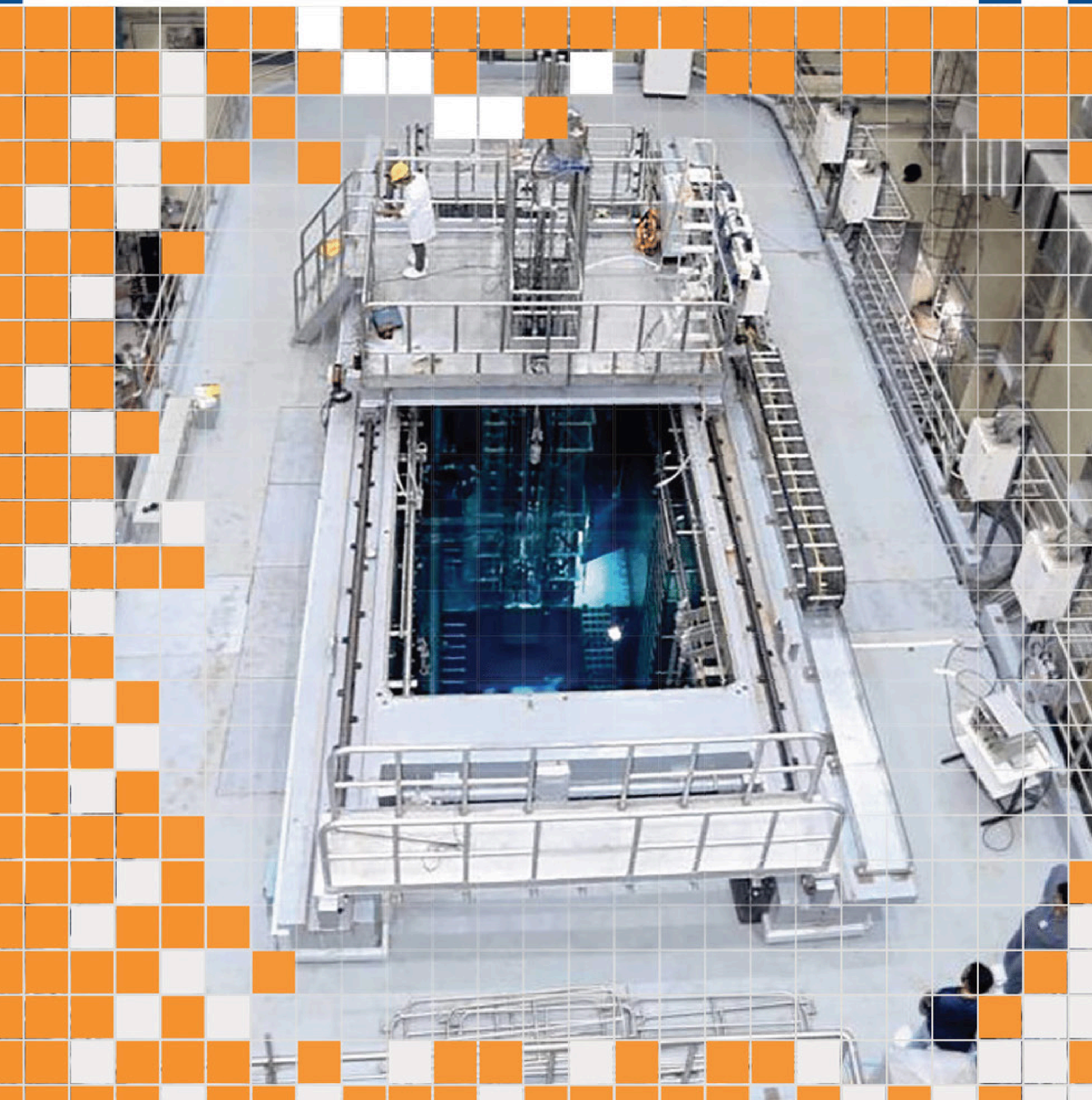
PART A

राष्ट्र की सेवा में परमाणु
पऊवि
DAE
ATOMS IN THE SERVICE OF THE NATION

DEPARTMENT OF ATOMIC ENERGY
RESEARCH & DEVELOPMENT

Advancing the Frontiers of Science and Technology

AMRIT KAAL VISION DOCUMENT



परमाणु ऊर्जा विभाग

DEPARTMENT OF ATOMIC ENERGY

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अमृत काल AMRIT KAAL

संकल्प प्रलेख VISION DOCUMENT

PART – A

Constituent Institutes of DAE

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Atomic Energy Programme for a Sustainable Socio-economic Growth

India is poised for another exciting phase in its history. Riding on the back of glorious achievements of the past seven decades, the country has now set its sight on tapping new and sustainable growth engines to realise an accelerated pace of development. The Government of India's (GoI's) flagship 'Amrit Kaal' 2047 roadmap envisions the country's rapid transition to a global powerhouse of advanced capabilities for sustaining high rates of economic growth. Science and technology will continue to be a mainstay in GoI's long-term goal of transforming the country into 'Viksit Bharat' by the year 2047 by promoting national scientific research and innovation landscape.

Dr. Ajit Kumar Mohanty
Secretary to the Government of India,
Department of Atomic Energy &
Chairman, Atomic Energy Commission

The GoI's 'Amrit Kaal' roadmap envisions a broad-based shift towards clean energy mix to augment the national energy generation capacity and to accomplish the ambitious goal of curtailing emissions to the targeted 'net zero' gradually by 2070. The broader outcomes envisaged by the nuclear energy vision would immensely contribute to India's 'net zero' commitment.

In 1955, Dr. Homi Jehangir Bhabha, in his Presidential address at Geneva Conference, said- "In a broad view of human history, it is possible to discern three great epochs. The first is marked by the emergence of the early civilizations in the valleys of the Euphrates, the Indus and the Nile; the second by the industrial revolution, leading to the civilization in which we live; and the third by the discovery of atomic energy and the dawn of the atomic age, which we are just entering. Each epoch marks a change in the energy pattern of society".

Dr. Homi Jehangir Bhabha emphasized that "for the continuation of our civilization, and its further development, atomic energy is not merely an aid, it is an absolute necessity". At the crucial juncture of the third epoch, deciding the roadmap for achieving a new energy mix for a sustainable socio-economic growth of the world is significant, and nuclear energy would be in the vanguard. In this positive spirit, the Department has now chalked out a robust 'Amrit Kaal' roadmap for guiding its future course of action in core and advanced areas of nuclear energy programme of the country.

Seventy glorious years of Dedication, Advancement and Excellence:

Research Reactors and Nuclear Power Programme

Dr. Homi J. Bhabha recognized the importance of energy for the growth of our nation and the role that nuclear energy has to play in India. Synchronized with this philosophy, the Department of Atomic Energy (DAE) has been successful in delivering the objectives over the last 70 years in the true spirit set in a self-reliant manner. The Indian nuclear energy programme was launched as early as in 1948, when the Atomic Energy Commission (AEC) was constituted and later the Department of Atomic Energy (DAE) was established in 1954. Thus began India's journey for harnessing nuclear energy and radiation technology for peaceful purposes in the areas of power production, applications of radioisotopes in the fields of medicine, agriculture, industry and research. The initial thrust to the nuclear programme was provided with the commissioning of a 1 MW, swimming pool type research reactor 'APSARA' in 1956 at Trombay, Mumbai. In just over a year, scientists and engineers of the department completed the construction of APSARA, and with that India became the first Asian country outside erstwhile Soviet Union to have designed and built its own nuclear reactor. The entire world was eying the phenomenal initiation and development of Indian Nuclear Energy Programme. On 20th January, 1957 during the formal inauguration of APSARA, and Atomic Energy Establishment at Trombay (AEET) by the then Honourable Prime Minister Pandit Jawaharlal Nehru, a delegation of 50 high level foreign dignitaries representing 30 countries witnessed the occasion.

Research reactors are primarily meant to provide neutron source for fundamental research and their applications in a variety of areas including healthcare. All upcoming technologies are first proven in a research reactor prior to their application in a nuclear power reactor. APSARA was instrumental in carrying out advanced research in the field of neutron physics, fission physics, radiochemistry, and R&D on reactor technology for the Indian scientist and engineers. Neutron radiography carried out in APSARA had been used for components of space programme.

This success and experience led to the construction of a vertical tank type 40MW, the second research reactor in 1960, named Canada India Reactor Utility Services or CIRUS. The need was already felt for a high neutron flux high power research reactor, which would cater to the additional requirement of radioisotope production, and for more advanced research. This reactor built under close collaboration with Canada, was similar to Canadian NRX reactor, but with few changes based on location and requirement. CIRUS reactor was solely catering to the country's radioisotope requirements till August 1985, when the third research reactor 'DHRUVA' became operational. This is an even higher neutron flux, 100 MW capacity research reactor designed, constructed and commissioned indigenously. For last 40 years Dhruva has been extensively utilized for engineering and beam tube research, testing of equipment and material, and large-scale production of radioisotopes. Later, looking at the strategic interest of the country, and Bhabha's vision of three stage nuclear programme, indigenously built reactors were, ZERLINA, PURNIMA series at Trombay and KAMINI at Kalpakkam.

In parallel, the nuclear power programme also began its journey with the establishment of the twin units of Boiling Water Reactors (BWRs) at Tarapur in 1969. The power programme has now expanded significantly with 24 reactors being currently operational with a capacity of 8780 MW (excluding RAPS 1) in the country. In addition, 8 reactors with total of 6600 MW are under construction, and 10 reactors with total capacity of 7000 MW are in the advanced stage of beginning the construction. On progressive completion of these reactors by 2031-32, the installed nuclear capacity is expected to reach 22,380 MW (excluding RAPS 1). As a new initiative towards energy security, the Government of India approved 'Anushakti Vidhyut Nigam Ltd.' (ASHVINI), a Joint Venture (JV) between NPCIL and NTPC Ltd., to build, own, and operate nuclear power plants in the country. To start with, the Mahi Banswara Rajasthan Atomic Power Project (MBRAPP), a 4x700 MWe PHWR project has been undertaken by ASHVINI.

Three Stage Nuclear Power Programme

The celebrated three stage nuclear power programme of India envisioned by Bhabha, begins with (Stage -1) the Pressurized Heavy Water Reactors (PHWRs) where natural uranium (U) based fuels are used to generate electricity, and in turn fissile plutonium (^{239}Pu) is produced. In the second stage (Stage-2), Pu based fuels are used to enhance nuclear power capacity, and further to convert fertile thorium (Th) into fissile ^{233}U, a key step for utilisation of vast thorium reserves in India and provide energy security to the country. To achieve success in the Stage-2, Fast Breeder Reactors (FBR) are to be made operational. The Fast Breeder Test Reactor (FBTR), the flagship reactor of the second stage of the Indian nuclear power program, attained first criticality on 18th October 1985, when all eyes were at Kalpakkam. As a signature of advancement, in March 2022, the reactor was successfully operated at its design capacity of 40 MWth. Further to this direction, a 500 MWe Prototype Fast Breeder Reactor (PFBR) is in the advanced stage of achieving criticality. In a historic moment at the 70th year of formation of DAE, the Honourable Prime Minister Shri Narendra Modi witnessed the commencement of "Core Loading" at India's first indigenous Fast Breeder Reactor (500 MWe) at Kalpakkam, Tamil Nadu on 4th March 2024. In line with the true spirit of Atmanirbhar Bharat, PFBR has been fully designed and constructed indigenously by DAE with significant contribution from Indian industries. Once commissioned, India will only be the second country after Russia to have commercial operation of Fast Breeder Reactor. The Stage 3 of the power programme, consisting of advanced thermal and breeder reactors, will use the ^{233}U so produced in Stage 2 for the country's long-term energy security. The three-stage nuclear power programme thus ascertains optimal utilization of uranium and thorium reserves.

The attainment however, is inter-linked with the establishment of an efficient closed fuel cycle approach with recycling of both fissile and fertile components of the spent fuel to appropriate reactor systems. Starting way back in 1964 with the commissioning of a plant based on PUREX technology to reprocess spent fuel from the research reactor CIRUS followed by building a power reactor reprocessing facility, India has mastered in exercising closed fuel cycle involving reprocessing, recycling of fissile material and conditioning of radioactive waste. Looking at the growth of nuclear power programme of the country, the department is constructing an Integrated Nuclear Reprocessing Plant (INRP) at Tarapur. In parallel, to meet the challenges of PFBR spent fuel reprocessing, a Demonstration Fast Reactor Fuel Reprocessing Plant, has been constructed, which was ceremonially dedicated to the nation by the Honourable Prime Minister Narendra Modi on 2nd January, 2024. The large-scale commercial Fast Reactor Fuel Cycle Facility (FRFCF) is also under construction at Kalpakkam.

