic energy as a priority area for the new India, post-independence. Looking to the future, he argued that with rapid industrialization, the power demand would rise steadily and conventional sources of energy in the country would not suffice to ensure an adequate standard of living for our population. Nuclear power would thus be called upon to make a greater relative contribution, so it would be necessary to develop industrial experience in the field, and to acquire the necessary skills. Further, in order to utilize India's abundant and cheap resources of thorium, it would also be necessary to have substantial quantities of fissile plutonium available, so that enriched fuel power stations, with lower capital cost, could also be utilized without the need to import fuel.

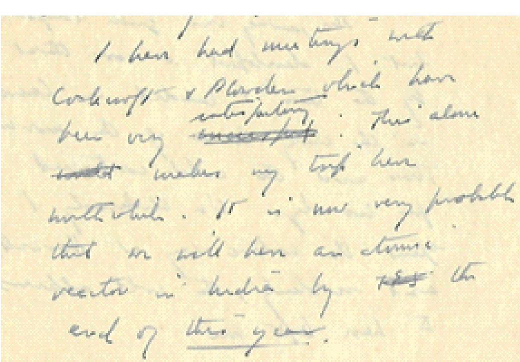
In order to guarantee safe passage of such a large enterprise, Bhabha pro-actively took a series of crucial legislative and administrative steps to channelize the effort and make it effective. In a crisp “Note on the organization of atomic research in India” addressed to the Prime Minister in April 1948, Bhabha made a case for administrative and other measures that should be taken to develop this branch of science. At Bhabha's urging, the Indian Atomic Energy Act was framed in 1948 to give the Government powers to carry out surveys for atomic minerals, to work on them on an industrial scale, to conduct research on the scientific and technical problems connected with atomic energy and to develop personnel to do such work. To carry out these tasks, the Government created a Commission chaired by Bhabha. Initially, the Atomic Energy Commission (AEC) had three members (Bhabha, S. S. Bhatnagar and K. S. Krishnan) and its work was carried out at TIFR. A major decision, namely to build an Atomic Energy Establishment at Trombay (AEET), was taken in January 1954. Further, using the powers under the 1948 act, the Department of Atomic Energy (DAE) was created in 1954, charged with the development of nuclear energy for peaceful purposes. The Department was in the direct charge of the Prime Minister, and Bhabha was appointed Secretary of the Department. A resolution by Bhabha in the Lok Sabha in 1958 defined the powers and responsibilities of the AEC, vesting the full executive and financial powers of the government with the Commission. New legislation in 1962 amended the Atomic Energy Act to empower the Government to also provide control over radiation hazards and public safety, with the central government using the DAE as the instrument to accomplish these objectives. The DAE continued to operate under Bhabha as its Secretary, and ex-officio Chair of the AEC. These steps, taken in the formative years of the atomic energy programme, were vital for its success. Each step was carefully planned and executed, and the resulting structure was finally robust enough to handle the needs of the programme.

Parenthetically, it is noted that the AEET was re-named the Bhabha Atomic Research Centre (BARC) by Prime Minister Indira Gandhi in 1966, after Bhabha passed away. It is as BARC that the establishment is well known today.

The growth of the atomic energy programme, and more generally the scientific enterprise in the country, owed much to the consonance of Bhabha's vision with that of India's first Prime Minister, Jawaharlal Nehru. His firm support was vital in helping to translate Bhabha's vision into action and reality. In January 1955, Bhabha made a trip to Britain where he met Sir Edwin Plowden, Chairman of the Atomic Energy Authority and Sir John Cockroft (his colleague from Cambridge days, and then director of the Atomic Energy Establishment at Harwell) to explore the possibility of Britain supplying enriched fuel elements to India. In a letter to his mother Meherbai and his brother Jamshed, Bhabha wrote that his meeting was *“very satisfactory. This alone makes my trip worthwhile. It is now very probable that we will have an atomic reactor in India by the end of the year.”*

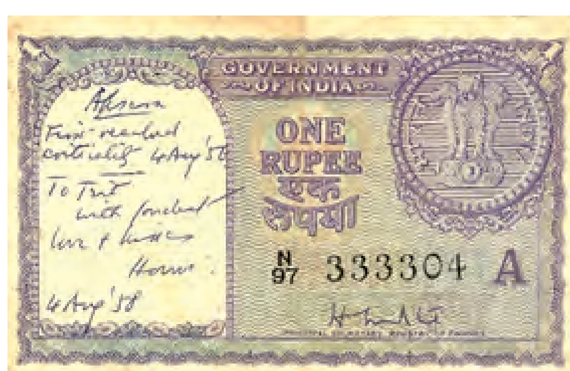
Bhabha with E.C. Allardice, Controller of the AEET (1955)

The decision to build a light water reactor was taken in April 1955, and the design and experimental facilities were decided in August. It took about a year to complete its construction. Other than the fuel rods, which were supplied by Britain, all components were made indigenously. Assembly commenced in 1955, and most physicists associated with the project, who were earlier housed in Colaba, now moved to Trombay. On reaching the milestone of the reactor becoming functional, Bhabha presented his mother with a one rupee note, on which he wrote "Apsara first reached criticality, 4 August 1956".



I have had meetings with Cockcroft & Plowden which have been very satisfactory. The above makes my trip here worthwhile. It is now very probable that we will have an atomic reactor in India by the end of this year.

Bhabha's letter to his mother Meherbai Bhabha and brother Jamshed Bhabha (1955)



Note presented by Homi Bhabha to his mother Meherbai Bhabha (1956)

The reactor Apsara at AEET was formally inaugurated by the Prime Minister Jawaharlal Nehru (1957).

At the inauguration of the AEET and swimming pool reactor in January 1957, the Prime Minister dedicated the facility to the nation. In his speech, Bhabha noted that *"A plentiful supply of energy is the first requirement of modern civilization"* and argued for the economic feasibility of atomic power. At the same time, he emphasized that atomic energy would have many other uses: *"The aim of the Department of Atomic Energy is to develop atomic energy as a source for electric power, and to promote its use in agriculture, biology, industry and medicine. On the industrial side we intend to produce all the materials required for a full atomic power*

Bhabha with Norman Hilberry, Director, Argonne National Laboratory, R. Ramanna and P.K. Iyengar (1957)

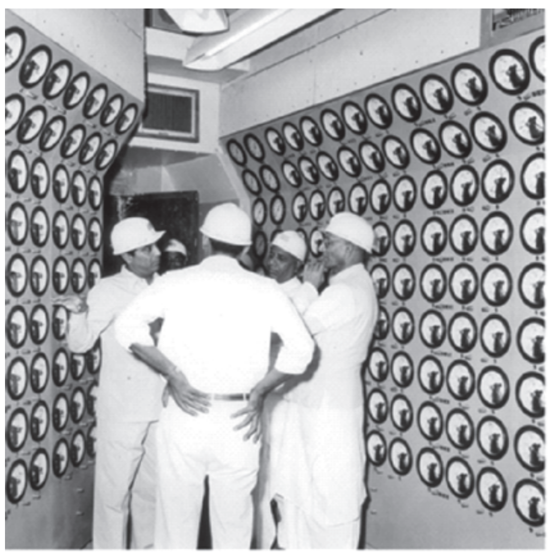
programme." Commenting on innovative makeshift arrangements that had to be made in the absence of buildings, he said: *"We did not wait for the new buildings to come up to start the research activities of the Establishment. The Physics and Engineering Divisions were located in TIFR at the Yacht Club, and in war-time hutments on its new site at Colaba. A warehouse at another part of Bombay was converted for housing the Chemistry Division, while the Biological and Medical Divisions were set up at the Indian Cancer Research Centre…Many parts of the control system were made in our sister organization, TIFR, while the grid plate of the reactor was made in the Naval Dockyard".* Other steps taken were also outlined, including the establishment of a plant to treat monazite sands on the west coast. Bhabha also discussed the next project to be taken up, namely the design of a powerful high flux reactor for engineering research.

Working on APSARA had raised considerably the levels of know-how and confidence of the engineers and physicists involved with the project. Bhabha turned his attention next to the design of a heavy-water based reactor, which would have the advantage of using natural uranium as the fuel, removing the dependence on other countries for the import of enriched fuel elements. The first plant to manufacture heavy water was set up at Nangal close to the Bhakra dam, and demonstrated that the country had the capability of producing this crucial component.

In order to move to this next phase, it was deemed necessary to partner with a country where such reactors were already in operation. Canada already had functioning heavy-water reactors, as part of its atomic energy programme, which was led by W. B. Lewis, Bhabha's friend ever since they met in Cambridge in 1927. In early 1955, the Canadian government offered to set up a reactor of the NRX type (in use at Chalk River, Canada) at Trombay. Subsequently Bhabha met Lewis in the 1955 Geneva conference on the peaceful uses of nuclear energy, and a Canada-India tie-up was agreed on. The Canada-India Reactor (CIR) project entailed sending a team of Indian engineers to the site in Canada while construction of the facility proceeded at a pace in Trombay. The Indian-made fuel elements performed very well and CIRUS became operational in 1960.

Bhabha with reactor engineers at Trombay (1960)

In January 1961, several important new facilities were inaugurated at Trombay by the Prime Minister, including the CIR. In his speech, Bhabha made the point that *"The environment of Bombay is very different from Chalk River… and several problems had to be considered.*" He added: *"That the reactor has not yet reached its full power is due to a number of very interesting teething troubles, from which valuable experience is being gained."* Eventually, many improvements were made on the system over the next two years in response to unanticipated difficulties like the growth of algae in the primary system, corrosion and rupturing of the rods. Describing this later in a letter to the Prime Minister in January 1962, Bhabha wrote: *"…all problems connected with its operation have been overcome by our staff. In overcoming these difficulties, the staff of the Reactor Operations Division were helped in an important way by the staff of other Divisions, as for example the Analytical Chemistry, Radiochemistry, Metallurgy and Biology Divisions. Unless the work of the Establishment covered all the other fields, we would not have been able to overcome the difficulties on our own. The scientific staff of the Establishment, and especially that of the Reactor Operations Division, have put up a very creditable performance."*



Bhabha with Morarji Desai at Trombay (1960)

A crucial feature of the heavy-water reactor was the efficient production of plutonium, important as a key element of the three-stage programme enunciated by Bhabha, and adopted by the DAE. The full programme was well summarized by Bhabha: *"The total reserves of thorium in India amount to 500,000 tons in the readily extractable form, while the total known reserves of uranium are less than a tenth of this. The aim of long-range atomic power programme in India must therefore be to base the nuclear power generation as soon as possible on thorium rather than uranium. The first generation of atomic power stations based on natural uranium can only be used to start up an atomic power programme…. The plutonium produced by the first generation power stations can be used in a second generation of power stations designed to produce electric power and convert thorium to* U^{233} *… or depleted uranium into plutonium with breeding gain … The second generation of power stations may be regarded as an intermediate step for the breeder power stations of the third generation all of which would produce more* U^{233} *than they burn in the course of producing power."*

Inauguration of the Plutonium Plant by Prime Minister Lal Bahadur Shastri (1965)

Bhabha knew that the key resource for the success of the atomic energy programme was the right people. At the inauguration of AEET in 1957, he outlined his plan: *"To ensure a steady supply of trained scientific and technical personnel, we are starting a training programme in June this year, in which 250 young graduates and engineers will be recruited annually from the universities and given supplementary training for a year to fit them for work in our atomic energy programme."* This was the start of the BARC Training School which, over the years, has imparted unique skills to thousands of graduates, and has been indispensable in producing the core manpower required for the multifarious activities of the DAE. An important point about this mode of training was noted by Bhabha in his final address to ICSU in January 1966: *"... this method of building up our staff does not drain away senior persons from the universities, but on the contrary gives training, employment and opportunities to young graduates passing out of the universities."*

In his speech during the inauguration on the new facilities at Trombay, Bhabha made a couple of other important points. He was acutely aware that the health of workers in and close to nuclear establishments needed to be well protected, and made the point: "*As atomic energy grows in the country and its uses become more widespread, the need to safeguard the health of the scientific workers and the general public will increase. An efficient health physics service is, therefore, essential, and this is provided by the Health Physics Division."* Separately, broaching the question of sharing our knowledge and expertise in setting up reactors with others, Bhabha had this to say: *"With the facilities we have built up here, to which the CIR is a major addition, Trombay has become an important centre for atomic energy work in the world. In the spirit of* *cooperation which has built the CIR, we would be happy to share the scientific knowledge and technical know-how we have acquired with other countries, who wish to use atomic energy for peaceful purposes and for the good of their peoples. We would be particularly happy if advantage were taken of these facilities by the countries of Asia, for we are convinced that eventually atomic energy is bound to make an important contribution to their industrial development and welfare. It is our firm resolve to use atomic energy only for peaceful purposes and for the good of the people of India and the world as a whole."*

Opening of the International Conference on Peaceful Uses of Atomic Energy Left to right: Swiss president Max Petitpierre, U.N. Secretary General Dag Hammarskjold, Homi Bhabha, President of the Conference, and Walter G. Whitman from the U. S., Conference Secretary General (Geneva, 1955)

As a key figure in the atomic energy landscape worldwide, Bhabha was held in great esteem by his counterparts from other countries, for his contributions to physics and to scientific policy and planning, and for his general erudition. Little wonder then, that at the first international conference on "Peaceful Uses of Atomic Energy" held in Geneva in 1955, Bhabha was unanimously elected President of the Conference. His inaugural address makes for wonderful reading, putting, as it does, atomic energy in a historical perspective. Arguing that "each epoch marks a change in the energy pattern of society", he traces successive stages of development --- energy from muscle power in olden times was supplanted by chemical energy, leading ultimately to the industrial revolution. Given that resources for chemical energy are rapidly dwindling, Bhabha argues for *"the absolute necessity for finding a new source of energy, if the light of our civilization is not to be extinguished because we have burnt our fuel reserves."* He adds *"For the full industrialization of the underdeveloped countries, for the continuation of our civilization and its further development, atomic energy is not merely an aid, it is a necessity. The acquisition by man of the knowledge of how to release and use atomic energy must be recognized as the third epoch of human history."*

Of course, Bhabha was fully cognizant of the potential of atomic energy for wide-scale destruction. He urged the USA and USSR to jointly maintain peace and stop proliferation of nuclear weapons in the next ten to fifteen years. He concludes *"If this is not achieved in this period, the situation may well go outside their control, and the world become a much more unstable place"*. He continued to espouse these views on non-proliferation at various fora. At the Pugwash conference held at Udaipur in January 1964, he drew attention to *"proliferation dynamic inherent in the situation, which made it imperative that urgent action be taken within the framework of the United Nations"* and then added *"It would, therefore, appear to be in the interest of everyone to see that substantial progress towards general disarmament is made as soon as possible."*

Space and Electronics

Bhabha contributed in an important way to India's space programme in its early days. In late 1961, when the Government wanted to start the programme, the responsibility was allocated to the DAE. Presciently, Bhabha remarked that space research is likely to yield *"results of great practical interest and importance in the near future, and we would be falling behind the advanced countries in technology if we were not to look ahead and prepare ourselves to take advantage of these new developments also…If we do not do so now, we will have to depend later on buying know-how from other countries at much greater cost…"* He went on to add: *"In space research we are today at the stage where we were in atomic energy work over ten years ago…in the DAE we have (today) the largest scientific research organization in the country. I therefore expect that within a few years our present modest beginnings will grow appreciably and Indian scientists will be making important contributions in the field of space research…"*

Bhabha with Cecil Powell, Patrick Blackett and Vikram Sarabhai

Bhabha was instrumental in setting up the Indian National Committee for Space Research under the chairmanship of Vikram Sarabhai. Further, the Thumba Equatorial Rocket Launching Station was set up, and plans for an Indian Space Science and Technology Centre were put in place.

Bhabha's engagement with electronics had its origin in the atomic energy programme. In his address to the second conference on Nuclear Electronics in 1965, Bhabha stated that *"in any* *developing country which does not already have an organized electronics industry, a self-reliant atomic energy programme will necessitate not only the indigenous development of nuclear electronic instruments, but also organized work on other aspects of nuclear electronics and computers, process instruments and control systems".* With this background and first-hand knowledge of what could be accomplished in the country, the AEC recommended to Government that an electronics committee be set up to survey the needs of the country in electronics and to recommend measures for planned development to achieve self-reliance in the shortest possible time and in the most economical manner. The Electronics Committee was formed in 1963 under the chairmanship of Bhabha. He remarked: *"Our country came to realize rather belatedly in 1963 that electronics is not just something for the entertainment industry but one of the most vital and essential branches of modern technology"*. The Committee's report was finalized towards the end of 1965, but was presented to the Prime Minister only in February 1966, after Bhabha's death.

Music, Art and Gardens

Throughout his life, Bhabha was passionate about music and the arts. In a letter to his brother Jamshed written during his student days at Cambridge, he describes a concert he had just attended (a performance of Beethoven's Ninth Symphony): *"Never before have I been so moved. The performance was by no means faultless, but all the faults are forgotten in the greatness of the work. I was drawn out of myself and raised to sublime heights, and my mind hardly got back to earth till a long time after the end ..."*. Jamshed later noted that "In his last fifteen years …he would find relief from tension and fresh stimulus in listening to music at night. There was hardly a single free evening at home when he would not be listening to music after dinner and before taking up his mathematical work till late at night". He added: "For Homi Bhabha, the arts were not just a form of recreation or pleasant relaxation; they were among the most serious pursuits of life and he attached just as much importance to them as to his work in mathematics and physics. For him, the arts were, in his own words, 'what made life worth living'."

Bhabha was a good artist himself, and his paintings and sketches of various subjects provided a creative outlet. He was also immensely appreciative of good art, and strongly encouraged young artists in the 1950s. Members of the Bombay Progressive Artists' Group, which included F. N. Souza, K. H. Ara, M. F. Husain, Tyeb Mehta and S. H. Raza, benefited from his abiding interest and patronage. Today, many of their paintings adorn the corridors of TIFR, which has one of the finest collections of art in the city.

A sketch of young M. F. Husain by Homi Bhabha

Bhabha had a love for trees and gardens. The art critic Rudi von Leyden, who was a friend, visited him at home, and noticed: "…there stood, near his desk, an enormous drawing board with huge printed plans, pinned to it. It appeared they were the first layouts for the afforestation schemes and suggested gardens at Trombay…He spent many hours at night poring over these plans, trying to visualize in his mind's eye the setting of this new city, which he had founded and built nestling below the tree-grown flanks of the Trombay Hill and within a vast arrangement of gardens. The planning, design and the style of these gardens fascinated him…"

A Tragic Loss

On his way to Vienna to attend a meeting of the Scientific Advisory Committee of the International Atomic Energy Agency, Homi Bhabha died on board an Air India Boeing which crashed on Mont Blanc in the Alps on January 24, 1966.

The world lost a great physicist and advocate of the peaceful uses of atomic energy. India lost a dedicated visionary and patriot, in the best sense of the word, who worked relentlessly towards bringing the advances of science and technology to bear on the development of the country.

A condolence meeting held at TIFR on January 25, 1966 passed the following resolution:

"The hearts of all present are too full to find expression that would be truly fitting or appropriate for this most gifted son of India, whose splendid vision and imagination were ever at the service of his country, whose unsurpassed energy and enthusiasm were a driving force that spurred men to give their best, and whose humane and gentle thoughts were for his family and others nearest to him and yet moved out to larger and ever widening circles of all who needed his care, attention and regard."

At a condolence meeting held at the Atomic Energy Establishment, Trombay on the same day, Vikram Sarabhai read out a condolence resolution, from which an excerpt is quoted below:

"The meeting places on record its deep sense of inconsolable grief at the sudden and tragic passing away of Homi Jehangir Bhabha, one of the greatest scientists and engineers of the country, and the most versatile genius India has produced.

The death of a great man does more than put an end to a scientific career. It destroys an accumulation and synthesis of knowledge, skill, judgement and experience that cannot be transmitted and preserved in its entirety because it is incommunicable. To all of Homi Bhabha's associates and colleagues these were the best part of what by devotion, industry, enthusiasm and intelligence of the highest order he had made of himself in almost every field of human endeavor – the arts, sciences and humanities – an achievement even greater than his contributions to atomic energy, and never to be replaced. His contributions to research will perpetuate his scientific memory. But as a unique personality who sparked the development and advancement of atomic energy, and as one, who more than any single individual in this country, at any time in its history, recognized the importance of science in its manifold aspects for the progress of civilization and as one who ardently advocated the cause of scientific progress in developing countries, Homi Bhabha was one of the great experiences in the life of the country and in this sense he will never die unless science itself ceases to exist."

"I know clearly what I want out of life. Life and my emotions are the only things I am conscious of. I love the consciousness of life and I want as much of it as I can get. But the span of one's life is limited. What comes after death no one knows. Nor do I care. Since, there, I cannot increase the content of life by increasing its duration, I will increase it by increasing its intensity. Art, music, poetry and everything else that I do have this one purpose-increasing the intensity of my consciousness of life."
Homi Bhabha in a Letter to Jessie Maver, 1934

Acknowledgements

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I have drawn extensively on material from the following books:

- "Bhabha and his Magnificent Obsessions" by G. Venkataraman, Universities Press (1994)
- "Homi Jehangir Bhabha on Indian Science and the Atomic Energy Programme: A Selection", Tata Institute of Fundamental Research (2009)
- "The Visionary and the Vision", based on the TIFR Permanent Exhibition

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Vikram A. Sarabhai- Innovator, Industrialist and Visionary

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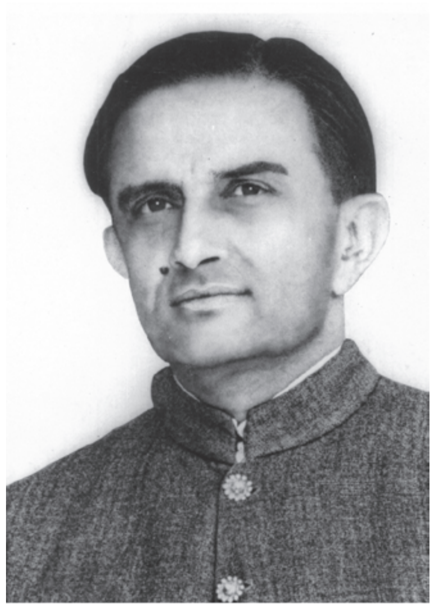
Those that can apply their insights to the problems of the community and of the nation, discover an exciting area of activity where effort is rewarding even while the results show slowly….

-Vikram A. Sarabhai



Vikram A. Sarabhai 1919-1971

Preamble

The story of the growth of Indian science and technology in independent India has two prominent personalities embellishing its pages- Dr. Homi J. Bhabha and Dr. Vikram A. Sarabhai. Both these great sons of India gained pre-eminence in their respective spheres – Dr. Bhabha as the father of the Indian nuclear programme and Dr. Sarabhai as the father of the Indian space programme. Their lives and careers met and intermingled in numerous ways, as students, scientists, institutional builders and visionaries. The story of Dr. Bhabha has already been detailed in the previous chapter and in this article, we shall try to delve into the life, career and achievements of Dr. Vikram Sarabhai.

The Birth of a Scion

Vikram Ambalal Sarabhai was born on August 12, 1919 at Ahmedabad, Gujarat. A fair and handsome baby with a large forehead, it was his big ears which stood out prominently, and were the cause of much amusement amongst his siblings. Father Ambalal Sarabhai was an affluent industrialist, and a well-known citizen of the city, owning multiple businesses. They lived in a large mansion which was known as 'The Retreat', with 50 rooms, outhouses, garages, swimming pools, tennis courts and a cricket ground. It was a mini township, with a retinue of servants looking after the premises which also had a dhobi ghat, a cowshed and a stable with horses for every member of the family.

Growing Up

Ambalal Sarabhai and wife Sarla Devi, in tune with their affluence and privileged status, were progressive and modern in their outlook and thinking, but were equally steeped in the basic mores of Indian traditions. They had eight children, who were loved and cherished, pampered yet disciplined, not wanting of anything, yet taught to value the worth of everything. Searching for the perfect mix of education and upbringing for their children, they found none in the traditional

The Retreat

Family with Rabindranath Tagore

schools of those times in the country. They came across the work of an Italian physicist Maria Montessori, who propagated an education system with the credo *'first the education of the senses and then the education of the intellect'*, and were convinced that this was the best method for their children. Not being short of funding or resources, they started their own school at 'The Retreat' for their eight children. The faculty was a rich pick from the academic and arts worlds, including PhD's and graduates from european universities as well as local experts and stalwarts. The curriculum was wide and varied- including languages, history, geography, mathematics, physics, chemistry among others. Training in arts such as drawing, painting, dance, music, pottery as well as sports were part of the curriculum. The main premise of education at this unique school was that the primary function of the teacher was *'not merely imparting knowledge but stimulating in the pupil its love and pursuit'*. To broaden the horizons further, the family went on periodic vacations, both within India and abroad.

Vikram was a precocious child, and had fallen in love with sciences and engineering at an early age. A full-fledged workshop as well as physics and chemistry labs were specially set up for him to tinker and experiment. He built a steam engine with tracks, large enough for him to sit on and ride. A particularly amazing fact about his precocity is that he used to write a letter to himself on some topic of interest and post it to himself. His teacher commented '*I could see in him a mind with an intellectual awareness. Even at a young age, Vikram's pursuit of knowledge was all-encompassing'*. Vikram's upbringing was further enriched by exposure to some great minds of the time who visited 'The Retreat', such as Rabindranath Tagore, J.C.Bose, C.V.Raman, Rukmini Arundale, J.Krishnamurti, Sardar Patel, S.Radhakrishnan, Jawaharlal Nehru, M.K.Gandhi, and many others. As a child, his discussions with Mahatma Gandhi on the social problems of the country particularly touched him as Gandhi spoke to him on equal terms despite his tender age.

His evolution as a person and of his beliefs in the application of scientific methods to all his pursuits perhaps owes much to the foundations laid at the Retreat. He was to say in a talk *'Many people suppose that there is an absence of the imaginative and intuitive element in the pursuit of science. This is a fallacy. A true scientist has the compelling urge to test his concepts in terms of observations. He is ready to let his castle crumble to dust on the results of his experiments'*. He went on to successfully extend the application of scientific methods to a variety of fields such as management, design, manufacturing and market research, eventually culminating into forays in space science and atomic energy at the zenith of his career.

On completion of basic education from The Retreat and clearing his matriculation from a local School, he joined the Gujarat College for the Intermediate course. He excelled in Chemistry which he topped and narrowly missed the top position in Physics, losing marks due to an answer not provided in the expected manner. He also learnt sanskrit poetry and played cricket for the college team. Armed with a recommendation from Rabindranath Tagore- *'He is a young man with a keen interest in science and comes from a wealthy, cultured family. He is a fit and proper person for admission to the university'*-he left for Cambridge in 1937. He was at Cambridge from 1937-1940, completing his tripos in natural sciences, before the war brought him back to India. He continued his post graduate studies under Sir C.V.Raman at the Indian Institute of Science, Bangalore, carrying out Cosmic Ray research under his supervision. His first paper 'The Time Distribution of Cosmic Rays' was published in 1942. It was during this period that he came into contact with Dr. Homi Bhabha, who like Vikram, had also returned from England during the war and was a reader at IISc. They were of similar backgrounds and soon formed a professional and personal relationship which lasted a life time and which had great significance in the future technological developments of India. He received some exposure to Hindu philosophy and the Vedantas at the nearby Ramakrishna Mission during this period, which perhaps refined and clarified his thought process. He was to develop a taste for classical Indian music and dance during this period and he met Mrinalini Swaminathan in connection with organizing a fund-raising concert. They fell in love and were married at Bangalore in 1942, in the throes of the Quit India movement. None of his family members could attend the wedding due to the ongoing national stir. They left Bangalore for Ahmedabad soon after the wedding, where he continued his

At Cambridge

With Wife Mrinalini Sarabhai

scientific research despite trying circumstances, with four of his sisters and two aunts being in jail. Such was his interest and dedication to research that he organized a team of 90 persons and undertook a strenuous trek on ponies to reach the location in Kashmir to carry out experimental studies on cosmic rays at high altitude. Returning to Bangalore, he plunged into research once again and completed the first part of his thesis work before leaving for England in 1945 to complete his PhD. In his thesis, amongst others, he thanked Dr. Bhabha for '*helpful discussions regarding cosmic rays*, and Sir C.V.Raman for his '*continuous encouragement and for supervising his work in Bangalore*'. Completing his dissertation and oral examination by the distinguished P.M.S.Blackett, he returned to India in 1947, just before India attained independence. The speech of the Prime Minister, Pandit Jawahar Lal Nehru, at the stroke of midnight on August 15, 1947, '*The future is not one of ease or resting, but of incessant striving, so that we may fulfill the pledges that we have so often taken, and the ones that we shall take today',* was perhaps what inspired him to work relentlessly on multiple fronts. He indeed epitomized the spirit of these pledges, taking no rest till his last breath.

Institution Building and More

On his return to India, being a trained scientist as well as the son of a mill owner, Vikram Sarabhai, along with his father Ambablal Sarabhai and S.S. Bhatnagar, conceived of a textile research institute, Ahmedabad Textile Industry's Research Association (ATIRA), to improve and modernize the textile manufacturing processes in India. This arose from his firm belief in the benefits of applied science. He said '*The history of science is full of examples which alternate from being extremely practical to being extremely basic in their approach, and it is through the interaction between the basics and the empirical and practical problems that we find the greatest and the most fruitful developments of modern science and technology. Those who can pose basic questions are the ones who can do applied work"*

He was appointed as the Honorary Director of ATIRA and plunged headlong into the activities of one of the first industrial research unit set up in the country. After some difficulties and resistance initially experienced in implementing novel ideas, he could eventually convince

Family Business Meeting

the workers and management of the benefits of industrial research and win over their minds and hearts. The work at ATIRA managed to save tens of crores to the textile industry. His experiences in dealing with the scientists, management and workers in the textile industry convinced him to set up a wing on industrial psychology led by Ms. Kamla Chowdhry, another first in the Indian industrial scenario.

His interest in scientific research did not however take a back seat and seeing a lack of research facilities in the country, he decided to set up the Physical Research laboratory in November 1947, to further research activities in cosmic rays and other related programmes. He roped in K.R.Ramanthan as the first director of PRL , which operated from temporary premises for a few years. The foundation stone for a new building was laid in February 1952, in the presence of S.S.Bhatnagar, Homi J. Bhabha, C.V.Raman and other dignitaries. The building was completed and inaugurated within a short span of two years by the then prime minister, Pandit Nehru, in April, 1954.

At Inauguration of PRL

The new institute attracted a number of students interested in nuclear and cosmic ray physics, such as Praful Bhavsar, R.G.Rastogi, E.V.Chitnis, U.R.Rao and many others, all going on to lead important scientific programmes in the country in later years. Despite his scientific interests and commitments, he also continued to participate in the family businesses and took over the chairmanship of Sarabhai Chemicals at Baroda in 1950, converting it into one of the first professionally managed companies in India. Sarabhai Chemicals signed agreements for the manufacture of Tinopal and Vitamin C, both of them going on to achieve huge successes. Manufacture of antibiotics was also pioneered by this company and his vision of complete backward integration of industries was slowly gaining ground. He travelled to Sarabhai Chemicals, Baroda only once a week, leaving it upto the management to take all decisions. Even the time taken to travel to Baroda was not wasted, as he utilised the travel time to carry out research discussions with his students at PRL, who accompanied him on the trips. He was also a visiting professor at MIT in Boston, which he visited every summer, carrying out work in X-Ray Astronomy and Space Plasma Physics.

Keen as he was upon the use of science and technology as the means for national progress, he was equally convinced that modern management techniques were required towards achieving the best outcomes in private as well as public enterprises. He was instrumental in setting up the first management institute, Indian Institute of Management (IIM) at Ahmedabad in 1962 as well as the first market research agency, Operations Research Group (ORG) in the country. The National Institute of Design (NID) was another Sarabhai led initiative, though helmed by his brother and sister, Gautam Sarabhai and Gira Sarabhai. The Nehru Foundation for Development, a think-tank organisation, dedicated to promoting basic environmental education and thinking on current problems of development at individual and societal level was founded in 1965. The Community Science Centre, an institute set up to promote and popularize science education and scientific temperament amongst students, teachers and public was also established under his patronage in the 1960s, apart from the Darpana Academy for Performing Arts at Ahmedabad with his wife Mrinalini Sarabhai, way back in 1949.

Innauguration of IIM

What is remarkable about these initiatives is the fact that these were first of its kind institutes in the country, with no prior experience or foreknowledge about their success and viability in a country still gaining its feet after centuries of colonial exploitation. They were leaps of faith, built upon the dreams and beliefs of a visionary and an ardent patriot, keen upon seeing rapid growth of the nation across multiple fronts.

But much more still awaited this great son of India. The two superpowers, USA and USSR had launched atomic energy and space programmes. Keen not to be left behind in the use of these technologies in the socio-economic development of the nation, Vikram Sarabhai was to play a crucial role for the country in these two spheres over the years to come.

Launching into Space

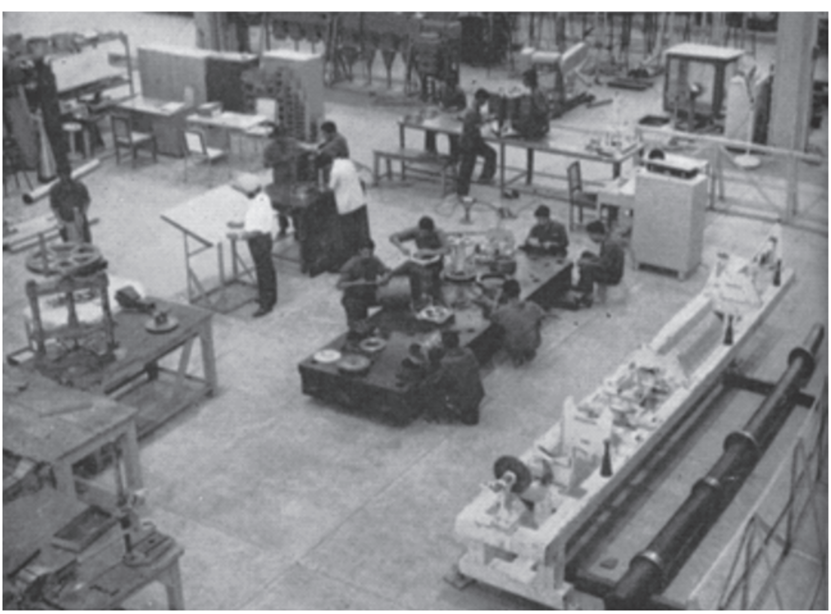
Dr. Sarabhai had learnt a great deal of the applications of space sciences and satellites, being in touch with some of the leading space scientists of the world, and was keen to pursue this activity in India. The opportunity came calling when Dr. Homi Bhabha established a programme on 'Space Research and the Peaceful Uses of Outer Space', in DAE in 1961, with PRL being identified as the centre for R&D in space sciences. Dr. Sarabhai was inducted into Atomic Energy

Commission (AEC) to oversee this activity. The Indian National Committee for Space Research (INCOSPAR) was subsequently founded in 1962 under the Chairmanship of Dr. Vikram Sarabhai. Thus began a very successful odyssey of Dr. Sarabhai into space research, which has resulted in the country becoming one of the leading nations in the world in space science, launch vehicles, and communication satellites.

With Dr. Bhabha at Thumba

The voyage began modestly, with the setting up of a sounding rocket programme at Thumba near Trivandrum. Dr. A.P.J.Abdul Kalam, one of the first recruits to this programme was an active member of the team, just beginning a career in space research and its applications and eventually rising to great heights. He recalled his first encounter with Dr. Sarabhai which left a lasting impression- *'l was almost immediately struck by Dr Sarabhai's warmth. He had none of the arrogance or the patronising attitude which interviewers usually display when talking to a young and vulnerable candidate. Dr. Sarabhai's questions did not test my knowledge or skills, rather they were an exploration of the possibilities which I was filled with. He was looking at me as if in reference to a larger whole. The encounter seemed to me to be a total moment of truth, in which my dream was enveloped by the larger dream of a bigger person'*.

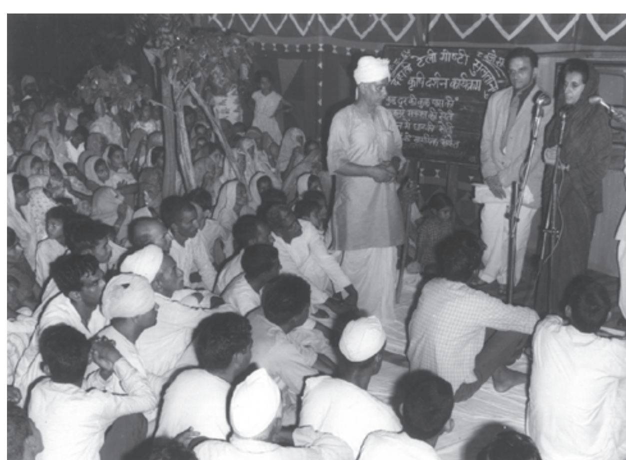
The first rocket was successfully launched on November 21, 1963 after some glitches, under the watchful eyes of Dr. Bhabha, Dr. Sarabhai and several other dignitaries. Elated with the success, Vikram sent home a telegram-'*Gee whiz wonderful rocket launched'*. However, he was not a man to rest on his laurels and following this initial success, Dr. Sarabhai quickly upped the



Rocket Building Workshop

target to the building of a satellite launch vehicle. He explained his goal thus- '*The sun provides the driving force for almost everything that happens on earth, weather, rivers, vegetation, fossil fuels and of course life itself. But in contrast to the apparent constancy of the sun and the complete dependability of sunrise and sunset, we experience a capriciously variable environment, the fury of hurricanes and lashing ocean waves, drought, floods, starvation one year and bumper crops another, and uncertain radio communications. The natural scientist looking for the subtle links through which the sun effects the earth and our lives has at last acquired in the exploration of space a dramatic new capability for study'*. He believed that space science will find applications in agriculture, forestry, oceanography, geology, prospecting, etc. His thoughts and ideas were perceived to be much before his times, the stuff of science fiction as it appeared to most people then, but which have proven to be prophetic. He was also confident that the requirements of space science would catalyse growth across multiple domains of science and technology. His focus remained firmly fixed on the peaceful applications of space technology and the socioeconomic benefits accruing from it. The space activity grew with the addition of a satellite telemetry station and a computer centre at Ahmedabad. Vasant Gowarikar was drafted in at the newly established Space Science and Technology Centre (SSTC) for the manufacture of sounding rockets named 'Rohini'. Abdul Kalam, nicknamed Busybee, was an important team member. Indigenisation was the buzzword and every component was manufactured from scratch using basic materials. Those were heady, fearless days, full of challenges and inconveniences, but such was the leadership and motivational skills of Dr. Sarabhai that almost no one quit. The Thumba facility was officially renamed as the Thumba Equatorial Rocket Launch Station and dedicated to the UN. Meanwhile, a full-fledged feasibility study for building a satellite launch vehicle began in earnest under the guidance of Dr. Sarabhai. On account of his farsighted ideas, vision and acumen, he gained prominence in the space science community and was nominated to be the Scientific Chairman of the 'United Nations Conference on the Exploration and Peaceful Uses of Outer Space ', in August 1968. He said at the conference - *'It is important to note a fundamental aspect of human development that knowledge cannot for long be contained within artificial boundaries and one has to learn to share rather than control harmful effects through withholding transfer of technology or knowledge. Restrictions on the transfer of technology which are involved in the peaceful uses of outer space merely jeopardise the security of the world through retarding the progress of Nations'*.

His passion for using space for developmental activities led him to conceive a country wide Satellite Instructional Television Experiment (SITE), the world's first experiment in direct satellite broadcast, for relaying instructional material on weather, health, agriculture etc. across 2400 villages in India. An American satellite was taken on loan for this purpose and earth stations were built at Ahmedabad and Delhi.



SITE Programme

In a significant development, space research activities which expanded significantly riding on the support of DAE, were constituted into a dedicated space research organisation ISRO in 1969 under Dr. Sarabhai's leadership. A satellite Launch Station at Sriharikota was established in the same year while work on the satellite launch vehicle was gathering pace at Thumba. His ten year profile plan also included the development of a wide range of space craft subsystems and other equipment.

At the Helm of DAE

Dr. Sarabhai had already been inducted into some of the DAE activities by Dr. Homi Bhabha. He was a member on the board of the crucial electronics committee for expanding electronics research and production in India as well as the Chairman of INCOSPAR. The sudden demise of Dr. Bhabha in an air crash had left a vacuum and Dr. Sarabhai was deemed to be a worthy successor for the post of Chairman, AEC. On being offered the post, he wrote to the Prime Minister-' *While I have great job satisfaction in my present work, I am attracted by the opportunity for taking over the work which was started by Dr Bhabha. The task of pushing ahead with the application of science and technology for the needs of the nation under your leadership is an aspiring one, which I am happy to shoulder, accepting full responsibility'.*

Many of the programmes initiated by Dr. Bhabha were taken forward by Dr. Sarabhai in quick time. Indigenisation and self-reliance were encouraged across all segments of the nuclear power program. He mooted several ideas and proposals in his prospective Profile Plan for the quick expansion of nuclear energy and space research applications in India for the decade 1970-80. This included the enhancement of nuclear power generation as well as the design of larger capacity 500 MW thermal reactors to lower the capital costs of power generation while producing plutonium for future fast breeder reactors; completion of the fast breeder test reactor to gain experience in the technologies of plutonium enriched fuel, sodium coolant and thorium bred U-233 fuel; construction of a 500 MW Prototype Fast Breeder Reactor at the second stage of the nuclear power programme, as a pivot in the realisation of India's three-stage nuclear power generation program; development of gas centrifuge technology for U-235 enrichment, and applications of radioisotopes in industrial processing, food preservation, medical sterilisation, nuclear medicine and other research programmes. His strong business and management background was evident in his vision plan which envisaged the creation of an integrated organisation with the participation of public as well as private enterprises of the country, to back up and implement the programmes in all its phases- from the production of raw materials to the fabrication of specialised equipment, as well as the erection and commissioning of major plants and projects within stipulated time frames. To meet this objective, he consolidated the activities of many atomic energy R&D new public sector undertakings, namely Electronics Corporation of India (ECIL) for design and manufacture of reactor control systems and electronic components, Uranium Corporation of India Ltd. (UCIL) for extraction of Uranium from various mines including from low grade ores of the Narwapahar mines, Nuclear Fuel Complex (NFC) for

At BARC with Dr. Sethna and other dignitaries

fabrication of special materials and Uranium fuel elements, and a Power Projects Engineering Division (PPED), the precursor to the current Nuclear Power Corporation of India Ltd (NPCIL), for designing, constructing commissioning and operation of nuclear power reactors.

A Research Reactor Center (RRC) dedicated to fast reactor technology- later rechristened as Indira Gandhi Centre for Atomic Research (IGCAR) in Kalpakkam- is one of Dr. Sarabhai's important contributions to the nuclear power programme of the country. His five year tenure as AEC Chairman also saw the prioritisation of Heavy Water production - critical to the operation of a nuclear reactor. All activities relating to it were brought under one roof and Heavy Water Board (HWB) was constituted in 1968 to expedite implementation of Heavy Water Projects. Plans were drawn for setting up of new greenfield industrial plants in Baroda, Tuticorin and in other parts of the country. Ongoing indigenous research in BARC based on H_2S- H_2O process was encouraged towards fruition, eventually leading to the establishment of a globally first-of-its-kind large scale plant at Manuguru. Variable Energy Cyclotron Centre and the PURNIMA reactor projects were also initiated during his tenure.

He garnered considerable international recognition on account of his ambitious plans and visionary outlook, and was nominated to the to the 14th General Conference of IAEA held in 1970 at Vienna as its President.

The Final days

Though Dr. Sarabhai was tirelessly pursuing his numerous activities across the country, the hectic schedules were beginning to take some toll on his energy levels. He evolved a method of taking two-hour sleep breaks between work schedules and a monthly break off to rejuvenate himself. He left for his customary weekly visit to Thumba on 28th December, 1971 and the next two days were packed with meetings and official engagements at Thumba. He spoke to Abdul Kalam on the phone on the 29th and told him to meet him at Trivandrum Airport the next morning on his way to Mumbai. He never did make that journey, passing away in his sleep sometime during the night. He was found peacefully still under a mosquito net, a book lying upon his chest. He was cremated at Ahmedabad on December 31st, 1971. Daughter Mallika lit the funeral pyre as son Kartikeya could not arrive from USA on time. His ashes were scattered in the Indian Ocean near Thumba.

Dr. Sarabhai received several honours such as the Shanti Swarup Bhatnagar Prize for Physics research in 1962, Padma Bhushan in 1966 and Padma Vibhushan posthumously in 1972. In a fitting tribute to this man who was a rare combination of innovator, industrialist and the visionary, the BESSEL Crater on Moon was named after Sarabhai in 1974.The legacy and

The Final Journey

contributions of this great son of India to the development of science and technology have left a far-reaching impact in the socio-economic development of the country.

The Legacy and the Lessons

The legacy and extraordinary contributions of Dr. Vikram Sarabhai are the stuff of legends. In a relatively short span of 24 years, he established institutions and set into motion numerous programmes of great national significance. What made this man tick? His privileged upbringing and wealthy background did open doors at the right times in the initial phase of his career. However, it was his hard work, ability to deliver successful outcomes, courage and vision, coupled with his leadership skills and human qualities, which propelled him into a different league thereafter, leaving behind a legacy which is perhaps beyond comparison in the annals of Indian science.

There are many facets to his personality which are worth recalling and emulating. He had the ability to dream big, the capacity to build institutions to implement his ideas, fearlessly adopt novel methods and systems and have the courage of conviction to follow them through despite the challenges faced. He was an eternal optimist, not afraid to take risks and encouraging his team to do the same. He did not frown upon failures and setbacks, treating them as part of the process for the greater good of the system. This resulted in strong teamwork, with members willing to take up any challenge, supporting and encouraging each other every step of the way. He did however make sure that lessons were learnt from failures, by setting up suitable review systems.

His greatest asset was his ability to connect with people and motivate them to take up even the most challenging pursuits without flinching. He would identify talented people, imbue them with a sense of purpose, and then give them a free hand to push ahead. He was highly approachable, being simple and unassuming in his manner, and maintaining good cheer and a sense of informality with all his subordinates. He was extremely warm and friendly towards all those he met, friends, colleagues, subordinates and superiors. For him people were to be respected regardless of their position in the organisation.

He had the quality of being able to build rapport across varying professional strata and earn the support and respect of all those he dealt with, including vastly superior intellects- on account of his sincerity and undiluted passion. Always a keen listener, he gave equal importance to views not in agreement with his own, firmly believing that all views had to be heard and considered before arriving at a decision.

He believed in the delegation of authority to speeden the decision-making process. This remained the method all through his career, allowing him to smoothly carry out fruitful collaborative work with a host of institutes and scientists. He would seed projects and leave them in capable hands once it had made reasonable progress, moving on to other work. However, he had indefatigable energy to absorb information and monitor numerous projects simultaneously, through periodic meetings and site visits as well as by thoroughly reading the reports submitted.

The following quotation of Dr Vikram Sarabhai sums up his leadership style and success mantra quite aptly- '*There is no leader and no led. A leader, if one chooses to identify one, has to be a cultivator, rather than a manufacturer. He has to provide the environment in which the seed can grow'*.

References

1. Vikram Sarabhai, A Life', by Amrita Shah. Published by Penguin Books. 2007.ISBN 9780143426745.
2. Nuclear India: Various Issues.
3. Physical Research Laboratory (PRL) https://www.prl.res.in

Atomic Mineral Exploration in India: Landmarks and Vision

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Preamble

The Department of Atomic Energy (DAE) of India has adopted a closed nuclear fuel cycle for enhanced nuclear power generation in order to ensure efficient use of uranium resources, reduction of high level waste and utilisation of large thorium resources of the country. Atomic Minerals Directorate for Exploration and Research (AMD) is mandated with the exploration and augmentation of atomic mineral(s) resources (uranium, thorium, niobium, tantalum, lithium, zirconium, beryllium and REE minerals) of the country in the front phase of nuclear fuel cycle to support the Nuclear Power Programme of India. The Directorate also caters to geotechnical investigations of potential sites for nuclear power plants and geological repositories for long term disposal of radioactive waste in the end phase of fuel cycle.

Introduction

Mineral resources play a major role and act as basic ingredients to meet energy, defence, space research, industrial, civilian and technological requirements of a nation. The exploration, mining, extraction and utilisation of these minerals are guided by national goals and perspectives and closely integrated with the overall strategy of the country's economic development. To reduce import dependency, it is essential to discover large tonnage high-grade deposits so as to secure the sustained supply-chain of industrial mineral resources.

The need to establish indigenous atomic mineral(s) resources was first realised by the visionary scientist Dr. Homi Jehangir Bhabha. Dr. Bhabha laid the foundation of the Nuclear Power Programme (NPP) of the country and the Government of India accepted his proposal and the

Atomic Energy Commission (AEC) of India was constituted on 10th August, 1948 comprising three eminent scientists of Independent India, Dr. Homi J. Bhabha as Chairman, Dr. K.S. Krishnan as Member and Dr. S.S. Bhatnagar as Member Secretary. The Commission constituted by the President of India had three prime missions- (1) to protect the interests of the country in connection with Atomic Energy by exercise of the powers conferred on the Government of India by the provisions of the Atomic Energy (AE) Act (2) to survey the territories of the Indian Dominion for the location of useful minerals in connection with Atomic Energy and (3) to promote research in their own laboratories and to subsidise such research in existing institutions and universities. The Department of Atomic Energy (DAE) was setup on August 3, 1954 under the direct charge of the Prime Minister through a Presidential Order. Subsequently, in accordance with a Government Resolution dated March 1, 1958, the AEC was established in the DAE.

In India, the basic framework of mineral prospecting, concession and mining regulation is guided by the Mines and Minerals (Development and Regulation) Act, 1957 (MMDR Act-1957) and the Rules thereunder. Atomic minerals refer to such minerals, which are or may be used for the production or use of atomic energy or research into matters connected therewith. Atomic Minerals are specified in Part B of the First Schedule to the MMDR Act-1957 and some of these are included in the list of prescribed substances under the AE Act, 1962. These include mainly the minerals, their derivatives or compounds containing uranium, thorium, Rare Metals (RM) viz. niobium, tantalum, lithium and beryllium, which are required to support the Nuclear Power Programme (NPP) of India.

In the pre-independence era, during the Second World War (1939-1945), Geological Survey of India (GSI) had created the Rare Minerals Survey Unit (RMSU) with the sole purpose to procure beryl from the mica mines of the country. Dr. Bhabha's efforts fructified in transferring the RMSU, which was then functioning under GSI, to Ministry of Natural Resources and Scientific Research in 1948 and consequently the RMSU was brought under the control of AEC w.e.f. July, 1949 with a focused mandate of exploring strategic minerals and metallic elements of interest to atomic energy programme of the country such as uranium, thorium, beryllium, graphite etc. Dr. Bhabha entrusted the mandate of exploration of atomic minerals in the country to an eminent geologist, Dr. D.N. Wadia. Consequently, Dr. Wadia, the then geological advisor to the Government of India and Head of RMSU, created the first task force of geologists for conducting countrywide exploration for atomic minerals by mobilizing geoscientists from various Universities and organizations. In 1953, RMSU was re-named as Raw Material Division (RMD) and later as Atomic Minerals Division in 1958. On its Golden Jubilee in 1998, the organization was rechristened as Atomic Minerals Directorate for Exploration and Research (AMD). AMD, is thus the oldest unit of DAE, which in the front end of the fuel cycle shoulders the responsibility of exploration, evaluation and augmentation of atomic mineral inventory of the country mainly uranium, thorium, Rare Metals (RM) viz. niobium, tantalum, lithium, zirconium, beryllium and Rare Earth Elements (REE) to support the NPP of India. The organization also caters to the geotechnical investigations of potential sites for nuclear power plants and geological repositories for long term disposal of radioactive waste in the end phase of fuel cycle.

After the Jaduguda uranium deposit was established in Singhbhum, Bihar by erstwhile RMSU in 1950s, DAE created the Uranium Corporation of India Limited (UCIL), a public sector undertaking under Government of India in 1967 with the sole purpose of mining and processing of uranium ore in the country for the three stage nuclear programme. During August, 1950, with the primary intention of taking up commercial scale processing of monazite sand, Indian Rare Earths Limited (IREL) was incorporated as a private limited company jointly owned by the Government of India and Government of Travancore, Cochin with its first unit namely Rare

Earths Division (RED) at Aluva, Kerala for recovery of thorium. The IREL became a full-fledged Central Government Undertaking in 1963 under the administrative control of DAE. In 2019, IREL was renamed as IREL (India) Limited. These three units of DAE viz. AMD, UCIL and IREL (India) Limited are responsible for the supply of raw materials required for the NPP of the country. These units are ably supported by the Bhabha Atomic Research Centre (BARC), which is involved in ore dressing and other research involved in processing of the raw material for converting them into fuel.

This article presents a documentation of the major landmarks achieved by AMD in augmentation of atomic mineral(s) resources in India, advancements brought about in its exploration capabilities and the vision of the Directorate for attaining self-reliance in atomic mineral resources to support the comprehensive three-stage NPP to cater to the long term energy security of the country.

Historical perspective of exploration for Atomic Minerals in India

The history of exploration for atomic minerals in India dates back to the discovery of the occurrence of monazite bearing black sand along the southern and south-western coast of India by a German Chemist, Schomberg in 1909. The first report of uranium in India is documented in records of Indian Geological Survey of 1913 when occurrence of gummite (altered uraninite) and a 36 pound pure uraninite nodule was discovered from a pegmatite rock of Gaya district, Bihar.

The Singhbhum Copper Belt in Eastern India became the obvious first choice for surveys for uranium in India following the analogy of vein type, structure controlled, shear induced, hydrothermal uranium deposits established by that time in Shinkolobwe, Congo and the Rocky Mountains, USA. Torbenite, a secondary uranium mineral, reported from Singhbhum in the early 1920s by a private prospector (E.F.O. Murray) and documented in the records of the GSI in 1921, helped in framing the policies for early surveys. The first extensive surveys for uranium began in 1949 in Singhbhum by a joint team of geologists from the AEC, GSI and Damodar Valley Corporation (DVC) who discovered some 57 uranium anomalies. Follow-up exploratory drilling to prove the depth continuity of these anomalies commenced in December 1951 by contracting the services to M/s. Associated Drilling & Supply Company, London, who were later joined by Indian Bureau of Mines (IBM) and RMD (now AMD) between 1953-55 (Fig. 1).

Fig. 1: Exploratory drilling in Singhbhum in 1955.

A total of ~70 km had been drilled and mineable uranium deposits were established at Jaduguda, Bhatin, Narwapahar and Keruadungri till 1963. Closely following the discoveries in the Singhbhum Shear Zone (SSZ), surveys carried out in western India during 1955-56, led to discovery of uranium mineralisation in calcareous/carbon phyllite at Umra in Aravalli Fold Belt and pegmatite at Bhunas in Rajasthan.

The introduction of airborne surveys was a major input to the exploration activities of AMD. AMD first carried out airborne scintillometer survey in parts of Rajasthan during 1955 utilising helicopter of Indian Air Force, which was later replaced by a hired, light-weight, twin-engine 'Dominie' aircraft due to limited capabilities of helicopter. Various geological domains in parts of Andhra Pradesh, Bihar, Gujarat, Madhya Pradesh, Tamil Nadu, Karnataka, Odisha, Rajasthan and West Bengal were covered by flying over 1,19,330 sq. km. area between 1957-62. This exploration technique was in infancy stage in India during the fifties when indigenously designed and fabricated scintillometer assembly optically coupled to photomultiplier tubes, a counting rate-meter and a Graphic Page Recorder were being used while flying altitude used to be as low as 60m. The detectors and systems have progressively evolved over last seven decades since the start of airborne surveys in 1955.

The exploration to augment the resources of RM (Nb, Ta, Li and Be) were initiated in the pegmatite belts of Bihar, Andhra Pradesh and Rajasthan and the beach sand placers were being explored for thorium resources in 1950. Lepidolite, ambligonite, spodumene (Li minerals); beryl (Be minerals); columbite-tantalite, pyrochlore-microlite, ixiolite (Nb-Ta minerals); monazite, xenotime (Y, Rare Earth Elements [REE] minerals), were the important RM and REE minerals which attracted RMSU/RMD's early exploration interest. Based on the approval by Dr. Bhabha, stockpiling columbite-tantalite for indigenous use was initiated in 1953 and this led to the stockpiling of substantial quantities of Nb, Ta, Li and Be minerals for the NPP of the country.

Exploratory mining commenced in Jaduguda as well as in Umra in 1957. In Umra, the mineralization had both primary and secondary uranium minerals with higher grades recovered through a shaft (Fig. 2) and processed for its contained uranium at the Atomic Energy Establishment, Trombay (AEET), the precursor to Bhabha Atomic Research Centre (BARC).

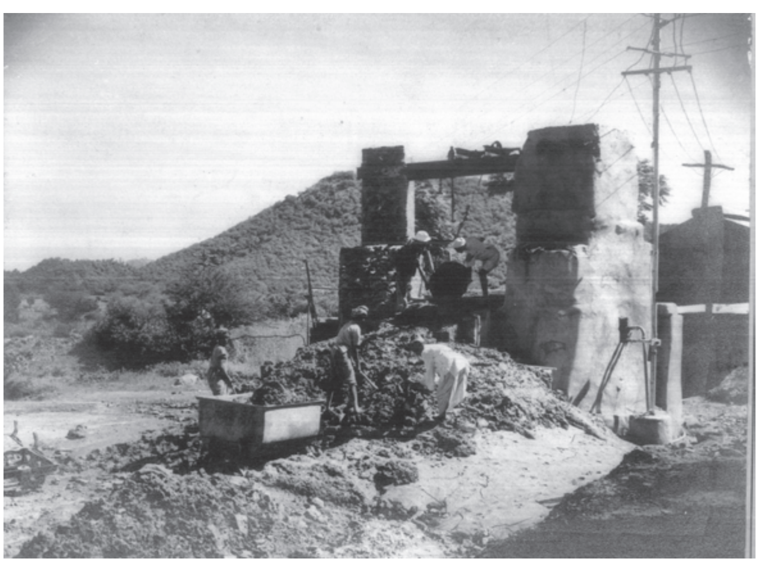

Fig. 2: Exploration activities at Umra, Rajasthan during 1957 – 1975

The uranium metal required for the research reactor CIRUS was obtained from treatment of the pegmatite mineral, cyrtolite from Bhunas, Bhilwara district and near surface ore from Umra, Rajasthan. The reactor was extensively used for production of radioisotopes and material irradiation and was ultimately used to produce plutonium for India's first successful nuclear test (Operation Smiling Buddha on 18th May, 1974) at Pokhran Test Range, Rajasthan.

Development of strategy and techniques for exploration of atomic minerals

The formative years in the exploration for atomic minerals in India were very challenging. The foremost challenges were paucity of availability of literature on geology and geochemistry of atomic minerals, lack of trained man power and non-availability survey instruments, laboratory and standards. Today, multidisciplinary techniques for survey and prospecting for uranium and other atomic minerals in diverse geological domains of the country have become the major inputs for exploration. In reconnaissance stage, apart from the direct radiometric methods for shallow surficial deposits, concealed and deeper exploration targets are invariably prioritised based on application of high resolution remote sensing, airborne and ground geophysical techniques. The heliborne geophysical surveys usually employ gamma ray spectrometry, magnetic and time domain electromagnetic (TDEM) methods besides the state of the art Audio Frequency Magneto Telluric (AFMAG) and gravity methods (Fig. 3). These techniques are enormously effective in narrowing down the exploration targets, especially the concealed and deep seated targets.

Fig. 3: Heliborne Geophysical Surveys conducted by AMD

Applications of advanced hyper-spectral remote sensing technique are being utilised for delineation of alteration zones associated with mineralisation and subsequent target selection. In addition, ground geophysical methods such as electrical, magnetic, gravity and electromagnetic methods are employed where airborne surveys have indicated potentiality to define target in localized scale. Presently, exploration targets are being invariably prioritised based on the interpretation of ground and heliborne geophysical data including the conventional geological and geochemical studies before taking up detailed radiometric surveys (Fig. 4). The areas having anomalous concentration of atomic minerals and other favourable parameters are taken up for detailed evaluation by trenching, pitting, geological and structural mapping, shielded probe logging and sampling to establish the plan dimension of mineralisation. Geographical Information System (GIS) has facilitated the integration of digital geophysical/geological data. Technological advancements such as use of mobile GPS mapper, microprocessor based total station survey instrument, handheld GPS, CAD/GIS software based thematic mapping, portable XRF and indigenous development of portable 4-channel gamma-ray spectrometer have eased the hardships faced by field geologist on course of ground geological/ geochemical/ radiometric surveys and mapping in earlier days. Subsequently, subsurface exploration is carried out by drilling to assess the subsurface continuity and homogeneity of the mineralization (Fig. 5). Based on the gamma-ray logging of the boreholes, geological examination of drill cores (Figs. 6 and 7) and radiometric/chemical assay of the samples the three-dimensional configuration of the ore body is mapped and ore resources are estimated. Mechanised borehole multi para-logging system, microprocessor based borehole trajectory logging system, core imaging system etc. are utilised to facilitate high quality data generation. In beach sand placer mineral exploration, a type of sludging equipment called 'Conrod Bunka' drill was conventionally used till 1980, but later vibro-coring drills and dormer drills, made of aluminium rods were introduced, which are comparatively better in terms of progress and depth penetration of 10-12 meters. More recently, 'sonic drilling' has been initiated to probe up to 50m depth in the coastal placer sand deposits for augmentation of heavy mineral resources, including monazite.

Fig. 4: Detailed radiometric and geological surveys by AMD geologists

Fig. 5: Sub surface exploration for uranium by crawler mounted hydrostatic drilling rig

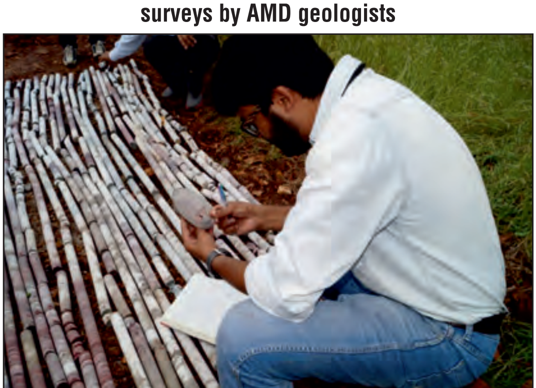

Fig. 6: On-site drill core examination by AMD geologist

Fig. 7: Gamma ray logging of borehole

Besides, software based ore body modelling, 3D visualization, volumetric analysis, resource estimation and ore body simulation utilising the sub-surface exploration data are carried out in line with best global practices to facilitate planning of exploratory/commercial mining and understanding the aspects of uranium metallogeny.

The analytical capabilities of AMD have witnessed noticeable advancements since its inception. The Geochronology, Stable Isotope, Petro–mineralogy, XRD, XRF, Electron Microprobe, Mineral Technology, Radiometric and Chemical laboratories of AMD are equipped with state-of-the-art equipment / instrumentations like Thermal Ionisation Mass Spectrometer (TIMS), Isotope Ratio Mass Spectrometer (IRMS), modern petrological microscope aided with image analysing software systems, X-Ray Fluorescence instruments (Wavelength and Energy Dispersive), Electron Probe Micro Analyser (EPMA), Inductively Coupled Plasma – Mass Spectrometer (ICP-MS), Atomic Emission Spectrometry (ICP-AES), Induced Coupled Plasma–Optical Emission Spectrometer (ICP-OES), Atomic Absorption Spectrometer (AAS) etc., which facilitates generating analytical data to support the exploration programme and understand the genetic aspects of mineralisation. Gamma-ray spectrometry, alpha spectrometry, utilisation of high resolution HPGe detectors and Instrumental Neutron Activation Analysis (INAA) technique has facilitated assaying uranium up to trace level and several major and trace elements in geological samples. AMD has indigenously fabricated portable calibration pads for their easy transport to various helibases in the country for supporting the heliborne geophysical surveys. The Chemical laboratories of AMD are equipped with state-of-the-art instruments for estimation of uranium up to parts per billion (ppb) level and most of the other elements up to parts per million (ppm) level. The various analytical facilities aid quantitative estimation of target elements, associated/path finder elements, bulk chemical analysis of whole rock/mineral concentrates, mineral identification, morphological, textural, compositional analysis of discrete mineral phases and determination of radiometric and stable isotopic compositions. Such analytical outputs facilitate delineation of the mineralized domain from barren domain of earth and ore-genetic studies.

Major landmarks achieved in augmentation of atomic minerals in India

Uranium Exploration

Till 1970s, exploration efforts were based mainly on investigating shear zone and granite related uranium mineralization. Granitic rocks are known to constitute the most potential source rocks for uranium. Thus, terrains with late Archaean granitoids and younger granites become the first order targets. Subsequently, there was a paradigm shift in uranium exploration strategy in the 1970s and beyond. The Proterozoic and Phanerozoic sedimentary basins contiguous to such fertile granitoid-rich provinces became potential targets for exploration. Follow up ground surveys resulted in discovery of several promising uranium anomalies which were taken up for follow up sub-surface exploration. Sustained efforts by AMD over last seven decades have established four (04) uranium metallogenic epochs ranging from 2,800 Million Years (Ma) to Recent and five (05) major uranium provinces in India. These are:

1. 2200 – 2800 Ma: Uranium mineralisation hosted in quartz pebble conglomerate at the base of the greenstone belts in Dharwar, Singhbhum and Aravalli cratons belong to this period.
2. 800 – 2000 Ma: This is the major metallogenic epoch in India. The uranium deposits / occurrences in Cuddapah Basin, Singhbhum Shear Zone, Chhotanagpur Granite Gneiss

Complex (CGGC), Aravalli Fold Belt, intracratonic basins such as Bhima, Kaladgi, Vindhyan, Bijawar, Shillong and Chhattisgarh, Crystallines of Himalayas and Kotri – Dongargarh Belt belong to this epoch.

3. 0.011 – 540Ma: Uranium mineralisation associated with phosphorites and black shales of Krol–Tal sequence in Lesser Himalaya, the sandstone type uranium deposits/occurrences in Cretaceous Mahadek basin, Permian-Cretaceous Satpura-Gondwana Basin and Miocene-Pleistocene sedimentary sequences in Siwalik Basin belong to this period.
4. post 0.011 Ma: Uranium mineralisation associated with the Quaternary calcrete / playa in Western India occurs in this period.

Two major geographical units of India, namely the Peninsular Indian Shield and the Himalayan belt, host a variety of uranium deposits and occurrences. Over the last seven decades AMD has been carrying out integrated multi-disciplinary exploration over several geological domains based on conceptual models which has led to identification of several potential geological domains for uranium investigations viz. southern and northern parts of Cuddapah basin in parts of Andhra Pradesh and Telangana; Singhbhum Shear Zone, Jharkhand; North Delhi Fold Belt, Rajasthan and Haryana; Bhima basin, Karnataka and Mahadek basin, Meghalaya.

In addition, several other potential geological domains have been identified where the focus is to convert some of the occurrences into uranium deposits in near future. These are the areas encompassing CGGC in Madhya Pradesh, Uttar Pradesh and Jharkhand; Siwalik Group, Himachal Pradesh; Satpura Gondwana basin, Madhya Pradesh; Dongargarh - Kotri Belt, Chhattisgarh; Gulcheru Formation in western part of Cuddapah Basin, Andhra Pradesh; Northern and southeastern margins of Chhattisgarh Basin, Chhattisgarh; Proterozoic basins such as Bijawar and Vindhyan, Madhya Pradesh and fracture systems surrounding the Proterozoic basins such as the Cuddapah, Andhra Pradesh and Chhattisgarh, Chhattisgarh. AMD, till date has established a total of 44 uranium deposits located in different states (Fig. 8) of the country which hold more than 3,58,000 tonnes of uranium oxide resources as on August, 2021.

Fig. 8: State-wise distribution of uranium resources in India

Rare metal (RM) Rare Earth Element (REE) Exploration

Owing to their strategic nature, the rare metals (Nb, Ta, Li and Be) are categorised among the 'Prescribed Substances' under Atomic Energy Act, 1962. RM and REE are mainly concentrated in pegmatites, granites, peralkaline and peraluminous volcanics and alkaline–ultramafic and carbonatite complexes and granite pegmatites are important source of Li, Be, Cs, Nb, Ta, Sn, Y and other REE. Alkaline-ultramafic and carbonatite complexes are the major source of niobium and an increasingly important source of REE. Additionally, other economically-viable REE minerals are also found in placer deposits, iron-oxide copper-gold (IOCG), marine phosphates, and residual deposits from deep weathering of igneous rock. Accordingly, in India, the pegmatites belts, granites, peralkaline and peraluminous volcanics and alkaline–ultramafic and carbonatite complexes are most explored for RM and REE resources.

The pegmatite belts are most explored over the last seven decades for RM. Lepidolite, ambligonite, spodumene (Li); beryl (Be); columbite-tantalite, pyrochlore-microlite, ixiolite (Nb-Ta); monazite, xenotime (Y, REE), are the important RM and REE minerals in these pegmatite belts and carbonatite complexes of India. The in-situ and eluvial soils, derived from the mechanical weathering of host pegmatites, typically contain rare metal minerals namely columbite-tantalite (niobium-tantalum), beryl (beryllium) and spodumene and lepidolite (lithium). The soil containing these minerals are excavated, treated and collected in the plants normally established near the source (Fig. 9). Recent advances in its high value applications and rising global demand for Li-ion batteries has made exploration of this element a priority. AMD has developed indigenous expertise in lithium exploration and is also engaged in R&D activities for processing of lithium from spodumene ore and Li rich brines on laboratory scale. Exploration efforts in pegmatites of Allapatna-Marlagalla area in Mandya district and Mangaluru area in Yadgir district of Karnataka have brought to light promising target for Nb-Ta and spodumene (Li mineral) minerals. Recent exploration inputs have established immense potential for REE and RM mineralisation in carbonatite complexes of Ambadungar, Panwad - Kanwant (LREE rich) in Gujarat and per-alkaline granite-rhyolite of Siwana Ring Complex (HREE rich), Barmer district, Rajasthan. Similarly, other alkaline complexes such as Sung Valley, Meghalaya, Samchampi, Assam, Sevattur and Pakkanadu, Tamilnadu are also being investigated.

Further, some of the inland stream placers in Chhattisgarh and Jharkhand containing higher concentration of xenotime (a mineral containing yttrium) are also collected in small scale plants setup near the sources (Fig. 10). These small scale collection units are providing a steady supply of RM for the space and atomic energy programmes of India.

Fig. 9: Rare Metal Collection Plant at Marlagalla, Mandya district, Karnataka

Fig. 10: Operations for collection of Xenotime bearing polymetallic concentrate, Jashpur district, Chhattisgarh.

Beach Sand and Offshore investigations for thorium and REE

As compared to the limited uranium resources, India is bestowed with abundance of natural thorium resources in the form of monazite (Th + REE) mineral in beach and inland placer deposits of the country. India has a long coastal stretch of approximately 6,000 km spread over the states of Odisha, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Maharashtra and parts of Gujarat where surveys and exploration have brought to light several rich deposits of heavy mineral (HM) placers. The HM placers comprise a suite of seven minerals which co-exist in their natural state. These include monazite (Th + REE mineral), ilmenite, rutile and leucoxene (titanium bearing minerals), garnet, sillimanite (industrial minerals) and zircon (zirconium mineral).

India has abundant quantity of thorium and REE resources contained in the mineral monazite occurring in the beach sand placer deposits in parts of Kerala, Tamil Nadu, Odisha, Andhra Pradesh. The sands containing heavy mineral resources are mined and treated in the plants operated by government agencies M/s Indian Rare Earths Ltd. (IREL) and Kerala Mines and Mineral Ltd. (KMML). Evaluation of HM resources of Chhatrapur, Berhampur district, Orissa and Neendakara-Kayankulam, Kerala in 1971; evaluation of HM resources of Kuttumangalam and Vettumadia sand deposits in 1988; discovery of beach sand HM deposit at Kalingapatnam Coast, Srikakulam district, Andhra Pradesh in 1992 and the rich HM concentration at Bramhagiri, Puri district, Odisha in 2002 are the major landmarks of Beach Sand and Offshore investigations by AMD. Further, the inland placer sands of Odisha and Andhra Pradesh and Teri (red-colored) sand occurring in the southern part of Tamil Nadu also contain heavy minerals. Recent introduction of sonic drilling (Fig. 11) in the coastal placer deposits to probe the beach sand HM concentration up to 30-50 meters is expected to substantially enhance the HM resources of the country.

Fig. 11: Sonic Drilling in Beach sands of Brahmagiri area, Puri district, Odisha.

There are 130 deposits of beach sand and inland placers minerals identified so far by AMD along the coastline and inland placers of India with a total of more than 1,200 million tonne of economic HM resources containing more than 12 mt of monazite (~6 mt of LREE) resource (Fig. 12).

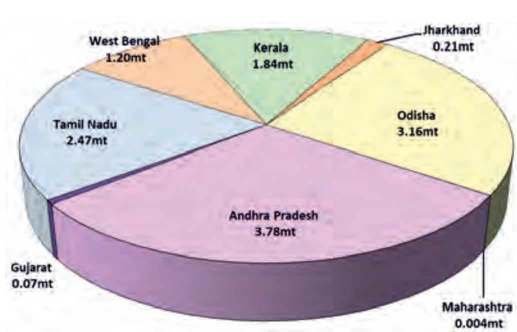

Fig. 12: State-wise distribution of monazite resources in India

Vision and way forward for self-sufficiency in atomic mineral(s) resources

The progressive technological, instrumental and conceptual advancements in exploration for atomic minerals in India facilitated the discovery of several new uranium and other atomic mineral(s) occurrences/deposits over last seven decades (Fig. 13). AMD's drilling productivity has increased manifold during the recent years and has also become a bench mark for other exploration agencies in the country (Fig. 14) and this has promoted progressive growth of uranium resource augmentation in India, which is the prime mandate of AMD (Fig. 15).

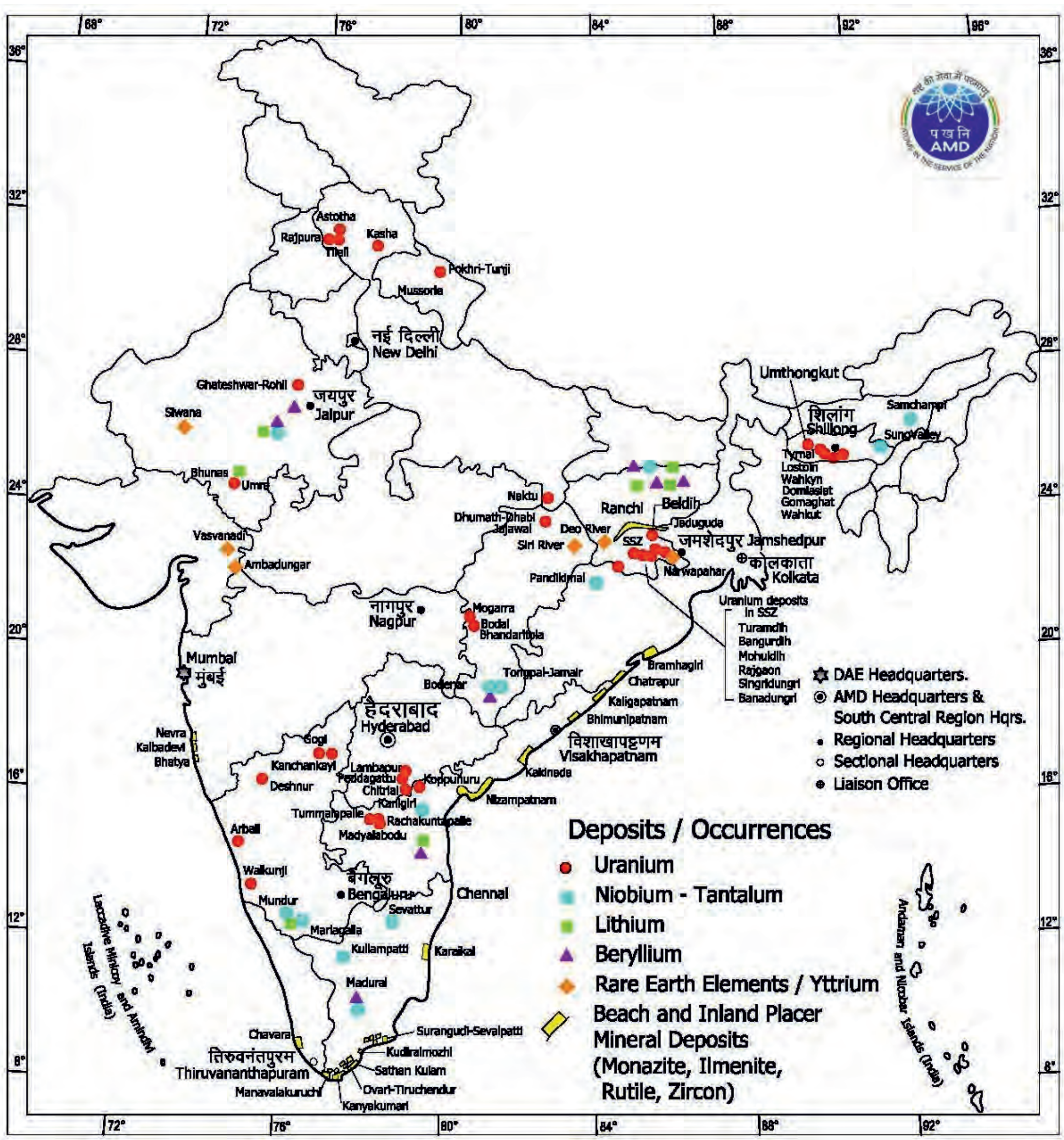

Fig. 13: Distribution of atomic mineral(s) occurrences/deposits established by AMD in India

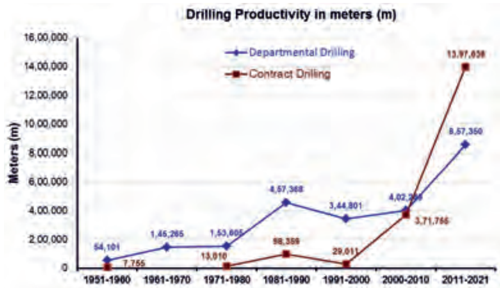

Fig. 14: Progressive increase in drilling efforts for atomic mineral resource augmentation in India

Fig. 15: Progressive growth of uranium resource augmentation in India

AMD has systematically planned the future lay out for the exploration strategy for augmentation of atomic mineral resources. Exploration inputs are to be intensified in the first order target areas for enhanced resource augmentation while R&D and phase-wise exploration inputs in the identified greenfield areas (future target) will be focused to develop these areas for further exploration.

AMD envisages around 2 million line kilometers of heliborne geophysical surveys and 5 million meters exploratory drilling to establish nearly 3,50,000 tonnes uranium oxide within a period of 10-15 years (2020 -2035), which is approximately the same amount established in India in last seven decades. AMD in collaboration with GSI has systematically planned the layout of the exploration strategy for augmentation of REE resources and the vision through a joint plan.

Collaboration with other units of DAE and premier academic institutions is high on agenda to fingerprint the genetic aspects of different types of atomic mineral deposits including REE so as to develop new conceptual exploration models and analytical techniques for augmentation of atomic mineral resources from concealed deeper (>1 km) sources. Focus is also on adaptation to modern exploration techniques, developments in instrumental and microanalytical techniques and miniaturization of analytical instruments to provide near-real time sampling guidance in the field.

India is endowed with favourable geological domains spread across length and breadth of the country which can host potential uranium, RM and REE deposits. Considering the availability of huge thorium resources, India has the most technically ambitious and innovative three stage NPP with an aim to base the future nuclear power generation on thorium rather than on uranium in its third stage. The expansion of the NPP and self-reliance in domestic atomic mineral(s) resources will be catered by the forward looking and the state-of-the-art exploration strategy of AMD and mining/ production by UCIL and IREL. The endeavour will be supported by BARC through core R&D on mineral processing techniques, material synthesis and recovery of high purity metals required for the NPP of India.

References

1. Indian Geophysical Union http://iguonline.in
2. SpringerLink Journals https://link.springer.com
3. India Brand Equity Foundation (IBEF) https://www.ibef.org/

Uranium Mining and Processing in India

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Preamble

The paper explains, in brief, the purpose of the establishment of Uranium Corporation of India Limited (UCIL) by the Government of India, its significance, and its contribution to the implementation of the three-stage nuclear power programme of the country. It discusses the uranium deposits in different geographical locations within the country, the deposit types, and the potential of such deposits. The paper also discusses the history of individual mines and uranium ore processing plants opened in different states and the future expansion proposals to meet the growing demand for indigenous uranium for the PHWR reactors.

Introduction

The Uranium Corporation of India Limited (UCIL), a Public Sector Undertaking (PSU) under the Department of Atomic Energy (DAE), was incorporated on October 04, 1967, as a sequel to the formation of the Atomic Energy Commission in 1948. Owned fully by the Government of India, UCIL has the mandate to mine and process uranium ore in the country to meet the fuel requirements of the nuclear power programme of the country.

Dr Homi J. Bhabha (father of the atomic energy programme of the country) formulated a three-stage nuclear power programme for India to achieve self-reliance in atomic fuel production and the spirit of indigenization of the programme. The first stage is based on pressurized heavy water reactors (PHWR) fuelled by natural uranium. The second stage envisages the utilization of plutonium produced and re-processed from the spent fuel of the first stage. The third stage is based on thorium, for which R&D efforts are in progress. These three stages are discussed in an earlier chapter.

In the year 1944, Dr Homi Jahangir Bhabha (1909-1966) said, “When nuclear energy has been successfully applied for power production, in say a couple of decades from now, India will not have to look abroad for its experts but will find them ready at home." Six decades later, India has the second largest number of nuclear power plants under construction in the world. India has a very ambitious and optimistic nuclear power programme, perhaps the largest and most unique among all the developing countries.

Fig.1: Dr. Homi J. Bhabha, visit to Jaduguda

UCIL shipped its first batch of uranium concentrate in 1968. Since then, the company has grown manifold, multiplying the uranium production by the opening of new mines and processing plants in the country. UCIL plays a very significant role in the nuclear power generation of the country by fulfilling the requirement for uranium for the Pressurized Heavy Water Reactors.

Uranium production in India has maintained a steady progressive trend. Uranium production from UCIL has its exclusive use in the indigenous nuclear programme of the country. Its role in the first stage PHWR reactors of the strategic three-stage nuclear power programme has a vital link to utilizing the large thorium resource of the country, paving the way for long-term energy security.

Uranium production, the front-end activity of the nuclear programme of the country, has always remained a challenging task considering the limited availability of good quality uranium resources in India. UCIL, over the years, has excelled on various fronts with technological advancements in all areas of its operations. The practices of uranium mining, processing, and waste management adopted by UCIL are under continuous up-gradation and are in line with eco-friendly global best practices. In the international arena, UCIL has received due recognition for its technology and practice of uranium mining and extraction.

Uranium deposits in the country

Only a small part of the land mass in the Indian subcontinent is assumed to be geologically favourable for hosting uranium deposits. Uranium exploration in our country, spanning over 70 years, has brought out the presence of five major types of uranium deposits (vein type, sandstone type, strata-bound type, fracture-controlled type, and unconformity proximal type) in different geological settings. The major uranium deposits of the country occur in geological basins of the Singhbhum shear zone (Jharkhand), Cuddapah basin (Andhra Pradesh and Telangana), Mahadek basin (Meghalaya), Delhi Supergroup of rocks (Rajasthan) and Bhima basin (Karnataka). Of the total uranium (U_3O_8) resources identified in India, Jharkhand accounts for about 26%, Andhra Pradesh 49%, Meghalaya 9%, and the remaining in other states. However, most of these uranium deposits are small and of far lower grade compared to those in the leading uranium-producing countries in the world.

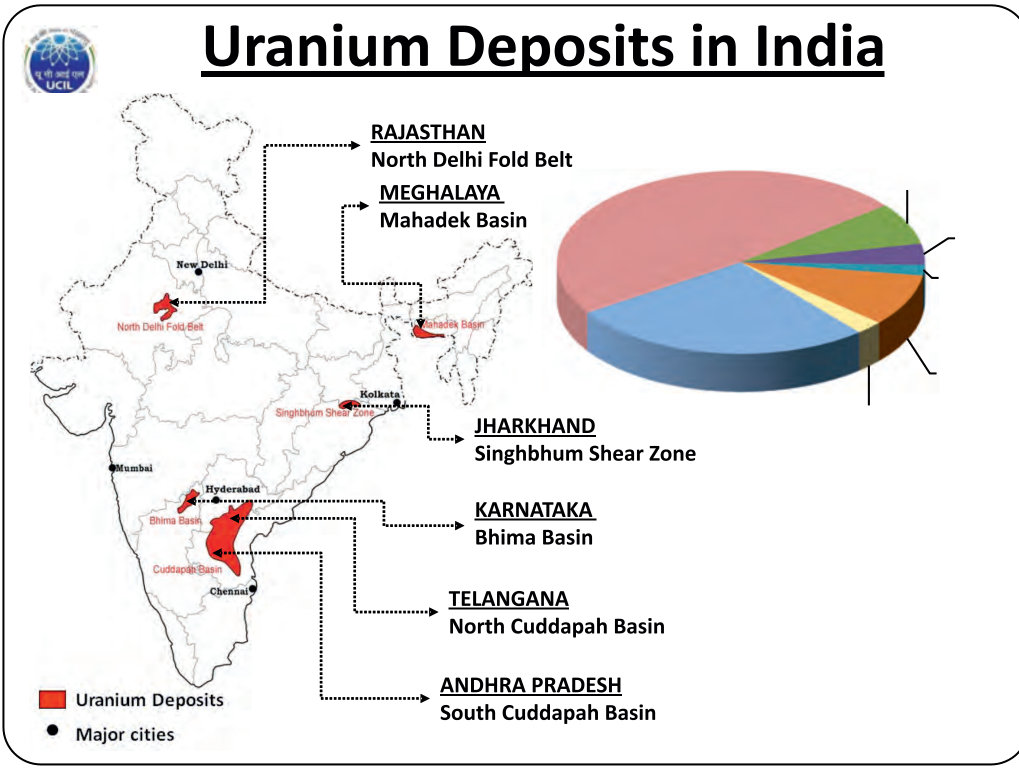

Fig.2: Uranium Deposits in India

Uranium production in the country

UCIL operates six underground mines (Bagjata, Jaduguda, Bhatin, Narwapahar, Turamdih, and Mohuldih) and one open pit mine (Banduhurang) in the Singbhum shear zone in the State of Jharkhand. Ore produced from these mines is processed in two processing plants located at Jaduguda and Turamdih in the same region.