Harnessing Atomic Energy for Societal Benefits

Cancer Care

In addition to the nuclear power programme, radioisotopes produced in research and power reactors have played a key role in improvement of health care, agriculture, food preservation, and several other areas to benefit the societal programmes of the country. Nuclear medicine, a widely recognized field utilizes trace amounts of radioactive substances for the diagnosis and treatment of various conditions, including cancer, neurological and cardiac disorders. In India, DAE is the sole producer of radioisotopes from the time of the operation of CIRUS and DHRUVA reactors where number of radioisotopes such as ^{99}Mo, ^{131}I, ^{125}I, ^{153}Sm, ^{32}P, and ^{177}Lu for medical applications were produced to meet the demand of radioisotopes of the country. It is worth mentioning that millions of patients in India have been benefitted for nearly half a century from the radioisotopes produced in the CIRUS reactor. The availability of indigenously produced radioisotopes opened up the opportunity of using these isotopes in formulating radiopharmaceuticals in nuclear medicine. DAE is involved in the production as well as the development of targeted disease-specific radiopharmaceuticals for improved outcomes. More than 18 radiopharmaceuticals / radiochemicals and freeze-dried kits have already been developed. These are being used in hospitals for tumour imaging; bone pain palliation; liver, breast, and prostate cancer therapy and so on. The medical cyclotron facility in Kolkata, Cyclone-30 has been facilitating the production of cyclotron-based radioisotopes for healthcare applications. Production and regular supply of ^{18}F-FDG, an extremely critical short-lived radiopharmaceutical used in the PET detection of cancer, Gallium-68 used in Gallium-based radiochemicals such as $^{68}GaCl_3$, for imaging of neuroendocrine cancers and prostate cancer are examples of radioisotopes being produced in the country for the first time using this medical cyclotron. Recently as a significant milestone for scientific and industrial advancement, the Heavy Water Board (HWB) of DAE has achieved a groundbreaking capability in the production of ^{18}O enriched water, which is required for Positron Emission Tomography (PET) scanning for ascertaining the presence of cancer cells / malignancies.

DAE has played pivotal role in country's cancer care programme by employing radiation technology developed in-house. Radiation has the property of killing cancerous cells and radiation therapy can be administered externally for treatment of tumours, which are approachable from outside without collateral damage to healthy tissues. A teletherapy machine, has been developed for this purpose, which has been deployed extensively in India and some centres in abroad as well. A recent contribution of DAE has been the development of an eye plaque for treatment of ocular cancer. Ru-106, a radioisotope recovered from the spent fuel is integrated into circular eye plaques for use in the treatment of eye cancer. Extremely small Yttrium-90 glass spheres measuring just 30 micrometres in size and known as Bhabha Spheres, have been developed for the treatment of a specific type of liver cancer. I-131 based radiopharmaceuticals for thyroid cancer, Lu-177 based radiopharmaceuticals for treatment of neuroendocrine cancer and Sm-153 based radiopharmaceuticals for bone pain palliation are some other prominent examples.

More than five lakh patients receive affordable treatment every year at Tata Memorial Centre (TMC) in Mumbai, which is a constituent unit of the DAE. From 740 beds in 2017, TMC - Hospital has grown to 2700 beds. TMC has now expanded to six other hospitals located in Varanasi, Guwahati, Sangrur, Visakhapatnam, Chandigarh and Muzaffarpur. The Advanced Centre for Treatment, Research and Education in Cancer (ACTREC) has increased its capacity to 900 beds, offering state-of-the-art treatments with specialized facilities for solid tumour chemotherapy, management of haemato-lymphoid cancers, radionuclide isotope therapy, and Proton Beam therapy unit with three gantries, the first-of-its-kind in the government sector. Further, the National Cancer Grid (NCG) has been established with the aim of creating a coordinated system for cancer care that would ensure that patients receive the best possible treatment, regardless of their location or socio-economic status. The NCG includes more than 280 cancer centres and research institutions across India, and it is supported by the Department of Atomic Energy and the Tata Memorial Centre. One of the key objectives of the NCG is to improve the quality of cancer care in India by promoting the use of evidence-based treatments and best practices. The network treats over 750000 new cancer patients annually, which is over 60% of India's cancer burden. TMC has been recognised as an Anchor Centre for the International Atomic Energy Agency's (IAEA) 'Rays of Hope' programme.

Agriculture and food preservation

Continuous mutations in biological systems occur on a very slow time scale, influenced by environmental conditions. However, direct exposure to ionising radiations such as gamma rays from a radioisotope can induce accelerated mutations. DAE has an extensive programme on creating induced mutations in various crops, a technique known as mutation breeding. The method involves exposing seeds to controlled beams of gamma radiation, leading to favourable as well as unfavourable mutations in them. Seeds with desirable traits are selected and multiplied. 71 Trombay crop varieties including groundnut, rice, mustard, mung bean, cow peas, chick peas, and wheat, with enhanced traits such as non-GMO, climate resilience, high-yield, early maturity, and improved disease resistance, have been developed through mutation breeding and are widely cultivated across the country.

Pest infestation, contamination and mould infestation are some of the major problems being faced by the agricultural sector, leading to substantial losses to the extent of 20-30% of the produce. Prevention of post-harvest spoilage is therefore of great significance. The radiation processing offers an eco-friendly solution to this problem. India's first pilot radiation facility 'The Food Package Irradiator', was commissioned in 1967 at BARC. Since then, four additional food irradiation facilities have been commissioned in the Government Sector across Maharashtra and Gujarat. Food irradiation processing is a method approved by several organizations including International Atomic Energy Agency (IAEA), World Health Organization (WHO), Food and Agriculture Organization (FAO), and Food Safety and Standards Authority of India (FSSAI). DAE has also developed irradiation technology for preservation of fruits, vegetables, pulses, spices, sea food etc. by radiation processing and has transferred the technology to private entrepreneurs. DAE has developed an integrated operating procedure utilizing irradiation and onion-specific cold storages, demonstrating the extension of the storage period for 'rabi' onions up to seven and a half months. This breakthrough not only ensures an extended storage life but also maintains the high quality of onions. The KRUSHAK food irradiation facility in Lasalgaon, Nashik, Maharashtra, has been upgraded for conducting the preservation trials and technology demonstrations of the breakthrough protocol in 2024. The successful demonstration of the large-scale trial marked a major milestone in advancing food preservation and hygienisation practices in India, reflecting DAE's unwavering commitment to agricultural innovation. Currently, 28 such commercially operated facilities are available around the country. Radiation processing protocol for mangoes has been developed successfully, and these fruits are now being exported to four countries across the world, USA, Australia, Malaysia and South Africa.

These are just a few glimpses of the vast potential of nuclear energy and radiation technology applications across various aspects of our lives. Achieving a balance between maintaining and sustaining our ecosystem and biodiversity, as pursuing developmental goals, requires innovative solutions. Many of the technologies developed by the DAE are steps in that direction, offering far-reaching benefits in energy, healthcare, nutrition and general well-being in a sustainable manner.

Basic Science Research

It is logical to believe that fundamental research serves as the backbone of scientific discoveries which actually creates the groundwork for applied research and technological advancements, towards improving the quality of human life, as all these are closely connected. Indeed, the history of science has shown that all genuine knowledge has been for the potential use of mankind.

"The pursuit of science and its practical application are no longer subsidiary social activities today. Science forms the basis of our whole social structure without which life as we know it would be inconceivable…"

~ Homi Bhabha
(in his lecture at the inauguration of TIFR in December 1945)

Bhabha believed that science has advanced at an accelerating pace since the early 20th century, widening the gap between the Global North and lower-middle-income countries. It is only by adopting the most vigorous measures and by putting forward utmost efforts into the development of science can bridge the gap. Undoubtedly, by this time Indian scientists including luminaries like C. V. Raman, Satyendra Nath Bose, Meghnad Saha and many others, had made significant contributions to the advancement of science, which are now integral to the fabric of modern science. With the aim of advancing science in India at a pace befitting the country's talent, Bhabha sought Sir J R D Tata's support to provide the necessary conditions and financial backing for establishing a scientific institute. This institute would promote original research at the frontiers of nuclear physics, cosmic rays and high energy physics. With financial support from the Sir Dorabji Tata Trust, Tata Institute of Fundamental Research (TIFR) was initially established within the premises of the Indian Institute of Science (IISc), Bangalore. Later it was shifted to Bombay, where it was formally inaugurated on December 19, 1945. Since 1955, the main funding responsibility of the institute lies on GoI through DAE. Starting with high energy cosmic ray research, TIFR has now grown to become one of the most premier and prestigious research institutes of this country, pursuing research activities across physical, chemical and life sciences. The approach to fundamental research as exemplified by the atomic energy program, has been characterized by a commitment to curiosity-driven research, crucial for driving innovation, creating paradigm shifts, and contributing to long-term national development. Starting with the establishment of TIFR, Bhabha facilitated creation of various other institutions of excellence, such as Saha Institute of Nuclear Physics, Institute for Mathematical Sciences. Later, the DAE has either established or aided institutes like, Harish-Chandra Research Institute (HRI), National Institute of Science Education and Research (NISER), Institute of Physics (IOP) and Institute for Plasma Research (IPR). The latest in this series is the Homi Bhabha National Institute (HBNI), a deemed-to-be university, which continues to advance scientific research and innovation in the country through its constituent DAE, and DAE-Aided institutes. DAE support and nurture basic research in Indian institutes and universities by funding through the Board of Research in Nuclear Sciences (BRNS). Collaborative programmes between researchers in universities and DAE scientists, are encouraged by BRNS in order to increase academic interactions.

Dr. Bhabha initiated the balloon experiments in India at TIFR in 1948 for research in Astronomy, Astrobiology, and High Energy Physics. The TIFR balloon facility in Hyderabad today has the capability to launch heavy pay loads up to 1200 kg gross weight to altitude of 32 km for astronomy experiments and lower payloads for high energy physics research. The facility achieved the landmark of 500 scientific balloon launches in 2018. In cosmic ray research, India thus has a rich and long history. Researchers at TIFR detected the atmospheric Cherenkov radiation in early seventies, and also established an array of 25 distributed Cherenkov telescopes, known as the Pachmarhi Array of Cherenkov Telescopes (PACT), in Madhya Pradesh. Later in 2002 an array of seven telescopes was setup at Hanley to observe high energy gamma rays from celestial objects at lower energy. GRAPES-3, a near-equator astroparticle physics research facility at Ooty is being led by TIFR and operated by international consortium of several institutes of India and Japan.

The Giant Metrewave Radio Telescope (GMRT), an array of 30 radio telescopes used for investigating a variety of radio astrophysical phenomena ranging from the nearby solar system to the edge of the observable universe, is developed by TIFR, a grant-in-aid institution of DAE. Located at Narayangaon in Pune, GMRT has been accorded the prestigious IEEE Milestone status in 2020 in recognition of the global impact of GMRT, with users from 40+ countries worldwide, and the fact that it was designed and built entirely in India, with innovative ideas. GMRT is only the third such IEEE Milestone recognition for an Indian contribution to date, after the one for the pioneering work by Sir J. C. Bose on radio waves in 1895 and the one for the Nobel Prize-winning discovery by Sir C. V. Raman in 1928.

Bhabha Atomic Research Centre (BARC) started the Very High Energy gamma ray astronomy programme by setting up country's first imaging telescope called TACTIC at Mt Abu in 1997. The same year, it detected gamma ray emission from the Active Galactic Nuclei, Mrk 501 first time along with four other imaging telescope facilities around the globe. A high-altitude research laboratory at Gulmarg is also managed by BARC, where research in the field of cosmic ray astrophysics, radioastronomy, and atmospheric neutron monitoring is being carried out. Recently, the Major Atmospheric Cherenkov Experiment (MACE) Observatory at Hanle, Ladakh was formally inaugurated as a part of the Platinum Jubilee year celebrations of the DAE. MACE is the largest imaging Cherenkov telescope in Asia, situated at an altitude of approximately 4,300 meters, making it the highest of its kind in the world.

The DAE has placed paramount importance on accelerators-based research in the country. Over the years India has achieved the capability to design, build and operate accelerators and carry out accelerator-based research programmes in the frontiers of nuclear science. In the 1960s, a 5.5 MV Van de Graaff accelerator was installed at BARC, Mumbai. Later a folded 7 MV tandem accelerator has also been installed at BARC. These low energy accelerators are meant for basic and applied research in several interdisciplinary areas. The variable energy cyclotron was commissioned in the early 80's and was the first accelerator facility in the country for advanced experimental nuclear physics research. The 14 MV tandem Van de Graaff (Pelletron) accelerator was set up and commissioned at the TIFR campus in 1989, as a collaborative BARC-TIFR program. Several low energy electron accelerators are being operated at different institutes of the country including DAE for fundamental research and applications. As the beginning of an active programme to develop accelerator-driven technology for nuclear waste transmutation and power generation, BARC has recently demonstrated 20 MeV proton beam in its Low Energy High Intensity Proton Accelerator (LEHIPA) facility.

Two synchrotron radiation sources INDUS-I and INDUS-2, which are 3rd generation light sources, have been designed in the nineties and are being operated at RRCAT, Indore. Indus-1 was the country's first synchrotron generator with a 450 MeV storage ring. Indus-2 has a beam energy of 2.5 GeV and critical wavelength of about 1.98 angstrom. The beam lines developed by DAE scientists in INDUS-1 & 2 are also being used by several universities and institutions for pursuing research in the areas of material science, electronic structures, spectroscopy, imaging and crystallography.

International Collaboration and Mega Science

India is also collaborating with major international accelerator facilities in Europe, USA and Japan. Under the CERN-India agreement, India is making in-kind contributions, to the Large Hadron Collider (LHC) at CERN. The scientists from DAE have also participated in the DØ experiments at the FERMILAB, USA, which led to the discovery of the top quark. As part of Indian Institutes and FERMILAB collaboration, several new and advanced technologies for high-intensity proton accelerators are being developed at multiple centres of DAE. The groups from BARC had joined the PHENIX collaboration for relativistic heavy ion collision experiments using the BNL relativistic heavy ion collider (RHIC) in the past.

As a part of Mega Science, India has conceived an international project, Laser Interferometer Gravitational-wave Observatory "(LIGO)-India", which is a collaborative project between the USA and India. The LIGO-India testing and training facility at RRCAT, Indore was inaugurated in December, 2024, which would serve as a staging and assembly lab for LIGO-India detector subsystems.

DAE-BARC in close association with other defence departments of Government of India, is continuously working on developing technologies for national security. I recall that, two weeks after "Operation Shakti", the then Honourable Prime Minister Shri Atal Bihari Vajpayee stated that "India is now a nuclear weapon state". He further emphasized, "Our strengthened capability adds to our sense of responsibility", a principle that India upholds with pride. The Silver Jubilee of "Operation Shakti" was celebrated on 11th May 2023 in the Pragati Maidan, New Delhi, when the Honourable Prime Minister, Narendra Modi virtually inaugurated five nuclear technology-linked cancer care centres in two states, and a rare earth permanent magnet plant in Visakhapatnam.

Way forward: Entering the era 'Amrit Kaal'

The milestones already achieved by DAE institutions are vast and encompass a broad range of areas. In this positive spirit, DAE has now chalked out prospective growth drivers for nuclear and allied sector expansion in the country in the next two-and-a-half-decade period. It is envisioned to design, construct, install and commission new general purpose research reactors & developmental reactors for special purpose in BARC-Vizag campus, where infrastructure development work is progressing in full swing. Developmental reactors such as high temperature reactor are for green hydrogen production and utilisation of thorium after breeding into uranium. The new reactor programme would also support the three-stage nuclear power programme by emphasizing on indigenous technology development for IPWR and FBR for 1^{st} & 2^{nd} Stage of Indian nuclear power programme as well as for realization of 3^{rd} stage for long term energy security. The nuclear fuel cycle covering front end as well as back end of fuel cycle will back up the ambitious programme. An integrated nuclear recycle plant (INRP) being constructed would integrate all the facilities operating in spent fuel storage, reprocessing, waste management and MOX fuel fabrication. A fast reactor fuel cycle facility (FRFCF) will be commissioned at Kalpakkam.

"The five Public Sector Undertakings (NPCIL, BHAVINI, UCIL, ECIL & IREL) of DAE are primarily responsible for *development* in production of nuclear power to provide support in achieving energy security in a sustainable manner. Together NPCIL and BHAVINI envision to reach installed capacity of about 58000 MW by 2047. The other PSUs will work in tandem and support the programme by augmenting fuel production facility, developing required electronics and instrumentation and by supplying necessary rare materials.

The accelerator programme aims at long term energy security in a sustained manner through phase wise development of high energy proton accelerators typically 1 GeV for accelerator driven sub-critical systems, as well as for transmutation and incineration of nuclear waste. For the same purpose a high-energy high-intensity proton cyclotron systems with a final energy of 800 MeV is also envisaged. It is now proposed to indigenously develop a state-of-the-art 4th generation high brilliance synchrotron radiation source (Indus-3) in India. The proposed Indus-3 (6 GeV, 200 mA) will provide a significant boost to the national scientific and research community as well as applied and industrial research.

In radio astronomy, expanding the GMRT facilities to reach unprecedented sensitivities would enable transformational, high-impact science. In astrophysics research, looking ahead, the MACE project and its proposed expansion with array telescopes aim to foster international collaborations, advance India's contributions to the study of the universe, and bolster India's position in the global scientific community. The observatory will also serve as a beacon of inspiration for future generations of Indian scientists, encouraging them to explore new frontiers in astrophysics. The mega science project LIGO-India will be built at Hingoli in

Maharashtra by DAE and the Department of Science and Technology (DST), GoI, in collaboration with the National Science Foundation (NSF), USA. Honourable Prime Minister Shri Narendra Modi laid the foundation stone of (LIGO-India) on National Technology Day, 2023. The scientific goals of which are to advance research in astronomy and fundamental physics. The source of gravitational waves, which are predicted to be emitted by collision of the objects like black holes, neutron stars and supernova, is expected to be detected.

Progress is an open-ended endeavour and I am confident that DAE institutes together will leverage the insights within the roadmap to propel the organizations forward, contributing to the realization of a brighter and more technologically advanced India.

I am extremely happy to announce the release of the report titled 'Amrit Kaal Vision Document,' a comprehensive document that represents charting a strategic course for the continued success of the R&D Units, PSUs, Industrial Units, and Aided Institutions. All the Unit Heads of DAE anchored this activity, and the collective efforts of all units are commendable. The roadmap will be instrumental in achieving our collective ambition—the creation of a self-sufficient and technologically unparalleled India by 2047.

Jai Hind

Ajit Kumar Mohanty

Dr. Ajit Kumar Mohanty

August, 2025

Secretary, DAE and Chairman, AEC

The Department of Atomic Energy

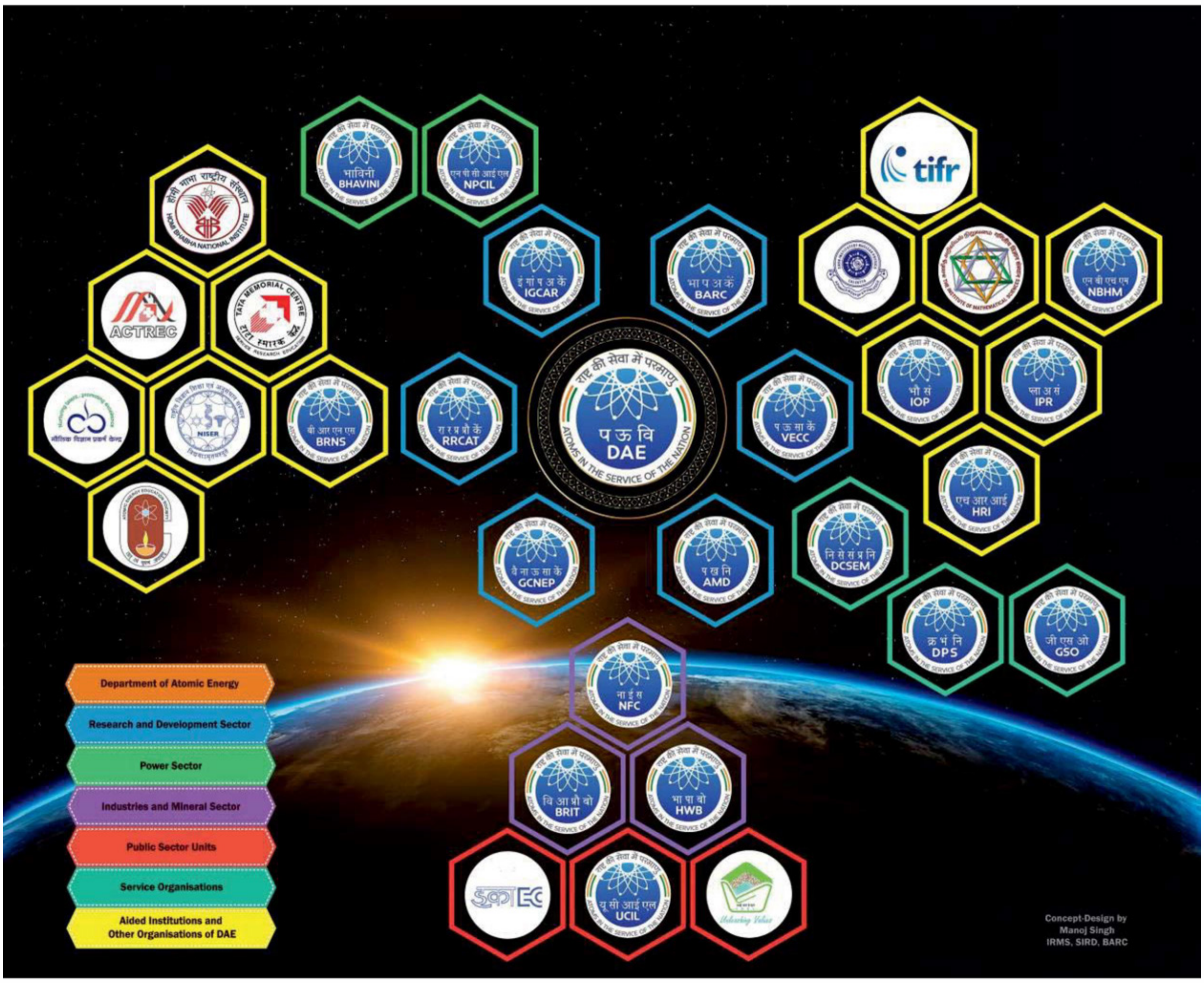
Department of Atomic Energy (DAE), since its inception, has been pursuing a focused mandate for development of indigenous technologies in all the facets of nuclear science and its applications. The core idea is to harness the potential of environmentally benign nuclear energy for achieving long-term energy security of the country in a sustainable manner. The vitally correlated objective is to make use of radiation technologies for societal benefits which include, healthcare, food security, water and waste management, advanced material development, and so forth.

To achieve self-reliance in the field of nuclear power and radiation technologies, it is pertinent to develop indigenous capabilities in the fields of reactor technologies, front- and back-end of fuel cycle, manufacturing technologies, cutting-edge radiation technologies, synchronised with capacity-building and skill-development, and to identify and address the gap areas for achieving development.

This vision document comprises of flagship programmes of Constituent Institutes (CIs) of DAE (i.e. BARC, IGCAR, VECC, RRCAT, NFC, AMDER, HWB, BRIT, and DCSEM). While commemorating the 100th anniversary of independent India, the nation aspires to become 'Viksit Bharat' (developed India) by the year 2047. All the major R&D activities planned by the Department during the Amrit Kaal are fully aligned with India's attainable ambition of becoming Atmanirbhar in the field of nuclear science and technology.

DAE Secretariat since 1954 at Mumbai's iconic 175-year-old Old Yacht Club

The DAE Family



The Department of Atomic Energy is at the fore-front of research and development, leveraged by a strong synergy between R&D and technology development in a number of core disciplines of national and international importance. DAE comprises 6 research centres-BARC (Mumbai), IGCAR (Kalpakkam), RRCAT (Indore), VECC (Kolkata), AMDER (Hyderabad) and GCNEP (Bahadurgarh), 3 industrial organizations- NFC (Hyderabad), HWB (Mumbai) and BRIT (Mumbai), 5 public sector undertakings- NPCIL (Mumbai), BHAVINI (Kalpakkam), ECIL (Hyderabad), UCIL (Jaduguda) and IREL (India) Limited (Mumbai) and 3 service organizations-DCSEM (Mumbai), DPS (Mumbai) and GSO (Kalpakkam). DAE has 11 grant-in-aid institutes of international repute engaged in research in basic and applied sciences, cancer research and education (TIFR, SINP, TMC, HRI, IoP, NISER, IMSc, IPR, HBNI, UM-DAE CEBS and AEES). It also has under its aegis, 2 boards (BRNS and NBHM) for promoting and funding extramural research in nuclear and allied fields and mathematics.

Brief Introduction of Nine CIs Participated in Chintan Shivir:

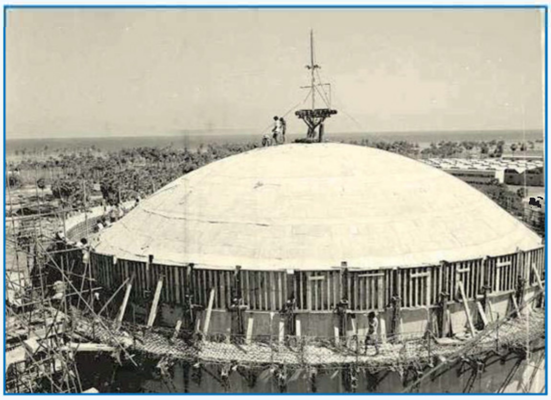
Bhabha Atomic Research Centre (BARC) established in 1954 in Mumbai as India's premier nuclear R&D organisation, has now expanded its multi-disciplinary and multi-scale activities at various places of the country. Its mandate focuses on advancing nuclear science and technology for its peaceful applications in the areas of in energy security, improved healthcare, advanced agriculture, and industrial development, while ensuring the nuclear safety. Guided by its vision, BARC strives to drive innovation and self-reliance in harnessing nuclear power as a sustainable source of energy, while leveraging cutting-edge research to improve the quality of life of the Indian citizens.