Apart from this, UCIL operates a large underground mine and processing plant in the Proterozoic Cuddapah Basin at Tummalapalle, YSR District in Andhra Pradesh. This plant adopts a new indigenous alkaline leaching technology suitable for processing very low-grade uranium ore.

The uranium concentrate produced from these plants is sent to the Nuclear Fuel Complex, Hyderabad, for further purification, and fabrication of nuclear fuel rods.

Uranium production in the country - Jharkhand

Jaduguda mine

Jaduguda is the first mine in the country to produce uranium ore on a commercial scale. The main entry into the mine is through a vertical shaft of 640 m deep, which was sunk in two stages - from surface to 315 m and then from 315 m to 640 m. The mine has been further deepened by sinking an underground vertical shaft from a depth of 555 m to 905 m. The production levels of the mine are generally developed at vertical intervals of 65 meters. The principal stoping method adopted in Jaduguda Mine is horizontal cut-and-fill using de-slimed mill tailing as the fill. The broken ore in the stopes is mechanically handled using Load Haul Dump (LHD) equipment and is transferred to the ore transfer passes. Hauling of ore at levels is carried out using locomotives and side discharge Granby cars. Finally, the ore is dumped into the central ore pass through grizzlies. After primary crushing (~6" size) ore is hoisted through a skip and sent to the Jaduguda mill through a conveyor belt. Jaduguda mine is presently the second deepest operating mine in the country.

Fig. 3: Shaft of Jaduguda Mine

Bhatin mine

Bhatin is a small uranium deposit situated 3 km west of Jaduguda which was commissioned in 1987. Entry into the mine is through adits. The lower levels are accessed by two principal winzes and are equipped with double drum winders with provision for man winding. The levels are developed at 50 m intervals. The stoping method is similar to that of Jaduguda. Ore from the Bhatin mine is transported by road to Jaduguda for processing and the de-slimed tailing from the Jaduguda mill is sent back for mine back-filling.

Fig.4: Adit Entry of Bhatin Mine

Narwapahar mine

It is a large deposit located 12 km west of Jaduguda which was commissioned in 1995. A 7° decline has been developed as an entry into the mine in the footwall side of the ore body through which tyre mounted underground diesel-hydraulic /electro-hydraulic machineries enter underground. From the decline, ramps ups /ramp downs are developed as entries into mineral blocks under extraction, called stopes, located at different elevations, which facilitates the movement of twin-boom drill jumbo, low-profile dump

Fig.5: Decline entry of Narwapahar Mine

truck, service truck, passenger carrier, low profile grader, scissor-lift etc. This system of mining has resulted in early commissioning of the mine with high productivity and low mining cost. It has also provided the flexibility to adopt different stoping methods suitable for different widths and inclinations of ore lenses. Movement of men and hoisting of ore from deeper levels is done through a vertical shaft sunk up to a depth of 355 m. Cut-and-fill is the principal method of stoping adopted in Narwapahar mine. Ore from this mine is sent to Jaduguda by road for processing. The de-slimed mill tailings from the Jaduguda mill and the waste generated from the mine are used as the filling material. The split ventilation system adopted in the Narwapahar mine facilitates the supply of clean air to all working places. The micro-processor-based bulk ore assaying system with automatic grade estimation and subsequent computation is a distinctive feature in this mine.

Bagjata mine

A small deposit is located at Bagjata which is about 30 km east of Jaduguda. This mine has been planned in line with the mine layout of Narwapahar employing trackless mining technology with a decline entry. It was commissioned in the year 2008. The ore from this mine is transported to the Jaduguda mill for processing.

Fig.6: Decline Entry of Bagjata Mine

Turamdih mine

Turamdih uranium deposit is located about 24 km west of Jaduguda. It was commissioned in 2003. The entry into the mine has been established through an 8° decline which provides facilities for using trackless mining equipment like passenger carriers, drill jumbo, low-profile dump trucks etc. The development faces are ventilated by auxiliary ventilation systems using auxiliary fans and flexible ducts. A vertical shaft of 5 m diameter has been sunk from the surface up to a depth of 260 m with facilities for ore hoisting and movement of men and material. The ore from this mine is processed in a plant constructed adjacent to the mine site at Turamdih.

Fig.7: Decline Entry of Turamdih Mine

Banduhurang mine

This deposit is the western extension of the Turamdih mine, where part of the ore body outcrops at the surface. It is a low-grade, large tonnage deposit. After the initial evaluation, the technique of computerized ore body modeling and mine planning using SURPAC software was applied. The first opencast uranium mine in the country was made operational at Banduhurang in 2007. The pit will attain the ultimate depth of 160 m with ore to overburden ratio of 1:2.7. Ultimate pit slope has been designed for 47^{o} up to a depth of 120 m and 44^{o} below 120 m. It is a conventional opencast mine using an excavator dumper combination. Careful selection of earth moving equipment has been done to maintain ore benches of 6 m height and overburden /waste benches of 6 m /12 m height with due emphasis on ROM quality as well as stripping requirements. The ore of this mine is sent by road to the Turamdih mill for processing.

Jaduguda processing plant

The first operating plant in the country at Jaduguda has been in operation since 1968 and it is based on acid leaching technology. The process know-how has been indigenously developed and upgraded time-to-time keeping pace with the global developments. The plant has been expanded twice; nearly doubling the original processing capacity to 2500 tonnes per day to treat the ore of Jaduguda, Bhatin, Bagjata and Narwapahar mines. In the Jaduguda plant, the ore of different sizes undergoes crushing followed by two stages of wet grinding. The ground ore in the form of slurry is thickened and leached in leaching pachucas under controlled pH and temperature conditions. The leached liquor is then filtered and undergoes ion exchange in which uranyl ions get absorbed in the resin. The final product of the Jaduguda plant is uranium peroxide, which is sent to Nuclear Fuel Complex, Hyderabad for further processing into nuclear-grade fuel.

Fig.8: Aerial view of Jaduguda Processing Plant

Turamdih processing plant

The ore processing plant at Turamdih has been set-up in 2007 with a processing capacity of 3,000 tonnes per day to treat the ore of Turamdih and Banduhurang mines. Later, ore from Mohuldih mine is also being fed in this mill. The plant follows the acid leaching process and a flow sheet similar to that of the Jaduguda plant. With several automated process control mechanisms and an online monitoring system, the practices adopted at the Turamdih plant are comparable with the best in similar industries anywhere in the world.

Fig.9: Aerial view of Turamdih Processing Plant

Uranium production in the country – Andhra Pradesh

Tummalapalle mine

A large mine of 3000 TPD capacity and plant at Tummalapalle, Andhra Pradesh in the southwestern parts of the Cuddapah Basin has been successfully commissioned. Present mining, over a strike length of 5.6 Km, has been taken up and is already in production through innovative mining technology with three declines in the apparent dip o direction (9^{o}) and conveyor hoisting system. On either side of the decline, advance strike drives (ASDs) are driven in the strike direction at different levels connected by ramps within the ore body. The method of mining adopted in this mine is the Room & Pillar mining method with a combination of Cut and fill. The mined-out ore (ROM) is being transported to the processing plant at Tummalapalle through a conveyor belt.

Fig.10: Decline Entry of Tummalapalle Uranium Mine

Tummalapalle processing plant

The alkaline processing technology adopted for the plant at Tummalapalle is developed by a joint team of BARC, AMD and UCIL through pilot plant studies and has been adopted for the first time in the country. The processing plant has been in continuous operation since 2017 with the desired capacity of 3000 tonnes per day.

Fig.11: Aerial View of Tummalapalle Processing Plant.

Uranium production in the country - Upcoming projects

Further detailed exploration of the uranium resource within the existing leasehold areas has given some encouraging results and initiatives have been taken for expanding the capacity and extending the operational lives of these mines.

Keeping in view the growing demand for indigenous uranium for the PHWR reactors of the country under domestic safeguard which generate the required plutonium for the second stage fast breeder reactors; UCIL is also working to open up some new deposits discovered by the Atomic Minerals Directorate for Exploration and Research (AMD) in different parts of the country which are techno-economically viable for commercial exploitation.

References

1. Uranium Corporation of India Limited (UCIL)http://ucil.gov.in
2. Indira Gandhi Center for Atomic Research (IGCAR) http://www.igcar.gov.in
3. Atomic Minerals Directorate for Exploration and Research (AMD) http://www.amd.gov.in
4. IAEA Publications http://www-pub.iaea.org
5. Laboratory for Zero-Carbon Energy, Institute of Innovative Research, Tokyo Institute of Technology, Japan http://www.nr.titech.ac.jp

Journey from scarcity to surplus-success story of India's Heavy Water Production

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Preamble

Since 1962, India has had Heavy Water Production for achieving the goal of nuclear power production based on reactor designs that use natural uranium and Heavy Water. Although the path that led to success was not smooth, India matches the footsteps of the developed countries in the technology for production of Heavy Water.

Through this article, an attempt has been made to unfold the story behind the success of Heavy Water production in a sequential manner as far as possible in the backdrop of science and technology challenges, research and development activities and acknowledging the contribution of our pioneers. This is the story of our challenging past to competent present carving the path towards a sustainable future.

In this article we will see how integration of the knowledge of basic sciences with various branches of engineering led to successful development of technology for production of Heavy Water in India.

A. Introduction

The discovery of deuterium by Prof. H.C. Urey in 1931 was a key event in the history of science for which he was awarded Nobel Prize in the year 1934. In Urey's Nobel lecture, delivered on February 14, 1935, he stated that;

"The discovery of deuterium and the marked differences in the physical and chemical properties of hydrogen and deuterium, together with an efficient method for the separation of these isotopes, have opened an interesting field of research in several of the major branches of

science. It is my expectation that the next few years will witness the separation of the isotopes of the lighter elements in sufficient quantities for effective research in chemistry, physics and biology. If this can be effected, the work on deuterium is only the beginning of a very interesting scientific development."

After a couple of years of the above statement, considerable interest in heavy water was aroused in 1939 when Hans von Halban and Lew Kowarski suggested that heavy water could be used as a neutron moderator in a nuclear reactor using natural uranium. The Manhattan Project's heavy water production programme was taken up in the codename P-9 Project. Under this project P-9, the Cominco operation at Trail, British Columbia, took up the activity to produce heavy water. Also, DuPont built three plants in the United States between 1943-1945.

Heavy water availability was a problem due to its scarcity, and thus required quantity was not available for reactors. Urey's mentor Gilbert Newton Lewis could generate pure heavy water in 1933 using electrolysis. However, the economics of this process was not great. In subsequent years, water electrolysis, water distillation and hydrogen distillation were investigated as potential hydrogen-deuterium separation processes. During World War-II, USA and Germany exerted extensive efforts to evaluate and develop potential heavy water production processes. Two promising chemical exchange processes identified as : water-hydrogen and water-hydrogen-sulfide. The water-hydrogen process became basis of the first industrial scale plants for heavy water production at a reasonable cost. The water-hydrogen-sulfide, eventually known as the GS process, became basis of large scale heavy water plants.

Karl-Hermann Geib in Leuna in 1943 developed what we know as the dual temperature sulfide exchange process which is cost effective process for Heavy Water production. Contemporaneously, the process was also developed by J.S. Specvack at Columbia University and his process became the basis of the post war North-America plants under the name of the Girdler Sulphide (GS) process named after the company which first exploited it.

The method is an isotopic exchange process between H_2S and H_2O which is highly energy intensive for production of heavy water.

Throughout the fifties and sixties, many processes were considered, and few were taken up for laboratory investigation in pilot plants, but only a handful were adopted for production of heavy water.

Major research and technology development for heavy water production has been carried out by nearly all the countries that built prototype heavy water power reactors like Canada, France, Germany, India, Italy, Sweden, Switzerland and United Kingdom. Despite this large effort involving hundreds of man-years by chemists, physicists and engineers, no other method has reached the stage where it can challenge the GS process as the major source of heavy water.

Until its closure in 1997, the Bruce Heavy Water Plant in Ontario (located on the same site as Douglas Point and the Bruce Nuclear Generating Station) was the world's largest heavy water production plant. It used the Girdler sulfide process to produce heavy water, and required by mass 35000 units of feed water to produce 1 unit of heavy water.

The first such facility of India's Heavy Water Board to use the Girdler process is at Rawatbhata near Kota, Rajasthan. This was followed by a larger plant at Manuguru, Andhra Pradesh. Other plants exist in the United States and Romania for example.

Another viable process of deuterium isotope separation is ammonia-hydrogen exchange process using potassium amide as catalyst. In this process, ammonia synthesis gas (which is mixture of Hydrogen and Nitrogen) is the deuterium source and it is commonly known as mono-thermal ammonia-hydrogen exchange process, first used at Mazingarbe in France. Based on this, two heavy water plants are installed in India.

Urey's prediction proved true over the years since after the discovery of deuterium and in present times, basic science on deuterium has shifted towards development of various technologies utilizing the potential non-power applications of deuteriumin in various fields viz. pharmaceutical , spectroscopy, semiconductor, optical fibre etc.

B. Heavy Water Programme of India and Heavy Water Board:

Dr. Homi Jehangir Bhabha, architect of Atomic Energy Programme in India, laid the foundation of an integrated three-stage nuclear power programme. His vision led to India pursuing an ambitious nuclear programme comprising of R&D and industrial deployment with significant societal benefits.

Recognizing the fact that India has limited uranium resources but rich thorium reserves, Bhabha formulated a three-stage nuclear power generation programme, which has been discussed in chapter on Nuclear Power in India.

The success of first phase of Indian Nuclear Power Programme (INPP), using natural uranium as fuel and Heavy Water as moderator, was depending on timely and sustained availability of Heavy Water for PHWRs. Heavy Water Board (HWB), a constituent unit (I&M) under Department of Atomic Energy, is the sole agency in the country mandated for production and supply of Heavy Water for the INPP.

The first Heavy Water Plant was set up at Nangal based on electrolysis followed by cryogenic distillation of Hydrogen.

Industrial plants set up at Baroda and Tuticorin based on Ammonia Hydrogen mono-thermal exchange process has led to successful indigenous deployment of second generation plants at Thal and Hazira. Hydrogen Sulfide - Water Bi-thermal exchange process (Girdler-Sulfide process) was indigenously developed starting from laboratory studies to pilot plant and breakthrough was achieved by setting up first industrial plant at Kota. The consolidation of process could be achieved by setting up a second generation plant at Manuguru.

HWB is fulfilling the growing demands of Heavy Water for Indian Nuclear Power Programme and after making the country self-reliant, it is also exporting high quality Heavy Water to countries like Republic of Korea, United States of America, France etc. for nuclear and non-nuclear applications. Presently, India is the one of the largest global producer of Heavy Water and is the only country using multiple technologies for production.

HWB has now diversified into other activities like industrial production of other nuclear materials required for first and second stage of nuclear power programme. These include Sodium and ^{10}B enriched Boron Carbide for fast breeder reactors, nuclear grade solvents used in front-end and back-end of nuclear fuel cycle, rare metal recovery from secondary sources by solvent extraction. HWB's mandate includes development and deployment of spin-offs, allied and separation technologies on industrial scale for lighter molecules in particular, like production of oxygen-18 enriched water, hydrogen, helium etc; identifying and promoting non-nuclear uses of Heavy Water/deuterium, as deuterium labeled compounds for industrial and medical applications.

C. Heavy Water Production for the first stage of INPP

i. Mission at Nangal

Heavy Water was essential for the first phase of the Nuclear Power Programme based on PHWRs. The production of Heavy Water had to be taken up on a large scale to match the projected nuclear power programme.

In early 1954, when DAE began exploring the feasibility of producing Heavy Water indigenously, it considered two processes viz., electrolysis of water and distillation of water. The electrolysis process economics were analysed for the scenario of Heavy Water being a stand-alone product and also a by-product of a fertilizer plant based on electrolytic Hydrogen. India's Heavy Water production programme thus took off with the decision to set up the first Heavy Water plant with 14 Te/Annum capacity at Nangal, Punjab. This was a very significant move as it exploited the available potential for production at an economical price and gave an early start to the Heavy Water Production Programme. The plant was completed and commissioned without any undue delay and India could produce first drop of Heavy Water on August 9, 1962 which remains a red-letter day in the history of indigenous Heavy Water production. This plant, when built, was the largest plant of its kind in the world. The plant continued to operate steadily until 1978. Since demand for power for alternate uses in the region was growing, the fertilizer plant had to switch over to an alternate method for production of Hydrogen, thus abandoning most of the electrolysis plant. Also with the successful development of the other technologies for production of Heavy Water at much lesser energy input, distillation of Hydrogen became an obsolete method for industrial scale production.

Heavy Water Plant, Nangal

ii. R&D at BARC

Heavy Water& Stable Isotope Production (HW & SIP) Section as part of the Chemical Engineering Division (CED) at Atomic Energy Establishment Trombay, AEET (later renamed as BARC) launched the indigenous effort by setting up pilot plants based on water distillation and dual temperature H_2S-H_2O exchange process for collection of data. Subsequently, a core group was constituted for working on process development, generating of flow sheet, sizing of equipment and for carrying out test loop studies for establishing suitability of materials and components for H_2S-H_2O based process. Several studies were carried out viz. measurement of surface tension, foaming characteristics of water saturated with H_2S, corrosion behavior, effluent treatment etc. Monitoring methods for H_2S and procedure for pre-conditioning of carbon steel, by formation of protective sulfide film were developed. Various analytical methods for analysis of deuterium were developed and standardized.

It was envisaged that the final enrichment in Heavy Water plant (HWP) would be carried out by the distillation process. To start with, a 1" dia column and later a 4" dia column with Dixon ring packing was set up and operated. Special type of ordered packing were developed by Heavy Water Division (HWD), BARC. The development of packing made of phosphor bronze wire mesh with corrugation led to sizable reduction in plant volume and capital cost.

iii. Journey from Scarcity to Self-Reliance – pursuing multiple technologies with success

Way back in 1956, Bhabha observed that ……."*there was every indication that its (Heavy Water) uses in atomic energy are not likely to diminish*". He, therefore, urged that, "*the production of Heavy Water should be maximized without hesitation*". This was to set the course for the Heavy Water production programme.

In order to give a thrust to the Heavy Water production programme, on the eve of its entering the large industrial scale production era, on May 1, 1969, DAE created a separate unit known as "Heavy Water Projects Board" for managing the projects for the production of Heavy Water. On February 17, 1989 this unit was renamed as "Heavy Water Board" to bring it in consonance with the emphasis on the nature of the unit having shifted from projects to plants.

The H_2S-H_2O dual temperature exchange process was known to be the process employed for large-scale production of Heavy Water in the world. However, very little information and data were available about the technology. DAE, having pronounced preference and penchant for development of indigenous technology and philosophy of self-reliance, decided to develop this process virtually from scratch. Indigenous development became successful by setting up pilot plant based on water distillation and dual temperature H_2S-H_2O exchange process for collection of data. Rajasthan Atomic Power Station (RAPP) I and II at Kota were capable of generating about 10-15% of extra steam over the rated capacity which seemed to be an excellent opportunity for obtaining steam for Heavy Water production. Thus, it became evident that setting up of the Heavy Water plant in the close proximity of RAPP I&II would ensure, adequate electric power supply, meet the process steam requirements at lower cost, also vast source of water from Rana Pratap Sagar reservoir and required land were available at that site. This resulted in setting up of first H_2S-H_2O based Heavy Water Plant at Kota.

Heavy Water Plant, Kota

Another successful technology for large scale production of Heavy Water developed during 1957-1960 was mono-thermal ammonia-Hydrogen exchange. Around mid-1968, Gujarat State Fertilizer Co. (GFSC), Baroda had a large single stream ammonia plant. Thus it was decided to put up a Heavy Water plant integrating with GFSC plant. The plant produced Heavy Water for the first time in July, 1977.

Since the requirements of Heavy Water were pressing with the additional PHWRs, efforts were intensified for setting up the third Heavy Water Plant. This resulted in setting up of mono-thermal ammonia-Hydrogen based HWP in integration with the fertilizer plant of SPIC, Tuticorin. The plant was commissioned in 1978.

It came out that a bi-thermal Ammonia-Hydrogen exchange process developed by UDHE, Germany is more attractive than the mono-thermal process owing to the fact of inherent lower energy requirement. DAE approved the project of setting up a HWP based on this process at Talcher in integration with Fertilizer Corporation of India (FCI). Unfortunately, the fertilizer plant could not carry out satisfactory sustained operations at a reasonable load. The synthesis gas supplied by the fertilizer plant was seldom in adequate quantity and of required purity. With great deal of difficulty, HWB commissioned the plant and it produced its first drop of Heavy Water in October, 1984. However, the plant could not be operated on sustained basis at the required capacity.

Having had the cumulative experience of setting up, commissioning, de-bugging the technology and stabilizing the operations of Heavy Water Plants, HWP felt confident about setting up of two more mono-thermal ammonia-hydrogen based plant at HWP Thal and Hazira and one bi-thermal H_2S-H_2O based plant at Manuguru. HWB also set up a Captive Power Plant (CPP) to meet the power and steam requirement of HWP Manuguru.

Heavy Water Plant, Manuguru

iv. Export

By 1990's, after becoming self-sufficient vis-à-vis domestic requirements, the scenario changed to that being surplus in Heavy Water and being in a position to sell too as was dreamt by Bhabha.

An opportunity for export came when the South Korean company Korea Electric Power Corporation (KEPCO) wanted HW for their PHWR. India thus got a foothold in the international market as an established supplier of HW. HWB won accolades from South Korea for the quality of HW supplied. As fulfillment of Bhabha's dream, HWB could establish itself as a major supplier in the international market by exporting 227 Te of HW in a decade's time by executing as many as 15 export orders. All consignment met stringent specifications of the users and followed all regulatory requirements. Superior quality of Indian product has earned due recognition for DAE in the international market.

In 2007, for the first time, HWB supplied high quality HW to M/s Spectra Gases, USA for non-nuclear applications. Subsequently HWB executed export to CIL, USA.

Recently, in 2021, HWB executed two export orders to S. Korea and Japan for non-nuclear applications. Also in this year HWB participated in an international bid for supply of HW to Argentina for nuclear applications. HWB is receiving various export inquiries from the countries like, US, Russia, Germany etc. for supply of high quality of Heavy Water which is indeed a matter of pride for the country achieving the goal towards “Make in India”.

Export consignment of Heavy Water

v. Present Scenario in Heavy Water Production

Environment and energy conservation are the two key issues for sustainable development of industrial growth and for corporate social responsibility.

Concentrated efforts were put to reduce the cost of production of Heavy Water to maximum possible extent. This was achieved through process intensification, re-optimization of operating parameters, energy audits, use of energy efficient equipment, integration of heat transfer loops etc. Thrust was given to increasing the throughput by system analysis and debottlenecking the process, pinch analysis for heat exchange networking, re-optimization of CPP heat cycle, evaluation of the hydrodynamics of the systems, waste heat recovery, performance evaluation of rotary equipment etc.

All the above concentrated efforts have resulted in a significant reduction of over 30% in specific energy consumption for all the plants taken together over last decade. This amounts to a cumulative saving of over few hundreds' crore. Milestones in energy efficiency have been reached and yet new targets are set every year with regards to energy efficiency.

Beginning with Nangal in1962, total eight HWPs were built in India to meet its requirement of INPP. The demand and supply did not always match. Initially, the supply lagged the demand, but during 1990s, it overtook and surpassed the demand.

The H_2S-H_2O exchange process-based plants, being independent ones, proved their worth. They account for the major production of heavy water today.

Over a period of time, Heavy Water production has been increasing and specific energy consumption improving continuously.

Heavy Water Board has been giving utmost importance to industrial, occupational & environmental safety, right from site selection to designing, construction, commissioning and during operation of plants. Various design safety features were incorporated in the plants. Those are closed drain and vent system, scramming and dumping system, toxic gas monitoring system and fire detection and protection system. Further, for the safe operation & maintenance of the plants, various safety systems were implemented. Those are plant audit, inspection and surveillance system, reporting and investigation system for reportable injuries, near-miss incidences and first aid injuries, safety work permit system, emergency preparedness and planning system and authorization system for operation & maintenance personnel. The functioning of these systems are audited and improved continually.

All the plants are certified for IS: 9001(QMS), IS: 14001(EMS) & OHSAS 18001/IS: 18001. As a result, HWB's safety record is the best among the Chemical Industries in India.

Heavy Water Plants consume large amount of power, water & chemicals. Therefore, conservation of natural resources, energy and environment protection were given due importance right from the beginning. Reduce, reuse & recycle of the natural resources is an ongoing process.

D. Non-Nuclear Applications of Heavy Water/Deuterium

Over a period of time it has been realized that other than application in nuclear reactor, deuterium has tremendous potential for applications in various high technological fields as predicted by Urey.

Deuterium isotope effect modifies the kinetics of chemical/bio-chemical reactions, which leads to many gainful applications in bio-science and advanced technologies. These applications are called in a broader term as 'Non-Nuclear Applications' (other than nuclear application of Heavy Water in pressurized Heavy Water reactors).

The applications include metabolism studies, NMR solvents, deuterated drugs/Active Pharmaceutical Ingredients (API's), optical fiber, semiconductors etc.

Recognizing the vast potential of Non-Nuclear Applications of Heavy Water and Deuterium, HWB had initiated various activities in this field since late 90s. A project was initiated by HWB in collaboration with Entero Virus Research Centre, Mumbai to validate the published data on thermostabilization of Oral Polio Vaccine (OPV) in heavy water medium. Though it was established that OPV in heavy water medium can retain its potency at much higher temperature compare to that in normal water medium, this benefit could not be potentially exploited for actual application due to other issues. However, that was not the end, as it triggered the beginning of our journey towards developmental work on non-nuclear applications of heavy water and deuterium.

Non-nuclear applications of Heavy Water picked up momentum in recent years as was clear from the increased number of inquiries received by HWB for supply of Heavy Water in bulk quantity to private industries for a wide range of applications viz. in NMR solvents, in medicinal chemistry, in optical fiber etc.

- **Development of deuterated compounds by HWB**

  HWB as a part of its diversification programme has taken up development of D-labeled compounds including NMR solvents. Presently all the compounds are being imported in the country. Heavy Water Plant (HWP), Baroda laboratory took up the activity of setting up the facility for in-house developments of methods for deuterium labeling of Hydrogen bearing compounds like $CDCl_3$, acetone-d6, acetonitrile-d3, DMSO-d6, benzene-d6, etc. under the DAE approved XII Plan R&D project of BARC. HWB successfully executed the project. Hands on experience in process selection, process optimization, quality control for development of deuterated compounds has been achieved through this project. Till now this facility is being utilized for synthesis of deuterated NMR solvents under applied R&D and products are being marketed through Board of Radiation &Isotope Technology (BRIT), DAE. An augmented facility for production of CDCl3, DMSO-d6, Acetone-d6 and Acetonitrile-d3 is being set up at HWP Baroda.

- **Collaborative agreement with Indian Private Parties**

  HWB has entered into collaborative agreement with two Indian Parties, M/s Clearsynth, Hyderabad and M/s SyNMR, Bangalore for development of deuterated NMR solvents, reagents, APIs and other value added products. Both the parties have made good progress in the intended work, using Heavy Water supplied by HWB.

- **Supply of Heavy Water for non-nuclear applications**

  HWB is promoting research and commercial activities by supplying Heavy Water within the country. Demand of Heavy Water for non-nuclear applications is consistently increasing and number of users in the country has also been on the rise.

- **Deuterium Depleted Water**

  Deuterium Depleted Water (DDW) is another field that is gaining prominence due to reported benefits for its application in therapeutic uses mainly in cancer treatment as adjuvant therapy.

  Preliminary results from a project with ACTREC, Mumbai were encouraging in regard of anticancer potential of DDW in specific cancer cell lines. A collaborative project for further systematic study in this line is being taken up with ACTREC.

  DDW with various deuterium content is available in international markets. HWB being the largest producer of Heavy Water has the capability of producing large quantities of deuterium depleted water and supply the same at various concentrations ranging between 30 ppm to 120 ppm for societal purpose.

E. Diversified activities of HWB

i) Production of Nuclear Grade Solvents for closed nuclear fuel cycle

Various Organo-phosphorous and Amide based nuclear grade solvents were identified as essential inputs to the front-end and back-end of nuclear fuel cycle for recovery and separation of Rare Earth & other valuable metals for fuel processing or reprocessing of spent fuel.

During the journey of last two decades, HWB in collaboration with BARC & IGCAR has developed industrial scale technologies for production of solvents viz. Tri butyl phosphate (TBP), Di-2 ethyl hexyl phosphoric Acid (D2EHPA), Tri octyl phosphine oxide (TOPO), Tri alkyl phosphine oxide (TAPO), Di nonyl phenyl phosphoric acid (DNPPA), N,N-di hexyl octanamide (DHOA), Tri iso-amyl phosphate (TiAP), 2-Ethylhexyl phosphonic acid mono-2-

ethylhexyl ester (PC88A) etc. 1,3-Dioctyloxycalix[4]arene-crown-6 (CC6) solvent also known as Calix Crown-6 has been identified as one of the potential candidate for selective separation of ^{137}Cs from high level waste of spent fuel. This solvent has been developed by NRG, BARC at lab scale. Scaling up for higher production was taken up at HWP, Talcher, and trial runs yielded few kg of CC6 which has been handed over to NRG, BARC.

ii) Boron Isotopic Enrichment and production of enriched boron compounds for second stage of Indian Nuclear Power Programme (INPP)

Prototype Fast Breeder Reactor (PFBR) being set-up at Kalpakkam as a part of IInd stage of NPP requires ^{10}B Enriched Boron Carbide for Control Safety Rod (CSR) and Diverse Safety Rod (DSR) sub-assemblies. HWB has successfully demonstrated & deployed the technology for production of ^{10}B Enriched Boron Carbide complying to CSR & DSR specs. Considering urgent need for supply to PFBR, HWB have installed enrichment facility at HWP-Talcher and Elemental Boron, B_4C conversion and pelletisation facilities at HWP-Manuguru. The initial requirement of enriched boron carbide has already been met successfully.

iii) Production of Nuclear Grade Sodium for second stage of INPP

HWB is entrusted for setting up of industrial scale Sodium Metal plant to meet sodium requirement of Second phase of INPP. Presently, there is no indigenous manufacturer of Nuclear Grade (NG) sodium in India. Hence, for meeting the demand of NG sodium for future FBRs and making FBR programme successful, self-reliant, it is necessary to have an indigenous source of sodium metal. A 2 kA test cell has been setup, commissioned & operated at HWP-Baroda. Based on operating experience and various modifications incorporated on 2 kA cell, 24 kA single cell design has been finalized and installed at HWP Baroda, which would serve as prototype cell in setting-up of multiple 24 kA cell for 600 MTPA NG sodium plant. While developing the prototype cell, HWP Baroda has installed a sodium purification unit based on technology provided by IGCAR. Subsequently, HWP Baroda produced 3 MT NG sodium metal and supplied to IGCAR.

Based on the operating experience in running the prototype unit and purification unit, further activities for setting up of 600 MTPA facility is being taken up by HWB.

iv) Production of ^{18}O enriched water

^{18}O enriched water, a specialty material finds wide spectrum of applications in the field of nuclear medicine and biomedical research. ^{18}O enriched water with >95 % IP (^{18}O) is required for carrying out PET scanning for detection and staging of cancer in patients.

HWB has adopted the Heavy Water distillation process (under vacuum) for enrichment of ^{18}O. Being first of its kind for HWB and DAE, a tedious technology development cycle from literature survey to the commercial production had to be followed.

Based on the optimizing studies carried out, a ten stage cascade was finalized to achieve reasonable inventory built-up time of around 4 years. The product of this cascade is $D_2{}^{18}O$, which needs to be split and recombined with pure Hydrogen at the back-end to give the desired product form $H_2{}^{18}O$.

Recently, during January-2022, 1st drop of ^{18}O enriched water has been produced at HWP Manuguru with isotopic purity > 95.5%.

v) Developmental activities

HWB has also taken up various developmental activities in collaboration with BARC viz. recovery of cobalt from secondary resources, recovery of Gallium from Aluminum industry, recovery of Helium from Fertilizer plants, development of novel contacting devices for liquid-liquid extraction.

F. Dream realized

Realization of dream of indigenous production of Heavy Water in India was possible due to sustained efforts of an array of leaders from Heavy Water family. Bhabha's vision on self-sufficiency in the production of Heavy Water and subsequent export could be translated to reality through the dedicated efforts and perseverance of our pioneers like Shri D.C Gami, S. Fareeduddin, P.G. Deshpande, K.S. Bhimbat, R.K. Bhargava, S. Sharma. A dream to Drum to Diversification---the successful journey of HWB is attributed to its dedicated team of staff who has put in untiring efforts in achieving the goal.

Moving from scarcity to surplus with respect to production of Heavy Water through sustained production with continual improvement, HWB has contributed in realizing the mission of 1^{st} stage INPP. HWB has, over past few decades, mastered the highly complex and energy intensive technology of Heavy Water production through multiple processes including H_2S-H_2O and NH_3–H_2 isotopic exchange processes. Presently HWB is capable to design, construct and operate Heavy Water Plant on its own.

During last four decades of its journey in the field of Heavy Water, HWB also developed a large talent pool and expertise in various facets of chemical process plant right from concept to commissioning, including process and technology development, project implementation, etc.

HWB is demonstrating a strong presence in all the stages of India's Nuclear Power Programme. HWB is actively contributing to Nuclear Fuel Cycle by sustained supply of nuclear materials like Heavy Water for PHWRs, organo-phosphorus solvents for front and back-end of nuclear fuel cycle, ^{10}B enriched boron for FBR etc. HWB is also working on other areas of advanced technology for nuclear, societal and environmental applications. HWB is committed to take up more and more challenging assignments in the Indian Atomic Energy prograamme.

Applications of deuterium in non-nuclear field are now diversified at large. HWB is putting efforts to enter in to new horizons by taking up various research projects on developmental work on applications of deuterium in medicinal chemistry/biological field in collaboration with academics/research institutes/industries, utilizing the deuterium resources as well as knowledgebase available in the country.

Though the dream has come true and HWB has delivered, it is not the end of the journey. It continues and HWB remains active and vibrant as ever ready to face the future challenges.

As per data available, there are only few countries who are presently into manufacturing of deuterium oxide. Number of global sources for heavy water is reducing with heavy water plants in other countries near in entering shut down. There is a huge scope for HWB to play a key role in the global market of heavy water in near future by tapping the benefits of changing market trends for this market. HWB has demonstrated its core competence in field of heavy water production technology and is widening its horizon in line with the HWB's enlarged mandate of identification and promoting non-nuclear uses of heavy water/deuterium as deuterium labeled compounds for industrial and medical applications.

References

1. Wikipedia https://en.wikipedia.org
2. Amazon Simple Storage Service (Amazon S3) object storage service https://s3.amazonaws.com

Nuclear Physics Research in BARC

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Preamble

An overview of the Nuclear physics research programme pursued within BARC and other DAE institutions since inception and its subsequent growth is presented from the historical perspective. The diverse theoretical and experimental studies carried out by utilizing the research reactors and particle accelerators over the years have been described.The seminal contributions made in the area of fission physics in particular and nuclear reactions have been highlighted. Significant contributions made into the area of accelerator physics and nuclear instrumentation have been presented. Experiments performed in high energy physics through international facilities have also been described.

1. Introduction

Nuclear physics research programme in its early days was supervised and nurtured by Dr. Homi J. Bhabha under the umbrella of the India's atomic energy programme. Initial work done using the Cockcroft-Walton neutron generator at Tata Institute of Fundamental Research (TIFR) in early 1950's laid a good foundation in nuclear physics research. Dr. Bhabha provided strong, dynamic leadership in very early years, whereby two research reactors 1 MW APSARA reactor and 40 MW CIRUS reactor with assistance from UK and Canada, respectively, became operational at Trombay. These two facilities provided unique opportunities for carrying out the experimental nuclear physics research in the country. Dr. Raja Ramanna, who had earlier joined the faculty of TIFR, was called upon to take the leadership for the development of nuclear physics programme in the Atomic Energy Establishment, Trombay (AEET). Dr. Ramanna led the programme of utilization of research reactors for nuclear physics and other research purposes. He was also responsible for initiating programmes for the development of particle accelerators in the country as well as their utilization for nuclear physics research and other applications. At Trombay, an electrostatic accelerator (Van de Graaff Accelerator) was set up in the early 1960's. The Variable Energy Cyclotron (VEC) was commissioned at Kolkata in late 1970's. These provided new avenues for nuclear physics research in the country. Later with the installation of BARC-TIFR Pelletron accelerator in late nineteen eighties, the nuclear physics research has blossomed many folds leading to many types of developments in detector technology and electronics instrumentation.

The nuclear physics research using particle accelerators that provide charged particle beams and reactors with thermal neutrons enabled a wide variety of research for studying nuclear phenomena such as fission, nuclear reactions and nuclear structures of broad range of nuclei. A number of state-of-the-art detector arrays have been built for these investigations. In parallel, there has been considerable interest in the sub-nuclear and sub-nucleon phenomena which are explored at high energies, and are carried out by international collaboration using accelerator facilities abroad. All these research interests have also been supplemented by extensive theoretical studies. Of late, experimental setups involving measurements of antineutrinos from reactor and high energy cosmogenic particles have also been established. Nuclear Physics research is expanding broadly in three directions: Investigation of the nuclei away from the line of stability to map the nuclear landscape and studies relevant for nuclear astrophysics; shape evolution of the nucleus as a function of excitation energy and angular momentum; Study of nuclear matter at high energy and density. Besides these areas, the field of neutrino physics is receiving worldwide attention in recent years. The growth of nuclear physics research has been possible mainly due to the concurrent development of accelerators which delivered light and heavy ions, versatile detector set ups, high density electronics and state-of-the-art data acquisition system.

2. Reactor based Nuclear Physics studies in BARC

One of the early explorations in the field of nuclear physics studies in the country was the Nuclear Fission phenomenon using the research reactors. The Nuclear Fission process, which involves complex nuclear dynamics had been a subject of contemporary interest worldwide at the time of commissioning of APSARA and CIRUS reactors. Therefore, from the beginning of operation of these reactors, the reactor neutron beams were utilized to carry out extensive investigations in fission to understand the mechanism of the fission process. Studies were carried out with regard to the post-scission characteristics involving the radiations emitted in fission such as prompt neutrons, gamma rays, K-X-rays and long-range alpha particles (LRA) as well as the fission fragment mass and kinetic energy distributions and their inter-correlations. These studies yielded new and detailed information on both the static and dynamic aspects of the fission process.

Among the first studies to be carried out at Trombay was the measurement of angular distribution of prompt neutrons emitted in the thermal neutron induced fission of ^{235}U to determine the fraction of pre-scission neutrons. A new technique based on the gridded ionization chamber was employed to detect fragments in a 2π geometry measuring both kinetic energy and angle of the fission fragment with respect to electric field direction of the chamber, which was also chosen to be the direction of detection of the neutrons. The research work carried out by S. S. Kapoor and R. Ramanna using this novel technique could compete with the similar work being carried out elsewhere with higher flux reactors, mainly due to innovation in experimental techniques. The angle of the fission fragment with respect to the neutron direction was determined by employing the pulse height information of both the grid and the collector pulse associated with the detected fission fragment. The time-of-flight technique was used to measure prompt gamma intensities and prompt neutron energies at selected angles with respect to the direction of the fission fragments of selected energies. The experimental study of the early sixties on the emission of prompt gamma rays in the thermal neutron induced fission of ^{235}U using neutron beams from APSARA obtained the landmark experimental result that a significant angular momentum is generated in the fragments produced in the fission process. Studies with APSARA reactor neutron beams and later with CIRUS reactor beams obtained results on the neutron emission spectra and neutron-fragment angular correlations which yielded new information on the post-scission, pre-scission neutron multiplicities, effective temperatures and level densities as a function of the emitting fragment mass and total fragment kinetic energy. An important result obtained was that about 10% of the prompt neutrons were pre-scission neutrons and not emitted from the moving fragments. It was proposed that these "pre-scission neutrons" may be evaporated from the excited fissioning nucleus during the passage between the saddle and the scission stages of the fission process. This, however, required a rather long ($\sim 10^{-19}$s) saddle-to-scission time. From the experimental heavy ion physics and also theoretical studies of nuclear dynamics including nuclear viscosity effects, it is now realized that such long saddle-to-scission time in fission are indeed possible. Fig.1 gives a view of the experimental set up used at APSARA reactor for these studies of the fission process.

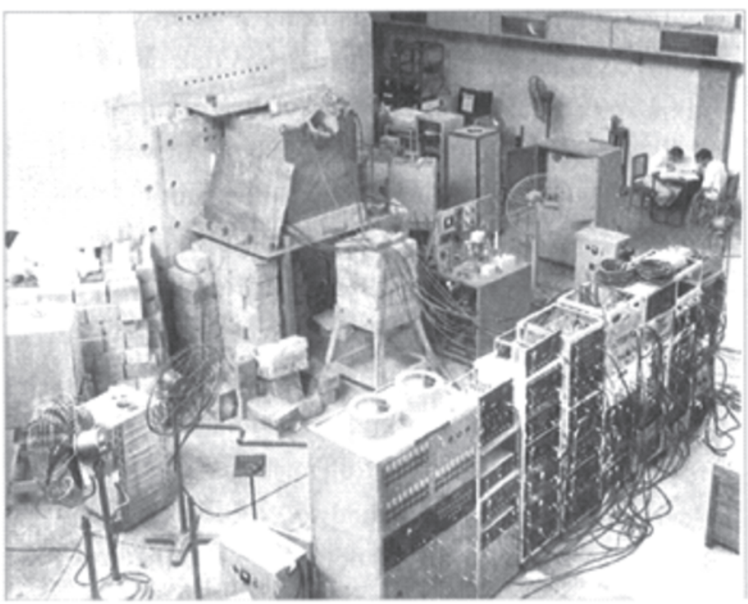

Fig.1: A view of the experimental arrangement for the study of the fission process used at the Apsara reactor

Further experimental research work in fission with CIRUS neutron beams aimed at the studies of the light charged particles emitted occasionally in fission which provides information directly on the static and dynamic state of the scission configuration and indirectly on the nature of large scale motion of nuclear matter from saddle-to-scission in the fission process. Some of these experiments involving rare modes of fission such as ternary and quaternary fission could be performed only because of the indigenous experimental techniques and multi-parameter data recording methods that were developed. Consequently, experimental data covering a number of correlations among parameters of interest in light charged particle accompanied ternary fission were obtained with the available neutron fluxes at the Trombay CIRUS reactor in an area of research which otherwise fell within the reach of only very high flux reactors. These experimental studies, which involved multi-parameter recording and computer analysis of the data provided important information on nuclear viscosity in the motion of fissioning nucleus from saddle-to-scission.

In the late sixties, a setup of high-resolution cooled Si (Li) detector spectrometers was built indigenously at a time when worldwide these were in the early stages of development. With these detector systems, a series of detailed studies of K-X-ray emission in fission were undertaken at Trombay, both in thermal neutron fission of ^{235}U and spontaneous fission of ^{252}Cf, which provided new insight on the de-excitation mechanism and regions of deformations of neutron rich fragment nuclei. Studies were started for the energy dispersive X-ray analysis of materials in the late sixties with these indigenously set up X-ray detectors, much before the advent of commercial systems using this technique.

In addition to the above-mentioned studies, APSARA, CIRUS and DHRUVA reactors have been extensively used to carry out basic and applied research work in the areas of nuclear fission using radiochemical, gamma spectrometric and solid-state nuclear track detector techniques. These include studies of mass, charge and kinetic energy distributions in the neutron induced fission of actinide nuclei such as ^{232}Th, ^{232}U, ^{233}U, ^{237}Np, ^{239}Pu, ^{241}Pu, ^{241}Am and ^{245}Cm. In these studies, in several cases, angular momenta of fission fragments were also determined via measurement of isomeric yield ratios. These studies have made significant contributions to our understanding of nuclear shell effects on the fission process.

At the DHRUVA reactor, a multi- clover detector setup has been recently installed for carrying out nuclear spectroscopy studies of highly neutron rich fission fragments, far away from the beta stability line.

3. Accelerator based Nuclear Physics in BARC in the Early Years

One of the important aims of modern science has been to acquire a deeper understanding about the fundamental constituents of matter and the forces governing the natural phenomena. Most of our understanding of the structure of the atomic nucleus has come through the study of nuclear reactions caused by the energetic charged particles such as protons, deuterons, alpha particles and heavy ions. However, in order to penetrate the nucleus, the kinetic energy of these particles should be larger than the height of the Coulomb barrier caused by the repulsive force between the positively charged nucleus and the impinging charged particle. Particles of higher and higher energies are also needed to investigate the microscopic structure of matter on shorter and shorter wave-length scales. Hence, several types of particle accelerators have been developed and over the years, progress in nuclear and particle physics research has been intimately linked to the advances in accelerators in providing particle beams of different types and increasing energies. These accelerators which were developed for basic research in the various areas of atomic, nuclear and particle physics are also finding applications in various fields such as analytical science, medicine, industry etc.

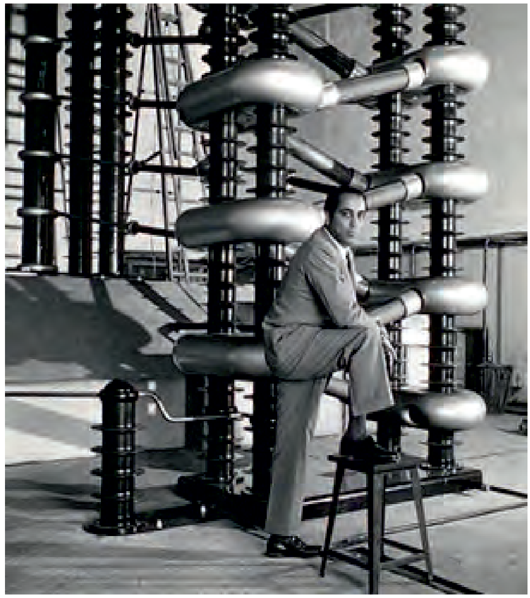

Fig. 2: 1 MV Cockcroft-Walton Accelerator (Cascade Generator) at TIFR,in 1953

Particle accelerators have always been the driving force of nuclear physics studies. While a few accelerators, notably a one Million-Volt Cockcroft Walton accelerator (Cascade Generator) at TIFR (Fig. 2), were operational in fifties and sixties at other places, the accelerator based nuclear physics research work took a significant leap in the sixties with the setting up of the 5.5 MV Van de Graaff accelerator at the Bhabha Atomic Research Centre (BARC) in 1962 (Fig. 3 (i)). This facility enabled pursuit of research in several areas of nuclear physics of contemporary interest. It should be mentioned that amongst others Drs A. S. Divatia, M. K. Mehta and N. Sarma had made pioneering contributions to nuclear physics research at the Van de Graaff in the early years.

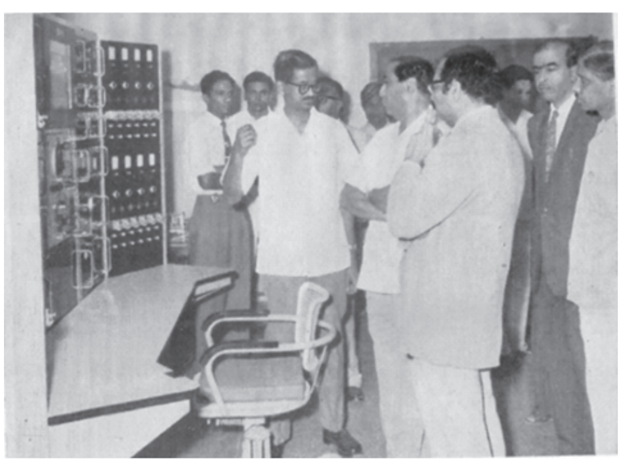

Fig. 3 (i): A photograph of Dr.Homi Bhabha with Dr. R. Ramanna at the time of the inauguration of 5.5 MV Van de Graaff Accelerator at Trombay. (Seen in the photograph from right to left: Dr. Athavale ,Dr. Jagadish Shankar, Dr. H. N. Sethna, Dr. A. S. Divatia, Dr. Homi Bhabha, Dr. Raja Ramanna, Dr. N. S. Thampi and Dr. Joseph John)

Charge independence of nuclear force in medium and heavy weight nuclei led to the observation of Isobaric Analogue States (IAS) and this was the topic in the forefront during the 1960's and 1970's. At Trombay, systematic studies were carried out to investigate IAS through (p, p), (p, n), (p, gamma) and (alpha, gamma) reactions on various targets ranging from ^{37}Cl to ^{80}Se. Using (p, n gamma) reactions as a probe, systematic measurements were carried out to determine the nuclear structure of bound states of medium-heavy nuclei. Proton optical model potentials were determined at sub-Coulomb energies for medium weight nuclei from a comprehensive analysis of proton reaction cross sections measured for A = 37 – 80. An efficient 4pi neutron counter was built for these investigations. Other studies include: (i) High precision proton elastic scattering from Pb to put a stringent limit on the strength of the long-range nuclear interaction. (ii) Alpha elastic scattering excitation functions in light nuclei up to A=40 to determine the excited states with large alpha parentage.

Secondary beams of monoenergetic neutrons with energies ranging from keV to MeV were produced by energetic proton reactions on ^{7}Li and ^{3}H targets to study neutron induced reactions. In the fast neutron induced fission studies, the correlations between the fragment angular anisotropy and the fragment mass-asymmetry were measured at an excitation energy where multiple chance fission are absent to investigate the mechanism of the mass division in fission. In another study, anomalous behaviour of fission cross-section was observed when (p, f) cross-section measurements on ^{238}U were extended to deep sub-barrier energies. The low energy protons and alpha particles were also used for material modification and characterization studies as well as Proton Induced X-ray Emission (PIXE) studies of variety of samples for various practical applications. By the beginning of eighties, this machine was exploited to its fullest potential for nuclear physics research and applications.

In the nineties, this machine was dismantled and in its place in the same building utilizing the available infrastructure, a 6MV Folded Tandem Ion Accelerator (FOTIA) has been installed, as shown in Fig. 3 (ii). This accelerator is being used for low energy heavy-ion based research covering interdisciplinary fields.

Fig. 3 (ii): Accelerating column of FOTIA at Van de Graaff, Trombay

In order to extend nuclear physics research, the nuclear physics community planned for higher energy accelerators, which was realized through the indigenous development of VEC at Kolkata which became operational in 1977. This was followed by commissioning of Pelletron accelerator in late eighties. Availability of beams of alpha particles, deuterons and protons for a variety of nuclear reaction studies at VEC spurred the activities in diverse areas. Elastic and inelastic scattering, mass and charge distribution of fission fragments, reaction mechanism for emission of high energy gammas and formation of intermediate resonance structures in light nuclear system were some of the notable experiments that were studied utilizing the available alpha beams.

Recently, ion beams have been accelerated through superconducting cyclotron K500, developed in-house, at Variable energy Cyclotron Centre (VECC) . Presently, VECC has three functioning cyclotrons; K130, K500 and 30 MeV Medical cyclotron, and pursuing an upcoming project named as Advance National facility for Unstable Rare Ion Beam (ANURIB).

A 3MV high current accelerator FRENA (Facility for Research in Nuclear Astrophysics) at SINP, Kolkata, will enable the programme of nuclear reaction studies of Astrophysical interest.

4. Nuclear Physics using Pelletron – LINAC Facility (PLF)

In the eighties, a considerable interest had grown globally in the studies of nucleus-nucleus collisions at medium energies. At that time scientists from BARC and TIFR also initiated a proposal to set up a heavy ion accelerator facility in the country to pursue heavy ion-based physics research. A Medium Energy Heavy Ion Accelerator (MEHIA) was set up in the eighties under a collaborative project of BARC and TIFR at the campus of TIFR at Colaba in South Mumbai. The 14MV Pelletron accelerator in Mumbai was formally inaugurated on 30th December 1988 and marked an important milestone providing a big leap in nuclear physics research in India (Fig. 4 (i), (ii) and (iii)). This accelerator also facilitated research in atomic physics, condensed matter physics and interdisciplinary areas. The Pelletron LINAC facility, a joint venture between the BARC & TIFR, has been a major research centre for the heavy ion accelerator based research in India.

Fig. 4 (i): Installation stages of Pelletron

Fig. 4 (ii): Ground breaking ceremony for Pelletron, in 1983

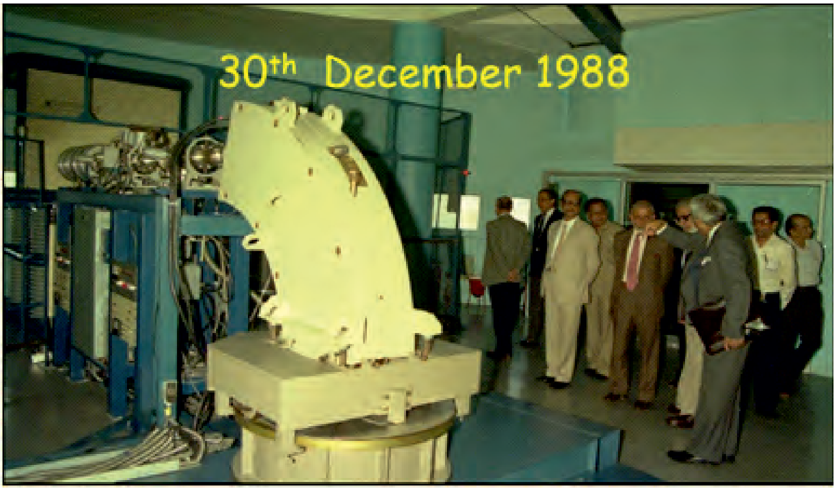

Fig. 4 (iii) Commissioning of 14UD Pelletron accelerator on 30th December 1988

This facility was further augmented with an indigenously developed superconducting LINAC booster to enhance the energy of the accelerated ion beams. The phase-I of LINAC booster was commissioned on 22nd September 2002 and the full facility was dedicated to users on 28th November 2007 after the completion of the phase-II. A variety of state-of-the-art experimental facilities have been developed at this centre to pursue frontier research in nuclear, atomic, condensed matter and multidisciplinary areas.

Over more than three decades, the Pelletron accelerator has been consistently working with very high efficiency, delivering a wide variety of ion beams ranging from proton to Iodine. A number of developmental activities have been carried out in-house to improve the performance of the accelerator, (Fig. 5 (i) and (ii)). While a majority of the researchers at this facility are scientists from BARC and TIFR, the experimental community includes researchers and students from VECC, SINP and universities within India and abroad. About 150 Ph.D. theses and about 750 publications in international refereed journals have resulted from the research activities at the PLF. These include a large number of publications in high impact international scientific journals.

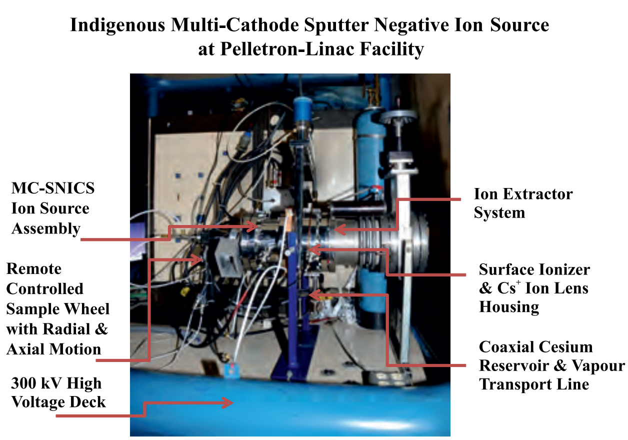

Fig. 5 (i): Multi-Cathode sputter negative ion source

Fig. 5 (ii): 6m High Current Irradiation Set Up at Pelletron

Major experimental facilities developed at PLF include (Fig. 6):

- Multipurpose scattering chamber having 150 cm diameter, with two independently rotatable arms permitting detector rotation and target ladder adjustment with remote control without beam interruption by using indigenously developed Programmable Logic Controller, to carry out experiments in charged particle spectroscopy and fission studies
- An array of Clover Detectors for discrete gamma ray spectroscopy along with auxiliary detectors
- Array of strip detectors for charge particle spectroscopy and study of cluster structure, and direct reactions
- BaF_2/$LaBr_3$ array for high energy gamma ray studies with BGO/Na(Tl) multiplicity filter
- Charged Particle Array based on pad (ΔE) and CsI(E) detectors
- Neutron Detectors Array of Liquid Scintillation detectors and Annular parallel plate avalanche counter having 12 segments with angular coverage from 5° to 11°, for Time-of-Flight Technique based compound nucleus residue tagging
- MWPC gas detectors for fission fragment mass and kinetic energy distribution
- High current proton irradiation facility and secondary neutron production through (p,n) reaction on Li, Be targets.
- A Versa Module Europa (VME)–based DAQ and advanced digital DAQ with analysis programmes

A versatile data acquisition and analysis package, LAMPS (Linux Advanced Multi Parameter System) has been one of the key indigenous developments responsible for pursuit of frontier research in nuclear physics.

Fig. 6: Experimental facilities set up at PLF a) 1.5m diameter Multipurpose scattering chamber for reaction studies b) High granularity large solid angle strip detector array for charge particle detection c) Liquid scintillator array for neutron measurements d) BaF_2 array for high energy gamma rays measurements e) CsI array for light charge particle detection f) MWPC detectors for fission measurements g) High efficiency, high resolution Indian National Gamma Array (IGNA) for gamma ray measurements

Research programmes in nuclear physics that have been pursued with the Pelletron facility include studies of (i) Fast rotating nuclei-their structure, spectroscopy, decay properties and dynamical behaviour; (ii) Nuclear scattering and reactions, elastic and inelastic scattering, few nucleon transfer reactions and strongly damped collisions; (iii) Heavy-ion fusion, sub-barrier fusion, fusion dynamics, compound nucleus formation and decay; (iv) Fission and fission-like reactions; (v) Spectroscopy of exotic nuclei far off the stability line; (vi) Giant Dipole Resonances (GDR); and (vii) Nuclear moments of excited states. Research programmes have also been undertaken in other areas such as (i) Atomic physics of highly charged ions (ii) Nuclear chemistry (iii) Condensed matter physics and (iv) Radiation damage studies with societal applications.

Similar to the BARC-TIFR Pelletron facility, a 15UD Pelletron - LINAC facility has been set up at IUAC (Inter University Accelerator Centre), New Delhi by University groups. The superconducting LINAC booster has been indigenously developed based on Nb resonator cavities. The accelerator facility is functioning very efficiently catering to various University institutions. DAE scientists from BARC, VECC, TIFR and SINP have been also using this facility to pursue nuclear physics research in a number of frontier areas. Nuclear Physics Division (NPD), BARC and IUAC (formerly called Nuclear Science Centre) continue to have mutually beneficial collaborations since inception, covering accelerator operations and effective utilization to the development of accelerator systems and experimental facilities. This facility has been further augmented by adding a high current positive ion injector to the LINAC booster.

At BARC-TIFR PLF, various application-oriented programmes such as radioisotopes production, radiation damage studies (space bound devices, yield improvement in wheat and rice seeds), secondary neutron production for cross-section measurements, radiation dosimetry studies, ion irradiation in semiconductor crystals for photoconductive Tera Hz emitters, Accelerator Mass Spectrometry, and production of track-etch membranes, are also pursued. Experimental facilities are attached to dedicated beamlines installed in the Cascade beam hall for Pelletron energies and two new LINAC beam halls I and II for both Pelletron and LINAC boosted energies.

Nuclear Physics Research highlights from PLF

Various interesting results and new findings have resulted from the research programmes undertaken at Pelletron accelerator facility and some are mentioned below:

Trombay group has long tradition in fission research. Many pioneering contributions related to the damping of shell effects and dynamical aspect of nuclear reaction have been made in the past. Fission fragment angular distributions around Coulomb barrier have shown enhancement in angular anisotropy, leading to conclusion that the potential energy surface governs the fission path in mass equilibration in fission process. Recently, by carrying out experiments and systematic analysis of the available experimental data from Pelletron LINAC Facility, the origin of newly observed asymmetric fission in pre-actinide nuclei (near Pb/ Bi) has been identified. The results provided the evidence for the general dominance of proton shells in low-energy fission. A rare fission mode from neutron rich ^{257}Md nucleus at high excitation energy has been observed in another study.

In the past few years, nuclear reaction studies with weakly bound stable nuclei (^{6,7}Li, ^{9}Be) to study role of coupling to low lying continuum on elastic scattering and fusion has been one of the main activities at PLF. The new findings include, clear evidence for the two-step process, transfer followed by breakup, origin of large alpha production, different resonant states arising due to different cluster structure configurations to name a few.

A novel sensitive and selective technique has been developed at PLF, for measuring ultra-low cross-sections by performing KX-γ–ray coincidence of the decay radiations within a low background setup. Using this method, the fusion cross-section up to nano-barn (10^{-33} cm^2) has been measured which is the lowest cross-section ever measured in heavy ion induced fusion at deep sub-barrier energies. These results have given a new direction to the present understanding of the fusion hindrance at low energies.

The cluster structure studies have been pursued at PLF through resonant capture, resonant breakup, knock out and direct reactions. The precise measurement of the radiative transition probability at different energies, has provided crucial evidence for the 2α-dumbbell-like structure of ^{8}Be nucleus.

Nuclear level density is another area where a lot of measurements have been performed to study influence of angular momentum, isospin, pairing, collective enhancement, shell effect etc. The extent of shell effect and it's washing out with excitation energy as theoretically formulated earlier by Trombay group, was confirmed by experimental measurement of nuclear level density in ^{208}Pb region.

In recent years, the surrogate reaction methods in various forms have been employed to get indirect estimate of neutron induced fission reaction cross sections of many compound nuclear systems in actinide region, which are not accessible for direct experimental measurements. The surrogate reaction methods have been successfully employed to determine ^{233,234}Pa(n,f), ^{236,239,240}Np(n,f) and ^{238,241}Pu(n,f) compound nuclear cross-sections in the equivalent neutron energy range around 10 to 20 MeV.

5. Nuclear collisions at high energies, Hadron Physics and Quark Gluon Plasma (QGP) and Studies

In parallel to experiments using home-based accelerators in MeV energy range, there has been considerable interest in the sub-nuclear or sub-nucleon phenomena which are explored at high energies. These interests have been pursued by extensive theoretical studies as well as by participating in the collaborations like COSY at Germany, PHENIX and STAR experiments at BNL, CMS and ALICE experiments at CERN, as well as India based mega projects like INO. Along with these, in-house detector laboratories and experiments involving high energy particles reaching Earth via cosmic particle interactions have been established. The collaborations enabled us to participate in frontline experiments and gain new knowledge in physics and technology.

Hadron physics

In NPD right from eighties, there have been noticeable theoretical studies on calculating production of hadronic states like eta, rho, omega, phi and delta in few GeV proton-nucleus collisions and investigate their role in nuclear dynamics. Experimental studies in these areas were carried out using multi GeV proton beams at Cooler Synchrotron (COSY) Germany. During 2002-2006, a large coverage plastic scintillator detector ENSTAR readout via optical fibres was built at NPD and was installed at COSY. The experiment hinted formation of eta-mesic nucleus in ^{24}Mg.

Nuclear collisions at high energies and Quark Gluon Plasma (QGP)

By late eighties, the standard model of particles was well established, all the three generations of leptons and quarks had been detected except the heaviest top quark which was discovered at Fermilab in 1995. The huge mass difference among these generations were understood in terms of mass generation mechanism in standard model formalism which predicted a new yet to be detected particle called Higgs boson. Another open problem was, although experimentally proven, that protons and neutrons are made of quarks, no experiment could detect a free quark. It is understood that after big bang, early universe at high temperature was in the phase of free quarks and gluons (QGP) along with all the other fundamental particles. It was soon proposed that such high temperatures could be created in lab by colliding two large nuclei at relativistic energies. The experiments with collisions of heavy nuclei started gaining momentum when gold ions with energy 14.6 AGeV were accelerated at BNL and soon Lead ions with energy 160 AGeV got accelerated at CERN. These were fixed target experiments and hence the required centre of mass energy remained small. A Relativistic Heavy Ion Collider (RHIC) which could collide gold beams of 100 AGeV energy each was planned at BNL. Soon after, a Large Hadron Collider (LHC) machine using existing LEP ring was planned at CERN.

The possibility of DAE institutions participating in these international experiments provided a renewed interest in physics activities in these areas. Significant work was done on aspects of the quark-hadron phase transitions, equation of state of the high temperature nuclear matter and chemical equilibration of matter in heavy ion collisions. The experimental probes of heavy ion collisions signal at high energies were modelled. STAR and PHENIX experiments at BNL started taking data on Au-Au collisions in 2001. The BARC group made hardware contribution for the muon arm of PHENIX detector and the VECC group made the Photon Multiplicity Detector (PMD) for the STAR detector. The analysis of data at VECC and BARC concentrated on study of probing the system with photons, muons, strange mesons and baryons produced in Au-Au collisions and study of QCD phase diagram. The formation of QGP was discovered in these studies for the first time.

CMS experiment at LHC studies both Higgs bosons as well as QGP matter in addition to various other aspects in standard model. The silicon sensors made for the pre-shower detector were developed in India with participation by BARC. BARC along with Panjab University made significant contribution in making RPC, a new type of large area gas detectors for muon identification. The VECC and SINP groups made significant contributions in photon and muon detection systems and their readout electronic hardware in the ALICE experiment at CERN. These experiments led to the discovery of Higgs particle and the robust signals of QGP, a phase which has fundamental importance to the early and the most eventful evolution of the universe.

The physics contributions include, observation of suppression of higher mass Upsilon states, detailed measurements of all quarkonia states and the detection of Z boson for the first time in heavy ion collisions. A series of systematic measurements of quarkonia states and their ratios in Pb-Pb collisions during (2011-2016) has helped establishing the colour screening behaviour of QGP. A systematic understanding of signals of QGP via experimental work is followed by theoretical modelling of the data.

In the area of muon detection, an experiment has been setup at Van de Graff laboratory to measure the angular distributions of cosmic muons and their interactions with matter. The energy deposition and excellent timing of scintillators is exploited to construct two dimensional tracks of muons and hence angles of muons. After establishing the method muons are used to study the interactions with matter.

6. Theoretical research highlights

Theoretical research forms an important and integral part to interpret and understand nuclear phenomena. Nuclei in their ground and excited states exhibit many structure changes due to the interplay of single particle and collective behaviour of nucleons. At very high energies, the underlying degrees of nucleons such as pions, quarks and gluons are exhibited in interactions producing variety of sub nuclear particles. All these aspects are investigated theoretically that provide rich information on the nuclear reactions and phenomena. In DAE, various groups at BARC, TIFR, VECC, SINP and IOP, Bhubaneswar have actively contributed in the theoretical studies. Some of the highlights of this vast field of work are enumerated below:

i The shell effects in the fission process leading to double hump fission barrier have been investigated. The washing out of shell effects with excitation energy or temperature was shown for the first time.

ii The asymmetric mass distribution in fission of actinide nuclei was explained to be due to stochastic Markov process by nucleon exchange of nucleons between newly formed fission fragments.

iii The evolution of nuclear shape, structure in the nuclear landscape was studied by nuclear shell model calculations.

iv Direct nuclear reactions such as stripping, pickup and knockout were investigated by optical model and DWBA analysis.

v Sub nucleonic degrees of freedom were studied to explain particle production at high energies.

vi The formation and evolution of QGP have been investigated in detail through hydrodynamic and statistical models.

vii The structure of neutron stars and supernovae have been studied by nuclear matter calculations.

viii Astrophysical processes in the formation of exotic proton and neutron rich nuclei are being studied.

Nuclear physics research is proceeding along new frontiers with the setting up of advanced accelerator facilities in India and abroad, throwing new challenges in experimental and theoretical areas.

7. Neutrino Physics with ISMRAN

Neutrinos are the second most abundant particle but remain elusive due to their feeble interaction. To study these particles, in recent years, a vibrant physics programme of neutrino physics studies has been started for the measurements of antineutrinos through inverse beta decay process at Dhruva reactor. For this purpose, a large area plastic scintillator ISMRAN (Indian Scintillator Matrix for Reactor Antineutrino) detector along with shielding was designed, fabricated and installed inside Dhruva reactor hall, as shown in Fig. 7. ISMRAN presents the first attempt in the country towards building the capability to perform research in a totally new exciting area of reactor neutrino physics with primary goals of sterile neutrino search and resolution of reactor antineutrino anomaly.

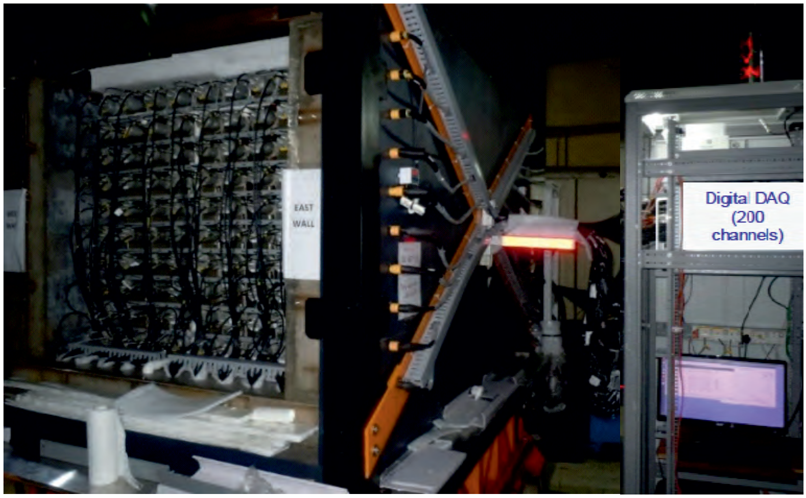

Fig. 7: ISMRAN detector installed inside Dhruva reactor hall for antineutrino measurements

8. Concluding Remarks

Nuclear physics research has been and continues to be an integral and core research area in the Department of Atomic Energy since beginning. In this article, an attempt has been made to give an overview of development of the nuclear physics in BARC which has been primarily driven by experiments utilizing the research reactors and particle accelerators. Development of theoretical and experimental reactor physics and the technological capability to design and construct research reactors as well as power reactors has been the foundation on which our experimental nuclear science programme rests. The neutron beams from the Trombay reactors were utilized for basic nuclear physics research in several areas, in particular fission physics, as well as for radioisotope production and applications. Accelerator-based research programmes have been pursued with the low energy accelerators as well as with medium energy, variable energy cyclotron and BARC-TIFR Pelletron LINAC Facility.

For future programme, the proton accelerator proposed for the ADSS (Accelerator Driven Subcritical Reactor System) at accelerator complex in Vizag, is planned to be used as the driver accelerator for RIB (Radioactive Ion Beam), once it reaches 40 MeV of proton energy, followed by a post-accelerator downstream. A 30 MeV electron accelerator is also planned at Vizag, producing RIB via photo-fission route. At BARC, a fast neutron facility is envisaged based on a high current ECR source enabling measurements of fission observables in the fast neutron region thereby contributing to the development of data driven models for fission which is being intensely pursued worldwide.

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References

1. Development of Nuclear Science in India by S. S. Kapoor; Chapter 13, Book on "India in the world of Physics: then and now " edited by Asoke N. Mitra (2009).
2. APSARA – Four Decades of Operating Experience and utilization of India's First Research Reactor, Publication of Library & Information Services Division, BARC, Trombay, August 1996.
3. An overview of accelerator activities at VECC – B. Sinha; Status of 224 cm Cyclotron at Kolkata – C. Mallik et al; Status of the K=500 Superconducting Cyclotron – R.K. Bhandari; in Proc. of DAE-BRNS Indian Particle Accelerator Conference – 2005 (InPAC 2005)
4. BARC-TIFR Pelletron Accelerator Facility, S.S. Kapoor et al, in special issue on “Physics Instrumentation in India”, Part II, in Indian Journal of Pure and Applied Physics Vol. 27 (9&10) (1989).
5. Status report on the BARC-TIFR superconducting LINAC booster, R. G. Pillay et al, Indian Journal of Pure and Applied Physics 35 (1997) 152 and in Proc. of InPAC 2005.
6. Taylor & Francis Group https://www.taylorfrancis.com/

Research Reactors in India

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Preamble

Research Reactors have been the back bone of the nuclear industry. They have provided a valuable support in development of the Indian Nuclear Power Program in many ways, viz. testing of materials, fuel, equipment, shielding experiments, validation of codes etc. During the course of construction of these reactors lot of new technologies were developed which turned out to be the fore runners for use in power reactors. In addition to the above these, reactors have also provided lot of societal benefits by way of radioisotope production. This paper highlights the history of development of Research Reactors and their role in nuclear industry.

Historical Perspective

On December 2nd, 1942, something incredible happened at the squash courts of the University of Chicago. Enrico Fermi, the Italian born Physicist demonstrated, to the world, the feasibility of extracting controlled energy from self-sustaining neutron chain reaction. Shortly thereafter, as early as in 1944, even before India attained independence, Dr Homi Bhabha was already formulating the strategy for setting up a nuclear research programme in India.

In line with his vision, one of the earliest decisions he took was to build research reactors (RR) of different types. Each of these rapidly accelerated the understanding of the complex issues involved in the control of nuclear chain reaction. The design of reactors involves high levels of optimisation of geometry, fuel design, safety, material selection, irradiation behaviour of fuel and structural materials. These could be mastered only by building test reactors, which use different types of fuels, structural materials, coolants etc. Toward this end, several research reactors were systematically designed and built during different stages of the programme. The first of these reactors was a swimming pool type of reactor, aptly christened “APSARA” – the celestial nymph by Pandit Nehru himself. The basic design of the reactor was frozen in July 1955 and Indian scientists and engineers completed the construction in just over a year. With APSARA, India became the first Asian country outside the erstwhile Soviet Union, to have designed and built its own nuclear reactor.

The next crucial step involved the planning of larger reactors having much higher neutron flux and power than what was available at APSARA. This plan materialised in 1960 with the building of CIRUS, a high power (40MWt) research reactor. This reactor, then known as the Canada India Reactor or CIR for short, was built in collaboration with Canada. These early gains catapulted India into an ambitious nuclear program. CIRUS and APSARA have provided the necessary confidence and expertise for design and safe operation of many nuclear reactors in the country.

In early 1961, a zero energy critical facility named ZERLINA (Zero Energy Reactor for Lattice Investigations and New Assemblies) was built, for studying various geometrical aspects (lattice parameters) of a reactor fuelled with natural uranium and moderated with heavy water.

The three stage programme calls for building plutonium based reactors in the second stage. Therefore, the next logical step was to build a critical facility, which used plutonium as fuel. Such a test reactor was built in 1972 and was named PURNIMA (Plutonium Reactor for Neutronic Investigations in Multiplying Assemblies). This reactor was intended for studying the behaviour of plutonium fuel in a pulsed fast reactor (PFR). Following this, a critical facility called PURNIMA-2 was designed, with a solution containing 400 g of uranyl nitrate serving as the fuel for this facility. It attained criticality in 1984.

In the early seventies, a need was felt for a research reactor having even larger neutron flux and irradiation volumes than CIRUS, for meeting the growing requirements for radioisotopes and research. This culminated in building of a totally indigenous 100 MWt research reactor, having the highest flux in Asia at that time. It attained criticality in August 1985 and was named DHRUVA.

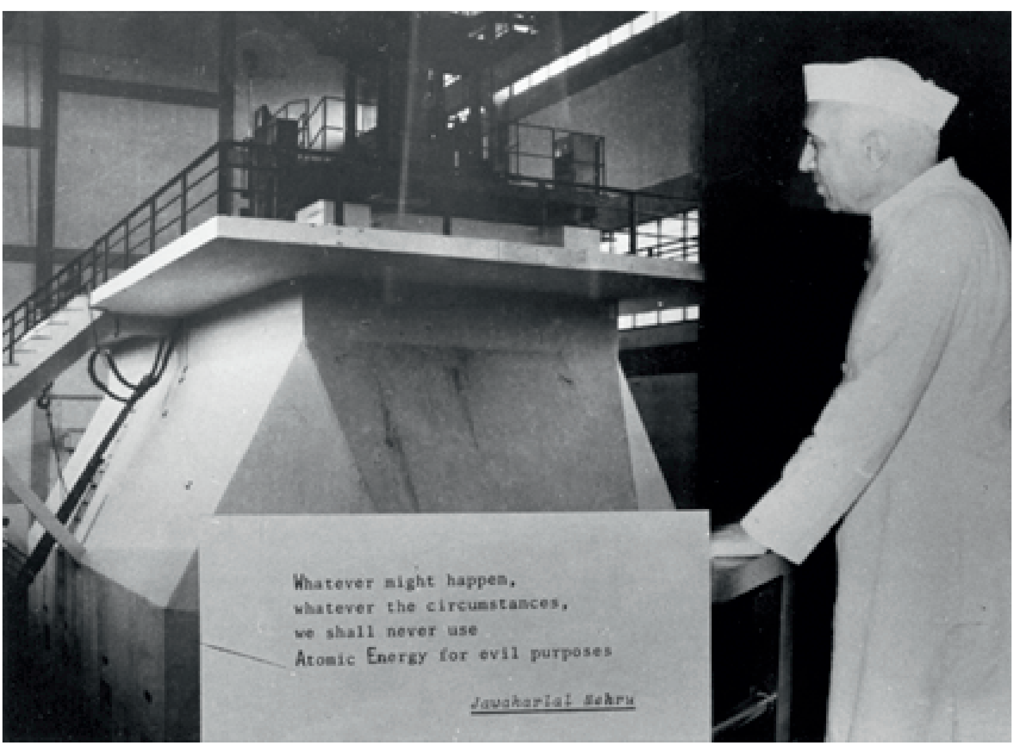
Research Reactors – Salient Features

Research Reactors have been the back bone of the nuclear energy program. They have supported the program in many ways, viz. testing of materials, fuel, equipment, shielding experiments, validation of codes etc. During the course of construction of these reactors several new technologies were developed which turned out to be the forerunners for use in power reactors. In addition to the above, these reactors have also provided lot of societal benefits by way of radioisotope production.

Research reactors are primarily meant to provide neutron source for research and applications in healthcare, neutron imaging, neutron activation studies, neutron scattering etc. Generally, any upcoming technologies are proven in a RR before their implementation in commercial power reactors. RRs are generally simpler and smaller than commercial power reactors with power level varying from zero power to few hundreds of MW, and generally operate at a low temperature. They use much less amount of fuel than a power reactor, but their fuel may require uranium with much higher enrichment (U-235). They may have a very high power density in the core. Being flexible, RRs are best suited for testing of nuclear fuels of various reactor types, studying the safety margins of nuclear fuel, and developing accident tolerant and proliferation resistant fuels for future reactors. Unlike power reactors having standardised design, different RRs have distinct designs and operating modes. A common design is a pool type reactor like Apsara, where the core is a cluster of fuel elements housed in a large pool of water. In a tank type reactor like Dhruva and CIRUS, core is contained in a closed vessel as in the power reactors. In tank-in-pool type reactor, the core is enclosed in a tank which is in turn located in a pool of water. Most of the RR cores have channels to locate materials for irradiation experiments. In addition, beam tubes which penetrate the reactor vessel, pool and shielding provide neutron and gamma beams for experimental use in reactor hall or adjoining guide tube laboratory.

APSARA

The very first research reactor of Asia, named Apsara, was commissioned in BARC (then AEET) in the year 1956. It was a 1MW, swimming pool type reactor fueled with enriched uranium–aluminium alloy clad with aluminium. The reactor core was housed in a stainless steel lined pool of 8.4 m long, 2.9 m wide and 8 m deep, filled with demineralized light water. The core, suspended from a movable trolley, could be parked at three positions to facilitate wide range of experiments at beam tubes, thermal column and a shielding corner in addition to the in-core irradiation. The maximum thermal neutron flux available in the reactor was 10^{13}n/cm^2/s. Apsara enabled the Indian scientists and engineers to understand the complexities and intricacies of operating a nuclear reactor safely. Simplicity of this reactor design had made it very popular among the researchers. Various experiments could be planned and carried out with relative ease, as the reactor core was easily accessible and movable. The thermal column and the shielding corner facilities in the reactor made it very versatile for carrying out experiments. Facility for irradiation of targets with only fast neutron was also available in Apsara. In a span of around 50 years, the reactor had been instrumental in carrying out advanced studies in the field of neutron physics, fission physics, radio chemistry, biology, irradiation techniques and R & D work on reactor technology. Neutron activation analysis technique developed with Apsara found wide applications in chemistry, archaeology and forensic sciences. Neutron radiography has also been carried out in Apsara, which has been used for components of space programme. Various shielding experiments to verify the design adequacy of shield configurations used in reactors such as Dhruva, PHWRs, 500MW Prototype Fast Breeder Reactor etc. had been carried out in the shielding corner of Apsara. The reactor was shut down permanently in the year 2009.



Apsara- The First Research Reactor of Asia at BARC

CIRUS

Subsequent to the experience with Apsara, a need for high power research reactors which would cater to the additional requirements of radioisotope production, irradiation facilities etc. was felt. This led to the construction of a high flux and high power research reactor known as Canada India Reactor (CIR). This reactor, built with the help of AECL, Canada, was similar to Canadian NRX reactor, but with few changes based on the location and requirement. CIR was later renamed as CIRUS by Dr. Bhabha. It was a vertical tank type 40 MWt reactor. The reactor was natural uranium fueled, heavy water moderated, graphite reflected and light water cooled. It produced a flux of 6.5 x 10^{13}n/cm^2/s. CIRUS became the work horse of the nuclear energy program, as it provided larger irradiation volume at larger flux. CIRUS reactor was solely catering to the country's radioisotopes requirements till Dhruva became operational in1985. The reactor had a pneumatic carrier facility, where short term irradiations could be carried out. This facility was extensively used for activation analysis, for determining trace quantities of materials in a given sample. The reactor had also been used for silicon doping experiments, much needed for electronics industry. CIRUS had a set of sixself-serve units, in which on-power irradiation of 30 samples could be done simultaneously, for production of short-lived isotopes. In order to utilize and develop thorium fuel technology, irradiation of thorium was started in graphite reflector region of CIRUS very early. The first charge of fuel for Kamini reactor was produced by irradiating thorium in CIRUS. An in-pile Pressurized Water Loop (PWL) of 400 kW heat removal capacity operating at a pressure of 115 kg/cm^{2}and temperature of 260°C was available at CIRUS, which was a valuable facility for test irradiation of power reactor fuel and materials. Utilizing this facility, development of MOX fuel for Tarapur BWR fuel program was taken up. This facility was also utilized for validating various design assumptions and analysis by carrying out test irradiations and later examining thefuel. Irradiation of various structural materials of the power reactors such as end shield and Zircaloy pressure tubes of PHWRs etc. were carried out at CIRS PWL. These experiments built the confidence for designing and operating power reactors.

In those days, CIRUS and Apsara became centers of excellence in nuclear education. People who got early experience in operating these reactors, later grew to lead various nuclear projects and programs. After four decades of successful operation, detailed ageing studies were carried out in CIRUS, which indicated possibility of substantial life enhancement by carrying out refurbishment of identified systems, structures and components. Refurbishment of the reactor

Research Reactor Cirus at BARC

was taken up during1997 to 2002.Along with this, major safety upgrades were also carried out to meet present safety standards. After operating the reactor for another 8 years, it was permanently shut down on 31st December,2010 to honor the Civil Nuclear Deal.

DHRUVA

During the early seventies, strong need was felt to build are search reactor with further higher neutron flux to meet the growing demand of radio-isotope production and advanced research in basic sciences and engineering. Accordingly, a highflux research reactor of 100 MW capacity was designed, constructed and commissioned indigenously. Originally named the R-5, and subsequently renamed as Dhruva by the then President of India Dr. Gyani Zail Singh, this reactor first went critical on 8 August 1985.

Dhruva is a 100 MW_t reactor with metallic natural uranium as fuel, heavy water as moderator, coolant and reflector, giving a maximum thermal neutron flux of $1.8 \times 10^{14} n/cm^2/s$. Many of the reactor structure designs were a forerunner; to be adopted for the standardized Indian PHWR being designed at that time. Manufacturing of the reactor vessel which is over 7 meters in height, 3.72 meters in diameter and weighing about 30 tons was taken up in the central workshop of BARC. Many evolving technologies such as plasma arc cutting of thick (50 mm)stainless steel plates, precision welding and electron beamwelding etc. were developed and successfully employed for the fabrication of reactor vessel. Fabrication of the 300 mm diameter beam hole re-entrant cans for the use in neutron beam research posed another big challenge. A cold rolling facility was set up at MIDHANI Hyderabad where the zircaloy-2 plates were cold rolled to the requisite uniform thickness. Technology for electron beam welding of zircaloy-2 plates in a glove box under argon atmosphere was developed in DRDL Hyderabad. Development of rolled joints for 300 mm diameter between SS and zircaloy-2beam tubes was a major developmental activity. Designing of there-fueling machine for safe and reliable operation was another challenging work. The machine carrying fuel assemblies was to make a leak tight joint with the coolant channel and continue cooling of the fuel during transit. For this, the fueling machine, having lead shielding and weighing over 300 Tons, is to be aligned with the channel within an accuracy of ± 0.25 mm.

Research Reactor Dhruva at BARC

The design, construction, commissioning and operation of Dhruva has been a completely indigenous effort. In addition to the engineers and scientists of BARC, several government institutions and public sector and private industrial organizations in the country have participated in the above, meeting very stringent requirements. This high flux reactor which was designed, constructed and commissioned entirely indigenously reflects the country's resolve to achieve self-reliance in nuclear technology. For more than 36 years, Dhruva has been extensively utilized for engineering and beam tube research, testing of equipment and material and large scale production of isotopes.