Dhruva (1985) and CIRUS (1960) Research reactors at BARC in Mumbai, Maharashtra

Apsara, commissioned in the then Atomic Energy Establishment, Trombay (now BARC) in 1956, was the first research reactor in Asia. CIRUS, commissioned in 1960, was the second research reactor in India

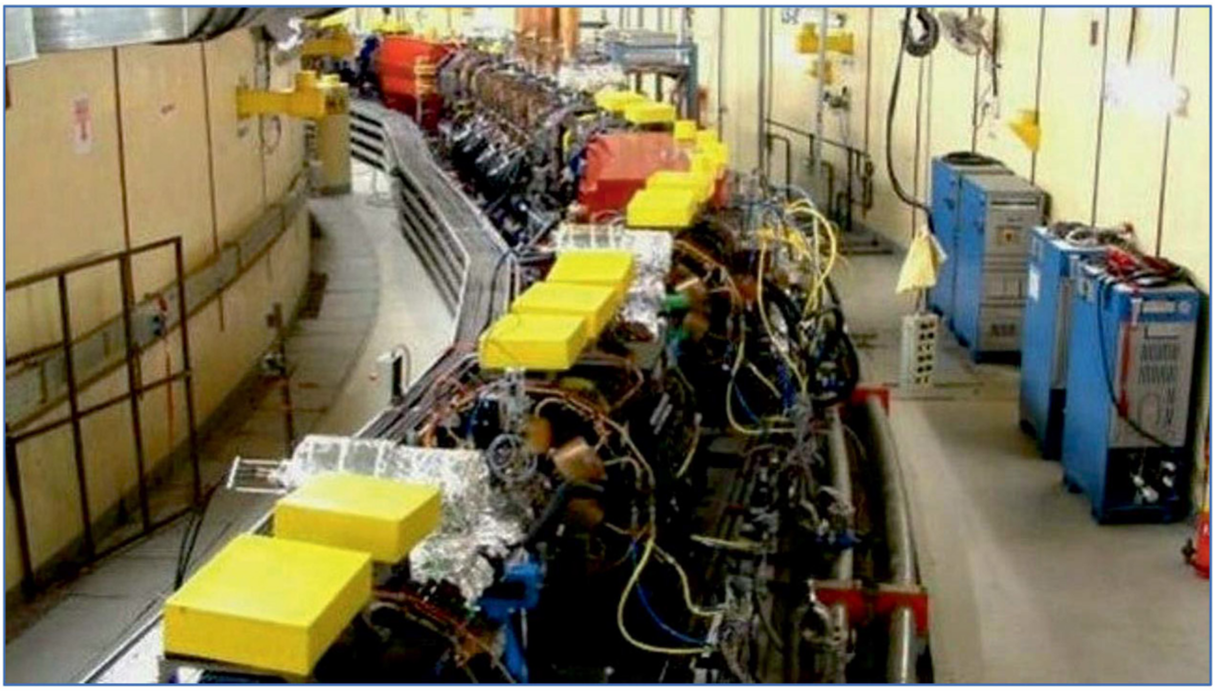
Indira Gandhi Centre for Atomic Research (IGCAR) established in 1971 at Kalpakkam, is the second-largest R&D establishment of DAE. Dedicated for fast reactor technology, its mandate is to carry out multidisciplinary programme of scientific research and advanced engineering to develop sodium-cooled fast breeder reactor (FBR) technology. It also encompasses basic research in materials science, reactor physics and safety engineering in fast reactor technology. This mission aligns with the second stage of Indian Three Stage Nuclear Power Programme for utilisation of vast thorium reserves for sustained energy security.

Prototype Fast Breeder Reactor developed by IGCAR at Kalpakkam, Tamil Nadu

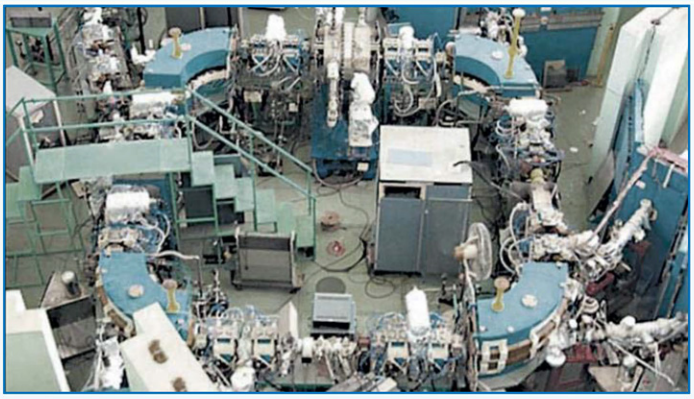


The Fast Breeder Test Reactor (FBTR), breeder reactor located at Kalpakkam, Tamil Nadu, first reached criticality in October 1985 making India the seventh nation to have the technology to build and operate a breeder reactor after United States, UK, France, Japan, Germany, and Russia. IGCAR and BARC jointly designed, constructed, and operate the reactor.

Raja Ramanna Centre for Advanced Technology (RRCAT) was established as a R&D unit in 1984 at Indore with a primary mandate to develop advance technologies related to lasers and accelerators. Distinct areas of research & development are high-power lasers, free electron lasers, superconducting cavities and synchrotron radiation sources. One of its major achievements is the establishment of the Indus synchrotron radiation facilities, for research in material science, biology, and nanotechnology.



INDUS 2 Synchrotron Radiation Source (2005) at RRCAT, Indore, Madhya Pradesh



The first Indian synchrotron radiation source Indus-1 was commissioned at RRCAT, Indore in May 1999. The injector system for Indus-1 consists of a classical microtron, which accelerates electrons to 20 MeV and in a synchrotron, which accelerates these 20 MeV electrons to 450 MeV.

Variable Energy Cyclotron Centre (VECC), established in 1977 at Kolkata, is a R&D unit with a primary focus on accelerator-based research and its applications in diverse fields such as nuclear physics, materials science, biology, and medicine. VECC's core mandate involves designing, developing, and operating advanced particle accelerators, conducting cutting-edge research in nuclear and high-energy physics. An advanced facility, Variable Energy Cyclotron at VECC supports fundamental research and applied studies deploying accelerated heavy-ion beams.

Variable Energy Cyclotron Centre (VECC), Kolkata, West Bengal

The Medical Cyclotron Facility of VECC has been catering to the requirements of radioisotopes and radiopharmaceuticals for the medical fraternity in and around West Bengal. For the first time in India, Thallium-201-Chloride was produced for Cardiac studies using this facility.

Atomic Minerals Directorate for Exploration and Research (AMDER), was established in 1949 at Hyderabad. AMDER's primary mandate includes the conduction of comprehensive geological surveys, exploration, identification, and evaluation of atomic minerals. The, main focus is on uranium, thorium, and other strategic minerals essential for Indian nuclear energy program. AMDER also conducts research in related areas, including beach-sands and offshore investigations, rare metal and rare earth resource assessments. Guided by a vision to ensure a stable and secure supply of nuclear raw materials, AMDER contributes significantly in strengthening the resource base for the nuclear fuel cycle, advancing exploration technologies, and fostering innovation in atomic minerals research.

Atomic Minerals Directorate for Exploration and Research, Hyderabad, Telangana

In 1955, airborne radiometric survey techniques, using helicopters were introduced by AMDER (erstwhile Raw Materials Division). Fixed-wing aircraft was used in 1956 for airborne survey covering large areas along the Himalayan foothills. India became one of the first few countries to adopt this technique for exploration.

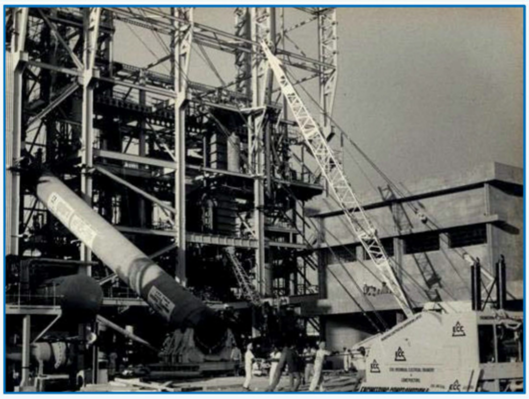
Board of Radiation and Isotope Technology (BRIT) is an industrial unit, established in 1989, to promote the application of radioisotopes and radiation technologies. Its primary mandate is to develop, produce and supply radiopharmaceuticals & isotopes. BRIT also provides a wide range of products and services, including essential radiopharmaceuticals for medical diagnostics and therapy, labelled compounds, sealed radiation sources, gamma chambers, blood irradiators, and radiography exposure devices, to empower India through technology, creation of more wealth and providing better life to its citizens while ensuring safe radiation practices.

Production of Radiopharmaceuticals at BRIT, Navi Mumbai, Maharashtra

BRIT established India's first Fission Molybdenum-99 Plant at Mumbai making India one of the few countries in the world producing Fission Molybdenum-99. This plant will not only fulfil the domestic demand but will also allow export of Molybdenum-99 to neighbouring countries.

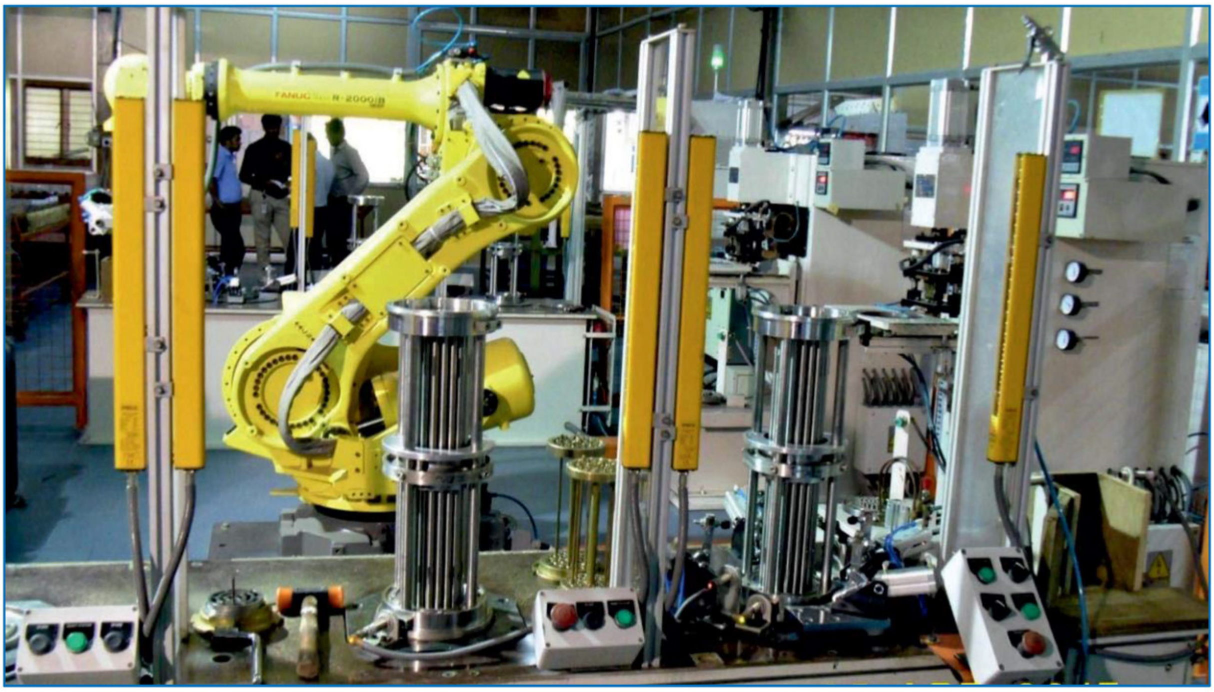
Heavy Water Board (HWB), an industrial unit established in 1962, is responsible for the production and supply of high-quality heavy water (deuterium oxide, D_2O) as well as development and optimization of technologies related to heavy water production. This is essential to meet India's growing nuclear energy needs and support the nation's self-reliance in nuclear power production. HWB is also responsible for the production and supply of special materials like enriched boron, nuclear-grade sodium, and nuclear solvents that supports India's Three-Stage Nuclear Power Program. Moreover, HWB exports and supplies heavy water and deuterium for non-nuclear applications in life sciences, pharmaceuticals, and other industries.

Heavy Water Plant at Manuguru, Telangana, the largest producer of Heavy Water in India

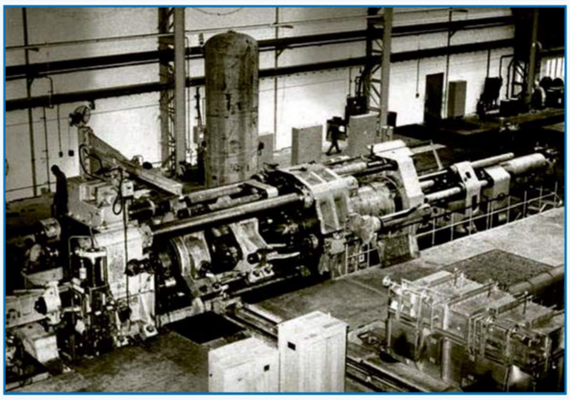


HWB Facilities, Vadodara, started in 1977, produces potassium metal, deuterated compounds, and solvents for in-house use. It also manufactures deuterium gas, which enhances optical fibre performance and aids in chemical synthesis. Deuterium gas is available for sale. Upcoming projects include sodium metal and versatile solvent plants to support India's nuclear power programme.

Nuclear Fuel Complex (NFC), an industrial unit established in 1968 at Hyderabad, is responsible for the production of nuclear fuel and the associated components required for India's nuclear power plants. NFC activities include the entire process of nuclear fuel production, from uranium extraction and conversion to fabrication & manufacturing uranium fuel, fuel bundles, nuclear reactor core components, zirconium-based alloy materials and supply of the final fuel elements. The Nuclear Fuel Complex (NFC) supports India's self-reliance in nuclear fuel fabrication ensuring high quality to accelerate the Indian Three-Stage Nuclear Power Program.



Fuel Fabrication Facility of NFC at Hyderabad, Telangana



NFC was established at Hyderabad in 1968 for indigenous manufacturing of fuel-bundles, structural components for the Indian nuclear power programme, and to provide advanced tools and technologies for fabrication of special alloy seamless tubes and high purity materials for strategic applications and nuclear power programme.

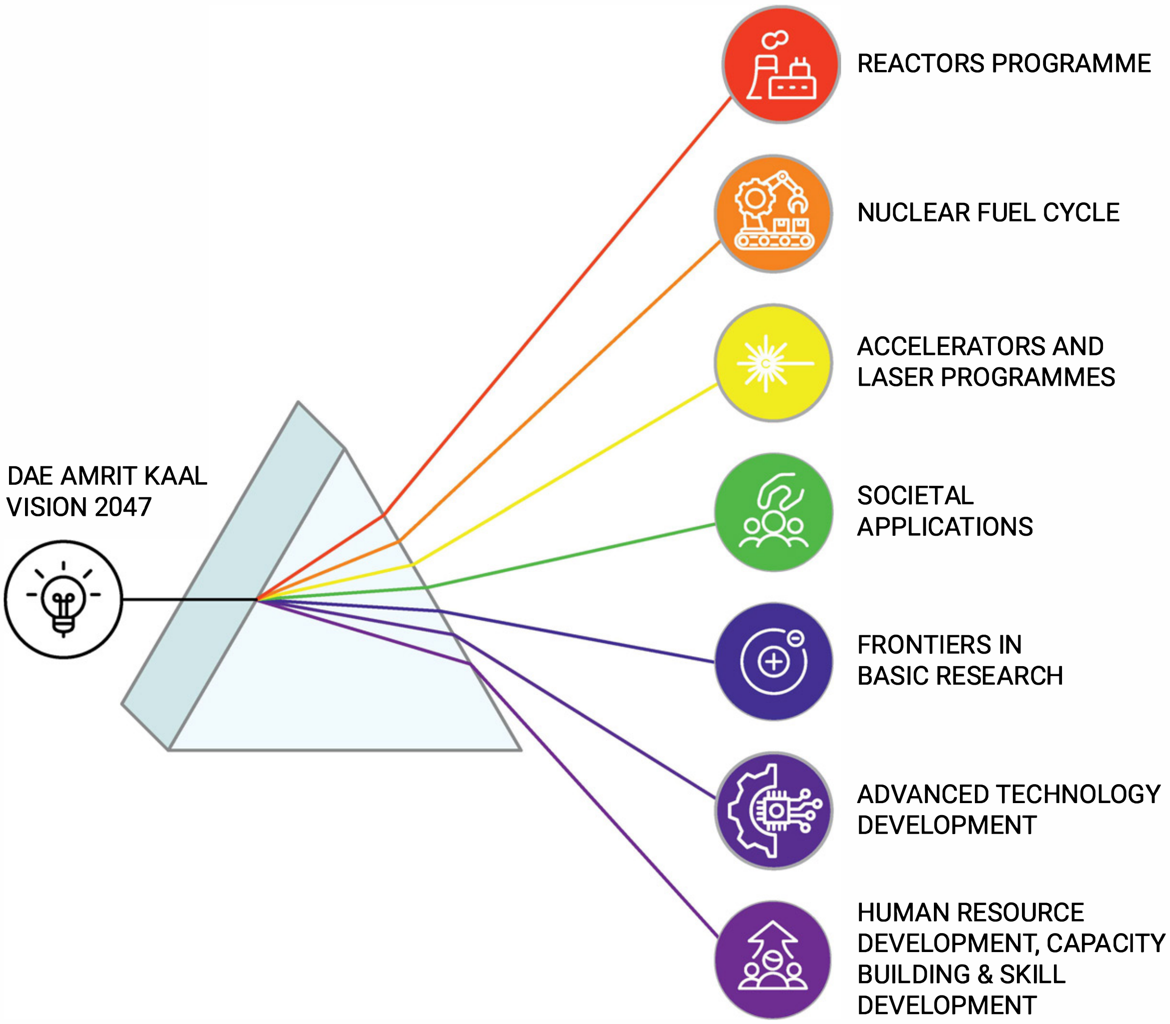
Directorate of Construction, Services, and Estate Management (DCSEM), a service organisation, was established in 1996. DCSEM is responsible for planning, designing, engineering, and executing civil, public health, electrical, air-conditioning, and ventilation works for various DAE units, including housing, hostels, schools, hospitals, laboratories and various public buildings for units of DAE including aided institutions. The Directorate also manages the custody of DAE lands, particularly in Mumbai. Additionally, DCSEM is involved in the operation and maintenance of electrical, mechanical, civil, and estate services for DAE facilities, ensuring a safe, efficient, and sustainable environment for the department's staff.

DAE Convention Centre developed by DCSEM at Mumbai, Maharashtra

The postgraduate hostel for HBNI and BARC located in Mumbai, is a harmonious cluster of buildings and landscape designed and constructed by DCSEM. This accommodation for a thousand PG students creates space and functionality.

Chintan Shivir and Seven Verticals:

In line with Government of India directives, the vision targets were finalised in the councils of various CIs. The targets were further refined in combined meeting of Heads of CIs. Subsequently two-and-a-half days Chintan Shivir was organised for all the nine CIs during 22nd to 24th Jan 2024 at BARC. After multiple rounds of discussion and deliberations with CIs, the Amrit Kaal targets were finalized.



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3	yellow	#f1e400
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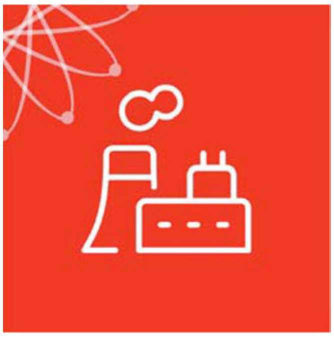
Amrit Kaal Vision 2047 Targets have been divided into seven verticals as described below:



Vertical 1 - Reactors Programme:

The flagship programmes under this vertical are design, development, construction, installation and commissioning of new research reactors as well as developmental reactors. Research reactors are utilised for isotope generation, reactor physics experiments, irradiation studies, research for development on new fuel and materials. Developmental reactors are for special purpose, like high temperature reactor for green hydrogen production and utilisation of thorium after breeding into uranium. The reactor programme essentially supports the three-stage nuclear power programme by emphasizing on indigenization of technology for Indian Pressurised Water Reactor and FBR for 1^{st} & 2^{nd} Stage. The programme would as well guide the development of demonstration reactor for realization of 3^{rd} stage for long term energy security and for achieving net zero carbon emission.

Vertical 2 - Nuclear Fuel Cycle:

This vertical covers the present status and future plans of front-end as well as back-end of fuel cycle. The programme emphasizes exploration and augmentation of uranium, thorium and other rare earth (RE) materials reserve. Essentially, expansion of fuel fabrication capabilities for sustained operation of existing reactors is vital, besides meeting the future requirements. Development of advanced fuel for futuristic reactors is an integral component of this programme. Thus, construction and commissioning of integrated fuel reprocessing plants for PHWR as well as FBR are necessary for recycling the fuel, above and beyond waste management technologies for safe disposal of nuclear waste.

Vertical 3 -Accelerators and Laser Programmes:

Indian accelerator programme aims long term energy security in a sustained manner through phase wise development of high energy accelerators especially, 1 GeV for Accelerator Driven Sub-critical Systems (ADSS). Deployment of ADSS is envisaged for utilization of thorium after breeding into uranium, in addition to transmutation and incineration of nuclear waste. Development of advanced material for accelerator components and super conducting components for self-reliance is the key. The programme also emphasises on development of accelerators for medical isotope production, and industrial applications.

Vertical 4 - Societal Applications:

The programme is directed towards development of radiopharmaceuticals for diagnostics and treatment of cancer, development & deployment of technology of large capacity food /grain irradiators. The programme also covers development of new crop varieties through radiation induced mutagenesis, seed breeding for food security, solid waste management and waste water management for reducing human load on environment.

Vertical 5 - Frontiers in Basic Research:

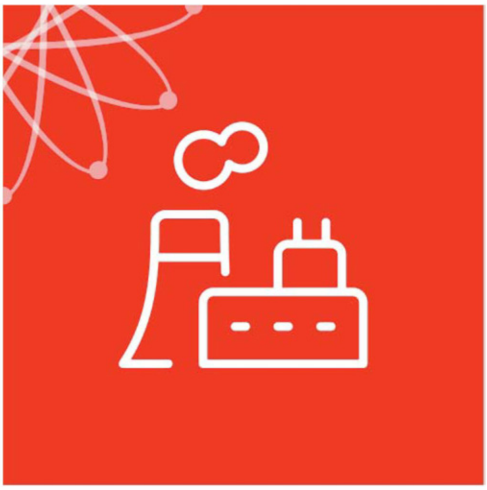
The vision for basic and directed research in the thrust areas of physical sciences, chemical sciences, biological sciences, material sciences are outlined herein. Health physics for reactor programmes, research on nuclear fuel cycle, and physics of accelerator programme are also covered under this vertical, including basic understanding of emerging science.

Vertical 6 - Advanced Technology Development:

The vertical primarily focuses on indigenization of technologies necessary to support reactor programme, nuclear fuel cycle programme, accelerator programmes, reactor safety, and program related to hydrogen production & storage. Cryogenic technology for accelerator programmes, indigenous development of detectors & instruments, and development of advanced metal joining techniques have also been envisaged in this programme.

Vertical 7 - Human Resource Development, Capacity Building & Skill Development

The vertical mainly comprise programme on augmentation of human resource to meet the requirement of future plans during the Amrit Kaal.



Vertical 1

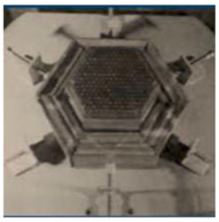
REACTOR PROGRAMME

HISTORY OF RESEARCH REACTORS AT BARC

APSARA India's first nuclear reactor attained criticality on August 4, 1956. The 1-MW swimming pool reactor, using enriched Uranium-Al alloy fuel and light water as moderator and coolant, provided valuable insights into reactor design, construction, and control. It also facilitated radioisotope production, neutron studies, shielding experiments, beam tube research, and training of scientists and engineers.

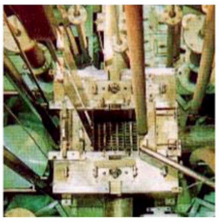
CIRUS A 40-MWth Indo-Canadian research reactor, attained criticality on July 10, 1960. Modelled on Canada's NRX reactor, it used natural uranium fuel and heavy water as a moderator. As Asia's largest research reactor of its time, CIRUS played a key role in nuclear physics research, reactor fuel development, and isotope production.

ZERLINA An indigenously designed zero-energy reactor, attained criticality on January 14, 1961. This 100-watt reactor, using heavy water as a moderator, served as a key experimental tool for studying various fuel-moderator combinations. Its 80 fuel elements were fabricated at Trombay from domestically produced uranium.



PURNIMA The 1-watt thermal fast reactor, using plutonium oxide fuel, attained criticality on May 18, 1972. As India's first fast reactor, it played a crucial role in advancing the country's fast reactor program. It provided valuable insights into plutonium-based reactor physics before being decommissioned in 1973.

DHRUVA A 100-MW vertical tank-type research reactor, attained criticality on August 8, 1985, marking a key milestone in India's indigenous nuclear technology. With a high neutron flux, it enables the production of high-specific-activity radioisotopes and supports advanced research in basic sciences. Declared a national facility, Dhruva meets the growing demand for radioisotopes and multidisciplinary neutron beam research.



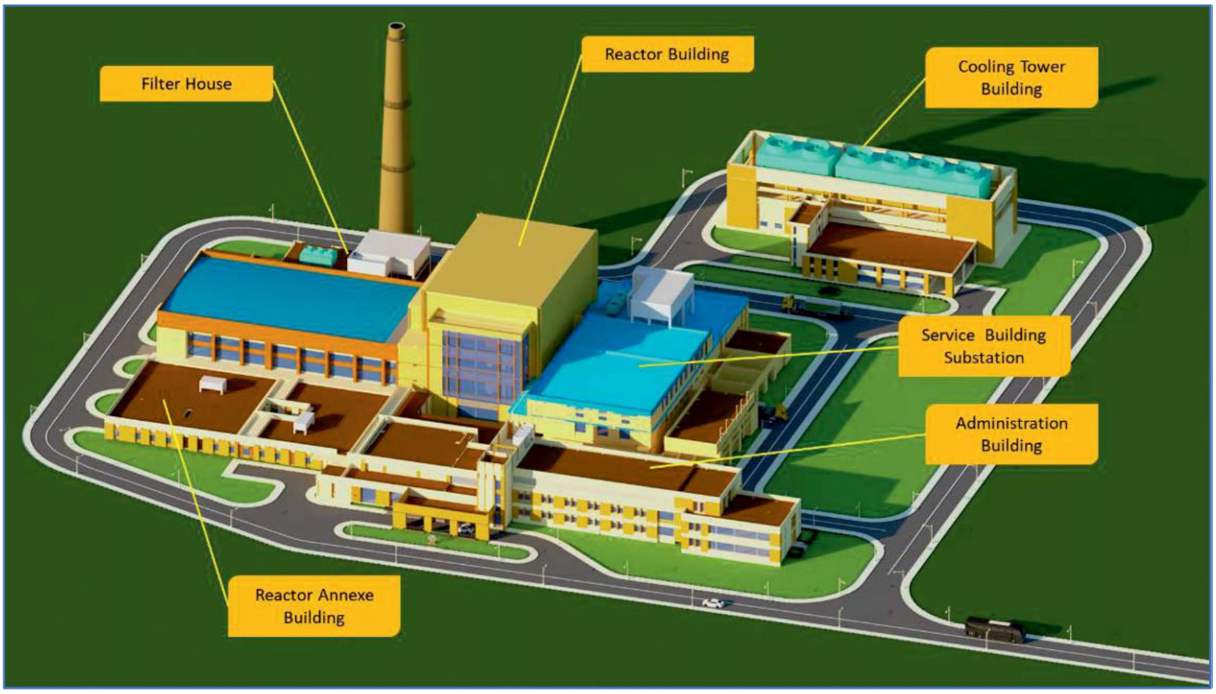
KAMINI A 30 kW-thermal reactor built by BARC and IGCAR, attained criticality on October 29, 1996. Using uranium-233 fuel produced from the thorium cycle, it is the world's only reactor designed specifically for this fuel. Cooled and moderated by light water, KAMINI serves as a precursor to India's three-stage nuclear power program.