APSARA-U

Apsara-U is an upgraded version of the Apsara reactor, with 2MW rated power. Here the reactor core is replaced with Low Enriched Uranium (LEU) in the form of U_3Si_2 dispersed in aluminium matrix as fuel to meet the international requirement. The core is surrounded by two layers of beryllium oxide reflectors. The reactor core is suspended from a movable trolley and can be parked at three reactor core positions inside the pool like the old Apsara reactor. The maximum thermal neutron flux is enhanced to 6.1×10^{13} n/cm^2/s in the core region and maximum thermal neutron flux in reflector region is increased to 4.4×10^{13} n/cm^2 /s. Maximum fast neutron flux is 1.3×10^{13} n/cm^2 /s. The higher neutron flux facilitates production of isotopes for applications in the field of medicine, industry and agriculture. The Apsara-U also provides enhanced facilities for beam tube research, neutron activation analysis, neutron radiography, neutron detector development & testing, biological irradiations, shielding experiments and training of scientists and engineers. All the systems and components of Apsara-U are designed and manufactured to meet enhanced power level for better utilization of the reactor adhering to the latest safety codes and standards.

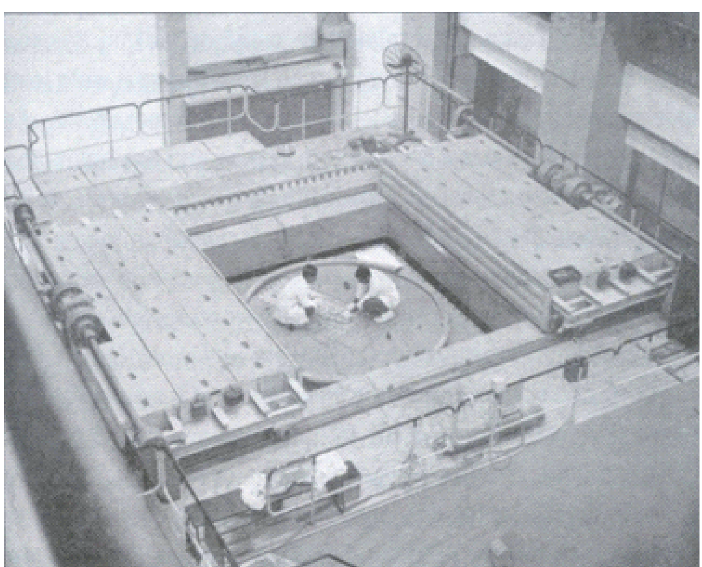
Apsara-U reactor core is mounted on a 140 mm thick aluminium grid plate having 64 lattice positions arranged in 8 x 8square array with a lattice pitch of 79.7 mm. The central 4 x 4lattice positions of the core are loaded with fuel assemblies and are surrounded by two layers of BeO reflector assemblies. The core has two types of fuel assemblies, viz. Standard Fuel Assembly (SFA) with 17 fuel bearing plates, and Control Fuel Assembly (CFA) with 12 fuel bearing plates. Various types of reflector assemblies are designed to satisfy the requirements of positioning of various components in the reflector region such as fine control rod, irradiation positions, fission counters, thermocouple, in addition to standard BeO reflector assemblies, reflecting the neutrons towards the core.

Reactor Pool of Apsara-U Research Reactor at BARC

Research Reactors offer a diverse range of applications such as neutron beam research for material studies and non-destructive examination, neutron activation analysis to measure very small quantities of an element, radioisotope production for medical and industrial use, neutron irradiation of fuel and structural materials for advanced nuclear power plants, neutron transmutation doping of silicon, etc. Besides, RRs have contributed significantly in education and training of operators, maintenance staff, radiation protection and regulatory personnel, students and researchers.

ZERLINA

Zerlina was the third reactor to be built in India and was a totally indigenous facility. This reactor was built for the purpose of studying various core geometries. The geometric arrangements of the fuel elements in the core, called the lattice has a significant bearing on the physics of reactors. At the time of embarking on a large power programme, there was a need for an experimental reactor in which different types of lattices could be assembled with ease. This would help evaluate their reactor physics characteristics and develop satisfactory computer coded for the design of both research and power reactors. Zerlina was made critical on January 14, 1961. All the measurements for Dhruva reactor lattice physics were carried out in Zerlina. This facility was also used for many experiments where computational modelling of neutron absorbing / producing assemblies is difficult. Zerlina played an important role in development of measurement techniques, inter-calibration of neutron activation foils of alloys and standardisation of counting set-ups. All these aimed at improving measurement accuracies. Zerlina played a key role in evaluating various design parameters and some of the components of Dhruva, like reactor instrumentation and start-up systems. The reactor core characteristics of MAPS reactor and various instruments, including safety related systems developed for India's nuclear programme by different agencies were also evaluated in Zerlina. Zerlina was decommissioned in 1983, as it was felt that a lattice experiment facility was no longer needed.



Zero Energy Reactor for Lattice Investigations and New Assemblies – Zerlina at BARC

Purnima Series of Reactors

The second and third stage of nuclear programme entails the construction of fast breeder reactors which use plutonium and thermal reactors using U-233 respectively. The Purnima series of reactors were built for gaining experience in designing such reactors. Purnima was designed as a zero-energy fast research reactor. It attained criticality on May 18, 1972. Later called as Purnima-1, the reactor was extensively used for carrying out detailed studies on fast reactor neutronics. The core of Purnima was dismantled after carrying out all planned experiments. The infrastructure developed for this reactor was later used to house the subsequent Purnima series of reactors.

After completion of Purnima-1, a ^{233}U uranyl nitrate solution fueled beryllium oxide reflected zero energy thermal reactor called Purnima-2 was set up. This reactor attained criticality on 10 May 1984. A major objective of this reactor was to perfect the technique of carrying out criticality experiments. Purnima-2 made a significant contribution toward development of ^{233}U fueled reactors. The reactor was shut down in 1986.

Purnima-3 was built and used as a test bed and zero energy critical facility to study the core of KAMINI (Kalpakkam Mini) reactor. In this reactor, ^{233}U-Al alloy (20%) flat plate type fuel subassemblies and beryllium oxide reflectors clad with aluminium/zircaloy were used. The reactor was made critical on April 29, 1992. Experiments were performed to study various core-reflector configurations of interest to Kamini reactor. The core of Purnima-3 was dismantled and the fuel was transferred to Kamini reactor in 1996.

Critical Facility

For conducting lattice physics experiments for validating Advanced Heavy Water Reactor (AHWR) design parameters, a 400 W reactor called Critical Facility was commissioned in 2008.

AHWR-Critical Facility at BARC

Core of AHWR-Critical Facility

Neutron Beam Research

The internal structures of matter at microscopic and atomic levels are very important to understand, as they determine macroscopic properties of a material, including how they react. The short range strong interaction of neutron with matter and its inherent magnetic moment

makes neutron scattering a unique probe to analyze solid and condensed fluid matter. An important advantage of neutron over other forms of radiation is that neutron, being neutral in charge, can penetrate the bulk of materials. The incident monochromatic neutrons are scattered without a change in their energy i.e. elastic scattering which informs about the arrangement of atoms in materials. When the neutrons undergo inelastic scattering i.e. a change in their energy during scattering, they can yield information about the dynamics of atoms. By performing neutron scattering, biologists understand proteins essential for the functioning of brain; how bones mineralize during development or how they repair or decay with age. Physicist can create more powerful magnet that could be of use in accelerators or levitated transport. Chemist improves batteries and fuel cell. Material scientist can improve steel for use in aircraft, nuclear reactor and many other challenging applications.

Radioisotope Production and Applications

A stable material can be made radioactive by bombarding it with neutrons in a nuclear reactor. The radioisotopes, thus produced, can be widely used for societal benefits especially in industry and medicine. Radioisotopes are now considered indispensable in the diagnosis of a variety of diseases and also in therapy. In diagnosis, two types of techniques are employed, the first one being the *in-vivo* techniques, where the patient is administered a radiopharmaceutical either orally or intravenously. The distribution of the injected radio-pharmaceuticals in different organs/metabolic pathways is studied from outside the body by using a suitable radiation detector such as gamma camera. Such techniques provide images of the organ function. Thus, the procedure not only provides anatomical information but also the more important functional information about the organ.

Neutron Activation Analysis

Neutron activation analysis is an important technique to determine elements at major, minor and trace concentration levels in samples of wide variety accurately and precisely. It is a sensitive and selective technique capable of quick detecting and quantifying multiple elements even from a small sample. The sample is subjected to neutron irradiation in a reactor facility and later the characteristic gamma radiation emitted by the activated nuclei is detected to identify trace elements in ppb range. The techniques are used in environmental and life science, forensic science, material science, quantification of elements in a mineral ore sample and archaeology. A large number of case exhibits (transmission wires, bullet materials) referred to from various central/state forensic laboratories, have been examined to give an opinion about source correspondences/commonness of origin. Determination of toxic trace element such as Chromium, Mercury in food materials and Arsenic in potable water have been carried out. Several rock samples, including meteoric sample have also been examined for their Rare Earth Element concentrations.

Neutron Imaging and its applications

Neutron imaging as a non-destructive testing method can be used for a broad spectrum of industrial/scientific applications. When a beam of neutrons passes through a sample, it leaves the image of the sample on a detector. The neutron interacts with nuclei of the atoms that compose the sample and the absorption and scattering properties of neutron make it possible to create the image. It can even produce image of lighter element like hydrogen. The neutron imaging technique finds application in fault detection in the engineering components, distribution of hydrogen, boron and cadmium in metals, water transport in soil/plant/fuel cell, study of cultural artefacts for preservation and restoration, real time neutron radiography is also used for flow visualization of two phase flow.

Neutron Transmutation Doping (NTD)-Si

Neutron Transmutation Doping (NTD)-Si, which is the process of creating non-radioactive dopant atom from the host Si atoms by thermal neutron irradiation and its subsequent radioactive decay, has been used extensively in manufacturing of high-power semiconductor devices. The quality of NTD-Si, both from the viewpoints of dopant concentration and homogeneity has been found superior to the quality of doped silicon produced by conventional methods.

Conclusion

Materials used for the nuclear energy programme are very different than those used for general engineering purpose since the nuclear properties exhibited by them play an important role in their selection. Irradiation behavior of any material is a very complex phenomenon and its testing in appropriate reactor environment is very important to understand its characteristics. Everything that goes into a power reactor is appropriately tested in a research reactor, qualified and only then it is allowed to be used in a power reactor. Research Reactors have played a pivotal role for the development of the Nuclear Energy programme in the country.

References

1. Superabsorbent BARC-Hydrogel (MRIDAMŔT) (मृदाअमृत) – Bhabha Atomic Research Centre (BARC) https://barc.gov.in/technologies
2. IAEA Publications http://www-pub.iaea.org

Nuclear Power in India

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Preamble

This year, as we celebrate Azadi ka Amrit Mahotsav, the 75th anniversary of our independence, we feel proud to be recognized by the world as a nation with advanced nuclear technologies. Today, India has expertise in all aspects of nuclear power - siting, design, construction, operation and maintenance, ageing management, renovation and modernization to decommissioning. For a country that had a very small technological base at the time of Independence, to have achieved such a status in this frontier technology is a great achievement. It is time to reflect on the evolution of our nuclear power programme, the efforts put in and the visionaries who made it possible.

Today, as the world struggles to contain the impending catastrophic effects of climate change and nations plan their energy transition towards net zero goals, clean energy sources like nuclear power and renewables are becoming increasingly important. Nuclear power in India, apart from helping its energy transition to a net zero economy by 2070, has a vital role to play in ensuring the country's long term energy security.

Nuclear energy development in India

Unlike in the developed countries where energy of the atom was initially harnessed for destruction (the atomic bomb), in India, nuclear energy development began with the objectives of improving the quality of life of the people and self-reliance in meeting their energy needs.

Three-Stage Programme

In 1954, Dr. Bhabha presented the three-stage nuclear power programme for the country, which remains robust and relevant even today. The adoption of the unique sequential three-stage programme and associated technologies was also based on the key principle of self-reliance. It envisaged optimum utilization of the indigenous nuclear resource profile of modest Uranium and abundant Thorium resources. The sequential three-stage programme was based on a closed fuel cycle, where the spent fuel of one stage is reprocessed to produce fuel for the next stage. The closed fuel cycle thus multiplies manifold the energy potential of the fuel and greatly reduces the quantity of waste generated. It was thus an inherently sustainable solution.

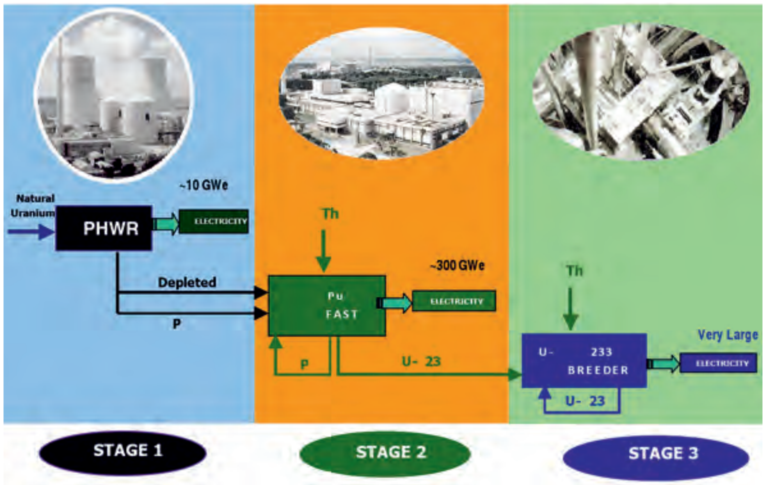

Fig. 1 :Three Stage programme

The three-stage programme comprises of Pressurised Heavy Water Reactors (PHWR) in the first stage, Fast Breeder Reactor in the second stage and thorium based systems in the third stage. The stages have important fuel cycle linkages.

The first stage comprises of Pressurised Heavy Water Reactors fuelled by natural uranium. Natural uranium contains only 0.7% of Uranium^{235}, which undergoes fission to give energy. The remaining 99.3% comprises Uranium^{238}, which is not fissile. In the fission process, among other fission products, a small quantity of Plutonium^{239} is formed by transmutation of Uranium^{238}, which again is fissile.

The spent fuel (spent of Uranium^{235}) is cooled for about five years to remove decay heat before reprocessing to recover Uranium^{238} and Plutonium^{239} and remove other fission products. The second stage, comprising of Fast Breeder Reactors (FBRs) are fuelled by mix of Uranium^{238} and Plutonium^{239} recovered by reprocessing of the first stage spent fuel. In FBRs, Plutonium^{239} undergoes fission producing energy, and at the same time, producing Plutonium^{239} by transmutation of Uranium^{238}. Thus, the FBRs produce energy and fuel, hence are termed Breeders. FBRs produce more fuel than they consume. Over a period of time, Plutonium inventory can be built by feeding Uranium^{238}.

Thorium^{232} is not fissile and has to be converted to Uranium^{233} by transmutation in a reactor for use as a fissile material. In the second stage, once sufficient inventory of Plutonium^{239} is built up, Thorium^{232} will be introduced as a blanket material to be converted to Uranium^{233}, which is fissile.

In the third stage, breeder reactors based on a Thorium^{232}-Uranium^{233} fuel cycle are planned to be deployed.

Building of Institutions

For going ahead with the nuclear power programme, the nation went about a process of building institutions to achieve self reliance.

Soon after independence, the Atomic Energy Commission (AEC), the apex policy making body was constituted for framing policies related to atomic energy in India. The Department of Atomic Energy was established in 1954 for implementing the national policies on atomic energy.

Institutions for Research & Development, exploration, mining and processing of minerals, production of heavy water, fuel fabrication, fuel and spent fuel management, nuclear instrumentation, etc. required for the nuclear power programme were established. Human Resource and training infrastructure was developed for the specialized skills needed for nuclear power.

In parallel, the Indian industry also evolved to manufacture components/ equipment required to the exacting standards of the nuclear industry with initial handholding and joint development.

The Atomic Energy Regulatory Board (AERB), a safety regulatory authority independent of the DAE was also established.

The nuclear power programme in the country went through distinct phases of Demonstration, Indigenisation, Standardisation, Consolidation, and Commercialisation thereafter.

Demonstration Phase:

India's first nuclear power plant – TAPS 1&2

To demonstrate the feasibility of introduction of nuclear power in the then existing electricity grids, after extensive studies, it was decided to set up two units of Boiling Water Reactors (BWR) to be supplied by GE, USA on a turnkey basis. The construction of these reactors commenced at Tarapur, Maharashtra in 1964. They began commercial operation in October 1969. At 210 MW each, they were then the largest size power plants in the country. They were the first nuclear power plants in Asia.

Fig. 2: Tarapur Atomic Power Station 1&2

India's first PHWRs – RAPS 1&2

Even as TAPS 1&2 were being constructed, India embarked on the construction of the first PHWR in collaboration with Atomic Energy of Canada Limited at Rawatbhata in Rajasthan. Canadians then had been building PHWRs in their country. This project was very important as it would be the harbinger of a series of PHWRs of 220 MW that were envisioned as the first stage of India's indigenous three-stage programme.

Fig. 3: Rajasthan Atomic Power Station 1&2

The Turning point

The first unit, RAPS-1 was completed in 1973. The second unit RAPS-2 was under construction, when in 1974 all assistance by Canada was withdrawn and an international technology denial and embargo regime commenced following the conduct of the first Peaceful Nuclear Experiment by India.

This challenge was overcome by Indian scientists and engineers who successfully completed and commissioned the unit in 1981, which continues to operate even today. This also set the ball rolling for full indigenization of the country's nuclear power programme.

Indigenisation:

Subsequently, MAPS units 1&2 (2X220 MW) at Kalpakkam, Tamilnadu were designed, constructed and commissioned with indigenous efforts. The setting up of MAPS involved challenges of evolving Indian designs, high precision manufacturing, challenges in construction and commissioning of units on the eastern sea coast and large scale construction planning. These units commenced commercial operation in 1984 and 1986, respectively.

Standardisation:

Following the successful operation of the first indigenous nuclear power plants at Madras, it was sought to standardize the 220 MW PHWR design for rapid expansion. In parallel, improvements in safety features were also made like introduction of secondary shutdown system, double containment, etc. The first standard Indian PHWR was set up at Narora,Uttar Pradesh (NAPS 1&2)

Consolidation:

The standard design of NAPS was further consolidated by setting up a 2X220 MW PHWR station at Kakrapar, Gujarat. While NAPS 1&2 commenced commercial operation in 1991 and 1992, respectively, KAPS 1&2 commenced commercial operation in 1993 and 1995, respectively.

Evolution of Organisations:

The design, construction and operation of nuclear power plants in the country was started as a departmental activity in the early sixties, by the Department of Atomic Energy (DAE), Government of India. In the year 1967, Power Projects Engineering Division (PPED), a division of the DAE, was formed and entrusted with this responsibility. PPED was converted to Nuclear Power Board (NPB) in the year 1984, with increased delegation of powers.

For the planned expansion of nuclear power programme, it was felt necessary to create a framework for faster decision-making and also to tap funds from capital market. Accordingly, NPB was converted into Nuclear Power Corporation of India Limited (NPCIL), a fully owned company of the Government of India, Department of Atomic Energy and registered on 3rd September 1987, under the Companies Act of 1956. The company started functioning from 17th September, 1987. The assets of the Nuclear Power Board excluding Unit-1 of Rajasthan Atomic Power Station (RAPS-1) were transferred to NPCIL on its formation.

NPCIL activities include all aspects of nuclear power reactors. These include Siting, Design, Construction, Commissioning, Operation & Maintenance, Renovation & Modernisation, Life Extension and Waste Management.

Similarly, another company, BHAVINI was incorporated to set up Fast Breeder Reactors of the second stage in the commercial domain in the year 2003.

Commercialisation & Expansion

The 220 MW PHWR design which evolved from RAPS 1&2 (AECL Canada) to MAPS 1&2 (first indigenous PHWR) prior to formation of NPCIL was indigenised, improved and standardised with NAPS-1&2 and KAPS-1&2. Eight more 220 MW reactors – Kaiga 1 to 4 and RAPS 3 to 6 of the design were set up by NPCIL.

The PHWR design was scaled up to 540 MW capacity and two such units (TAPS-3&4) were set up at Tarapur Maharashtra site. This design was further uprated to the state of the art 700 MW with advanced safety features; and the first 700 MW PHWR, KAPP-3 was synchronized to grid on 10th January 2021. Five more units of 700 MW PHWR are under construction and ten more have been accorded sanction, which are being set up in fleet mode. These are expected to be progressively completed by 2031.

Additionalities to the three-stage programme of India:

In parallel to the indigenous three-stage programme, additionalities based on imports have been introduced, essentially for faster nuclear power capacity addition in the near term, considering the lead times involved in the indigenous nuclear power programme.

International Cooperation in Nuclear Energy

Following the fruition of International cooperation in nuclear energy, international agreements for cooperation in nuclear energy were concluded to end the country's international isolation and access global markets for nuclear commerce. This opened up the possibility of import of fuel for use in reactors under IAEA safeguards and setting up nuclear power reactors based on technical cooperation with foreign countries.

NPCIL has also set up two 1000 MW Pressurized Water Reactors (PWR) in cooperation with Russian Federation at Kudankulam (KKNPP 1&2) and has gained valuable experience in construction and operation of these reactors. Four more 1000 MW PWRs (KKNPP- 3 to 6) are being set up at the same site in Tamilnadu.

Comprehensive capabilities

NPCIL has, over the years, developed comprehensive capability in the core nuclear technology. This encompasses design of Systems, Structures & Components, Safety analysis, Licensing, manufacture of nuclear equipment (with Indian industries), Construction and Operation of NPPs. In addition, NPCIL has developed technologies for life management and maintenance, in association with other units of DAE. Adopting these technologies, NPCIL has successfully carried out Enmasse Coolant Channel Replacement (EMCCR), Enmasse Feeder Replacement (EMFR), introduction of Spargers in MAPS-1&2, repair of Calandria Vault in KAPS-1, in situ repair of tri-junction joint in Kaiga-3 Endshield and Over Pressure Relief device in RAPS-1 etc.

Thus NPCIL has evolved today into an organisation with expertise in PHWRs of different sizes, BWRs, and large capacity PWRs.

Performance of Operating Plants:

a. Safety performance

Ever since its inception, Indian nuclear power plants have had an impeccable safety record. There has not been any accident or incident of release of radioactivity in the public domain beyond stipulated limits. Indian nuclear power reactors have registered over 570 reactor-years of safe operation (as of June 15, 2022).

Environmental Survey Laboratories (ESL) are established at each site before the start of reactor operation which collect site-specific baseline radiation data from natural sources like cosmic rays, rocks, soil etc. After the plant goes into operation, environmental matrices like air, water, soil, crops, fish, milk etc. are monitored for radioactivity in an area upto 30 km around the plant. The data collected over 50 years of operation in India has shown that the increase in radiation level around nuclear power plants has been negligible and within the variations in the natural background. The average natural background (dose for natural sources like radon in rocks, soil, cosmic rays etc.) dose is 2400 micro-Sievert per year.

The public dose at the site boundary of NPCIL sites vis-à-vis the AERB limit is shown below in Fig 4.:

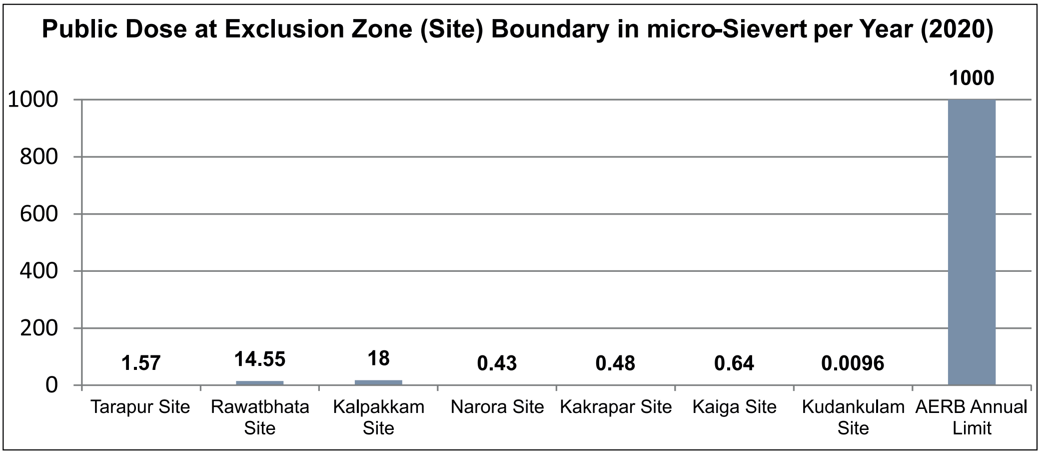

Fig. 4: Public Dose at NPP sites

Expert safety reviews, following the Fukushima incident in Japan, found that NPCIL reactors are safe against extreme natural events and have margins and features in design to withstand them. The recommendations made to take the safety to a higher level have also been backfitted in existing plants and incorporated in design of new projects.

b. Generation

Indian nuclear power plants have so far (upto March 2022) generated about 772721 Million Units of clean electricity, avoiding about 665 million tons of CO_2 emissions. Nuclear power presently contributes about 3.14% of the total electricity generation in the country.

Landmark Achievements

Completion of 52 Years of Safe operation of TAPS 1&2:

These reactors commenced operation in 1969 and were the first nuclear power reactors in India & Asia. They are presently the oldest reactors in operation in the world having completed 50 years of operation in October 2019. These were originally set up by IGE, USA on turnkey basis. Indigenous technological solutions were developed and implemented to ensure highest level of safety and efficient operation of the units (in an international technology denial and embargo regime prevalent from 1974 to 2008). The units underwent major upgradations in 2005 and 2016.

Continuous Operation - World Record of 962 Days by KGS-1

Kaiga Generating Station Unit-1 had set the world record by operating continuously for 962 days before being shutdown on 31st December 2018 for planned surveillance checks and mandatory tests (It now holds the record for the second longest continuous run among nuclear power reactors in world till date). Being a fully Indigenous PHWR fuelled by domestic fuel, this feat bears testimony to the maturity achieved by the country in all aspects of nuclear power technology.

In addition, NAPS-2 (852 days), RAPS-3 (777 days) and RAPS-5 (765 days) have operated continuously for more than two years. NPCIL reactors have operated for more than a year 39 times so far.

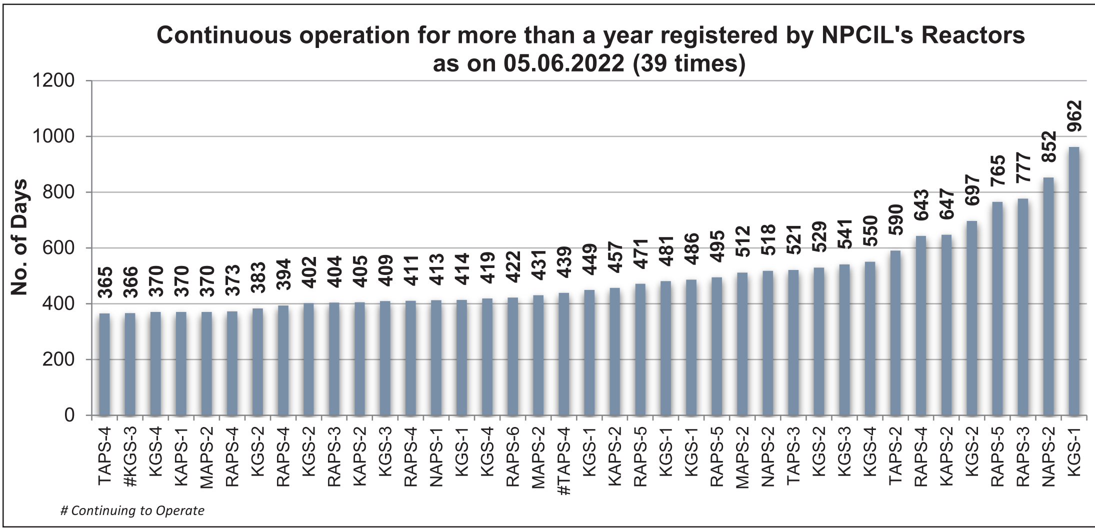

Fig 5. Continuous Operation of more than a year by NPCIL's reactors

Joint Ventures of NPCIL

NPCIL has entered into Joint Ventures (JV) with public sector energy majors for setting up future projects for meeting the equity requirements. Joint Venture companies between NPCIL and NTPC (Anushakti Vidhyut Nigam Limited), NPCIL and IOCL (NPCIL-Indian Oil Nuclear Energy Corporation Limited) have been incorporated. NPCIL is discussing with JV partners for identifying the projects to be taken up by the JV companies. The amendment in Atomic Energy Act-1962 has enabled participation of these Joint Venture companies in nuclear power generation in the country.NPCIL has also entered into a JV with M/s. L&T for manufacture of special steels and heavy forgings.

Present Status of Nuclear Power Programme

1. Reactors In Operation

There are presently 22 reactors with a capacity of 6780 MW, including RAPS-1 (100 MW), which is presently under long term shutdown. The details are:

Unit-Location	Reactor Type	Capacity (MW)	Commercial Operation
TAPS-1 Tarapur, Maharashtra	BWR	160	28 October 1969
TAPS-2 Tarapur, Maharashtra	BWR	160	28 October 1969
RAPS-1 Rawatbhata,* Rajasthan	PHWR	100	16 December 1973
RAPS-2 Rawatbhata, Rajasthan	PHWR	200	01 April 1981
MAPS-1 Kalpakkam, Tamilnadu	PHWR	220	27 January 1984
MAPS-2 Kalpakkam, Tamilnadu	PHWR	220	21 March 1986
NAPS-1 Narora, Uttar Pradesh	PHWR	220	01 January 1991
NAPS-2 Narora, Uttar Pradesh	PHWR	220	01 July 1992
KAPS-1 Kakrapar, Gujarat	PHWR	220	06 May 1993
KAPS-2 Kakrapar, Gujarat	PHWR	220	01 September 1995

KAIGA -2, Kaiga, Karnataka	PHWR	220	16 March 2000
RAPS -3 Rawatbhata, Rajasthan	PHWR	220	01 June 2000
KAIGA -1Kaiga, Karnataka	PHWR	220	16 November 2000
RAPS -4 Rawatbhata, Rajasthan	PHWR	220	23 December 2000
TAPS -4 Tarapur, Maharashtra	PHWR	540	12 September 2005
TAPS -3 Tarapur, Maharashtra	PHWR	540	18 August 2006
Kaiga -3 Kaiga, Karnataka	PHWR	220	06 May 2007
RAPS -5 Rawatbhata, Rajasthan	PHWR	220	04 February 2010
RAPS -6 Rawatbhata, Rajasthan	PHWR	220	31 March 2010
Kaiga -4 Kaiga, Karnataka	PHWR	220	20 January 2011
KKNPP -1, Kudankulam, Tamilnadu	LWR	1000	31 December 2014
KKNPP -2, Kudankulam, Tamilnadu	LWR	1000	31 March 2017

Note: '' Owned by DAE. Under extended shutdown from October 2004*

2. *Reactors Under Construction*

Of the reactors presently under construction, one reactor, KAPP-3 (700 MW) was connected to the grid on January 10, 2021. There are nine more reactors presently under construction by NPCIL. The details are:

Project	Location & State	Capacity (MW)
KAPP 3 *&4	Kakrapar, Gujarat	2 X 700
RAPP 7&8	Rawatbhata, Rajasthan	2 X 700
KKNPP 3&4	Kudankulam, Tamilnadu	2 X 1000
KKNPP – 5&6	Kudankulam, Tamil Nadu	2 X 1000
GHAVP 1&2	Gorakhpur, Haryana	2 X 700

**KAPS-3 was connected to the grid on January 10, 2021 and is generating infirm power*

In addition, the first commercial reactor of the second stage, a 500 MW Prototype Fast Breeder Reactor (PFBR) is at an advanced stage of construction.

3. *Reactors Accorded Administrative Approval & Financial Sanction*

The Government has also accorded administrative approval and financial sanction for the following ten (10) more reactors in fleet mode with a total capacity of 7000 MW, are scheduled to be completed progressively. The details are as follows:

Project	**Location & State**	**Capacity (MW)**
Kaiga -5&6	Kaiga, Karnataka	2 X 700
GHAVP – 3&4	Gorakhpur, Haryana	2 X 700
Chutka -1&2	Chutka, Madhya Pradesh	2 X 700
Mahi Banswara - 1 to 4	Mahi Banswara, Rajasthan	4 X 700

Pre-project activities are in progress at these sites. Land is available at Kudankulam, Kaiga, Gorakhpur and Chutka sites. Land acquisition proceedings are in progress at Mahi Banswara site. Process of obtaining various statutory clearances are in progress at various stages at the sites. Environmental clearance has been obtained for GHAVP, Chutka and Kaiga 5&6 projects. In respect of Mahi Banswara, public hearing has been held.

On progressive completion of the projects under construction and accorded sanction, the installed nuclear power capacity will increase to 22480 MW from 6780 MW at present

4. Future Sites

In addition to the projects under construction and new projects accorded sanction, the Government has accorded 'In-Principle' approval for the following sites for setting up nuclear power projects in future:

<table>
<tr><th>Location & State</th><th>Capacity (MW)</th><th>In Cooperation with</th></tr>
<tr><td>Bhimpur, Madhya Pradesh</td><td>4 X 700</td><td>Indigenous</td></tr>
<tr><td>Jaitapur, Maharashtra</td><td>6 x 1650</td><td>France</td></tr>
<tr><td>Kovvada, Andhra Pradesh</td><td>6 x 1208</td><td rowspan="2">USA</td></tr>
<tr><td>Chhaya Mithi Virdi, Gujarat</td><td>6 x 1000*</td></tr>
<tr><td>Haripur, West Bengal</td><td>6 x 1000*</td><td>Russian Federation</td></tr>
</table>

**Nominal Capacity*

Pre-project activities are initiated at these sites. At Jaitapur, land has been acquired and necessary statutory clearances from MoEF & CC have been obtained. The land acquisition and obtaining MoEF & CC clearance are in process at Kovvada.

Techno-commercial discussions to arrive at project proposals are in progress with M/s. EDF, France for Jaitapur project and with M/s Westinghouse, USA for Kovvada project.

Road Ahead

The national objective of becoming a net zero economy by 2070 involves a major energy transition from the predominantly fossil fuel based technologies to cleaner electricity generating technologies. Nuclear power in this context has a very important role. The present nuclear power capacity expansion is a step in this connection.

The sequential three-stage nuclear power programme envisioned by Dr. Homi Bhabha is robust and on course. Large capacity addition in the second and third stages is planned in future. The programme will be pursued along with LWRs as additionalities. Nuclear power, being a clean source of power has also an important role in production of clean Hydrogen, as the country makes strides towards a Hydrogen economy.

References

1. Taylor & Francis Group https://www.taylorfrancis.com/
2. Department of Atomic Energy (DAE) https://dae.gov.in
3. IAEA Publications https://www-pub.iaea.org
4. Nuclear Power Corporation of India Limited (NPCIL) www.npcil.nic.in
5. Atomic Energy Regulatory Board (AERB) www.aerb.gov.in

Evolution of Health and Safety Programmes

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Preamble

Health and Safety programmes in the Department of Atomic Energy (DAE) cover DAE's nuclear facilities and institutions using radiation sources nationwide for medical, industrial, agricultural and research purposes. The operating management of the nuclear installations and users of radiation carry out their activities judiciously without undue risk to workers, members of the public and the environment. Health and safety programmes in India were evolved side by side to support these objectives.

India's nuclear energy activities cover the entire nuclear fuel cycle: uranium and thorium exploration, mining, milling; fuel fabrication; operation of nuclear power and research reactors, decommissioning and safe management of nuclear waste. The other areas covered are accelerators, radioisotope production, applications of radioisotope in industry, diagnosis and treatment and transport of nuclear and radioactive materials.

This chapter chronicles the evolution of health and safety programmes in DAE. The emphasis of DAE right from its inception was on achieving highest levels of safety of various processes. Instruments and facilities established indigenously to meet health and safety requirements are also discussed,

1. Health and Safety programmes - early years

On February 27 1960, Dr Homi Bhabha issued an office order which stated thus: *"Radioactive material and sources of radiation should be handled in Atomic Energy Establishment ,Trombay (AEET) in a manner, which not only ensures that no harm can come to* *workers or anyone else, but in an exemplary manner so as to set a standard which other organizations in the country may be asked to emulate".*

The health and safety programmes of DAE put this most quoted mandate into practice in the units of DAE. Radiation safety programmes evolved over the years along with the atomic energy programme in India to meet the current safety requirements followed in international practices and national regulations.

The remaining paragraphs of Dr Bhabha' s office order which delegated powers of entry and inspection, in any Division in AEET, to the Head, Health Physics Division are very relevant to India's health and safety programme. Probably, Bhabha had in his mind two safety related occurrences of pre-1960 referred to in the DAE Annual reports and the absence of a formal Atomic Energy Act and rules with safety provisions when he issued the order. (An Act which contained safety provisions was then in draft stage).

In the first incident, scientists found that many tables, equipment, switches etc in several rooms in the physics laboratories in the Tata Institute of Fundamental Research (TIFR) were contaminated with polonium-210, an alpha particle emitting radioactive substance. Shri S D Soman who was already working in TIFR gave special training to some workers and satisfactorily decontaminated the rooms with their help. The second incident, which occurred in 1958 contaminated many rooms with uranium oxide dust while scientists in the Chemistry Division at Cadell Road were producing uranium metal by fused salt electrolysis. Shri. Soman organized the decontamination of these rooms as well.

As a follow up of Dr Bhabha's office order, the health and safety staff published a document called "Manual for Radiation Protection in AEET". This 124 page document is the first formal "regulations and standards" on radiation protection in India. This model document prescribes in detail the duties and responsibilities of officers in charge.

The work related to the health and safety of workers started in 1953-54 with the setting up of the Medical Section in the Medical and Health Division. The Section concerned itself with safeguarding the health of persons exposed to radioactive materials, suggesting and supervising the setting up of the monitoring facilities for personnel and equipment, setting up standards of safe radiation doses, compiling educational material on radiation hazards and carrying out research on basic questions on radiation biology.

Personnel Monitoring with a weekly film badge service to evaluate radiation dose received by radiation workers started in 1953-54. Shri K N Iyengar who later got transferred to Nuclear Physics Division, AEET, started the service. The Health Physics Section prescribed 300 mR (Roentgen-R- is a unit of radiation exposure; mR is a thousandth of a R) as the permissible weekly dose. The Section notified anyone who received above 300 mR and investigated the cause of over exposure. Medical department kept the yearly dose records of workers.

During 1956-57 the scientists in AEET used to bring samples of dust and rain water collected from Delhi, Kolkata, Nagpur and Bangalore by air and evaluated their radioactivity. They later added Srinagar to the sampling network. They started studying in detail nuclear fallout from atmospheric test explosions of atomic and hydrogen bombs during 1957-58 using samples from seven stations and submitted the data to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). They also started measuring activities of strontium-90, Cs-137 and Iodine 131, the most important fall out nuclides in the biosphere. By 1958, AEET scientists started a countrywide programme of radiological hazard control and offered about 1000 film badges weekly to 25 institutions.

In 1959, Dr. A S Rao, a close associate of Dr Bhabha, assigned to Shri P.N.Krishnamoorthy who was already working in TIFR, the responsibility of the Radiological Measurements Laboratory (RML) which Rao set up to provide radiological protection services to institutions outside the Department of Atomic Energy (DAE).

In 1963, DAE set up a separate Directorate to enforce radiation protection provisions in radiation installations outside the jurisdiction of DAE. Health Physics Division continued its activities in DAE.

The use of radioisotopes in medicine, industry, agriculture and research increased rapidly. RML provided personnel dose monitoring services, surveyed medical x-ray units and started developing and making radiation measuring instruments. The extracts from the annual reports of DAE from 1959-1964 indicate the rapid progress made in the field of radiological protection.

The Central Government promulgated the Atomic Energy Act 1962 which addressed the activities connected with the development and use of atomic energy including safety and related matters.

2. Environmental radiological surveillance at sites of nuclear installations and related R&D programmes

Dr A K Ganguly, who joined Dr Bhabha in 1956 was working as a research associate in the Department of Radiation Chemistry in the University of Notre Dam, USA. The teams of young researchers led by him carried out studies in mostly new and unchartered territories. They prescribed limits for radioactive releases and radiation levels at occupied areas for various installations based on the results of these dedicated efforts. These ensured protection of workers, members of the public and the environment. The investigators used the best available experimental data and appropriate safety factors in line with the international norms. Dr. Ganguly's team including Shri T. Subbaratnam, Shri S. Somasundaram, Dr. D.V. Gopinath, Dr. M.R. Iyer, Dr. K.S.V. Nambi, Dr. V. Shirvaikar, Dr. P.R. Kamath, Dr. K. C. Pillai, Dr. L.V. Krishnan, Dr. P. Kotrappa, Dr. M.A.R. Iyengar, Shri S. Krishnamony, Dr. C.M Sunta among others made priceless contributions to the field of radiation safety, environmental monitoring, impact assessment, emergency preparedness among other topics.

The Indira Gandhi Centre for Atomic Research (IGCAR) issued the "Manual on Emergency Preparedness for Kalpakkam DAE Centre", written by Shri A.R.Sundararajan, Dr L.V.Krishnan and Dr.D.V.Gopinath in 1985. In preparing this first of a kind document, the authors had the cooperation and inputs from the District Collectors during the period. Such fruitful interaction with the civil authorities based on mutual respect is very vital in emergency management.

2.1 Environmental monitoring

In order to establish the normal background radioactivity, which provides the basis for all safety measures, scientists periodically surveyed the Trombay area to obtain data on the radioactivity in soil, vegetation and marine life. Scientists started these programmes before they set up the installations and updated and maintained relevant data for timely review if the need arose.

2.2 Dilution factors provided by tidal waters

One of the most notable investigations carried out by Dr Ganguly's team of about 60 young researchers during the late 50's was an experiment to estimate the dilution factors provided by tidal waters in Trombay bay. These studies provided objective inputs to prescribe the permissible limits for the discharge of various radioactive materials into the bay.

2.3 Indian Standard Man

Realizing that the body weight and density, the intake by volume of water and air of the average Indian adult differ considerably from those of the standard man on which the International Commission on Radiological Protection (ICRP) has based its recommendations for dose limit, a team of health physicists worked on Indian standard man during the 60s.They gathered data including total weights and organ weights of over 13,000 post mortem samples of subjects who suffered accidental deaths(1).

During the 90s, another group of BARC scientists collected additional data from 24 medical institutions located in 18 cities in India covering almost the entire country to obtain the organ weights for the adults and younger population. They critically evaluated relevant data from about 14,500 post mortem cases (about 10,000 males and 4,500 females) of accidental deaths. These data were representative as these subjects were healthy when the accidents occurred. This latter analysis generated physical, anatomical, physiological and metabolic data for reference Indian man (2).

2.4 Natural background radiation and radioactivity levels

Explaining the variation of natural background radiation and radioactivity is a pragmatic way to reduce the anxiety of public on the contribution of man-made radiation

Natural background radiation emerges from radioactivity in soil and air and cosmic rays. During mid-80s BARC scientists led by Dr.K.S.V.Nambi carried out a nationwide survey of the outdoor natural background radiation. They measured indoor radiation levels at 214 locations in India, continuously for over a year, on a quarterly basis by using special thermoluminescence dosimeters (3). They estimated the national average value of radiation level as 775 micro Gray/ year; the lowest recorded value was 230 µGy/year at Minicoy (Laccadive Islands) and the highest was 26,730 µGy/year at Chavara, Kerala. (Gray-Gy- is a unit for absorbed dose, when ionizing radiation energy imparted to a kg of material is one joule; since Gray is very large, one thousandth of a Gray-milligray –mGy- and one millionth of a gray-microgray-µGy- are commonly used).

2.5 Radiation map of India

The level of gamma radiation varies from place to place. It depends on the amounts of natural radioactivity (mainly thorium, uranium and their decay products and potassium 40) in soil and rocks. Their concentration depends on the type of rocks.

Dr. A V Sankaran and a few scientists from BARC considered the typical abundance of radioactive elements of rocks and soil in different parts of the country. Choosing such data from 4100 sites covering the entire country using base geological maps (scale 1:2,250,000) divided into 28 km interval grids, they generated computer 3D graphics, bringing out the fluctuating profile of radiation across the individual States and the country as a whole.

2.6 Radioactivity levels in foodstuffs

Every food item contains very small levels of radioactivity. Based on radioactivity, milk being more radioactive is less appealing than beer! Banana is so radioactive that a truckload of it can trigger radiation monitors kept at the gates of some nuclear installations. Dr B Y Lalit and his colleagues in BARC have measured the radioactivity content of almost every food item in India. India benefitted from these early dedicated efforts, when the Atomic Energy Regulatory Board (AERB) prescribed permissible limits of radionuclides in foodstuffs when it apprehended that dairy products and other food materials contaminated with fallout from the accident at the Chernobyl nuclear power station might appear in imports from European countries.

The Laboratories of BARC at Kalpakkam, Kolkata and Trombay started testing for radioactive substances in samples of imported food items and issuing certificates.

BARC team led by Dr.U.C Mishra gave inputs to the expert committee set up by the Bombay High Court to decide, "*Whether milk and dairy products and other food products containing man-made radionuclides within permissible levels prescribed by the AERB on 27th August 1987 are safe and/or harmless for human consumption*". Based on the recommendations of the committee the Supreme Court dismissed a Special Leave Petition on imported Irish Butter. (https://indiankanoon.org/doc/819058/)

2.7 Trace elements and radionuclides in terrestrial ecosystem

BARC scientists studied the impact of releases of radionuclides and trace elements emitted from stationary and mobile sources to the terrestrial and freshwater aquatic environments. In terrestrial ecosystem, a layer of a few metres of soil at the interface supplies most of the nutrients necessary for all forms of life. Scientists find out the effects of trace elements and radionuclide accumulation on soil and water in particular, living organisms, by estimating levels of environmental contamination, transfer (bioaccumulation) and its biological effects (bioindicators).

BARC scientists provided site specific Transfer Factors for different matrices of the terrestrial environment of India based on studies conducted by various Environmental Laboratories.

2.8 Environmental Survey Laboratories (ESL)

BARC established Environmental Survey Laboratories (ESL) in the townships, several km away from nuclear power plants (NPP) before they started operation. Shri P R Kamath was a pioneer in this task. ESLs are equipped with state-of -the- art radiation measuring systems, and are independent of the plant management. ESLs participate in the emergency preparedness programme of NPPs, On-Site and Off-Site emergency exercises and in the public awareness programs in the nearby region to promote awareness of nuclear energy and natural radiation in environment.

The ESLs regularly collect: *(a)* samples of air, drinking water, and local representative dietary items to estimate the dose received by the members of the public and (b) samples of weeds, sediment, soil, grass, etc., which have a tendency to accumulate specific radionuclides to monitor the uptake of radionuclides. Besides, the ESLs monitor the quality of drinking water and sewage effluents as required by the pollution control board.

The regular monitoring programs, by ESLs at NPP sites, have shown that the levels of radionuclides in samples such as soil, crop, vegetation, milk, meat, egg etc. are at global fallout levels and there is no observable increase due to power plant operations.

ESLs collect meteorological data continuously. These data together with sophisticated atmospheric dispersion models help to estimate the concentration of radionuclides and external and internal radiation dose to public around Nuclear Power Plant sites for releases including Ar-41 and Fission Product Noble Gases (FPNGs) from reactors. The average radiation dose received by the members of the public living around different nuclear facilities is far below the AERB limit of 1000 micro-Sv/year and is negligible compared to 2400 micro Sv/y received from natural sources present at any location in the absence of any radiation installation. The data for nuclear power stations are available in the Annual reports of AERB.

3. Radiological surveillance and radiation protection at all the nuclear and radiological facilities of DAE

BARC scientists carry out radiological surveillance and radiation protection at nuclear fuel cycle facilities of IREL, NFC and UCIL including BARC facilities at Tarapur and Kalpakkam and DAE accelerator facilities at BARC, TIFR, RRCAT and VECC, Kolkata. They evaluate shielding and criticality safety for nuclear fuel cycle facilities and radiological environmental impact assessment for upcoming nuclear fuel cycle facilities and power reactors.

Scientists carry out study on long-range transport of radioactive aerosols to estimate its radiological consequences to the members of public as part of strengthening the capabilities of Real-time Online Decision Support System for handling off-site emergencies in nuclear power plants. They also conduct studies in NPPs at different sites to develop protection strategy during severe accidents. Radiological safety analysis carried out for various nuclear fuel cycle facilities assesses the design adequacy, effectiveness of the safety provisions and, additionally, quantifies the margin of safety available.

4. Measures taken to reduce dose to the workers and collective dose in nuclear and radiological facilities

India has been one among the handful of countries, which enforced the latest dose limits for workers and public as soon as the International Commission on Radiological Protection (ICRP) recommended them. India could achieve this status because of proactive measures taken by the operating management with the dedicated assistance from associated Health Physics personnel

Adequate shielding, remote operation, radioactive source control and minimizing the exposure time reduced the external exposures to personnel; isolation, ventilation, cleanliness and the use of appropriate protective clothing and respiratory equipment controlled the internal exposure. The health physics staff continuously monitors areas for radiological parameters such as ambient dose rate, air and surface contamination levels. This increased surveillance has resulted in early detection of areas with exposure potential. The number of installed instruments for radiation monitoring has steadily increased in nuclear facilities resulting in improvement in overall monitoring for radiation protection.

The operating management and the health physics staff implemented multiple measures in reducing radiation exposure to radiation workers in nuclear and radiological facilities. The radiological measurements have provided vital information about the general health of the plant and the management initiated immediate corrective actions based on the data.

The health physics monitoring contributed substantially to reduce doses during maintenance jobs, unusual occurrences/ incidents; their corrective actions have reduced the radiological impacts. The collective dose budget remains lower than approved budget over the years. The radiation protection measures adopted over the years has resulted in avoiding radiation dose above the AERB prescribed limit for the last 15 years, and the average dose to occupational workers is less than one mSv/year for research reactor facilities.

The health and safety staff from BARC, helped to lower radiation exposures to workers in uranium mines and mills and thorium handling facilities. The steps included: segregating high radiation areas, reducing manual handling, stopping wind-table operations, replacing plate and frame filters in filtering mixed hydroxide slurry, thorium concentrates and radium-bearing mixed cake with rotary vacuum filters. In uranium mines, the Health and Safety Group introduced a radon badge for personnel monitoring based on Solid State Nuclear Track

Detectors (SSNTDs), after ensuring its acceptable performance in an inter-comparison programme.

Replacing radium with safer substitutes and consequent use of manual or remote after loading in brachytherapy led to substantial reduction of dose to technicians and radiation oncologists who apply the source to the patients. Previously, these workers were among the most highly exposed.

5. Radiation safety in the medical, industrial, agricultural and research applications of radiation

Medical x-ray units are the most widely used sources of ionizing radiation in any country including India.

"Surgeon Major Walter C. Bevoor of the British army brought the first x-ray unit to India in 1898 within three years of the discovery of x-rays. It was a very primitive portable x-ray unit. Bevoor used it successfully in the North East Frontier Province"(Eurasia Review, Nov 19, 2018)

Based on the experience the British Government equipped its base hospitals with x-ray units.

The number of medical x-ray installations in India grew rapidly. According to Eurasia Review, during the 60s and 70s and the earlier part of 80s, regulatory control of medical x-ray equipment and practices were on an advisory basis. Initially, scientists from the erstwhile Directorate of Radiation Protection (DRP) /BARC and later Division of Radiological Protection visited major hospitals and carried out radiation surveillance programs.

The Eurasia Review article recalled that BARC sent a few officers to Australia, Canada and the UK under various schemes for being trained in medical physics and radiological protection. They served as resource persons in training programmes and for nationwide radiation surveillance activities among others. BARC held several short-term training programmes for the users of radiation and continues to organize such training programmes in a big scale. Particularly notable is the postgraduate diploma course in radiological physics. The programme started during the sixties and it was the first such programme in the country to provide Medical Physicists and Radiological Safety Officers (RSO) to serve radiotherapy centres nationwide.

5.1 Medical X-ray registration programme.

Regulatory control of medical x-ray units and installations is a daunting task. The first major step was a nationwide registration programme. BARC scientists organized six short-term courses to train one hundred and twenty five middle level officers from DRDO and CSIR located in different parts of the country to visit medical x-ray installations nationwide to register them and to collect essential safety- related information from each installation. The registration covered over 30,000 units and provided very useful information for further action.

Permitting the use of only type approved of X-ray equipment ensures built-in-safety. BARC supported AERB in type approval and installation approval for diagnostic and therapeutic installations during early years until AERB took up the responsibility.

5.2 Replacement of Radium in India

Radium, the earliest and once the most widely used radioactive substance in hospitals successfully treated tens of millions of patients worldwide. Techniques developed in France, Sweden, United Kingdom and the USA provided invaluable clinical experience making radium therapy a most effective form of treatment for certain types of cancers.

The first stock of radium in India arrived at the Radium Institute in Patna in 1930. During a nationwide stock taking BARC officers found that over the decades, 65 hospitals owned about 20 gram of radium in the form of fine powder in hundreds of thin platinum - iridium tubes and needles. Many of them were in bad shape due to rough handling and uncontrolled heat sterilization.

Physicians and technicians used to receive high doses during normal handling of sources because of lack of protective accessories. In some hospitals, many sources remained stuck in storage safes and containers of archaic design. Taking into account the deplorable safety status of radium, it was decided to replace it with Cs-137. The AERB endorsed the decision. With the arrival of Cs-137, physicians started after-loading application in place of pre-loading application; occupational doses reduced substantially and the accuracy of patient doses improved significantly.

BARC scientists also fabricated special containers using leak tight stainless steel tubes filled with activated charcoal to carry the sources (some of them leaky) safely from the far-flung hospitals to the Waste Management Division in BARC or IGCAR as appropriate for final disposal.

5.4 Monitoring of workers handling radio-luminous paints

During the 90s, watch manufacturing industries, telephone and defence agencies were using radioluminous paints (containing tritium or promethium-147). The radio-luminous paint will glow in the dark so that those handling the dials of watches and other instruments can see them in the night.

BARC scientists estimated the intake of these radionuclides by workers by using sophisticated instruments and bioassay techniques (urine/fecal analysis) wherever appropriate. Survey team recommended measures to reduce a few needless exposures. The team also guided the institutions on safe practices in handling luminous compounds.

5.5 Regulatory compliance of thorium in gas mantles

Avoiding excess radioactive material is a measure of environmental protection and personnel protection. In 1994, there were about 70 manufacturing units in India, employing about 400 persons handling about 150 tons of thorium nitrate to produce about 200 million mantles annually. BARC scientists verified whether the thorium content in Indian gas mantles comply with the stipulated limits. Scientists analyzed the gamma spectrum of mantle samples from 18 manufacturers and used the ratio of Ac-228/ Th-228 to evaluate the age. Using the age, they determined the Th-232 content. The results showed that nearly $11 \pm 2\%$ by weight of the mantle accounts for the weight of thorium.

5.6 Radiation Standards and Traceability of Radiation Measurement in India

Dr Bhabha identified the availability of radiation standards as one of the important areas as it plays a key role in radiation protection practices. During 1957-58, a small group of scientists started to develop radioactivity standards. They established a $4\pi\beta$ coincidence system for activity measurement. The laboratory also participated in the first international inter-comparison of radioactivity measurements in 1961.

There was total or near total absence of radiation dosimetry in radiotherapy practice in India (IAEA Bulletin,21 No 5). Radiotherapists carried out radiotherapy on an ad hoc basis depending on their clinical experience. As a first step, BARC researchers designed and developed primary standards such as free air chambers, graphite chambers and calorimeters for fundamental radiation units and also established a calibration facility for calibration of dosimeters on a countrywide basis. (4) They fabricated radiation measuring devices and dosimeters from locally available components and materials to the extent possible. They trained young and enthusiastic physicists, in radiological physics, offered short-term courses on radiation safety aspects in the industrial, medical and research applications of radiation.

After setting up the radiation standards, BARC offered dosimeter calibration service to all hospitals in India as well as to those in neighboring countries. They calibrated against reference standards for soft X rays, Orthovoltage X rays and Co-60 gamma rays. They also issued certificates specifying the calibration factors, accuracies and other essential information. Recognition of the BARC lab in 1976 as an IAEA/WHO collaborating centre for secondary standards radiation dosimetry was a shot in the arm.

There are over 500 radiotherapy institutions in the country totally operating more than 230 tele-cobalt and 350 accelerator units. BARC conducts TLD quality audit for radiotherapy centres periodically to ensure that dosimetry practices of these facilities are within acceptable limits. The BARC service which assures accuracy of radiotherapy is beneficial to tens of thousands of patients treated daily nationwide.

6. Development of Aerial Gamma Spectrometry System (AGSS) and Aerial radiation monitoring methodology.

After any nuclear accident, information on ground contamination in particular due to iodine -131 is crucial in planning and executing an effective emergency plan. Identifying this requirement, in 1993, Aerial Gamma Spectrometry System was developed in BARC under the leadership of then Head, RSSD, Dr.M.R.Iyer. Later, a team led by Dr. D.N. Sharma upgraded the system by developing software and monitoring methodology. The team developed the capability to asses radioactive contamination over large area qualitatively and quantitatively and to locate and identify orphan sources. The modified system can transfer the processed data online to display the contaminated area on the digitized map at a ground control centre to enable the decision makers to take countermeasures in case of any nuclear emergency- without need for waiting for the aircraft to land.

After further refinements in calibration methodology, radiation monitoring system, capability to prepare the digitized map of the area which indicates the positional information, hotspots, radioactivity profiles etc, the BARC researchers carried out aerial monitoring campaigns around the emergency plan zones (EPZ) of nuclear power plants at Kalpakkam, Narora and some selected sites in Pune, Noida, Ayanagar etc. They successfully tested AGSS in different types of helicopters at different sites.

Fig.1: Aerial Gamma Spectrometry System (AGSS) developed and used by RSSD team in many aerial Gamma spectrometry surveys using helicopters and during mobile radiological surveys.

7. Indian Environmental Radiation Monitoring Network (IERMON)

BARC scientists set up Indian Environmental Radiation Monitoring Network (IERMON) to carry out radiation surveillance across the country. The network consists of 545 Environmental Radiation Monitors (ERMs) to detect any increase in atmospheric background gamma radiation levels either due to any radiological / nuclear emergency or trans-boundary migration of radioactivity. These stations transfer data online to ICCM/ BARC Emergency Response Centre, Mumbai. Following atmospheric releases from Fukushima nuclear accident, the IERMON online data played an important role and addressed the concerns on the possibility of the radioactive plume reaching India. BARC shared the data with IAEA during that period.

Fig.2: Environmental Radiation Monitor (ERM) of IERMON installed at one of the sites

8. Development of preparedness for response to nuclear and radiological Emergencies

The Site Emergency Control Centre (SECC) for BARC set up in 1987 assesses and responds to any radiation emergency in BARC. One of the most important features of SECC was the Radiation Early warning System for the site with radiation monitors installed around the Trombay site with online data transfer to SECC. The system has been subsequently upgraded with more radiation monitors and radiological impact prediction software to predict movement of radioactive plume by using atmospheric dispersion models.

In the year 2001, DAE decided to develop 8 DAE-Emergency Response Centres (ERCs). DAE also set up 25 DAE-ERCs within the next 17 years with 25th DAE-Emergency Response Centre established in 2018. These DAE-ERCs with BARC-ERC as the nodal ERC at Mumbai have Emergency Response Teams (ERTs), state of the art radiation monitoring systems, stock of protective equipment, potassium Iodate tablets, decontamination agents etc. They participated in many national level emergency preparedness/response activities including Mayapuri radiological emergency(2010), training of Emergency Response Teams (ERTs), first responders, security agencies and mobile radiation monitoring of major cities Emergency Plan Zones (EPZs) of NPPs.

BARC has also developed and installed two Mobile radiological Impact Assessment Laboratories (MRIALs) with state-of- the-art monitoring systems with data transfer capability to ICCM/BARC-ERC. They periodically carry out environmental radiation monitoring around BARC sites, Mumbai-Navi Mumbai area, and other sites as per requirement. The BARC-ERC also coordinates the support of experts in dosimetry, dispersion modelling, radioactive waste management and medical management of radiation emergencies etc.

In 2018, the Site Emergency Control Centre (SECC) of BARC was upgraded for responding to any type of emergencies including nuclear and radiological emergency within BARC, Trombay site with the development and commissioning of ICCM. Trained teams operate the ICCM 24x7. ICCM is attached with a facility to handle decontamination and medical management of contaminated/exposed persons. In addition to IERMON online data, ICCM also provided online data of 'Radiation early warning system' developed for BARC site's emergency preparedness. To ensure that radioactive contamination/radioactive sources will not reach public domain inadvertently, installed monitoring systems under the supervision of ICCM also monitors all scraps going out of BARC sites.

The national level nuclear and radiological emergency preparedness and response are coordinated under the guidance of the designated Emergency Response Director [ERD] (Director, Health Safety & Environment Group, BARC who is also the member of DAE's Crisis Management Group (CMG))

9. Responses to radiation emergencies by DAE Teams

The DAE-ERCs have effectively responded to radiation emergency at Mayapuri and many suspected emergencies from various parts of the county.

9.1 Mayapuri accident (INES,IAEA Level-4) caused by inadvertent release of Co-60 sources

DAE's Emergency Response Teams (from ERCs of BARC, AMD-DELHI and Narora (NAPP and ESL) and regulatory teams of AERB with support from NDRF and Delhi Police recovered major part of the Co-60 sources within 24 hours (8-9th April 2010) and safely transported them to Narora for disposal. The ERC teams supervised decontamination of area and transported safely the recovered contaminated soil and scrap and disposed them off at an authorized disposal site at Narora. Recovery and decontamination were challenging jobs accomplished efficiently without any one getting undue exposure.

9.2 Radioactive sources recovery from Cooum River in Chennai

In October 1993, AERB received information on the theft of three highly radioactive sources used by an oil-well logging company. A team of scientists from BARC and IGCAR assisted the source recovery team. The company under guidance from scientists recovered the sources lying in slush at a depth of several metres after several days after constructing a cofferdam at the site.

9.3 Other instances

There were many other instances of lost or allegedly stolen radioactive sources in the country over the years. Most cases are medical sources or sources used in industry. BARC teams recovered most of them. In a few cases, there were radiation injuries to the persons who handled them unknowingly.

9.4. Ensuring Radiological Security & Safety during Major Public Events

Based on the request from MHA/NDMA, during the Common Wealth Games (CWG-2010), dedicated teams from DAE ensured radiological security & safety at Delhi and all Commonwealth stadia in line with IAEA's document on preparedness for 'Major Public Events (MPEs). BARC-ERC team trained selected teams from DAE-ERCs, Delhi police and NDRF before the CWG. The teams carried out detailed radiation monitoring of all relevant sites and

Fig.3: (a)'Source search' using 'Back Pack' Radiation Detection System, (b) monitoring of one of the stadia of CWG, (c) mobile monitoring of access roads to stadia

stadia until the games were over. The monitoring team installed AGSS in two helicopters and kept them ready for any quick monitoring / response.

9.5 Training on radiological safety and response to nuclear and radiological emergencies and Capacity Building

BARC has conducted many training workshops and field exercises on radiological safety and emergency preparedness and response for training the plant workers, other staff of DAE, customs, security agencies, and staff of DRDO etc.

10. Indigenous Design and development of Instruments

Right from inception, DAE has placed emphasis on indigenous development of instruments and equipment for Department's programs. In line with this approach, BARC has developed a number of instruments and equipment for the monitoring of radiation.

10.1. Development of Radiation monitoring equipment

The instruments developed include

a) Radiation Monitoring Watch (RMW) for First Responders / Emergency Response Teams,

b) Mobile Radiological Assessment Laboratory (M-RAL) for emergency response,

c) Quad-rotor based Aerial Radiation Monitoring System (QARMS) for search of orphan sources and identification of contaminated area by remote controlled Aerial survey,

d) Battery operated Dose rate logging system for Long term unattended operation for deployment in any affected site,

e) Backpack Gamma Spectrometry System (BGSS) to search, detect and identify orphan/lost radioactive sources in public domain,

f) Quick Scan Whole Body Monitor (QS-WBM) for internal dosimetry and Portable Thyroid Monitor for measurement of thyroidal radioiodine content,

g) Limb monitor and Portal monitor to detect illicit/ inadvertent movement of radioactive materials and

h) Vehicle Monitoring System (VMS) to detect illicit shipment of Special Nuclear Material and radioactive material.

Fig.4: Radiation Monitoring Watch (RMW)

Fig.5: Mobile Radiological Assessment Laboratory with screen display during a survey

Fig.6: Quad-rotor based Aerial Radiation Monitoring System (QARMS)

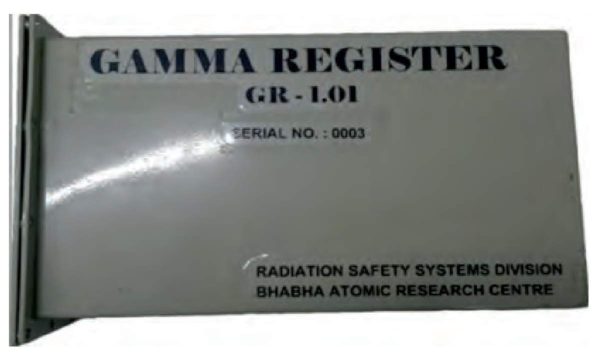

Fig.7: Battery operated Dose rate logging system

Fig.8: Backpack Gamma Spectrometry System

Fig.9: Quick Scan Whole Body Monitor (QS-WBM) and Portable Thyroid Monitor

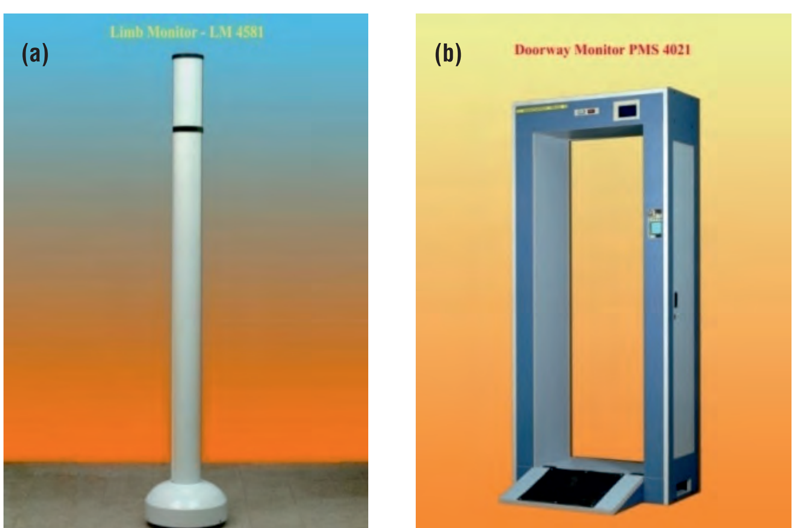

Fig.10: (a) Limb monitor (b) Portal Monitor

Fig.11: System developed for radiation monitoring of Vehicles and Cargos -VMS (ECIL has made many such VMS and installed them in the entrance and exit points of many facilities)

10.2 Indian Real-time Online Decision Support System (IRODOS)

BARC has developed IRODOS to provide Detection & Communication Network for Sensing and Assessment of Accidental Release. The IRODOS shows 72h weather & radiological forecast at any instant of time; through GIS shows the areas, villages, cities etc on which counter measures are to be implemented. It also provides State of Art Weather Prediction, Dispersion Modeling Techniques & Radiological Dose Calculation. IRODOS is currently modified to Decision Support System (DSS) for NPPs to handle an offsite nuclear emergency arising out of an unlikely event of a nuclear accident.

10.3 Indigenous Dosimeters

10.3.1 Thermoluminescence Dosimetry (TLD) system for research projects

During the 70s, Biomedical Group of BARC with the support of the Health Physics Division evaluated the long-term effects of high background radiation on selected population groups in Kerala coast. The scientists in the Health Physics Division developed a calcium fluoride TLD monitoring system to measure the radiation dose to a few thousand people residing in the area. They evaluated the doses to individuals with reasonable accuracy, reliability and reproducibility. The unique dosimetric survey covered about 20% of the households in each area in the region. The scientists distributed 12716 dosimeters and provided the needed personnel doses for the success of the project. The dosimeters were in the form of lockets ensuring ease of use. The study did not show any adverse health effect of radiation for the level of exposure they were subjected to.

10.3.2 TLD for Personnel Monitoring.

DAE started the official centralized Personnel Monitoring Service (PMS) for radiation workers in 1952 using Film Badges. Its limitations led to the indigenous development of a better dosimetry system, thermoluminescence dosimeter (TLD) by BARC.

TLDs are able to measure a greater range of doses in comparison with film badges. Staff can read TLDs on site instead of sending them away for developing and are easily reusable. An important part of the dosimeter is an indigenous technique to fabricate PTFE (PolyTetraFlouroEthylene) based $CaSO_4$: Dy TLD disc for dosimetry. This development led to replacement of Film Badge by TLD Badge in 1975 in a phased manner. Presently, 16 TLD Laboratories (Government and Private) located in various parts of the country provide PMS using the indigenously developed TLD Badge System.

Fig.12: (a) TLD Badge and TLD Card (b) TLD Badge Reader along with PC and other Accessories

10.3.3 Optically Stimulated Luminescence Dosimeters (OSLDs)

In TL, the heat energy acts as stimulation, while in the Optically Stimulated Luminescence (OSL) technique, light energy (generally blue or green) carries out the stimulation. The intensity of the emitted light is a function of dose, which forms the basis of dosimetry. OSL dosimetry system is popular because it is a simple system. It's other notable features are: (a) its optical nature (b) it can be used in a wide dynamic range of measured doses (c) It is easy to automate (d) it has re-read capability and (e) it has ability to perform imaging for determining the static or dynamic dose etc.

HSEG has indigenously synthesized Al_2O_3: C (Alumina), a standard OSL phosphor used worldwide for radiation dosimetry, on a large scale using the melt processing technique. This method is protected under the United States Patent granted to Muthe et al of BARC.

The OSL sensitivity and other properties of this phosphor are at par with the commercially available Al_2O_3:C. The complete dosimetry characterization of this phosphor is completed and new OSLD badge is designed and fabricated. A reader system is also developed indigenously to read out the OSLD badge. The rigorous testing and characterization of both the OSLD badge and the reader system is in progress. After successful completion of field trials it may replace TLD based personnel monitoring system.

10.3.4 Chemical dosimetry system

Division of Radiological Protection, BARC developed an accurate, simple, convenient and inexpensive spectrophotometric method or free radical dosimetry under an IAEA research contract. The Group has developed a dosimeter for low dose measurements. BARC has been using chemical dosimeters in very high dose rate areas for measuring dose. BARC developed an emulsion of PVC containing a pH sensitive dye that undergoes change in colour from yellow to red on irradiation. They are ideal to identify irradiated products.

10.3.5 Capability for internal dosimetry

The scientists of Internal Dosimetry Division/RSSD developed systems and methodology for in-vivo and in-vitro monitoring of suspected internal radioactive contamination (actinides, fission and activation products, radiopharmaceuticals) and assessment of internal radiation dose to radiation workers and members of the public; this include analysis and assessment of tritium, C-14, high energy beta and alpha emitters in biological and environmental samples; studies on biokinetic behaviour of radionuclides. The Scientists also developed an Automation System for radiochemical separation of radionuclides such as thorium, uranium, plutonium, americium, strontium etc. in bioassay samples.

11. National Occupational Dose Registry System

The dose received by radiation workers during their working life (occupational dose) is an important aspect in radiation protection. Maintenance of lifetime dose data of these radiation workers is also necessary to (i) ensure and review radiation safety of workers, (ii) certification and other legal purposes, and (iii) epidemiological studies. Indian Dose registry was networked for most of the DAE units in 2007 and later upgraded in 2013. The upgraded 'Networked National Occupational Dose Registry System (NODRS)' has main database and application servers at BARC. It is an integral part of DAE and countrywide personnel monitoring program, which plays a vital role in effective dose management. Its servers are connected to local servers of all Nuclear Power Plants as well as other DAE units through NPCNET/ANUNET. In addition to dose data and personal information, this system can store biometric information (photograph and finger print) of radiation workers. The system facilitates (i) online allotment of personal numbers to new radiation workers after incorporating personal and biometric data, (ii) online updating of dose data, (iii) identifying radiation workers with previous dose history, if any, using his/her fingerprint, (iv) tracking of radiation workers using fingerprint moving within DAE units, (v) linking of dose records, (vi) online availability of dose history of existing radiation workers.

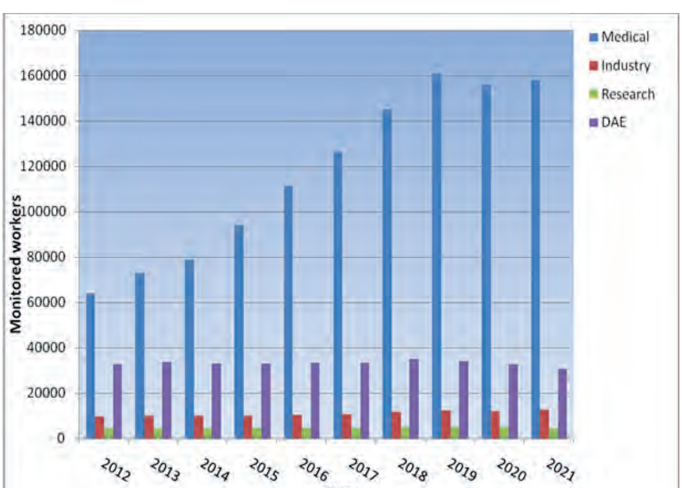

Fig.13: Monitored radiation workers in NODRS under various categories.

In 1954-55, when personnel monitoring service started in the Health Physics section under Dr Raja Ramanna, the section sent about 60 reports every week. Now the NODRS database has the record of 8,64,265 radiation workers and 42,439 institutions. Among them, 2,05,651 radiation workers and 20,434 institutions were active in 2021. It has linked data of 2,18,007-radiation workers, who had worked in more than one institution.

12. Manpower management and R&D needs

The Health & Safety activity in DAE has a rich tradition of research, which is essential for maintaining the vibrancy of the program. Dr A K Ganguly, former Director of Chemical Group mentored and trained dozens of health physicists and radiation protection specialists to provide the scholarly ambience and critical attitude essential for carrying out research in the field. One can see that over the years, the health and safety programmes contributed to many applied research projects, which addressed the needs of the Department by providing science-based answers to many vexing questions. If the "Ganguly school" thrives, health and safety programmes will thrive!

In this chapter, the authors have described some of the events and developments to reveal the humongous contributions of DAE in the field of health and safety since its inception. The health and safety professionals attempted to protect even the smallest sections of people who handled sources of ionizing radiation. They communicated safety aspects to public. While a few individuals carried on with the job exclusively on their own initiative, many others did it by actively participating in the programmes of professional associations such as the Indian Association for Radiation Protection and the Association(IARP) of Medical Physicists of India(AMPI).

Unbridled use of any technology is harmful. While remaining proactive, scientists in DAE Units and AERB have always strived to comply with what Dr Homi Bhabha advised. They handle radioactive material and sources of radiation "*in a manner, which not only ensures that no harm can come to workers or anyone else, but in an exemplary manner so as to set a standard which other organizations in the country may be asked to emulate."*

13. References

1. An evaluation of radiation protection standards for Indian populations, K Venkataraman, S. Somasundaram and S D Soman Health Physics Vol 9 pp 647-652
2. Studies of the anatomical, physiological and metabolic characteristics of the Indian population for setting up a reference man H S Dang, D D Jaiswal, M. Parameswaran and S.Krishnamony IAEA-TECDOC-1005 Vol 2, 1998
3. Natural Background Radiation and Population Dose Distribution in India, K S V Nambi, V N Bapat, M David, V K Sundaram, C M Sunta and S D Soman, Health Physics Division, Bhabha Atomic Research Centre 1986
4. The Development and Functions of the Indian Secondary Standards Dosimetry Laboratory, G , Division of Radiological Protection, BARC,IAEA Bulletin VOL 21, 5, 1979

Further Reading

"Anil Kumar Ganguly (1918-1988) And The Evolution of Health Physics Science in India: Collection of Memoirs", Ed. M.R.Iyer, Special issue of Radiation Protection and Environment, Jan-Mar 2018.

Historical Development of Nuclear Fuels Fabrication and Related Facilities in BARC

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Preamble

This article traces historical development of nuclear fuel fabrication and development of related facilities in Bhabha Atomic Research Centre (BARC). This is written keeping in view science students or persons from different walks of life but not related to development of nuclear energy. The article will cover general aspects of nuclear fuel, fissile materials, historical background of nuclear fuel fabrication in India and salient details of some of the types of nuclear fuel fabricated by BARC. It will also highlight efforts made in development of non-destructive examination of fuel, post irradiation examination facilities and future thrust areas in nuclear fuel fabrication.

1. Introduction

Thermal energy in a nuclear reactor is liberated from fission reactions. These reactions take place inside the nuclear fuel therefore, fuel acts as the primary source of energy and hence it is the key requirement of nuclear reactors. Nuclear fission was discovered and understood by combined efforts of several scientists; chief among them were Enrico Fermi, Otto Hahn, Lise Meitner, Fritz Strassmann, Otto Frisch, Leo Szilard, Niels Bohr, during the years 1934 to 1938. Initially studies were focused on fission of heavy nuclei like uranium. In a fission reaction, heavy nuclei splits into two nuclei, called fission fragments. Most of these fragments are radioactive and further their combined mass is slightly less than the original mass of heavy nuclei. This missing mass is of the order of 0.1 % of the original mass and it is this mass which is converted into energy, of an amount given by Einstein's energy-mass equation: $E = mc^2$. The energy per fission reaction is about 200 MeV (= 32.18×10^{-12} J). The resulting energy density, inside the nuclear fuel, is three million times compared to about 60 eV per reaction from combustion of fossil fuels, like coal. In addition, the fission reaction also yields 2 or 3 neutrons along with gamma photons. A typical fission reaction is shown schematically in Fig. 1(a). It was soon realized that these neutrons can be utilized to sustain stable fission chain reactions and continuous energy generation is feasible, see schematic in Fig. 1(b). This realization immediately led to an intense development of ways and means to harness this energy and the activities progressed with rapidity unprecedented in the history of scientific and technical research.

The result was creation of "Chicago Pile", at University of Chicago, in December, 1942. This was the World's first nuclear reactor; employing fission reactions as source of energy. Its fuel comprised of metallic natural uranium as well as natural uranium dioxide (UO_2). Metallic uranium of desired purity could not be processed in those days hence UO_2 was also used. Metallic uranium was in the form of slugs while UO_2 was compressed into circular disks (called "Briquettes" at that time), employing best techniques of powder metallurgy known at that time. In those days understanding of uranium metallurgy, to fabricate nuclear fuel, was a great challenge.

The natural uranium, employed as fuel constituent in "Chicago Pile", comprises of mainly 0.7% uranaium-235 isotope (U-235) and rest is mainly uranium-238 (U-238). Out of this main source of fission is U-235 and is one of the three known "Fissile Materials". U-238 also undergoes fission but with only high energy neutrons however, the contribution is very small and such materials are called "Fissionable Material".

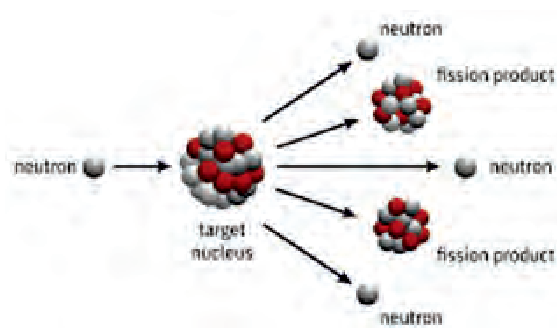

Fig. 1(a): Schematic of fission reaction inside any nuclear fuel. Each reaction yields 200 MeV and 2 or 3 neutrons. The energy density is very high. 1gm of U-235 yields 82000 MJ of thermal energy, which is equivalent to combustion of about 3000 tons of coal. Therefore, nuclear fuel design and fabrication is a challenge

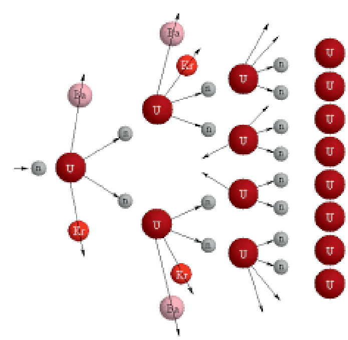

Fig. 1(b): Schematic of sustained and stable fission chain reaction. It is possible with incorporation of suitable absorber materials, which in turn ensure only one neutron enters into fission of next generation

Fission became a new source of energy after combustion of coal or oil or gas. Following successful project of "Chicago Pile", scientists and engineers immediately initiated activities towards utilization of nuclear fission for generation of large scale electricity and naval propulsion. In May, 1954 Obninsk Nuclear Power Plant, Russia, (then known as Soviet Union) became first Nuclear Power Plant (NPP) to be connected to electrical grid and produced 5 MW of electrical power. The nuclear fuel was 5% enriched uranium, that is, the concentration of U-235 isotope was kept equal to 5%, as against 0.7% in natural uranium. Such isotopic enrichments are achieved by physical or mechanical separation techniques.

In January, 1955, United States Navy succeeded in operationalizing compact nuclear reactor for propulsion of submarine called “USS Nautilus”, which became world's first nuclear submarine. It utilized zirconium cladded “Plate Type” fuel with Highly Enriched Uranium (HEU), having U-235 isotopic concentration of about 93%. HEU was essential for maintaining compact size and facilitating long refueling periods.

On August, 4, 1956, first Indian nuclear reactor, called APSARA, became critical. This was not only first in India but was also the first reactor in whole of Asia. It was designed by scientists and engineers of Bhabha Atomic Research Centre (then known as Atomic Energy Establishment, Trombay). It utilized plate type fuel having Uranium Aluminide alloy with Aluminum Clad. APSARA fuel also utilized HEU having U-235 isotopic concentration of about 93%.

Starting 1960s, worldwide large scale efforts were put towards technological development of robust and safe nuclear reactors for generation of electric power, naval propulsion, advanced nuclear research and medical/industrial isotope production. Nuclear energy is attractive because of three main reasons listed below. Nuclear fuel design and fabrication plays important role in all of these advantages.

(a) It is a source of green energy and almost no pollution, as compared to fossil fuel based plants, see Fig 2(a) and Fig. 3(a). Nuclear has very low carbon foot print. A typical 500 MWe coal combustion plants release CO_2 at rate of about 10000 ton per day and in contrast such releases from nuclear plant are insignificant. The fission fragments, including radioactive gases are retained within the nuclear fuel.

(b) Owing to high energy density, the fuel loading in nuclear reactors is infrequent and hence its demand on transportation infrastructure is insignificant as compared to coal or oil based thermal plants. For comparison, see Fig. 2(b) and Fig. 3(b). This fact is among the important factors responsible for relatively low operational cost of nuclear reactors.

(c) Nuclear energy also standouts among several types of renewable sources of energy, owing to its continuous or base load operation capability. This in turn is related to infrequent loading requirements of nuclear fuel. For example, annual electricity units generated by nuclear plant is roughly 3.3 times more than the solar energy station of same installed electrical capacity. This factor varies with the climate. It is higher during cloudy or rainy or snowing or dusty periods. It also increases as we move from equator towards poles. Capacity Factor (CF) of nuclear plants is generally high, for example, Unit # 1 of Kaiga Generating Station, in India, operated at full power continuously for 895 days.

As of the year 2021, there are about 450 numbers of nuclear power reactors all over the world producing about 400 GW of electrical power. In India, there are 22 nuclear power reactors with installed capacity of 6.75 GW of electrical power. Worldwide, 50 numbers of power reactors are under construction and among them 8 are in India. Worldwide 100 more power reactors are planned in immediate future and among them major percentage is in Asia.

The rest of the article will cover general aspects of fuel, fissile materials, overview of development of fuel fabrication and related facilities at BARC. The fabrication technology of fuel for Indian power and research reactors was fully developed by BARC. Currently the fabrication is being carried out by BARC and Nuclear Fuel Complex (NFC), Hyderabad.

2. General Aspects of Nuclear Fuel and Types of Fissile Materials

The nuclear fuel mainly comprises of nuclear material, clad, and structural material. It is the fissile content of nuclear material, which undergoes bulk of the fission reactions. The clad covers the nuclear material and its material selection and design ensures that the fission fragments are not released out under any normal operating condition and any design basis accident condition. Structural materials are required for formation of fuel assembly or fuel bundle and to locate the fuel assembly/bundle inside the reactor such that it maintains desired pitch/inter-space distance as demanded by reactor physics considerations and remains coolable under all the operating, design basis accident conditions and to the extent possible even during beyond design basis accidents. The coolant carries the heat from the fuel for further conversion to useful forms.

Fig. 2(a): A typical coal fired thermal power station. A typical 500 MWe coal fired unit releases about 10000 tonnes per day of CO_2, which has major bearing on green-house effect. In addition, copious amount of So_2, NOX gases and harmful Particulate Matter (PM) amongst others are also released. In the year 2021 India emitted about 1.4 billion tonnes of CO_2 owing to coal firing at power stations alone

Fig. 2(b): Transportation of coal from mines to power station site is expensive and puts heavy demand on transportation infrastructure. A typical 500 MWe unit demands two 50 wagons goods train carrying 5000 tonnes of coal daily from mines to power station site. In the year 2021 about 700 million tonnes of coal was transported for different utility and captive power stations in India

Fig. 3(a): 540 MWe Tarapur PHWRs Unit # 3 and 4. Nuclear plants do not release any pollutants and its carbon foot print is negligible. Nuclear fuel design and high quality fabrication assures that fission fragments and gases are retained within the fuel and hence there are no releases outside the reactor system

Fig. 3(b): Nuclear fuel is transported in trucks. 4 to 5 truck trips meet the annual nuclear fuel requirements of a typical 540 MWe Unit

There are three known nuclear fissile isotopes- Uranium-235 (U-235), Plutonium-239 (Pu-239) and Uranium-233 (U-233). Amongst them, only U-235 exists in nature. Natural uranium comprises mainly of 0.7% U-235 and about 98.3% U-238. The concentration of U-235 was about 32% during early stages of formation of earth. Owing to radioactive decay the isotopic concentration reduced to about 3% about 2 billion years back and now it is 0.7%.

Pu-239 existed after formation of universe but got exhausted by natural radioactive decay, before the earth was formed. About 2 billion years ago when the concentration of U-235 was about 3%, in natural uranium, an anomaly occurred at Oklo, Gabon, located in West Central Africa. Under the natural conditions prevailing that time a self-sustaining natural fission chain reaction initiated in which more than 500 tonnes of U235 fissioned leading to generation of Pu-239. This was the second occasion in which plutonium was formed in nature. However, over a period of 2 billion years this has decayed fully (having half-life of 24 x 10^3 years) leaving the trace of uranium unusually depleted in U-235 concentration thereby giving the secret away. Now Pu-239 does not exist in nature. However, Pu-239 is artificially transmuted from U-238, in nuclear reactors by neutron irradiation. In this manner, U-238 participates in fission reaction indirectly. Such isotopes which get transmuted to fissile isotopes are called “Fertile Materials”. Therefore, U-238 is both “Fissionable” and “Fertile”.

U-233 also does not exist in nature however; there are vast reserves of Thorium-232 (Th-232) in several parts of world. Th-232 can be artificially transmuted to U-233 by neutron irradiation in nuclear reactors hence this is also a fertile material.

In India, the relative abundance of thorium is far more as compared to known reserves of uranium. World's largest reserves of thorium are available in the beach sands of Kerala. Typical view of Kerala beach sands is shown in Fig. 4. Transmutation of Th-232 to U-233 requires large quantity of fissile materials. In order to maximize utilization of thorium, the Indian policy planners chalked out “Three-Stage Nuclear Power Programme” and hence adopted closed fuel cycle. The first stage programme involves construction and operation of uranium fueled reactors. In these reactors, while power is generated but another important output is transmutation of fertile U-238 to plutonium. Major thrust is on Pressurized Heavy Water Reactors (PHWRs), which produce highest quantity of plutonium per unit quantity of mined natural uranium. PHWRs are now fully indigenized. In addition, spent-fuel recycling facilities were also designed, constructed and now are being operated. The PHWR spent-fuel is being recycled to separate plutonium and depleted uranium. As plutonium is produced, various technologies were considered for boosting the quantity of plutonium further. The plutonium along with depleted uranium would fuel the reactors in the second stage, that is, in Fast Breeder Reactors (FBRs). The effective utilization of plutonium and transmutation of U-238 to Pu-239 is high under fast energy neutrons. The fuel for Prototype Fast Breeder Reactor (PFBR), which is under construction, is uranium-plutonium mixed oxide and is being fabricated based on powder metallurgy route. In the second stage the U-238 to plutonium breeding efficiency will be significantly high if “Metallic Plutonium-Uranium” nuclear fuels are used. Considerable efforts are underway to develop suitable uranium-plutonium metallic fuel for future FBRs. It is important to note that for optimal balance between utilization, fuel fabrication aspects and meeting adequate reactor safety margins, it is required that plutonium concentration in plutonium-uranium mixed oxide fuels is limited to about 30%. In case of metallic fuel, it should not exceed 15% to 20% to ensure absence of undesirable metallurgical phases. Exceeding plutonium beyond this limit will induce brittle phases, which in turn will deteriorate the fuel performance.

Fig.4: A typical view of Kerala beach coastline containing rich Thorium reserves. As of year 2020 the estimated thorium reserves, in India, stand at about one million tonnes. The concentration of Thorium is reasonably high and the typical radiation field in these beach sands is around 1 mR/h. At some of the locations peak radiation field is 2 mR/h. These beaches are well inhabited and in addition fairly large numbers of tourists visit regularly. [Note: In contrast the radiation field around any nuclear power plant of India is 100 to 200 times less than the average radiation field of Kerala beach sands. Despite this exclusion zone of minimum one km is maintained around the nuclear power plants and additional 5 km of sterilized zone exists]

Once sufficient plutonium is available and power production is reached wherein self-sufficiency is achieved, further growth in nuclear energy has to be achieved through breeding of U-233 from thorium within the fast breeder reactors. The third stage of Indian nuclear power progarmme would consist of utilizing U-233 for power production as well as breeding Th-232. The prospective reactor concepts are under formative stages. Some of these include fast breeder reactor, molten salt breeder reactor etc. In addition, Advanced Heavy Water Reactor (AHWR) is also being developed for technology demonstration towards thorium utilization and innovative passive safety systems. This is the "Key" to self-reliance in nuclear power even with limited uranium resources.

3. Historical Background of Fuel Fabrication in India

For APSARA research reactor (see Fig. 5(a)) the nuclear fuel was imported from The United Kingdom (UK). Thereafter, BARC carried out massive research and development in nuclear fuel fabrication. This resulted in several fuel fabrication facilities and in-house fuel for all the subsequent research and power reactors built in India. APSARA reactor pool and core are shown in Fig. 6(a) and Fig. 6(b).

Shortly after successful commissioning APSARA, the Canada India Reactor Utility Services (CIRUS) reactor (see Fig. 5(b)) construction started in active collaboration with Canada and first criticality was achieved in July, 1960. In order to fabricate fuel for CIRUS reactor two important facilities namely Uranium Metal Plant (UMP) and Fuel Element Fabrication Facility (which later was called Atomic Fuels Division (AFD)) were created at BARC. Expert Indian metallurgists worked on these projects, which resulted in understanding uranium metallurgy and development of fuel for CIRUS. This was the first ever nuclear fuel made in India and first consignment was delivered in 1959 (see Fig. 7(a)). At that time, this was one of the towering achievements of BARC. Shortly later Zero Energy Reactor for Lattice Investigations (ZERLINA) reactor fuel (in 1961) was developed on the lines of CIRUS reactor fuel.

In the years after CIRUS operationalization, research and development activities were initiated towards for new fuel fabrication techniques for metallic fuels, ceramic fuels and dispersion fuels. Technologies related to Powder Metallurgy (PM) and Ingot Metallurgy (IM) based routes were successfully developed, for fuel fabrication. These initiatives came handy when nuclear programme expanded further.

Fig. 5(a): APSARA Reactor: Outer View of Reactor Building. Fuel and Pool Details shown in Fig.6(a) and Fig. 6(b). (Operations started in the year 1956)

Fig. 5(b): CIRUS Reactor: Outer View of Reactor Building. Fuel details are shown in Fig. 9. (Operations started in 1961)

Fig. 6(a): APSARA, the pool type reactor is Asia first reactor which began operations in 1956. The figure above shows perspective view of APSARA reactor along with pool and top bridge houses structures for control rod drives. (see external view in Fig. 5(a))

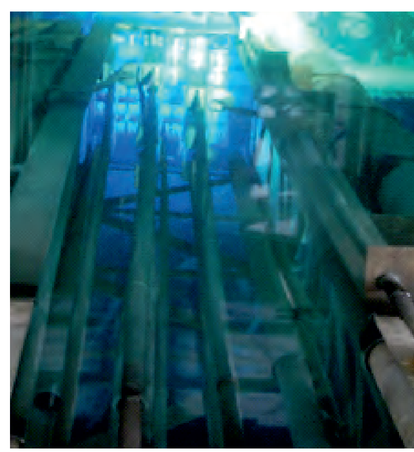

Fig. 6(b): APSARA Reactor Core while in operation, as seen from top of the pool. The view shows blue glow owing to Cherenkov Radiation from water within and around Fuel Assemblies (Plate Type)

Apart from fuel fabrication technologies, impressive developments were made in the area of Non-Destructive Examination (NDE) for assuring desired quality of fuels. The qualification of CIRUS fuel, for reactor, called for sound quality and tight quality control. In the year 1960 Ultrasonic Testing (UT) was used on cast uranium billet to detect piping and shrinkage cavity type of defects. Later Eddy Current Testing (ECT) was introduced for uranium fuel rods for detection of pitting, tool marks and slag inclusions on the surface, which are sites of potential hydride blister formation. During that time NDE methods like UT or ECT were unheard in Indian industry. In fact, application of UT to examine fuel was one of earliest application of this NDE technique in India. Application of UT and ECT for examination of uranium billet and rod are shown in Fig. 7(b).

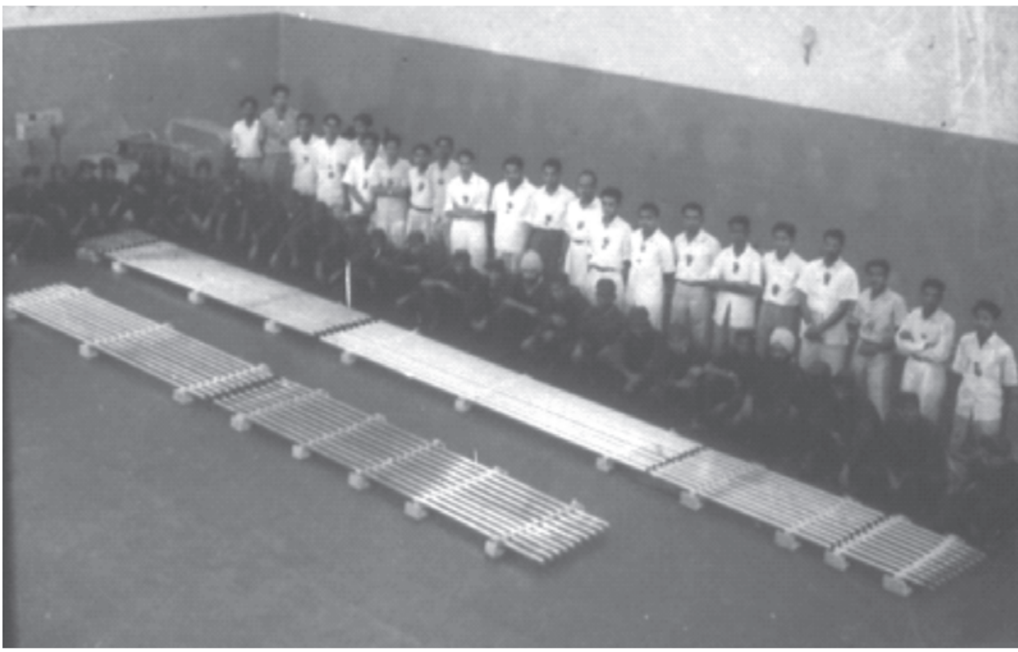

Fig. 7 (a): First consignment of fuel rods was delivered to CIRUS in 1959. The fuel is natural uranium metallic fuel. Metallic uranium fuels, till date, are fabricated only at BARC-Trombay. CIRUS reactor achieved criticality in July, 1960. (Much later, in the year 1984 production of metallic uranium fuel for Dhruva reactor was initiated at facilities created for CIRUS reactor)

Fig. 7(b): Left Picture -Ultrasonic Testing (UT) of uranium billet for CIRUS Fuel. Right Picture-Eddy Current testing (ECT) of CIRUS rod. These techniques were developed at a time when there was no know how of this subject, in Indian industry. Later experts from BARC took active initiative in disseminating knowledge gained in this field, to specialists of other industries.

Beginning of 1960's, India took bold step towards indigenous creation of Nuclear Power Plants (NPPs). To be consistent with our policy of Three Stage Programme, it was decided to build CANDU type of nuclear reactors. This activity was initiated in collaboration with Canada. After first two units at Rajasthan Atomic Power Station (RAPS-1 & 2), Kota, the technology was fully indigenized and several modifications were successfully incorporated in later units, built in India. Subsequently these reactors were called Pressurized Heavy Water Reactors (PHWRs). The development of fuel for power reactors also began at BARC and the natural uranium dioxide (UO_2) fuel bundles, for first core, was successfully fabricated and delivered during the years 1970 to 1971; see Fig. 8. RAPS-1 achieved first criticality in 1973. Later PHWR fuel fabrication technology was transferred to Nuclear Fuel Complex (NFC), which at that time was newly created for fabrication of power reactor fuels. As of now natural uranium oxide fuel bundles, for all PHWRs, are fabricated at NFC, Hyderabad. A new centre of NFC is under construction at Kota. This will facilitate fuel fabrication for new 700 MWe PHWRs. Over the years several improvements have been incorporated in the PHWR fuel fabrication facilities at NFC.

Fig. 8: First batch of Power Reactor Fuel for RAPS-1 PHWR was made in BARC and delivered during the period 1970 to 1971. Powder Metallurgy (PM) based technologies were established to fabricate fuel using natural uranium-dioxide. RAPS-1 achieved criticality in the year 1973. PHWR fuels are now fabricated at Nuclear Fuel Complex (NFC)-Hyderabad

In the year 1965 fuel reprocessing plant called Plutonium Plant (PP) was successfully commissioned at BARC. In 1968 plutonium production was started which marked the beginning of era of plutonium metallurgy in India. Plutonium is highly radio-toxic material and its handling requires extensive safety measures. In order to develop plutonium based fuels and understand the radiochemistry aspects, special radiological laboratory was commissioned in 1968, at BARC, Trombay. Active research by several expert radio-metallurgists resulted in development of plutonium fuels for research and power reactors.

Plutonium based fuel was first time fabricated for Plutonium Reactor for Neutronic Investigations in Multiplying Assemblies-I (PURNIMA-I), in May, 1972. Later technologies were developed for fabrication of fuel for Fast Breeder Test Reactor (FBTR) in October, 1985.

The FBTR fuel is uranium-plutonium mixed carbide. Radiological laboratory houses the only plant in the world for fabrication of mixed carbide fuel. This also marked the beginning of movement towards closed fuel cycle. Till date very few countries have mastered technology of plutonium based fuels.

Another important achievement was successful development of fabrication technology of uranium-plutonium (U-Pu) mixed oxide fuel for TAPS-BWRs (Tarapur Atomic Power Station Boiling Water Reactors Unit 1 & 2). This reactor was constructed and erected by General Electric Company, USA. Its fuel is Slightly Enriched Uranium (SEU) oxide based and is fabricated at NFC, Hyderabad. SEU import is under international safeguards. In the years following India's Peaceful Nuclear Explosion (PNE) in 1974, there was disruption in SEU supply. With the aim of reducing dependence on import of SEU indigenous development was carried out to fabricate U-Pu mixed oxide fuel for TAPS-BWR-1&2. Initial development was carried out at radiological laboratory, BARC, Trombay.

Successful operation of the radiological facilities at BARC, Trombay, led to creation of a larger facility at BARC, Tarapur, for fabrication of uranium-plutonium mixed oxide (MOX) fuels for fast breeder power reactors. This is known as Advanced Fuel Fabrication Facility (AFFF). Plutonium was first introduced, in AFFF, in the year 1993. Based on the technology developed at radiological laboratory, BARC, several fuel assemblies of U-Pu mixed oxide fuels were fabricated for TAPS-BWR-1&2. This was followed by fabrication of MOX fuel for fast breeder reactors.

In the year 1984 PURNIMA-II attained criticality and it was first reactor in India to operate using U-233 based Uranyl Nitrate solution. The core was basically homogenous solution of U-233. Subsequently in the year 1990 PURNIMA-III became critical using U-233 as fissile material. The fuel was plate type with aluminum clad. U-233 was transmuted by irradiating thoria in CIRUS reactor. Thoria was in the form of sintered pellets stacked in aluminum rods. These rods were fabricated in facilities were CIRUS fuel was fabricated. The U-233 fuel was fabricated in radiological laboratories of BARC. PURNIMA-III and its fuel was precursor to Kalpakkam Mini (KAMINI) reactor located at IGCAR, which achieved criticality in October, 1996. KAMINI reactor is the only reactor in the world using U-233 as driver fuel.

As part of civil nuclear cooperation agreement with USA, India decided to permanently shut-down the APSARA reactor in the year 2009. Thereafter, new swimming pool type reactor APSARA-U (See Fig. 13) was designed and constructed at BARC. Its fuel is Light Enriched Uranium (LEU) silicide cladded in aluminum plates. This was developed indigenously and has been fabricated successfully at radiological laboratory, BARC, Trombay.

In case of imported reactors, the TAPS-BWR-1&2 fuel is fabricated at NFC while that of Russian VVERs at Kudankulam the fuel is imported from Russia itself. Feasibility of fabrication within India is being actively explored.

The remaining part of the article covers the brief description of fuels fabricated for some of the research and power reactors, the development of fuel NDE techniques, post irradiation examination of discharged fuel and research and development areas for future fuels.

4. Brief Description of Nuclear Fuels Fabricated by BARC

4.1 Fuel for CIRUS Reactor

Uranium Metal Plant (UMP) and Fuel Element Fabrication Facility (FEFF) were set up for production of nuclear grade uranium metal ingots and metallic uranium fuel rods for CIRUS reactor, see Fig. 9. The first uranium ingot was delivered by UMP in January, 1959 and a prototype fuel element was fabricated in June, 1959. Fuel for CIRUS reactor was in the form of a natural uranium metal rod cladded in aluminium, see Fig. 9. Like APSARA reactor, CIRUS reactor was also permanently shut-down, in the year 2010, following civil nuclear cooperation agreement with USA.

4.2 Fuel for ZERLINA Reactor

Fuel for the ZERLINA reactor was developed on same lines as that for CIRUS reactor. The ZERLINA and CIRUS fuel differ mainly in geometrical sizes.

Fig. 9: Natural uranium metallic fuel fabrication facilities for CIRUS and Dhruva Reactor. Clockwise from top left: (a) Uranium metal ingot undergoing cutting. (b) Vacuum melting and casting facilities for uranium billets. (c) Fuel machining facilities. (d) Fuel rods for CIRUS Reactor

4.3 Fuel for Dhruva Reactor

Dhruva fuel, like CIRUS fuel, is also essentially metallic natural uranium with aluminium clads. However, unlike CIRUS Fuel, this fuel assembly comprises of cluster of 7 pins arranged in aluminium tubes by tie plates and spacers. The photograph of DHRUVA fuel sub-assembly is shown in Fig. 10.

Fig. 10: Dhruva Reactor Fuel Clusters. Left figure shows the overall assembly (3 numbers of them are seen). Right figure shows end view of one of the assemblies. It is a cluster of 7 fuel pins. Dhruva fuel fabrication facilities are more or less identical to those of CIRUS fuel, shown in Fig.9

4.4 Fuel for PURNIMA-I Reactor

One of the first outcomes of expertise developed in plutonium metallurgy was fuel fabrication for PURNIMA-I reactor. PURNIMA-I was a fast reactor. The fuel elements consist of a stack of sintered PuO_2 pellets, with an average density on 90% of theoretical. This gave invaluable experience of plutonium fuel performance and gave opportunity to reactor physicists to benchmark their computer programmes.

4.5 Fuel for FBTR

After PURNIMA-I, the major fast reactor to be designed and built was FBTR, which was operationalized in the year 1985. Its thermal power is 40 MWth. Its fuel is uranium-plutonium mixed carbide. Apart from radio-toxicity associated with plutonium, the carbide form is highly pyrophoric. The fuel is fabricated in ultra-high purity inert gas environment. Unlike in uranium-plutonium MOX or metallic forms the percentage of plutonium in mixed carbide form can be significantly higher than 30% (see section 2.0). In fact, in FBTR the PuC percentage is 70% hence it was possible to build compact core of FBTR. In case of uranium-plutonium MOX fuel, with plutonium fissile content restricted to 30%, and hence such compact core will demand significant quantities of enriched uranium. Carbide form with higher concentration of Pu-239 fissile material was opted for two reasons; firstly, unavailability of enriched uranium, in those days, and secondly the aim of adopting fast breeder technology was to enhance production of plutonium from limited resources of uranium. However, carbide form is very challanging to fabricate and requires several safety precautions. FBTR is the only reactor in the world using uranium-plutonium carbide fuel. FBTR fuel pellets and fabrication facilities are shown in Fig. 11. The fuel performance has been excellent and average burn-up is about 140 GW-Days/Tonne and peak burn-up of 165 GW-Days/Tonne.

4.6 Fuel for PFBR

PFBR is under construction, at Kalpakkam, and will be India's first fast breeder power reactor. It fuel is uranium-plutonium MOX, with plutonium oxide concentration less than 30%. The fuel is fabricated at AFFF, BARC, Tarapur and typical assemblies are shown in Fig. 12.

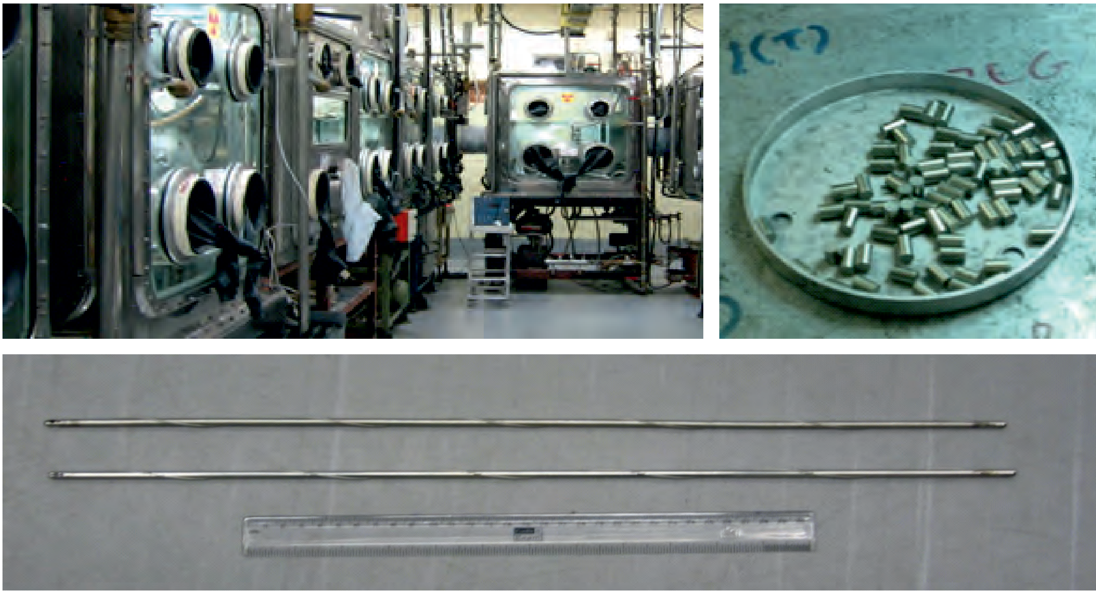

Fig. 11: Above: Glove Box Train for Uranium-Plutonium Carbide Fuel Pellet fabrication and fuel pellets inside the Glove Box. Below: Fuel Pin. The pellets undergo exhaustive physical and chemical quality control before they are accepted for fuel pin fabrication. Fabrication requires strict safety and operational measures. Glove boxes are leak tight to highest degree and operate under ultra-high purity inert gas atmosphere. Plutonium is highly radio-toxic and its carbide form is highly pyrophoric. Allowable plutonium concentration in air is 2.0 nano-grams/m^3 and inhalation of 20 mg is considered as LD50/60 lethal dose (that is, 50% of exposed persons will die in 60 days). The specially designed radiological laboratories account for strict requirements and include all the safety measures.

Fig. 12: Fuel assemblies for PFBR. It comprises of several pins each having uranium-plutonium MOX pellets. Since MOX is stable form of uranium and plutonium hence the fuel fabrication is carried directly in air media. However, leak tightness requirements are same as those of carbide fuel for FBTR (see Fig. 11) since radiological safety requirements are same for both. The fabrication is carried out at AFFF, BARC, Tarapur.

4.7 Fuel for APSARA-U Reactor

APSARA-U is upgraded version of old pool type research reactor APSARA. It has several new features as compared to earlier reactor. As brought out earlier; the APSARA fuel was HEU (~ 93% U-235) aluminide cladded in aluminium plates and was imported from UK. However, APSARA-U fuel was fully developed and fabricated by BARC. While developing the fuel, international practice of converting the reactor core from HEU to LEU was adopted. This was recommended by RERTR (Reduced Enrichment for Research and Test Reactor) programme which was later converted into GTRI (Global Threat Reduction Initiative) programme. Moving in line of international practices LEU-Silicide fuel was developed. Silicide facilitates higher loading of uranium hence the impact of reduction in enrichment is partly neutralized. The fuel has been successfully fabricated and has been put to operation in APSARA-U reactor. Fig. 13 shows the view of APSARA-U pool type reactor along with cutaway view of fuel assembly.

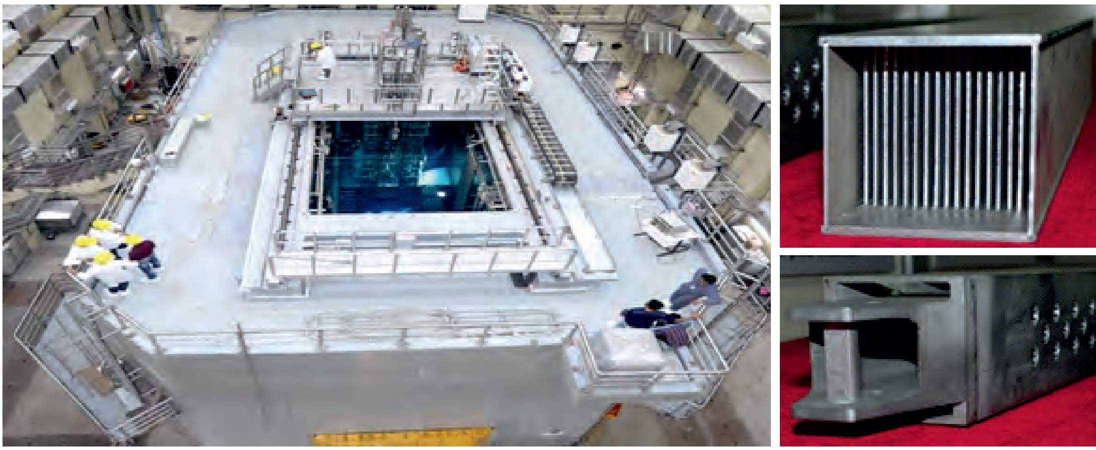

Fig. 13: Left Picture- APSARA-U reactor pool in operation. Bluish glow owing to Cherenkov radiation is seen. Right Pictures- APSARA-U fuel assembly Cut-away View and Full View. Uranium silicide fuel, for ASARA-U, is first of a kind in India

4.8 Fuel for KAMINI Reactor

The fuel for KAMINI reactor comprises of U-233 and pure aluminium mixture sandwiched in aluminium alloy clad. It is a plate type fuel and each assembly comprises of nine plates. Top view of KAMINI reactor along with its plate type fuel assembly is shown in Fig. 14. This fuel was first tested in PURNIMA-III reactor, at BARC, Trombay.

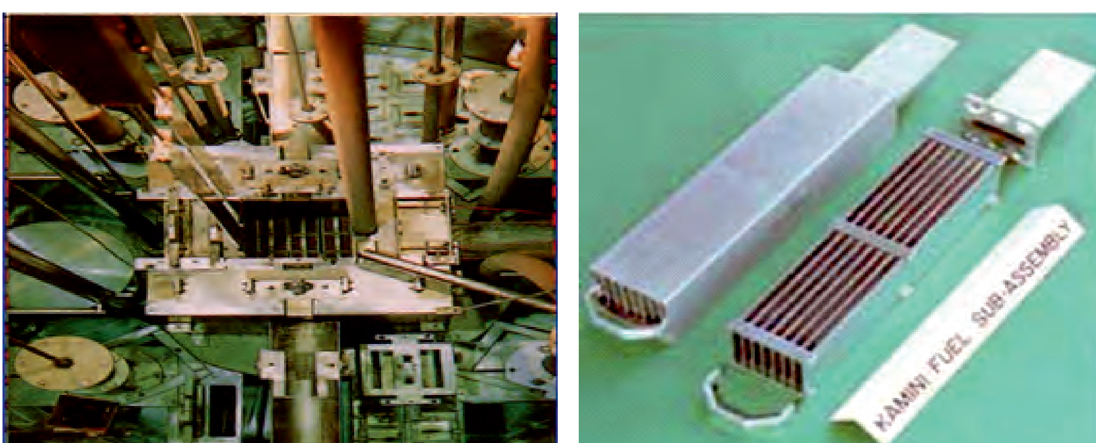

Fig. 14: Left Picture- Top View of KAMINI reactor. Right Picture- Plate type fuel assembly details. U-233 was handled with extreme safety precautions during plate fabrication at radiological laboratory, BARC. While irradiating Th-232, small amount of U-232 is invariably generated along with U-233. The concentration of U-232 increases with burn-up. The decay chain of U-232 produce hard gamma photons (energy = 2.6MeV) which poses radiological safety challenges in fabrication of fuels using such materials

5. Quality Control, Assurance and Development of NDE Techniques for Fuel

Quality assurance plays a vital role in performance of nuclear fuel that is manufactured indigenously for both research and power reactors. Variety of non-destructive examination (NDE) methods are employed during manufacturing of these fuels, which not only ensures that the design specifications are met, but also a close control on the manufacturing processes leading to lesser rejection and high recovery during production. Stringent quality assurance requirements during nuclear fuel fabrication has been responsible for *'first-time-use'* of variety of NDE methods in the country, such as ultrasonic and eddy current testing (see Fig.7(b)). Subsequently, these methods found applications in other core and industrial sectors. Even today, the demands during quality assurance of nuclear fuel is driving the growth in NDE science and technology leading to development of innovative and advanced NDE techniques.

Quality control during fabrication of fuel involves application of several destructive and non-destructive examination methods. Over the years several advancements have been implemented towards NDE of fuel during fabrication at BARC. As an example let us consider the case of Dhruva reactor fuel. Today every fuel clad tube and fuel element are eddy current tested using automated set-up. One of the critical weld joints is at junction between the plug and fuel clad. The geometry of these weld joints and stringent acceptance standards makes the task of inspecting each and every weld joint very challenging. X-ray radiography procedure has been developed for this purpose and is in use for the last several decades. Other tests that are employed during quality control of fuel include: glycol leak test of fuel elements, pneumatic and hydro-test for clad and flow tubes, mechanical testing for uranium rod, clad tubes and flow tubes, and visual examination at each and every step during assembly of fuel pins to form a cluster. Several innovative NDE techniques have been developed in the past few years to strengthen the quality assurance during Dhruva reactor fuel fabrication. One of the prominent amongst them is ultrasonic based critically refracted longitudinal wave technique for qualification of β-heat treatment of uranium rods. Post-extrusion, uranium rod develops texture, which needs to be randomized for assuring dimensional stability of fuel element during irradiation. Earlier practice to assure texture randomization was to subject small coupons to thermal cycling tests. These tests used to take several days and were possible on limited number of small coupons. Moreover, the test was destructive and hence could not be applied on every rod. The ultrasonic technique based on sound velocity measurement, is found to be very fast and accurate, and being non-destructive, is applied on all the rods, leading to comprehensive quality assurance and satisfactory performance of fuel cluster in the reactor.

Similarly, several advancements have been implemented in the production lines of power reactor fuel at NFC and BARC-Tarapur.

6. Post Irradiation Examination on Spent Fuels

BARC has created post irradiation examination (PIE) facilities for examination of spent fuels to evaluate fuel performance, understand reasons of premature failures and life limiting mechanism. Extensive studies are carried out at these PIE facilities (see Fig. 15 and Fig. 16) on different fuels. Some of these are for PHWR, Dhruva and APSARA-U reactor fuels. After the studies feedback goes to fuel fabricator for improvement in fabrication process. In addition PIE labs also have facilities for evaluating nuclear fuel clad integrity under accident conditions. More than 200 experiments have been conducted to quantify integrity of clads under accident conditions. Experiments are in progress and outcome of some of such experiments is shown in Fig. 17.

Fig. 15: PIE Hot Cell at BARC, for Metallurgical and Mechanical Studies on Irradiated Fuel and Reactor Core Materials such as Pressure Tubes of PHWRs. This is the Second Largest PIE Hot Cell in the world. It has 1.5 m thick concrete shielding and special Radiation Shielding Windows. Components having contact dose rate up to about 30000 R/h have been successfully handled in these hot cells

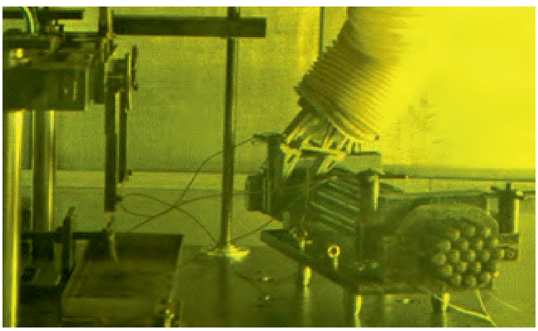

Fig. 16(a): Irradiated PHWR fuel bundle inside hot cell. The irradiated fuel bundles are received after different burn-ups for metallurgical examination (see Fig. 16(b)). Clad and structural materials are subjected to mechanical testing for determining ductility, burst strength etc.

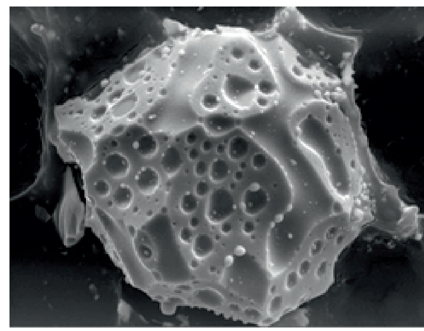

Fig. 16 (b): Grain from a high burn-up PHWR fuel showing fission gas bubbles, channels and metallic fission products. This is as seen in radiation shielded Scanning Electron Microscope (SEM). Grain size is ~ 30 μm

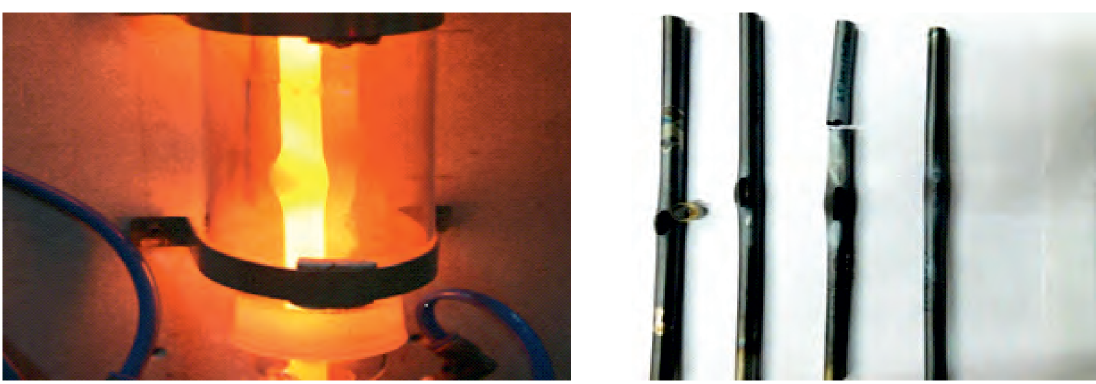

Fig. 17: Clad High Temperature Burst and Thermal Shock Shattering Tests. These tests are required to arrive at fuel failure criteria following design basis and postulated severe accidents in nuclear reactors. The above tests are for clad of Indian PHWRs. High temperature tests (up to 1200^{o}C) are for simulating power rise following Loss of Coolant Accidents (LOCA) and shattering tests are to assess clad structural integrity under thermal shock following cold injection of water from Emergency Core Cooling System (ECCS). Till date more than 200 numbers of such tests have been performed. These studies formed basis of Indian clad specific failure data required for severe accident safety assessment

7. Development of New Fuels and Fabrication Technologies

It was realized that the huge demand and growth expected for nuclear power in India can only be met through use of metallic fuels in fast rectors which promise high breeding ratio and lower doubling time. Hence R&D related to development of fast reactor fuels based on metallic fuels viz ternary U-Pu-Zr and binary U-Pu alloys was started at BARC, Trombay. In fact ternary metallic fuel is undergoing irradiation test at Fast Breeder Test Reactor (FBTR) to understand the irradiation characteristics. Development of metallic fuel is extremely beneficial for Indian fast reactor programme because of the impressive breeding ratio as compared to uranium-plutonium mixed oxide fuels.

New technologies in fuel fabrication are under development for handling nuclear materials having high radiation dose. Such situation will arise in at least two cases; firstly when plutonium recycled after from Fast Breeder Reactors has to be handled for further fuel fabrication. After each recycle the radiation does will increase owing to accumulation of Pu-240 isotope. Secondly important situation arises when U-233 transmuted from Th-232 has to be utilized for fabrication. In such cases small amount of U-232 is invariably generated and its concentration increases with burn-up. The decay chain of U-232 produce hard gamma photons (energy = 2.6MeV) which poses radiological safety challenges in fabrication of fuels using such materials. Activities are under way for developing automated remote handling facilities for fuel fabrication.

8. Discussion and Conclusions

This article covered the historical development of nuclear fuel in BARC. The fuel for India's first reactor that is, APSARA, was imported, thereafter massive research and development programmes were launched and several facilities related to fuel fabrication were created. The result is that fuel for all research and power reactors, built by India, were developed and / or fabricated by BARC and NFC. Some of the rare fuels fabricated are: uranium-plutonium mixed carbide fuels for FBTR, U-233 based fuel for KAMINI reactor. Specialists in uranium and plutonium metallurgy have undertaken systematic approach and successfully developed different routes of fabrication for different fuels being used in reactors or undergoing test irradiation.

Necessary facilities and expertise has been created for fabrication of plutonium based fuels required for successful execution of second stage of nuclear programme. In fact, India is among few countries to master plutonium fuel fabrication. Active research and development is underway for metallic fuel fabrication for future fast breeder reactors. This step is essential for movement towards third stage of the nuclear programme and our self-reliance even with limited reserves of uranium.

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Nuclear Fuel Complex - Meeting the challenging requirements of Indian nuclear power programme over the last five decades

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Preamble

Nuclear Fuel Complex (NFC) has been established to shoulder important and critical responsibility of supplying nuclear fuel as well as core structural materials for Indian nuclear power programme. The historical evolution of NFC in terms of its nucleation, evolution and meeting the challenging demands of thermal reactors (PHWR and BWR) over the last five decades is highlighted. Its important contributions to fast breeder reactor (FBR) programme in terms of high temperature and high burn-up compatible advanced stainless steel structural materials are enumerated. It also plays a vital role in important national missions in terms of design, development and testing of special materials. NFC stands as a testimony to "Atmanirbhar Bharat" mission of the country in indigenous design and development of nuclear materials as well as special materials.

I) Birth of Nuclear Fuel Complex

Nuclear Fuel Complex (NFC), a major industrial arm of the DAE, was conceived in mid of 1960s by the father of Nuclear Power Programme Dr. Homi J Bhabha. It came into existence formally in 1971 at Hyderabad. NFC is engaged in manufacturing and supply of Fuel sub-assemblies and other reactor core structural components to India's Pressurized Heavy Water Reactors (PHWR), Boiling Water Reactors (BWR) as well as Fast Breeder Reactors (FBR).

The production of nuclear grade materials with stringent quality requirements involves a mastery of many diverse technologies in the fields of mechanical, chemical and metallurgical processes. With comprehensive nuclear fuel manufacturing cycle under its belt, NFC is the only organization in the world to have capabilities to process uranium and zirconium streams from ore to core, all under one roof.

II) Production and technological milestones

After conceptualization of NFC during 1960s, a pilot plant was established in 1961 to produce nuclear grade natural UO_2 powder and pellets. Further, the half core of first PHWR (RAPS-I) was fabricated at Atomic Fuel Division (AFD), Trombay. The rich experience gained during this time has enabled DAE to embark upon commercial production of nuclear fuel and thus, Nuclear Fuel Complex (NFC) had come into existence with a production capacity of 100 Te of PHWR fuel and 24 Te of BWR fuel in 1972 at Hyderabad. The first 19 element PHWR fuel bundle with wire wrapped spacers was produced in NFC on 8th June 1973 with the available indigenous technologies and assistance from Russia & Canada.

It is appropriate to recollect the past that it took almost 21 years for NFC to produce first 1 Lakh fuel bundles and next 4 lakh fuel bundles could be produced in next 20 years time. Thus it took 40 years to manufacture first 5 lakh fuel bundles. However, NFC is now able to manufacture one lakh bundles in a year. This has been possible only with the adaptation and implementation of innovative and break-through technologies into manufacturing, inspection & testing methodologies. Every production plant in NFC has progressively increased their plant capacities by incorporating the state-of-the-art automation into their process and quality control systems.

To sum up, the successful journey that NFC made during last 50 years of its existence towards technological excellence from technology denial regime can be described in decade wise as follows:

1970 - 1980: Acquiring knowledge and first milestone

- India forayed into the domain of PHWRs and NFC was established at Hyderabad with a capacity to manufacture 100 TPY of PHWR fuel.
- It was all new for scientists and engineers to produce uranium and zirconium on industrial scale.
- Acclimatization of the processes and machinery of U and Zr production technologies.
- First 19 element PHWR fuel bundle with wire wrapped spacers in 1973.

1980 - 1990: Understanding the existing processes and introducing new ones

- The equipment and processes were either replaced or modified to make them suitable to Indian raw materials.
- Indigenization of processes has helped in scaling up the manufacture of Nuclear Fuel to 180 TPY.
- Graphite coating of clad tubes.
- The processes still remained manual and laborious, where uranium is seen moving from one process step to next process step.

1990-2000: Developing applications and second milestone

- This extra demand for fuel, due to new plants at Kaiga and Kakrapara plants, had thrown a serious challenge due to huge gap between demand and supply.
- Processes were modified suitably and scaled-up equipment were procured, installed and commissioned successfully to accommodate the newer demands.
- Manufacturing of first one lakh fuel bundle was completed in 1994.

2000-2010: Decade of innovations

- During this decade, NFC had implemented many process innovations and indigenized process equipment across all operations.
- Manufacturing technology for extremely thin-walled tubing was established and seamless Calandria tubes were produced for two 540 MWe PHWRs at Tarapur.
- 37-element PHWR fuel bundle was produced for the first time.
- NFC concentrated on development of engineering industry for its futuristic innovative requirements with respect to various reactor components, accessories for fuel assemblies and advanced automatic equipment.

2010–Till Date: Decade of technological revolution and significant milestones

- NFC has significantly exceeded its designed capacities by implementing automation in fabrication and inspection.
- Technology was developed to manufacture U-bend Alloy 800 tubing in 30 m straight length for Steam Generators of 700 MWe PHWRs.
- Established new manufacturing processes for seamless tubes in circular, square, hexagonal cross sections, double clad tubes, multi-clad varieties for different types of power reactors
- Manufacturing of 300 MT of Nuclear Grade Zirconium sponge at Zirconium Complex, Pazhayakayal.
- Manufacturing of first one millionth PHWR fuel bundle in 2018.

The diversified production activities of NFC for nuclear and non-nuclear applications are summarized in Fig.1. The range and diversity of products include the structural materials for thermal and fast reactors as well as nuclear fuels for PHWR and BWR reactors. NFC also takes the production of advanced and sophisticated components required for space, defence and strategic sectors.

During its 50 years of journey, NFC has attained complete self-reliance in the manufacture and supply of fuel and core components for PHWRs and BWRs operating in the country. In this process, it has achieved the following important milestones during PHWR fuel bundle production and the cumulative PHWR fuel bundle production as shown in Fig.2.

Successive Chief Executives of NFC had taken many visionary steps and brought forth many innovations in the plant in terms of production, novel instrumentation and automation, safety, quality & inspection and human resource development. Various Chief Executives and their time period is given in the Table 1.

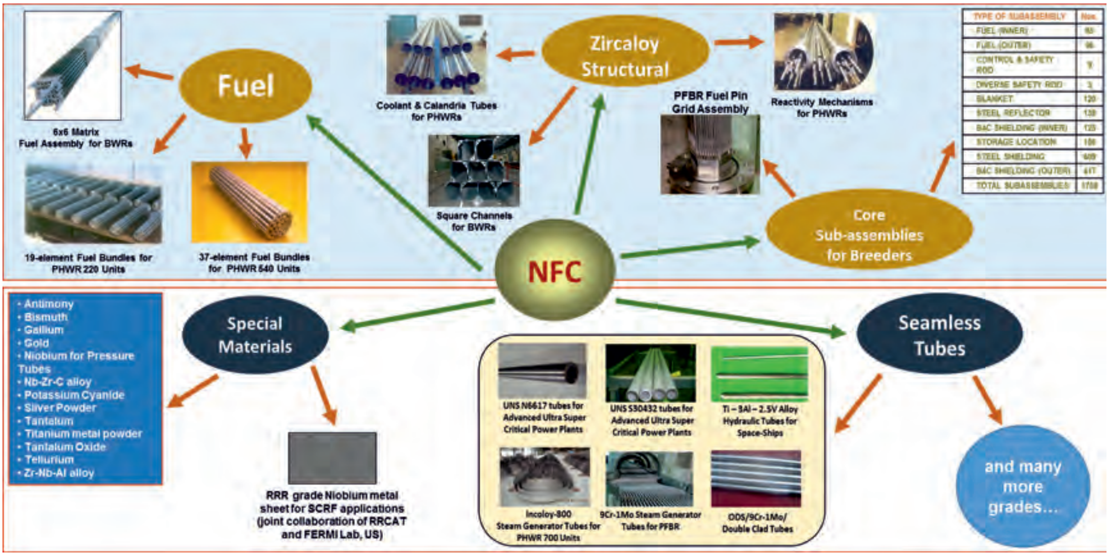

Fig.1: Diversified production activities of NFC

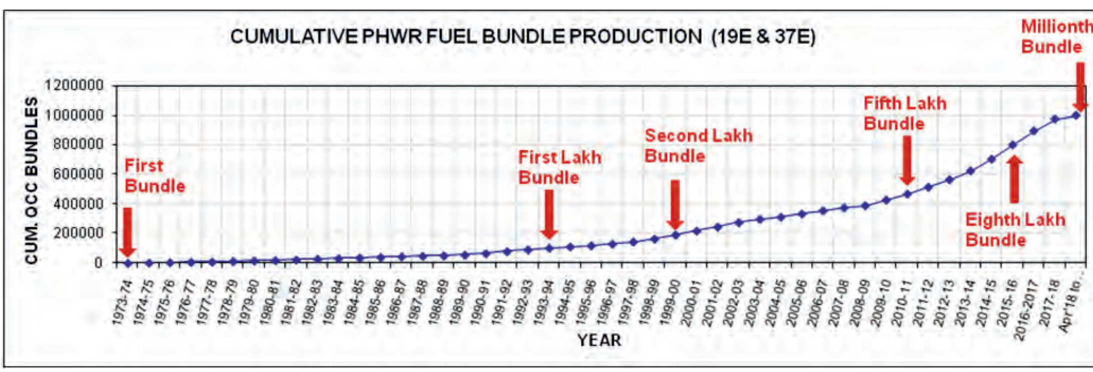

Fig. 2: Cumulative PHWR fuel bundle production over the years

Table1: Various Chief Executives of NFC and their leadership era

S. No.	Name	Time Period
1	Dr. N. Kondal Rao	1975 to 1984
2	Shri K. Balaramamoorthy	1984 to 1993
3	Shri K.K. Sinha	1994 to 1997
4	Dr. C. Ganguly	1998 to 2004
5	Dr. R. Kalidas	2004 to 2006
6	Shri R.N. Jayaraj	2006 to 2012
7	Dr. N. Saibaba	2012 to 2016
8	Shri G. Kalyanakrishnan	2016 to 2018
9	Dr. Dinesh Srivastava	2018 to Till date

III) Production activities in NFC

Nuclear grade natural Uranium Dioxide (UO_2) pellets are produced at NFC by converting variety of raw materials using a well-established conversion processes comprising of different stages like dissolution, solvent extraction, precipitation, calcination and reduction to get UO_2 powder. Subsequently, pellet fabrication is accomplished through granulation, pre-compaction and high temperature sintering of UO_2 powder. The resultant UO_2 pellets are then qualified for physical integrity and chemical purity for encapsulating them into zirconium alloy fuel tubes for fabricating the fuel sub-assemblies. The desired specifications are achieved by having a strict control on material manufacturing process. Control on manufacturing process can be achieved through monitoring the quality of materials taking part in the process and also with a strict vigil on process conditions. Chemical Quality Control (CQC) of raw materials, process intermediates and final products will ensure the desired quality of final products and thus, it becomes integral part of QA/QC program. As an independent department, Quality Assurance (QA) group ensures the quality at intermediate stages and final stage of production to ensure the compliance to the requirements of the customer. Safety and Environment Protection are also ensured with the designated departments during entire manufacturing process.

Besides this, NFC also manufactures different reactor components using special alloys including special steels for special application and also produces high purity materials of 5N & 6N purity for electronic & tool applications. Apart from principal customer NPCIL, the list includes DRDO, ISRO, HAL, BHAVINI, IGCAR, BARC, RRCAT etc.

Contributors to the success of NFC

NFC has been successful in meeting its challenging targets owning to its high quality production facilities as well as the technically strong and skilled manpower. They are engaged in manufacturing of nuclear fuel, in-core and out of core structural, special tubes and special materials backed up by a strong quality monitoring group to ensure the quality of the materials produced. Safety group is functioning to take of care of safety of all operations. The activities of individual production plants at NFC are described below:

1) *Nuclear fuel manufacturing plants*

Nuclear Fuel manufacturing is very critical and plays a vital role in nuclear fuel cycle. The stringent chemical, physical and metallurgical specifications of nuclear fuel need to be implemented into the nuclear fuel during its processing and manufacturing. The physical characteristics also need to be engineered based on the operation conditions of the nuclear fuels, which are quite harsh and also varying from reactor to reactor. The nuclear fuels during their operation are subjected to high temperature operating conditions, high neutron flux environment which leads to physical, chemical and metallurgical changes. Nuclear fuel is made for three types of nuclear power reactors, namely Pressurised Heavy Water Reactor (PHWR), Boiling Water Reactor (BWR) and Fast Breeder Reactor (FBR).

(a) PHWR Fuel Assemblies: Natural uranium dioxide (Natural UO_2) is the fuel for PHWRs and is obtained from different raw materials like Magnesium Di-Uranate (MDU), Sodium Di-Uranate (SDU) or Uranium Ore Concentrate (UOC). MDU/SDU concentrate is obtained from the indigenously milled uranium mines at Jaduguda, Jharkhand/Tummalapalli, Andhra Pradesh and supplied by Uranium Corporation of India Limited (UCIL) and UOC is imported from different countries. The processed UO_2 Powder is further converted into high-density cylindrical pellets by various operations like pre-compaction, final compaction and sintering at high temperature

(1700°C) in reducing atmosphere. The sintered UO_2 pellets are then centre-less ground to desired dimensions. The finished UO_2 pellets are encapsulated in thin walled Zircaloy tubes, both ends of which are sealed by resistance welding. Appendages such as spacers and bearing pads are resistance welded on these elements and 19 or 37 such elements of specified configuration assembled together by welding them on to end plates at either end to form 19-element fuel assembly designed for 220 MWe reactors and 37-element fuel assembly designed for 540 MWe and 700 MWe reactors. The three types of fuel sub-assemblies (bundles) fabricated in NFC are 19 Element bundle for 220MWe PHWRs, 37 Element bundle for 540/700 MWe PHWRs, 6x6 BWR bundle for 160MWe BWRs and these are shown in Fig. 3.

19 Element bundle for 220MWe PHWR

37 Element bundle for 540/700 MWe PHWR

6x6 BWR bundle for 160MWe BWR

Fig.3: Three types of fuel sub-assemblies (bundles) fabricated in NFC

(b) BWR Fuel Assemblies: Cylindrical UO_2 pellets of varying enrichments and chemical compositions imported from other countries are encapsulated in thin walled tubes of zirconium alloy, both ends of which are sealed by Tungsten Inert Gas (TIG) welding. Elements with varying compositions are placed in a specified configuration such as 6x6 array along with spacer grids, stainless steel tie plates, zirconium alloy spacers and flow nozzles to form 6x6 nuclear fuel assemblies for BWRs.

(c) Fast Breeder Reactor (FBR) Fuels: NFC is also responsible for fabrication of core subassemblies for Indian Fast Breeder Reactors deployed under 2nd stage of Indian Nuclear Power Program at Kalpakkam. The facility at NFC presently caters to the requirements of core subassemblies for two reactors namely 13MW(e) Fast Breeder Test Reactor (FBTR) and 500MW(e) Prototype Fast Breeder Reactor (PFBR). NFC fabricated all the core subassemblies such as fuel, blanket, nickel reflector, carrier and special assemblies for its initial core of FBTR in the beginning. Since then, it is also engaged in continuously supplying annual requirements of fuel and special subassemblies of FBTR. A typical FBTR fuel subassembly consists of 511 intricately machined components of 35 different types. The Core subassemblies are hexagonal in shape with very thin wall special grade stainless steel (SS) tubes (circular and hexagonal) and precision SS components. These were fabricated with in-house developed know-how and equipment/fixtures built with indigenous capabilities. Pelletisation of the thorium oxide (ThO_2) has been carried out for the first time on a large scale that involved considerable ingenuity and effort. NFC fabricated and supplied core subassemblies like Fuel, Blanket, Control & Safety Rod, Diverse Safety Rod, Reflector, Inner Boron Carbide Shielding, Diluent, Purger, Source and Instrumented Central Subassemblies for initial core of PFBR. A photograph of a typical Fuel Sub-assembly (FSA) of a fast breeder Reactor is shown in Fig.4.

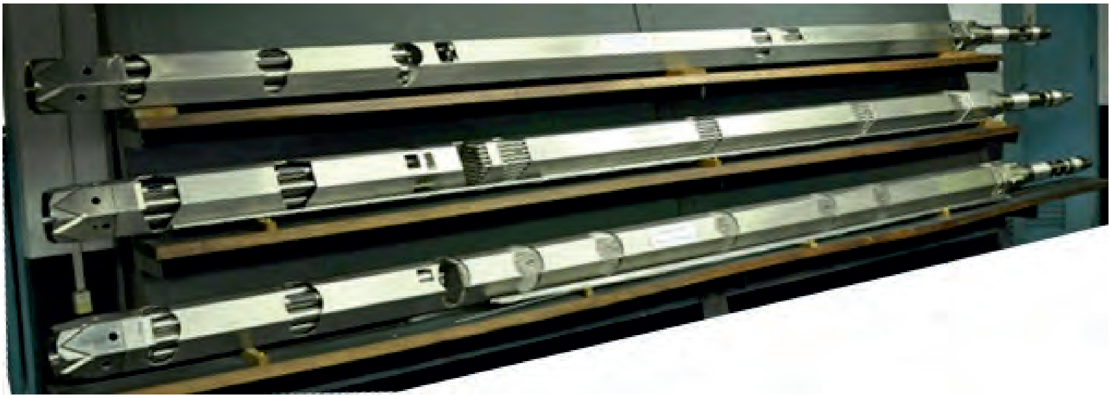

Fig. 4: FBR Fuel Sub-assemblies

2) *Reactor grade zirconium metal production plant*

Reactor Grade (RG) Zirconium metal (RG Zr metal) is produced by limiting critical impurity element Hafnium (Hf) making it suitable for nuclear applications. Zircon sand (zirconium silicate) is the raw material for the production of zirconium metal and it contains 67% zirconium with about 2% Hafnium. Hafnium being a neutron absorber element (due to its high neutron absorption cross section) making its removal as an essential step in the nuclear metallurgy of zirconium. The entire process of chemical separation, resulting in nuclear grade zirconium has been established at NFC so as to make required Zircaloy based structural materials for PHWR.

3) *Fuel Cladding and Assembly Components production Plants*

Chemically qualified zirconium sponge is converted into different types of zirconium alloys after addition of required quantity of alloying elements and melting. Zirconium metal and the alloying elements are compacted in hydraulic presses to obtain compacts / briquettes. These compacts are welded to each other by electron beam welding under vacuum to obtain a long cylindrical electrode. These electrodes are melted multiple times by consumable electrode in vacuum arc re-melting furnace in water cooled copper crucibles, with intermediate stage machining for obtaining final ingots. The typical composition of different Zircaloys manufactured at NFC is Table-2 as given below:

Table-2: Composition of various Zircaloys

Zirconium alloys type	Alloying elements (Weight %)				
	Sn	**Fe**	**Cr**	**Ni**	**Zr**
Zircaloy -2	1.5	0.12	0.1	0.05	Balance
Zircaloy -4	1.5	0.22	0.1	-	Balance

Zircaloy ingots are subjected to 1st stage of extrusion, machining and cutting. After making a hollow billet, it is subjected to beta-quenching, machining and 2nd stage extrusion in order to obtain a hollow blank. This hollow blank is stress relieved in vacuum and passed on for multi-stage pilgering with intermediate vacuum annealing etc. Tube finishing operations like straightening, grinding, cutting, etc. are also performed to obtain the requisite stringent quality. For this purpose, NFC possesses state of the art fabrication facilities such as extrusion & piercing press, cold rolling mills, vacuum annealing furnaces, special surface finishing and further, heat treatment equipment are available to achieve the desired mechanical and metallurgical properties of cladding tubes.

4) *Nuclear Reactor Core Component Production Plants*

Seamless tubes of different sizes are being manufactured using alloys of zirconium, titanium and special grade stainless steels. Pressure Tubes (Zr-2.5wt% Nb alloy), Calandria Tubes (Zircaloy-4) and Garter Spring (Zr-2.5wt% Nb-0.5wt% Cu alloy) are the critical core structural of Pressurised Heavy Water Reactors (PHWRs). Square Channels (Zircaloy-4) are used in Boiling Water Reactor (BWRs) and Hardware like Hexcans (SS316/ D9 alloy) are used in Fast Breeder Reactors (FBR). Manufacturing process routes for these critical cores structural are successfully developed and continue to be supplied to all the PHWRs, BWRs and FBRs. Also, manufacturing process route for reactor control assemblies required for PHWRs are successfully developed and continue to be supplied to all the PHWRs. These assemblies are designed for reactor power monitoring, control mechanisms and shut down. These are made of zirconium alloys and require high precision, reliable components and high quality tubes before welding. The manufacturing processes use hot extrusion, forging, pilgering, drawing of various sizes of tubes and punching, machining of components. These assemblies use combination of electron beam welding, TIG welding and resistance welding and have stringent quality specifications for soundness of welds and accurate dimensional control. In addition, NFC has contributed in various developmental programs of the DAE such as Compact High Temperature Reactor, Upgraded APSARA Reactor through advanced machining and welding of exotic materials.

5) *Stainless Steel and Special Alloy Tubes production plants*

These are exclusive facilities for development & manufacturing the seamless tubes using various advanced grades of Stainless Steels & Special alloys, Nickel based super alloys, Iron based super alloy, Titanium alloys, Maraging steels for Nuclear, Space and Defence strategic applications. They house state of the art manufacturing facilities like Cold rolling mills (Pilger mills), Tube straightening mills of different capacities & sizes, Draw-bench, heat treatment facilities like Bright Annealing furnace, Vacuum Annealing furnace, Roller Hearth (LPG fired) Annealing furnace, Chemical operations like De-glassing, Pickling, Passivation, Alkaline degreasing, Solvent degreasing and Inspection facilities like Ultrasonic, Eddy Current & Hydrostatic Pressure Testing , etc. NFC has played a pivotal role in indigenous development & manufacturing of these products as import substitutes and is an excellent example for Make in India policy.

6) *Special Materials Plant*

Nuclear Fuel Complex is also the country's premier facility engaged in manufacture of variety of high purity materials (5N/6N) and they find numerous applications in Electronics, Defence, Nuclear Industries, Scientific & industrial research organizations, institutions of higher learning and even in general engineering industry.

High purity materials such as antimony, bismuth, cadmium, tellurium, tellurium, gallium, phosphorous oxy chloride, antimony trioxide, gold, gold potassium cyanide (GPC), silver are produced. In addition, tantalum pentoxide, tantalum metal and reactor grade niobium metal in the forms of rod, sheet and crucibles are also produced. The high purity materials are used in semiconductor technology for the synthesis of compound semiconductors, and as dopants, diffusants, solders, etc. Tantalum is used in variety of high temperature and corrosive atmosphere. Tool grade tantalum pentoxide finds its application in tool industry. Reactor grade niobium is used in nuclear industry for alloying of zirconium to produce special ZrNb alloys. NFC has produced Residual Resistance Ratio (RRR) grade niobium metal for use in superconductivity cavity (SCC) applications. Advanced alloys such as NbTi, NiTi, NbZrC have been developed by electron beam melting route.

The production of these materials involves a variety of highly sophisticated equipment, advanced techniques, clean working environment and specialized technical skills. The gamut of operations include hydrometallurgy, pyro-metallurgy, electrolytic processes, solvent extraction, special distillations, zone refining, Electron beam refining, etc. Rigorous quality control is exercised at all stages of production to achieve required high quality and reliability of the products. The availability of wealth of talent, advanced equipment and state-of-art of technology, backed up by excellent quality assurance processes ensure the quality of the products.

Further, NFC has transferred developed technologies to prospective entrepreneurs. These include technology for the production of Magnesium granules, Zirconium metal power, production of high purity materials such as Phosphorous Oxy Chloride, Indium, Sodium Iodide, Gallium, Gold, Silver, Capacitor grade tantalum powder and Tantalum anodes etc., A new production plant is being set-up in collaboration with ISRO for the production of niobium for exclusive usage in Indian Space programme.

7) *Quality Assurance Group*

Quality is important in any field of human endeavour, more so in a critical, high-tech area such as nuclear power plants, where the costs of failure are extremely high with respect to material loss and also from the societal angle. The demands thus made on the Quality Assurance (QA) programs in DAE in general and NFC in particular, are altogether at different level compared to those in other industries. NFC is unique in its integrated approach to manufacture a variety of finished products from ore to core through employing enormous amount of Inspection, QA and Non-Destructive Evaluation (NDE) on an industrial scale. Because of these demands, NDE in NFC has, through years of experience, attained a high level of maturity. NFC is striving to achieve six sigma strategy as a part of continual improvement in its operations, products and services through technological excellence and well-integrated QA program. The exacting performance required by the nuclear fuel and hardware in the power reactor demands fulfilling stringent quality requirements of each product specifications.

NFC adopts well-structured quality assurance program. Sophisticated non-destructive evaluation facilities were developed and these techniques include ultrasonic test, eddy current test, X-ray radiography, dye-penetrate test, mass spectrometric leak detection and automated machine vision systems. Precision dimensional measurement systems and automatic physical measurements facilities caters the in-house needs for measurement and qualification of products.

An array of analytical techniques like Inductively Coupled Plasma Atomic Emission Spectrometry, Atomic Absorption Spectrometry, X-ray Fluorescence Spectrometry, Mass Spectrometry, Gas and Ion Chromatography, Laser Photometry are employed for analysis of raw materials, intermediates and final products. A number of online measurement and control equipments have been deployed all along the processes and production lines. The Advanced Material Characterization Lab is equipped with several sophisticated characterization instruments viz. TEM, SEM-EBSD, XRD, Dilatometer, X-ray residual stress analyzer for studying metallurgical characteristics like microstructure, texture, dislocation density, re-crystallization behavior, crystallography, nano-feature characterization, residual stress analysis etc. These facilities help in developing a variety of products and advanced alloys. NFC has over the past five decades earned a justifiable respectable place in the DAE as a reputed, reliable, quality conscious supplier of critical inputs to the nuclear power program in India.

8) *Safety Engineering Division (SED)*

NFC gives utmost importance to the safety of workers, environmental protection and prevention of accidents / incidents at field level. It is regulated by Atomic Energy Regulatory Board (AERB). For taking care of overall safety aspects, to achieve the objectives of safety and co-ordinate with various plants, Safety Engineering Division (SED) is formed in the initial years of NFC. SED coordinates with AERB on regular basis for the implementation of Factories Act, 1948 and Atomic Energy Factories Rules, 1996 and other statutes.

9) *Environment Protection*

While fulfilling the mandate of supplying the nuclear fuels and nuclear reactor components to Nuclear Power Program and to support strategic programmes of India, NFC gives utmost importance to protect environment by way of proper handling and disposal of by-products and effluents. A dedicated Effluent Management section comprising of expert chemical engineers is working towards this goal. The section is responsible for safe & prompt disposal of various process effluents generated during various activities at NFC to firms/establishments authorized by Telangana State Pollution Control Board (TSPCB).

IV) New Projects

(a) Zirconium Complex, Tamil Nadu (A Unit of NFC, Hyderabad):

In order to meet the additional requirements of production of zirconium metal, Zirconium Complex (ZC) was conceived in 2001 as a green-field project at Pazhayakayal, Tuticorin, Tamil Nadu. ZC was commissioned in November 2009 to produce zirconium oxide and zirconium sponge to meet the enhanced demand. During the last 13 years, the production capacity of the Plant has been gradually increased and the rated capacity was achieved in FY 2014–15.

ZC has future Plans of setting up of Magnesium Recycling Technology Development & Demonstration Facility and capacity augmentation of zirconium sponge production to meet the future demands commensurate with the nuclear power programme. The ground work in this direction has been already initiated by NFC. Further to this, a plan of action has been worked-out to enhance Zr production to 1300 TPY through capacity expansion at Zirconium Complex, Pazhayakayal in two phases.

(b) NFC-Kota, Rawatbhata, Rajasthan

A new fuel fabrication facility is being set up (NFC-Kota) at Rawatbhata near Kota, Rajasthan. This green field project is established with a plant capacity of 500 TPY PHWR fuel fabrication and 65 TPY fuel cladding fabrication. The capacity of fuel cladding fabrication will be further augmented by 100 TPY. NFC-K project envisaged to establish 37 element fuel bundle manufacturing facility to cater to fuel requirement of up-coming 700 MWe PHWRs. The project is in advanced stage of completion and is expected to take-up the production shortly.

(c) Developments in Zirconium Sponge Metal Production

Technology Demonstration Unit has been successfully commissioned at ZC, Pazhayakayal, Tuticorin, Tamil Nadu for the production of 1500 Kg batch against regular batch size of 950 Kg for the first time. Several batches are produced through this process. The efforts have been made to reduce the production cycle time and to meet the additional requirements of sponge metal. The chemical analysis of the 1500 Kg Zr sponge batches produced is meeting the technical specification. Higher productivity, improved purity, energy savings and improved recovery by 2% are the advantages. Fig. 5 shows the production facility with a picture of typical batch produced.

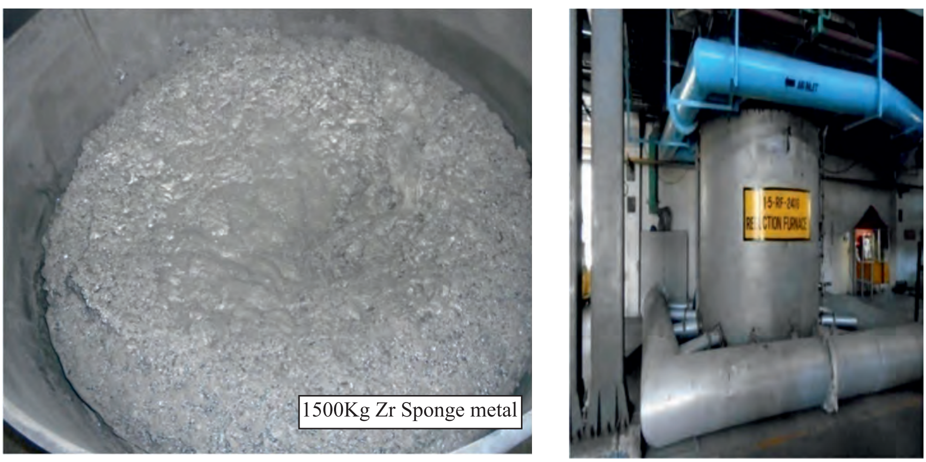

Fig. 5: 1500 Kg Zr-metal produced and Facility for its production

V) "Atmanirbharta"- a Make-in-India Initiative

(1) Indigenous EB Melting Furnace

In view of restricted technology, a successful effort was made in NFC to build indigenous electron beam melting furnace. The indigenously built EB Melting Furnace is used in melting and purification of refractory & reactive metals and alloys for strategic applications in Nuclear, Space, Defence fields. The efforts have resulted in huge revenue savings for the department and eliminated the dependency on external agencies for maintenance of the furnace. The EB Furnace was built for the first time in India using indigenously available resources and in the process India has become 4th country in the world to have such a facility. The facility was inaugurated by the President of India in May 2018 (Fig. 6) and since then being used for different the purpose.

Fig. 6: Indigenously built EB Melting Furnace and inauguration by H.E. Shri Ram Nath Kovind President of India in May 2018

(2) Manufacturing of Special Tubes

Several special grade steel tubes have been manufactured for special & strategic applications for first time in India as import substitutes. These include Incoloy-800 U bend SG tubes, Zr-1% Nb tubes, Titan-24/11 tubes, SuperNi 42, Inconel 690/600, Alloy 617 etc.

(3) Steam Generator Tubes for PHWR

NFC successfully manufactured Incoloy-800 U bend SG tubes first time in India. The production of 30 meter long Incoloy-800 U bend tubes is a technological challenge and NFC could do it successfully and delivered 8 sets for RAPS 7 & 8, KAPS 3 & 4 reactors. In view of very high demand, a dedicated facility has been established to double the production capacity to 6 sets per year. It generates significant revenue to NFC. It has opened an opportunity to NFC to become potential supplier of U bend SG tubes in International market. A typical picture of these tubes is shown in Fig.7.

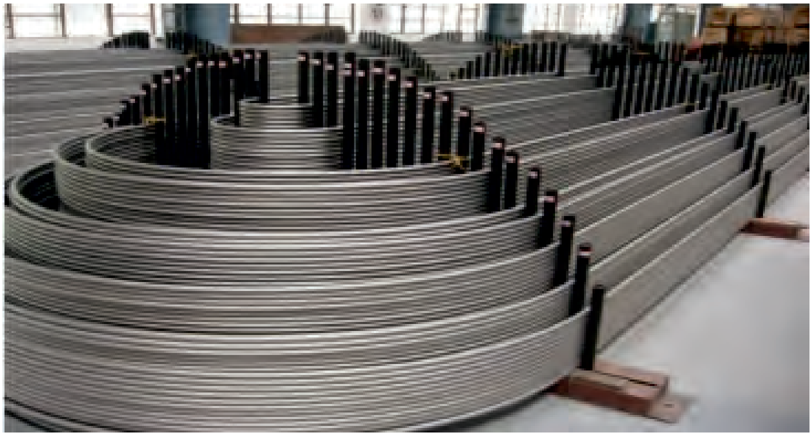

Fig.7: Incoloy-800 U bend SG tubes

(4) Titanium Tubes Manufacturing: Zirconium and titanium have similar metallurgical characteristics and processing routes (Extrusion, Pilgering , Heat Treatment, etc.). NFC with its vast experience of manufacturing Zircaloy tubes is well equipped to take up bulk manufacturing Ti-alloy tubes as import substitutes. Over the years, various Titanium alloy products like Titan-24 Tubes for strategic nuclear application, Ti-half alloy Truss rod Tubes for PSLV & GSLV, Ti half alloy Hydraulic Tubing for Light Combat Aircraft (LCA) have been developed. It is planned to augment capacity through an exclusive facility.

(5) SuperNi-42 Tubes: These tubes are of small diameter, extremely thin wall and have stringent specifications with respect to dimensional tolerances and metallurgical properties, as shown in Fig. 8. After initial trials for indigenous development in collaboration with BARC Mumbai, the manufacturing route was established for bulk production. The process consists of production through 10 stages of thermo mechanical processing followed by final finishing operations & stringent quality checks of mechanical testing, ultrasonic testing, dimensional & visual inspection.

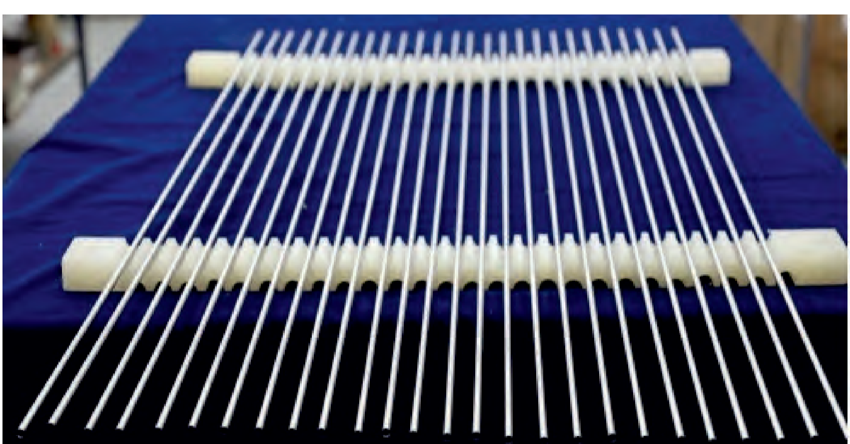

Fig.8: Typical picture of SuperNi 42 Tubes

(6) Other developmental works carried:

With well structured and established manufacturing process under its belt, NFC continuously made technological improvements to refine the processes. Some of them are as follows,

- NFC demonstrated with the production of 1500 MTe of natural uranium fuel, world's highest ever production.
- Manufactures and supplies 19/37 element Natural Uranium Fuel bundles for all the PHWRs and Enriched Uranium Fuel Assemblies of 6x6 types to BWRs. For the first time, 37 element fuel bundles with modified bearing pad design was made for the initial core requirement of India's first 700MWe PHWR at KAPS-3.
- In house development of Auto Ring gauging for PHWR fuel bundles, a mandatory requirement prior to loading of bundles in to reactor core.
- Development of automated vision based inspection system for surface examination and dimensional measurement of fuel bundle appendages viz. Bearing and Spacer pads to increase through-put with reliability.
- Development of High corrosion resistant SS - 304L pipes for Fast Reactor Fuel Cycle Facility(FRFCF).
- Development and manufacturing of D9 Fuel Clad Tubes and Pure Nickel Tubes for Prototype Fast Breeder Reactor (PFBR).
- Development of Alloy 617 tubes for Advance Ultra Super Critical (AUSC) power plant.
- Development and supply of Zr-1%Nb alloy tubes for strategic applications.
- Development and manufacturing of RRR Grade Niobium sheets for fabrication of Superconducting cavities.

Concluding remarks

NFC always sets a new benchmark in Never Fails in its Commitments attitude and continues to play a significant role in all NPCIL's ambitious future expansion programs, as well as its contributions to FBR programme and delivering the requirements of other departments like DRDO, ISRO as well. NFC has immensely benefitted from its synergistic interactions with BARC, NPCIL, IGCAR, BHAVINI, MIDHANI and many other national institutes in meeting its challenging goals in the service of the nation.

Evolution of Back End Fuel Cycle in India

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Preamble

As India Celebrates her 75th Year of Independence, the present timeline seems most appropriate to revisit our important milestones in the evolution of back end technology in India and to identify a road map for the future. While doing so, one cannot but get inspired by the monumental decisions and ground breaking developmental efforts that have not only led to expertise in this sophisticated field but is also ensuring sustainability of our nuclear power programme. This present paper attempts to trace evolution of the back end of fuel cycle in the Indian context and highlights its present status.

Historical perspective

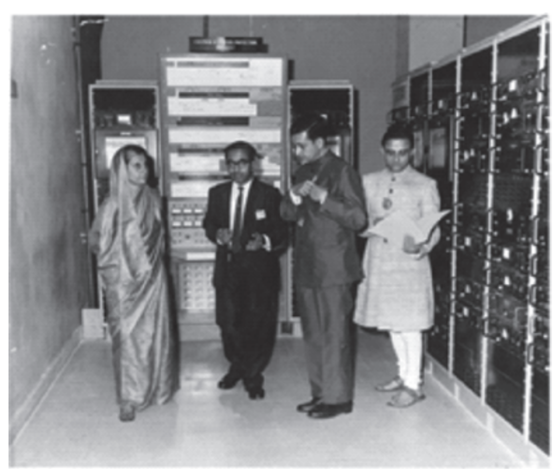
Closed fuel cycle involving reprocessing of spent nuclear fuel is considered a vital link to realise the Indian nuclear power program aiming at optimum utilisation of uranium and thorium resources. While spent nuclear fuel from nuclear reactor is considered as 'waste' in many countries, same is considered as 'material of resource' in the Indian context due to the presence of unused uranium and freshly formed plutonium in the 'spent fuel' that emanates from nuclear reactors. Recovery of such energy potentials, though highly desirable, is very complicated and involves a multidisciplinary approach which involves the complex technology of reprocessing. India today enjoys the special status of a country possessing this exclusive technology along with only a hand-full of countries in the world.

If Dr. Homi Jehangir Bhabha is credited with chalking out our well entrenched three stage nuclear power programme of our country, it was Dr. Homi Sethna who took the next epoch-making step towards the closed nuclear fuel cycle. As the adage goes…a Journey of a thousand miles starts with the first step and this first step taken by these great stalwarts paved the way for a self-reliant India and an Atma Nirbhar Bharat as it is today. The back end of the fuel cycle involves both complex technology with regard to reprocessing and the subsequent management of highly radioactive waste streams, both of which need massively shielded enclosures and completely closed environment so as to ensure negligible release of radioactivity into the environment. While embarking on this very challenging path, the highly radioactive waste was perceived as a hurdle, but the technological advancements in our country have changed this perception from that of a problem to a potential source of wealth. This is primarily due to adoption of a strategy that results in recovery of radionuclides like Cs-137, Strontium-90 and Ruthenium-106 for societal benefits

Recycling of Spent Nuclear Fuel

The Indian recycling programme was born with the setting up of India's first reprocessing plant at Trombay, Mumbai. It is indeed very interesting to note that the formal order to set up a plant to reprocess spent fuel from CIRUS reactor was issued dated December 31, 1958 at which timeline the reactor was still under construction. This project was aptly named "Project Phoenix". Just as the mythological bird Phoenix obtains new life by arising from the ashes of its predecessor, the project phoenix was also aimed to recover new fuel from the spent fuel of reactor. In the absence of much design details, the 'Project Phoenix' (there after renamed as 'Plutonium Plant') was designed literally from first principles of chemistry and chemical engineering and the fabrication of the equipment was taken up in-house to ensure effective quality control. Ultimately, the plant went 'hot' in August 1964 within 5 ½ years from the date of order – a significant achievement and the first button of plutonium metal was produced in August 1965. As a tribute to this path breaking achievement, 18th August is celebrated as "Reprocessing Day" at BARC.

Hon'ble Prime Minister (then)
Shri Lal Bahadur Sastri dedicating the
Plutonium Plant to nation (Year 1965)



Visit of Hon'ble Prime Minister (then)
Smt Indira Gandhi at Plutonium Plant
(Year 1967)

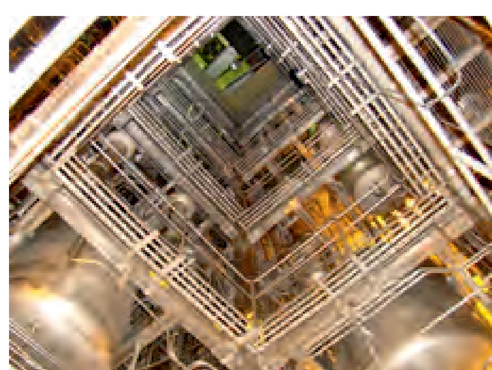
Initial challenges associated with reprocessing of spent nuclear fuel was addressed by Late Shri N Srinivasan in article of "IANCAS Bulletin, July 1998, Vol, 14, No. 2":

"While Canada India Reactor (CIR) was still under construction the formal order regarding the decision to set up a plant to reprocess irradiated fuel from it was issued. This was dated December 31, 1958. Apart from the historic nature of the decision it conveyed, the modalities set up for the implementation detailed in it were a veritable model for implementation of such path-breaking, scientifically challenging projects in a country which had been independent for only a decade. The freedom and flexibility in action allowed to the project management ultimately made it possible to complete the project within the sanctioned cost and the committed time schedule." [1]

A reprocessing flow sheet normally starts with a head end step commensurate with the fuel type, followed by complete dissolution of the spent fuel meat in nitric acid solution. The aqueous solution containing the nuclear material along with a plethora of radionuclides are subjected to solvent extraction cycles to separate and purify the uranium and plutonium from such undesirable elements. Such pure solutions are then subjected to a reconversion step to convert them into products meeting reactor specifications for their recycling into reactors. The PUREX based extraction process using 30% Tri-Butyl Phosphate (TBP) in n-Dodecane continues to be the heart of reprocessing plants, world over. While the TBP solvent preferentially picks up both uranium and plutonium, it is the partitioning agent which aids in their mutual separation. Replacement of ferrous sulphamate used during the earlier times with Uranous (U+4) is regarded as a special milestone, since the former would lead to choking issues in the plant leading to frequent down time of the plant. [2] Feedback generated from the plant was found very useful for construction and operation of successive plants. Although, formal regulatory body was yet to be established in the country, stringent safety review was carried out internally resulting in adherence of international safety stipulations with regard to radiation and industrial safety.

The experience of Plutonium plant, first reprocessing plant of India, resulted in to various developmental activities including process improvisation for better separation efficiency, solvent degradation and its management studies, analytical methods for analysing nuclear materials, corrosion studies and selection of better long lasting material of construction, which could be deployed in subsequent reprocessing facilities. Based on experience and technology development, second reprocessing plant of country, Power REactor Fuel REprocessing (PREFRE) plant with design capacity of 100 t/year, was built and commissioned at Tarapur site in year 1975 followed by Kalpakkam Atomic Reprocessing Plant (KARP), built and

PREFRE, Tarapur



Inside view of hot cell of reprocessing plant KARP

commissioned at Kalpakkam site for reprocessing of fuel from Madras Atomic Power Station. [3] This was followed by PREFRE II at Tarapur and more recently, another plant at Kalpakkam. The performance of these plants are rated at par with international standards both with regard to process performance and safety. The reprocessing process and flow sheet of PHWR fuel could be standardised for subsequent reprocessing facilities for enhancing the capacity.

With objective of bringing down the cost of fuel reprocessing and improving the economics of fuel cycle, high through put recycle facility, Integrated Nuclear Recycle Plant (INRP), is being constructed at Tarapur site. The plant is designed with 'Solid In Solid Out' concept with sharing of common utilities among various process block and thus minimising the overall cost. [4, 5] The valuable feed back of such operations of PHWR fuel reprocessing facilities were taken on board while addressing the closed fuel cycle for the upcoming recycle facilities for fast reactors. The challenges with regard to solvent degradation on account of high radiation dose and higher fissile material concentration are being addressed by deployment of centrifugal contactors. To meet the challenges of thorium based fuel cycle which is the nuclear fuel cycle of the future for India, R&D efforts are directed towards extractive metallurgy of thorium, fuel fabrication and its utilization in reactors, reprocessing of irradiated thorium for U-233 recovery and studies on U-233 based reactor systems. Demonstration facilities have been operated in all these domains and domain knowledge base is being built up for its implementation in the near future. [6]. In fact, India can claim to be one amongst the very few countries that have not only recovered U-233 from irradiated thorium/ thorium oxide, but also fabricated U-Al alloy fuel with the U-233 separated and commissioned a reactor (KAMINI at Kalpakkam) with this fuel as the driver fuel.

India has also built a Lead Minicell facility (CORAL) for reprocessing of uranium, plutonium mixed carbide fuel irradiated in Fast Breeder Test Reactor at Kalpakkam, and demonstrated recovery of plutonium from mixed carbide fuel irradiated to as high as 156 GWd/t. In fact, the Pu recovered was also used for fabricating fuel for FBTR subsequently, thus effectively demonstrating closure of fuel cycle. India is one amongst the very few countries in the world to have reprocessed mixed carbide fuel, and that too at high burn up and relatively short cooling.

Radioactive waste

Safe management of radioactive waste has been given prime importance since beginning of nuclear power program in India with objective to protect public, environment and future generation from harmful effect of radioactivity. Radioactive waste is generated at various stages

Centrifugal contactors used in CORAL plant

Conceptual image of integrated nuclear recycle plant of the nuclear fuel cycle, which includes the mining and milling of uranium ore, fuel fabrication, and reactor operation and spent fuel reprocessing. Besides these sources, radioactive waste is produced as a result of the ever-increasing use of radioisotopes in medicine, industry and agriculture. [7]

The essence of importance towards safe management of radioactive waste could be sensed from the address of Dr H N Sethna, Chairman, AEC (1972-1983) at IAEA General Conference in 1975:

"The radioactive waste management in the Indian Nuclear Programme has continued to ensure that man and environment are not endangered to release of radioactivity….While we have worked on the basis of 'as low discharge as possible' as a practical reality, our current efforts are directed towards the concept of limiting discharge activity to the environment…"

Waste from Reactor Operations

Waste from Reactor operations normally fall into the category of low and intermediate level waste and all planning for treatment and management of such identified waste streams were carried out along with setting up of reactors in India. While considering the treatment of low active liquid effluent, the major challenges include very high waste volume and extremely low concentration of radionuclide which are aimed to be removed prior to discharge. In initial years, R&D was focused towards process technologies and plant operations for low level effluent treatment to meet the permissible environmental discharge limits. Chemical precipitation was developed as robust and effective processing techniques for low level effluent treatment for removal of radioactivity to meet the discharge limits. To date chemical precipitation is being used for low level liquid waste treatment in addition to various new membrane-based separation technologies have been developed and deployed for their plant level adoption.