APSARA-U A 2 MW thermal swimming pool reactor with a compact core, attained criticality on September 10, 2018. By virtue of higher neutron flux, Apsara-U will enhance indigenous production of radioisotopes for various societal applications. Using low-enriched uranium fuel and light water as coolant and moderator, it enhances research, shielding experiments, and scientist training.

1.1 New Research Reactors

1.1.1 High Flux Research Reactor

Since its inception, one of the mandates of BARC is to provide reactor-based facilities to cater to the various needs of a vast pool of researchers in the field of material sciences, physics, chemistry, bio sciences, research and development work for nuclear power plants, and production of radio isotopes. Ambitious plans in this direction have been executed successfully and thus APSARA, CIRUS, DHRUVA have provided service to the nation for decades, recent launch being the APSARA-U reactor. DHRUVA and APSARA-U are currently in use for the purpose. To further consolidate and expand the scope of research in nuclear and allied sciences in a competitive world, an advanced High Flux Research Reactor (HFRR) is planned to be indigenised. India is eying to construct and commission a compact and simple to use pool type research reactor, which will provide a high neutron flux (10^{15} n/cm^2/sec) over a large irradiation volume. The proposed HFRR is one-of-a-kind reactors for advanced research applications, including cold neutron source and corrosion study facility. This would also play a crucial role in radio-isotopes production and provide advanced facilities for basic research and other areas related to development and testing of nuclear fuels & reactor materials.



The proposed setup for HFRR at BARC- Vizag

More precisely, the HFRR would serve as national facility for neutron beam research, for fuel & material irradiation; for radio-chemistry programmes, for neutron activation analysis (NAA), for neutron radiography, and for production of neutron transmutation doped (NTD) silicon. NTD of silicon is a technique used to achieve uniform doping by converting silicon isotopes into phosphorus through neutron irradiation. This method is particularly advantageous for high-power semiconductor applications, such as power electronics, electric vehicles, and renewable energy sectors, where precise control over resistivity is necessary. A study has been conducted to assess the feasibility of producing NTD-Si in reactor at BARC, Mumbai. Further plans include trial irradiations with larger silicon ingots (up to 200 mm dia.), followed by commercial-scale production.

1.1.2 Isotope Production Reactor

In today's world, the medical radioisotopes have become an integral part of diagnostics as well as therapy for the life-threatening diseases. In India, radioisotopes are produced at BARC, Mumbai from the existing research reactors. Presently the main source for production of radioisotopes is the Dhruva Reactor, following the decommissioning of the national pride, CIRUS reactor. A significant part of important medical isotopes e.g. **^{99}Mo, ^{131}I**, **^{177}Lu** is imported to meet the domestic demand. Dependency thus on single domestic facility, as well as ageing of the major international isotope producing reactors put constrain on ensuring uninterrupted supply of radioisotopes for medical purpose. The need of the hour is to build facilities for large scale production of medical isotopes which would not only meet the domestic demand but also help other nations through export.

DAE has been entrusted by the Government of India with the task of setting up large facility for the production of radioisotopes used in nuclear medicines and other applications. Considering this, it is proposed to build a dedicated isotope production reactor (IPR) and co-located isotope processing facility (IPF) for production of radioisotopes and radiopharmaceuticals to meet the domestic demand for making India self-reliant in the field of medical radioisotopes. It will increase the availability of affordable diagnosis and treatments for cancer and other diseases in India. The isotope production & processing facility (IPPF) is expected to enhance the capability factor by several folds for production of the major radioisotopes compared to the current situation by addition of annual production capacity of around 800 kCi.

The IPR is a 60 MWth tank-type reactor, cooled and moderated by light water and fuelled with low enriched uranium (LEU). The reactor core is surrounded by an annular reflector vessel filled with heavy water which acts as a neutron reflector. The reflector vessel provides a large irradiation volume. Together the IPR and IPPF would be dedicated to the nation for production of radioisotope. Major isotopes to be produced include ^{99}Mo, ^{131}I, ^{153}Sm, ^{166}Ho, ^{177}Lu, ^{90}Y, ^{188}W, ^{192}Ir, and ^{60}Co. leading India to be self-reliant and major global player in the field of production of radioisotopes by exporting the radioisotopes.

1.1.3 Dhruva – 2

DHRUVA, the testament of national pride is a 100MW heavy water moderated and cooled thermal research reactor commissioned in 1985. Since then, it is serving as a tool for research in frontier areas of nuclear science and technology. Dhruva has been operating for close to four decades and its operating life can be prolonged up to the year 2045 after carrying out safety up-gradations and ageing related maintenance. Nevertheless, replacement of this reactor is necessary in near future. Construction of another such reactor, named Dhruva-2 would ensure continued basic and applied research in physics, chemistry, material science, and nuclear engineering seamlessly.

During the years of operation, needful modifications/up-gradations have been carried out for DHRUVA. Based on the operating experience of APSARA, CIRUS, and APSARA-U research reactors, design of the new reactor is finalized. The basic features like fuel, moderator, coolant, reflector, and cover gas would be same as Dhruva. Some of the short-term targets are: Preparation of preliminary design basis report; Site selection studies, site evaluation report, dose apportionment and environmental clearance, and preparation of preliminary safety analysis as well as design basis reports for construction. The construction, commissioning activities, stipulated clearances, trial operations and regular operations are envisioned as medium and long-term goals. The new reactor would be a state-of-the-art neutron beam research, and also will continue producing radio isotopes including fission moly in bulk for medical and industrial use.

1.2 Developmental Reactors: Specific Purposes

1.2.1 Demonstration Molten Salt Reactor

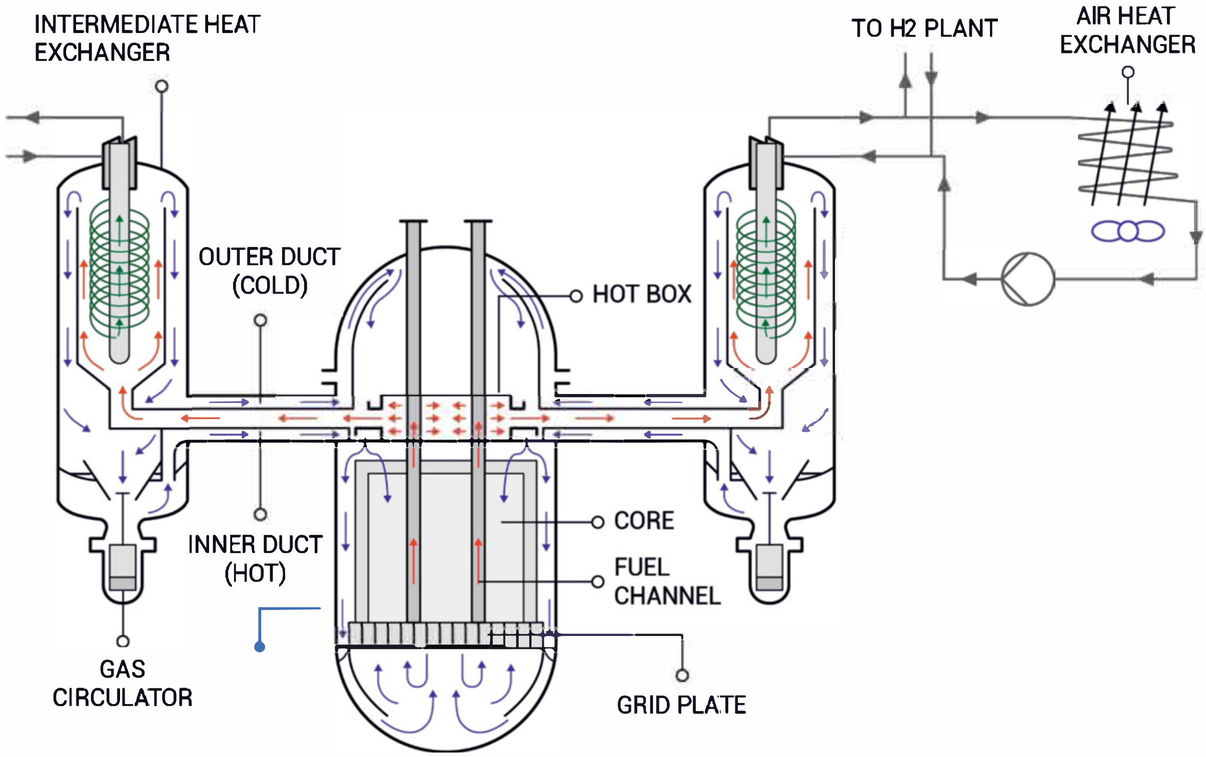
India from the very beginning, conceived the ambitious idea of three stage nuclear power program. This 3-stage program covers building of pressurised heavy water reactors, fast breeder reactors and thorium-based reactors on commercial scale. Obviously, the program also includes technology development relating to spent fuel reprocessing, waste management, safety and environment monitoring. India has limited uranium but vast thorium reserves and the Indian nuclear power program is geared towards using these reserves. The third stage of the Indian nuclear power programme prioritises efficient use of domestic thorium for long-term energy security. Molten salt reactor (MSR) is an attractive option for long term self-sustainable thorium utilization as part of the three-stage nuclear programme. Considering the large number of new technologies involved, it is worth designing a reactor operating at low power ($5MW_{th}$) as a demonstration facility to gain experience in molten salt reactor technology.

MSR is an ambitious programme that aims to develop various new technologies in several areas. These include fluoride salt component manufacture, salt purification, salt chemistry and handling, material development and characterization, component and instrumentation development, remote maintenance technologies and so on.

A roadmap has been outlined to develop essential technologies to design, construct, and operate a demonstration molten salt reactor. A low melting fluoride salt mixture has been selected as the fuel salt. Production of key components of the salt mixture has already been demonstrated. High nickel alloy for use in molten fluoride salt environment has been indigenously developed in collaboration with MIDHANI and Nuclear Fuel Complex (NFC). Design of various mechanical components for molten fluoride salt service line has been initiated. Computer codes have been developed to address the reactor physics aspects of such reactors. The construction, commissioning and demonstration of a small power MSR has been targeted as a long-term goal. Thus, India will develop technologies and their demonstration in a small power MSR.

1.2.2 High Temperature Gas Cooled Reactor

Due to exhausting world reserves of petroleum-based products and the environmental concerns with the use of fossil fuels, it has become important to find an alternative energy option for transport and process industry sectors. Hydrogen is one of the promising options of future energy sources. While there are various possibilities for production of hydrogen, nuclear energy-based hydrogen production by splitting water is a sustainable and environmentally benign option. High Temperature Reactor (HTR) technology development programme is aimed at nuclear hydrogen production by splitting of water. HTRs are planned for supplying energy for hydrogen production processes at required temperature conditions in a sustained manner. With a focus on operation at 650°C, suitable for hydrogen production process, a 5 MW_{th} gas-cooled reactor (GCR) is planned to be developed utilising conventional technologies.



Gas Cooled Reactor

Many technologies were developed to address challenges of HTRs. However, considering the time required for scaling and validation of these technologies, a conventional reactor design using slightly enriched oxide fuel, CO_2 as primary coolant and graphite as moderator is proposed for 5 MWth gas cooled reactor (GCR-5). The design of GCR-5 features advanced safety systems, including passive decay heat removal system, passive containment cooling system etc. The conceptual design of the 5 MWth GCR has been worked out along with preliminary activities related to reactor physics design, fuel cluster and fuel assembly design, structural design of core, initial sizing and design of components like reactor pressure vessel, heat exchangers and gas circulators. The detailed design and layout related activities are being taken as short-term goal however, the construction, commissioning and demonstration of a 5MWth Gas Cooled Reactor is expected to be achieved at the first half of coming decade.