The genesis of radioactive waste management in India was with the setting up and commissioning of an Effluent Treatment Plant (ETP) at Trombay in 1967 for treatment of low active effluent generated from CIRUS reactor with chemical precipitation as major treatment step for removal of radioactivity prior to discharge to meet discharge criteria. This plant continues to be operational and has adapted itself to low level effluents from reprocessing & other laboratories at Trombay as well. Operational experience of ETP, Trombay has gone a long way in designing and setting up of effluent treatment facilities for power reactor wastes and low-level effluents from reprocessing plants. [8]

Construction of Low level tanks at ETP (Year 1962)

Clariflocculator at ETP (Year 1966)

While India's first PHWR (RAPP I) was constructed and commissioned in active collaboration with Canadians at Rajasthan, Liquid Effluent Management Facility (LEMP) for this reactor was set up in parallel and commissioned solely as an indigenous effort. Though this facility continues to serve the intended purpose, it had to be augmented by a Facility based on Solar Evaporation, which is a preferred mode of evaporation for larger volumes of waste with low activity at sites, which have favourable climatic conditions such as high ambient temperature, low humidity and high wind velocity. In mid-seventies, augmentation of waste management facilities for TAPP I & II was carried out as the inbuilt radioactive waste system provided was found inadequate with respect to decay of Iodine and regenerant waste that required treatment. Accordingly, Tarapur Radwaste Augmentation plant (TRAP) was set up incorporating two numbers of 1000 cu.m. tank serving as delay tanks for I–131 followed by chemical treatment & ion-exchange. This augmentation plant has resulted in substantial reduction of activity discharge to the environment. Presently, all the Pressurised Heavy Water Reactors (PHWR) at various sites like Rajasthan, Madras, Narora, Kakrapar and Kaiga have dedicated waste management systems consisting of Liquid Effluent Segregation system (LESS), Treatment & Conditioning system (TDS), and waste disposal system (WDS) for discharge/disposal of waste.

Similarly, practices for management of radioactive solid waste was also conceptualised well in early 1960's. Focus was mainly on safe disposal of low and intermediate level solid in early years. Concept of 'multi barrier disposal system' based Near Surface Disposal Facility (NSDF) was adopted right from beginning & has given greater assurance of isolation to retard the migration of radionuclide to environment. The multiple barrier could be combination of engineered as well as natural barrier. The preliminary work on low-level solid waste disposal started in 1962 at Trombay, where the first laboratories of radiochemistry and isotope production had started functioning. This was followed by setting up of near surface disposal facility at Trombay. In subsequent years, developmental efforts were focussed towards further minimisation of discharge following As Low As Reasonably Achievable (ALARA) principle. For limiting the discharges, polishing of the supernatant from chemical co-precipitation process was considered essential right from the design stage. This was achieved by metering the supernatant through ion exchange columns with Cs specific sorbent, e.g. natural vermiculite. However, same was discarded due to low loading capacity of sorbent in early 90's. Efforts were continued for development of high capacity sorbents with better decontamination effect. Two class of sorbents, i.e. synthetic zeolites and Copper Ferro-Cyanide (CFC) impregnated on suitable substrate, were considered for further developments considering the large volume and characteristics of low level effluent. Parallel developments include, membrane based techniques including reverse osmosis based process that has been developed and demonstrated on pilot scale for treatment of low level effluents in early 2000's. Same also could not be deployed in regular operations due to operational problems such as fouling of membrane, lower volume reduction factor and higher cost associated with replacement of membranes.

In the recent decade, efforts were further channelized to attain concept of 'Near Zero Discharge' of radioactivity with advancements in membrane technology. Zeolite 4A based ion exchange resin has been demonstrated for effective removal of radioactivity, by more than 5 folds, from low level effluent. In view of the simplicity of ion exchange process, a plant based on ion exchange process was installed at ETP. The process flowsheet is provided with sufficient flexibility to use improved sorbents in future.

Recently, developmental works in low level effluent treatment have been directed towards realise the 'Hybrid Process' consisting of various advanced membrane technologies in combination to reduce the radioactivity at such a low level that recovered water can be reused as 'process water'.

High Level Waste Treatment:

In view of the importance of reprocessing in the Indian context, the challenges that could be faced for the management of high level liquid waste was well recognized. Accordingly, R&D activities with respect to management of high level waste were initiated from mid sixties. Efforts were directed to develop and characterise a number of alternative glass matrices suitable for immobilisation of HLW generated as first cycle raffinate (PUREX process) from the Indian reprocessing units on one hand and develop, evaluate and perfect conditioning processes and techniques on the other.

In line with the international practice, a three-stage programme for the management of high-level waste was evolved.

1. Conditioning of the highly radioactive liquid wastes wherein radio-nuclides present in the high-level waste are immobilised in suitable matrices that is inert, highly durable (resistant to chemical/aqueous attack), and in turn contained in high integrity storage units which are subsequently overpacked.
2. Interim storage under surveillance and cooling of overpacks containing conditioned wastes for periods ranging up to 30 years to allow reduction in decay heat to a level acceptable for geological disposal on the one hand and to ensure integrity of the waste form and its packaging on the other before a commitment is made for their irretrievable disposal.
3. Disposal in deep underground repository such that at no stage potentially hazardous radioactive materials are recycled back to human environment in concentrations that can subject living beings to a risk considered unacceptable.

Development of vitrification technology for high level waste – a challenging task

Even though immobilisation of high level waste in glass matrix could be demonstrated at laboratory scale with desire product characteristics like very low leach rate, the challenge was to develop engineered systems and scale up the process at industrial scale required handling of highly radioactive and corrosive nature of high level waste at elevated temperature of 1000^0 C. This called for development of special equipment – a melter, which can process high level waste up to 1000^0 C for immobilisation in glass matrix. The process of immobilisation of high level waste in glass matrix is called vitrification. The process of vitrification essentially involves sequential drying of the high level waste, calcinations and conversion to glass/vitreous product, usually with the aid of specially formulated glass forming additives, depending upon the chemical composition of the waste. In this process most of the radio nuclides present in the waste get immobilized in the vitreous matrix as network modifiers and a few get physically trapped in the interstitial spaces in the bulk of the vitreous mass. Induction Heated Metallic Melter (IHMM) was developed for vitrification of high level waste at industrial scale utilising 'pot vitrification' process. IHMM consists of a pot of high nickel-chromuim based metal alloy, Inconel, for glass making process utilizing induction based indirect method of heating, for various stages of vitrification and to reach 1000^OC for making glass. Based on laboratory scale experiments and pilot scale trials, a plan was drawn up to set up a facility for further development of the process on a plant scale. The aim was to carry out a thorough evaluation of the process in conjunction with the needed auxiliaries and fine tuning of the same before constructing the facility for processing of actual radioactive wastes from a near by reprocessing unit on a routine basis. Thus, the first industrial scale vitrification facility i.e. Waste Immobilization Plant (WIP) was born at Tarapur in 1980s. The plant was designed based on 'single cell concept' containing all the process systems in single concrete shielded hot cell. Active trials of high level waste vitrification resulted in generation of very valuable feed-back for next facility. Some of the important feed backs were to incorporate 'multi cell concept' as compared to 'single cell concept', design improvisation of IHMM, deployment of robust remote handling techniques for remote maintenance and dismantling in the future etc.

Incorporating the feed backs, the second vitrification plant was set up at Waste Immobilisation Plant (WIP), Trombay, for treatment of high level waste arising from first reprocessing plant, Plutonium Plant, of India. The plant was designed based on multi-cell concept, provision of maintenance cell above the melter cell, improvised design of IHMM etc. The plant was inaugurated in the year 2002 by then Prime Minister of India, Shri Atal Bihari Vajpayee. Even though the plant was built with improvised design, different sets of challenges were associated due to legacy nature of high level waste, as high-level waste of Trombay was stored since first batch of spent fuel reprocessing at first reprocessing plant of India. Over the period, reprocessing flow sheet was modified considerably resulting in generation of varied composition of high level waste collectively store in single tank. The Trombay waste is characterised with high concentration of inactive salts along many problematic components, such as sulphate, and hence has difficulties in processing. As a result, a special glass matrix was needed to be developed to accommodate the components of Trombay high level waste. Quite substantial numbers of operations could be carried out successfully at WIP, Trombay. The operation of WIP, Trombay has given good amount of experience during vitrification of high level waste with respect to process operations with handling of large amount of radioactivity, remote handling systems, dismantling and remote assembling of melter system etc. [9]

Waste Immobilisation Plant, Tarapur

Hon'able Prime Minister Shri Atal Bihari Bajpayee inaugurating Waste Immobilisation Plant, Trombay (Year 2002)

In order to meet the higher throughput requirement, the second generation vitrification plants were set up based on Joule Heated Melter Technology (JHCM). This works on Joule principle of direct heating and offers higher through put than IHMM. This design has been deployed in subsequent facilities and has performed satisfactorily.

Joule Heated Ceramic Melter, Tarapur

High-level vitrified wastes are characterized by decay heat and need to be cooled to a level where transportation and disposal in geological repository become viable and economical. This period of cooling is also used to generate data on the product behaviour under constant surveillance and monitoring. These data are essential for prediction of long-term behaviour of the vitrified products. These requirements necessitate interim storage of vitrified waste containing overpacks spanning over 30 years and more.

The first Solid Storage and Surveillance Facility (SSSF) co-located with a vitrification plant was also conceived and constructed at Tarapur. This facility has been designed for storing vitrified canisters in overpacks for a period of about 30 years for ensuring decay heat removal. This is achieved by natural convective ventilation induced by a tall stack. This is an inherently self-regulating system and takes care of the changes in decay heat. The cooling system ensures that the temperature within the vitrified waste product, under no circumstances, exceeds softening point of the vitrified mass.

Solid Storage Surveillance Facility, Tarapur

Partitioning of High Level Waste – major breakthrough

Along with working on vitrification technology, back-end specialists in India also started looking at ways and means for reducing the radiotoxicity associated with high level waste. Partitioning & Transmutation strategy held the key to this. The Fast reactor programme that India had embarked on, could also be used for transmutation purposes along with the proposed ADSS. This propelled R&D in the field of partitioning of high level waste culminating in setting up and operation of India's first Actinide Separation Demonstration Facility at Tarapur in the year 2013. The feedback of the successful operations were utilised to set up another such facility at Trombay. While, ASDF demonstrated the very exacting task of actinide-lanthanide separation, the facility at Trombay helped in separating all the radionuclides from the inactive component of waste. This not only resulted multi fold decrease in volume for final disposal but also open an opportunity to harvest useful radionuclides for societal benefits. [10, 11]

Hon'ble President of India Shri. Pranab Mukherjee, dedicating Actinide Separation Demonstration Facility, Tarapur to the Nation (Year 2013)

Recovery of valuable radionuclide from waste

The partitioning strategy, as adopted at Trombay, led to the opportunity of separating radionuclides for societal benefits. Recovered ^{137}Cs from High Level Waste is converted into non-dispersive sealed source of Cs glass pencil for its application in blood irradiation. India is the first country to deploy ^{137}Cs in non-dispersive glass form for irradiation application. ^{90}Sr is recovered and purified for milking of clinical grade ^{90}Y for radiopharmaceutical applications. ^{106}Ru based eye plaques, RuBy, of different configurations have been developed, utilising ^{106}Ru recovered from radioactive waste, for affordable eye cancer treatment. [12, 13]. These radioisotopes are normally handed over for commercial use through BRIT (Board of Research in Isotope Technology)

Handing over of first consignment of Caesium glass pencils for blood irradiator to BRIT (Year 2016)

Handing over of first consignment of 10 Ru plaque to BRIT (Year 2019)

Management & Disposal of Radioactive Solid Waste

Well characterised solid/solidified wastes conforming to regulations with regard to radioactive content and physical properties are only permitted for disposal. In the Indian context, since the country is fairly large, we have Near surface Disposal Facilities co-located with reactors at various identified sites. These are well engineered disposal modules which cater to waste containing only permissible limits of long lived actinides.

During initial stage, the focus was mainly on safe disposal of these waste in 'multi-barrier disposal system' at NSDF, since then innumerable improvements and requirements have been incorporated in design and construction of these disposal modules. Earth trenches, Stone Lined Trenches, Reinforced Concrete Trenches, Tile Holes are examples of engineered barriers. Mathematical models and their experimental validations for radionuclide migration from the disposal of radioactive solid waste from NSDF have been studied in detail to endorse the design of disposal facility ensuring no adverse effect to environment. Provisions for monitoring and surveillance are incorporated in the design of the disposal facility. Many NSDFs are under operation at various nuclear sites of India. A graded approach has been adopted for disposal of radioactive waste involving segregation and disposal of waste in different disposal module based on categorisation of waste. For example, low active category-I waste were disposed in earthen trench or stone lined trench, while intermediate active category II & III waste in reinforced concrete trench.

Vitrified waste containing long lived radionuclides are required to be disposed in Deep Geological Repositories. However, in the Indian context adoption of the closed fuel cycle and induction of cross cutting technologies with regard to partitioning of waste are ensuring that the need for Deep Geological Repository (DGR) are shifted by around a 100 year or so. In this regard, R&D activities with regard to site evaluation, waste-host interaction and environmental migration aspects are all being studied to accumulate a sufficient knowledge base for use at a later date whenever required. India presently does not have any Deep Geological Repository operational in the country.

As part of waste volume minimisation, design and operating practices were improvised to reduce the generation of solid waste and segregate them at source for their ease of management. Efforts were dedicated towards development of techniques for reduction of solid waste prior to disposal. Heavy capacity mechanical compactors have been developed and deployed for compaction of low active compressible waste to reduce the volume by about five folds. Incinerator system was deployed for incineration of low active cellulosic waste attaining volume reduction factor of about 30. The waste volume reduction techniques are still being utilised for reducing waste volume prior to disposal at NSDFs.

Recently, plasma-based incineration system has been developed and demonstrated for polymeric waste, contributing major fraction of low active waste, for waste volume minimisation. Developmental activities are focused to design the disposal module with optimum utilisation of space with desired quality of engineered barrier. [14]

Management of radioactive solid waste including safe disposal in NSDFs is under practice since early 1960's without any adverse effect to environment. Experience of more than six decades in the field of radioactive solid waste management and disposal has endorsed the design of NSDFs fulfilling the objective of safe disposal and also assured the capability of safe management of radioactive waste.

Conclusions

Recycling of spent nuclear fuel, as a long-term strategy has both environmental and resource advantage. In countries, where the energy needs have plateaued out, direct disposal of spent fuel is projected as an attractive option. Whereas in India, the need for effective utilization of limited resources along with environmental concerns necessitates adoption of reprocessing & recycling. Indigenous development of back-end technology and its maturing into standardized plants are ensuring sustainability of our Indian Nuclear Programme.

References

1. Srinivasan N, "Fuel reprocessing: the initial years", Nuclear Fuel Reprocessing; IANCAS Bulletin, July 1998, Vol 14, No 2.
2. Ramanujam A., "An Introduction to the Purex Process", IANCAS Bulletin, July 1998, 11-20
3. Dey PK, Bansal NK, "Spent fuel reprocessing: A vital link in Indian nuclear power program", Nuclear Engineering and Design, 236 (2006) 723–729
4. Kaushik CP, "CLOSED FUEL CYCLE - For Sustainable Growth of Nuclear Power Program in India", BARC newsletter, Vol. No. 380, 2022, 9 – 13
5. Smitha Manohar, Pradhan S, "Recycling Perspectives: Indian Experiences & Road Ahead", BARC newsletter, Vol. No. 380, 2022, 17-19
6. Smitha Manohar, Sanjay Kumar, "IRRADIATED THORIA-BASED FUEL - Experiences in Reprocessing", BARC newsletter, Vol. No. 380, 2022, 20 - 23
7. Raj K., Bansal N K, Prasad K K, "Radioactive waste management practices in India", Nuclear Engineering and Design, 236 (2006), 914–930
8. Anand G., "Progress in Radioactive Effluent Management – Hybrid process towards ALARA", BARC newsletter, Vol. No. 380, 2022, 34 - 37
9. Darshit Mehta et al, "Indian Experience in Vitrification of High Level Liquid Waste", BARC newsletter, Vol. No. 380, 2022, 24 - 27
10. Smitha Manohar et al, "Process Development for Bulk Separation of Trivalent Actinides and Lanthanides from Radioactive High-Level Liquid Waste", Nuclear Science and Engineering, Vol 156, 2007
11. Smitha Manohar, U Dani, "Partitioning of High Level Liquid Waste: Operational Experience and the Way Forward", BARC newsletter, Vol. No. 380, 2022, 28-30
12. Wattal PK, "Back end of Indian nuclear fuel cycle-A road to sustainability", Progress in Nuclear Energy 101, March 2017
13. Kaushik CP, Amar Kumar, N S. Tomar, S. Wadhwa, Darshit Mehta, R.K. Mishra, Jyoti Diwan, Suresh Babu, S.K. Marathe, A.P. Jakhete, Savita Jain, Anand G., and Kailash Agarwal., "Recovery of Cesium from High Level Liquid Radioactive Waste for Societal Application: An Important Milestone", BARC News Letter, March-April 2017, 3-4
14. Pancholi K C, "Radioactive Solid Waste Management - Practices and Advancements", BARC newsletter, Vol. No. 380, 2022, 73 – 75
15. IAEA Publications https://www-pub.iaea.org
16. Bhabha Atomic Research Centre (BARC) https://barc.gov.in
17. Department of Atomic Energy (DAE) https://dae.gov.in

Radiopharmaceuticals: Evolution and Accomplishments at DAE

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Preamble

The application of ionising radiation for societal benefits is a well-known branch of nuclear science and technology. Among them, the benefits available in the health care sector are very popular and also widely practised. Thanks to the early launch of our national programme of atomic energy soon after independence, India has been able to harness since the 1950s the applications of radiation-based medical practices, for both diagnosis and therapy. The utilization of certain radioisotopes (RI, e.g. ^{131}I) and their formulations, known as radio(active) pharmaceuticals (RPh), in the medical branch called nuclear medicine is unique, as it depends upon the regular availability of the RI of varying half-life, ranging from a few hours to days and which cannot be hence stored for long. There has been an evolutionary growth of products (RI, RPh) and procedures (diagnostic studies, therapy), as well as associated imaging technologies. India, through its Department of Atomic Energy (DAE) has enjoyed the privilege of being a contributor to the evolution of the field and has several accomplishments to highlight. The ensuing article is an attempt to trace the early beginnings, evolutionary growth and vital contributions made by the successive teams of professionals and all other staff of the concerned DAE Units over the past six decades.

1. Introduction

The use of radioisotopes for applications in health care has been one of the very early developments in the field of atomic/nuclear sciences. Thanks to the exemplary vision of Dr. Homi J. Bhabha, India made a very early entry in to the field, including the production and use of radioisotopes (RI). A major outcome of this early founding of Indian atomic energy program - at the then Atomic Energy Establishment - Trombay [AEET, which was later renamed as Bhabha Atomic Research Centre (BARC)] of the Department of Atomic Energy (DAE) - has been the indigenous availability over the past six decades of the benefits of radioisotope products, radiopharmaceuticals in particular, for medical uses in patients of our country. For this accomplishment, our society owes a lot to each and every leader of the program of the past over six decades. In this regard, citing the few early pioneers for records will be much appropriate: the doyen Dr. V. K. Iya for the overall growth of the field; (Late) Dr. R. S. Mani and Dr. N. G. S. Gopal for establishing the specialty of radiopharmaceuticals and their quality control, respectively; (Late) Dr. R. D. Ganatra for the clinical use in patients and sowing the seeds (along with the early pioneer (Late) Dr. S. K. Mazumdar in Delhi) for the birth of nuclear medicine (NM) in India; and (Late) Dr. S. M. Sharma for laying the foundation for radioiodine treatment of thyroid patients. It will be a stupendous task to justifiably describe in a small article all the contributions of the DAE Units in the field of radiopharmaceuticals. The authors have opted for a narration based on their personal and professional knowledge. The coverage is not designed to be exhaustive and apologies for inevitable and inadvertent omissions.

2. Historic Glimpses - Down the Memory Lane

Early years, until 1960

India embarked on pursuing atomic energy program quite early thanks to Dr. Homi J. Bhabha setting up Asia's first nuclear reactor, named 'Apsara' in August 1956. The availability of the reactor helped India to start the program of radioisotope production and supply of radiolabeled products from AEET for research and human healthcare in the late 1950s. Isotope Division was created in 1957 to undertake all the work related to radioisotopes and their applications. Temporary labs set up at Cadell Road in Bombay city were followed by isotope labs built at South Site of Trombay campus. AEET started producing medically useful radioisotopes, such as ^{32}P [$E_{\beta(max)}$ = 1.71 MeV, No γ, $t_{½}$ = 14.26 d] and ^{131}I [$E_{\beta(max)}$ = 606 keV, E_{γ} = 365 keV (81%), $t_{½}$ = 8.01 d], in small quantities, in Apsara reactor, by the end of 1958 and started supplying these products to hospitals for carrying out diagnostic studies.

1960-1980

Radioisotope program received a big boost in the year 1960 with the commissioning of the 40 MW_{th} CIRUS (Canada India Reactor for Utility Services) reactor. This reactor helped in production of a variety of medically useful radioisotopes (^{131}I, ^{32}P, ^{51}Cr, ^{24}Na, ^{82}Br, ^{198}Au, ^{203}Hg, ^{99}Mo, etc.) and in larger quantities. Treatment of patients using AEET/BARC supplies of ^{131}I, ^{32}P, ^{198}Au was a regular feature in many centres, apart from numerous diagnostic procedures performed using AEET/BARC supplies of ^{131}I, ^{51}Cr, ^{203}Hg. Supply of ^{99m}Tc of 6 hour half-life after separation from ^{99}Mo by solvent extraction was started, and in turn led to the launch of indigenous ^{99}Mo/^{99m}Tc radionuclide generator, popularly known as 'Trombay ^{99m}Tc cow' to facilitate interested hospitals to avail of ^{99m}Tc [E_{γ} = 140 keV (89%), $t_{½}$ = 6 h] product at the time of need. The hospital radiopharmacy concept was thus born in India in early 1970s! Another generator product (^{113}Sn/^{113m}In) of interest at that time was also developed by BARC, as well as trial runs performed for ^{18}F production (for bone scan) in CIRUS reactor by secondary nuclear reaction on enriched $^{6}Li_2CO_3$ target[1]. ^{131}I-labeled products, ^{57}Co-labeled Vitamn-B12[2], and kits for ^{99m}Tc compounds for liver, bone and kidney studies were the other highlights at that time. Augmented infrastructure, in terms of custom-designed laboratories and allied facilities, for safe-handling of large quantities of radioisotopes were set up during this period at the radiological laboratory (RLG) building at BARC. The radioisotopes produced in the CIRUS reactor helped several million patients of our country over nearly 50 years (until its permanent shutdown at the end of 2010).

In 1963, DAE established a dedicated wing to explore the clinical applications of radioisotope-based products, which was later christened as Radiation Medicine Centre (RMC) [co-located with Tata Memorial Hospital (TMH), Mumbai]. RMC has remained at the forefront of nuclear medicine in our country and contributed significantly for the growth of this medical specialty in India.

1980-2000

The construction and commissioning of a completely indigenous 100 MW_{th} R-5 reactor - later renamed as Dhruva reactor at Trombay enabled further expansion of indigenous radioisotope production and supplies. After the planned permanent shutdown of the CIRUS reactor at the end of 2010, Dhruva reactor has become the sole source of reactor produced radioisotopes in large-scale in our country.

In March 1989, DAE established a new unit carved out of BARC for specifically focusing on supply of products and services to users of radioisotopes, radiopharmaceuticals and radiation technology and allied equipment. This unit, named 'Board of Radiation and Isotope Technology' (BRIT) supplies various radioisotope products including radiochemicals, radionuclide generators, radiopharmaceuticals and freeze-dried kits for the formulation of radiopharmaceuticals to over 350 nuclear medicine centers of India.

India embarked on accelerator-based radioisotope production after the setting up of the Variable Energy Cyclotron (VEC) at Calcutta (now Kolkata). In early 1990s, BRIT and VEC Centre (VECC) used the VEC to produce a few medically useful radioisotopes, such as, ^{67}Ga [decays by Electron Capture, multiple gammas, $t_{½}$ = 3.26 d], ^{111}In [decays by Electron Capture, E_γ = 173 (90.5%) & 245 keV (94%), $t_{½}$ = 2.81 d] in limited quantities to cater to certain clinical needs.

Emergence of products beyond ^{131}I and ^{99m}Tc and development *cum* launch of products using reactor-produced ^{153}Sm [$E_{\beta(max)}$= 0.81 MeV, E_γ = 103 keV (28%), $t_{½}$ = 47 h] and ^{177}Lu [$E_{\beta(max)}$= 0.49 MeV, E_γ = 208 keV (11%) & 113 keV (6.4%), $t_{½}$ = 6.73 d] for therapeutic applications started during this period. Also, expansion of the range of ^{99m}Tc products took place for meeting clinically important imaging needs, e.g. of heart, brain and cancer.

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[1] *This approach, involving generating tritium by $^{6}Li(n,\alpha)^{3}H$ and using it in-situ for $^{16}O(^{3}H,n))^{18}F$ reaction, could not be pursued to its logical end, due to the inability to procure enriched $^{6}Li_2CO_3$ (strategic material) following the May 18, 1974 Pokhran test by BARC, India!*

[2] *A historic information pertaining to this period is the prestigious export of ^{57}Co-Vitamn-B12 consignments to Australia and Europe. The preparation of ^{57}Co (as also ^{58}Co)-labeled Vitamin-B12 (cyanocobalamin) required bio-synthesis and extensive purification. The product (capsule or injection) in microcurie level was needed for studies of pernicious anemia (Schilling's test). The exports waned only much later, after product registration related regulatory requirements in the recipient countries made it too expensive to export low-volume products!*

Since 2000

In 2002, DAE-BARC established the first medical cyclotron (MC) facility of India at Parel (Mumbai) in the premises of RMC with the support of the Tata Memorial Centre (TMC). Since then, this imported 16.4 MeV MC is being used for production of short-lived positron-emitting radioisotope ^{18}F and several ^{18}F-based radiopharmaceuticals required for PET (Positron Emission Tomography) imaging. Additionally, this also triggered the rapid growth of MC and PET centers in India (clearly reflected by the 24 medical cyclotrons and more than 280 PET-CT units now in India) serving thousands of patients every day.

DAE-BARC further complemented its radioisotope production capability by commissioning Apsara-U (upgraded), a pool-type reactor (like vintage Apsara reactor), on September 10, 2018. This indigenously built reactor has made it possible to produce clinically important radioisotopes, like ^{64}Cu [E_{β}^{+}: 0.653 MeV (17.4%), E_{β}^{-}: 0.578 MeV (39%), $t_{½}$ = 12.7 h] making use of its higher fast neutron flux. This reactor is envisaged to be used also for irradiation of ^{235}U targets for production of ^{99}Mo.

Another important milestone was achieved in 2018 with the commissioning of India's largest cyclotron facility, namely Cyclone-30, in Kolkata. This facility has started producing some medically important radioisotopes, such as, ^{18}F, ^{68}Ga and ^{201}Tl. VECC and BRIT have plans for full utilization of Cyclone-30 capabilities in near future.

Another medical cyclotron facility is presently being set up at 'Advanced Centre for Training, Research and Education in Cancer' (ACTREC at Kharghar, Navi Mumbai) to supplement and expand the operations of MC at Parel and to fulfill the demand for many important and emerging radioisotopes, e.g. ^{89}Zr, ^{64}Cu, ^{68}Ga, ^{123}I, etc. for various medical applications.

Since the launch of nuclear medicine imaging using gamma camera, ^{99m}Tc has played a very important role and still more than 70% of all nuclear medicine procedures are based on this radioisotope. BRIT has been supplying $^{99}Mo/^{99m}Tc$ alumina column generators using imported ^{99}Mo of fission origin. Considering the need to strengthen the self-reliant supply of ^{99m}Tc, DAE-BRIT is in the process of setting-up a fission-moly (^{99}Mo produced through nuclear fission of ^{235}U) plant at Trombay, which is expected to provide a significant boost to the indigenous production of $^{99}Mo/^{99m}Tc$ generators in future.

The growing importance of radioisotope-based therapy, supported by prior imaging of tumor lesions (by PET/CT), has led to the indigenous development and launch of ^{177}Lu products for treatment of certain cancers (e.g. neuroendocrine, prostate). DAE's unique advantage of access to fission-product isotopes from the reprocessing stream has been harnessed to avail ^{90}Y [$E_{\beta(max)}$ = 2.27 MeV, $t_{½}$ = 64 h] to complement the use of ^{177}Lu in this context.

Radioisotope processing laboratory, in the past (left) and at present (right)

3. Iodine-131 products: Reigning Ever in Nuclear Medicine

Iodine-131 is the one RI reigning all through the past six decades, and continues to be of high relevance for future too. Starting from small-scale production using TeO_2 targets and oxidative dissolution plus wet distillation procedure for isolation of ^{131}I, scaling up of production to a few tens of curies every week in tong-operated lead-shielded plants took place over time. Switch over to dry distillation process - for specific advantages of larger batch size, reduced waste generation, flexibility to avail high radioactive concentration, etc. - took place much later, well beyond 2000. In order to ensure greater reliability and safety of radiochemical process, augmented protection measures of plant ventilation were instituted. In addition, new processing facilities are being set up (in the old CIRUS building) for sustainability of product supplies. Currently the average weekly production of this RI is of the order of 40-45 Ci (1.48-1.67 TBq). In future, there is also scope for availing fission-produced ^{131}I, after setting up appropriately augmented processing facilities, at the Fission Molybdenum Plant (FMP) of BRIT (now in an advanced stage of completion) located near the South Gate of BARC campus.

Apart from formulation of ^{131}I as NaI in solution and capsule form (for treatment of hyperthyroidism and metastatic thyroid cancer), labeled product of meta-iodo-benzylguanidine - ^{131}I-MIBG is another important product launched in response to clinical demands and pursuant to its utility demonstrated by colleagues at RMC, who prepared it in-house (at the hospital radiopharmacy). In recent years, ^{131}I-labeled lipiodol and monoclonal antibodies have been developed and added to the list of ^{131}I products for therapy of certain cancers. Over 80% of all therapy procedures of NM use ^{131}I.

The early generation diagnostic products like Rosebengal-^{131}I (for liver scan), Hippuran-^{131}I (for probe renography) and human serum albumin-^{131}I (for blood pool studies) lost their place due to emergence of superior alternate products and/or techniques. The relatively large use of diagnostic $Na^{131}I$ capsules, well into 1970s for thyroid function studies, was overridden by estimation of thyroid hormones *in-vitro* using radioimmunoassay (RIA)[3] and other forms of immunoassay.

4. Technetium-99m products: The Workhorse of Nuclear Medicine Imaging

The serendipitous discovery of $^{99}Mo/^{99m}Tc$ generator at the Brookhaven National laboratory (BNL), USA in 1957, along with the invention of gamma camera by Dr. Hal Anger around the same time, laid the foundation stone for the field of diagnostic nuclear medicine imaging. Decay of ^{99m}Tc by isomeric transition with the emission of 140 keV gamma radiation [ideal match for imaging with (planar) gamma camera and SPECT (Single Photon Emission Computed Tomography)] and its relatively short half-life of 6 h (long enough for logistics of formulation, quality control tests and administration to patients; and yet adequately short for physical decay and biological excretion) are the significant merits, which drove the research and development to launch organ/lesion-specific products for imaging of patients. The versatility of making ^{99m}Tc complexes at various oxidation states (-1 to +7) and exploitation of a vast range of ligands (both known and innovatively designed ones) have made ^{99m}Tc overwhelmingly popular in nuclear medicine. Thus, of the 40 million diagnostic nuclear medicine scans performed worldwide annually, 70-75% are based on using ^{99m}Tc products. Currently, ^{99m}Tc-based radiopharmaceuticals

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[3] *BARC (RMC, RPhD) and BRIT played a significant role in developing radioimmunoassay programme and launching supply of reagents and kits for estimation of many hormones in-vitro, most notably the thyroid related ones. This area (not being within the domain of radiopharmaceuticals) is not covered in this article.*

are available for imaging every major organ of human body, while the large share of its regular clinical use is in the case of renal studies, myocardial perfusion, infection imaging, cancer metastasis, etc., earning ^{99m}Tc the title of '*work-horse of nuclear medicine*'.

Technetium-99m

By the late 1960s, BARC produced (n,γ)^{99}Mo and used solvent (methyl-ethyl-ketone, MEK) extraction methodology to obtain ^{99m}Tc in the laboratories at Trombay and the separated ^{99m}Tc supplied to RMC in Bombay city, co-located with TMH. The logistics of transport and keenness to get ^{99m}Tc early every day drove the colleagues in RMC to seek to operate the MEK extraction system at their end itself. The practices and procedures prevalent then (early 70s) were permissive to this arrangement and thus was born the Indian MEK extraction generator system for ^{99m}Tc, popularly known as 'Trombay Technetium Cow'. This manually operated system required certain operational facilities at the user end and training of the operators and was in extensive use in India since 1970s with the support from the radiopharmaceutical wing of BARC. Dr. O. P. D. Noronha of RMC, who has the credit of being the first hospital radiopharmacist of India, introduced a number of useful tools and procedures to facilitate the handling of MEK extraction process at the user end. After the creation of BRIT in 1989, there was a time when as many as 60 to 70 centres regularly used up to 40-50 Ci (1.48-1.85 TBq) ^{99}Mo per week.

The growth of nuclear medicine in India owes much to the early indigenous availability of ^{99m}Tc. The downside has been that there was no liberation from the MEK technology of DAE for a very long time. Only from late 1990s (opening up of economy, imports, foreign exchange etc.), nuclear medicine practices in India could shift to (a considerable extent) the use of imported alumina column (user-friendly) generators.

Earlier in 1976, in response to RMC's interest to avail the benefit of alumina column generator, there was an attempt by Radiochemistry Division (RCD) of BARC to produce fission molybdenum using natural uranium target. The method involved addition of mg level Mo carrier for precipitation of ^{99}Mo as its alpha-benzoin-oxime complex followed by many purification steps. This technique has been much cited in the literature. ^{99m}Tc was obtained at RMC from alumina column generator loaded with fission molybdenum produced at RCD, BARC. This demonstration on 'campaign-mode' was not pursued further, probably due to the complexity and issues involved in adopting it for regular/frequent production.

During 1979-80, there was a planned, prolonged shut-down of the CIRUS reactor and in order to sustain supplies to medical users, import of ^{99}Mo (available as fission produced) was necessary. The Radiopharmaceuticals Section quickly resorted to a shift in the methodology, in terms of opting for production of alumina column chromatographic generators. A lead shielding unit meant for another purpose was used along with other required items to produce and deliver column ^{99m}Tc generators to hospitals in Bombay and Delhi for a few months. This was however only a short-lived comfort for users at that time.

The major consideration towards column ^{99m}Tc generator took place much later after the formation of BRIT. The feasibility for taking up regular production of alumina column generators using imported fission-moly was seriously considered and engineering efforts were invested. This resulted in many developments and eventually led to BRIT undertaking, over a period of a few months in 1994, regular production and supply of sterile column generators for ^{99m}Tc, based on weekly import of a small quantity of fission ^{99}Mo from South Africa. The unresolved dilemma was whether to depend on permanent weekly imports of fission product ^{99}Mo!

India has been participating in the IAEA's (International Atomic Energy Agency) efforts towards development of alternate technologies for ^{99m}Tc generators, due to its preference to retain the option of (n,γ)^{99}Mo. The gel generator concept of Australia was one of the keenly pursued routes since mid-80s. The R&D level pursuits in gel generator moved up to technical feasibility studies (upon the closure of alumina column generator trials in 1994). There was consequently steady progress in BRIT pursuits of gel generator option. BRIT's GELTECH generators - based on zirconium molybdate gel column - of capacity 5.55 GBq (150 mCi), 9.25 GBq (250 mCi) and 14.8 GBq (400 mCi) have been supplied on weekly basis starting from 2005. The technology is suitable for supplies to a limited number of NM centres; furthermore, it cannot meet the high-activity generator needs of large NM centres.

In order to meet the needs of the large volume NM centres in India, around 2008, DAE-BRIT shifted again to reconsidering production of alumina column generators using imported fission-moly. This led to the setting up of imported processing plant facilities and launch of ^{99}Mo/^{99m}Tc COLTECH generators [capacity 11.1 GBq (300 mCi), 18.5 GBq (500 mCi) and 37 GBq (1000 mCi)]. This was a much welcome step for the NM community in India, although logistic reasons (procurement constraints, return of shielded container, etc.) kept the production and supply at a limited level (40-50/week)[4]. A significant portion of generators used in India is still by imports on regular basis. Since the large demand for ^{99m}Tc has to be sustainably met, it is necessary to secure reliable sourcing of fission-moly.

DAE/BRIT hence took up a project in 2014 for setting-up a FMP (Fission Molybdenum Plant) facility at the south site of Trombay campus. This 300 Ci (11.1 TBq) capacity plant, based on the Argentinian company INVAP technology, is presently in an advanced stage, nearing commissioning and is expected to be in operation later in 2022. Indigenous availability of fission-moly will enhance the share of BRIT's supplies of ^{99m}Tc generators to NM centres.


^{99}Mo/^{99m}Tc Generator Production Facilities at BRIT (Vashi, Navi Mumbai) - GELTECH Generator (left) and COLTECH Generator (right)

Kits for ^{99m}Tc Radiopharmaceuticals

Technetium-99m based radiopharmaceuticals, unlike other ready-to-use finished product drugs, need to be prepared afresh just prior to administration in patients, at the hospital radiopharmacy using the ^{99m}Tc-pertechnetate obtained from the ^{99}Mo/^{99m}Tc generator.

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[4]Brief mention can be made of also the following efforts to use (n,γ)^{99}Mo as source of ^{99m}Tc, though with limitations. BARC worked on high-capacity adsorbents for Mo to suit the low specific activity of (n,γ)^{99}Mo. BRIT team in Kolkata explored post-elution concentration of ^{99m}Tc obtained from large-bed alumina column holding (n,γ)^{99}Mo, and also in collaboration with VECC, launched automated version of MEK extraction system.

Clean room facility corridor (left) and preparation of Freeze-dried kits at BRIT (Vashi, Navi Mumbai) (right)

Table 1: Freeze-dried kits supplied from BRIT for the formulation of various ^{99m}Tc-radiopharmaceuticals

BRIT Code	Kit for	Applications
TCK-5	^{99m}Tc-Sulphur Colloid	Liver imaging
TCK-7	^{99m}Tc-DTPA	Kidney function studies
TCK-15	^{99m}Tc-GHA	Kidney function studies
TCK-16	^{99m}Tc-Phytate	Liver imaging
TCK-30	^{99m}Tc-MDP	Bone imaging
TCK-33	^{99m}Tc(III)-DMSA	Kidney imaging
TCK-35	^{99m}Tc(V)-DMSA	Medullary thyroid carcinoma imaging
TCK-38	Sn-Pyrophosphate	Red Blood Cells labeling
TCK-39	^{99m}Tc-Mebrofenin	Hepatobiliary function studies
TCK-42	^{99m}Tc-ECD	Brain perfusion imaging
TCK-43	^{99m}Tc-EC	Kidney function studies
TCK-50	^{99m}Tc-MIBI	Myocardial perfusion imaging
TCK-52	^{99m}Tc-Tetrofosmin	Myocardial perfusion imaging
TCK-53	^{99m}Tc-HSA Nanocolloid	Sentinel lymph node imaging
TCK-54	^{99m}Tc-HYNIC-TOC	Neuroendocrine tumor imaging
TCK-55	^{99m}Tc-TRODAT	Dopamine transporter imaging
TCK-56	^{99m}Tc-Macro-Aggregated Albumin	Lung perfusion imaging
TCK-57	^{99m}Tc-UBI	Infection imaging
TCK-58	^{99m}Tc-HYNIC-TATE	Neuroendocrine tumor imaging
TCK-59	^{99m}Tc-HYNIC-E[c(RGDfK)]$_2$	Imaging of Tumour Angiogenesis

Freeze-dried (lyophilized) kits are sterile and pyrogen-free formulations containing a mixture of all the non-radioactive pharmaceutical ingredients - ligand, reducing agent, stabilizer, fillers, etc. - in freeze-dried/lyophilized powder form, for use at the hospital radiopharmacy for the formulation of various radiopharmaceuticals. The kits when reconstituted with sterile, pyrogen free sodium-[^{99m}Tc]-pertechnetate solution (obtained from ^{99}Mo/^{99m}Tc generators) following the prescribed procedure, produces the desired injectable ^{99m}Tc radiopharmaceuticals.

BRIT/BARC has made significant contributions in this area matching with the global developments and Indian NM demands. Since the 1970s, scientists working in the radioisotope program in both Isotope Group and RMC have carried out intense research for the development of various freeze-dried kits, demonstrated their utility and deployed such kits in the hospitals for the imaging of patients. Beginning with colloidal products used for liver studies and other products for excretory organs like kidneys and hepato-biliary system, products for imaging the skeletal system (bone being a frequent site of cancer metastasis), blood pool, blood flow to heart and brain, infection, certain tumors, etc. have been developed and launched for regular clinical use. In some cases, the required ligands or precursors have also been synthesized in-house. In light of the injectable nature of the kit products, the production has to be done in clean-air laboratories under GMP (Good Manufacturing Practice) conditions, adopting practices followed in conventional pharma-labs. Such facilities have been evolved and established by DAE-BRIT at Vashi - Navi Mumbai campus.

In the area of kits, the share of BRIT supplies has been around 80%, with direct imports by users much limited (cf. the case of ^{99}Mo/^{99m}Tc generators). Presently, BRIT supplies 20 different types of freeze-dried kits (Table 1) for various radiopharmaceuticals required for diagnostic imaging of organs or diseases or dysfunction of physiological processes. They enable imaging applications pertinent to brain, heart, lungs, liver, kidneys, lymph nodes, thyroid, red-blood cells, dopamine transporters, angiogenesis, tumors, various types of cancers, etc.

5. Cyclotron-based products: High-value Utility for Patient Management

There was a strong case for cyclotron-produced radioisotopes (neutron-deficient ones, decaying by electron capture or positron emission) to complement the reactor-based ones for applications in medicine. When the VEC became available to users, BARC/BRIT team carried out feasibility studies for production of some medical RI of interest at that time. Limited quantity of ^{67}Ga as gallium citrate was regularly produced and used in early 1990s, apart from demonstrating technology for ^{111}In products. Experience was also gained in developing targetry systems, recovery of precious target materials, etc. at the radiopharmaceutical laboratories located at VECC. There were limitations in large-scale RI production due to varying needs of VEC users, availability of projectile and energy, etc.

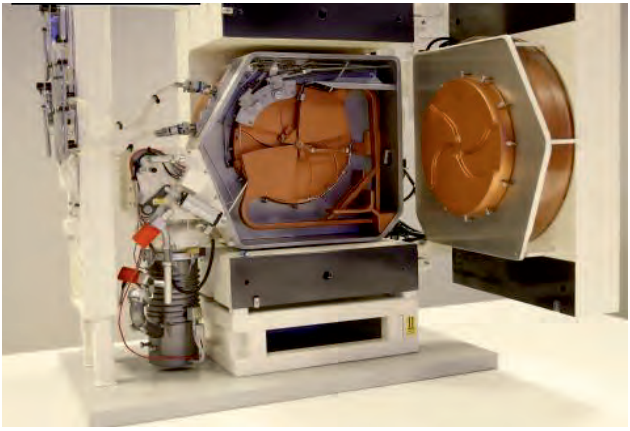
All along, the RI teams of BARC and BRIT have been persuading BARC/DAE management to support establishing a dedicated cyclotron facility for all relevant RI, for both SPECT and PET imaging. ^{201}Tl (69-80 keV X-rays, $t_{½}$ = 73 h,) was then the product of very high interest for myocardial SPECT imaging. Its production involving (p,3n) reaction required use of 28-30 MeV protons as projectile. IBA, the Belgian company, had very successfully launched Cyclone-30 model (30 MeV proton cyclotron, rugged system, high current machine) and several units were in operation in various countries. The same system was much desired by the stakeholders in India. Both BRIT and VECC sought support to set up MC in the plan period 1997-2002.

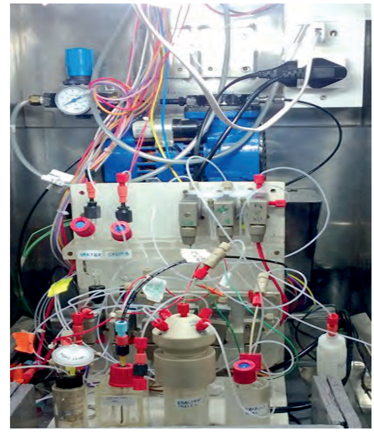
Thanks to Dr. Bikash Sinha (then Director, VECC and SINP) recognizing the opportunity to foster cyclotron-based RI, available VECC expertise and his keen interest there emerged scope (around 2000-2001) for IBA setting up, along with the participative support of VECC/DAE, a Cyclone-30 facility in Kolkata to meet the Indian needs and also of other countries in the Asian region. However, such a (partnership) venture was not then commonplace and could not get the required support for implementation. This led to the planning and pursuit of VECC/DAE's own project on medical cyclotron at Kolkata. IBA and its already planned supporting entity in Kolkata/India got left out, though their role and support were crucial for the VECC/DAE project. Due to multiple reasons the project ran into considerable delays. The Cyclone-30 system could be finally installed and commissioned in 2018, aided much by the in-house competency strength of VECC. BRIT has made use of the facility and started regular production of ^{18}F, ^{68}Ga and also ^{201}Tl (on demand basis) in the last couple of years.

What was the much-cherished goal of the 5-year plan periods of 1997-2002 and 2002-2007, could thus finally become a reality after 2018 only. The RI scenario and imaging procedures have however undergone much transformation during the intervening period. Some products have become obsolete (e.g. ^{67}Ga), while the high demand for ^{201}Tl has considerably reduced (due to alternate products). Lower energy MC and radiotracers for PET imaging have emerged as the larger interest for medical use. Yet, the 30 MeV proton cyclotron, Cyclone-30, is a powerful addition to the national nuclear infrastructure. It can meet the needs for PET imaging (growing area) and also help in making other medically useful RI in demand, e.g. ^{68}Ge/^{68}Ga, $^{123/124}$I, etc. (apart from meeting also R&D needs beyond RI domain). BRIT and VECC have demonstrated the high utility of Cyclone30 and also cited plans for further enhanced utilization of the Cyclone-30 facility in the coming years.

The other medical cyclotron facility pursued in parallel by DAE in Mumbai (1997-2002 plan project) for the establishment of a 16.4 MeV unit (GE Petrace) at the basement of TMH building in Parel progressed well in time, despite severe constraints of space and other issues (narrated elsewhere, Sl. No. 5 in Bibliography). The MC facility and associated radiopharmacy laboratories, along with a PET system for RMC, were set up by October 2002, ushering in the era of PET tracers and their applications in India. Two dedicated publications in 2012 (Sl. No. 5, 6 in Bibliography) and a thematic issue of IANCAS Bulletin in 2014 (Sl. No. 7 in Bibliography), contain detailed account of the project team's sustained efforts, challenges faced and eventual accomplishments. This facility rendered daily production and use of ^{18}F (97% positron emission, $t_{½}$ =110 min) products a reality. ^{18}F-FDG (2-Fluoro-2-deoxyglucose) in particular is the most widely used product for management of cancer patients, apart from Na^{18}F and other ^{18}F-based radiopharmaceuticals. The advent of the hybrid imaging system PET/CT (CT: Computed Tomography) in 2001 coinciding with the DAE's launch of India's first MC in Mumbai, became an important turning point. The leadership of (Late) Dr. (Mrs.) A. M. Samuel for DAE's MC + PET project deserves to be highlighted, as well as her subsequent role in TMH setting up the first PET/CT-based nuclear medicine services using radiopharmaceutical supplies from the MC at RMC.

Many other institutions followed the BARC model for setting up MC in the subsequent years. They are successfully operating the MC and associated radiopharmacy, including some in commercial mode.





India's first Medical Cyclotron at RMC (BARC, Mumbai) (left) and automated module for the preparation of PET radiopharmaceuticals like ^{18}F-FDG (right)

BARC has also developed kits for the formulation of ^{68}Ga labeled products (e.g. ^{68}Ga-DOTA-TATE, ^{68}Ga-PSMA-11) for PET imaging of cancer metastases to help the centres importing ^{68}Ge/^{68}Ga generator. The kits are also useful for recipients of ^{68}Ga supplies from Cyclone30 facility at Kolkata.

Currently, the MC at RMC, jointly operated by BRIT and BARC, has the following major performance credits (Table-2).

Table 2: Major Radiopharmaceuticals supplied by BRIT from MCF at RMC, BARC

Radiopharmaceuticals	Application using PET	Production and supply commenced from
^{18}F-FDG	Imaging of cancer mets	2002
^{18}F-NaF	Imaging of bone metastases	2007
^{18}F-FLT	Marker for tumor proliferation	2010
^{18}F-MISO	Imaging of tumor hypoxia	2010

6. Radiopharmaceutical Therapy Products Beyond Iodine-131: Unique Importance for Personalised Treatment

Products for Bone Pain Palliation

The successful use of radioiodine for the treatment of thyroid related disorders way back in 1960s was followed by the potential utility of radiopharmaceutical therapy for palliation of bone pain due to diffused metastasis in cancer patients (for better quality of life for patients in mostly terminal stage). The bone seeker ^{89}Sr [$E_{\beta(max)}$ = 1.49 MeV, $t_{½}$ = 50.5 d], being calcium analog, emerged as the global choice. However, it was difficult to produce ^{89}Sr (involved ^{88}Sr(n,γ) reaction of very low cross-section or ^{89}Y(n,p) reaction using fast neutrons) in those early years. ^{32}P [$E_{\beta(max)}$ = 1.71 MeV, $t_{½}$ = 14.3 d] as sodium phosphate of BARC/BRIT was used in many centres since 1980s as a practical alternate to ^{89}Sr, although with limitations due to inevitable bone marrow toxicity.

The development of ^{153}Sm-EDTMP (ethylenediamine tetramethylene phosphonic acid) with superior radiochemical and biological features (phosphonates were known drugs for pain palliation) in University of Missouri, Columbia (USA) led to BARC-BRIT scientists exploring its formulation and supply for use in India. Concerted efforts and extensive work carried out (including large animal studies in collaboration with Christian Medical College, Vellore) helped in establishing regular production of ^{153}Sm-EDTMP using natural samarium oxide targets, and subsequently with enriched ^{152}Sm targets, by neutron activation in medium flux reactors at BARC. By the end of 1990s, BARC started producing medical grade ^{153}Sm in sufficient quantities and this enabled BRIT to formulate and supply ^{153}Sm-EDTMP injection for palliative care of cancer patients in various medical institutions. The initial monthly production frequency was improved to fortnightly/weekly, depending on the demands of users.

Later on, with the development of ^{177}Lu based products for radiopharmaceutical therapy at BARC, the additional advantage of the relatively longer half-life of ^{177}Lu and similarity of chemistry, ^{177}Lu-EDTMP was developed and clinical studies initiated from 2008 to supplement the use of ^{153}Sm-EDTMP. This was also an important contribution to a Coordinated Research Project (CRP) of IAEA. Thus currently, users have the choice of using both ^{153}Sm-EDTMP and ^{177}Lu-EDTMP. BARC has also developed and evaluated another phosphonate ^{177}Lu-DOTMP (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetramethylene phosphonic acid) for bone pain palliation. Kits for formulation of both ^{177}Lu-EDTMP and ^{177}Lu-DOTMP are also available from BARC/BRIT for formulation at hospital radiopharmacy end.

In light of the fast neutron flux available at FBTR (Fast Breeder Test Reactor) and the knowledge of the importance of ^{89}Sr, scientists in IGCAR, Kalpakkam took up considerable efforts to use mono-nuclidic Y in place of a fuel element to produce ^{89}Sr by ^{89}Y(n,p) reaction and its subsequent recovery by radiochemical processing[5].

BARC has also developed and launched kits for formulating ^{188}Re-HEDP (1-hydroxy ethylidene-1,1-diphosphonic acid) at hospital end for similar use in cancer patients for bone pain palliation and enabled the interested NM centres in making more effective use of the imported, expensive ^{188}W/^{188}Re generator (^{188}W is a product of successive neutron capture and its production in useful quantities require reactors having neutron flux of 10^{15} n.cm^{-2}.s^{-1}, which is available only in a very few reactors in the world).

Launch of ^{177}Lu for Targeted Tumor Therapy

Since the beginning of 2000, the Radiopharmaceuticals Division (RPhD) of BARC started exploring the feasibility of producing ^{177}Lu as another therapeutic radionuclide using the medium flux research reactors at BARC. The first irradiation of natural lutetium oxide target was carried out in 2000 and was followed by the production of high specific activity ^{177}Lu from enriched ^{176}Lu target in mid-2001. Extensive studies were carried out to optimize the production of this radionuclide, with maximum achievable specific activity and radionuclidic purity, using the highest available flux positions in the reactor and irradiating the target for an optimum duration. This enabled production of ^{177}Lu with adequately high specific activity for the preparation of target-specific therapeutic radiopharmaceuticals.

^{177}Lu is being produced on a regular basis at BARC since the end of 2006 for carrying out clinical investigations using ^{177}Lu-based radiopharmaceutical product. The most noteworthy development is the successful formulation and translation to clinical use of the new therapeutic

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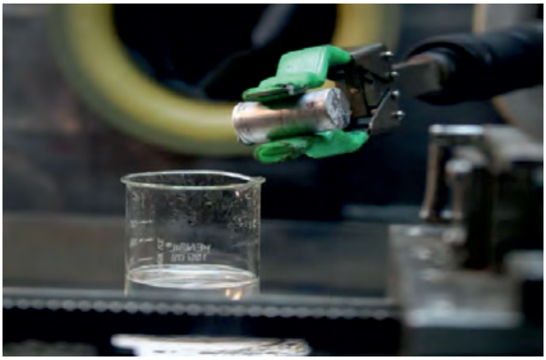
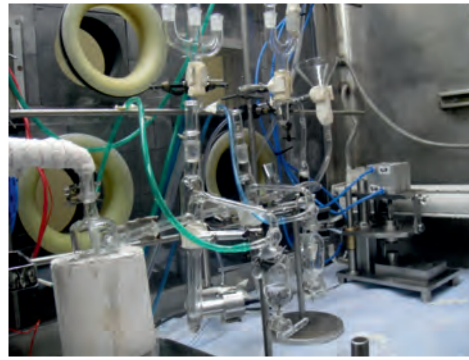
[5]It may not be necessary to pursue further such demanding efforts on ^{89}Sr production, in light of easy-to-produce, effective alternate products available from BARC/BRIT for clinical use.





In-cell gadgets inside the lead shielded plants for radiochemical processing of ^{177}Lu (left) and ^{131}I (right)

radiopharmaceutical, ^{177}Lu-DOTA-TATE (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid coupled Tyr^{3}-Octreotide), receptor binding peptide-based product used for targeted therapy of neuroendocrine tumours (e.g. pancreatic cancer).

BARC started commercial supply of $^{177}LuCl_3$, as the precursor radiochemical, and along with know-how transfer for the formulation of the finished radiopharmaceutical product, ^{177}Lu-DOTA-TATE (and also ^{177}Lu-EDTMP) at hospital end. This pragmatic approach helped the collaborating nuclear medicine centres to formulate the finished product and perform clinical procedures by the end of the first decade of 2000 onwards. Since then, ^{177}Lu of medium specific activity is being regularly produced at BARC and supplied to various nuclear medicine centres in India through BRIT. The subsequent addition of another important product denoted as ^{177}Lu-PSMA-617 (Prostate Specific Membrane Antigen binder ligand conjugate) by BARC, for treatment of one type of prostate cancer patients, is another significant accomplishment, keeping India at the forefront of targeted radionuclide therapy. This product received US-FDA (Food and Drug Administration of United States of America) approval very recently and is likely to be more extensively used in future.

It is noteworthy to mention that the production and use of ^{177}Lu have seen a phenomenal growth in the last two decades all over the world and the Indian contribution is acknowledged in several citations. Presently the use of ^{177}Lu is second to ^{131}I among all the therapeutic applications. Currently, BRIT supplies ^{177}Lu, both as precursor radiochemical and as ^{177}Lu-labeled radiopharmaceuticals, to more than 50 nuclear medicine centres of India.

In view of the need for no-carrier-added ^{177}Lu, for formulations involving very small quantities of targeting binder (vector) moiety, the production of ^{177}Lu by isolation from its precursor ^{177}Yb (produced by irradiation of enriched ^{176}Yb targets) is also being developed at BARC and BRIT.

There are also other products of ^{177}Lu in use, mostly due to favourable radionuclide features, for bone pain palliation (covered in the earlier sub-section) and treatment of inflammatory joint pain (covered later in this section).

Leveraging the Closed Fuel Cycle Pursuit of India to Deliver ^{90}Sr/^{90}Y

High-level radioactive liquid waste of the back-end of the fuel cycle stream contains various useful fission products, such as ^{137}Cs, ^{90}Sr, ^{106}Ru, etc. The Nuclear Recycle Group (NRG) of BARC has been striving to make available these products for applications in human healthcare.

The very long-lived ^{90}Sr ($t_{½}$ = 28.79 y) decays to ^{90}Y ($t_{½}$ = 64 h), which has a high energy beta emission of 2.27 MeV. It is thus useful for therapy of large tumors or where deeper penetration is required to reach target lesions. ^{90}Y is an ideal complement to therapy products of ^{177}Lu for clinical use.

NRG has developed in-house a strontium-selective extractant and successfully deployed for separation - recovery of ^{90}Sr from high-level radioactive liquid waste and converting into $^{90}Sr/^{90}Y$ radionuclide generator system. Two systems for separation of ^{90}Y from ^{90}Sr have been developed at BARC - the first involving 2-stage liquid membrane technology (by NRG), and the other using electrochemical means (by RPhD). The latter has been adopted and converted into an automated, commercial unit (named *Kamadhenu*) by a company in Europe.

During the recent past, ^{90}Y is periodically recovered (*milked*) from purified ^{90}Sr and supplied by NRG to RMC for the preparation of therapeutic radiopharmaceutical, ^{90}Y-DOTA-TATE. Building up an adequate stock of a few curies of ^{90}Sr and delivering ^{90}Y in several hundreds of mCi on weekly basis will be needed for regular clinical use in India.

Other products for targeted therapy

Radiolabeled monoclonal antibody (MoAb) to tumor-associated antigen as vector for targeted tumor therapy was explored by many leading centers including BARC, but could not yield satisfactory results, mostly due to unfavorable pharmaco-kinetics. With advances in immunotherapy of cancer patients (as part of systemic therapy), an altered approach for using RI - as additional *pay-load* - along with the specific antibody administered (as drug) in large quantities for immunotherapy of cancer was proposed by Dr. R. A. Badwe, Director, TMC. Reduced dose of MoAb quantity, combined with suitable particulate radiation of RI, can render this therapy more affordable and efficacious. In this connection, the collaborative pursuit between BARC and TMC and the ongoing clinical evaluation of three radiolabeled antibodies, namely, ^{131}I-Rituximab, ^{177}Lu-Rituximab (both for the treatment of non-Hodgkin's lymphoma, a type of blood cancer) and ^{177}Lu-Trastuzumab (for the treatment of metastatic breast cancer), are noteworthy.

The emerging area of targeted tumor therapy requires alpha emitters due to the known merits of the high LET (Linear Energy Transfer) radiation for efficacious delivery of radiation dose to the tumors. In the recent years, ^{225}Ac ($t_{½}$ = 10 d, multiple alphas) has been attracting the global attention, as its use has shown promising results in patients of prostate cancer. BARC has made a beginning by locating old legacy stock of ^{229}Th for separation of ^{225}Ac in very limited quantities for initial studies. BRIT and BARC are also looking at options and strategies for planning the production of this RI of envisaged high demand in future. Other potential alpha emitter RIs are also being explored by BARC.

Products for Therapeutic Applications Involving Loco-Regional Instillation

***Rph for treatment of hepatocellular carcinoma*:** Apart from the targeted therapy approach using ^{90}Y obtained from ^{90}Sr, ^{90}Y-labeled hard-microspheres have been in use for treatment of a certain type of liver cancer (unresectable (non-operable) hepatocellular carcinoma, HCC). This is based on intra-arterial delivery of the product to the tumor (loco-regional delivery of the therapeutic product). The product (TheraSpheres®, glass microspheres containing ^{90}Y) is imported from commercial sources in Europe at very high cost and used in limited cases on patients who can afford to pay the high cost of import. The multi-disciplinary expertise of BARC has been harnessed recently to develop an import substitution. Scientists of RPhD, in collaboration with the researchers of the Materials Group, BARC have been successful in developing ^{90}Y-incorporated glass microspheres (fondly named as BhabhaSpheres). Here ^{90}Y is produced by neutron irradiation of the said spheres, which contain yttrium as one of its constituents. This has been used for the treatment of a limited number of liver cancer patients at TMH, Mumbai. Many other centers have also shown interest in using the product. This development, when completed, is expected to increase the accessibility to such therapy of HCC and also at significantly reduced cost.

There are also other alternate products to the hard-particulate based agents in use for HCC therapy. Viscous formulations of lipiodol labeled with ^{131}I and ^{188}Re have been in use. BARC has developed and made available these products for such therapy. BRIT has subsequently taken up regular production and supply of ^{131}I-lipiodol. BARC developed kits for use with imported $^{188}W/^{188}Re$ generator and formulation of ^{188}Re-lipiodol have also been helpful in this context. The recent demonstration of the utility and technology capability in terms of BhabhaSpheres may render some of the above products redundant in future.

***Rph for therapy of inflammatory joint pain (Radiosynovectomy)*:** Therapeutic RI labeled non-dispersible particulate formulations have been proposed for treatment of joint pain due to inflammatory processes (e.g. Rheumatoid arthritis, bleeding joints in patients of hemophilia). Depending upon the size of the joint, low or medium or high energy beta emitter RI formulations are in use. Since the late 1990s, BARC has developed and evaluated a number of products for this purpose, e.g. ^{166}Ho-labeled hydroxyapatite (HA) was used for large joints. Later, BRIT launched ^{32}P-labeled colloidal formulation of samarium phosphate for similar use. Currently, ^{90}Y obtained by direct irradiation of the mono-nuclidic ^{89}Y target is used for preparing ^{90}Y-HA for similar treatment of pain in large-joints. The product ^{90}Y-HA is supplied through BRIT. ^{177}Lu-labeled HA particulate formulations are similarly useful for medium and small joints and are made available by BARC/BRIT.

7. Technology and Other Core Capabilities Underpinning DAE's Radiopharmaceutical Program

The foregoing contributions of the various types of products and their indigenous availability would not have been a reality without the support of the large, competent teams of DAE Units and the variety of technology and other core capabilities that they could pool together as well as augment when needed (e.g. pharmacy and pharmacology expertise). It will be difficult to describe in detail all the underpinning strengths in the development and launch of the vast range of RI and radiopharmaceutical products covered in the previous sections. The following bullet points will give glimpses of the range and diversity of competences deployed/harnessed.

- Radioisotope production systems and facilities in nuclear reactor and cyclotron - targets, handling systems, cooling, radiological safety, etc.
- Radiochemical processing: Separation systems; Rapid synthesis/formulation & purification; Amenability to remote handling and automation.
- Chemical synthesis of ligands, precursors, other reagents including peptides.
- Radioanalytical, pharmacological & biochemical methods for evaluation (including animal studies) and QC tests for rapid certification.
- Automation of high-activity processes and production modules.

The multi-disciplinary expertise in BARC, BRIT, VECC and other Units of DAE have been the backbone for leveraging most of the above capabilities and allied competences. An additional initiative was launched in May 1999 (continued until 2019), in terms of identified senior professionals in the radiopharmaceuticals program being given concurrent roles and responsibilities in both BARC and BRIT (Adjunct Post holders), to strengthen synergies and deliverables.

An internal peer review scheme for the self-regulatory functions of DAE-produced radiopharmaceuticals, called the Radiopharmaceuticals Committee (RPC) of BARC/DAE, has been an important mechanism in place since 1968. This has helped in relevant experts' (including from non-DAE entities) reviewing and facilitating the transfer of the products from the laboratory stage to clinical use in patients, by taking care of the quality standards and ascertaining the product's safety and efficacy. The scientists of DAE Units have also been involved with the Indian Pharmacopoeia Commission (IPC) in getting many of the regularly used products incorporated in the Indian Pharmacopoeia (IP 2014 onwards).

8. Future perspectives: Keeping an Eye on the Horizon

Two major emerging areas in radiopharmaceutical are: MC-based product developments and targeted therapy of tumors. For the first, enriched targets of many elements are essential for RI production and for the latter, alpha emitter ^{225}Ac is an urgent and important need. In addition, increasing longevity of the population is leading to increasing number of patients burdened with neuro-disorders (and also cancer). The role of radiopharmaceuticals for management of patients of neurology is envisaged to be very high (especially PET tracers for neuro-receptor imaging as well as in aiding new drug development) and due attention in this direction will be a key future need. DAE is also advantageously placed (due to its multi-disciplinary ambience) to similarly leverage the on-going efforts for development of novel targeting molecules for imaging the cardiac plaques, amyloid, angiogenesis, etc. Based on objective identification along with clinical experts, DAE Units can contribute to development and launch of such products of clinical relevance.

Most enriched targets for RI production are based on electro-magnetic enrichment process (in calutrons). Such targets are invariably difficult to access or expensive to procure and building indigenous capability for enriched targets is much needed. The recently reported initiative of BARC to develop indigenous facility for this technology is very crucial to address future needs. The Heavy Water Board of DAE has set up a facility to produce oxygen-18 enriched water to be used as target for ^{18}F production. When fully established, this will be a much-needed addition to serve the MC facilities in India as well as for exploring exports.

The importance of high-LET based alpha radiation for targeted tumor therapy has been known since long, while the recent success of ^{225}Ac in treating one type of prostate cancer patients, and the earlier initial success in the use of ^{223}Ra for treating bone metastases, have led to growing interest in alpha therapy. Projects with huge investments are underway in some countries in building up large-scale production capacity for ^{225}Ac. DAE/BARC is uniquely placed with its all-round expertise in handling alpha emitters. DAE Units may choose any of the three methods of production of ^{225}Ac and position itself to serve the NM users in India with ^{225}Ac and/or other similar alpha emitters of potential high utility.

Towards sustaining the DAE Units' crucial role in supporting the availability of indigenous RI and radiopharmaceutical products for NM practices, it is necessary to consider further strengthening *cum* expanding the larger infrastructure required. This will be by way of planning for an additional reactor, dedicated to RI production (likely to be met by the proposed new research reactor under Public-Private-Partnership mode), and a high-current (proton) cyclotron of 60-70 MeV. With 350+ NM centers in operation and continuing overall growth in medical facilities in India, the additions proposed are vital for meeting the future needs of NM practices and sustaining affordable clinical benefits to patients.

9. Concluding remarks

The development and utilization of radiopharmaceuticals for nuclear medicine practices have gone through a series of 'continual change for the better' over the past five to six decades. Thanks to the multi-disciplinary teams of the DAE Units, BARC and BRIT in particular, and strong support of the Units' leaders for sustained pursuits - both R&D and production-supply services, availability of most radiopharmaceutical products has been ensured for NM practices in India, and in turn, leading to nearly half a million procedures performed every year for the benefit of patients. There are over 350 NM centers (85+ % in private sector), 250+ SPECT-gamma cameras, 24 MC, more than 280 PET/CT units, and 3 PET/MR units in India. Almost all the NM centers depend on BARC-BRIT for most of the reactor-based RI and radiopharmaceutical products. In addition, there is further scope, as well as need, for BARC and BRIT to plan and address some of the emerging needs of products for NM applications, e.g. alpha emitter radioisotopes, as well as augmentation of infrastructure for RI production. As India is celebrating its 75^{th} year of independence - *Azadi Ka Amrit Mahotsav* - it is highly appropriate to recall the past creditable achievements and record them, being worthy of special mention, and also serve as motivation for the current leaders and professionals in the field to continue to strive for sustainable delivery of products and services for patient benefits in future.

Bibliography

1. Fifty Years of R&D at RLG Laboratories, BARC, November, 2017
2. N. Ramamoorthy, Expanding Impact of Radiopharmaceuticals on Health Care Delivery, NUCAR-2019 Souvenir, BARC-BRNS (Jan. 2019).
3. N. Ramamoorthy, Radioisotopes in Human Healthcare: Role and Contributions of DAE-BARC. NSD-2020 Souvenir, BARC (Feb, 2020).
4. Tapas Das. Evolution and Present Day Status of Radiopharmaceuticals Program at DAE. In: Non-Power Applications of Nuclear Technologies (Edited by Dr. A. K. Mohanty and Dr. A. K. Tyagi). BARC Publication, Mumbai, India. ISBN: 978-81-954733-2-8.
5. A Decade of Operation of the BARC Medical Cyclotron Facility, RMC, BARC (Oct. 2012).
6. M. G. R. Rajan, S. Nandy, N. Lakshminarayanan, B. K. Sharma, A. Mitra, A. Kumar, S. Nayak, K. Kushwaha, G. Arjun, R. Chinagandham, N. Yuvraj. BARC Medical Cyclotron Facility: Performance and Achievements in the First Decade after Commissioning. BARC NewsLetter, Issue No. 329, Nov-Dec, 2012, pp. 41-47.
7. Positron Emission Tomography: Products and Applications (Guest Edited by Dr. N. Ramamoorthy and Dr. M. G. R. Rajan). IANCAS Bulletin, Vol: XII, (2014).
8. A. M. Samuel. Growth of Nuclear Medicine in India. Defence Science Journal, Vol: 40 (1990) pp. 335-346.
9. Radiopharmaceutical Programme: Progress Report for the Decade 1989 - 1998, BRIT (March 1999)
10. Two Decades of BRIT, Special issue of Inside BRIT, BRIT (March 2009)
11. Annual Reports of BARC, BRIT and DAE - www.barc.gov.in; www.britatom.gov.in; www.dae.gov.in

Industrial Applications of Radiation Technology and Radioisotopes

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Preamble

'Isotopes' of an element are the atoms of the same element but with different number of neutrons in their nuclei. Though, the number of protons remain identical, the different neutron numbers in their nuclei affect the nuclear properties. Due to different combinations of neutrons and protons, some of the isotopes possess unstable nuclei. Usually, upto mass number 40, it is observed that proton/neutron (N/P) ratio remains as 1, and then slowly starts increasing. With increase in mass number, Coulombic repulsion due to protons increases and this leads to destabilization. Uranium is the last naturally occurring element and beyond A=209, there is no stable nuclide. Some isotopes have been artificially produced, either by bombarding the atoms with neutrons in a nuclear reactor, or with charged particles in an accelerator. Instability of a nuclide results in radioactive decay, also known as disintegration, (within the nuclei), and attain stability, resulting in the emission of particles and electromagnetic radiation, and hence they are named radioisotopes.

Radiations that are emitted by different radioisotopes can be used in a range of measurement systems for various applications, such as agriculture, cancer treatment, medical diagnosis, sterilization of medical products, radiation processing of spices, onion, etc., quality control in industries, non-destructive testing and processing of polymeric materials. The constant pursuit for new technologies in the atomic era has contributed meaningfully towards the economic as well as societal benefits. India is among the very few early entrant nations in the world in the field of atomic sciences, possessing advanced facilities and knowledge for the production of a range of radioisotopes, radioisotopes-based medical and engineering products & associated equipment for value addition. This was due to the great visionary, Dr. Homi Jehangir Bhabha. Board of Radiation & Isotope Technology (BRIT) is the industrial unit of the Department of Atomic Energy (DAE) and is focused on bringing the benefits of the use of radioisotopes and radiation technology across the industry, healthcare, research and agricultural sectors of the society and serve the nation.

Introduction

The search of new tools and developing new techniques has been the reason behind advancement of mankind. Discoveries, such as radioactivity and X-rays were new tools for applications in industry. The first controlled nuclear fission chain reaction had been demonstrated by Enrico Fermi on December 02, 1942. This can be considered as the beginning of using the nuclear fission reaction to produce energy in a nuclear reactor. As a spinoff of the nuclear reactors, commercial use of radioisotopes became viable by enabling production of artificial radioisotopes.

The last few decades have witnessed use of radiation technology for peaceful development and social benefits. Radioisotopes and radiation technologies support most nuclear applications and contribute in many ways to healthcare, food safety and industrial development worldwide. Radioisotopes and radiation technologies also provide economically viable strategies for sterilization of medical products, cancer treatment, disease diagnosis therapy, waste-water treatment, gamma scanning for industrial radiography and tomography, tracer techniques, food preservation, development of high-yielding crop seeds and other similar areas.

The programme of the Department of Atomic Energy, right from the early stage, gave a lot of importance to this aspect and, as a result of that, significant advancement has taken place in the areas of radioisotope applications and radiation technology in the fields of medicine, industry, agriculture and research. The pioneering R&D work in BARC has helped to attain a high degree of self-reliance in the development of a variety of radioisotope related products and services, which has laid a firm foundation for utilization of radioisotope techniques and radiation technology in the country. In order to focus this activity in a more concrete way and for commercial utilization of some of the results of R&D, the Board of Radiation & Isotope Technology (BRIT) was engraved out of Bhabha Atomic Research Centre, as an independent industrial constituent unit of Department of Atomic Energy, on March 01, 1989.

In this chapter, an attempt is made to highlight the sources of radioisotopes and some of the important industrial applications of radioisotopes, including the infrastructures built at BRIT, over three and half decades, to cater to the customers with the related products, services and equipment.

Production Sources of Radioisotopes

Nuclear reactors are the primary source for large-scale production of neutron-rich radioisotopes by utilizing available excess neutrons produced during nuclear fission reaction. Few important neutron-rich radioisotopes are separated from fission products obtained from the spent fuel. Proton rich radioisotopes are produced by using particle accelerators. Cyclotrons are used in several countries, including India, for production of certain medical radioisotopes, e.g., ^{201}Tl, ^{18}F, ^{67}Ga, ^{68}Ge, etc.

In India, radiation and isotope programme took a concrete shape after the commissioning of APSARA reactor at Trombay in August 1956, under the Isotope Programme of BARC. The availability of APSARA reactor made India one of the very few countries at that time to produce radioisotopes locally, as well as nurture the development of their applications. The programme expanded in volume, when in 1963, the CIRUS reactor attained its rated capacity of 40 MWt, augmenting the production capability. The field of radiation technology was also rapidly growing through 1970's and BARC kept pace with most of the relevant developments in radiochemical, radiation sources, radiation processing using gamma sources, radiography cameras, radiopharmaceuticals, etc. A major increase in the production capacity of radioisotopes was observed when the 100 MWt reactor, Dhruva, had attained criticality in 1985. Dhruva is one of the large research reactors in the world and caters to the production of a wide spectrum of radioisotopes for use in medicine, industry, agriculture and research. All these reactors are located at Bhabha Atomic Research Centre (BARC), Trombay, and have ably supported the domestic production capabilities for radioisotope-based products and associated technologies and services to end-users. APSARA (U) launch, in recent years, is another supplementary source. Cobalt-60, an isotope that is used for several industrial and medical applications, including radiation processing, is produced in the power reactors operated by Nuclear Power Corporation of India Ltd. (NPCIL) and recovery *cum* processing facility (RAPPCOF) of BRIT is located at RAPS, Rawatbhata, Rajasthan. DAE/BRIT, India, is one of the very few sources in the world having the large-scale 60Co production – supply capacity and technology capabilities.

The facilities, need to be well-equipped with hot-cells for handling and processing large quantities of radioactivity. BRIT operates processing facilities for radioisotopes. The hot-cell facilities at the Radiological laboratories and at the High Intensity Radiation Utilization Project (HIRUP) were established at BARC, Trombay, during 1973-74; and at the Rajasthan Atomic Power Plant Cobalt-60 Facility at Kota, Rajasthan (RAPPCOF) in the year 1975. The facility at RAPPCOF is augmented with the growing demand for the radioisotopes. These are used for processing the irradiated Cobalt-60 (from the Nuclear Power Plant) and for fabrication of the radiation sources. These processing facilities are as per the designs approved by regulatory agencies. Recently, ^{137}Cs radioisotope has also become commercially available, after successfully processing the spent fuel, isolating it from other fission products and formulating a safe glass vitrification technique.

Production of radioisotopes is challenging in terms of preparing them with the appropriate specific activity and radionuclidie purity, while conforming to the specifications, for varied applications for which they are used. For example, the low specific activity (~60 Ci/g) Cobalt-60 would suffice for radiation processing applications, whereas very high specific activity (>250 Ci/g), is needed for teletherapy applications. In order to achieve high specific activity radionuclides, the irradiation conditions need to be appropriately adjusted, e.g., high flux reactors, irradiation position in suitable reactors, etc.

Ionizing Radiation, Radioisotope Sources and Radiation Technology for Industry

Ionising radiation are defined as radiation with adequate energy which can ionise/excite atoms in the interacting matter. This includes both electromagnetic radiation such as γ-rays and X-rays, and energetic particles such as α- and β-particles, and neutrons, which although may not be directly ionising, but are capable to produce secondary ionising radiation. Ionising radiation is often named after the origin of the radiation. *Nuclear radiation* may be defined as the radiation emitted by an unstable nucleus in an element, *a radioisotope*, which disintegrates to become stable.

The use of radioisotopes and radiation technology in industrial applications spans over a wide range. There are three different basic modes of applications of radioisotopes, based on the varied properties of radiation. The first category depends on the fact that the radiation affects the material, as in the case of radiation processing (Physical or chemical changes are induced in the target material by deposition of radiation energy). This property is used in radiation therapy of cancer, sterilization of medical products, food irradiation and in cross-linking of polymers. Second category is the applications of radioisotopes which utilizes the effects of radiation on materials leading to assessment of qualitative and quantitative properties of materials, as in the case of non-destructive testing, which is based on attenuation of radiation (mainly due to its absorption and scattering. The extent of attenuation depends on the composition and geometry of the object as well as energy and type of radiation). It ensures good quality industrial products, while bringing down the cost of manufacture. A third category of applications is in industrial, hydrological or biological systems, which is based on the tracer principle. and is known as radiotracer applications (Ease of detection of radioisotopes in extremely small quantities makes them useful as tracers for investigation of biological, industrial and environmental processes). Keeping in mind the ALARA (As Low As Reasonably Achievable) principle, which basically involves a risk-benefit analysis to achieve low radiation dose level, for the particular application, the following radiation source properties could be considered:

(a) Category or physical form
(b) Radiation type
(c) Energy and spectral purity
(d) Intensity
(e) Half-life
(f) Chemical form and compatibility with process stream (tracers)
(g) Availability, classification and cost

Radioisotope source may be used as sealed source, where the radioisotope remains permanently within an encapsulated form and makes no direct contact with the process material, and/or as open source, where it is not encapsulated and is used for various applications in industry and healthcare.

Industrial Applications of Sealed Sources

Radioactive sealed sources have been used for several years for a wide range of applications in a variety of shapes, sizes and radioactivity levels. In Industry, they are widely used for non-destructive testing (NDT), radiation processing, 'on-line' process control systems, 'on-line' elemental analysis, smoke detection, etc. In medicine, they are commonly used in teletherapy and brachytherapy for the treatment of malignant diseases, and for bone density measurements.

In research, a variety of sources are used, for different applications most commonly, for elemental analysis (i.e., X-ray and neutron activation analysis) and material structure studies. Radionuclides commonly used for industrial sealed sources are ^{60}Co, ^{63}Ni, ^{90}Sr, ^{137}Cs, ^{147}Pm, ^{169}Yb, ^{170}Tm, ^{192}Ir, ^{241}Am and others. The demand and scale of industrial applications of sealed sources, such as ^{60}Co seems to be the highest, whereas, the demand for ^{137}Cs is mainly for its use in blood irradiators and hence stable, and the need for ^{192}Ir sealed source is expected to increase in the coming years.

Sealed source assembly are radioactive materials that are encapsulated, usually in stainless steel capsules or pencils, and makes no physical contact directly, either with the plant or the process material. These sealed sources emit ionizing radiation only through the capsule wall which is directed at object, and by analyzing the modified radiation pattern, either in transmitted or in scattered beam, it is possible to draw conclusions about the internals of the test sample. For high energy γ-emitters, such as ^{137}Cs, ^{192}Ir and ^{60}Co, the capsule can be usually made using appropriately thick stainless steel, as the γ-radiation can still exit the capsule without significant absorption. Radionuclide based instruments or equipment, such as radiography cameras, gamma chamber and blood irradiators, have been extensively used in industry. Radiation technology equipment based on ionizing radiation emitting radionuclides offer following advantages:

- Radiation being penetrating, the measurements are made without direct physical contact of the source with the material being measured
- On-line, non-destructive measurements can be done on moving material
- The source is stable and little maintenance is required
- Substantial cost-saving

For industrial use, various sealed radiation sources supplied by BRIT:

- **Iridium-192:** ^{192}Ir, [Chemical form: Ir, half-life: 74.3 days γ/MeV – 0.31; 0.47 & 0.60 and main Eβ/MeV 0.54; 0.67], is a useful radioisotope for use in radiography techniques, mainly for the examination of a variety of industrial products. BRIT uses high specific activity ^{192}Ir for radiography cameras as most of the radiography cameras have the capacity of loading upto 120-150 Ci.
- **Cobalt-60:** Highly penetrating gamma rays from radioactive ^{60}Co source [Chemical form: Co, half-life: 5.27 years, Eγ/MeV – 1.33 and 1.17 and main Eβ/MeV 0.31], is another important radioisotope for gamma radiography for non-destructive examination in industries. The radioisotope in sealed source form (with varied specific activities) is also useful for low-dose laboratory irradiators, nucleonic gauges, radiation processing plants for irradiation of food and medical products, and teletherapy machines.
- **Cesium-137:** [Chemical form: CsCl, half-life: 30 years, Eγ/MeV – 0.66; and main Eβ/MeV - 0.51], obtained from the high level liquid waste (HLLW) obtained after reprocessing of spent nuclear fuel and vitrified in glass pencils (at BARC). The vitrified glass pencils are encapsulated inside the SS tubes and welded from both sides to form ^{137}Cs sealed sources which are successfully used in low-dose application for blood irradiators supplied by BRIT.

A. Radioisotopes (as Sealed Sources) in Non-Destructive Testing (NDT)

I. Industrial Gamma Radiography

Use of isotope radiography for NDT implies that the technique is to be used for detecting, locating, characterising and sizing of defects in industrial systems. Such equipment is designed and fabricated to meet the requirement of relevant industry codes and standards. The discovery of the ability of radiation to penetrate matter and form images on photographic plates, opened up great potential in both medical as well as industrial fields worldwide. Industrial radiography for non-destructive testing of welds, castings, pipelines and components, has grown into a major activity during the years.

Utilisation of radioisotopes for industrial application was one of the early verticals in the Indian nuclear programme. Use of radiography technique for testing of flaws in welds and castings had been started in India, way back in 1957, during the construction of the CIRUS reactor. Radiography uses the radiation attenuation principle and estimation of transmitted radiation to detect flaws in the material. With the establishment of many high-flux nuclear reactors, a variety of isotopes are now available. Most commonly used sealed sources for radiography are ^{192}Ir and ^{60}Co. However, depending on the requirements, radioisotopes such as ^{137}Cs and ^{241}Am may be used. Linear accelerators and betatrons, which are capable of providing high energy and high intensity X-ray beams are also used for inspecting thick materials (upto 500 mm steel equivalent) in short exposure times. Advantages of use of isotope sources for radiography testing over X-ray machines, are the ease of portability, no requirement of electric power on site and the possibility of use of tiny isotope sources, in otherwise, inaccessible areas of industrial system.

The importance of the technology was realized and its indigenous development was started. Fabrication of radiography sources was initiated only after the successful production of Ir-192 and 60Co radioisotopes, first in APSARA reactor, and subsequently, on a larger scale in CIRUS reactor. Parallelly, radiography cameras using Ir-192 (most common) and 60Co (for high density, thick objects) were developed in 1960s and made available to the industry. A lot of evolution has taken place in this field since then and the first indigenous remotely operated camera model, ROLI-1, has become the workhorse for industry. These cameras cover an inspection range of 10 to 70 mm of steel. As the use of this technology grew, it was ensured that the cameras also kept

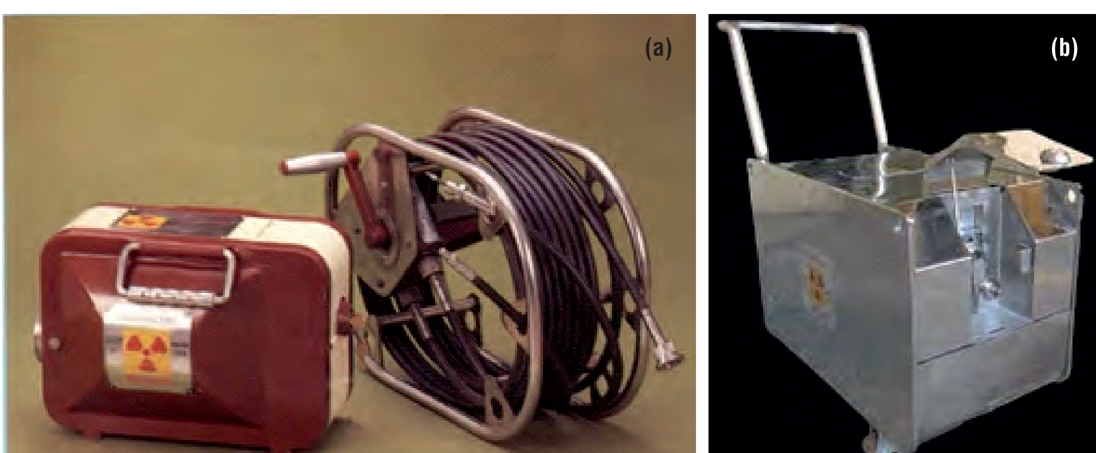

Fig. 1: Radiography devices supplied by BRIT: (a) ROLI-2 and (b) COCAM-120

improving. Launch of improved versions and completely indigenous gamma radiography exposure cameras, ROLI-2, with higher capacity, and more recently during 2021, the launch of COCAM-120, with Cobalt-60 sources, hence, improving the inspection range to 40 to 200 mm has brought BRIT to newer heights for its service to industries. Various types of radiography cameras supplied by BRIT are shown in Table 1. The supply of radiation sources for these cameras as well the imported cameras has also been maintained to the satisfaction of industry. It must be noted that radiography is the most preferred technique for non-destructive testing of all welded joints and castings. Use of 2500 radiography cameras in India demonstrates its use for quality control parameter to every conceivable industry. DAE is in the forefront for the development of radiography cameras for Non-Destructive Testing (NDT).

Table1: Details of Radiography Cameras offered by BRIT

Specification	ROLI-2	ROLI-3	COCAM-120
Isotope	Iridium - 192	Iridium - 192	Cobalt-60
Half life	74 days	74 days	5.27 years
Maximum capacity	2.4 TBq. (65 Curies)	0.74 TBq. (20 Curies)	4.4 TBq. (120 Curies)
Inspection range	10 mm to 70 mm steel or equivalent	10 mm to 25 mm steel or equivalent	40 mm to 200 mm steel or equivalent
Shielding material	Lead & heavy alloy	Lead & heavy alloy	Lead, heavy alloy& depleted Uranium
Camera operation	Remotely operated (Teleflex cable drive)	Remotely operated (Teleflex cable drive)	Remotely operated (Teleflex cable drive)
Maximum operating distance	8 meters from the camera	8 meters from the camera	14 meters from the camera
Front guide tubes (2 Nos.)	3 meters and 1 meter long (one each)	3 meters and 1 meter long (one each)	3 meters long
Overall dimensions	375 mm long, 250 mm wide, and 275 mm height	530 mm long, 370 mm wide, and 181 mm height	375 mm long, 250 mm wide, and 275 mm height
Package	Type B (U)	Type A	Type B (U)
Weight	38 kg (approx.)	25 kg (approx.)	316 kg (approx.)

Recently launched COCAM-120, the Cobalt-based camera with hybrid shielding, has become a boon for the heavy engineering industry where welding of large thick plates is frequently used. Servicing, maintenance and source replenishment of these cameras is also carried out by BRIT, on a regular basis.

At present, ^{192}Ir and ^{60}Co radiography sources are fabricated in the RLG hot cells of BRIT inside the BARC campus. The present demand is 1200 sources/y. The growth in demand for radiography sources has a high correlation to the growth rate in infrastructural industry and a steady demand is expected over the next 25 years.

II. Industrial Computed Tomography (ICT)

Taking cue from medical tomography, such as, magnetic resonance imaging (MRI) and ultrasound, a similar technique has been developed for non-destructive testing of engineering and industrial specimens. An experimental prototype computer tomographic system (CITIS) had been set up at Isotope Division, BARC, using a 7 Ci (260 GBq) source of ^{137}Cs and a NaI (Tl) scintillation detector. This system provided a unique cross-sectional image of the internal structure of test objects. The method involves collection of transmission data of the penetrating radiation through an object at different planes and subsequent reconstruction of a 3-D image using the two-dimensional planar profiles of the effective linear attenuation coefficients at designated points. The computed tomography imaging system consists of a gamma ray sealed source, a collimated detector assembly, a precisely controlled mechanical manipulator and a data acquisition system along with a PC. This prototype unit is capable of scanning specimens of small diameters (upto 100 mm) and of varying densities. The system has been upgraded with an X-ray source and an array of cadmium tungstate detectors. Industrial Computed Tomography system is expected to be useful for NDT of a number of precision components for cross-sectional examination (3-Dimensional) of various objects like reactor fuel assemblies and solid propellants in rocket motors. Computed tomography using neutron source is gaining importance for material characterization. Unlike X-rays and gamma rays, neutron attenuation is generally higher for low atomic number elements and vice versa. This property makes neutron CT inspection more advantageous in certain cases where conventional X- or gamma ray techniques have limitations.

Industrial Electron Linac: Electron accelerators from 500 keV to 10 MeV energy are employed for surface irradiation, food preservation, medical sterilization, cargo scanning and other industrial products. BARC has indigenously developed cargo scanners for inspecting and identifying goods in transportation systems by employing high power electron beam accelerators. Cargo scanners are required at different locations in the country for checking incoming and outgoing cargo. Because high energy X-rays are required to penetrate the cargo, an electron linear accelerator is used as the X-ray source. Linac-based cargo-scanning systems have three main components – the X-ray source, the detector array and the conveyor. In these systems, the accelerated electron beam is made incident on a tungsten/tantalum target to produce X rays, which are then used for scanning purpose. A 9 MeV linac cargo-scanning system has been set up at ECIL, Hyderabad, and a 6 MeV compact linac cargo scanner has been set up at Trombay, Mumbai. BARC has also demonstrated the use of electron beam irradiator for waste water treatment by DC accelerator and medical sterilization/food irradiation using electron beam LINAC.

III. Gamma-Ray Scanning

Distillation columns, extraction, stripper and related systems are critical components in petroleum refineries, gas processing installations and chemical plants. Malfunctioning of any of these industrial columns can lead to fire hazards and atmospheric pollution, in addition to resulting in huge revenue losses. Many problems can develop during the operational life of these systems, which may lead to mechanical damage to their internals, or problem may arise in the process itself. In conventional trouble shooting tests, it will be essential to shut down the plant before any inspection is undertaken, which will add on to production losses.

For process diagnostics of distillation columns, interface measurements are frequently carried out by γ-ray scanning. Gamma-ray scanning, using a radiation sealed source, is a non-disruptive and on-line inspection technique, which is used to diagnose process malfunctions or assessment of internal damage within industrial distillation process columns in petroleum refineries and chemical plants.

In practice, a collimated sealed radioactive source and detector are positioned in the horizontal plane, either across the diameter (in tray type column) or across the different equi-length chords (in packed bed columns). Both, the source and detector are then moved synchronously along the length of the column and radiation intensity is recorded at desired elevations. Analysis of the data with reference to the internal loading and hardware configuration of the columns gives valuable information about the column. 'Signature scans' obtained at normal working or at pre-commissioning trials could be used for comparison and to derive useful information of the internal configuration of the column.

Gamma scanning technique is rapid, versatile, accurate and have wide applications in trouble shooting, debottlenecking, predictive maintenance and for design optimization of industrial columns.

In India, gamma scanning technique was initiated in 1995, under MoU with the Engineers India Ltd [EIL]. Isotope Application Services (IAS) was started by BRIT in the Year 2007 on commercial basis. Presently, IAS, BRIT, offers required gamma scanning services to industries for on-line troubleshooting and process optimization of industrial process columns. Over 180 columns of different types including tray and packed beds upto 10 m diameters have been investigated, resulting in savings of several hundred crore of rupees to Indian industry. About 30 major petroleum, petrochemical and chemical process industries have benefitted from the gamma scanning technology.

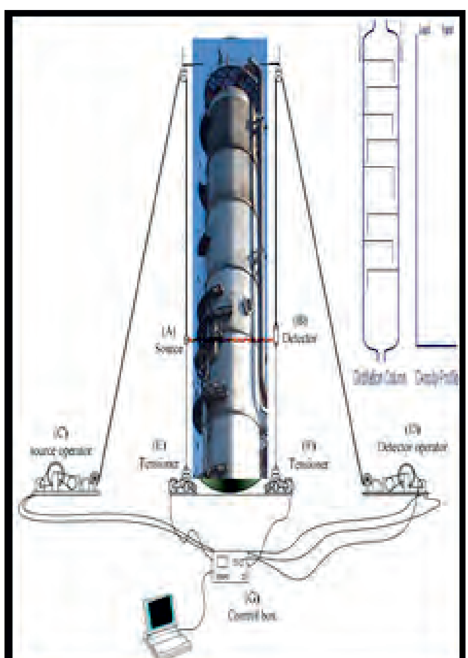

Fig. 2: Gamma-ray scanning process

IV. Nucleonic Control Gauges

Chemical industries, refineries, oil platforms, mining and mineral industries make extensive use of sealed source radioisotope-based gauges and have found radiometric density and liquid level gauges applicable to solve many of their problems. These gauges are based on the principle that radiation transmission through or scattering from a material as a function of its properties, i.e., when γ-rays travel through matter they are attenuated to an extent that depends upon the density and composition of the matter and the distance the rays travel in it. During the manufacturing process, it is possible to measure and monitor thickness of sheet materials, such as films and sheets of metals and plastics, by proper selection of γ-rays of the correct energy. Radioisotope-based gauges, such as thickness gauges, level gauges, density gauges and moisture gauges are put in for practical purposes such as monitoring during the manufacture process, quality control checks and inspection. These gauges can improve process efficiency, assume an important role in quality control and thus yield large savings through avoidance of several types of losses during production.

The level of liquids in closed or large tanks can be conveniently measured and controlled using radioisotope gauges kept external to the tanks. Basically, a γ-ray sealed source (such as ^{60}Co or ^{137}Cs) and a miniature radiation detector are inserted simultaneously down adjacent tubes in the bundle, and the radiation transmitted through the tube walls is recorded. When carrying out this procedure for each pair of tubes, a comprehensive picture of the position and degree of the corrosion over the entire bundle can be recorded. The technique has an advantage of being rapid compared with other inspection methods and is capable of high accuracy. The scanning of heat exchanger bundles, performed using radioisotope gauge, is often incorporated into many plant shutdowns, so that the extent of corrosion can be observed.

Chemical companies use radioactive density gauges for routine, continuous measurements process materials such as hot brine, sulfuric acid, milk of lime and organic compounds. In most of these instances, the reasons for installing a radioactive density gauge have been that it is more precise, accurate, less time consuming, less susceptible to human error, or much safer than the conventional methods. Density gauges have also been used effectively in aiding the control of certain processes, such as, during polymerization of butadiene and styrene, it is important to know the density of the product in order to measure the degree of polymerization. Density gauges, in such cases, would provide the direct means of controlling the process.

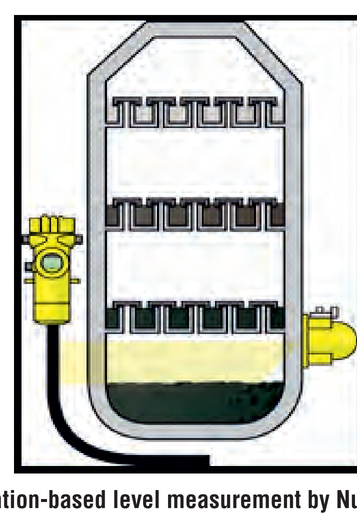

Fig. 3: Radiation-based level measurement by Nucleonic Gauge

Similarly, radioactive density gauges have been used by the rubber industry to measure and control the density of foamed latex. Typical products gauged include rubber-coated tyre fabric, rubber floor covering, pressure-sensitive rubber adhesive tape and rubber sheeting. In these cases, the radioactive thickness gauge has replaced magnetic capacitance, radio-frequency, and air-operated gauges. The advantages are those common to most radioactive thickness gauge applications including closer tolerances, continuous operation, being independent of operating temperature and humidity, as well as independent of composition and hardness of the product. Rubber companies using such gauges have reported savings attributable to more efficient use of materials, less scrap production and reduced labor requirements.

B. Radioisotopes (as Sealed Irradiator Sources) for Radiation Processing

Some of the most promising areas for application of sealed radioactive sources are sterilization of medical products, food preservation, hygeinization of sewage sludge, etc. Radiation processing essentially is an application based on the principle of radiation chemistry. High-energy ionizing radiations have unique ability to produce reactive, short-lived ionic and free radical species at any temperature and in any phase – solid, liquid or gas, in a variety of material. These reactive species induce many chemical reactions. This property of ionizing radiation has been beneficially used for various industrial processes such as modifying the polymerization processes. The ability of radiation to destroy micro organisms by reacting with DNA molecules of growing cells is effectively harnessed for several radiation processing applications, such as, sterilization of medical products, disinfestation of food and food products and treatment of sewage sludge.

Radiation processing involves controlled application of energy from ionizing radiations. This can be either radioisotope based or particle accelerator-based. Gamma rays and X-rays are radiations with short wavelength of the electromagnetic spectrum. Gamma rays are emitted by radioisotopes such as cobalt-60 and caesium-137, while electrons and X-rays are generated by machines using electricity. Gamma rays can penetrate deep into food materials and bring about desired effects.

Table 2: Sources (with their energy) used for radiation processing.

Source	Type of radiation	Energy (MeV)
Cobalt -60	Gamma rays	1.17 and 1.33
Cesium -137	Gamma rays	0.66
Electron beam	Electron s	Up to 10 MeV
X-rays	X-rays	Up to 5 MeV

I. Radiation Sterilization of Medical Products and Food Irradiation

Sterilization of medical products by ionising radiation is an economically viable alternative to conventional sterilization methods, such as, dry/wet heat or treatment with ethylene oxide (EtO). Unlike the conventional heat energy, which is mainly deposited in the translational, rotational and vibrational modes of the absorbing molecules, these high-energy radiations mainly interact with the orbital electrons and excites absorbing molecules to higher excited states, which results in formation of highly reactive ions or radicals. EtO is also a surface sterilant, and, is not effective for killing entrapped or deep-seated micro organisms. Products sterilized by this method will also contain residual EtO and its reaction products. The major advantage of radiation sterilization, mainly using Cobalt-60 (~1 MCi capacity), is that heat resistant and bulky materials can also be effectively sterilised by the penetrating radiation. This technique is mainly a cold process. It is used for disposable medical devices made from heat-sensitive plastics. A dose of 25 kGy is delivered to the products to be sterilized in sealed packages to achieve sterilization. The gamma rays penetrate through these sealed packages and destroy micro-organisms.

The ISOMED plant at Trombay, set up in 1974, under a UNDP project, for sterilization of medical products, gave a very early lead to BARC (and BRIT) in building expertise in operations of gamma radiation plants. This facility houses 1 MCi ^{60}Co source, and which over the years, has gained tremendous popularity and acceptance in society, mainly due to its simplicity and reliability. It has provided ample services to Indian pharma industry (large corporates, small and medium companies, entrepreneurs and researchers) and been the forerunner to a few other plants, which came up subsequently in Delhi (Shriram Institute of Industrial Research, still in operation) and Bangalore (adjoining a cancer hospital - KMIO); now decommissioned.

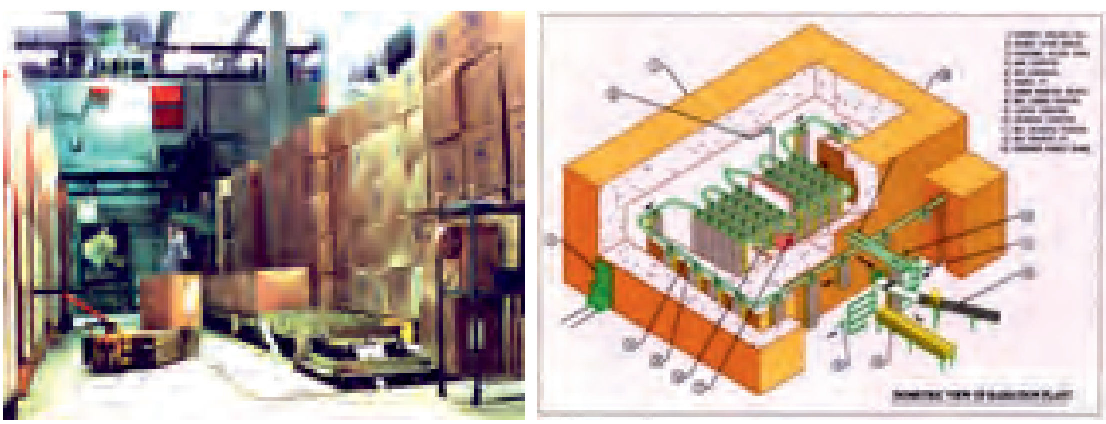

Fig. 4: ISOMED Facility (BRIT) for Sterilization of Medical Products

The first approval for radiation treatment of food products was accorded in 1994, by the Government of India. DAE has since then set up two industrial scale technology demonstration irradiation plants. One gamma radiation plant indigenously designed and built by BRIT in the Year 2000 (1 MCi ^{60}Co capacity) is in commercial use since its inception at Vashi Complex for radiation disinfestation of spices and several other food-products (30 ton per day) requiring medium to high radiation doses (upto 14 kGy). Similarly, another demonstration of gamma irradiation plant for applying low dose irradiation (capacity 10 ton per hour), to prevent sprouting in onions (and potatoes), was also indigenously built and commissioned by BARC in Lasalgaon, near Nashik, in the Year 2002. This plant was upgraded for processing of mangoes for export to USA in 2007. Ever since then, it is being used for phytosanitary treatment of (Alphonso) mangoes.

Fig. 5: Radiation Processing Plant (RPP) at BRIT, Vashi Complex

Utilising the technological support rendered by DAE, through BRIT, there are over 26 gamma radiation-based food processing units (0.5 to 1 MCi capacity) operating in private sector (in most cases handling both food and medical products). Another 7 units are under construction. DAE Units' developed indigenous plant designs and technologies developed by DAE units are being made available on technology transfer (low cost, non-exclusive) basis. Life-time supplies of ^{60}Co sources for these plants are envisaged to be made available by BRIT.

Electron accelerators, also called electron beam (EB) machines, form the alternate technology to gamma plants for radiation processing technology. They can provide variable energy from a few 100 keV up to 10 MeV and also variable dose rate to exactly match the requirement of product(s) to be (radiation) treated. Use in both electron mode and X-ray mode is possible, the latter involving high-Z target system (e.g., Ta) to enable availing of Bremsstrahlung radiation (continuous energy X-rays) and help overcoming penetration limitation of electron radiation. All EB system require stable and reliable high-quality electrical power supply. They do not have limitation of source strength aspect of radioisotope (c.a., ^{60}Co) or issues of high-intensity RI source movement/transport.

RRCAT of DAE has an active programme related to indigenous EB system development and utilization. A system has been installed in Indore agro-market area, which is the first large-capacity indigenous electron accelerator-based radiation processing facility for food and agro-products.

Presently, irradiation sources are being supplied by BRIT for industrial and laboratory irradiators. ^{59}Co is loaded in nine 220 MWe reactors of NPCIL. It is proposed to load ^{59}Co in the 700 MWe reactors as well. Another facility is being set up at Kota for the handling of absorber rods of 700 MWe reactors. The activity generated is sufficient for present and future requirements.

The facilities available are one pool, two hot cells for recovery of ^{60}Co and two hot cells for fabrication at RAPPCOF, Kota. Another facility at HIRUP, BARC is being used for the fabrication of sealed sources. A new hot cell facility is started, namely, IFRT at BRIT for carrying out these jobs.

II. Sludge Hygeinization

Water-borne community wastes, which are composed of drain water, and consists of human waste discharged from domestic premises, industrial wastes, etc. is cumulatively known the sewage sludge wastewater. It is composed of nearly 99.9% water and 0.1% pollutants, by weight. Even if the wastewater contains only a very small part of pollutants, these may endanger public health as well as the environment. Many disease-causing pathogens in sewage sludges, such as, viruses (e.g., polio virus), parasites (worm eggs, e.g., taenia), and bacteria (e.g., salmonellas), in addition to organic and inorganic matter can enter from almost anywhere in the community. These pathogens often originate from people and animals that are infected with, or, are carriers of a disease. For economic considerations, recycling of wastewater, which has high percentage of organic matter, nutrients and trace elements, stands important, but only after proper treatment. World over, many studies have proven effective utilization of ionizing radiation for environmental remediation, especially hygeinization of sewage sludge. Treatment of sludge is very important before being released for use as manure.

Radiation technology is a promising alternative, because it has high efficacy to inactivate pathogens; is effective to oxidize organic pollutants, eliminate odor, etc. This, in turn, will facilitate the down-stream process of sludge treatment and disposal. Radiation dose of ~ 8-10 kGy is found to reduce the pathogen concentration in dry sewage sludge. Gamma rays penetrate well in water and sludges; the half value thickness of the gamma rays of ^{60}Co (1.3 MeV) is about 28 cm in water and not less than 25 cm in normal liquid sludges. Penetration of gamma rays assures irradiation effect in the total quantity of sludge. ^{137}Cs (as CsCl) can also be used as gamma source for this purpose. Radiation energy of this source is 0.66 MeV, with a half value thickness of 24 cm in water. As CsCl is water-soluble, it is regarded as less safe in case of the source leakages or accidents. Thus, ^{137}Cs is not widely used as sealed radioactive source in gamma irradiation plants that require high activity. Use of radiation technology has shown advantages over conventional methods of aerobic and anaerobic digestion, which do not reduce the pathogen concentration to safe levels. Due to reduction of microbial load, the hygienized sludge can be inoculated along with the useful bacteria, to result in value-added biofertilizer. Both, ^{60}Co gamma sources and electron accelerators can be used for irradiation of sewage sludge. Gamma sources have better penetration allowing thicker layers of sludge to be irradiated, although they are less powerful and take longer irradiation time than electron sources. Sludge Hygeinization Research Irradiator (SHRI) Facility of DAE located at Baroda, Gujarat, uses ~150 kCi ^{60}Co source for treatment of sewage.

III. Treatment of Flue Gases

Municipal and industrial activities lead to environment degradation. Flue gas is the gas released to the atmosphere via a flue, which is a pipe or channel for conveying exhaust gases from a fireplace, oven, furnace, boiler or steam generator. High concentrations of pollutants like Sulphur dioxide, oxides of Nitrogen and particulate matter from the emission of flue gas, which is released from coal or oil-fired boilers in power stations and engineering industries, result in environment degradation. There are conventional and emerging techniques to remove toxic components from the gas effluents, i.e., chemical and radiation techniques. Among conventional methods, a combined technology of selective catalytic reduction of NO_x by Ammonia and neutralization of SO_2 by $Ca(OH)_2$ is most frequently used. Radiation techniques, using electron beam technology and/or gamma ray irradiation, generally using ^{60}Co, to convert the gaseous pollutants into useful fertilizer constituents like ammonium sulphate and ammonium nitrate, are also being used. Flue gas from a boiler is passed through a mechanical filter and saturated with water vapour before admission into an irradiation chamber. In presence of radiation and Ammonia, gascous oxides get converted to their salts. A radiation dose of ~ 10-20 kGy is required for this purpose.

C. Teletherapy Sources of ^{60}Co

Radioisotopes and radiation technology have provided tools for cancer treatment. Teletherapy involves use of radioactive material, such as ^{60}Co sealed source, for production of an external beam of gamma rays for treatment at a distance from the radioactive source (‘tele’, meaning “at a distance”). Cobalt teletherapy units are used for delivering strong dose of gamma radiation to the affected parts of the body. For tumour treatment by teletherapy, only the collimated beam of ionizing radiation emanating from the radioactive sealed source is directed towards the tumour, where the ^{60}Co source is placed in the shielded housing. The patient remains stationary, and the area of treatment is at the centre of the orbit of the source head, while the source head can be moved and fixed in any desired position. The radiation source commonly used is ^{60}Co, because of the desired nuclear characteristics, like, high specific activity, high radiation output per curie and long half-life.

Fig. 6: ^{60}Co Teletherapy Unit

BARC had taken up initiative to indigenously develop cobalt-based teletherapy systems, which resulted in the launch of 'Bhabhatron', in 2007. The technology was later transferred to a private company in Bangalore. Over 40 Units are in operation, in India and abroad. BRIT supplies cobalt teletherapy sources to a large number of Cancer hospitals in the country. In near future, BRIT is also going to launch, the indigenously made HDR Brachytherapy unit, 'KARKNIDHAN' with ^{192}Ir source.

Earlier teletherapy sources were fabricated and supplied to users in India using imported ^{60}Co. About 200 kCi teletherapy sources are now prepared using indigenous ^{60}Co, to meet average 12-15 replenishment source needs per year. At present 15-20 sources per year are supplied. Also, over the years, BRIT has obtained export orders of ^{60}Co.

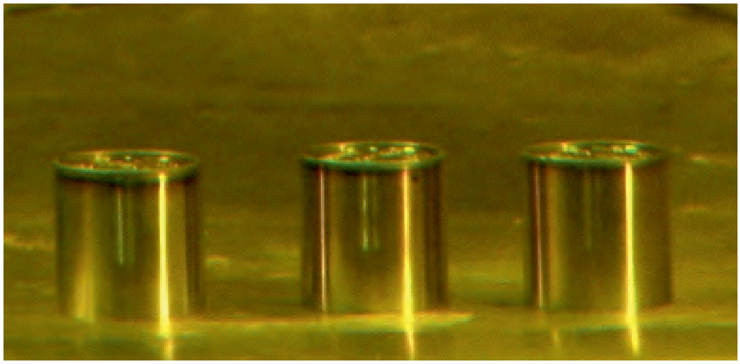

Fig. 7: ^{60}Co Sealed Sources (CTS) for Teletherapy Machines

Import of ^{60}Co teletherapy sources (CTS) is not required and BRIT supplies > 250 kCi high specific activity CTS, thanks to NPCIL's NPPs which are operating at consistently higher capacity factor. Also, storage capacity at RAPPCOF has been increased and BRIT can meet the growing demands.

D. Laboratory Research Irradiators& Blood Irradiators

The laboratory research Irradiator, called gamma chamber (GC), is one of the engineering equipments supplied by BRIT. It contains ^{60}Co source and an irradiation chamber of a few litres capacity. It has been instrumental in supporting radiation research studies including food preservation, phytosanitary support for trade or shelf-life extension, polymer/composite development, treating seeds for preparing crop mutants, etc. Since 1990s, BRIT has developed and supplied gamma chambers (e.g., GC-5000 of 14 kCi ^{60}Co, 5 L chamber volume) to facilitate such applications in India and abroad.

Fig. 8: Low Dose Irradiator

Low dose rate gamma chamber unit of ^{60}Co has also been used for blood irradiation (BI), for ensuring safety of transfusion to immuno-compromised patients. More recently BI units containing BARC-developed vitrified ^{137}Cs source have been developed and supplied. Use of ^{137}Cs (half-life: 30 y) obviates the need for source replenishment required in the case of ^{60}Co-based BI units.

E. Industrial Radiotracer Techniques

Minute quantities of radioactive substances can be precisely measured and this is exploited in collecting all the information about spatial and temporal distribution of the tracer in a system. Achieving high degree of specificity and sensitivity are two major factors common to most tracer applications. The radioactive material sent as a tracer can be "traced" by using radiation detection instruments, even though it may be chemically and physically identical with the other material in the process.

Because radioisotope tracers can be used *in-situ*, its capability for detection of blockages, leakages or seepage, estimation of mean residence time, residence time distribution, flow rate, mixing/blending time evaluation, etc., can be very useful to industries. Mechanism and kinetics of chemical reactions, important phenomenon like catalysis, adsorption and absorption, chemical exchange, solvent extraction and polymerization, etc. can all be studied in detail, using radiotracers. Industries which presently employ tracers, include coal, oil, natural gas, petrochemical, cement, glass, rubber, building materials, ore-processing, paper and pulp, iron and steel, and automotive industries.

Object to be studied is labeled with radiotracers prior to the experiment and either by following the trace movement, changes in concentration or distribution between phases, measurements/studies such as material conditions, flow rate measurements, wear rate studies, residence time distribution (RTD), leak detection in buried pipelines & high pressure heat exchanger systems, diffusion rates, etc. may be studied. Gaseous/liquid radiotracers are used for these studies and selection of suitable tracer for a particular study needs careful evaluations of material parameters, reaction mechanisms and kinetics. Tracer studies are also widely used in physical and chemical research. ^{82}Br ($t_{1/2}$= 36 h), ^{46}Sc ($t_{1/2}$= 84 d), ^{24}Na ($t_{1/2}$= 15 h), ^{41}Ar ($t_{1/2}$= 110min) and ^{203}Hg ($t_{1/2}$= 46.6 d)are extensively employed as industrial tracers.

I. Leak Detection, Detection of Blockage in Buried Pipelines & Maintenance

The tracer method is particularly useful for buried pipelines since alternatives such as radiometry are possible for the over ground pipelines.

Free flow of materials in pipelines and other industrial systems are obstructed due to blockages, which may occur due to variety of reasons, such as, involuntary introduction of foreign materials during construction and because of scaling on walls during operation. Leakages may occur in the pipelines due to corrosion or faults in the joints. These defects can lead to operation of plant at much lower efficiency causing substantial economic losses. Radioactive tracer technique offers elegant approaches for easy detection and location of blockages and leakages.

- Leak detection in buried pipelines and movement or location of specific objects in underground pipeline

The leakage in long and buried pipelines or those in industrial plants can be monitored with a suitable short-lived isotope like ^{82}Br ($t_{1/2}$=36 h). The radiotracer is injected into the pipeline and the velocity of fluid flow is measured in different section of the pipeline by monitoring the time taken by radiotracer to pass different points along with pipelines. The drop-in velocity in any particular section is indicative of blockage in the pipeline.

Alternately, the pipeline is filled with the radiotracer solution, which is pressurized so that a small quantity of radiotracer leaks into the soil at the point of leak. Subsequently the pipeline is flushed with water and a portable radiation monitor, when moved along the entire length of the pipeline, identifies the point of leak. Even minute leaks spotted by this method, results in huge savings and manpower. Likewise, any leaks in dams and reservoirs, may also be detected.

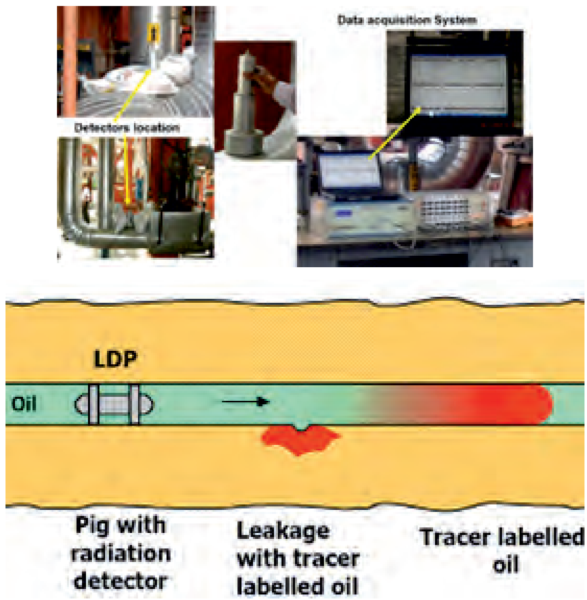

Fig. 9: Leak Detection using Radiotracers

Radionuclides are also used to determine the movement or location of a specific object, such as cleaning tool or scrapper in an underground pipeline. The radioisotope is used as a sealed source attached to the object to be traced. As the object moves through the pipeline, its movement can be traced on the surface by scanning the ground with an appropriate radiation detection instrument. This application is extremely useful in tracing the uncharted course of a pipeline system or in locating an obstruction in the pipeline, thus avoiding huge expenditure that would be otherwise required to excavate the entire line.

- Leak detection in high-pressure heat exchanger systems

In an industrial heat exchanger system, two process fluids flow in opposite direction through the two independent sub-systems exchanging the heat. There are multiple heat exchangers in the system and many times, there is significant pressure difference between the two sub-systems. For high pressure systems, there are no tapping points and hence it is not possible to identify the leaky heat exchanger with conventional methods if there is a leakage.

In such cases, radiotracers can be very effectively used for identification of leaky heat exchanger. A radiotracer with compatible physicochemical properties and suitable radioactivity is injected into the high-pressure side and the low-pressure side is monitored for presence of leaked radiotracer. The leaky heat exchanger is identified unambiguously.

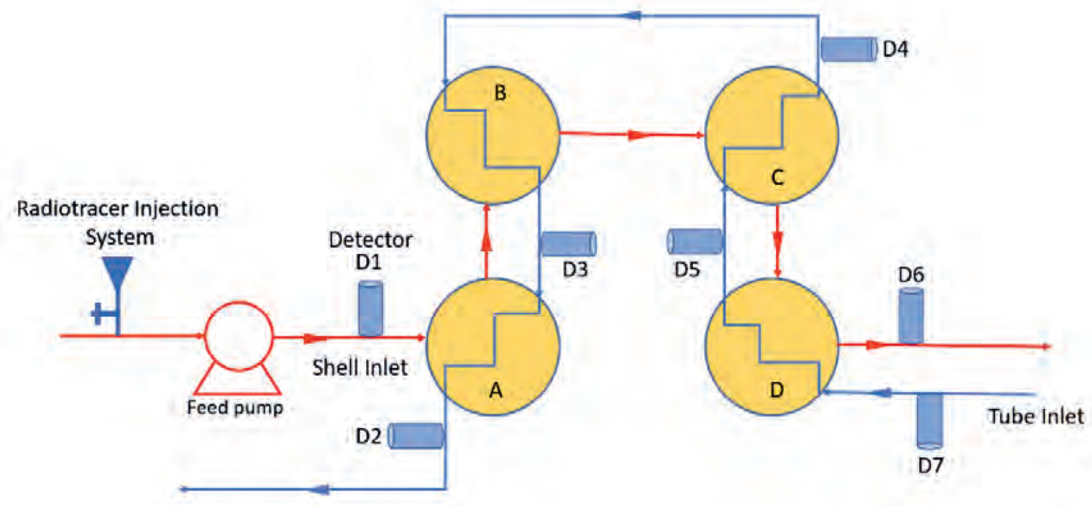

Fig.10: Experimental set-up for Identification of Leaky Heat Exchanger

II. Process Investigation Parameters

A major application of radiotracers is the residence time investigations to determine limits for chemical plant optimizations, modeling and automation. Continuously operating industrial systems are designed to have certain fixed pattern of flow parameters. Deviations from the optimum flow parameters affect the quality and efficiency of process. The deviation may be due to either malfunction or due to efficiency of the process. Hence, estimation of residence retention distribution (RTD) is one of the important parameters that can provide information on the characteristics of the reactor, such as the flow pattern that occurs, diagnose possible system malfunctions, such as presence of dead or foul volume, bypassing, leakage, blockage, channeling, and back-mixing, and to help estimate the quality of mixing. The RTD, which depends on flow hydrodynamics and reactor geometry, influences the chemical reactor performance by affecting reaction properties, use conversion and yield. The RTD can be measured by evaluating the concentration of a tracer, usually a short-lived radiotracer like ^{82}Br in a suitable chemical form, which is added as a stimulus at the system inlet. At the outlet, the detector connected to a data acquisition system is placed to record the data. The mean residence time (MRT) of the reactor could be estimated from the time taken between the two measurements. From the MRT and by knowing other parameters of the reactor, the effective volume of reactor can be determined. Difference in effective volume and standard geometric volume will give the information about the functioning of the reactor.

Tracer experiments would indicate the deviations from optimum conditions, once the optimum performance of the plant has been attuned. The reasons for malfunctions, such as, undesirable by-pass streams or obstruction of vessels and pipes can be determined and remedied. Necessity for a plant shutdown can be assessed and vital information for required repairs may be obtained prior to shut down.

III. Flow Rate Measurements

A common tracer application is to provide flow rate information introducing radionuclide directly into the moving material, generally a liquid. This originated with the petroleum industry, and was designed to mark the interface between two different petroleum products being pumped through a pipeline that may handle as many as twenty different products in sequence. A small amount of radionuclide is introduced at a pumping station, just before a new product is pumped into the line. Radiation detectors located along the pipeline indicate when the radionuclide, and hence the interface between the two products, passes. This technique is reliable, even though the switching station may be several hundred miles away from the pumping station, where the radionuclide is injected. It is also faster, more accurate and less costly than alternative techniques.

IV. Mixing

One of the main applications of radiotracers in chemical and cement industries is measurement of homogeneous mixing efficiency. In order to obtain a predetermined degree of homogeneity, mixing involves blending of two or more miscible fluids. Process industries use stirred tanks to accomplish many different operations, including the blending of miscible liquids into a single liquid phase, suspension of solids, promotion of heat and mass transfer, gas-liquid and liquid-liquid mass transfer, crystallization and chemical reactions. When a mechanically stirred vessel is used, numerous purposes must be fulfilled. Using radiotracers, some of these objectives, including the homogenisation of single or multiple phases at a specific temperature and concentration of components, which can be affected by the physical properties of fluids that are being mixed, can be studied.

Mixing is a critical phase in many processes, which may consume a lot of time and energy and make use of costly equipment. Radiotracer applications are ideally suited to determine optimum time needed for adequate mixing of components in process vessels. For example, insertion of radionuclide in melting furnaces makes it possible to check the influence of mixing and of turbulence on the speed with which homogeneity is achieved. In order to estimate the extent of mixing, isotopes are introduced into the molten metal and simultaneous readings are taken at frequent intervals at all the furnace openings. The metal is then poured into identical moulds to form samples, and the degree of homogeneity can be ascertained.

V. Wear and Corrosion

The oldest industrial application of radioisotopes predates World War II, when a patent was issued covering the use of radioactive isotopes for measuring friction wear. At that time, the tracer material was plated onto the surface of the object to be tested. Wear was then calculated on the basis of amount of radioactivity worn off the plated surface or on the amount of radioactivity transferred to the surface against which the test specimen was worn. Subsequently, tracer techniques for measuring wear have expanded greatly.

Since early sixties, BARC, DAE, has made pioneering contribution towards the development and promotion of radiotracer technology in India and Asia Pacific region for trouble-shooting and process optimization in industry. BARC has so far carried out more than 500 field-scale radiotracer investigations to benefit the Indian industry, be it steel and oil industries, petroleum refineries or chemical industries.

Role of BRIT in providing Isotope Application Services to Industries

Isotope Application Services (IAS) of BRIT, DAE, involve sealed source and radiotracer application in various process industries, especially in petroleum refineries, to pinpoint the cause of malfunctions in plant equipment such as distillation columns, cyclones, heat exchangers, pipelines, tanks, separators, etc. These applications are very helpful to take decisions regarding shutdown and maintenance, which reduces plant downtime. It provides great economic benefits to the industries as well as BRIT to earn revenue.

BRIT started Isotope Application Services (IAS) in 2007 on commercial basis. However, research activities related to industrial application of sealed sources and radiotracer are carried out by BARC. Being the most popular activity among industries, gamma scanning was the main focus. For the first time in India, manual scanning of columns was replaced by fully automatic gamma scanning machine, which enhances the performance drastically. Around 180 columns have been scanned at various refineries of India. As per the demand, radiotracer applications, radiometry, pipe scanning and other relevant jobs were added to the profile.

BRIT primarily deals with the gamma scanning of process columns, identification of leaky heat exchangers, radiometry of radiation shielding objects and pipe scanning. Indigenously developed fully automatic gamma scanner and compact multi-channel data acquisition system is being used for column scanning and radiotracer studies, respectively. In-house development of organic ^{99}Mo as radiotracer provided higher accuracy, faster service delivery and safer handling. As the environmental safety norms have become stringent, radiotracer studies for fly-ash disposal into the open mine voids have been carried out for thermal power plants since last few years. Tritium injection for oil field analysis has been done and future injections are also planned.

Isotope application techniques are getting more popular now a days in India. Due to increasing demand and to meet customer requirements in the competitive market, it is intended to continue R&D for machineries and equipment development based on cutting edge technology. These developments will improve the quality of services provided to the clients so that they can

Table 3: Examples of benefits resulted to Indian Industry with Radiotracer Applications

Application	Savings / Benefits
Gamma scanning of industrial process columns	- ~ Rs 6 crore for a typical small gamma scanning columns - Shutdown time reduced - Pinpointing of the problem area
Leak location in underground pipelines	- ~ Rs.18 crore for a typical 50 km long petroleum product pipeline - No need to dig open the suspected section of the pipeline - Pin pointing the leak location
Blockage location in underground pipelines	- Rs. 80 lakhs for a typical 50 km long pipeline - Reduced down time of t he pipeline - Accuracy in locating
Studies for dead volume estimation in chemical reactors 3 m diameter reactor	- Rs. 105 crore per year - Reduction in shut -down period
Mercury inventory in caustic soda cells	- Rs. 75 lakhs/ month for a plant having about 50 electrolytic cells. - No plant shutdown is required - Handling of mercury for inventory is completely avoided.

take critical decisions with more confidence. More value-added services such as previous reports access, on-site interpretations, offering signature scanning, etc. will be provided. It is also planned to launch new marketing campaigns like use of social media to reach and spread awareness among target clients. It is intended to penetrate other chemical industries, heavy engineering units, thermal power plants and oil & gas sector in apart from petroleum refineries.

Important applications of tracer technology, resulting in vast economic benefits are summarized in Table 2.

Conclusion

Evaluation and identification of use of radioisotopes and radiation technology in medical, industrial and research sector is a rapidly growing requirement. Techniques involving radioisotopes and radiation technology have been widely applied in various fields of industry. This is possible because of the properties of radioisotopes, i.e., it can selectively label certain process media and represent their movements and/or pathways, or the ability to reveal much of the inner details while its transmission and attenuation or its ability to deposit radiation energy at the desired location inside the exposed matter to reveal physical, chemical and biological changes.

Applications of radioisotopes and radiation technology in medicine, industry, food, agriculture and research, constitute some of the important beneficial effects of peaceful uses of atomic energy. Development of appropriate techniques and technologies for production and applications of radioisotopes is an ongoing process. Unlike many other advanced technologies, isotope applications have a low gestation period. A technology developed in the laboratory is often successfully applied in field within very short time period. This makes the isotope technology one of the highly visible peaceful uses of nuclear research. The Indian industry has been one of the early beneficiaries of indigenous isotope techniques and processes. Concerted efforts at the Bhabha Atomic Research Centre (BARC) and the Board of Radiation & Isotope Technology (BRIT) are helping in production of sources of radiation and spreading the applications of radioisotopes for Industrial processing, non-destructive testing, trouble shooting in processing plants and for designing and commissioning of new plants, followed by deployment of such technologies. Department of Atomic Energy (DAE) is constantly trying to reach the production as well as user agencies for wider deployment of such technologies, so as to provide larger benefits to society.

References

1. Indian Association of Nuclear Chemists and Allied Scientists (IANCAS) Publications https://www.iancas.org.in
2. Industrial Applications of Radioisotopes and Radiation http://docplayer.net/42486286-Industrial-applications-of-radioisotopes-and-radiation.html
3. Board of Radiation & Isotope Technology (BRIT) https://www.britatom.gov.in
4. Bhabha Atomic Research Centre (BARC) https://www.barc.gov.in

Nuclear Agriculture: Crop Mutant Varieties and Related Agri-Technologies for Societal Benefits

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Preamble

India is an agrarian country, whose economic development is vastly dependent on sustained growth and achievements in agriculture sector amid raising population, shrinking arable land and adverse effects of climate change. Current and future challenges in Indian agriculture need to be addressed through innovative agricultural research along with appropriate policies, effective delivery and market systems. Synergistic blend of conventional and advanced methodologies in crop improvement, crop production and crop protection would holistically contribute to agricultural research for achieving national food and nutritional security. Crop improvement through mutation breeding, among various breeding methodologies, has played an important role in inducing novel genetic variability, improving existing popular variety and developing promising varieties in different crop plants. BARC has been engaged in mutation breeding since fifties using ionizing radiations like x-rays, beta particles, gamma rays and electron beam. Using radiation-based mutants and their derivatives in crosses; BARC has developed 55 varieties with improved traits in different crops in collaboration with State Agricultural Universities and ICAR research institutes. These varieties have been released for farmer cultivation across India. Several of BARC varieties have been cultivated extensively by farmers from different states and have immensely benefitted them by enhancing their farm income.

1. Introduction

The agriculture sector is an important sector for India's economic development for alleviating poverty and ensuring food and nutritional security. Current and future challenges in Indian agriculture need to be addressed through synergistic blend of conventional and advanced methodologies in crop improvement, crop production and crop protection for achieving national food and nutritional security.

Crop improvement is a continuous process for evolution of promising and improved varieties for which, a basic necessity is to ensure greater genetic variability for target traits. In nature, new variability is generated by spontaneous genetic changes (mutations) due to effect of natural radiations and other factors, which occur at extremely low frequency (one in a million). Using atomic radiations and/or other chemical mutagens, mutation frequency can be enhanced to several folds (one in thousands). Development of such mutants (induced mutagenesis) has been successfully employed for improvement of most of the crops (mutation breeding). Bhabha Atomic Research Centre (BARC) has been contributing in the field of agriculture by using radiations to develop newer crop varieties through mutation breeding; to control insect pests; to trace the pesticide residues and uptake of fertilizers and other nutrients.

The phenomenon of induced mutagenesis for crop improvement dates back to early 20th century with the occurrence of changes in barley seedlings and sterility in maize tassels after X-ray irradiation as shown by Stadler in 1928. In line with the national breeding programs towards enhancing production of cereals, oilseed and pulse crops, BARC has been undertaking genetic enhancement of these crops through radiation induced mutagenesis. Way back in 1957, experiments were initiated in over 50 varieties of several crop plantst o understand the effect of radiations like x-rays, neutrons and gamma rays by studying radiosensitivity, mutation frequency, cytological aberrations, morphological, biochemical and physiological traits [1-4].

2. Protocols in Mutation Breeding

In mutation breeding, the main goal is to develop suitable varieties with enhanced seed yield and nutrients, earliness, desired seed size and dormancy, tolerance to diseases, insects, drought, salinity, heat, etc. Seeds of existing popular cultivars, varieties, mutants, selections, hybrids or advanced lines of target crop are treated with different radiations (Mutagen) like, x-rays, beta rays, gamma rays, fast neutrons, electron beam (M_1 generation). The effective dose ideal for mutant induction was close to Ld_{50} (50% lethal dose) depending on radio-sensitivity factors. These treated seeds of different crops are sown in the agricultural fields. Usually genetic variants (mutants) are identified from next generation (M_2) onwards. In the subsequent generations, breeding behavior of the induced mutants is studied and is followed till the induced mutant becomes genetically stable (attaining homozygosity). Indian Council of Agricultural Research (ICAR) through their coordinating units and the State Agriculture Universities (SAUs) evaluate these stabilized mutants with the existing varieties over the locations and seasons to find their suitability and adaptability. Based on the superiority of new mutant, varietal identification committee of ICAR/SAU recommends the suitable mutant for release. Further, Department of Agriculture and Cooperation, Ministry of Agriculture & Farmers Welfare, Government of India releases and notifies new mutant for commercial cultivation [6]. Sometimes, such mutants are crossed with other mutant or variety to integrate the beneficial traits from both the parents (Recombination or cross breeding). BARC/SAUs undertake breeder seed production of new mutant varieties followed by foundation and certified seed production by the national and state seed corporations, seed companies and other seed agencies to reach the farmers with the seeds of new mutant variety.

3. Development of Trombay Mutant or Mutant Derived Varieties

Using radiation induced mutagenesis, hundreds of mutants with various desirable traits were developed in different crop plants at BARC. Such mutants were directly utilized or judiciously blended to develop 55 varieties, which have been released and Gazette notified for commercial cultivation across the country during 1973-2022 period. These include 16 varieties in groundnut; 8 in mungbean; 7 each in mustard and rice; 5 each in urdbean and pigeonpea; 2 each in cowpea and soybean and one each in linseed, sunflower and jute. These Trombay varieties have extensive public acceptance and are being widely cultivated. Synergistic research collaborations and memoranda of understandings (MoUs) between BARC and ICAR institutes and SAUs have enabled successful development and dissemination of Trombay varieties wide across the country.

3.1 Oilseed crops

3.1.1Groundnut

Groundnut mutation studies were started with X-ray irradiation in 1957 at BARC, followed by gamma rays and electron beam. Initially, mutant gene pool having many divergent mutants was created with repeated mutational events. Consistent breeding efforts using these mutants in recombination breeding has developed and released 16 Trombay groundnut (TG) varieties for cultivation in different states. The first BARC variety was TG 1 with large seed developed in 1973 by X-ray irradiation. With this, saga of release of mutant variety was continued at BARC with one more X-ray mutant variety, TG 3. Inter-mutant crosses resulted in the development of TG 17 variety. Crosses involving both TG 1and TG 17 was carried out to develop a large seed variety, TKG 19A. Further, these TG mutants and their derivatives were genetically diversified by other varieties to develop TGS-1 (Somnath) and TG 22. Multiple crosses involving these mutants and M 13 has resulted in the development of four varieties, TAG 24, TG 39, TLG 45 and RARST-1 (TG 47). Genetic diversification of these mutants was sustained by involving more parents for incorporation of newer characters, which has evolved five varieties, TG 26,TG 37A, TG 38, TPG 41 and TG 51 for different states [6]. Recently, a gamma ray mutant, TAG 73 has been released for Maharashtra. In state groundnut breeding programmes, TG varieties were used as parents in the development and release of another 14 varieties by different agricultural universities in Andhra Pradesh, Gujarat, Karnataka, Maharashtra, Rajasthan and Telangana.

Various characters like compact plant type, large seed, early maturity, fresh seed dormancy, drought tolerance, high oleic acid found in TG varieties were advantageous for different cropping systems and situations. Based on the indent and demand from various seed agencies, around 700 tonnes breeder seeds of TG varieties were produced and supplied by BARC for further foundation and certified seed production in several states including Gujarat, Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh, Odisha, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal. Most of these TG varieties have considerably benefited thousands of farmers, traders and exporters. Photograph of actual seed multiplication of groundnut variety (TG 39) on farmer's field in Maharashtra is depicted in Fig 1. Produce from this field is used as seed for sowing purpose in the next season by the farmers.

Fig. 1: Breeder seed multiplication field of groundnut variety TG 39 in Maharashtra

3.1.2 Mustard

Mutation breeding in Indian mustard at BARC has generated a wide spectrum of mutations for morphological, physiological, biochemical, yield and yield contributing characters. Sustained breeding efforts involving these mutations have evolved seven mustard varieties, which are released in different states. In mustard, yellow seed coat mutant has more oil, more protein, thinner seed coat and lower fiber compared to brown seed coat parents. First yellow seed coat mutant in India, Trombay Mustard 1 (TM1) was developed by BARC from variety Rai 5 using beta rays from Phosphorus-32 (^{32}P) radioisotope. Recurrent selection in the same mutant has resulted in high yielding variety, TPM 1 (Fig. 2). TPM 1 has reduced erucic acid up to 25% compared to 47% in traditional rapeseed-mustard oil. Earlier years, a direct mutant TM2 and a mutant derivative TM4 have been released. TM4 and TPM1 are yellow seed coat varieties. Recently, another yellow seed variety TBM204 has been released for West Bengal. In 2022, three more varieties have been released: Trombay Him Palam Mustard 1 (THPM-1) for Himachal Pradesh; Birsa Bhabha Mustard-1 (BBM-1) for Jharkhand and TAM 108-1 for Maharashtra.

Fig. 2: Trombay mustard variety, TPM-1

3.1.3 Other oilseed crops

In soybean, radiation induced mutagenesis has generated diverse genetic variability both for quantitative and qualitative traits. BARC has developed two soybean varieties viz., TAMS 38, a gamma ray mutant of JS 80-21 and TAMS 98-21, a cross derivative with superior seed yield, non-pod shattering, resistance to diseases and pests. Both the varieties were cultivated widely by the farmers in Vidarbha region of Maharashtra. Linseed oil contains mainly unsaturated fatty acids like oleic acid (16–24 %), linoleic acid (18–24 %) and linolenic acid (36–50 %). Its oil is unfit for edible purpose as it develops off-flavours during storage due to its oxidation. Varieties with low linolenic acid will enable linseed oil to use as edible oil. BARC has developed yielding variety, TL 99 with 2-5% linolenic acid which was released for commercial cultivation in 2019. TL 99 is the first Indian variety released for edible oil. In sunflower, gamma ray mutagenesis of zebra stripped seed coat variety Surya has resulted in high yielding black seed coat variety, TAS 82, which was released for cultivation in Maharashtra.

3.2 Pulse crops

Pulses are the vital component for dietary proteins in carbohydrate rich staple food for our sizable vegetarian population. BARC has been actively engaged in the genetic improvement of pulse crops namely, blackgram/urdbean, greengram/mungbean, pigeonpea, cowpea and recently in chickpea and cluster bean through mutation and recombination breeding. Gamma rays have been found to be the most potent among different mutagens. BARC has developed 20 varieties in pulses which include eight in mungbean, five each in urdbean and pigeonpea and two in cowpea [7]. Most of these Trombay pulse varieties are mutant derivatives developed by mutant-genotype or inter-mutant (TAT-10 in pigeonpea) hybridizations, while some varieties (TAP-7 in mungbean, TT-6 in pigeonpea and TRC77-4, TC-901 in cowpea) are direct mutants. In urdbean, large seed mutants, UM-196 (dark green leaf mutant) and UM-201 were hybridized with popular cultivar T-9 resulting in three improved varieties, TAU-1, TAU-2 and TPU-4. Similarly, in pigeonpea, a fast neutron induced large seed mutant variety TT-6 was hybridized with ICPL 84008 and three high yielding varieties (TT-401, TJT-501 and PKV-TARA) with early maturing period have been developed. In mungbean, crosses involving Kopergaon and TARM-2 have resulted in the development of TMB-37 variety with early maturity characteristics. Some of the mutant varieties like TM-96-2, TM-2000-2 (mungbean), TU-40 (urdbean) and TRC-77-4 (cowpea) are also suitable for rice fallows. Cowpea variety, TC-901 is the first summer suitable variety in the country.

Many of the Trombay pulse varieties are popular among the farmers owing to their superior yield and disease resistance attributes. Near about 155 tonnes of breeder seeds have been produced and distributed to the farmers during the last five years. The urdbean mutant TAU-1 is the most successful variety occupying more than 50% of the urdbean area in Maharashtra. The recently released urdbean variety TU-40 associated with high yield has become popular in the southern states. The mungbean variety, TMB-37 though initially released for North-East plain zone, is gaining popularity across the country and has been re-adopted in 2018 by Punjab owing to its large seed, yellow mosaic virus resistance and suitability for summer cultivation. The early maturing pigeonpea variety, TJT-501 occupies almost 60% of the area under pigeonpea in Madhya Pradesh (Fig. 3). The farmers of Maharashtra are reaping high yields by cultivating pigeonpea variety PKV-TARA especially under drip irrigation [8].

Fig. 3: Trombay pigeonpea variety, TJT-501

3.3 Rice

Radiation induced mutagenesis has been successfully employed at BARC for rice improvement resulting in the release of seven varieties. Among these, Trombay Chhattisgarh Dubraj Mutant-1 (TCDM-1), Vikram-TCR, CG Jawaphool Trombay, Trombay Chhattisgarh Vishnubhog Mutant (TCVM) and Trombay Chhattisgarh Sonagathi Mutant (TCSM) all being gamma ray mutants, have been released for commercial cultivation in Chhattisgarh, while a mutant derivative, Trombay Karjat Kolam Rice (TKR Kolam) has been released for Maharashtra. TCDM 1 has retained the aroma and grain quality of parent variety, Dubraj. TKR Kolam has superfine grain and better taste. Vikram-TCR is high yielding, dwarf, non-shattering and non-lodging, mid-early maturity with long slender grain, drought tolerance and better puffed rice making quality. CG Jawaphool Trombay is high yielding, semi-tall, non-shattering and non-lodging with aromatic short grains and better Kheer making quality. These rice varieties have been developed in collaboration with Indira Gandhi Krishi Vishwavidalaya (IGKV), Raipur, Chhattisgarh and Dr. D.B. Sawant Konkan Krishi Vidyapeeth, Dapoli, Maharashtra.

4. Dissemination of Trombay Mutant Varieties

BARC has followed multi-pronged approaches to disseminate Trombay varieties wide across the country. It has participated in exhibitions, Kisan Melas and conducted field demonstrations under the Public Awareness Programme on Peaceful Uses of Atomic Energy in order to create awareness about the Trombay varieties. As per the national indent from various seed agencies and seed growers, nearly 1000 tonnes of breeder seed of Trombay varieties were multiplied and supplied to National Seed Corporation, State Seed Corporations of Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Maharashtra, Odisha, Rajasthan and West Bengal; National Institutes; State Agricultural Universities; State Agricultural Departments; Seed companies; Non-Governmental Organizations and farmers. Apart from this, different State Agricultural Universities also distributed hundreds of tonnes breeder seeds of BARC crop varieties. Such variety of the seed was further multiplied, distributed and spread horizontally to thousands of hectares and widely accepted by the farming community in turn contributing significantly towards food and nutritional security of the country (Fig. 4).

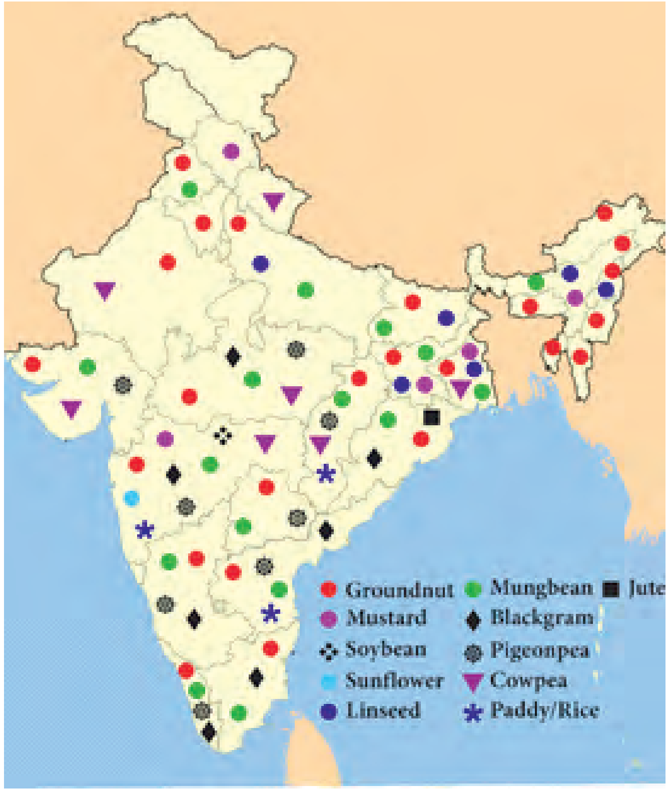

Fig. 4: Deployment of Trombay varieties across the country.

5. In Vitro Mutagenesis

Noteworthy research has been carried out in the areas of plant/cell tissue culture, in vitro mutagenesis, molecular stress biology, molecular markers, micropropagation, cell culture /hairy root based production of bioactive compounds, cloning of desirable genes and developing transgenic plants for stress tolerance. Transgenic banana plants have been developed for biotic and abiotic stress tolerance. In vitro mutagenesis of banana with gamma rays at BARC resulted in desirable dwarf mutants [9]. Dwarf mutant, TBM-9 has performed better in national multi-location trials. In vitro mutagenesis of sugarcane along with cellular selection for salt tolerance at BARC has identified mutants, AKTS-01 and AKTS-02 having superior total plant height, millable cane height and number.

6. Agro-based BARC Technologies

In addition to crop improvement, radiations and radioisotopes are used in agricultural research to manage insect pests, to monitor fate and persistence of pesticides, to study fertilizer use efficiency and also to preserve agricultural produce. BARC has developed various technologies for micropropagation of banana, pineapple, turmeric, ginger; bio-control formulations; for detection of insecticides; for decomposition of different types of biodegradable wastes and soil organic carbon detection kit, which have been transferred to several agencies across the country (Table 1).

Table 1: BARC agro-based technologies along with their applications

Technology	Application
Bio-fungicide formulation Tricho BARC of an improved *Trichoderma Virens* Mutant Strain	Seed treatment for bio-control of seedling diseases in crop plants
Nisargruna biogas technology	To decompose biodegradable and to provide high quality manure and methane gas. It has potential of solving the solid waste management issue in the urban areas.
Compact Helical Biodegradable Waste Converter, SHESHA	To decompose biodegradable waste and to generate good quality fuel and manure for soil applications.
A rapid composting technology for decomposition of dry leaves, kitchen waste and temple waste	Microbial decomposition of kitchen/market waste, dry plant matter (including coconut leaves), straw/agricultural residue and waste from temples
A rapid, continuous and renewable method for multiplication of *Ophiorrhiza Rugosa*	Sustainable source of anticancer drug camptothecin.
Micropropagation protocol for banana, pineapple, turmeric, ginger	Multiplication of disease free, good quality planting material throughout the year and can also be used in germplasm conservation of elite varieties.
Biopesticide formulation based on *Bacillus thuringiensis* Subsp. *Kenyae* HD-549	Control of different agriculturally important insect pests.
Biosensor kit for Organophosphate and organo-carbamate pesticides	Detection of organophosphate and organo-carbamate pesticides in food samples, which will be useful for farmers, traders and consumers
Superabsorbent BARC hydrogel (MRIDAMŔT)	Hydrogel can absorb and retain pure water up to 550 times of its own weight and supply to plant roots. It increases the soil water holding capacity.
Soil organic carbon detection kit	To help farmers to understand their field's carbon status in 15-20 minutes

7. Conclusion and Future Prospects

A judicious blend of mutation and recombination breeding has been found promising in the genetic improvement of crop plants as exemplified by crop breeding efforts undertaken at BARC, Trombay. Mutant varieties also have been used extensively as parental material in the national and state breeding programmes in respective plant species. Additionally, induced mutants are ideal resource genetic material for studying functional genomics. Crop improvement is a continuous process wherein new mutants and breeding lines in different crops including vegetatively propagated plants will be developed by employing gamma rays, proton beam, electron beam-based mutagenesis and targeted mutagenesis to accomplish the future needs of the farmers particularly under changing climatic conditions. Such breeding cycle will be hastened by adopting in vitro mutagenesis, speed breeding and marker-assisted breeding techniques.

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References

1. BY Bhatt, KC Bora, AR Gopal-Ayengar, SH Patil, NS Rao, HK Shama Rao, KC Subbaiah RG Thakare. 1961 Effect of Ionizing Radiations on Seeds, IAEA, Vienna. Pp 591-607
2. BY Bhatt, KC Bora, SH Patil 1961 Effect of Ionizing Radiations on Seeds, IAEA, Vienna. Pp 591-607 pp 441-459
3. KC Bora, SH Patil, KC Subbaiah KC 1961 Effects of ionizing radiations on seeds, IAEA, Vienna pp 203–216
4. Patil SH, Bora KC (1961) Meiotic abnormalities induced by X-rays in Arachis hypogaea L. Indian J Genet 21:59–67
5. SH Patil (1968) Cytogenetics of X-ray induced in aneuploids in ArachishypogaeaL. Canadian J Genet Cytol 10:545–550
6. AM Badigannavar, SJ Jambhulkar, JG Manjaya, J Souframanien, BK Das,AMBadigannavar, TR Ganapathi and P Suprasanna 2021 In "Non-power Applications of Nuclear Technologies" (Eds. Tyagi A.K. and Mohanty A.K.) BARC, Mumbai, India. pp. 33-49.
7. J. Souframanien, and T. R. Ganapathi, Plant Breed. Genet. Newslet. Vol. 46, pp. 23-25 (2021).
8. J. Souframanien, A. Joshi Saha, V. J. Dhole, P. Dhanasekar, and G. Misra, IANCAS Bulletin Vol. XV (1), pp. 71-80 (2020).
9. T. R. Ganapathi, K. M. Ujjappa, and A. M. Badigannavar, Int. J. Fruit Sci., Vol. 16 (3), pp. 310-322 (2016).
10. Bhabha Atomic Research Centre (BARC) https://barc.gov.in
11. IAEA Publications https://www-pub.iaea.org

Radiation Processing as a Sustainable and Green Technology to Ensure Food Security, Safety and Promote International Trade

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Preamble

With respect to production of horticultural and agricultural commodities India ranks second in the world. However, its rank in the global hunger index (GHI) is disappointing. Post-harvest losses are one of the prime reasons behind this paradox. Besides contribution of agriculture sector in national GDP has shown a gradual decline since independence. Technological and processing interventions could be considered as possible remedial measures. A significant amount of agricultural produce is lost during post-harvest storage primarily due to insect infestations, microbial contaminations, and other biological and physical damages. Prevention of post-harvest losses can help in ensuring food security to the greater extent. The chemical fumigants used for the control of insect pests, quarantine treatment of agricultural and horticultural produce and for microbial decontamination of food commodities are being phased due to their harmful effects on human health and environment. Therefore, there is an utmost need of an alternate environment-friendly green technology to address these issues.

The beginning of radiation technology

Radiation processing of food is more than 100 years old technology as the first related patent was granted in 1905 in the United Kingdom to bring about an improvement in the condition of foodstuffs and in their general keeping quality deploying radiation technology. However, the technical limitations worked as hindrance in its rapid growth. The radiation sources proposed to be used under this patent was alpha, beta or gamma rays from radium or other radioactive substances. The radium preparations suggested by these inventors as sources of ionizing radiation were not available in sufficient quantity to irradiate food commercially. Research in the area of radiation processing of food was sponsored by the Department of the Army, the Atomic Energy Commission, as well as private industries in the United States during the period between 1940 to 1953. Early research in this duration focused on the potential uses of different types of radiation including electrons, neutrons, alpha particles, X-rays as well as ultraviolet light for food preservation. It was concluded from this study that only electrons had the necessary characteristics of efficiency, safety, and practicality. X-rays was considered to be impractical that time due to very low conversion efficiency from electron to X-ray in the existing set up. As ultraviolet light and alpha particles have limited ability to penetrate the matter, were too considered to be impractical. Neutrons were considered inappropriate for use in food because of the potential for inducing radioactivity, although it exhibited great penetration and therefore very effective in the destruction of bacteria. In 1950, a coordinated research activity was initiated on the use of ionizing radiation for food preservation by United States Atomic Energy Commission (USAEC). It provided spent-fuel rods of nuclear reactors as source of ionizing radiation, which had limitations with regard to exact dosimetry. Subsequently ^{60}Co source was opted as sources of gamma radiation for food preservation by USAEC.

Radiation sources approved for processing of food products

FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food approved following four radiation sources for treating foods which was also endorsed by the Codex General Standard for Irradiated Foods:

(A) Radioisotopes based sources:

- Cobalt-60 radioisotope (Gamma Energy 1.17/ 1.33 MeV)
- Cesium-137 radioisotope (Gamma Energy 0.66 MeV)

(B) Machine based radiation sources

- X-rays (Energy not exceeding 5 MeV)
- Electrons (Energy not exceeding 10 MeV).

Food irradiation: Working principle

Food irradiation is a physical process in which food and agricultural commodities are exposed to a controlled amount of radiation energy to achieve desirable effects. These commodities can be exposed to radiation either in pre-packed form or in open bulk state depending upon the desired objectives. Food is placed in containers that are moved by a conveyor into a shielded room, where it is briefly exposed to radiation emanating from a source. Radiation by its direct effect on macromolecules and indirect effect through radiolysis of water inactivates essential biomolecules of insects, parasites, and microorganisms, and destroys them. At low doses, it also causes inhibition of physiological processes such as sprouting in potato and onion and delay in the ripening and senescence in certain fruits and vegetables.

Applications in food preservation

On the basis of radiation dose, food applications are classified into low dose (< 1 kGy), medium dose (1-10 kGy) and high dose (> 10 kGy) applications. Radiation dose is the measure of radiation energy absorbed per unit mass of material under consideration. The unit of absorbed dose is Gray (Gy). 1 Gray is the energy absorption of 1 Joule per kilogram.

Low Dose Applications

Sprout inhibition in bulbs and tubers:

Irradiation in the range of 0.06 to 0.15 kGy inhibits sprouting in tubers such as potato, bulbs such as onion, rhizomes like ginger and corms such as taro. Potato and onion needs to be cured for two weeks just after harvest followed by radiation treatment. For better shelf- life radiation treated potato and onion are recommended to be stored at low temperature. For potato, post-irradiation storage temperature of 14-15°C and relative humidity 93-95% are considered effective in yielding better shelf- life whereas for onion temperature of 0.2-0.5°C and relative humidity 65-68% is considered to be highly effective. Conventionally, in commercial cold storage, potato is stored at 2-4 °C. Though sprouting is inhibited at this temperature, the commodity starts sprouting profusely as soon as it is taken out from the cold storage and moved down the supply chain. Thus, radiation processing of potato and subsequent storage at 14 to15°C conserves energy and also prevents sweetening of potato. Such phenomenon commonly occurs at very low temperatures. Therefore, it gives advantage to the chip making food industry because low sugar potato give desired lighter color to chips and fries.

The alternate process such as use of chemical sprout inhibitors like isopropyl-N (3-chlorophenyl) carbamate (CIPC) and maleic hydrazide (MH) has not found to be very effective under subtropical or temperate climates. CIPC has also recently banned by many countries.

Non-irradiated **Irradiated**

Control of Sprouting in Potato and Onion using radiation processing (Shelf life around 8 months in cold storage at specified conditions)

Delayed ripening of fruits (e.g. Mango)

India is a major producer of tropical fruits and vegetables. The Alphonso and Kesar varieties of mango are popular all over the world and have great export potential. Irradiation of these fruits at hard mature pre-climacteric stage at ≤0.75 kGy delays the ripening process up to 2-3 weeks if stored at low temperature. Thus, the extent of delay in ripening will depend upon the storage temperature as well as varieties of mango. The radiation doses used for delay in ripening are also effective in destroying quarantine pests.

Indian mangoes were not allowed to be imported in USA for 18 years prior to 2007 due to quarantine issues. When the United States Department of Agriculture (USDA), approved KRUSHAK (Krishi Utapdan Sanrakshan Kendra) irradiation facility, Lasalagaon, Nashik, export of Indian Mangoes to USA started in 2007 and is continued till date. At present, mangoes after radiation treatment are exported to USA by air that has quite high transportation cost. This also limits its volume of export and therefore share of Indian mango in the USA resulting in low export earnings. Use of sea route for transportation would result in substantial cost reduction and enable export of larger volumes enabling deeper penetration in the USA market. A technology has been developed at BARC for delayed ripening of Indian 'Kesar' mangoes which will enable its sea-route shipment to USA. The SOP of the technolopgy has been approved by USDA.

Delay in ripening of mango using radiation treatment
(Shelf life extension up to 30 days in cold storage)

Radiation processing to control insect infestation in grains

Grains including cereals and pulses are often infested with insect pests leading to huge post-harvest losses during storage. Current existing practices of using fumigants such as ethylene dibromide (EDB), methyl bromide (MB), ethylene oxide (ETO), malathion, aluminum phosphide etc. are deleterious to the health as well as environment. Therefore, use of such chemicals has been recommended to be phased out by the statutory bodies including WHO.

However, radiation treatment of such commodities provide a green and safe technology to control their losses. As the quantum of grains being produced is quite high and therefore their storage requirement, radiation technology needs to be customized to fulfill the need possibly through design development to operate in continuous mode and integration with modern storage facilities like silos.

Non-irradiated

Irradiated

Control of insect infestation in cereals (Shelf life extension for a year at ambient storage in packed condition)

Medium Dose Applications

Shelf-life extension of sea-foods, meat and meat products:

India is one of the major producer and exporter of sea-foods. With a coastline of over 4500 km, fish production has steadily increased over the years. Fresh catch of fish is prone to rapid spoilage due to improper storage conditions, and contamination with pathogens under usual handling and processing practices. This poses serious health risk to consumers. Under ice, fish like Bombay duck, pomfret, Indian Salmon, Mackerel, and shrimp can be stored for about 7-10 days. Studies have demonstrated that irradiation at 1-3 kGy followed by storage at melting ice temperatures increases its shelf- life nearly threefold. In India, meat and meat products are marketed either fresh or in frozen form. Meat and meat products including poultry have a shelf-life of about a week at 0-3ºC, which could be extended up to four weeks by applying a dose of 2-5 kGy, which inactivates spoilage bacteria. Radiation treatment has been employed to enhance the shelf-life of intermediate moisture fish and meat products.

High Dose Applications

Hygienization of spices: India is a major spice producing and exporting country. However, due to inadequate handling and processing conditions, spices often get contaminated with insect eggs and microbial pathogens. When incorporated into semi-processed or processed foods, particularly, after cooking, the microbes, both spoilers and pathogens can outgrow causing spoilage and posing risk to consumers. Many of the spices develop insect infestation during storage. An average absorbed dose of 10 kGy brings about commercial sterility while retaining the natural characteristics of spices.

Non-irradiated **Irradiated**

Control of insect infestation and microbial decontamination in spices
(Shelf life extension for a year at ambient storage in packed condition)

Regulatory approval

Determination of required radiation dose is one of the major parameters for optimal processing which is addressed through R&D activities at Food Technology Division, BARC, Mumbai. This is based upon the nature of commodity as well as the purpose. First of all, Government of India approved radiation processing of onion, potato and spices for domestic market in 1994 by amending the Prevention of Food Adulteration Act (1954) Rules. Recently, Food Safety and Standard Authority of India (FSSAI) has endorsed 'Generic class-based approval of radiation processing of food" which is as per the Radiation processing of food and Allied Products Rules, 2012. This has been subsequently Gazette notified by the Government of India in 2016 (F.No.1-120(2)/Standards/Irradiation/FSSAI-2015) (Table 1& 2).

Food irradiation facilities

In India, the first pilot radiation processing facility "The Food Package Irradiator" was commissioned in 1967 at the Food Irradiation Processing Laboratory (FIPLY), Bhabha Atomic Research Centre, Mumbai. Later four food irradiation facilities were commissioned in the Government sector in states of Maharashtra and Gujarat namely, Krishi Utpadan Sanrakshan Kendra (KRUSHAK) at Nashik; Irradiation Facility Centre (IFC), Maharashtra State Agriculture and Marketing Board (MSAMB), Vashi; Radiation Processing Plant (RPP), Vashi; and Gujarat Agro Industries Corporation Limited, Ahmedabad. Three of these facilities (except RPP, Vashi) were used primarily to treat fresh fruits and vegetables. In the last two decades additional 20 plants have been established under private entrepreneurship. Thus, currently 24 gamma irradiation plants are operational in the country treating food and allied products

Conclusion

Radiation technology provides a very effective solution to the post-harvest losses of food while ensuring their safety. It has helped in overcoming quarantine barrier of trade enabling the import of fruits and vegetables across the countries including USA. Existing numbers of food irradiation plants are minuscule in India with respect to the quantum of produce limiting the visibility of radiation treated food in domestic market(s). Therefore, India is in dire need of many more food irradiation plants coupled with cold chain, storage and appropriate transportation facilities. Government of India has launched many schemes to promote establishment of such facilities including cold storage and pack houses to cater the need. Ministry of Food Processing and Industries (MoFPI) is providing financial support to establish food irradiation and other required facilities. Under the reforms proposed in the atomic sector, the Honorable Finance Minister, Government of India too has announced the establishment of irradiation technology facilities in public-private partnership (PPP) mode for food preservation. Research activities at BARC are aimed to develop Standard Operating Procedures (SOPs) for preservation and quality evaluation of various food commodities and allied products deploying radiation technology. With increasing awareness and educated population in the country food irradiation has a promising future ahead as a green and ecofriendly technology to ensure national food security.

Acknowledgement

The contributions from scientific & technical staffs of Food Technology Division, BARC, Mumbai in taking the national food irradiation program on a successful path is gratefully acknowledged.

Bibliography

1. FAO/IAEA/WHO, High-dose irradiation: Wholesomeness of food irradiated with doses above 10 kGy. WHO technical report series 890. Geneva: World Health Organization, (1999).
2. Diehl JF, Food irradiation-past, present and future. Radiat. Phys. Chem, 63 (2002) 211.
3. Farkas J, Irradiation for better foods. Trends Food Sci. Technol., 17 (2006) 148.
4. Sharma A, Radiation Technology Enabled Market Access to Indian Mango. BARC News Letter, (2008) 296: 2.
5. Kume T & Todoriki S, Food irradiation in Asia, the European Union, and the United States: A status update. Radioisotopes, (2013) 62: 291.
6. Roberts PB, Food irradiation is safe: Half a century of studies. Radiat. Phys. Chem., 105 (2014) 78.
7. Gautam, S and Tripathi J. Food Processing by Irradiation——An effective technology for food safety and security. Ind. J. Experiment. Biol., (2016) 54: 700.

Structural Materials for Nuclear Industry

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Preamble

Since its inception, DAE has given special attention on the development of materials for nuclear applications and beyond. These special efforts culminated into the development of a host of materials up to their commercial usage. This chapter provides a glimpse of the all-around development of materials including the journey of few of the materials from ore to the finished products. Special efforts made in the Materials Group, BARC to assess the performance of the materials, modifications introduced to improve their performances and development of special materials to cater to the specific needs in nuclear industry are briefly presented.

1. Bhabha's Vision

Nuclear installations, be it reactors, heavy water plants or waste immobilization facilities, use a variety of materials out of which some are load bearing or structural materials. It is very difficult to procure these materials from abroad because of the many restrictions on nuclear installations of the country. The founder of our nuclear programme, Dr. Homi Bhabha had exemplary foresight and had foreseen the hurdles, the country would be encountering in taking its nuclear energy programmes ahead. He started taking steps for achieving self-reliance in all aspects of our nuclear energy programme, right from the beginning. A different department was created to first start exploring the presence of elements useful for nuclear energy programme in the earth crust of the country. This required scientists with good geological knowledge. Once a promising deposit was located, it needs to be mined and processed. The mined material needs to be subjected to mineral dressing and the knowledge of how to convert the concentrated ore into metal. So, there was a need for creating an indigenous knowledge bank of mineral exploration, mining, ore dressing, chemistry and thermodynamics and different aspects of metallurgy. In order to create a research base on the aforementioned subjects, research centres were setup. Atomic Minerals Directorate was setup for exploration, mining and to do research on some aspects of mineral dressing. Bhabha Atomic Research Centre (BARC) had scientists working on mineral dressing and extractive metallurgy. The scientists of this centre carried out extensive research on extraction of metals from Indian resources. The knowledge bank so created was helpful in developing flow sheets for metal extraction from Indian ores. Since, the Indian ores are different from those from other countries in many cases, the technology developed was India specific. Based on these technologies, Uranium Corporation of India was set up for making uranium oxide and Nuclear Fuel Complex was set up for making Zr and the Zr based alloys.

Once the element or metal is produced, it needs to be mixed with other elements to make a suitable alloy or a compound catering to the need of the applications. Here, a detailed knowledge of alloying and alloy design aspects are needed. The metal produced is transferred to a melting facility where an ingot is produced. The ingot produced is subjected to various thermo-mechanical operations like forging or extrusion to break the cast structure. Here, knowledge about physical metallurgy of the alloy is needed and so is the knowledge about mechanical metallurgy which essentially focuses on the hot and cold deformation behaviour. The broken cast structure is further subjected to the different rolling or extrusion operations to give it a desired shape. The knowledge of the effect of deformation and heat treatment not only on the microstructure but also the crystallographic alignments of grains representing texture is very important so the alloy not only gets a useful shape and has the desired microstructure but also texture. Once a product is made, it needs to undergo various quality checks to ascertain to its defect free nature. It may also be tested for its mechanical properties, corrosion behaviour and in some cases irradiation tolerance. Since the irradiation tolerance against neutrons is rather difficult to evaluate outside a nuclear reactor, proxy ion irradiation is used in the Variable Energy Cyclotron Centre (VECC).

As can be seen from the aforementioned description of sequences of steps required for manufacturing a product from Indian raw materials, involvement of many agenises is required. Accordingly, Bhabha's long standing vision led to the creation of all these agencies and an infrastructure for making almost all structural materials needed for the Indian nuclear energy programme from Indian resources.

2. Structural Materials for Nuclear Reactors: An Introduction

The keystone for the development of nuclear structural materials is the containment of nuclear fuel and radiation generated fission products during normal as well as abnormal reactor operating conditions. Therefore, reliable performance of structural materials is the most important criterion for the successful operation of a nuclear reactor. These structural materials are subjected to high-energy neutrons, corrosive environment along with intense mechanical and thermal stresses during their use in the reactor. The performance of a nuclear reactor can be improved by selecting suitable structural materials which offer higher margins for safety and better flexibility in the material design, in particular, by offering higher strength, better thermal creep resistance and superior corrosion properties and higher tolerance to neutron radiation damage. In nuclear industry, structural materials require special attention in terms of their compositions and microstructures, as any minor unwanted alteration may affect the life span of the material in the reactor. For example, zirconium-based alloy components which form the major part of the in-core structural material are processed in different manner for each component to achieve the most suitable combination of their properties required for the application. Attaining such microstructures which offer most optimum properties in these alloys through proper selection of the processing parameters is a major challenge for metallurgists. This aspect also draws considerable attention in the processing of these material. In general, strategy for designing high-performance materials takes several factors into account. Considerable research has gone in the development of these nuclear materials.

2.1. Zirconium based alloys:

Among all the structural materials used in various reactors, Zr based alloys like zircaloy-2, zircaloy-4 and Zr-2.5%Nb, are the most prominent material currently being used for reactor core structural applications. However, their anisotropic properties, composition and the methods of fabrication need special attention. By tailoring microstructure and texture of zirconium-based alloys based on specific requirements suitable properties can be induced in the structural component. Such optimization in the microstructure can be achieved by the selection of complex thermo-mechanical processing during the fabrication of the structural components for nuclear reactors. Microstructure developed through these process determines the long and short term properties of the components. In addition, these alloys have shown variety of phase transformations. Due to amenability to these phase transformations-involving both diffusion-less and diffusional transformation-a variety of microstructures can be produced in Zr based alloys.

2.2. Steels

Steels are another structural material which are used on a large tonnage basis in nuclear industry. Plain carbon steels are used as piping and components in the secondary circuit of nuclear power plants (NPPs). Such plain carbon steels are highly prone to flow accelerated corrosion (FAC) and an extensive pipeline thinning management program has been put in place in Indian NPPs to avoid unexpected failures.

Stainless steels (SS), austenitic, ferritic and martensitic varieties, are used in different components in NPPs, nuclear spent fuel reprocessing and waste management plants and various other plants in nuclear industry. Materials Group, BARC has been working on all the varieties of stainless steels used in NPPs and has made significant contributions in improving the corrosion resistance of SSs and establishing degradation modes in operating plants. While sensitization, intergranular corrosion (IGC), intergranular stress corrosion cracking (IGSCC) are the most prominent issues, newer concepts of grain boundary engineering and development of the understanding of IGC of even solution annealed stainless steels in highly oxidizing nitric acid conditions (near transpassive potential regime) have been developed. Role of addition of nitrogen to type 304L stainless steel in improving IGSCC resistance, detailed understanding of the susceptibility of martensitic SS e.g., type 420 SS are some examples of the novel approaches used to improve the performance of these structural materials in the nuclear industry. Recently developed, *R*educed *A*ctivation *F*erritic-*M*artensitic (RAFM) steels is an example of the development of a steel for specific applications in nuclear industry. Maraging steels are another important category of steels that rely on alloying additions and microstructural control to obtain high strength, hardness and flowability/fabricability. In-depth understanding of the mechanisms of strengthening in maraging steel has been developed in BARC.

2.3. Nickel Based Alloys

Another alloy system, which is commonly used in nuclear industry, are nickel-based alloys. Mostly, these alloys are used as steam generators (SG) tubes in NPPs. Hence, the importance to keep the corrosion damage as well as the corrosion rates to a minimum is of primary importance. The currently preferred SG tubing materials for NPPs are alloy 690 and alloy 800. Although many reactors are still in operation with alloy 600 as the tubing material,but this alloy has experienced many corrosion-related problems and is being replaced by alloy 690. It may be noted thatalloy 600 and alloy 690 are categorized under Ni-Cr-Fe alloys whereas Alloy 800 as a non-ferrous alloy. Other Ni based alloys are also, in general, used for high temperature applications e.g., reformer tubes in Heavy Water Plants. In addition, Ni based alloys are also being developed as a structural material for Gen IV nuclear reactors. Development of Ni-Mo-Cr alloys for high temperature Gen IV reactors is an ongoing research activity.

3. Pioneers in Materials Development:

In the program on the development of Materials for nuclear reactors, many scientists, Dr. Brahm Prakash, Dr. C. V. Sundaram, Dr. P. R. Roy, Dr. C. K. Gupta have made pioneering contributions in the extraction, processing and scaling upto the commercial production for many metals and its alloys (Fig.1).While Dr. Brahm Prakash was instrumental in the establishment of commercial unit like Nuclear Fuel complex, Dr. Sundaram and colleagues developed the solvent extraction process for separating Zr and Hf as well as process flowsheets for refractory metals like Nb and Ta. Among these, Dr.Srikumar Banerjee was a pioneer metallurgist who devoted his life-time in understanding phase transformation in Zr, Tiand Ni based alloys and tailoring microstructure/grain boundary engineering to obtain optimum performance from steels and stainless steels. His basic approach to first generate an understanding of the material and its microstructure and then correlating it to the properties of these structural materials was a key element in the success of materials development.

Fig.1: Brahm Prakash showing the fabrication and testing of the indigenously produced Zr based tubes to Shri Lal Bahadur Shastri, then Prime Minister of India

4. Materials Requirements for Nuclear Reactors

Currently two types of water-cooled nuclear power reactors are under operation. In the first type, the entire core of a reactor is enclosed in a large steel pressure vessel filled with ordinary water. The water acts as a heat transfer medium and neutron moderator. Such reactors, commonly known as pressurised water reactor (PWR) and boiling water reactor (BWR). In these reactors zirconium-based alloys are used for the cladding tubes which encapsulate the uranium dioxide fuel pellets. The reactor operating at Tarapur near Bombay is an exampleof the BWR reactor and the reactor operating at Kudankulam is an example of PWR.

In the second type reactors, the pressure vessels are replaced by a large number of pressure tubes through which heavy water flows under high pressure to extract heat from individual fuel elements. These pressure tubes pass through a calandria vessel containing cool, heavy water as moderator. Each pressure tube is separated from the surrounding by a calandria tube and an insulating gas is provided to separate hot pressure tubefrom ambient temperature the moderator water. Operating reactors of this type are commonly known as the pressurised heavy water-cooled reactors (PHWR). PHWRs are the back bone of Indian nuclear program on electricity generation. In PHWR, the fuel-cladding tubes, the pressure tubes and calandria tubes are all made of Zr- alloys. Among these tubes, fuel tubes are thin-walled tubes (0.4 to 0.8 mm) which undergo complex sequence of bi-axial and tri-axial tensile stresses, creep and recovery strains during their typical operating life time of 30,000 hours. The pressure tubes in PHWR, on the other hand, are six-meter-long tubes with the minimum of 3.5 mm wall thickness. Unlike the fuel-cladding tubes which are timely replaced by a fresh lot, pressure tubes remain inside the reactor nearly to the life-time of a reactor. Therefore, a typical pressure tube must maintain its very high integrity throughout a life span exceeding 200,000 hour. Although, small cracks and even failure of a tube can be tolerated and faulty tubes can be replaced intermittently, such an exercise is an expensive proposition and not a desirable condition. The calandria tubes typically have a wall thickness of ~1.25 mm and ~107 mm internal diameter. Generally, the conditions on calandria tubesare less severe than those prevail on fuel or pressure tubes. Based on inputs from the research and development on Zr alloys, its mechanical and corrosion behaviour, Nuclear Fuels Complex (NFC) produces various components of Zr based alloys for nuclear reactors, as shown in Fig. 2.