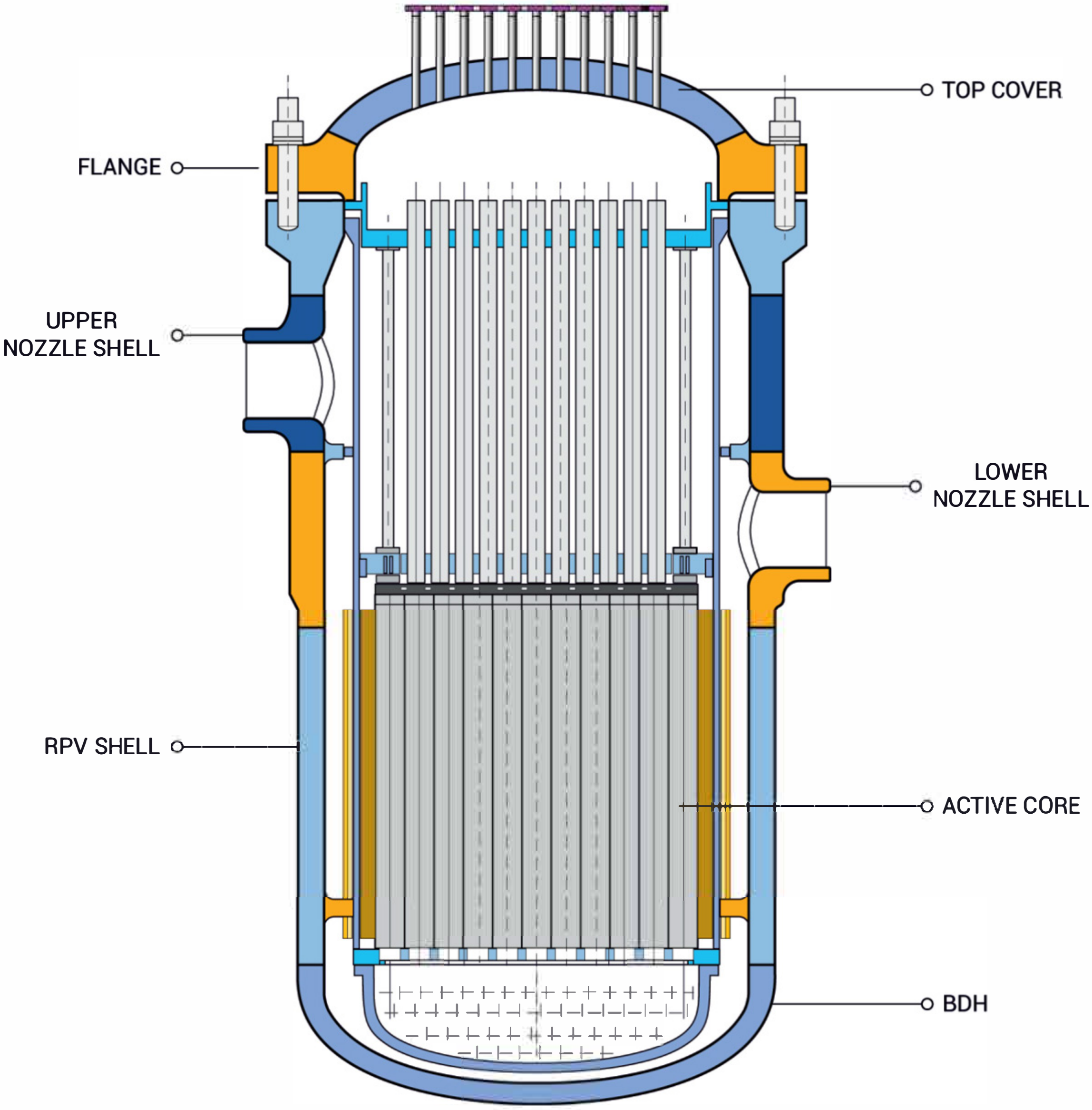
The GCR for hydrogen production promotes Atmanirbhar Bharat in nuclear-based hydrogen production, diminishing reliance on fossil fuels. This initiative is an important step towards fostering a more sustainable future, where nuclear energy plays a key role in addressing energy needs while prioritising environmental concerns.

1.3 Developments for Power Reactors-Thermal Reactors

1.3.1 Indian Pressurized Water Reactor

Light water reactors, specifically pressurised water reactors (PWRs) are expected to play a major role in increasing the installed capacity of nuclear power in India. Previously DAE had pursued induction of PWR-based nuclear power plants (NPPs) in India with foreign collaboration through NPCIL. It has been decided to initiate development of an indigenous PWR i.e. Indian Pressurised Water Reactor (IPWR). One of the crucial technologies required to be mastered for realisation of IPWR is manufacturing of rector pressure vessel (RPV). Development of manufacturing technology for RPV for IPWR NPP has been initiated by BARC in collaboration with NPCIL and is based on an assessment of the existing capability within the country. The same has been concluded to be adequate for a reactor of around 700 MWe capacity. It is also proposed to make the best use of the already matured designs of the steam turbine and the balance of plant of the Indian pressurised heavy water reactor (PHWR) programme for faster realisation of IPWR NPP. In the proposed collaboration between BARC and NPCIL on IPWR, BARC will undertake development of RPV, reactor core and core internals, control rod drive mechanisms (CRDMs) and nuclear instrumentations, while NPCIL will be responsible for development of primary heat transport (PHT) equipment such as steam generator (SG) & primary coolant pump and secondary systems and the balance of plant. Development of technology for other grades of nuclear materials and weld consumable has been identified for initiating further activities in this direction.

The PWR NPP design envisages the use of indigenous materials and equipment. The technology for making forgings for nozzle shell and shell flange regions of large sized RPVs has been already developed by BARC earlier, in line with DAE’s goal of becoming Atma Nirbhar in nuclear technology.



Schematic of Reactor Pressure Vessel with core

There is adequate expertise available in-house for taking-up the detailed design of reactor core and internals, CRDMs, nuclear instrumentation, engineered safety systems, fuel handling system and the plant control & instrumentation (C&I) systems.

The proposed programme has been envisaged as medium-term activity involving detailed design of various reactor systems and equipment. Evolving detailed design of indigenous IPWR NPP would also facilitate augmentation of installed nuclear power in addition provide import substitute for critical equipment of reactor of foreign origin.

1.3.2 Reactor Pressure Vessel for Indian PWR (IPWR)

Special quality large sized low alloy steel forgings are required for manufacturing of reactor pressure vessel (RPV), one of the critical nuclear equipment of Indian Pressurised Water Reactor (IPWR). Major forgings of RPV comprise of shell in core belt zone, shell with nozzles, shell in flange area and a dished head at the bottom. The technology development for making nozzle shell and shell flange forgings of typical large sized RPVs has been already completed by BARC. In order to ensure development of the complete manufacturing technology of IPWR RPV for self-reliance, it is planned to develop technology of formed nozzles from nozzle shell, welding process for qualification of thick (~320 mm) weld joints along with development of weld consumables.

RPV forging from APURVA

BARC had successfully developed APURVA grade large low alloy steel (LAS) forged shells of diameters OD (Ø4900 mm - Ø5300 mm) with thickness of 350 mm - 750 mm keeping in mind manufacturing of IPWR RPV. As a part of efforts in light water reactor (LWR) program, BARC had qualified welding up to 120 mm thick LAS joints. Cladding of RPV with stainless steel (SS) and carrying out thick SS weld joints were also established. However, weld consumables are being imported presently. Further development of welding process technology for thick RPV welds using commercially available consumables and characterization of weld joints including HAZ by detailed testing (mechanical, metallography, corrosion study etc.) would be taken up in stages.

Development of technology for RPV forgings and its manufacturing technology will facilitate indigenous manufacturing of nozzles by forming on shell forging for nozzle region of RPV of up to 700 MWe IPWR. Based on the development of nozzle forming technology, it will be possible to manufacture the nozzle shell forgings from relatively smaller LAS ingots for which manufacturing technology has already been developed. With this, more effective working of forging and enhanced material properties can be ensured. Major outcome of the project will be indigenous capability to manufacture nuclear grade welding consumables and Indigenous RPV fabrication capability for small to medium Indian PWR of up to 700 MWe.

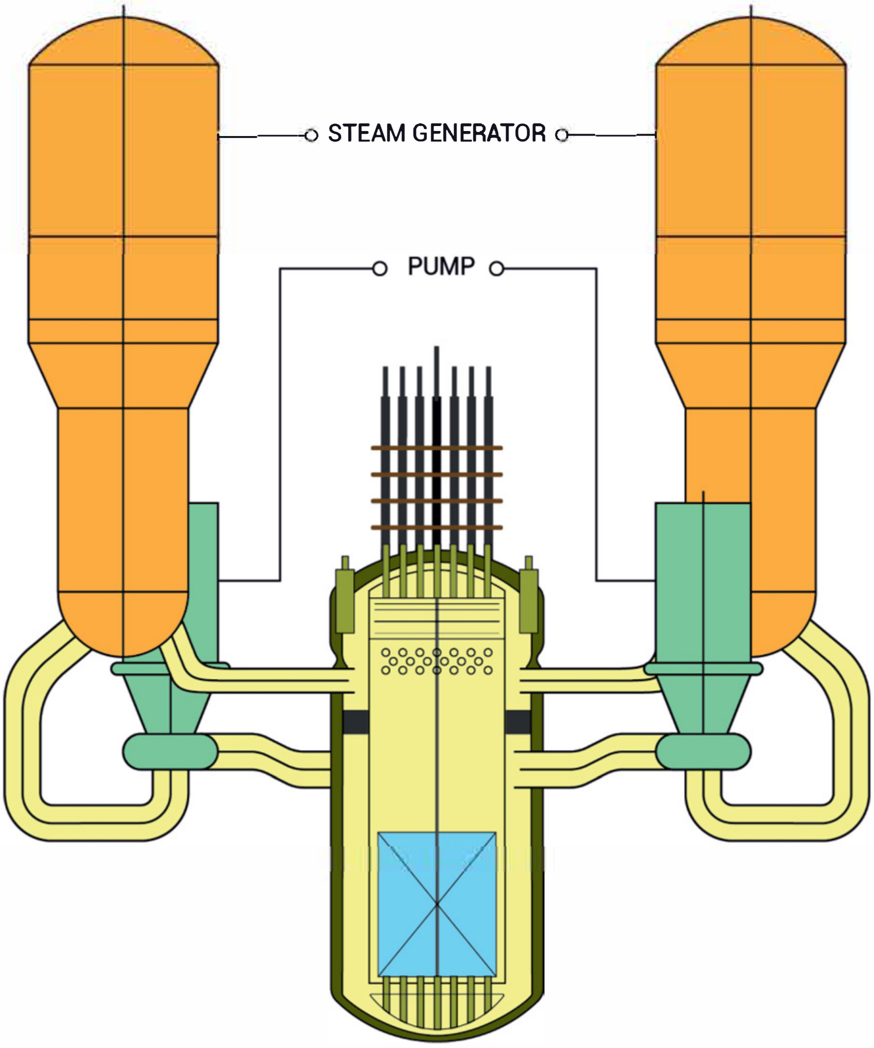
1.3.3 Development of Small Modular Reactor

In order to fulfil India's commitments for Net-Zero carbon emission, large size nuclear power plants (NPPs) have to be deployed in green field sites to increase the total nuclear power generation capacity. Since the number of green field sites are limited, further necessity is to deploy small modular reactors (SMRs) in brown field sites such as retiring coal plants, captive plants for nuclear power with targeted applications and power supply to remote isolate places. Worldwide, SMRs are gaining importance due to their enhanced safety characteristics, rapid deployment potential and lesser overall capital cost requirement for construction. Presently, more than 80 SMRs designs have been reported worldwide. Majority of them are water cooled, based on PWR technology, owing to matured manufacturing technology, proven materials, rich operating experience and well-defined licensing and regulatory criteria. Loop type and block type designs of SMRs, based on expertise gained and resources available, are under consideration in India.

Loop type and block type SMR design options of SMRs with respect to safety requirements, industrial manufacturing capability, commercial viability, sustainable and scalable supply chain and faster deployment are being pursued. Conceptual design of these options is being worked out for the SMR. Required technologies are being identified and development activities will be prioritised in near future. Regulatory clearances, engineering, manufacturing, installation, erection and commissioning of SMR will be carried out jointly with NPCIL.

Loop Type SMR

In this SMR the reactor coolant system equipment like steam generators (SG), pumps etc. are connected to the reactor pressure vessel (RPV) through large size pipe. Its design is simpler and cost is lower in comparison to block type design. Transition version of loop type SMR is aimed with 200MWe capacity. It is planned to utilise technologies for PWRs in primary side and secondary side will be similar to 220 MW PHWR with suitable modification to enhance the safety.