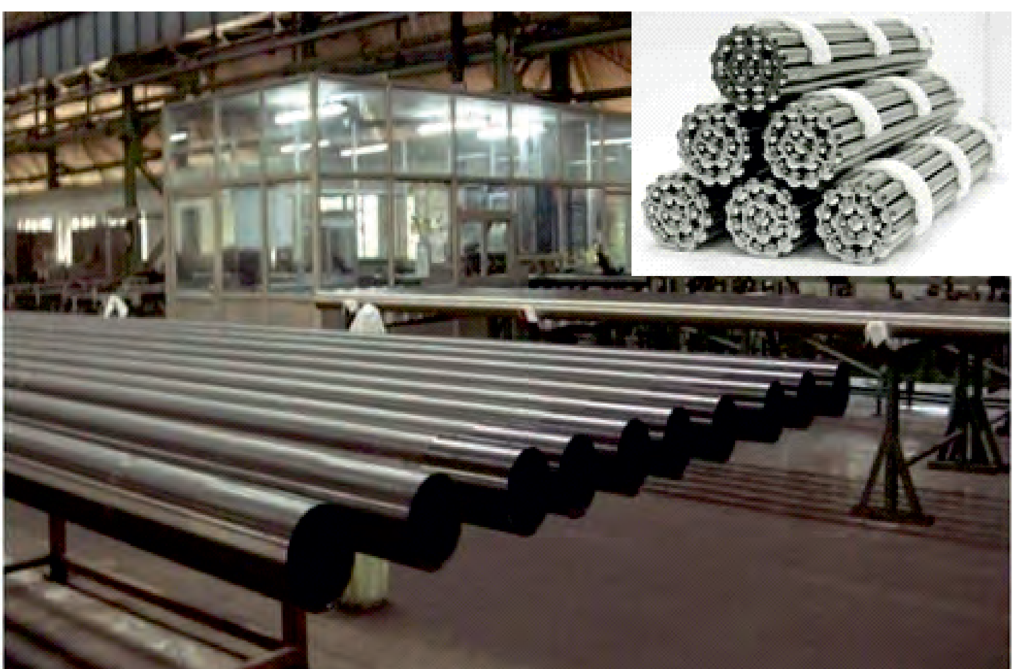


Fig. 2: Photo of pressure tubes produced at NFC. Inset shows fuel bundles produced at NFC

4.1. Zr Based Alloys

The work on the development of metallurgy of zirconium based materials is essentially due to their applications as structural material in the nuclear industry. Zr based alloys show their unique combination of low capture cross-section for thermal neutrons and good corrosion resistance in high temperature water (~300°C) [1].

The principal source of zirconium is zircon (zirconium silicate ($ZrSiO_4$)) which is found in the coastal beach sand in India. This sand also contains many other valuable minerals because of which a special physical beneficiation technology for the separation of the individual minerals was first established at BARC, Trombay at a pilot plant scale and subsequently, a plant was established in Tamil Nadu by Indian Rare Earths Limited (IREL) for the processing of Manavalakurichi beach sand. The zircon contains about 2.5% Hf, an element chemically similar to Zr and it was successfully separated at BARC using vapour phase dechlorination technique. A process for separation of Zr and Hf was developed by chlorination of Zircon, purification to obtain $ZrCl_4$ and $HfCl_4$mixed salt, selective dichlorination of $ZrCl_4$ from the vapour phase. This led to the formation of pure ZrO_2 in the residue by adjusting the ratio of the flowing gas mixture composed of chlorine and oxygen at high temperatures leaving the volatiles enriched with $HfCl_4$. Solvent extraction process was developed later for a more effective and larger scale separation of the two elements. Chlorination of $ZrO_2$was further optimized using static-bed reactor technology. Magnesio-thermic reduction of $ZrCl_4$ producing pure zirconium, Kroll process, was used for making zirconium sponge at BARC, Trombay and a schematic of the initially designed assembly having different heating zones used for carrying out Kroll process is shown in Fig. 3a [2].Iodide refining technology (Van Arkel-De Boer Process) was developed and demonstrated by C. V. Sundaram and his colleagues at BARC for making ultra-pure zirconium from impure zirconium and zirconium alloy scraps [2]. Fig. 3b shows anoutlook of the zirconium crystal grown by iodide refining process, and the inset of the figure represents the overall view of the crystal bar zirconium formed on U-shaped zirconium filament. Zirconium produced by Kroll process was subsequently vacuum arc melted to produce various zirconium alloys, such as Zircaloy 2, Zircaloy 4, Zr-2.5Nb, Zr-2.5Nb-0.5Cu, for structural components in nuclear reactors. A dedicated plant was further established in 1971 for the production of Zr and its alloys, and for the fabrication of different reactor components at NFC, Hyderabad.

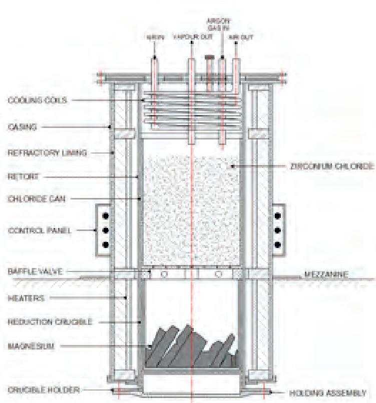


Fig. 3a: Schematic of the Kroll reduction assembly for zirconium sponge production designed at Bhabha Atomic Research Centre, Trombay

Fig. 3b: Zirconium crystal bar grown by iodide refining technique at BARC campus and the inset shows the crystal bar zirconium formed on U-shaped zirconium filament

In the early stage of development of zirconium-based technology, emphasis was given on the purity of zirconium as the raw material. However, very soon it was realized that very high purity of the product was not necessary. In fact, very soon it was realized that purer material has lower corrosion resistance in comparison to the impure materials. It was attributed to the presence of impurity elements like Ni, Cr or Fe, which were helpful in improving the corrosion resistance to Zr.

The first stage of the development program of Zr-alloys was to identify elements which can improve the corrosion resistance of Zr. First set of elements which were identified in decreasing order of effectiveness are tin, tantalum and niobium. Tin was selected as it was most effective in improving corrosion resistance without seriously affecting the neutron economy. The first series of Zircaloys was nearly binary alloy with nominal composition as Zr-2.5%Sn. This alloy was named as 'Zircaloy-1'. Zircaloy-1, when subjected to long-term high temperature water corrosion testing, gave disturbing trends. In place of expected decreasing rate of corrosion, the corrosion rates after a transition time increased and remained constant thereafter. Thus, an urgent search for an alternative alloy was initiated. Desperate attempts led to an accidental discovery of an alloy which, in fact, was the contamination of Zircaloy-1 with stainless steel. The resultant material proved to have substantially improved corrosion resistance. Subsequently the optimized alloy composition was worked out in terms of the iron content which was nominally set at 0.15%, nickel 0.05% because of its beneficial effect on high temperature corrosion resistance, 0.1% chromiumwas picked up as an impurity from the stainless-steel reacting vessels and Sn was reduce to 1.5 %, which was found to be adequate to mitigate the deleterious effects of nitrogen. This new alloy composition was designated as 'Zircaloy-2'. Zircaloy-2 was the structural material used for all nuclear reactors of that generation.

It was assumed that with increasing time Zircaloy-2 would also show accelerated corrosion similar to Zircaloy 1. A new alloy was therefore proposed where Sn was reduced to 0.25% and addition of 0.25% Fe was maintained to increase the strength of the alloy. This new alloy was designated as Zircaloy-3. During corrosion testing, this alloy could not outperform Zircaloy-2 and its inferior mechanical properties in comparison to Zircaloy-2 led to the discontinuation of the work on the alloy. During this time, deleterious effects of hydrogen on the strength of Zr component used in the core of a nuclear reactor was realized. A correlation between the hydrogen concentration and impact toughness led to intense research on the understanding of hydrogen behaviour in Zr alloys. In one such set of experiments, coating of nickel on Zircaloy plates showed significant increase in hydrogen pick-up. This observation led to the removal of Ni in the composition of Zircaloy-2 and the new alloys was called as “Ni-free Zircaloy-2”. However, this new alloy was having poor corrosion resistance. In later alloy when the loss of the Ni was compensated with increase in Fe, the alloy matched all the properties of Zircaloy-2 and with pick up of hydrogen nearly half of the Zircaloy-2. This new alloy was called “Zircaloy-4”

Currently, Zircaloy-2 and Zircaloy-4 are widely accepted Zircaloy-series of alloys for nuclear applications. However, hydrogen related problem became a daunting issue as the picked-up hydrogen during the operation of the reactor started precipitating in certain crystallographic direction during the cooling of reactors making the tubes susceptible for catastrophic failures. This led to the development of another alloy system with second best choice of element, niobium.

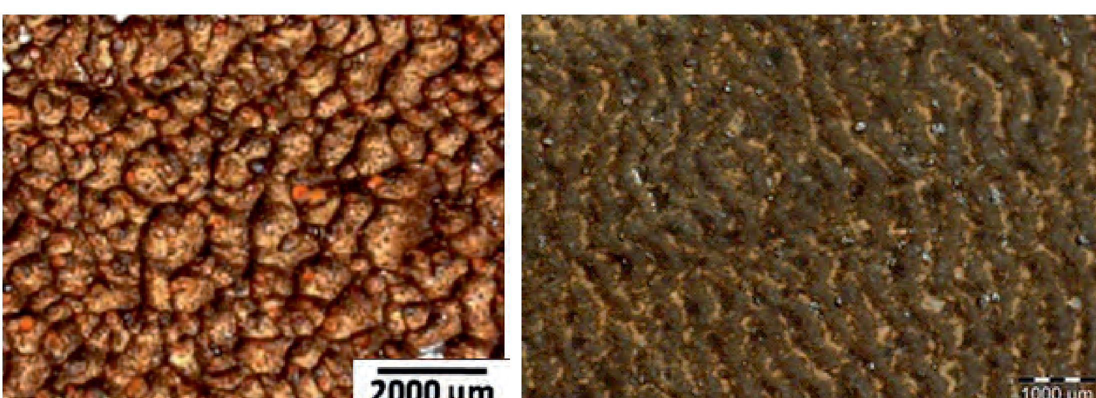
Initial development work on Zr-Nb alloy was carried out by Russian researchers. Among various alloys of Zr-Nb alloy systems, Zr-2.5Nb alloy was selected for pressure tube materials. The two-phase structure of the alloy offered much higher strength with adequate ductility. The presence of Nb in the alloy reduced the oxidation and hydrogen pick up in the pressure tubes. These qualities of Zr-2.5Nballoy allowed it to outperform Zircaloy-2 and, therefore, in later reactors Zr-2.5 Nb alloy replaced Zircaloy-2 as pressure tube materials.

Typical fabrication route for Zr-2.5 %Nb pressure tubes involves a combination of hot and room temperature working. The hot working is generally carried out in the (α+β) phase field where either forging or hot extrusion and involved. The room temperature work is in India is carried out using a pilgering route. This complex themo-mechanical treatment determines the volume fractions of the two phases, and their compositions, the aspect ratios of the α and β-grains and the crystallographic texture of the product. High strength along with a good ductility and toughness of Zr-2.5%Nb pressure tubes is essentially derived from the fine (α+β) fibrous microstructure consisting of elongated α-grains and the β phase stringers primarily located at α-grain boundaries. These microstructures are being constantly reproduced in nuclear fuel complex in components as large as 6 meters which could be considered as engineering marvels produced by Indian scientists and engineers [3].

4.2. Steels

4.2.1. Plain carbon steels

AISI A333 Grade 6 and AISI A106 Grade Bare extensively used for various pipelines and other components in the secondary circuit of NPPs (PHWRs and PWRs). A generic degradation mode is flow assisted corrosion (FAC) – both single phase FAC and two-phase FAC. FAC is a corrosion mechanism in which normally protective oxide layer on a metal surface dissolves in a flowing water. The underlying metal corrodes to re-create the oxide, and thus, the loss of the metal continues. Based on an extensive program, BARC examined the inner diameter surfaces of the components affected by thinning and removed from service from all the NPPs in Indiaandlarge database was created correlating the scallop size to the FAC rate. This database is now used to predict the FAC rate at a given location of a component. Typical signature patterns of single and dual phase FAC have been captured from the affected components and used to independently establish the mode (single or two phase FAC or erosion) of degradation (Fig.4). After establishing FAC prone segments in secondary circuit and from the basic knowledge available on such degradation, changes in chemical composition specification have now been incorporated for the feeder piping in primary circuit to impart additional resistance to FAC [4,5].



(a) (b)

Fig. 4:Typical signature pattern for (a) Single phase FAC (Scallops) and (b) Dual phase FAC (tiger stripe pattern) observed on Indian PHWRs secondary circuit components

4.2.2. Low alloy steels

Low alloy steels involving alloying elements likeMn-Ni-Mo (commonly known as western grade steels) orCr-Mo-V steels (commonly known as eastern grade steels)are widely usedas the structural material for the fabrication of reactor pressure vessel (RPVs) due to theirhigh strength and toughness. Prolonged operation under reactor operating conditions (neutron flux and temperature) results in the degradation of properties. The major degradation in mechanical properties of the RPV steel during reactor operation is ascribed to irradiation induced embrittlement. Since, the life of a reactor depends on the integrity of the RPVs, understanding the microstructural developments that occur all along in-service and their effect on the performance is of paramount importance. A detailed study wascarried out on acceleratedthermal aging at 450 °C up to 8,400 h. These experiments showed that the thermal aging embrittlement of Mn-Ni-Mo steel is primarily due to phosphorous impurity segregation at the grain boundaries.

In the easterngrade steel,both impact toughness and hardness reduced monotonically with transgranular cleavage fracture region increasing of aging duration. In this steel though sign of impurity segregationwere absent, transformation of Cr-rich M_7C_3 to $M_{23}C_6$ (M= Fe, Cr & Mo) carbides along with its coarsening and the corresponding Cr-Mo depletion at the carbide-matrix interface region appear to be the main reasons responsible for thermal aging embrittlement in these steels.

In order to evaluate the properties of these steels a relatively new approach was adopted where in place of full-size sample, small punch testspecimens were (miniaturised mechanical testing; 10 mm × 10 mm × 5 mm) used, which enabled easy extraction of specimens from the components in service (including irradiated specimens). SP tests could clearly capture the embrittlement due to thermal aging for both the steelsas investigated by the conventional CVN testing.

4.2.3. Stainless steels

It is a well-known fact that stainless steels derive their stainless properties due to the presence of oxides of chromium at the grain boundaries. Any depletion of these oxides compromises the corrosion resistance of the steel. Therefore, special efforts were made in BARC to improve the properties of the steels. The key features of the work on stainless steels are

(a) Grain boundary engineering to improve resistance to sensitization, intergranular corrosion (IGC) and intergranular stress corrosion cracking (IGSCC),

(b) development of nitric acid grade (NAG) SS and its use in spent fuel reprocessing and waste management plants,

(c) developing understating of IGC of austenitic SSs in applications in nitric acid with high operating potential and alternate alloys suitable for such applications,

(d) mechanism of addition of nitrogen to type 304L SS in improving its resistance to IGSCC in reactor simulated operating conditions and the role of a higher nitrogen making it even more prone to IGSCC, even in an annealed condition (in a worked condition) and

(e) establishing the mechanical and corrosion properties of a 13% Cr martensitic SS and correlating the effects of various austenitizing and tempering heat treatments on its properties, including hydrogen embrittlement (HE).

4.2.3.1. Grain boundary engineering

Stainless steels, like 304L and 316L,though highly resistant to uniform corrosion, are prone to sensitization making them susceptible to IGC and IGSCC. Extensive research at Materials

Group, BARC has unequivocally shown that a very high concentration of random boundaries offers an effective means of improving resistance to both IGC and IGSCC in austenitic stainless steels [6].

With cold working, increase in the fraction of random boundary from about 30-40% in the AR condition to about 70-80% after 80% cold rolling(followed by controlled solutionizing) was observed. The degree of sensitization (DOS) increased with increasing random boundary concentration, but dropped significantly beyond a "critical" value irrespective of the type of rolling (e.g., unidirectional or cross rolling).These results show significant decrease in the DOS at high percentage of reduction and correspondingly high randomization of grain boundaries. Also, the IGC rates, were lower for the 80% cold rolled, annealed, and sensitized samples in comparison to samples cold worked for20-60% followed by annealing. These results have clearly shown that samples with a very high fraction of random boundaries have high resistance to IGSCC.

4.2.3.2. Nitric acid grade of SS 304L

The operating conditions in nuclear fuel reprocessing and nuclear waste management plants, which handle nitric acid, are highly oxidising in nature and at high operating potentials in the nitric acid streams, the corrosion rate of structural materials are high. Austenitic SS used for these applications exhibits several corrosion problems as these steels are prone to IGC also in nitric acid environments which is attributed to chromium depletion and segregation of elements like silicon and phosphorus at grain boundaries. Tubular products of stainless steels are also prone to *end grain corrosion* [7] which is observed in the exposed cross-sectional faces of materials that contained inclusions or have segregation of Si and P along their working directions.

The general corrosion rate in oxidising nitric acid environments is as important [8] as the IGC and end grain corrosion. The corrosion of SSs in strong oxidising nitric acid medium occurs due to the oxidation of the surface film, Cr_2O_3, to form chromic acid in the solution making environment more oxidising and aggressive. This phenomenonis observed in those components in which nitric acid fluids are recycled or not refreshed periodically, as the corrosion products would keep on accumulating increasing the oxidising power of the process fluid.

This understanding of corrosion in oxidising environments led to the development of a nitric acid grade (NAG) of stainless steel [8,9]. The type 304L NAG has been indigenously developed and now being used in the nuclear reprocessing plants and in applications handling radioactive waste dissolved in nitric acid. The key approaches used in the development of 304L (NAG) were [8]: (a) control of intergranular corrosion by controlling C, Ni, Si and P in the SS and resorting to lower grain size, (b) control of end grain corrosion by reducing inclusion content in SS, specifically by controlling Mn and S content, (c) reducing segregation of elements, specially P, at grain boundaries to avoid end grain corrosion in highly oxidizing nitric acid environment (in the transition to transpassive regime) and (d) control over uniform corrosion by minimizing the concentration of corrosion products that are in higher valence state. A small amount of cold work is also known to improve the corrosion resistance.

4.2.3.3. Corrosion of non-sensitized stainless steels in high operating potential regimes in nitric acid service

Stainless steels have inherent limitations in nitric acid environment. The limit of potentials upto which a given SS can be used without intergranular attack (even for a non-sensitized microstructure) can be varied either by chemical composition or by microstructural features like grain size and cold working effects.

A methodology was developed at BARC to study the corrosion of SS in boiling nitric acid environment and measuring/applying any given potential [10]. This novel methodology enabled the measurement of weight loss during the exposure test and in establishing if the corrosion attack was due to intergranular corrosion. This methodology helped in establishing the effects of variables, like chemical composition, grain size, microstructure (step/dual/ditch structure), inclusions etc., on the propensity of intergranular corrosion at any applied potential. In addition, the methodology allowed to simulated the role of fission products present in nuclear spent fuel reprocessing studies at an applied potential.

Establishment ofpotentio-dynamic polarization behaviour at various temperatures in different concentrations of nitric acid showed the existence of a threshold potential above which intergranular corrosion of a given SS takes place and below which only uniform corrosion occurs [11]. Higher threshold potential represents superior resistance to IGC. This fundamental work led to many profound observations for stainless steel in nitric acid service, including the effect of the effect of temperature, nitric acid concentration and presence of oxidizing ions on increasing the operating potential. At a given applied potential, intergranular corrosion rates are in the order of type310L < type 304L (NAG) < type 304L.The studies also showed that the grain boundary engineering is effective in transpassive regime of potentials.

4.2.3.4. Improving resistance to IGSCC in simulated environment of NPP

An extensive work to establish the basic mechanism of IGSCC and to improve the resistance to IGSCC in high temperature high pressure aqueous environment on type 304L SS with addition of nitrogen content [12] has shown that nitrogen addition of 0.12 wt% helped in improving the resistance to IGSCC in reactor operating environment [12]

4.2.3.5. Martensitic stainless steels

Martensitic stainless steels (MSSs), such as type 403, 410 and 420, are widely used in different industrial sectors including nuclear power industry. The mechanical and corrosion properties of these MSSscan be tailored by the heat treatments. Typical heat treatment cycle consists of annealing followed by austenitization (hardening) and finally tempering.

The effect of different tempering treatments on localized corrosion, mechanical properties and hydrogen embrittlement (HE) of 13wt.% Cr MSS (e.g. type 420 SS) which is used in Indian light water nuclear reactors was studied in-depth. Localized corrosion resistance (intergranular and pitting) in tempered MSSs was shown to be lower than that of austenitized condition with the least resistance shown by MSS tempered at 550 °C

Tempering affected the mechanical properties too. Drastic reduction in impact toughness with intergranular (IG) cracking at room temperature was observed after tempering in the temperature range of 500 to 600 °C and ascribed to temper embrittlement phenomenon. The results obtained in this study showed that the 13Cr MSS when tempered at 700 °C, provides optimum mechanical properties, moderate resistance to localized corrosion and HE.

4.2.4. Reduced activation ferritic-martensitic steel

Reduced activation ferritic-martensitic steels are the one of the proposed candidates for first wall structure in fusion reactors. Reduced activation is achieved by the selection of appropriate alloying elements and by controlling substitutional and interstitial impurities. Reduced activation ferritic-martensitic steel are the derivatives of the commercially available modified 9Cr-1Mo steel where constituents producing radioisotopes having long half-lives (e. g. Mo, Nb) have been replaced by relatively lesser active counterparts (like W, Ta). Several countries have developed their own reduced activation ferritic-martensitic (RAFM) steels. India has developed its own IN RAFM steel which has nominal composition as Fe-9.04 Cr-0.08 C-0.55 Mn-0.22-V 1.4-W 0.06-Ta. Detailed characterization of IN RAFM steel has been carried out and when this steel was compared with other RAFM steels showed its performance similar to other steels. Detailed studies on their interactions with Pb-Li, a proposed coolant for fusion reactors, has shown that IN RAFM perform slightly better than the other steels [13]. The Presence of W appears to provide stability to oxide layer which improves liquid metal corrosion of the steel. Detailed studies on liquid metal corrosion of the steel under various conditions have been carried out at BARC, leading to development of a detailed mechanism of corrosion and various methods of mitigation of the corrosion.

4.2.5 Maraging steels

Maraging steels have a mutually exclusive combination of high strength and high ductility, high concentration of alloying elements and good weld ability, multiple phases and high corrosive resistance. These properties in this steel are achieved by lowering the carbon concentration to 0.03%, which ensures bcc-martensite while the high strength in the steel is achieve by the precipitation of intermetallic phases like Fe_2Mo and Ni_3Ti. Presence of several alloying elements in high concentration make the process of precipitation in these steels a very complex phenomenon and requires precious control over the aging treatment. Detailed studies on the precipitation process were carried out by Srikumar Banerjee and group [14] and not only many metastable phases were identified but their phase fields and crystallographic details were also determined. These details were used to generate crystallographic relations among them and sequences of phase transformations were established. Such studies have not only addressed several unresolved issues in the steel but also paved the way to design better maraging steels.

4.3. Nickel Based Alloys as Structural Materials in NPPs

4.3.1. Alloys for Steam Generator tubing

BARC has been working on all the three alloys (alloy 600, alloy 800 and alloy 690) to establish the sensitization behaviour, IGC susceptibility of the alloys after welding and to understand the mechanism of oxidation in SG, especially during hot conditioning of PHWRs (Fig.5).

In SG tubing materials, alloy 690 and alloy 800, heat affected zone (HAZ) formed due to autogenous welding is more susceptibleto IGC in comparison to any other part of the material, as these regions are exposed to the temperature regime of sensitization [15]. In the case of alloy 600,however, weld fusion zone (WFZ) was found to be more susceptible to IGC than HAZ. In laser welded condition, the DOS values for both WFZ and HAZ were comparatively lower than that in tungsten inert gas (TIG) weldments for all the alloys indicating that the higher heat input of TIG welding with slower cooling rates resulted in increased sensitization.

4.3.2. Alloy 600: Improving the resistance to sensitization and IGC by grain boundary engineering

Alloy 600 is known to be highly prone to sensitization and has high susceptibility to IGC; even in as-received annealed condition. Sensitization occurs when these alloys are exposed to a temperature range of 450 to 850 °C which led to the formation of Cr-rich carbides with concomitant Cr-depletion regions at the carbide-matrix interface regions. Alloy 600 is processed through suitable thermo-mechanical processing route to improve its resistance to sensitization/IGC resistance by increasing the percentage of low energy boundaries. The experimental results have shown that underas-received annealed condition the alloy is highly susceptible to IGC in boiling solution of ferric sulphate-sulphuric acid (G 28, ASTM test).

Various grain boundary engineering methods are used to improve the percentage of low energy boundaries to above 85%. This increase in fraction of low energy boundaries reduced the DOS values to 0.78% and 0.37%. Samples subjected to grain boundary engineering conditions showed no IGC attack in G 28, ASTM test, thus making the Alloy 600 resistant to IGC.

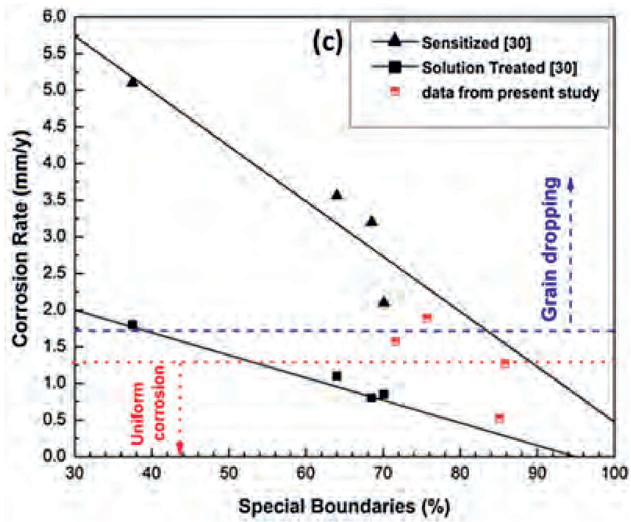


Fig.5: Decreased corrosion rate as a function of increased fraction of special boundaries

4.4. High Temperature Alloys

There are classes of alloys which can be used at high temperatures. This broad category of alloys includes superalloys and alloys based on refractory metals. Superalloys are high temperature alloys which can be used at a high fraction of their melting points. These have several other important properties like very good mechanical properties particularly creep strength, and resistance to high temperature corrosion. The temperature range of application of the superalloys is limited to about 1300 C. However, these can withstand oxidising atmosphere very well and hence find application in different parts of gas turbine engines. These applications also require very high creep resistance which the superalloys are capable of showing. Most of the superalloys are based on Ni.

4.4.1. Monel K 500

Monel family of alloys are Ni-Cu based alloys where their ratio is kept close to 70:30.Alloys of this family are known for their corrosion resistance in a variety of environments and hence find application in marine fittings, oil well drilling collars, pump shafts, impellers, condenser tubing etc. Monel K 500 is a precipitation hardenable alloy The alloy has small amounts of Al, Fe, Mn, S, Si and C which provide this alloy a good combination of strength and excellent corrosion resistance even in very aggressive environments like hydrogen embrittling condition or sulphide stress corrosion environment. Dey *et al*. showed that in this alloy the precipitation occurs by the classical homogeneous nucleation process with the precipitates maintaining their coherency and spherical morphology even after prolonged ageing. Dey *et al.* [16] have also examined the structure property correlation in this alloy at different temperatures and have shown that the alloys shows all test book features a typical precipitation hardenable alloys.

4.4.2. Alloy 718 and 625

Alloy 718 and alloy 625 are superalloys which have excellent combination of high temperature mechanical properties including very good creep resistance and corrosion resistance in hostile environment. these alloys derive their strength from metastable, ordered g" phase (tetragonal DO_{22} structure) [17]. This structure is based on the composition Ni_3Nb. Since this phase contains substantial amount of Nb, these superalloys contain a good amount of Nb. Due to the fact that" phase is a meta-stable phase, there is tendency for the stable Ni_3Nb phase to form which is the delta phase. The formation of this phase in a controlled manner leads to an improvement in the stress rupture ductility. On the other hand, formation of this phase in the coarse form in large amount leads to degradation of strength of the superalloys. In India, these alloys are produced by MIDHANI. Alloy 625 is used very extensively in Heavy Water plants.

4.5. Refractory-Metal Based Alloys

Niobium (Nb), tantalum (Ta), molybdenum (Mo), tungsten (W) and rhenium (Re) are mainly designated as refractory metals, based on their high melting points (>1925C). Except Re, their common areas of application are in steel industry and production of sintered carbide tools in the form of respective ferroalloys and carbides, respectively. Specific application such as that of niobium in the field of metallic superconductor and nuclear reactor, tantalum as miniature capacitor and tungsten as incandescent filament, molybdenum as heating element and cathode support and rhenium as alloy softener bestowed them prominent recognition. Refractory metals and their alloys are capable of meeting an environment aggressive with respect to radiation, temperature, corrosion (gaseous and liquid metal) and stress for prolonged period. These materials are therefore, being considered as high temperature structural materials, for new generation reactors like accelerator driven system (ADS), high temperature reactor (HTR), fusion reactors and reusable launch vehicles. Conventional superalloys containing nickel, cobalt or iron–nickel as the major constituents, meet restricted high temperature applications and fail to qualify the benchmark of aerospace and nuclear industries. Beyond 1200K, the refractory metal-basedalloys are the only candidate materials for structural purposes.

The technology for aluminothermic reduction of the respective oxides (Nb_2O_5, Ta_2O_5) to produce massive forms of niobium and tantalum metals was developed at BARC. The thermit metal is further refined and consolidated using electron beam melting in which purification is done by vacuum degassing, carbon deoxidation and sacrificial deoxidation mechanisms. Technology for the production of capacitor grade Aluminothermic reduction reactor was specially designed for making thermit vanadium with low amount of nitrogen, and subsequent electron beam melt refining. These metals were also produced by molten salt electroextraction using metal carbide as anode feed. The process flowsheet has also been established on laboratory scale at BARC to recover several refractory metals from low grade indigenous sources and various secondary sources. The flow sheet for low grade wolframite concentrate was developed with the objective of recovery of tungsten and other valuable associates. Process knowhow was established for producing tungsten metal powder by hydrogen reduction of WO_3.

4.5.1. Niobium based alloys

Niobium based alloys exhibit good combination of high temperature strength, chemical compatibility with most liquid metals, relatively easy fabricability, and stability under nuclear environments. Due to these unique properties, Nb alloys have found many applications ranging from structural components in space nuclear reactors, high temperature reactors, aero-space engine and several biological applications. An alternate process consisting of aluminothermic co-reduction of mixed oxides followed by arc and electron beam melt refining was developed for preparation of Nb-1Zr-0.1C alloy at Materials Group, BARC. The ingots of the homogenized alloy were produced after electron beam melt consolidation The lower deformation temperature (800°C) also provides an opportunity to jacket the material with Cu (Fig. 6). A high temperature liquid Lead-Bismuth Eutectic (LBE) loop named as kilo temperature loop (KTL) made of Nb-1Zr-0.1C alloy was set up in BARC for thermal hydraulics, instrument development and material related studies relevant to compact high temperature reactor(CHTR) [18]. The loop was operated up to 1100°C using natural circulation of molten LBE, and the potential use of the Nb-1Zr-0.1C alloy for high temperature reactor was demonstrated.

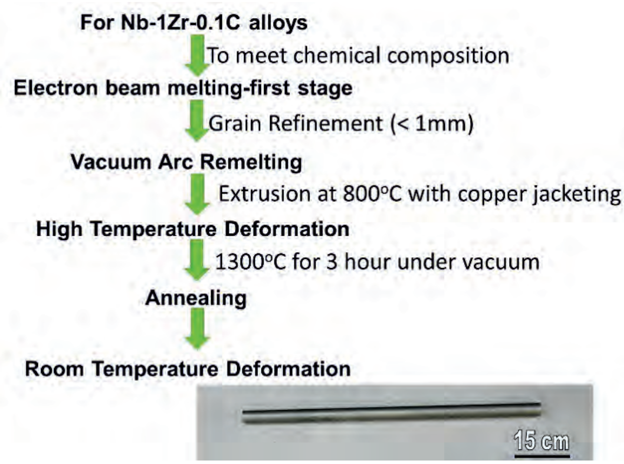


Fig. 6: Flow sheet showing processing of Nb. In the inset fabricated tube is shown.

4.5.2. Vanadium based alloys

Attractive properties of vanadium alloys, such as low neutron activation, superior resistance to irradiation swelling, low helium generation, superior liquid metal corrosion resistance, moderate thermal conductivity, and adequate mechanical strength make them potential candidates for structural applications in nuclear fusion and fast fission reactors. V-4Cr-4Ti alloywas identified as the structural material for fusion reactors operated in the temperature regime of 400-700°C. The temperature limit of the operational window of V-4Cr-4Ti alloy is majorly limited by the reduction in the strength and the issues related with helium embrittlement at elevated temperatures (exceeding 700°C). Addition of Ta as an alloying element in V-Ti system could improve the capability of the alloy for higher temperatures.

4.5.3. Tungsten based alloys

Tungsten has high melting point (3410°C), high density (19.26 g/cm^3) and superior mechanical strength at high temperatures. Tungsten metal is being considered to be used as plasma facing components of fusion reactors (ITER). Tungsten based heavy alloys (WHA) such as W-Ni-Fe and W-Ni-Cu possess distinguished properties with respect to absorbing radiation, mechanical strength and machinability. These are the ideal materials for a wide range of applications, such as in aerospace, the automotive industry, medical engineering and the construction industry. Different shapes of WHAs are used as gamma radiation shielding in the cancer therapy machines such as Bhabhatron. WHAs are used in the kinetic energy penetrators for military application.Technologies were demonstrated for preparation of pure tungsten metal powder and its subsequent consolidation by vacuum hot pressing. The components of WHA (W-2Ni-1Fe) were fabricated using liquid phase sintering approach and the product showed the desired mechanical properties and targeted density [19].

References

1. S. Banerjee and M. K. Banerjee, Encyclopedia of Materials: Metals and Alloys, Volume 1, (2016), 350-363.
2. R. B. Subramanyam, C.V. Sundaram, Trans. Ind. Ins. Metals, (1966) 9-20.
3. Phase Transformations Examples from Titanium and Zirconium alloys Ed. S. Banerjee and P. Mukhopadhyay, Pregamon Press,2007.
4. V. Kain, S. Roychowdhury, P. Ahmedabadi, D. K. Barua, Engineering and Failure Analysis 18(8) (2011) 2028-2041.
5. Vivekanand Kain, Proceedia Engineering, 86 (2014) 576-588.
6. D. Wasnik, V. Kain, I. Samajdar, B. Verlinden and P. K. De, Acta Materialia, Vol. 50, No. 18, (2002)4587-4601.
7. Vivekanand Kain, S. S. Chouthai and H. S. Gadiyar, British Corrosion Journal, Vol. 27, No. 1, (1992)59-65.
8. Vivekanand Kain and P.K. De, International Journal of Nuclear Energy Science and Technology, Vol. 1, Nos. 2-3, (2005)220-231
9. Vivekanand Kain, Corrosion Reviews, (2009)463-492.
10. Vivekanand Kain, Shagufta Khan, A.V.R. Reddy, P.K. Wattal, Advanced Materials Research (2013) 517-529.
11. S. Khan, Vivekanand Kain and A.V.R. Reddy, Corrosion, 70 (2014) 19-28.
12. S. Roychowdhury, V. Kain, M. Gupta and R. C. Prasad, Corrosion Science, Vol. 53(3), (2011)1120-1129.
13. P.Chakraborty, N.Naveen Kumar, N.Sai Krishna, N.K.Maheshwari, S.Bysakh, A.Bose, V.Kain, R.Tewari,Corrosion Science, Volume 183, (2021), 109321
14. R. Tewari, S. Mazumdar, I.S. Batra, G.K. Dey and S. Banerjee, Acta Materialia, vol. 48, (2000)1187-1200.
15. Geogy J. Abraham, RajanBhambroo, Vivekanand Kain, G. K. Dey and V S Raja, Journal of Materials Engineering and Performance, Vol. 22 (2) February (2013) 427-432.
16. G. K. Dey, R. Tewari, P. Rao, S.L. Wadekar and P. Mukhopadhyay, Metallurgical Transactions A, Vol.24A, (1993),2709-2719.
17. M. Sundararaman, P. Mukhopadhyay, S. Banerjee; Metallurgical Transactions, 19A (1988) 453.
18. B. Vishwanadh, K. Vaibhav, S.K. Jha, K.V. Mirji, I. Samajdar, D. Srivastava, R. Tewari, N. Saibaba, G.K. Dey, Journal of Nuclear Materials 427 (2012) 350–358.
19. Sanjib Majumdar, Jugal Kishor, Bhaskar Paul, Vivekanand Kain, Journal of Alloys and Compounds 818 (2020) 152897

Laser based Technologies and their Applications: DAE's Accomplishments

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Preamble

Department of Atomic Energy (DAE) has been working in the areas of nuclear research and nuclear power program along with many other frontier areas of science and technology. Lasers is one such frontier area that has revolutionized concepts and technologies, and has been deployed across the whole gamut of present day applications in diverse fields such as industrial processing, manufacturing, meteorology, defence, communications, medical procedures, diagnosis, and scientific research. DAE is actively pursuing Research and Development in the area of laser and photonics as it finds direct applications for various core programs of DAE like material processing, nuclear reactor refurbishment, mineral exploration, safety systems, meteorology, societal health applications, specialized component manufacturing etc.

1. Historical Background

DAE initiatives in the development of laser technology and planning their applications go back, not lagging much behind the time when the first laser system was demonstrated in 1960 at Hughes Research Laboratories, USA. The DAE stalwarts including Dr. Raja Ramanna quickly grasped the importance of laser technology and the role it can play in shaping DAE future projects and this paved the way to start laser activities in BARC. In 1965, BARC demonstrated GaAs semiconductor laser to set up a line of sight open air optical communication link between BARC (Trombay) and TIFR (Colaba). The DAE laser program got a fillip when in 1967, Dr. Dilip Devidas Bhawalkar joined the program, at the behest of Dr. Ramanna, as Scientific Officer at BARC after resigning from his lectureship at Southampton University, UK. Dr. Bhawalkar has brought in the dual expertise, into the system, of laser physics and electronics, with the degrees of

M.Sc. (Physics) from Sagar University, MP, India and M.Sc. (Electronics) & Ph.D. (Laser Physics) from Southampton University, UK. Under stewardship of Dr. Bhawalkar, BARC developed mature laser technology of gas CO_2 lasers, solid state Nd: Glass, Nd: YAG, Ruby lasers and liquid Dye lasers. These laser technology developmental efforts were accorded due recognition in the department with creation of Laser Section in 1973, then Laser Division in 1984 in BARC. With steady progress on the front of laser technology, enough confidence was generated to plan and pursue large scale application of laser based technologies. These included, studies on high resolution laser spectroscopy, laser plasma interaction, laser isotope separation, encompassing several Divisions of BARC including Spectroscopy Division, Chemistry Division and Multi-Disciplinary Research Section (MDRS) with guidance and contributions from eminent personalities such as Dr. P. R. K. Rao, Dr. U. K. Chatterjee, Dr. J. P. Mittal, Dr. B. A. Dassancharya and Dr. S. K. Sikka.

With the laser program firmly in place in BARC and witnessing a steep growth, in 1980s there was a need felt at DAE that a new centre needs to be set up dedicated to R & D on laser systems due to space and manpower constraints at BARC which was inhibiting further expansion of program. This was with a view to fully exploit the potential of laser based technologies for the departmental projects as well as for the applications in engineering, instrumentation, medicine, defence and basic research. In 1981, the Atomic Energy Commission (AEC) took a decision to establish a new research centre, focussed on development of advanced light sources such as lasers and high energy electron accelerator based synchrotrons, and development of associated technologies. This decision was duly approved by Government of India and a site selection committee was constituted in 1982 under the Chairmanship of Dr. Ramanna. The committee finally chose Indore to host the new centre. In fact, Dr. Ramanna, much later, reflected on the choice of the site as,

"As I recall, the centre was started for the propagation of advanced Science and Technology in the state of Madhya Pradesh. The more information is available to the Universities and the public at large, the better it will be for the beautiful state of Madhya Pradesh to take up the leadership in these fields once again, as it did in the ancient past."

DAE decision to set up new R & D centre at Indore was very enthusiastically approved by Government of Madhya Pradesh and then by Government of India. About 650 hectares of land was made available, around the picturesque 'Sukhniwas Lake' to the new centre. DAE formally started the new institute, named as 'Centre for Advanced Technology (CAT)' by an official order dated 27th June, 1983. 'CAT' was inaugurated, for commencement of project work by Honourable President Shri Giani Zail Singh on 19th Feb, 1984 in the presence of Dr. Raja Ramanna (Chairman, AEC). The construction activity at CAT, started in May, 1984. In June, 1986, first batch of scientist and engineer shifted to CAT to initiate the scientific activities. On 13th March, 1987, Dr Bhawalkar assumed the charge as founding director of CAT at a relatively younger age of 47, a post he continued for 17 years till his superannuation in 2003.Dr. U. K. Chatterjee handled the laser activities at BARC for many years after Dr. Bhawalkar shifted to CAT. On 17th December, 2005, 'CAT' was renamed in the honour of late Dr. Ramanna, as 'RRCAT –Raja Ramanna Centre for Advanced Technology' by honourable Prime Minister Dr. Manmohan Singh.

RRCAT now stands to be the largest scientific institute in the country engaged in research, technology development, establishing facilities and utilization of Lasers. Particle accelerators is the other major work area of RRCAT. Synchrotron based light sources Indus-1 and Indus-2 are developed at RRCAT and now operating as National facility in round the clock mode. RRCAT has distinction to be the only place in the country having synchrotron based light sources. Overall, RRCAT is spearheading the efforts in country on generating awareness on the application of laser/light sources in the spirit of 'Photons in The Service of Mankind through Science and Technology'. The subsequent sections of this article present the noteworthy DAE accomplishments in the field of development of laser systems, laser/photonics based technologies and their applications. Considering limitation of the space some of the major accomplishments are covered having substantial contemporary relevance.

2. Laser Technology Development

It has always been the motto of DAE to indigenously develop advanced technologies so that the technology deployment and utilization continue unhindered largely independent of imports. DAE primarily took the projects on the development of laser technology based on potential applications within the department. The laser systems crucial for DAE programs such as Copper vapour laser (CVL), Dye laser, Nd:YAG, Nd:Glass laser, Fiber laser, CO_2 laser, optical parametric oscillators, etc. have been developed at RRCAT/BARC. Brief description of these developed laser systems is mentioned below. The drafting of developed laser systems into the laser based technologies is elucidated in the next section.

2.1 CVL and CVL Pumped Dye Laser Oscillator-Amplifier Chain

Atomic vapour laser isotope separation was considered to be an efficient solution because of high separation factor. In this process, the isotopic atom can be selectively excited by matching laser wavelength (without affecting other isotopes) which is finally photo-ionized and separated out. DAE embarked on the development of laser based technology for this objective. The kHz repetition rate, 10s of ns pulse duration, high average power CVLs and their configuration to operation in oscillator-amplifier (MOPA) chain as the pump source of wavelength tunable high power dye laser chain, provided the best solution. The development facility of high repetition rate (5 -10 kHz) copper vapour laser (wavelengths, 510 nm & 578 nm), as a pump source to wavelength tunable dye laser is established at RRCAT. Simultaneously, development of dye laser oscillator-amplifier MOPA was taken up in BARC. In collaboration, RRCAT developed CVLs are used (as pump source) in BARC dye laser facility, aimed at isotope selective excitation/ionization based on multi-colour resonance ionization. The establishment of CVL and Dye Lasers chain systems made a very good success story of laser technology development and deployment in DAE.

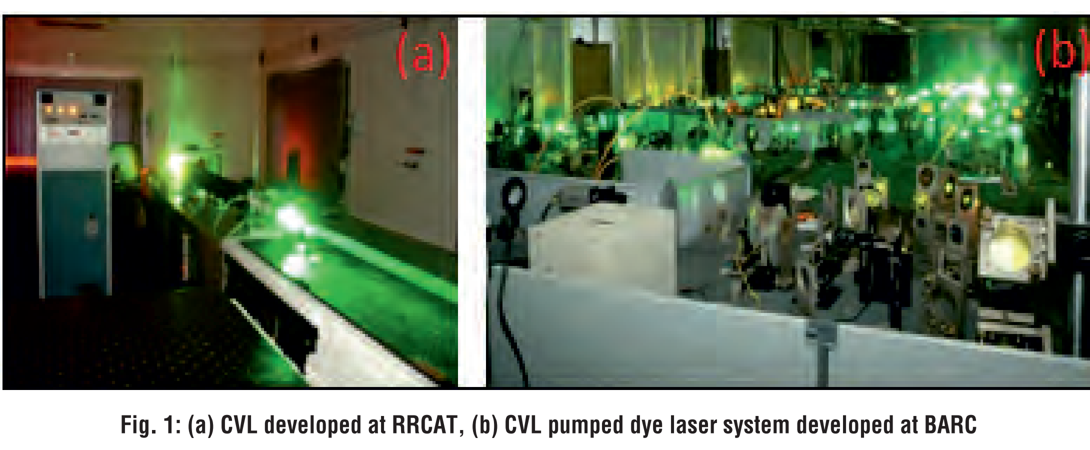

Fig. 1: (a) CVL developed at RRCAT, (b) CVL pumped dye laser system developed at BARC

2.2 Nd: YAG and Nd: Glass Lasers

DAE has established expertise in the development of Nd: YAG, Nd: Glass and other solid state lasers. RRCAT developed pulsed and continuous wave (cw) Nd:YAG lasers are the work-horses in laser based systems used within DAE for material processing applications such as metal cutting, drilling, welding, shock peening and additive manufacturing. Single frequency cw solid state lasers find application in precision laser interferometry. High pulse energy Nd:Glass laser MOPA systems are established at RRCAT/BARC for basic research in laser plasma interaction and shock wave physics. The laser systems developed at RRCAT are,

(a) Flashlamp pumped, high average power (250 -1000 W), high peak power (5 -20 kW), 2-40 mspulse duration, 1-100 Hz repetition rate,IR (~ 1064 nm) Nd:YAG laser systems

(b) 1 kW average power CW diode pumped, IR (~ 1064 nm) Nd:YAG lasers

(c) 7 J/10 ns, flashlamp pumped, IR (~ 1064 nm) Nd:YAG system

(d) Frequency doubled, green 532 nm, kHz repetition rate, 10s of ns pulse duration diode PumpedNd:YAG lasers

(e) Single frequency diode pumped CW Nd:YAG and Nd:YVO_4 lasers

(g) 100 J/1ns flashlamp pumped, IR (~1054 nm)Nd:Glass MOPA system

So far about 50 solid state laser systems have already been developed and are being utilized at different DAE institutes, majority of them in reactor maintenance as described in next section.

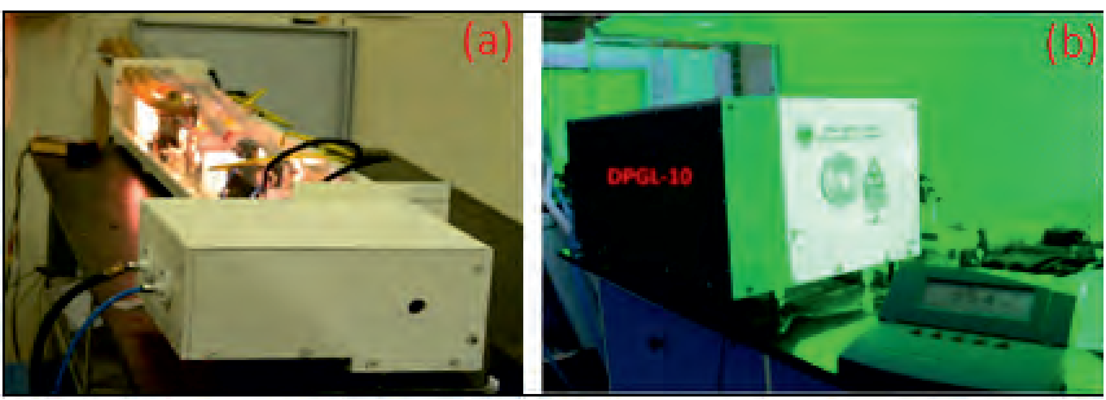

Fig. 2: RRCAT developed (a) Flashlamppumped IRNd:YAG laser and (b) Diode pumped greenNd:YAG laser

2.3 Fiber Lasers

Fiber laser systems are projected to be the future of industrial processing, additive manufacturing and medicine (surgery) industry. This is due to fiber lasers being highly robust, efficient, compact and high beam quality even at kW level average laser powers. No external optics is needed as fiber Bragg gratings (FBGs), fused with gain fiber at both the ends, act as resonator mirrors. Hence fiber lasers are free from alignment issues which are quite prevalent in other lasers. RRCAT took projects in the development of kW class CW fiber laser systems for field deployment as well as the development of femto-second pulse duration mode locked fiber laser for basic research. The major accomplishments are,

(a) Development of 1000 W, laser diode pumped Yb doped CW fiber laser system (~1080 nm) for material processing applications

(b) Development of 100 W, laser diode pumped Thulium doped CW fiber laser system (~1940 nm) in eye safe regime for surgical applications

(c) Development of 50 W, laser diode pumped Erbium doped CW fiber laser system (~1600nm) for sensing applications

(d) Development of 4 W, mode locked (~ 160 fs) Yb doped fiber laser MOPA system

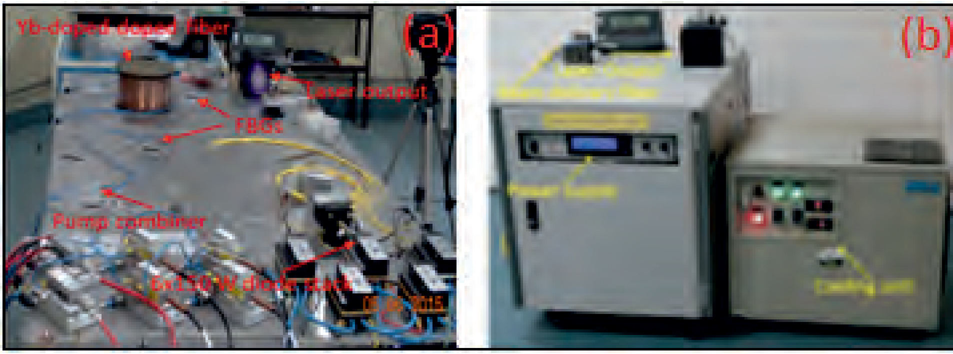

Fig. 3: RRCAT developed CW Fiber Laser (a) Inside component view, (b) Assembled Laser system

2.4 CO_2 Laser, Excimer Laser and N_2 Laser

The development of high average power and pulse energy IR (~ 10.6 µm) CO_2 laser started very early in BARC and subsequently taken up in RRCAT. This is in view of their large applications due to their high absorption in organics, glass, plastic, tissues and water. Variety of CO_2 lasers of CW operation with kW average power, pulsed operation with several Joules pulse energy and line-tunable lasers have been developed in RRCAT. There is a recent trend to replace CO_2 laser with solid state lasers with advantage of fiber optic beam delivery. However, for niche applications, CO_2 laser are still being heavily used. DAE has also successfully developed pulsed UV (250-350 nm) Excimer and N_2 lasers. Utilization of Co_2 and N_2 lasers in industrial/ medical applications is successfully demonstrated by RRCAT by taking onboard the end users.

2.5 IR Free Electron Laser (IR-FEL)

RRCAT has designed, developed and commissioned an IR-FEL. This laser system is a very complex technology based on the suitable combination of a high energy electron linear accelerator (LINAC), an undulator and the laser resonator. Electron linac of energy, 18 – 25 MeV is used to obtain tunable 12.5 – 40 µm, wavelength laser operation with high peak pulse power and low average power. This IR tunable FEL is a complementary coherent laser source to the laser systems already discussed and have huge application potential in material science and other fields.

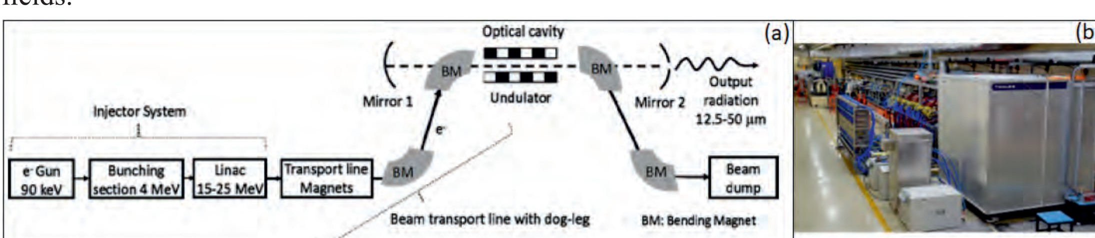

Fig. 4: RRCAT developed IR FEL, (a) System schematic, (b) IR-FEL system depicting e Gun bunching, bunching section and linac part.

3. Laser and Photonics Based Technologies and their Applications

In DAE, the lased based technologies, mostly based on laser systems developed at RRCAT and also a few of them based on readily available laser sources, have been developed and deployed with excellent outcomes. The deployment has been in the field our nuclear power programs, industry, production, healthcare application etc. Some of these technology applications pursued are presented here.

3.1 Nuclear Power Programme

Laser based cutting/welding technologies to address specific challenging demands related to maintenance of nuclear power reactors are very much required. Some novel, unique solutions are developed for this purpose by RRCAT. The laser systems have performed extremely well. Deployment of the laser systems at various Nuclear power plant sites is indicated in Table 1.

Table 1: RRCAT developed laser systems as deployed for nuclear reactor refurbishment

Laser system deployed for	Nuclear Site	Year
Bellow lip cutting during en-masse coolant channel replacement (EMCCR) campaigns	*NAPS-1, NAPS-2, KAPS-1, KAPS-2, KAPS-1*	*2006, 2008, 2009, 2017, 2018*
Removal of single selected coolant channels for PIE studies	*KAPS-2, KAPS-1, RAPS-4, TAPS-4, KGS-1*	*2005, 2012, 2016, 2017, 2018-19*
Retrieval of PT stubs for PIE studies	*KAPS-2, KAPS-1, RAPS-4, TAPS-4, KGS-1*	*2013, 2016, 2017, 2018-19*
Cutting of triangular yoke blocks	*RAPS-3*	*2014, 2016, 2018*
Cutting of SG tube and axial slitting at rolled joint region	*NAPS-2, RAPS-5&6, KGS-3&4*	*2009, 2014, 2018*
Removal of SG tubes for condition monitoring	*KKNPP-2*	*2016*

In these systems fiber coupled flash pumped Nd:YAG lasers are used. This technology brings in the high advantage of remote and faster material processing in difficult to reach locations such as between the congested 306/392 coolant channels of 220/540 MWe PHWRs as well as in Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs). Special optical beam delivery methods with/without assist gas, nozzles, mechanical fixtures, etc. are developed as a part of the system. Enormous reduction in process time, MANREM consumption, and cost are the attributes of laser based technology as applied to nuclear reactor refurbishment as compared to conventional mechanical techniques. This is essential for safe use of nuclear reactors with longer operating lifetimes. Laser welding process for Prototype Fast Breeder Reactor (PFBR) fuel pins is also established using RRCAT developed pulsed Nd:YAG laser. RRCAT also developed and patented laser welding of superconducting RF niobium cavities. Fabrication of these RF cavities is a crucial technology area for development of advanced accelerators.

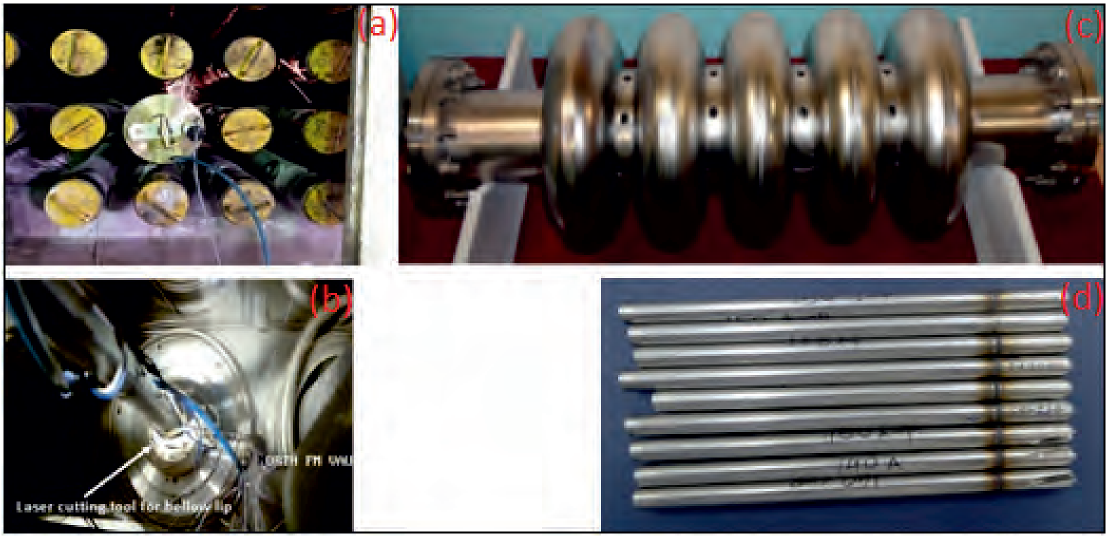

Fig. 5: RRCAT developed Laser based technologies for departmental applications, (a) In situ laser cutting during EMCCR, (b) Bellow lip cutting of TAPS-4, (c) Laser welded 5 cell SCRF niobium cavity (d) Laser welded PFBR fuel pins

3.2 Fiber Sensors

RRCAT has established a laser based technology for production of Fiber Bragg Grating (FBG) sensors. These fiber sensors are basically used for temperature and strain monitoring. These sensors are immune to electro-magnetic interference (EMI) and can withstand nuclear radiation, thus have vast applications in high EMI/radiation, nuclear and accelerator installations of DAE. FBG fabrication facility is a truly indigenous technology as the laser (CVL), its second harmonic (λ = 255 nm), and FBG writing set up, are all developed at RRCAT. The FBG temperature sensor is based on monitoring/recording the Bragg Wavelength shift (BWS) vs change in object temperature to which FBGs are attached in proximity. Single point/distributed FBG based temperature sensors have been installed at Advanced Fuel Fabrication Facility (AFFF), Tarapur and at Indus-2, Indore. RRCAT developed FBGs are being shared with national research institutes and industries for sensor development for different applications. Under the RRCAT incubation centre, custom made FBGs are being shared with a startup based at IISc Bengaluru. The sensors are found to be satisfactory in field trials by the startup company for various safety monitoring systems for Indian Railways. Deployment of many innovative systems for the railways will be possible due to availability of the FBG sensor fabrication technology from RRCAT.

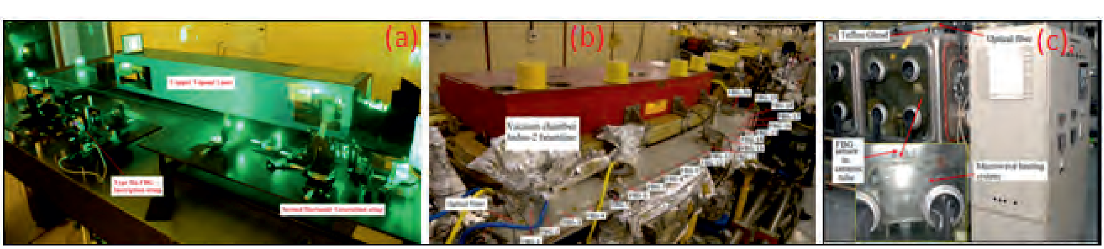

Fig. 6: RRCAT developed FBG Sensor technologies (a) FBG fabrication set up; Distributed FBG temperature sensors installed at (b) Indus-2 vacuum chamber& (c) AFFF, Tarapur

RRCAT also developed another type of distributed fiber temperature sensor based on optical Raman scattering of laser pulses, propagating in a multimode optical fiber. This sensor system is named 'Agni Rakshak (AR)' in view its potential to detect the onset of fire as well as marking the fire location. Raman backscattered 'anti-Stokes' signal determine the temperature of hot spot/fire and Optical time domain reflectometry (OTDR) principle determines the location of fire. The 'Agni Rakshak (AR)' is installed, as fire safety system, in 172 m circumference ring of Indus-2, all along high current cable that powers Indus-2 subsystems. The AR technology is being transferred to industry and is also made available under incubation.

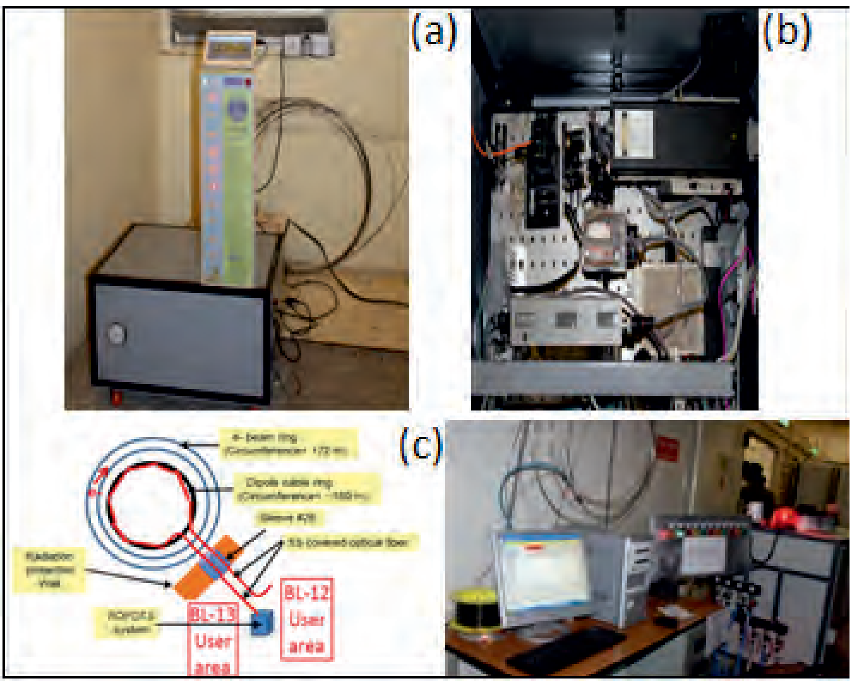

Fig. 7: RRCAT developed Laser based technologies for departmental applications, (a) In situ laser cutting during EMCCR, (b) Bellow lip cutting of TAPS-4, (c) Laser welded 5 cell SCRF niobium cavity (d) Laser welded PFBR fuel pins

3.3 Meteorology and inspection

RRCAT has developed photonics machine-vision based technologies for precision metrology i.e. dimension measurement of nuclear components such as fuel pellets, fuel pins, end caps, end plate, bearing & spacer pad, spring support, etc. Conventionally these tasks, handled by skilled operators, are time consuming and prone to errors. Repetitive high speed performance along with the desired accuracy (~ a few microns) of the measurement system as desired for quality assurance purpose for the expanding nuclear power program is achieved by the machine vision systems. The collimated light (LED) based system captures the 2D shadowgraph of the illuminated object on a CCD camera. The image is processed using advanced machine vision algorithms to extract dimensional data of the object. Many such systems have been developed in RRCAT and are incorporated in the production line of NFC, Hyderabad, for the meteorology and inspection of components fabricated for PHWR, BWR and FBTR.

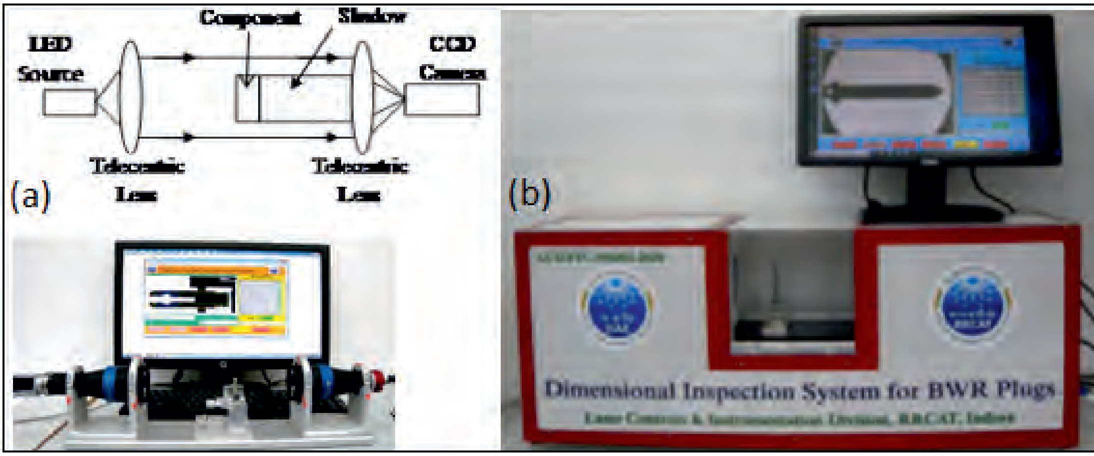

Fig. 8: RRCAT developed nuclear metrology set up, (a) Operating principle, (b) Full System

3.4 Additive Manufacturing

Laser Additive Manufacturing (LAM), opened up novel ways to manufacture components of very complex shapes and of varied material combination, hitherto considered very difficult or impossible. In view of high potential of LAM technology, RRCAT initiated a comprehensive LAM R&D activity involving system design and development, material processing, material testing, qualification and validation, and multi-physics process modelling. RRCAT developed and established both types of LAM system technologies, based on Laser Directed Energy Deposition (DED) and Powder Bed Fusion (PBF).

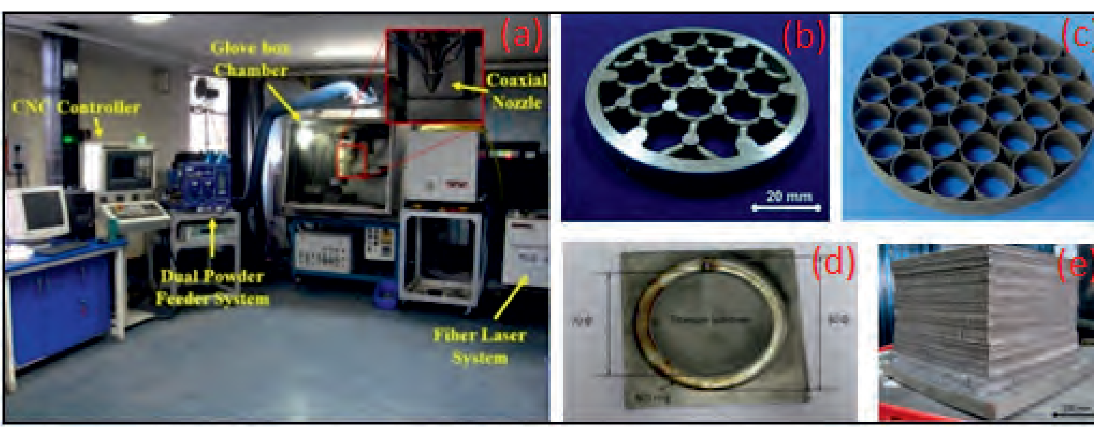

Fig. 9: 8RRCAT developed nuclear metrology set up, (a) Operating principle, (b) Full System

The DED system is equipped with 2 kW CW fiber laser, twin powder feeder, glove box chamber, gas analyser and five-axis manipulator. The PBF system, uses a CW fiber laser of 500 W power. Both systems have maximum building volume of 250 x 250 x 250 mm^3. Few examples of components, recently developed using LAM facility at RRCAT,

(i) *Honeycomb geometry orifice plate* as pressure drop device in Fast Breeder Reactor (FBR) for enhancing the desired temperature and flow distribution of liquid sodium coolant.

(ii) Mesh type spacers as needed in 540 MWe PHWR fuel bundle for fuel cluster simulator.

(iii) Nickel-Titanium (Ni-Ti) Shape Memory Alloy (SMA) structure as actuator in micro-pump and valves in Micro-Electro-Mechanical-Systems (MEMS).

*(iv) Other Components:*200µm thick SiC layers on Zircaloy tube and Molybdenum deposition on CuCrZrfor high temperature applications such as ITER.

RRCAT LAM expertise is being shared with other DAE units and the spare capacity will be shared with industry under Incubation policy of RRCAT.

3.5Biomedical applications

A very active and focussed program on Biomedical Applications of Laser/Light sources is being pursued at RRCAT. The aim is to develop novel optical technologies for advanced diagnosis and also for treatment of disease and dysfunction. Active research areas include the development of point-of-care medical devices for improved healthcare.

Table 2 lists the details of some of the recent RRCAT developed healthcare technologies. It is interesting to note that the earlier models of OncoDiagnoScope were based on N_2 laser. However in the latest models, a LED is used as the source of UV radiation.

Table2: RRCAT developed biophotonics healthcare technologies

Devicefor Healthcare application	Functioning	Current status
TuBerculoScope	*Fluorescence imaging device for rapid detection of tuberculosis*	*Technology transferred, 2018, 2 units shared for clinical trials at hospitals in Varanasi*
OncoDiagnoScope	*Optical spectroscopybased point-of-care device for instant non invasive diagnosis of oral cavity cancer*	*Technology transferred, 2019, Validation at cancer screening camps and clinical trials at hospitals*
OncoVision	*Fluorescence imaging tool for identification of malignant and potentially malignant lesions of oral cavity*	*Technology transferred, 2022*
Raman Probe	*In situ measurement of good quality Raman spectra from low Raman active materials like biological tissues*	*Technology transferred, 2018*
NeelBhasmi (नीलभस्मी)	*UV based area sanitization device to inactivate various micro-organisms including corona viruses*	*Technology transferred, 2020. Deployed in many installations.*

RRCAT also developed medical technologies such as '*Green Laser Photocoagulator'* for diabetic retinopathy which was demonstrated and successfully used in hospital. Technology of precision Laser welding of titanium heart pacemaker was developed and transferred to Industry. RRCAT is also pursuing research on non-invasive, in-vivo Raman scattering based differentiation between normal and malignant tissues. Research into Photodynamic therapy and low level laser therapy is also being carried out.

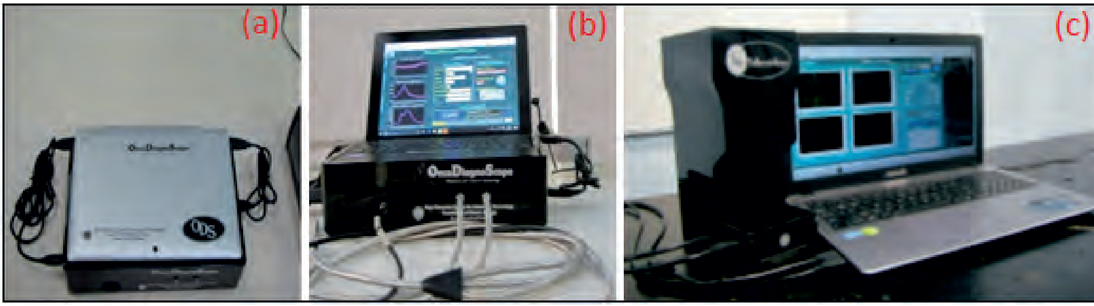

Fig. 10: RRCAT developed healthcaretechnologies, (a) OncoDiagnoScope, (b) GUI for OncoDiagnoScope, (c)TuBerculoScope

3.6 Research and Development Activities in the Advanced Areas Using Lasers

Laboratory facilities are established at RRCAT and BARC based either on in-house developed laser systems or imported laser systems for research and development in advanced areas. This includes setting up of high energy, high power Nd: Glass laser chain for studies at high pressure & temperature. Ti-Sapphire laser system with peak power of 1PW and 25 fs pulse duration is recently commissioned at RRCAT. The high peak power laser systems are used for studies at ultra-high intensity, electron acceleration, wakefield acceleration etc. Ultra-low temperature studies using laser cooled atoms, demonstration of atom chip and Bose-Einstein condensate are also carried out at RRCAT. Laser Interferometer Gravitational Wave Observatory (LIGO) is a much talked Mega-Science project and RRCAT is the nodal agency for establishing the Laser Interferometer Gravitational Wave Observatory in India with other institutes like, IPR (Gandhinagar), IUCAA (Pune) and DCSEM (Mumbai) in collaboration with partners in USA. A site in Hingoli district in Maharashtra state is being developed to set up the LIGO observatory which will complement two similar observatories in the USA. This challenging and prestigious project got in principle approval in 2016. The LIGO facility in India will open up new vistas in the field of science.

4. Concluding Remarks

This article covers the initiation and development of laser program activities in Department of Atomic Energy (DAE). Historical perspective on formation of Raja Ramanna Centre for Advanced Technology, Indore, the premier institute in India in the area of laser is presented. Laser systems developed in RRCAT are briefly covered along with their prominent applications. Overview of Photonics based systems developed at RRCAT, as a part of laser program activity, is given. The machine vision based systems are developed to specifically address the DAE specific requirements whereas the biophotonics systems for societal health applications are outcome of research in the area of lasers in biology and medicine. Research and development activities taken up in the advanced areas using specialized laser systems are briefly indicated. RRCAT/BARC built laser technologies not only supported the departmental projects but has also been applied to the industry and healthcare fields and have been instrumental in creating awareness of the importance of laser field throughout the country.

Acknowledgements

The authors acknowledge the dedicated efforts of all the colleagues in BARC and RRCAT, instrumental for the development and utilization of the laser based technologies as presented in this article. Efforts of trainees, researchers and partners outside the DAE, in developing the laser systems and applications of the laser systems, are duly acknowledged.

Indian Accelerator Program-An overview

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Preamble

Accelerators are playing an important role both in basic research and beneficial applications in the fields of healthcare, national security, environmental science, food preservation, etc. In India, very significant progress has been made, during last few decades, towards design and construction of accelerators. A large number of small and big accelerators have been built and being regularly used. Funding agencies are also supportive for the new projects particularly for societal and industrial applications. In this article, an overview of the Indian accelerator development program is given.

1. Introduction

A particle accelerator is an instrument used to increase the kinetic energy of charged particles such as electrons, protons and heavy ions. For an experimental nuclear scientist, the particle accelerator is similar to that of a microscope to a biologist and chemist or a telescope to an astronomer where the resolution/resolving power of the instrument depends on the wavelength of the probe/particles. In accelerators, higher the energy smaller will be the wavelength so resolving will be better and one can investigate the smaller size objects. Accelerators are part of our daily life and we are using them every day. In general, we are regularly watching television (TV), where the electron beam is accelerated, focused, deflected and scanned.

Accelerators were initially developed for fundamental research with primary aim to understand the structure of the nuclei, the nature of the nuclear forces and the properties of the nuclei not found in nature. Currently, accelerators play very important role both in basic and applied research. They are now used very extensively, in addition to basic research, for medical science, industry, national security, environmental science, production and study of new particles and super-heavy elements, etc. The radioisotopes produced using accelerators are used for medical diagnostics and treatment, particularly for cancer therapy. Electron accelerators are used for food preservation, and as Synchrotron Radiation Sources for material science research. Recently, it is proposed to use accelerators for nuclear energy generation using Thorium (^{232}Th) as fuel [1] which is abundantly available in India. These thorium-based systems are expected to be inherently safe. Today, accelerators in the energy range of keV to TeV have been designed and built. The large accelerators are used in research on the fundamental interactions of the elementary subatomic particles.

In 1919, Rutherford discovered proton through following reaction between a nitrogen nucleus and alpha particles [2]:

$^{14}N + {^4}He \rightarrow p + {^{17}}O$

Discovering proton was a landmark experiment and he was given Nobel Prize in 1908 for disintegration of elements using alpha particles from radioactive sources. Till 1932, most of the nuclear physics studies were done using energetic alpha particles released by the decay of radioactive elements. The maximum kinetic energy of these naturally emitted alpha particles was 6-8 MeV, which was not enough to disintegrate heavy elements and hence it was felt that in order to disintegrate heavier nuclei by alpha particles, it would be necessary to accelerate alpha particles to higher energies. Although, at that time it looked difficult to generate, in laboratory, voltages sufficient to accelerate particles suitable for nuclear research, the calculations of Gamow [3] indicated that considerably less-energy ions would be sufficient for the purpose. This was known to happen due to the tunneling effect. This inspired scientists and engineers to build accelerators that could provide ions with sufficient energy for nuclear physics research.

Charged particle accelerator development in the world started in the late 1920s. In the next 40 to 50 years, the growth towards development of technology and a variety of accelerators all over the world was phenomenal for fundamental research as well as beneficial applications.

The first successful experiments with artificially accelerated ions (protons) were performed by Cockcroft and Walton in 1932 [4]. Using a voltage multiplier, they accelerated protons to more than 700 keV and bombarded them onto the lithium nucleus to produce two alpha particles:

$p + {^7}Li \rightarrow {^4}He + {^4}He$

This was the first nuclear physics experiment where a nucleus was transmuted using artificially accelerated proton beam. They received Nobel Prize in 1951 for this work.

2. Brief History of Accelerator Development

By 1931, R J Van de Graaff had constructed the first belt-charged electrostatic high voltage generator [5]. In a Van de Graaff generator, the voltage is generated by transferring charge to high voltage terminal using a belt made up of an insulating material like nylon or rubber. The high voltage terminal along with pressure vessel forms a capacitor and develops a voltage V (= Q/C) when charge Q is transferred to the capacitor. Here C is the capacitance of the capacitor. The structure of Van de Graaff accelerator was modified by adding one more high voltage column section and putting the ion source outside at ground potential (tandem accelerator). In a tandem accelerator [6], negative ions are injected into the low energy accelerating tube. They are converted into positive ions in the stripper system located in the high voltage terminal before their acceleration in the second accelerating tube. This allows acceleration of heavy ions also and to higher energies. Charging was further improved by replacing the belt by pellet chain and the accelerators are called pelletrons [7]. Tandem accelerators up to 35 MV terminal potential [8] have been designed and built. The SF_6 is used as insulating gas in these accelerators.

In 1928, the principle of the linear accelerator was demonstrated by Wideroe [9]. He used alternating high voltage to accelerate sodium and potassium ions to energies twice as high as those imparted by one application of the peak voltage. In 1931, E O Lawrence and David H Sloan at Berkeley, USA, employed high-frequency fields to accelerate mercury ions to 1.2 MeV energy. The cyclotron was conceived by Lawrence as a modification of linear accelerator. The particles in a cyclotron follow circular orbits under the influence of a magnetic field making it a compact accelerator. Lawrence and Livingston demonstrated the principle of the cyclotron in 1931 [10], accelerating ions to 80 keV and protons to more than 1 MeV energy. In 1940, Kerst constructed the first betatron [11], a magnetic-induction accelerator for electrons. During the period of 1930s, the accelerator physics and technology developed very rapidly all over the world. Accelerators even in TeV energy range have been designed and built. Some of big accelerator laboratories where high energy accelerators are developed are CERN, Geneva, Switzerland; Fermi National Accelerator Laboratory, USA; Brookhaven National Laboratory, USA; DESY, Hamburg, Germany; KEK, Tsukuba, Japan; Nuclear Physics Laboratory, Dubna, Russia to name a few.

3. Indian Accelerator Programme

In India, accelerator development started in the 1940s, when Meghnad Saha decided to build a 38" cyclotron, based on the Lawrence's cyclotron at Berkeley, at the Saha Institute of Nuclear Physics (SINP), Calcutta (now Kolkata). He sent his student (B D Nagchaudhuri) to Berkeley to learn the technology. It delivered an internal proton beam current of 50-70 μA at 4 MeV in 1960 and later an external beam for experiments. Although it took time to complete the project it gave lot of confidence and encouragement to the Indian scientists to take up the accelerator developmental work. At the Tata Institute of Fundamental Research (TIFR), Mumbai, a 300 keV open air Van de Graaff accelerator was built and operated and also development work on a 1 MeV electron linear accelerator was carried out. Simultaneously, Cockcroft-Walton accelerators were built at the SINP and the Bose Institute, Calcutta (Kolkata), a 1 MV Cockcroft-Walton accelerator (Cascade generator) was bought and installed at TIFR, Mumbai and a 150 kV neutron generator was built at the Aligarh Muslim University (AMU), Aligarh [12].

For the first time a large accelerator, a 5.5 MV Van de Graaff accelerator, purchased from the High Voltage Engineering Corporation (HVEC), USA, was setup in 1962 [13] at the Bhabha Atomic Research Centre (BARC), Mumbai. Though the accelerator was purchased, the switching magnet, beam lines and experimental setups were built indigenously. It provided μA beam currents of protons and alpha particles. The facility was used extensively for nuclear physics and atomic physics experiments. Fig. 1 shows Homi Bhabha, Raja Ramanna and other senior scientists during inauguration of the Van de Graaff accelerator at BARC, Trombay, Mumbai.

Sometime later, a 2 MV Van de Graaff accelerator, also purchased from the HVEC, was installed at the Indian Institute of Technology (IIT), Kanpur, and a 2 MeV electron accelerator was built indigenously at the Indian Institute of Science (IISc), Bangalore. Using these accelerators for research, stimulated the scientists and a need for bigger accelerators was strongly felt. Homi Bhabha, the then Chairman, AEC, addressed the issue and convened a meeting in 1964 at the IISc. In the meeting, it was decided to have two large accelerators for the nuclear physics experiments for the Indian scientists. It was decided to buy a heavy ion tandem accelerator and build an AVF cyclotron, indigenously. With this decision we entered into a new field of building large accelerators. Later, the University Grant Commission (UGC) also decided to set up an

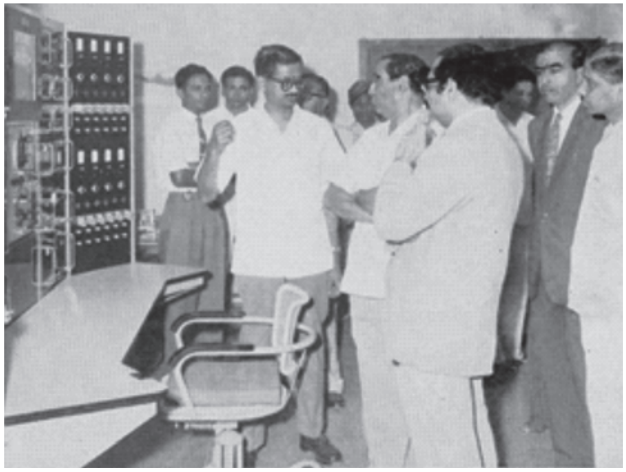

Fig. 1: Raja Ramanna, Homi J Bhabha, H N Sethna and other senior scientists at the time of commissioning of the 5.5 MV VandeGraaff at Trombay, BARC in February 1962.

accelerator centre at New Delhi mainly for the university users. It was called the Nuclear Science Centre (NSC) and later renamed as the Inter-University Accelerator Centre (IUAC).

India has presently a large number of small and big accelerators [14]. Most of them are used in hospitals and industry. Only few accelerators are used for nuclear physics and allied sciences studies. Presently, there are 4 major accelerator centres for research in India. They are: Bhabha Atomic Research Centre (BARC)/Tata Institute of Fundamental Research (TIFR), Mumbai; Variable Energy Cyclotron Centre (VECC), Kolkata; Raja Ramanna Centre for Advanced Technology (RRCAT), Indore and Inter-University Accelerator Centre (IUAC), New Delhi.

A 14 UD Pelletron accelerator facility was set up in Mumbai [15]. Scientists and engineers of BARC and TIFR steered the project to its conclusion. Though accelerator components were purchased from M/s NEC, USA, the pressure vessel, beam lines and experimental systems were developed indigenously. The accelerator was commissioned in 1989. Since then, it has been in use for basic and applied research in nuclear and allied fields. It has been delivering light and heavy ion beams (up to ^{127}I) to users for advanced scientific experiments. In order to increase the particle energy further, it has been augmented with a superconducting linac booster, which consists of 28 lead-plated Quarter Wave Resonators [16]. The output energy can be boosted by about 3 MeV/q for heavy ions.

The 5.5 MV Van de Graaff accelerator at BARC was converted into a 6 MV Folded Tandem Ion Accelerator (FOTIA) [17], which was commissioned in the year 2000 and has been in continuous operation since then delivering both light and heavy ion beams. As part of the Accelerator Driven subcritical Systems (ADS) program, BARC has also taken up a project to design and develop a 1 GeV, 30 mA proton linear accelerator [18]. In order to understand accelerator physics issues at low particle energies, where space charge phenomenon dominates, BARC is building a Low Energy High Intensity Proton Accelerator (LEHIPA) [19, 20]. It consists of a 3 MeV four vane type Radio Frequency Quadrupole (RFQ) [19] and a Drift Tube Linac (DTL) [20] to accelerate proton beam energy to 20 MeV. The LEHIPA is presently in the process of commissioning. A 11 MeV proton beam has been obtained recently at the end of the second DTL tank. High energy part of the ADS accelerator will be built at Vizag, BARC and will have superconducting accelerating structures.

BARC initiated development on electron accelerators (3 MeV, 30 kW DC; 10 MeV, 10 kW RF accelerator;10 MeV, 5 kW; 6/4 MeV dual energy accelerator) at the Electron Beam Centre (EBC), BARC for industrial applications [21]. Broad range of applications are concluded with these accelerators such as biological waste management; Flue gas treatment; seed mutations to develop new varieties of beans, rice, moringa etc.; mass scale irradiation of onion and other food commodities; exotic coloration of various types of gemstones and many research applications for different divisions of BARC. In addition to S-band RF linac, a 6 MeV X-band linac has also been designed and developed for medical applications and it is under trials.

Going back in time, construction of the first large accelerator in India was carried out in Calcutta, indigenously, by a dedicated team of scientists and engineers during 1970-77 [22]. It is an Azimuthally Varying Field (AVF) cyclotron based on the design of the 88" cyclotrons at Berkeley and Texas, USA. It is a room temperature cyclotron capable of delivering variety of light and heavy ion beams up to energy 130(q^2/A) MeV. This cyclotron is called Variable Energy Cyclotron (VEC). The Variable Energy Cyclotron Centre (VECC) at Kolkata started around this accelerator. The cyclotron is in use for nuclear physics and allied research by experimentalists from all over the country. In 1998, an indigenously developed 6.4 GHz Electron Cyclotron Resonance (ECR) heavy ion source was installed to accelerate heavy ion beams. Beams of neon and oxygen ions were routinely accelerated.

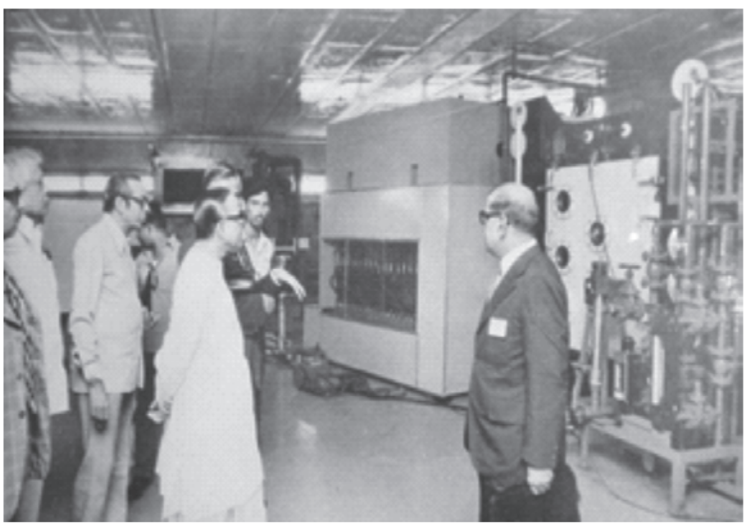

Fig. 2: Former chief minister of West Bengal Jyoti Basu visiting the Variable Energy Cyclotron in 1976 when it was nearing completion. Senior scientists like Raja Ramanna, C Ambasankaran, A S Divatia, Santimay Chatterjee, A K Ganguly and B B Bhattacharjee can also be seen in the picture.

With the users demanding higher ion energies, VECC has also built, indigenously, a superconducting cyclotron with K= 520 [23]. This cyclotron can accelerate light ions to 80 MeV/nucleon and heavy ions to 10 MeV/nucleon energy. The pole diameter of the superconducting main magnet is 142 cm. The superconductor is niobium-tin strands embedded in copper. The magnet is designed to produce maximum hill field of 5.5 Tesla and maximum valley field of 4.5 Tesla. It is the largest iron-core superconducting magnet operational in the country. A 14.5 GHz ECR source is used to produce heavy ions for acceleration in the cyclotron.

In trial runs, nitrogen beam was accelerated to 252 MeV. More beams will soon be available for experiments.

It is always a desire of the nuclear physics community to study elements far away from the β-stability line as it can provide highly interesting new physics. Several phenomena occurring in the outer space and stars can be simulated in the laboratory. An ISOL- post accelerator type of Rare (Radioactive) Ion Beam (RIB) facility has been developed at VECC [24]. In the present system, nuclei are produced inside a thick target using high intensity proton and alpha beams from the VEC. The radioactive atoms diffusing out from the thick target are ionized to charge state $q=1^+$ in the integrated target-cum-source and then transported to an on-line ECR ion source where $q=n^+$ radioactive ions are produced in a two-ion-source mode. These ions are then accelerated to high energies using a four-rod type RFQ and IH linac structures to about 1MeV/nucleon energy. In the next phase, the RIBs will be produced through photo-fission process using a 50 MeV, 2 mA superconducting electron linac (CW) and actinide targets [25]. The electron linac is being developed in collaboration with an advanced accelerator laboratory TRUMF in Canada. In the subsequent phase, radioactive ion beams can be accelerated to 100 MeV/nucleon energy using a cyclotron. The most difficult front-end part of the RIB accelerator facility has already been designed, built and commissioned at VECC.

More than 1500 cyclotrons are operating all over the world as dedicated machines for radioisotope production for medical applications. More than half of such cyclotrons deliver 10–20 MeV energy protons and about 75% of them are dedicated for the production of the radioisotope ^{18}F ($T_{1/2}$ = 109.8 min) for cancer diagnostics. The Fluorodeoxyglucose (FDG) molecules labelled with ^{18}F radioisotope are produced through radiochemistry processes. FDG is injected into the patient's body for scanning with a PET camera. These scans help doctors to effectively diagnose the cancerous parts. In India, over 40 cyclotrons are operating solely for the production of FDG in hospitals and commercial organizations. All these machines are purchased from international manufacturers. Cyclotrons delivering beams of 30 MeV protons or more, can also produce other useful radioisotopes such as ^{67}Ga, ^{111}In, ^{123}I, ^{201}Tl, etc. They are relatively long-lived isotope, and are also useful for medical diagnostics. A 30 MeV medical cyclotron facility has been set up by VECC at Kolkata [26]. Some radioisotopes are routinely produced and supplied to hospitals.

The Raja Ramanna Centre for Advanced Technology (RRCAT), Indore is the largest accelerator and laser technology centre of the Department of Atomic Energy (DAE). It houses two indigenously designed and constructed synchrotron radiation sources [27], namely, INDUS1(450 MeV) and INDUS-2 (2.5 GeV). An electron beam extracted from the source is first accelerated to 20 MeV using a microtron accelerator and injected into a 550 MeV (maximum) booster synchrotron. The electron beam is then injected either into INDUS-1 or INDUS-2, where it is accelerated and stored for several hours/days. During bending in the dipole magnets of the storage ring, the beam emits synchrotron radiation having critical wavelength 61 Å for INDUS-1 and 2 Å for INDUS-2. Both storage rings are operational and being used for experiments. The INDUS-2 was commissioned for experiments in December 2005. The Fig 3 shows the then Prime Minister of India Dr. Man Mohan Singh inaugurating the facility and dedicating it to the nation. The Centre was also renamed as Raja Ramanna Centre for Advanced Technology (RRCAT) from the earlier Centre for Advanced Technology (CAT). Both INDUS-1 and INDUS2 have several beam lines as well as advanced research facilities for experiments in material science, condensed matter physics, biological science, etc. A very large research community from various research and academic institutions are carrying out experiments.

Fig. 3: Former Prime Minister of India Dr. Man Mohan Singh inaugurated the INDUS-2 and dedicated the SRS facilities to the nation in Dec 2005. The Centre was also renamed as Raja Ramanna Centre for Advanced Technology

The Centre has been instrumental in indigenous development of very large number of hi-tech accelerator systems and components as well as technologies. To increase the shelf life of the agriculture products by irradiating them with radiation, RRCAT has also set up an Agriculture Radiation Processing Facility (ARPF) at Indore [28]. It uses an indigenously developed, state-of-the-art electron linac (10 MeV) as the main radiation source.

As mentioned earlier, in order to meet the growing accelerator-based research needs of our universities and academic institutions, the University Grant Commission (UGC), Government of India has set up the Inter-University Accelerator Centre (IUAC)) in New Delhi. It houses several accelerator facilities. A 15 UD Pelletron machine, purchased from M/s NEC, USA is the main accelerator at the Centre [29]. It was later augmented with an indigenously designed and developed superconducting linac utilising niobium-based accelerating structures [30]. Beams from the Pelletron accelerator are injected into this linac booster. The facility can accelerate a variety of heavy ion beams to 5-10 MeV/nucleon energy. The Pelletron can also be used as a stand-alone accelerator for advanced experiments. A High Current Injector (HCI) facility has also been built at the Centre [31]. It consists of an ECR ion source, an RFQ and a DTL. The indigenously designed and developed HCI facility can accelerate beams to about 1.8 MeV/nucleon energy. It has recently been commissioned. The beam from HCI would be transported and injected into the superconducting linac booster for further acceleration to higher energy. More intense and higher energy beams would then be available for experiments to the users. In addition to the above, the Centre has several other low energy accelerator-based facilities. They include 1) Negative ion beam facility; 2) Accelerator Mass Spectroscopy (AMS) facility; 3) Rutherford Back Scattering (RBS) facility; 4) Table-top Accelerator; 5) Free Electron Laser facility (called DLS) (under development); 6) Positive ion beam facility. A new National Geochronology Centre is also being set up at IUAC for advanced studies in the fields of geology, oceanography, climate change, environment sciences, archaeology etc. Main scientific activities will be based on utilization of AMS techniques using a 6 MV Pelletron accelerator. The setting up of this Centre has been entrusted to the IUAC by the Ministry of Earth Sciences (MoES), Government of India.

The Indira Gandhi Centre for Atomic Research (IGCAR) has set up two accelerators (400 kV and a 1.7 MV Tandem for heavy ions) to simulate the radiation damage and its analysis in the fast breeder reactor components [32]. Several small accelerator facilities have also been set up by various research and academic institutions all over the country. Some of them are 3 MV Pelletron at Institute of Physics (IOP), Bhubaneshwar, 3 MV Pelletron at Guru Ghasidas Vishwavidyalaya, Bilaspur, 3 MV Tandetron at NCCCM, Hyderabad, 3 MV Tandetron at SINP and 1.7 MV accelerator at IIT Kanpur. An 8 MeV electron accelerator at ECIL, Hyderabad is being used to test electronic components. An indigenously developed 8 MeV microtron (by RRCAT) has been operational at the Mangalore University for applied research by several institutions for over 2 decades now. In 1960s, Prof H S Hans brought an 8 MeV proton cyclotron from Rochester University as a gift. It was set up at the Punjab University, Chandigarh and is still in use for experiments. SAMEER, Ministry of Electronics and Information Technology, Government of India has developed 4/6 MeV electron accelerators for cancer therapy. They are also in the process of mastering the technology for 30 MeV electron accelerators. The Apollo Hospital in Chennai is using 230 MeV cyclotron for proton therapy for cancer. The Tata Medical Centre (TMC), Mumbai is also setting up a 230 MeV cyclotron at the Advanced Centre for Treatment and Education in Cancer (ACTREC), Kharghar for cancer therapy using protons. TMC is also planning for a heavy ion accelerator for cancer therapy. With all these design and developments activities, India has now matured enough to take up bigger challenges in the field of accelerators.

4. International Collaboration

Accelerating gradients in the room temperature structures are restricted, due to breakdowns, to about 1-2 MV/m in DC accelerators and less than 10 MV/m for RF accelerators.

In order to build the modern, state-of-the-art high energy, high intensity accelerators, it is necessary to master the superconducting RF technology where gradients of upto 100 MV/m are possible to achieve. Even higher gradients (100-300 GV/m) can be achieved, in principle, in the Laser Plasma accelerators. Some development work has been done at RRCAT and TIFR. However, this is still in R&D stage and will take considerable time to mature for utilization. All these are highly complex technologies and, therefore, it has been decided to collaborate with the advanced international accelerator laboratories who have enough experience and expertise in the field and are willing to share the technologies with Indian institutions on mutual benefit basis.

The DAE and several Indian universities/institutions were already participating, both in accelerator components building and experiments, at many international laboratories particularly CERN, the European Council for Nuclear Research, Geneva towards construction of the Large Hadron Collider (LHC). India has supplied nearly 2000 superconducting sextupole and decapole corrector magnets, nearly 3000 quench protection system power supplies, nearly 7000 precision magnet positioning jacks as well as design/control software. The RRCAT played a major role in this collaborative program. Also, the Indian scientists and engineers participated in extensive magnet measurements for the LHC project. After successful collaboration with CERN, India has established collaboration with the Facility for Antiproton and Ion Research

(FAIR), GSI, Germany and Fermilab, USA. The Fermilab is building a high beam power accelerator using superconducting accelerating cavities. This collaboration will help us in development of high intensity proton linear accelerators for our ADS and Spallation Neutron Source (SNS) programs. Superconducting cavities, precision magnets and RF power amplifiers designed and developed in India (in collaboration with Fermilab) have met the stringent specifications. The VECC is also participating in FAIR project and making in-kind contributions by supplying, among others, large gap superconducting magnets and several hundreds of power supplies for various systems. The components supplied to FAIR have met the demanding specifications.

All this gives us strong confidence for taking up the challenges towards building bigger accelerators for our own frontline research and applications programs.

5. Mega Science Accelerator Programmes

Following accelerator projects have been envisaged:

1) 1 GeV, high intensity, CW proton accelerator as ADS driver for thorium breeding and nuclear power generation in the near future.
2) 1 GeV, high current, pulsed proton accelerator for SNS benefitting frontline research in material sciences and applications.
3) Fourth generation synchrotron radiation source for discovery science experiments.

5.1 Accelerators for ADS Programme

In 1985, Carlo Rubia at CERN proposed an Accelerator Driven sub-critical reactor System (he called it Fast Energy Amplifier) [33] which can 1) generate electricity using thorium as fuel, 2) manage the nuclear waste (incineration of long-lived minor actinides) and 3) transmute the long half-life fission products. In an ADS, about 1 GeV proton beam from an accelerator falls on a heavy target, such as lead, and produces 25-30 neutrons/incident proton through spallation reaction. These neutrons then interact with ^{232}Th to convert it into ^{233}U which is fissionable. In the ADS, the `reactor' is sub-critical and the required extra neutrons are provided by the accelerator, thereby making the ADS an inherently safe system. This is because the accelerator beam can be withdrawn very quickly in case the reactor tends to became supercritical for any reason. The ADS is very important for India as we have large deposits of ^{232}Th. In view of this, the DAE has initiated a program to develop ADS. Once successful, our `green' nuclear power program can be sustained for centuries to come.

One of the most important components of ADS is a high intensity proton accelerator. For the Indian ADS program, physics design of a 1 GeV, 30 mA proton accelerator has been done

at BARC [18]. It consists of a 50 keV ion source, 3 MeV RFQ, 20 MeV DTL and superconducting accelerating structures to accelerate beam up to 1 GeV energy. Due to extremely high beam currents, space charge effects are highly dominant at low energies. In order to understand and resolve these issues, a 20 MeV, low energy high intensity proton accelerator (LEHIPA) has been designed and built [20]. As mentioned earlier, the installation and commissioning of LEHIPA is in progress at BARC.A 10 MeV cyclotron-based system to study ADS related issues at low energies was also planned at VECC [34]. A high current ECR ion source was built and several experiments related to space charge effects were done [35]. In order to gain experience in designing and building the superconducting RF cavities, etc.,

Fig. 4: Signing of MOU for collaboration between Indian Institutions and Fermilab, USA (IIFC) for development of high intensity systems on Feb 10, 2010

an MoU to jointly develop accelerator sub-systems was signed between Indian Institutions (BARC, RRCAT, VECC, IUAC) and Fermilab on February 10, 2000 to formalize the collaboration [Fig. 4].

Excellent progress has been made in developing various components and sub-systems under this collaboration. Superconducting RF cavities at operating frequency of 1.3 GHz and 650 MHz were designed and fabricated in India. They were processed and tested at the Fermilab. The accelerating gradients exceeding 37.5 MV/m, $Q > 10^{10}$ for 1.3 GHz cavity and 19.3 MV/m, $Q > 10^{11}$ for single-cell cavities at 650 MHz was obtained. This performance is very satisfactory and of international standards. IUAC also designed and fabricated the spoke resonators, complex superconducting accelerating structures at the low energy end of the accelerator, and supplied to the Fermilab. They were also found to be of international standards. Excellent infrastructure for state-of-the-art technologies have thus been created at various Centres, namely, BARC, RRCAT, VECC and IUAC.

5.2 Spallation Neutron Source

There is a high demand for intense beams of high energy neutrons for condensed matter research. For neutron-based research, a Spallation Neutron Source (SNS) is planned at the Raja Ramanna Centre (RRCAT), Indore. It consists of a high current ion source, RFQ, DTL/SDTL up to 100 MeV and superconducting RF cavities for acceleration from 100 MeV to 1-2 GeV [36]. It will be a pulsed accelerator with repetition rate of 20 Hz. Presently, R&D is going on to develop the accelerator subsystems.

5.3 Fourth Generation Synchrotron Radiation Source

In order to meet the growing requirement of modern facilities for condensed matter research, a need is felt to set up a 4^{th} generation Synchrotron Radiation Source in the country [37]. Several discussions have been held in the scientific community to decide on its parameters and location. The general consensus is to build a 6 GeV electron storage ring to meet the requirements of the research community.

Conclusions and General Remarks

Particle accelerators are invaluable machines that are used to do fundamental and applied research in several branches of science. They are, at the same time, extremely useful for diagnosis and treatment of dreaded diseases/disorders like cancer. Their applications in industry have reached to the levels, elsewhere in world, where they are contributing, directly and indirectly, to the national economy. India has made significant progress in the field of designing and building accelerators. However, most of the accelerators have been built in national R&D institutions and there is a strong need to proliferate them to universities/academic institutions. We should also involve industry in these developments. Strong emphasis needs to be given in India to exploit the immense potential of accelerators for societal applications and industrial development.

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References

1. E Carminati, R Klapisch, J P Revol, Ch Roche, J A Rubia and C Rubia, Report CERN/AT/9347(ET)
2. E Rutherford, Proc Roy Soc (London) 117, 300 (1927)
3. G Gamow, Z Physik 52, 510 (1928)
4. J D Cockcroft and E T S Walton, Proc Roy Soc (London), A136, 619 (1932); A137, 229 (1932)
5. R J Van de Graaff, Phys. Rev 38, 1919 (1931)
6. W H Bennett and P F Darby, Phys Rev 49, 97 (1936); L W Alvarez, Rev Sci Instru 22, 705 (1951), R J Van de Graaff, Nucl Instru Meth 8, 195 (1960)
7. R Herb, http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/herb-rg.pdf
8. M Letourne, IEEE Transactions on Nuclear Science, 30(4), August 1983.
9. R Wideroe, Arch Elektrotech 21, 387 (1928); G Ising Ark Math Astrom Phys 18, 45 (1925)
10. D H Sloan and E O Lawrence, Phys Rev 46, 539 (1934), M S Livingston, PhD Thesis, University of California, April 14,1931; E O Lawrence and S Livingston, Phys Rev 37, 1707 (1931)
11. D W Kerst, Phys Rev, 58, 841 (1940); 60, 47 (1941)
12. C S Khurana and H S Hans, Indian J Phys, 32, 465 (1958); Mohd Shuaib and B P Singh, Physics Bulletin, AMU, Feb 2022, pp 1.
13. A S Divatia et al AEET/NP/5, 1962
14. R K Bhandari, Current Science, 118, 1341 (2020); B Lalremruate et al., DOI: 10-13140/RG 2 2 24839.50087, IAEA Report No.: INDC (IND)-0050, Nov 2017; S Kailas and R Chidambaram, Proc. Ind. Natl. Sci. Acad. 85, 3 (2019); P Singh, Invited Talk, Int. Symp. on Vacuum Science & Technology of Accelerators and their Applications (IVSTT2020), Feb 16-19, 2020, BARC, Mumbai

15. S.S. Kapoor. V A Hattangadi and M.S. Bhatia, Indian J. Pure and Applied Phys. 27. 623 (1983).
16. R G Pillay, M B Kurup, M K Pandey, B Srinivasan, and M G Betigeri, Indian J. Pure and Applied Phys. 35, 152 (1997)
17. P Singh, Pramana J Phys, 57, 619 (2001); S. Santra and P Singh, Pramana J Phys. 59, 53 (2002).
18. Rajni Pande, Shweta Roy, S V L S Rao, P Singh and S Kailas, Pramana-J Phys., 78, 247 (2012).; P Singh et al., Particle Accelerator Conf, (InPAC-2013), VECC, Kolkata, Nov 1922, 2013; P Singh et al., Accelerator development in India for ADS program, Pramana, 68, 331 (2007)
19. S V L S Rao and P Singh, Pramana - J Phys, 74, 247 (2010)
20. Shweta Roy et al., J Instruments 9, 06007 (2014); Jose V Mathew, LEHIPA commissioning to 6.8 MeV by acceleration through the first DTL Tank, Indian Particle Accelerator Conf. (InPAC-2022), March 22-25, 2022, VECC, Kolkata.
21. R. C. Sethi, Electron Beam Technology for Industrial Accelerators: BARC's Endeavour, www.dae.gov.in/node/248, Electron Beam Accelerator for Material Processing, www.dae.gov.in/node/writereaddata/.pdf_44; K C Mittal, In Proc. Ind. Particle Accelerator Conf. (InPAC-2013), VECC, Kolkata, 19–22 November 2013, pp. 62–65; http://www.barc.gov.in/btdg/appd/electron.html; Nishant Chaudhry et al., Chemistry Africa 3, 571 (2020); B Nayak et al. J Inst, 12, A2001 (2017).
22. A S Divatia and C Ambasankaran, Pramana 24, 22 (1985)
23. R K Bhandari and B Sinha, KEK Proceedings 1998, accelconf.web.cern.ch; B Sinha and R K Bhandari, 3rd Asian Particle Accelerator Conference 2004, accelconf.web,cern.ch
24. R K Bhandari, Proc. of the 18th Int. Conf. on Cyclotrons and their Applications, Catania, Italy, 1–5 October 2007, pp. 87–89; Jayanta Debnath, Indian Particle Accelerator Conf. (InPAC2022), March 22-25, 2022. VECC, Kolkata
25. A Chakrabarti et al., Current Science, 108, 22 (2015), http://www.iuac.res.in/event/afad2019/ Webupload/plenary%20talk/P5Vaishal%20Naik.pdfRIB
26. Sumit Som, 30 MeV Medical Cyclotron Facility at VECC, Physics News 50, 42 (2020); Bikas Sinha, Indian Particle Accelerator Conf. (InPAC-2022), March 22-25, 2022, VECC, Kolkata.
27. S S Ramamurthi and G Singh, Nucl Instru and Meth A359, 15 (1995); G Singh, G K Sahoo, Deepa Angal, B Singh, A D Ghodke and Pradeep Kumar, Ind J Pure and Applied Phys. 35, 183, (1997); Tushar Puntambekar, Ind Part Acc conf. (InPAC-2022), March 22-25, 2022, VECC, Kolkata.
28. J Dwivedi, Proc. of the Indian Particle Accelerator Conference (InPAC–2018), RRCAT, Indore, 9–12 January 2018, pp. 47–49; http://www.rrcat.gov.in/technology/accel/mal/index.html
29. G K Mehta, A P Patro, Nucl Instru and Meth in Physics Res A268, 334 (1988); G K Mehta, Nucl Instr and Meth in Physics Res A287, 31 (1990); M Narayanan et al., Nucl Instr and Meth in Physics Res A348, 13 (1994); D Kanjilal et al., NuclInstr and Meth in Physics Res A28, 97 (1993); S Chopra et al, Proc 8th Int Conf Heavy Ion Accelerator Technology (HIAT), Editor K W Shepherd, AIP 1999 pp 39.

30. P N Prakash et al., PRAMANA - J Phys, 59, 849 (2002); S Ghosh et al., Phys. Rev. Spl. Topics - Accelerators & Beams, 12, 040101 (2009)

31. R Mehta et al., Ind Particle Acc. Conf.(InPAC-2015), Dec 21-24, 2015, BARC, Mumbai; R Mehta et al.,2nd Int. Workshop on ADS and Thorium Utilization during Dec 11-14, 2011, BARC Mumbai, India.

32. K. Suresh et al, Nucl Instru Meth in Phy Res, B447, 92 (2019); K. Suresh et al., J Inst 13 , 5011 (2018); K. Suresh et al, J Inst 15, 05008 (2020).

33. C Rubia et al., CERN Report CERN/AT/95-44 (ET); C Rubia et al., CERN/ AT/93-47 (ET); S S Kapoor, Use of Accelerators for Nuclear Energy Generation, Proc. Conf. Accelerator Based Research in basic and Applied Sciences, Feb 25-27, 2001, Nuclear Science Centre (now Inter-University Accelerator Centre), New Delhi.

34. P Sing Babu et al., Nucl Instru Meth 624, 560 (2010)

35. V S Pandit et al., Nucl Instru Meth, 377, 424 (2013); Anurag Misra et al. Rev Sci. Instru86, 113301 (2015)

36. D D Bhawalkar and A S Rajarao, Proc 2nd Asian Particle Accelerator Conference, 2001, Beijing, China, pp 16; Arup Ratan Jana and Vinit Kumar, *Nucl Instru Meth in Phy Res* A942, 162299 (2018).

37. A D Ghodke et al., RRCAT Report 10, 2017; A D Ghodke et al., Indian Particle Accelerator Conference (InPAC), New Delhi, Nov 18-21, 2019.

Fusion and Plasma Research

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Preamble

Plasma physics is the science of ionized matter. Its importance has grown manifold due to its numerous fundamental contributions and diverse practical applications, including the prospect of developing a fusion reactor. The Institute for Plasma Research (IPR), with its main campus located in Gandhinagar, Gujarat, has the mission of R&D in Plasma Science & Technology, with special emphasis on Magnetic Confinement Fusion, Societal/industrial applications of plasmas, basic research in Plasma Science etc. This article presents an overview of development and progress in the field of plasma research at IPR.

I. Historical Perspective

Research in Plasma Physics started in India with Prof. M.N. Saha, known for the Saha-ionisation equation. Much of the early work was in the context of astrophysical and ionospheric plasmas. Although small-scale experimental studies of plasma processes continued to be carried out in various university departments, national laboratories and institutes of technology, plasma research in India majorly remained of theoretical nature. In the early 1970's, responding to a call by Dr. Vikram Sarabhai for starting a focused experimental plasma physics activity that would act as a precursor for a future fusion research program in the country, several noted scientists working in different Institutions in India and abroad joined the Physical Research Laboratory, (PRL) Ahmedabad. They included Prof. R. K. Varma, Prof. Bimla Buti – a former student of Prof. S. Chandrasekhar, Prof. R. Pratap, Prof. A.K. Sundaram, Prof. Predhiman Krishan Kaw, Prof. A.C. Das and Prof. A. Sen.

After the sudden demise of Dr. Sarabhai, Professor P.K. Kaw - who had earned his Ph.D. from IIT Delhi at the age of eighteen, took the lead in fulfilling Dr Sarabhai's dreams. An experimental plasma physics program had been launched under the guidance of Prof. Satya

Prakash, with Prof. P.I. John, a faculty member at Aligarh Muslim University and Prof. Y.C. Saxena, who had worked on cosmic ray research in the Kolar Gold Fields, joining the group. Prof. S.K. Mattoo, who had worked in solar physics, also joined the group. The plan was to establish an experimental program oriented towards the simulation of space plasma phenomena with the underlying purpose of eventually acquiring the skills necessary for fusion research.

In 1982, the Department of Science & Technology, realizing the importance of starting an indigenous fusion research activity, established the Plasma Physics Program (PPP) in PRL under its "Intensification of Research in High Priority Areas" initiative. PPP grew into the Institute for Plasma Research (IPR) in 1986, with Prof. P.K. Kaw as its founding director. The first indigenously built tokamak, ADITYA (meaning 'The Sun' in Sanskrit), was commissioned in 1989. Along with the tokamak project, a thriving plasma physics and plasma technology program was started. An essential objective of the program was to develop indigenous expertise in the construction of experimental devices for hot plasmas and to create infrastructure within the country that would pursue fusion power when it became viable. IPR quickly grew and became a premier institute conducting theoretical and experimental research in plasma sciences with the infusion of fresh talent from TIFR, IITs, several universities in the country and abroad.

India's tokamak research started with the building of ADITYA tokamak at the IPR. IPR indigenously built and operated the first Indian tokamak (ADITYA) and widened its scientific activities to include fundamental experiments in plasma physics. Another smaller tokamak, purchased from Toshiba, Japan, was installed at the Saha Institute of Nuclear Physics, Kolkata. At that time very few countries had tokamaks.

Along with the successful commissioning and operation of the ADITYA tokamak, several plasma technologies were developed for industrial and fusion applications. A significant jump in IPR's growth came in the mid-90s, when its proposal to build a state-of-the-art superconducting steady-state tokamak (SST-1) was approved by the Government. The construction and operation of SST-1 tokamak has led to several technological advancements in fusion technology in India. Furthermore, the ADITYA tokamak has been reconstructed with additional magnetic coils to produce shaped-plasmas. The progress made by IPR in designing, developing and operating conventional and superconducting tokamaks enabled India to become an equal partner in the biggest international fusion program – the International Thermonuclear Experimental Reactor (ITER), under construction in Cadarache, France. IPR has recently worked out a 25-year roadmap that includes the indigenous development of fusion technologies, building a series of progressively larger and more complex fusion machines, a focused and large-scale program for the societal applications of plasmas and new directions in basic plasma research.

Given its multidisciplinary, technology-intensive nature, plasma/fusion research has yielded numerous spin-offs in disciplines ranging from medical technology and environment to agriculture and material sciences to national security and Space. Several plasma-based technologies developed in IPR for meeting societal needs have been transferred to industries towards attaining an 'Aatmanirbhar Bharat'. The experimental plasma physics program has a strong synergy with theoretical and computational research, which has led to overall development of the field in India.

II. ADITYA Tokamak:

Nuclear fusion reactions power the sun and all of the stars of the universe. Reproducing these reactions on earth provides an attractive solution for meeting the ever-increasing demand of energy for the growing world population. It is quite well-known that when light nuclei fuse together, they liberate energy because the binding energy per nucleon of the resultant increases. As the nuclear forces dominate over the electrostatic forces at nuclear distances, bringing the lighter elements at nuclear distances is the key for realizing a nuclear fusion reaction. This can be achieved by subjecting the nuclei to very high energies through heating them to high temperatures ~ 10^8 K, so that they overcome the coulomb repulsion. At this temperature any mater will be in the plasma state. The most favorable reaction for achieving the controlled thermonuclear fusion on earth is the deuterium – tritium (D-T) reaction, which produce neutrons of 14.1 MeV.

The methods to harness the fusion power on earth are diverse, each with its own advantages and disadvantages. Over the past few decades significant progress has been made around the world. The decades of research have led to good understanding of the physics of both inertial confinement fusion and magnetic fusion, and forms the base for big experiments like magnetic fusion based ITER, and inertial fusion based NIF and LMJ. The most promising and well-researched candidate for the magnetic-confinement based nuclear fusion reactor is 'Tokamak', a toroidal device where high temperature plasmas are confined with special arrangement of magnetic fields. Strong magnetic fields, produced by electromagnets, are used to confine the high-temperature plasma in a toroidal, doughnut-shaped vacuum chamber to physically isolate and thermally insulate the plasma from the solid surfaces surrounding it. The plasma in a tokamak is heated mainly by driving high-currents through it, by launching radiofrequency waves and/or injecting energetic neutral particle beams. The ITER is based on tokamak concept which envisages to demonstrate generation of efficient fusion power (Q > 1) using Deuterium - Tritium (D-T) reactions through fulfilling the Lawson criterion, the triple product of plasma density (n_e), temperature (T_e) and confinement time (τ_e), $n \times T \times \tau e \geq 3 \times 10^{21} m^{-3} keV\text{–}sec$ (deuterium-tritium fusion). A reliable and efficient fusion reactor producing electricity will also likely be a tokamak based reactor.

The design, fabrication and installation of the indigenously built ADITYA tokamak (Figure 1) took place during 1983-1988, and it was commissioned in 1989. It created the first hydrogen plasma discharge in September 1989. The medium-sized tokamak has a major radius of 0.75 m, a minor radius of 0.25 m, and a maximum toroidal field of ~1.5 T. The ADITYA tokamak had several electromagnetic coils, namely the toroidal field (TF) coils: 20 numbers, Ohmic (OT): 5 sets and Vertical field (VF): 2 sets, for producing different magnetic fields required for sustaining super-hot plasmas at several million degrees Centigrade. The successful operation of ADITYA realized technological advancements in pulsed-power, vacuum, electronics, diagnostic and data acquisition for the first time in the country. ADITYA, when commissioned, had the largest Ultra High Vacuum volume ~ 1 m^3, the largest pulsed power system drawing ~ 50 MW for 5 seconds, the first and the largest inductive energy storage system in the country. The notable contribution of ADITYA in nation-building lies in the fact that the machine was constructed

Figure 1: ADITYA-U tokamak

indigenously with major contributions from Indian industry. The data acquisition system for acquiring data from a pulsed discharge with high time resolution was developed in-house using Vax11/730, PDP11 and CAMAC based systems.

ADITYA operated for more than two decades, studying the magnetically confined hot plasmas using more than 30,000 plasma discharges, which validated its design and robust construction. Plasmas with maximum temperature ~7 million degrees Centigrade (~ 600 eV) was confined in ADITYA for quarter of a second (~ 250 ms) duration and with plasma currents up to 160 kilo-Amperes (kA). ADITYA achieved an energy confinement time of ~10 milliseconds.

Along with constantly improving plasma performance, several experiments have been carried out in ADITYA. A remarkable achievement of ADITYA was the discovery of `intermittency', i.e., the nature of the particle and energy transport in the tokamak edge region is bursty and not continuous. The probability distribution functions of broadband plasma density and potential fluctuations were non-Gaussian, a key feature depicting the intermittency in the tokamak edge region. This critical finding of the "BURSTY" nature of plasma transport obtained from careful and systematic experiments in ADITYA has substantially enriched the understanding of the transport of energy and particles from tokamak plasma. This discovery has opened up new avenues of research on this topic worldwide. A variety of other experiments were conducted on ADITYA, which led to significant progress in fusion research, such as the efficient control of plasma disruption and Runaway electrons in tokamaks.

III. ADITYA Upgrade Tokamak

ADITYA tokamak produced circular plasmas formed by a circular graphite ring, called a limiter, placed inside the vacuum vessel. Over the years, the technological advancement of tokamaks has shown better alternatives to the limiter-based circular shaped plasmas through defining the plasma boundary by means of magnetic fields. ADITYA tokamak was dismantled and rebuilt with new electromagnetic (divertor) coils to produce the magnetic fields defining plasma boundary and shaping the plasma. Complete up-gradation was carried out indigenously with the new divertor coils wound in-situ. An Indigenously developed equilibrium code, IPREQ, has been used to reconstruct the equilibrium of shaped plasmas (double-null configuration) for identifying the divertor coil locations. The ADITYA-U tokamak is now a part of an elite group of medium-sized tokamaks (HL-1M-China, COMPASS-Czech Republic, ASDEX-Germany, WEST-France, TCV-Switzerland, MAST-UK), capable of producing plasma in circular, single and double null divertor configurations.

The main objective of ADITYA-U tokamak is to prepare the technological base for future Indian machines along with pronounced understanding the physics by conducting experiments focused on critical areas, such as generation and control of runaway electrons, disruption prediction and mitigation studies, and real-time plasma position control and confinement improvement studies with shaped plasmas. To date, in the ADITYA-U tokamak, a plasma with temperature ~7 million degrees C (~ 600 eV) has been confined for 0.4 seconds. Plasma-shaping experiments have been initiated in ADITYA-U by powering the new divertor coils and encouraging preliminary results are obtained. This is the first time that shaping of the plasma column has been attempted in an Indian tokamak. Till recent times only hydrogen (H) plasmas are produced in ADITYA and ADITYA-U tokamaks. For the very first time in an Indian tokamak, fully deuterium (D) plasmas have been produced successfully in the ADITYA-U, a significant step towards future developments in fusion research.

Plasma disruption event is a huge cause of concern for ITER as it can lead to considerable damage to the machine structure and plasma-facing components, and a search for a mitigation technique is still underway. An inductively driven pellet impurity injector, for the first time in any tokamak, has been fabricated, installed and operated in ADITYA-U tokamak in collaboration with BARC, Vishakhapatnam to inject micron-sized particles at high velocity (~220 m/s) as a plasma-disruption mitigation technique. The world tokamak community is also searching for a good strategy for mitigating high-energy electrons, called runaway electrons. Numerous experiments have been executed in ADITYA-U to effectively control the runaway electrons.

IV Superconducting Steady-State Tokamak (SST-1)

Until the late 1980s, all tokamaks used resistive copper magnets. However, use of resistive magnets is not viable for a reactor operating at steady-state, since it would consume a large amount of electrical power. The solution lies in using magnets made of superconductors. To acquire knowledge about technologies related to steady-state operation of tokamaks and to study the characteristics of tokamak plasmas under steady-state conditions, a steady-state superconducting tokamak (SST-1) has been designed and built in IPR to have plasma pulse length of several seconds. The Superconducting coils were fabricated by BHEL, Bhopal, whereas BHEL, Tiruchirappalli fabricated the vacuum vessel, cryostat and support structures. The conceptual design of the Helium Cryo-plant (1.3 kW at 4.5 K) for superconducting coils was also carried out by a group of IPR engineers and scientists. The Liquid nitrogen storage facility, consisting of large storage tanks, was fabricated and installed by INOX-India. Transfer lines and phase separators were developed with the help of Linde-India Ltd., Kolkata.

Figure 2 shows a recent picture of the SST-1 tokamak and its various subsystems. The major and minor radii of SST-1 tokamak are 1.1 m and 0.20 m respectively. The maximum toroidal magnetic field of 3.0 T can be produced at the machine centre. The SST-1 superconducting magnet system contains about 35 tons of cold mass at 4.5 K and is the largest cable-in-conduit-conductor (CICC) based forced-flow superconducting magnets in India. The CICCs are made up

Figure 2: The SST-1 tokamak

of NbTi/Cu, which are successfully cooled down to 4.5 K using a helium cryogenics system. The cooling of the magnet system is achieved using a dedicated custom-designed helium cryogenic system, which is the largest helium cryogenics system in the country and has been operational for two decades. A 2.7 T main (toroidal) magnetic field has been generated in the SST-1 machine. The TF magnets have been operated for a record 15 days at a stretch during plasma operation in SST-1 with a single day maximum duration of ~ 7.5 hours.

Plasma formation in superconducting tokamaks requires strong pre-ionization, i.e., partial breakdown of hydrogen gas before applying the tokamak electric field for plasma current ramp-up. In SST-1, this is achieved by launching an electron-cyclotron (EC) wave using a 42 GHz Gyrotron source of 100–300 kW. As a result, a maximum plasma current of ~98 kA has been sustained for ~0.65 seconds in SST-1 assisted by Lower Hybrid Current Drive. The SST-1 tokamak is constantly improving its plasma performance and efforts are on to enhance the plasma duration beyond 1 second, with the help of the Ohmic, ECR pre-ionization and LH current drive in the coming experimental campaign.

V Fusion Plasma Diagnostics

Due to its high temperature, measuring devices cannot be inserted into a tokamak plasma. Hence it requires specialized diagnostic techniques and equipment for measuring its properties mostly from external measurements, such as density, temperature, magnetic and electric fields, radiations etc. Laser based diagnostics, such as the Thomson scattering system, based on collecting laser light scattered by thermal electrons are used to measure the electron-temperature and density. Tokamak plasmas radiate over the entire EM spectrum, covering hard X-rays, soft X-rays, UV, visible, IR and microwaves. These measurements are interpreted using sophisticated software to yield plasma parameters. The total radiated power is measured using bolometers. NaI-, CdTl-, LaB6-detector based systems have been used for hard X-ray measurements, whereas AXUV and surface barrier diode detectors are developed for soft X-ray measurements. Several spectroscopic systems in the visible and VUV regions have been designed and developed in-house for the measurements of emission from fuel and impurity ion/neutral species. Furthermore, for measuring the plasma density independently, heterodyne and homodyne microwave interferometer systems have been developed. The neutral particles coming out of the plasma are detected by a neutral particle analyzer (NPA) to obtain the ion temperature of the plasma. A fast visible camera gathers the images of the edge (low-temperature) region of the tokamak plasma, whereas an IR camera is used for measurement of temperature rise of the plasma-facing surfaces inside the tokamak. Numerous magnetic and Langmuir probes are deployed for magnetic and electric field measurements inside and outside the plasma.

VI Fusion Technologies

(a) High power RF systems:

Passage of a large toroidal current in a tokamak leads to joule heating. But this Ohmic process is very inefficient above a temperature of 30 million K, as the plasma resistance falls rapidly with rise in temperature. Therefore, auxiliary heating power is required to raise the plasma temperature beyond 30 million K. RF waves transfer electromagnetic energy to the plasma electrons and ions gyrating in the magnetic field through resonance processes. The RF waves are also required for maintaining the plasma current to provide plasma equilibrium in tokamaks.

Furthermore, in superconducting tokamaks like SST-1, RF waves are required to produce the seed plasma for initiating a tokamak discharge. Hence, simultaneously with tokamak development, several RF-based heating and current-drive technologies such as Electron Cyclotron Resonance Heating (ECRH) system, Ion Cyclotron Resonance Heating (ICRH) system and Lower Hybrid Current Drive (LHCD) system have been developed and used in IPR tokamaks. The plasma current in the SST-1 tokamak is driven using the LHCD system, which is based on klystrons and can deliver continuous wave (CW) power of ~1 MW at 3.7 GHz. A 42 GHz Gyrotron based ECRH system, which can deliver 500 kW power, caters to both the ADITYA-U and SST-1 tokamaks. The ECRH system is used for producing the seed plasma in both the tokamaks as well as for heating the plasma when it is fully formed. A tetrode-based ion cyclotron resonance heating (ICRH) system has been successfully tested at a maximum power of ~ 500 kW (CW) [maximum power ~1.5 MW (CW)] in the range of 20 - 47 MHz.

(b) Neutral Beam Systems:

The plasma in a tokamak can also be heated by injecting energetic neutral particles (NBI). An Indian Neutral-beam Test Facility (INTF), a R&D facility, is under development in IPR which will support IPR's negative ion beam based neutral beam injector (NBI) system development program. As part of the INTF system, an ultra-high-vacuum class stainless steel vacuum vessel that is 9 m long and 4.5 m in diameter with a top openable lid has been manufactured, tested, and installed at IPR to generate a diagnostic neutral beam. It is a first-of-its-kind facility in India, with a beam transport length of ~21 m. The IPR scientists designed the beam dump to absorb the ion beam power up to 6.1 MW using hyper-vapotron technology. Its construction is based on heat transfer elements made of CuCrZr material which has been developed under MoU with NFTDC, Hyderabad.

(c) Power Supplies:

Sophisticated Power supplies capable of delivering various power outputs (kW to MW) are the backbone of fusion research. Regulated High Voltage Power Supply (RHVPS), capable of delivering several megawatts of power are used for driving the RF and NBI systems at IPR and in ITER. RHV power supplies for diagnostic neutral beam (10 kV, 140 A extraction PS, 90 kV, 70 A acceleration PS), ICRH driver-stage / end-stage PS (8-18 kV, 250 kW / 27 kV, 2.8 MW) and ECRH PS (55 kV, 5.5 MW) towards India's commitment to ITER are under development. ITER India has already supplied a 100 kV, 70 A power supply to the RFX Consortium, Padua, Italy, to support the ion beam acceleration from the SPIDER beam source on the SPIDER testbed, which is under regular operation.

(d) Material Testing for Plasma Facing Components:

Material components which come in contact with the high-temperature plasma are subjected to very high heat loads of several MW/m^2 and also the fusion-neutron flux. The suitability of the armor materials for fusion machines is tested in the High Heat Flux Test Facility (HHFTF) at IPR. In this facility, testing of heat removal capability and operational life time of plasma facing materials and components for tokamaks including ITER is carried out. A tokamak Divertor simulator device has also been developed indigenously for fusion relevant plasma surface interaction (PSI) research. This can reproduce ITER-like ion-flux ($\sim 10^{24}\ m^{-2}s^{-1}$), heat-flux ($\sim 5 \times 10^{6}\ Wm^{-2}$) and ion-fluence ($\sim 3 \times 10^{27}\ m^{-2}$), under steady-state conditions at the CPP-IPR, Guwahati for testing and qualifying reactor-grade plasma-facing materials. An accelerator-based 14-MeV neutron generator facility (design yield $\sim 5x10^{12}$, present yield $\sim 7\ x\ 10^{11}$ neutrons/second) has recently been setup at IPR and will be made operational after regulatory approval.

(e) Remote Handling:

One of the challenges of a big machine like ITER is in-situ inspection and repairs and require advanced remote monitoring and handling of different systems and subsystems mounted inside the vacuum vessel. IPR scientists have developed an In-Vessel-Inspection System (IVIS) to perform remote in-service inspection inside a toroidal vacuum vessel. The IVIS can work in ultra-high vacuum and at 100 °C temperature in a noisy tokamak environment. IVIS is now being integrated with an Immersive Virtual Reality "Cave" facility at IPR.

(f) Tritium Permeation Barriers:

Indigenous development of tritium-permeation-barrier coating is another critical development infusion technology. Since tritium, a fuel gas of fusion reactors, is expensive and highly radioactive, a coating of the reactor walls with a Tritium Permeation Barrier reduces its leakage through metals. A magnetron-sputtering based coating system has been developed in-house, which coats Erbia (Er_2O_3) on stainless steel, obtaining a 100-fold reduction in the hydrogen permeation rate through stainless steel. Towards its tritium breeding blanket development program, a Pb-Li experimental loop has been fabricated and assembled at IPR, which has successfully demonstrated reduction in Pb-Li flow rate in the presence of magnetic field.

(g) Tokamak Fueling and Evacuation Systems:

Efficient fueling of a fusion reactor requires pellets of frozen fuel gas to be injected into the burning plasma. A single barrel pellet injection system has been developed and installed in the SST-1 tokamak. Cylindrical pellets (volume ~5 mm^3) made of hydrogen ice are formed in-situ in a barrel, for subsequent acceleration and launching into the tokamak. Another significant accomplishment towards attaining 'Atmanirbharta' in the field of vacuum technology is the indigenous development of liquid nitrogen cooled cryo-pumps for ultra-high vacuum applications in tokamak, defense and space sectors. These pumps are used in SST-1 tokamak and have also been delivered to the Space Applications Centre (SAC-ISRO), Ahmedabad.

(h) Cryoplant:

Recently, a prototype helium Cryo-plant, with a large indigenous content, has been developed and operated with encouraging results, boosting the 'Make in India' initiative.

VII India's Participation in ITER

The indigenous progress made by India in tokamak research paved the way for joining the ITER mega-project. The ITER is an experimental fusion reactor for realizing the scientific & technological feasibility of nuclear fusion as an abundant source of energy of future. The ITER facility is under construction in Cadarache in France. An agreement, known as ITER-agreement, between the seven partners was signed at the Elysée Palace in Paris on 21st November 2006 (Dr. Anil Kakodkar, the then Chairman, AEC signed on behalf of India). ITER partners are the European Union, China, India, Japan, South Korea, Russia and the USA.

The largest component of the ITER reactor, the cryostat, the giant vacuum vessel enclosing the entire tokamak, has been supplied by India. The cryostat, weighing over 3,800 tons, was made by M/s Larson & Toubro at its Hazira, Gujarat Unit. The Cryostat Base section has already been installed in the Tokamak pit at the ITER site on 28 May 2020, as shown in figure 3. The base structure, 29 m in diameter and 6 m tall, weighing ~ 1250 tons, has been placed with less than 3 mm positional accuracy. The 2nd of the 4 sections of the cryostat, the lower cylinder was also

Figure 3: Cryostat base of ITER at ITER site, manufactured in INDIA

successfully lowered onto the base section of the cryostat. Special welding techniques and weld inspection methods have been developed to meet the stringent dimensional control tolerance of 0.3% and sub-mm flatness control accuracy over 30 m size. The in-wall shielding, made up of borated steel (SS304B4, SS304B7) and ferritic steel are also been made in India by M/s Avasarala Technology Ltd. and M/s Larsen & Toubro, under the supervision of a team of IPR engineers. This in-wall shielding is required for shielding the fusion-neutron and also for reducing the ripple in toroidal field. ITER-India has also delivered and installed 4 km long cryo-lines and 7 km long warm-lines at the ITER site.

Several other in-kind components are under development and fabrication in ITER-India including 9 Ion Cyclotron Resonance Frequency sources of 2.5-3 MW; two Gyrotron sources, each having 1 MW power output at 170 GHz with a pulse length of 3600 seconds for the ECRH system of ITER, along with few advanced diagnostics. While the vacuum tubes for these systems are imported, there is a large indigenous component as well.

VIII Plasma Based Societal Technologies and spinoffs of Fusion research

Apart from Fusion Technology development, both for ITER and as part of the domestic program, IPR has a long-standing, focused program for developing plasma technologies for a variety of societal applications in the field of surface-engineering, Processing of Minerals, waste management, medical/health, agriculture, textile, industrial, space and defense. IPR has been actively involved with industries and external agencies on collaborations in the aforementioned fields to deliver technological solutions for the user. For facilitating need-based technology development for societal applications, a separate center named "Facilitation Centre for Industrial Plasma Technologies (FCIPT)" had been established in 1997 in a separate campus in the Gandhinagar industrial area. FCIPT takes up the development of plasma processing technologies from concept to commercialization, facilitates close interaction with entrepreneurs and organizations, and promotes awareness of the applications of plasma technologies. Over the years, the FCIPT has developed and transferred several plasma technologies to Indian and foreign industries. An overview of IPR's activities in these areas is shown in Figure 4.

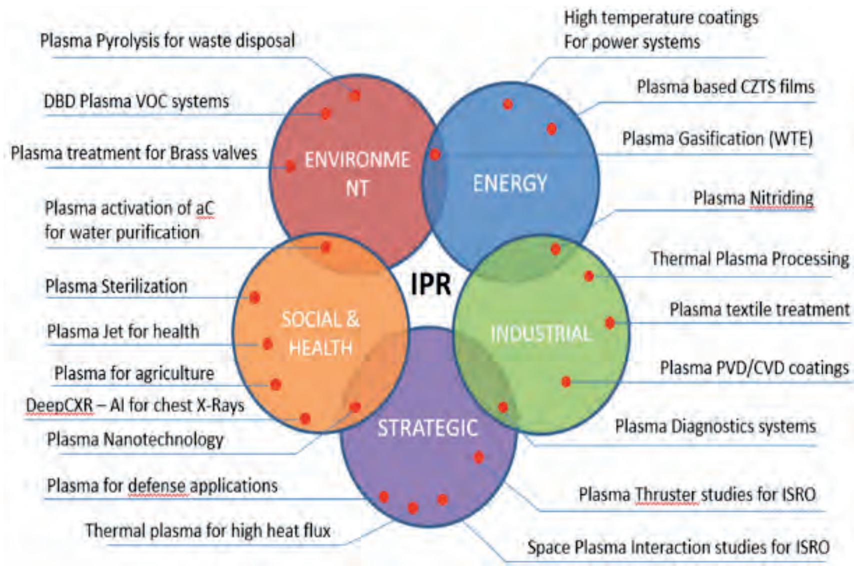

Figure 4: IPR's activity landscape on plasma technologies developed for various sectors of Industry/society

Incorporating atomic nitrogen on metal surfaces by immersing them in nitrogen-hydrogen plasma, known as plasma-nitriding, produces a hard, wear-resistant surface. FCIPT houses different sizes of plasma nitriding reactors to suit various industrial tools, gears, machine parts etc. FCIPT also houses the 3rd largest Plasma Immersion Ion Implantation (PIII) set up in the world for nitrogen incorporation in unique materials. Other surface treatment techniques include plasma surface treatment to produce improved adhesion of rubber to brass for the manufacturing of valves, CZTS-based solar cell production using sputtering, Teflon-coating for large-sized elastomer seal, plasma-based TiN coating system, plasma synthesis of advanced ceramics, plasma polymerization system to coat brass articles for Moradabad cottage industry. The coatings are characterized and tested with the state-of-art diagnostics including the SEM, XRD, XRD, XPS, AES, and SIMS etc.

Plasma pyrolysis is a process by which any organic mass can be thermally disintegrated into hydrogen, CO and lower hydrocarbons in an oxygen-starved environment. Plasma pyrolysis completely eliminates the formation of toxic molecules such as dioxins, furans, poly-aromatic hydrocarbons etc. unlike its conventional incinerators counterparts. Hence, it is an environmentally friendly process for the safe disposal of waste. The advantages of plasma pyrolysis are chemistry-independent heat generation, fast heating and fast quenching, pathogen-destruction by high ultraviolet radiation flux, high processing rates and compact reactors. It works equally well with dry or wet wastes, and most importantly recovers energy in the form of CO and H_2. Several Plasma pyrolysis systems have been developed, fabricated and delivered to different organizations by FCIPT-IPR for safe & eco-friendly disposal of biomedical waste (BMW), Municipal waste & Solvent waste, energy recovery from crude oil residue, ceramic catalyst for ozone treatment. For safe disposal of BMW, Plasma pyrolysis is approved under the Gazette of India.

Significant progress has been achieved in the application of plasma-based technologies in the medical & health sector with the development of Portable plasma-jet for sterilization of surfaces, Nano-coatings on PPEs for anti-viral and anti-bacterial properties, for treatment of fungal skin infections; for faster coagulation of blood; for cancer treatment; and a plasma-based air purification system. Preliminary results on a plasma-treated catheter surface have shown significant alteration of surface chemistry and morphology of catheter surface. 90% reduction in the bacterial adhesion on plasma-treated silicone catheter surface as compared to the untreated one, has been obtained. Automated detection of TB in chest X-rays has been carried out using an AI-based software, capable of running on mobile devices, by training it with chest X-rays from a large number of hospital/medical research centers.

In the agriculture sector, several plasma-based systems are developed for increasing the life of agricultural implements using plasma nitriding, for pesticide removal from vegetables using plasma jets, plasma treatment of seeds for improved germination of seeds. Specialized plasma systems have been developed to process polyester fiber& Khadi for making them suitable for dying using natural dyes instead of synthetic dyes and to modify the surface properties of angora wool for commercial manufacturing of 100% Angora products. In a major thrust towards realizing the Make in India program, specialized electrodes for Plasma Spray systems, currently an import-item, are developed and delivered to Indian industry. These electrodes have yielded performance at par with imported electrodes.

Basic research in Helicon plasmas at IPR has led to the development of Plasma thrusters, which are one of the advanced means for satellite attitude control in space. A prototype helicon plasma thruster, designed, fabricated & operational at IPR, has successfully demonstrated a thrust of >90 mN with 5 kW RF power, using both electromagnets and permanent magnet-based operation with Ar gas. Upgrade to 10 kW is presently underway, and the existing system is equipped with a variety of advanced diagnostics for in-depth understanding.

Based on its developmental capabilities in the area of large-volume vacuum systems, IPR has been chosen as a major contributor to the construction of the Laser Interferometer Gravitational-wave Observatory, LIGO-India project, the other partners being RRCAT Indore, DCSEM Mumbai and IUCAA Pune. The LIGO Division at IPR is responsible for designing, procurement, installation, and commissioning a vacuum system with a volume of ~ 10,000 m^3 operating in Ultra High Vacuum (~ 10^{-9} mbar) range. IPR is also designing and developing the Control and Data System (CDS) for the LIGO India project.

IX Basic Plasma Experiments

Basic research leads to new knowledge and provides scientific capital. IPR has continuously invested in many basic plasma physics experiments that verify new concepts and identify new paths for investigation. For example, research on a Helicon plasma device built by a PhD student in IPR has led to the development of a prototype Helicon plasma thruster system described in the previous section. At IPR, the major basic experiments are the BETA machine (a predecessor of ADITYA); Large-volume plasma device (LVPD): where space plasmas are experimentally simulated; Non-neutral toroidal plasma - applications of which include: precision atomic clocks, trapping of antimatter plasmas and antihydrogen production, quantum computers etc.; Dusty plasma experiments: throwing light on interplanetary space dust, comets, planetary rings, dusty surfaces in space, and aerosols in the atmosphere etc.; Experiments on negative-ion sources: for generating high power neutral beams, Inertial Electrostatic Confinement Fusion (IECF) Device: a neutron source with several applications, and so on. Pictures of a few devices are shown in Figure 5.

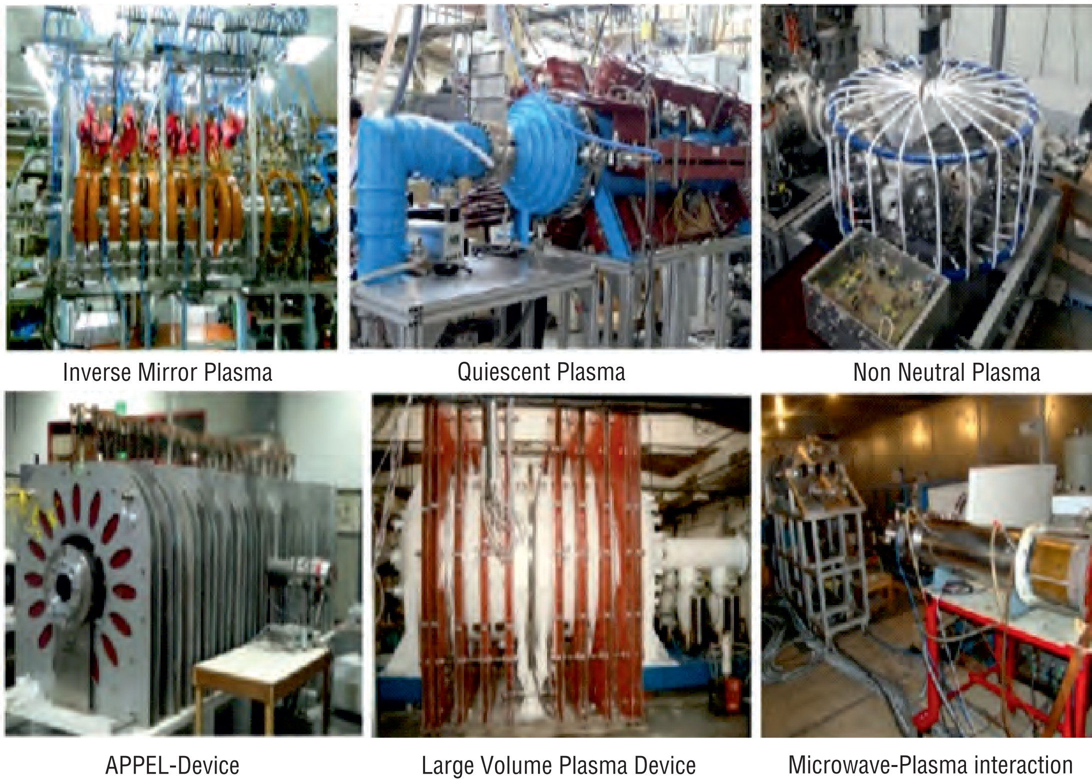

Figure 5: Basic experimental devices at IPR

X Theoretical and Computational Research

Since the beginning, IPR has been pursuing a vibrant program on theoretical analysis and computer simulations in fundamental plasma science, fusion research; space and astrophysical plasmas; and plasma technology. As a result, several important discoveries have been made in the field of fusion and tokamak plasmas, Laser-matter interaction and inertial fusion, dusty plasmas, magnetohydrodynamics (MHD), electron-MHD, coupled limit-cycle oscillators and so on and are published in several renowned international scientific journals including, Physical Review Letters and Nature Communications.

It has been shown for the first time that plasma wave breaking leads to the generation of second harmonic and hard X-rays in ultra-intense ultrashort laser pulse-plasma interaction. Studying the dynamical behavior of two limit cycle oscillators that interact with each other via time-delayed coupling, it has been shown that even if they have the same frequency, the time delay can lead to amplitude death of the oscillators. An important application of this concept is in the assembly of cardiac pacemaker cells where cessation of rhythmicity can lead to a disaster.

A plasma with suspended nanometer or micrometer-sized particles in it, is known as dusty plasma (or complex plasma). Dusty plasmas are found in comets, planetary rings, dust in interplanetary space, interstellar and circumstellar clouds, laboratory plasmas and even in the tokamak edge region. The dusty plasmas are of particular interest as they can form liquid and crystalline states, plasma crystals. Notably, one can view the dynamics of the charged dust grains even with the naked eye. IPR scientists have pioneered the modelling of the dust dynamics using the generalized hydrodynamics description to show the influence of strong correlations on low frequency collective modes in a dusty plasma.

Towards a noted contribution to the 'Atmanirbhar Bharat', a faster and superior state-of-art computer code, ACTYS has been indigenously developed by IPR scientists to carry out nuclear activation analysis of fusion system. The code has been approved by ITER for its usage in ITER. Furthermore, continuing with its long-standing focus on high-performance computing facilities, IPR now hosts a 1-Petaflop HPC facility, which is ranked 11th in the country (as on July 2020) in terms of its computing power. This HPC system is named 'ANTYA' (meaning 10^{15} in Sanskrit) and has more than 10,000 cores that can perform 10^{15} Floating-point Operations per Second (FLOPS). ANTYA has been used extensively for fusion and basic plasma research in IPR. An example of simulations carried out in ANTYA on tokamak plasma and basic plasma is shown in figure 6. The figure shows the interaction of the magnetic islands in a plasma.

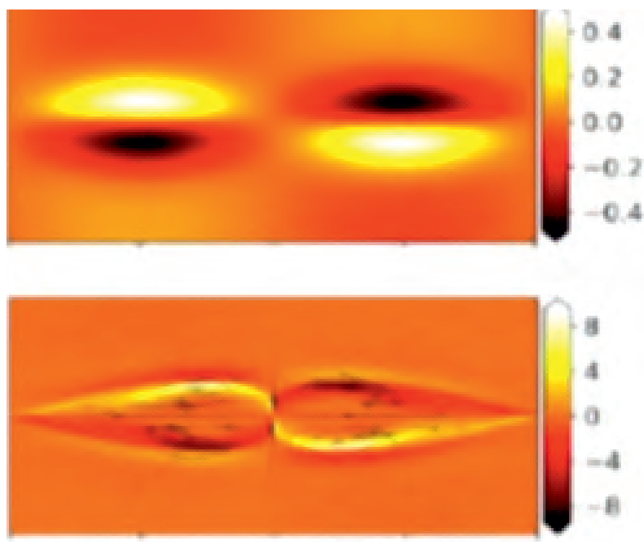

Figure 6: Interaction of magnetic islands

XI Summary and Future Directions

IPR is the main repository of plasma/fusion science and technology in India, having produced 159 PhDs and published more than 3500 research articles in national/international journals and conferences. Simultaneously, 60 patents have been filed from IPR on technological innovations. IPR has nurtured strong collaborations with various R&D organizations, the corporate sector, research institutions, IITs/Universities and colleges to develop user-specific technologies through contract research, equipment development and supply, technology transfer & consultancy, feasibility study investigations etc. A recently-drafted 25-year roadmap envisages the indigenous development of fusion technologies, the construction of a spherical tokamak-based Fusion Neutron Source and later of SST-2, a national program linking societal technology development in IPR with domain experts in medicine/health, waste disposal, agriculture, industry, defense, aerospace etc., and new directions in basic plasma research.

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Preamble

Right from its inception, the Department of Atomic Energy (DAE) had placed due emphasis on the sustained development of human resources for carrying out various functions related to the mission programmes of DAE. This resulted in the setting up of the BARC Training Schools at various campuses of DAE to train young scientists and engineers to take up a career in the development of nuclear energy. The setting up of Homi Bhabha National Institute (HBNI) was an extension of this idea, aimed to provide a thrust to academic programmes in DAE institutions towards enhancing the research capabilities. Set up in 2005 as a Deemed to be University, HBNI has today grown into a highly reputed research university with high-value contributions to DAE as well as to the society. This article provides a broad perspective of the growth of HBNI.

1. The Genesis

The visionary decision to establish a University under the aegis of DAE was taken by Dr. Anil Kakodkar, then Secretary, DAE and Chairman, Atomic Energy Commission, DAE based on a report by a committee chaired by Prof. P. Rama Rao. In January 2004, DAE submitted a proposal to the Ministry of Human Resource Development (MHRD) to establish Homi Bhabha National Institute (HBNI) having the status of a Deemed-to-be University under section 3 of UGC Act 1956. The entire process of obtaining the UGC recognition was steered by Dr. R. B. Grover, then Director, Knowledge Management Group, BARC. The following R&D centres and grant-in-aid institutions were proposed to be the Constituent Institutions (CIs) of HBNI.

R&D Centres:

- Bhabha Atomic Research Centre (BARC), Mumbai
- Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam
- Raja Ramanna Centre for Advanced Technology (RRCAT), Indore
- Variable Energy Cyclotron Centre (VECC), Kolkata

Grant-in-aid Institutions

- Saha Institute of Nuclear Physics (SINP), Kolkata
- Institute for Plasma Research (IPR), Gandhinagar
- Institute of Physics (IoP), Bhubaneswar
- Harish-Chandra Research Institute (HRI), Allahabad
- Tata Memorial Centre (TMC), Mumbai
- Institute of Mathematical Sciences (IMSc), Chennai

An Expert Committee appointed by the UGC visited on March 28, 2005, to evaluate the HBNI academic infrastructure and based on the report of the Expert Committee, University Grants Commission advised the Government of India to declare the HBNI, Mumbai as a Deemed-to-be University along with 10 constituent institutions under the UGC Act. The recommendation was accepted by the Government of India and an announcement in this regard was made by the Prime Minister during his visit to BARC on June 4, 2005. Academic programmes under HBNI started in all the 10 CIs in 2006 under the dynamic leadership of the founding Director, Dr. R. B. Grover. HBNI was registered as a Society on November 18, 2004 and as a Trust on June 02, 2005 under relevant legal provisions applicable to such entities in the State of Maharashtra. On February 19, 2014, a notification was issued by the DAE declaring the HBNI as a 'Grant-in-Aid Institution'. National Institute of Science Education and Research (NISER), Bhubaneswar, became an Off-Campus Centre (OCC) of HBNI later on February 5, 2016.

2. HBNI today

HBNI has catalysed the indigenous development of nuclear technology by creating high-quality human resources in the country that could address challenging issues related to the indigenous development of nuclear technology and other high technology areas, through academic programs, viz., Integrated Master, Master and Ph.D. degrees in Chemical, Engineering, Life, Mathematical, Medical & Health and Physical Sciences while encouraging inter-disciplinary research. Additionally, academic programs in the domain of Applied Systems Analysis have also been identified to ensure the availability of adequate qualified human resources to address issues pertaining to nuclear law, the economics of nuclear power, nuclear security, nuclear proliferation, intellectual property rights and humanities and social science domain issues, etc. Presently, HBNI offers 43 academic programmes in different disciplines and some of which are very unique eg. M.Sc. (Hospital Radiopharmacy), M.Sc. (Public Health and Epidemiology), etc. HBNI has an excellent faculty pool (total=1127) comprising all those who join its CI/OCC as a faculty member in grant-in-aid institutions. However, only about 10% scientific officers having Ph.D. degree and vast research experience in R&D institutions are recognized as HBNI faculty member after following a rigorous screening process. For recognitions of medical doctors at BARC-RMC and TMC as HBNI faculty members, procedure laid down by MCI/ NMC is strictly followed.

2.1 Academic Programmes of the Institute

The HBNI offers a range of academic programmes in chemical sciences, engineering sciences, medical &health sciences, life sciences, mathematical sciences and physical sciences. It also has a programme in Applied Systems Analysis. All institutions, except NISER, conduct academic programmes for which entry-level qualification is a Bachelor's degree or a higher. NISER admits Higher Secondary passed students for its five years Integrated M.Sc. programme.

Ph.D. degrees in varied disciplines are offered by HBNI under the following Board of Studies.

- Physical Sciences
- Chemical Sciences
- Mathematical Sciences
- Engineering Sciences
- Life Sciences
- Medical & Health Sciences
- Applied Systems Analysis

Doctoral students also work in the area of computational biology, medical and health sciences and theoretical computer science. HBNI also offers an integrated Ph.D. programme where students study for M.Sc./ M.Sc.(Engg) followed by Ph.D. both in single and double degree options. It has also initiated an integrated MD-Ph.D. program at TMC. The Institute offers a unique Ph.D. programme where students are encouraged to work at the interface of basic research and technology development. Under this programme, they work under the guidance of two supervisors, one having strength in basic research and the other in technology development.

M.Tech. degree in Engineering Sciences is also offered. The course work is offered at all campuses of BARC Training School. Project work is offered at BARC, IGCAR, RRCAT, VECC, IPR and other units of DAE. Those who are not able to pursue or not interested in pursuing a project/research work have the option to get a post-graduate diploma in lieu of M.Tech. degree. M.Sc. (Engg) programme of two-and-a-half-year duration offered by HBNI has more emphasis on research as compared to M.Tech. The duration of the project work under this programme is one and a half year, while the duration of the course work is up to one year.

M.Sc. (Physics) is offered at HRI. Five years of Integrated M.Sc. in Chemical Sciences, Life Sciences, Mathematical Sciences and Physical Sciences are offered at NISER.

HBNI offers Post Graduate Courses in Medical & Health Sciences at TMC as well as at the Radiation Medicine Centre (RMC) of BARC with various specializations eg. MD (Pathology, Anesthesia, Radio-diagnosis, Radiation Oncology, Microbiology, Nuclear Medicine, Palliative Medicine, Immuno-Hematology and Blood Transfusion at TMC; MD (Nuclear Medicine) at RMC. Super Specialty Courses offered in Medical & Health Sciences at TMC include Doctor of Medicine (DM) in Medical Oncology, Pediatric Oncology, Gastroenterology, Critical Care, Oncopathology and Interventional Radiology and Master of Chirurgiae (MCh) in Surgical Oncology and Gynecological Oncology, Head & Neck Surgery and Plastic and Reconstructive Surgery. HBNI also runs Certified Fellowship Programmes of two years duration in Medical &

Health Sciences at TMC. These value-added courses are offered with specialization in Orthopedic Oncology, Breast Oncology, Thoracic Oncology, Uro Oncology, Interventional Radiology, Surgical Pathology, Haematopathology, Dental & Prosthetic Surgery, Onco-Anaesthesia and Pain, Cancer Imaging, Radiation Oncology (IMRT, IGRT), Haemato-Oncology, Preventive Oncology, Infectious Diseases & HIV Medicine, Gastroenterology and HPB Oncology, Pulmonary Oncology, Molecular Haemato-Oncology, Oral Oncology with Reconstructive Surgery, Plastic and Reconstructive Oncology, Solid Tumor Oncology and Pediatric Oncology.

2.2 Skill Development

In addition to the academic programs mentioned above, HBNI also runs several medical academic programmes that are aimed at skill development. These include M.Sc. (Hospital Radiopharmacy) and M.Sc. (Nuclear Medicine and Molecular Imaging Technology) at RMC; whereas M.Sc. (Nursing), M.Sc. (Clinical research) and M.Sc. (Nuclear Medicine and Molecular Imaging Technology), M.Sc. (Public Health and Epidemiology) and M.Sc. (Occupational Therapy in Oncology) at TMC. A Diploma program in Radiological Physics has proved to be an excellent source of trained personnel who take up a career in radiation safety at various hospitals and other institutions handling radioactivity or radiation sources.

2.3 BARC Training School

The BARC Training School constitutes an important source of manpower for the DAE's programmes. Set up in 1957 by Dr. Homi Bhabha, the BARC Training School (originally called AEET Training School) has trained scientists and engineers to take up challenging mission programmes of DAE. From the first (1957–58) to the 65th (2020–21) batch, approximately 2000 trainees in science and 5000 trainees in engineering have graduated from the BARC Training School; in fact, almost all the leaders of the atomic energy programme during the past two decades have been products of the Training School.

After the setting up of HBNI, the trainees successfully graduating from the Training School are granted a Post-graduate diploma in nuclear science and engineering, with the option of pursuing an M. Tech program by carrying out a project. Over a period of time, innovations have been introduced in the curriculum of the training program, to prepare the students to take up challenging projects for the development of nuclear science and technology and at the same time, provide them with the necessary academic base to evolve into a consummate researcher.

3. The Academic Philosophy

HBNI provides flexibility to the student in his learning process by providing access to all the Constituent Institutions (CIs)/Off-campus Centre (OCC) with regard to the use of their research facilities and academic guidance. Credits can be earned by students pursuing research-based degrees, by attending courses at other CI/OCC subject to approval by the Doctoral /Monitoring Committee. Research students can also have co-guides from other CIs to take advantage of the expertise and knowledge base available across the CIs. HBNI has signed MoUs with several reputed Universities/Institutes at the National and International levels for Academic collaborations. As a part of such MoUs, a doctoral student can carry out course work in another institute to meet credit requirements. There is also a provision to jointly guide a student for Ph.D. degree.

All the CIs and OCC have world-class experimental facilities and it is indeed one of the objectives of HBNI to encourage the students to collaborate across institutions and get access to national facilities to work on problems that are at the frontiers of contemporary research. All the CIs and OCC have excellent library facilities, with a large collection of books and subscribes to a large number of research journals. These facilities help the students in shaping their academic careers.

4. Academic Output and Accreditation

HBNI has been accredited by NAAC with an A+ grade in the second cycle. In the MHRD's National Institutional Ranking Framework (NIRF) exercise for the year 2021, results of which were announced in July 2022, HBNI received 11th rank under Research University and 17th rank in the University category.

The total number of journal publications with HBNI affiliation during the calendar year 2021, as indexed by Scopus is 2922. Based on high-quality publications in the Nature Group of Journals, the Nature Index 2021 placed HBNI in the second position among all institutions in India, and in the first position with regard to publications in Physical Sciences.

Figure 1 displays intake of students in different academic programmes of HBNI during 2021-22 and the progress in human resource output of HBNI is depicted in Figures 2 to 5. The total number of Ph.D. degrees awarded by HBNI till 31st March 2022 stands at 2058 and the number of doctoral students who completed their academic programme during 2021-22 is 253. HBNI has awarded 55 M.Tech., 3 M.Sc. (Engg), 12 M.Sc. (Physics), 94 Integrated M.Sc., 5 M.Sc. (Nursing), 11 M.Sc. (Clinical Research), 128 post-graduate & super specialty medical degrees with specializations in Oncology, 11 post-graduate Diploma in Nuclear Science and Engineering, 5 diploma in Medical Radio-isotope Techniques (DMRIT) and 10 post graduate diploma in Fusion Imaging Technology (PGDFIT) during 2021-22.

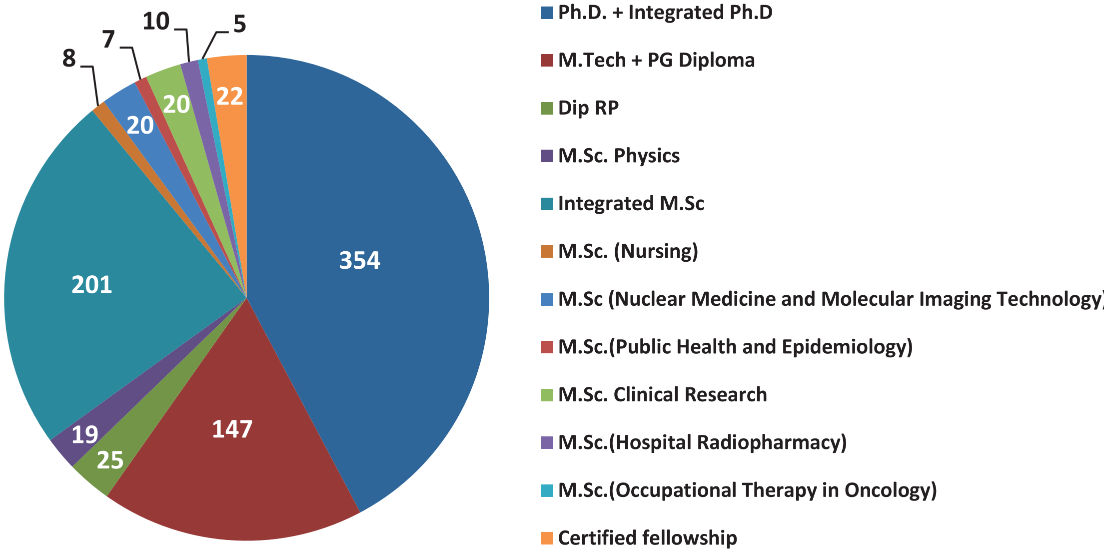
Eight hundred and thirty-eight students were admitted in different academic programmes during 2021-22, out of which 354 students were for Ph.D. programmes. At present about 1900 students are pursuing Ph.D./ Int. Ph.D. in various disciplines.

5. Conclusion

The setting up of HBNI was primarily aimed to strengthen DAE- relevant programme-based linkages among the R&D centres and grant-in-aid institutions through academically oriented higher education and research for enhancing the capabilities to meet the imminent and future challenges, and at the same time to make available the excellent faculty pool and strong infrastructures at DAE to outside students for research programmes.

The academic governance system of HBNI has encouraged the pursuit of excellence in sciences (including engineering sciences) and mathematics in a manner that has major significance for the progress of indigenous nuclear technological capability. HBNI has provided an academic framework for integrating basic research with technology development and encouraged inter-disciplinary research. In addition to providing a strong human resource base for the R&D programs in DAE as well as other institutions in the country, HBNI also continues to generate specialists and superspecialists in cancer care, treatment and research that would go a long way in aiding India's fight against cancer. The success of the HBNI experiment augurs well for the development of high-quality S&T man power for the country and especially for the DAE.

Fig.1: Programmewise Admission Details during 2021-22



Academic Programme	BARC	IGCAR	RRCAT	VECC	SINP	IPR	TMC	IoP	IMSc	HRI	NISER	Total
Ph.D. + IntegratedPh.D	118	4	18	15	19	15	21	12	31	17	84	354
M.Tech + PG Diploma	119	20	....	....	....	8	....	....	....	....	....	147
MD	....	....	....	....	....	....	....	....	....	....	....	0
Dip RP	25	....	....	....	....	....	....	....	....	....	....	25
DM/MCh	....	....	....	....	....	....	....	....	....	....	....	0
M.Sc. Physics	....	....	....	....	....	....	....	....	....	19	....	19
IntegratedM.Sc	....	....	....	....	....	....	....	....	....		201	201
M.Sc. (Nursing)	....	....	....	....	....	....	8	....	....	....	....	8
M.Sc (Nuclear Medicine and Molecular Imaging Technology)	10	....	....	....	....	....	10	....	....	....	....	20
M.Sc.(Public Health and Epidemiology)	....	....	....	....	....	....	7	....	....	....	....	7
M.Sc. Clinical Research							20					20
M.Sc.(Hospital Radiopharmacy)	10	....	....	....	....	....	....	....	....	....	....	10
M.Sc.(Occupational Therapy in Oncology)	....	....	....	....	....	....	5	....	....	....	....	5
Certified fellowship	....	....	....	....	....	....	22	....	....	....	....	22
Total	282	24	18	15	19	23	93	12	31	36	285	**838**

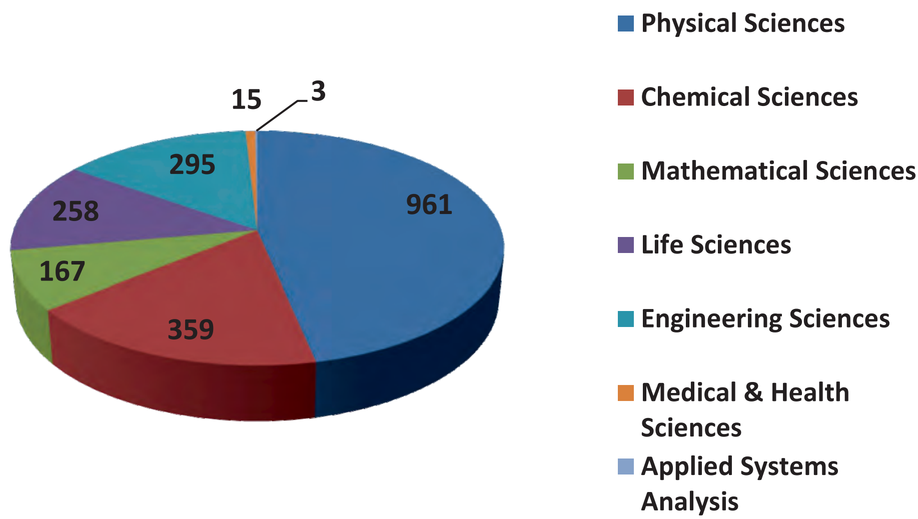


Fig.2: Programme wise Ph.D results declared since inception (Total=2058)

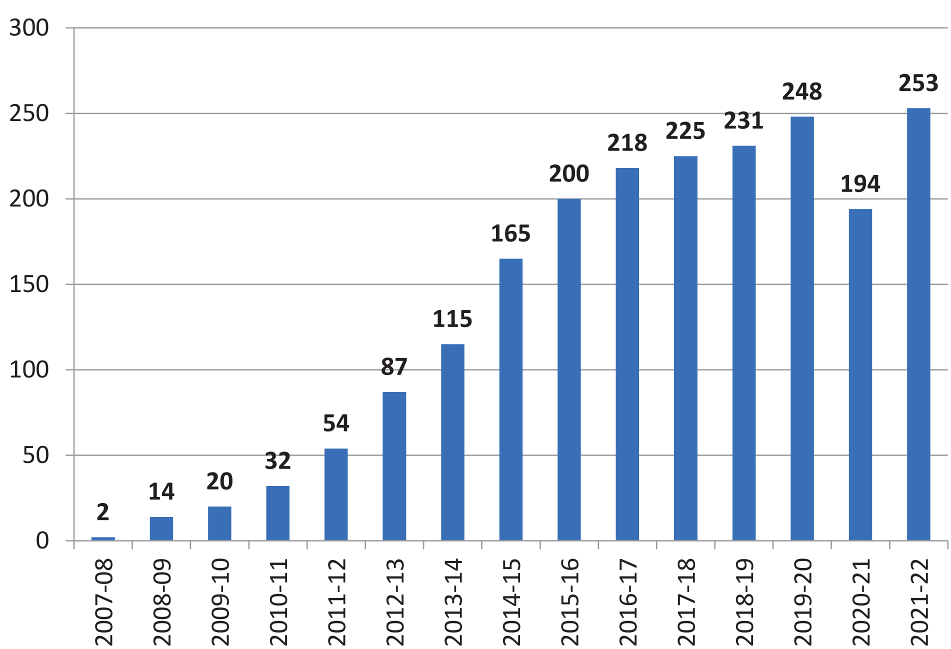


Fig. 3: Year wise Ph.D. results declared
Total Ph.D. Output = 2058

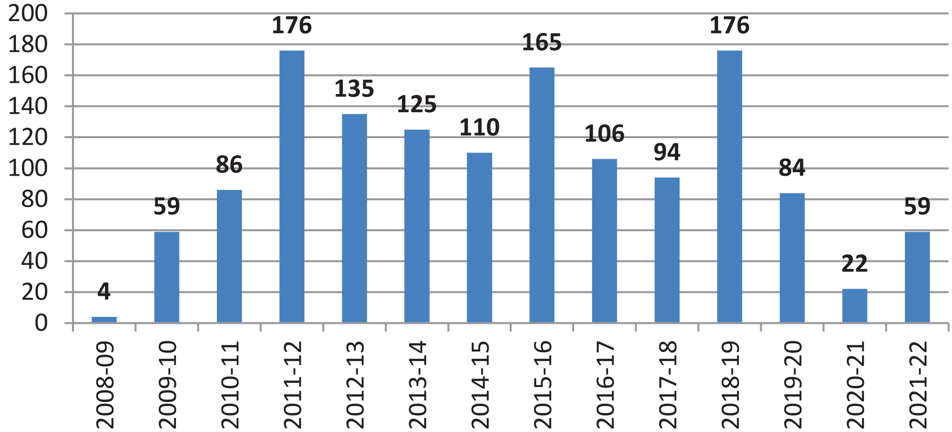


Fig. 4: Year wise M.Tech. results declared
Total = 1401

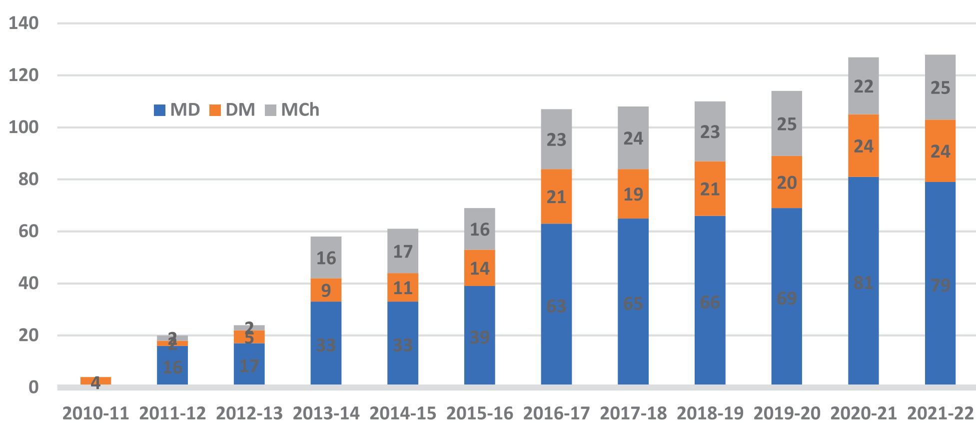
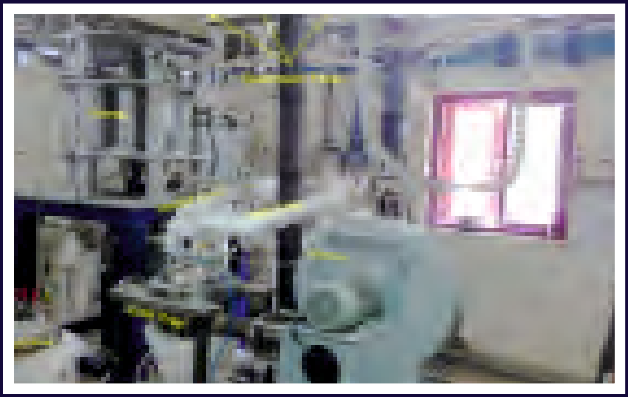


Fig. 5: Year wise MD/ DM/ MCh results declared
Total MD=561, DM=174, MCh=194

Old Yacht Club at DAE Mumbai

Apsara, 1 MW_{th} (1956)
Asia's first reactor

Kakrapar Atomic Power Station



Indian Lead-Lithium cooled Ceramic Breeder (LLCB) Test Blanket Module (TBM)

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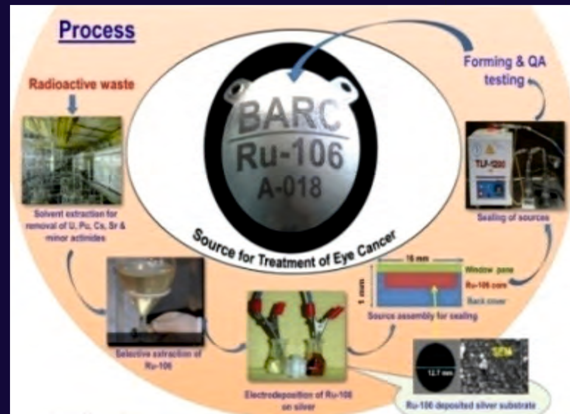

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