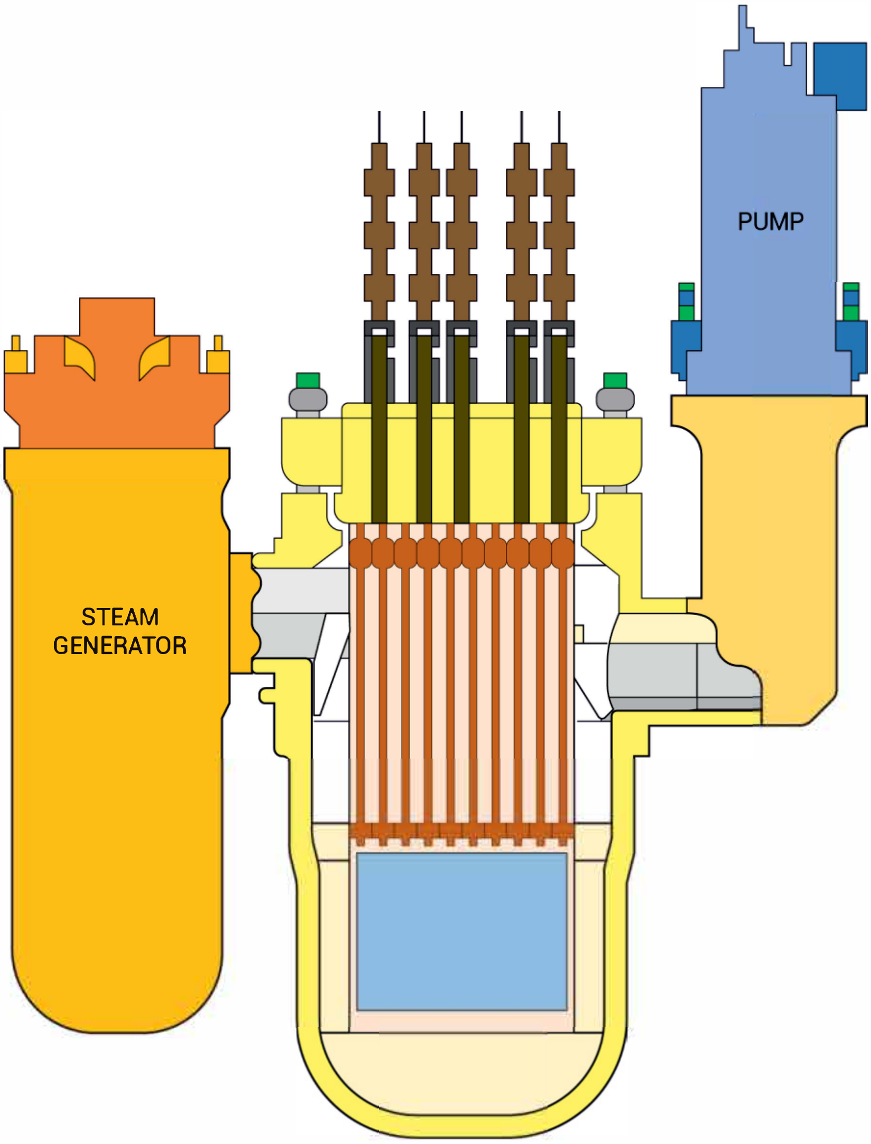
Schematic of Loop Type SMR

Block Type SMR

In this SMR, the equipment (SG, pumps) are directly welded to the RPV, thus eliminating large size pipes and requiring smaller footprint. The elimination of large size pipes minimises the large break probability resulting in enhanced safety.

The technology readiness level is relatively better for capacity around 50MWe block type SMR. Capability of equipment manufacturing is already established through Indian industries. The design and operating experience of similar reactor is available and efforts for proving the concepts for regulatory acceptance are likely to be minimal. It is planned to scale up the design to higher capacities after successful demonstration of around 50MWe block type SMR.

Integral type SMR designs though have most complex design option and considered as the safest, will also be evaluated and pursued in long term after successful demonstration of block type SMR. It is foreseen that in long term Indian industry will develop competence to handle such design for delivering modules of integral type SMRs for large scale deployment.

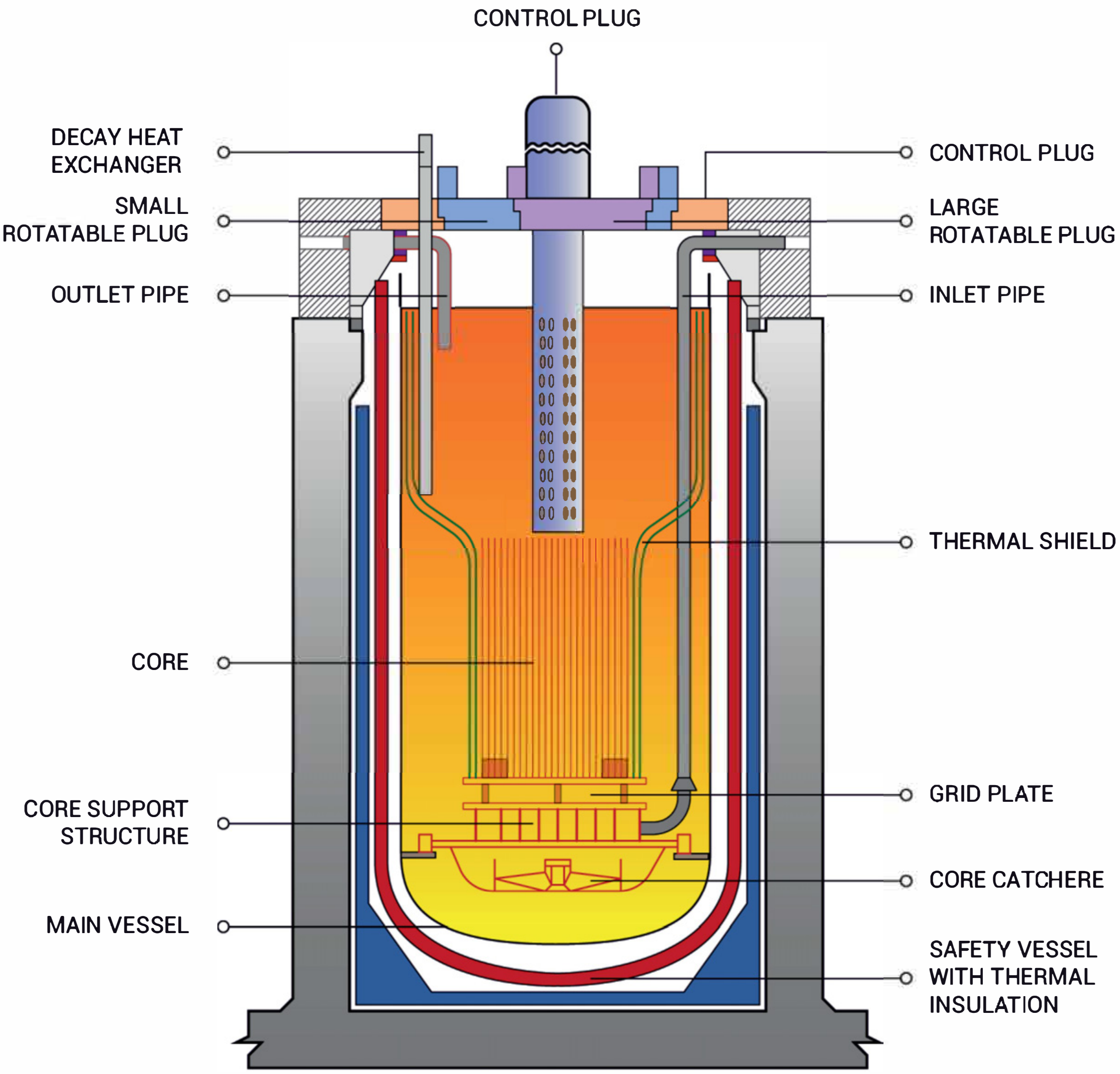


Schematic of Block Type SMR

1.4 Developments for Power Reactors-Fast Reactors

1.4.1 Fast Breeder Test Reactor -2 (FBTR-2)

In order to rapidly realize higher nuclear power potential, early introduction of fast breeder reactors (FBRs) with high breeding ratio is essential. Among the various fuels, metallic fuel offers great potential for breeding. Hence, the future fast reactors beyond MOX fuelled FBR-1 & 2 are planned to be designed and operated with metallic fuel. To understand the metal fuel behaviour and master the metal fuel reactor and fuel cycle technology, a dedicated Test Reactor with metal fuel (FBTR-2) with optimized minimum power of 100 MWe (320 MWth) is essential for the demonstration of safe and high performance of metal fuel FBR with closed fuel cycle mode. FBTR-2 will serve as a test bed for metal fuel sub-assemblies of commercial power reactor size before going for power reactor.

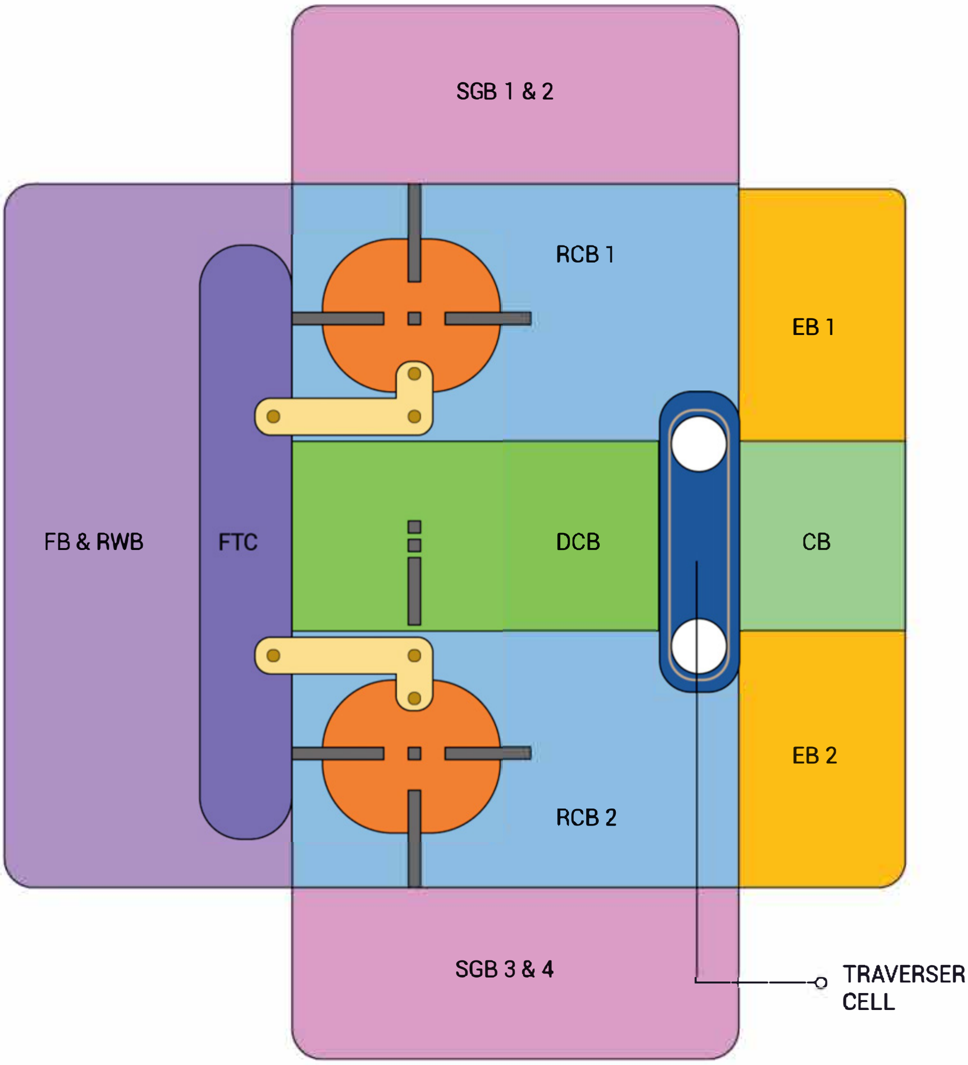


Schematic of FBTR-2

Two sub-assemblies (SA) with three pins each of metal fuel are irradiated in FBTR and discharged for post irradiation examination. Subsequently, it is planned to irradiate full metal SA followed by outer row with metal fuel SAs. In parallel, development of pyro-processing technology in lab & pilot scale is also pursued towards demonstration of closed fuel cycle. International experience with the ternary fuel (U-Pu-Zr) and also with the binary system of U-Zr with Zr content equivalent to 6% is limited. FBTR-2 will be designed, commissioned and operated by IGCAR and will be located at Kalpakkam complex. Even though the commissioning and full power operation of FBTR is planned as long term (15 years) target, the design finalization and beginning of construction would be taken as short- and medium-term activities, respectively. The expected outcome of the proposal is of many folds. However, indigenous technology demonstration for metallic fuel based fast reactor is indeed very important for self-sustainability

1.4.2 Fast Breeder Reactor -1&2 (FBR1&2)

Prototype fast breeder reactor (PFBR) is in an advanced stage of integrated commissioning. The design, R&D, safety review, construction, and commissioning experience of PFBR have motivated the commercial exploitation of MOX-fuelled sodium-cooled fast reactors (SFRs) with closed fuel cycles.



Schematic of FBR 1&2 Twin unit layout

Accordingly, in the roadmap prepared for the fast breeder reactor (FBR) development and deployment beyond PFBR, twin fast breeder reactors (FBR-1 & 2) at the adjoining site of PFBR at Kalpakkam to make use of co-located fast reactor fuel cycle facility (FRFCF) have been conceived.

The R&D and technology development towards detailed design of FBR-1 & 2 (2 x 500 MWe) are being carried out at Indira Gandhi Centre for Atomic Research (IGCAR). A few design modifications have been incorporated in the design of FBR-1&2 compared to PFBR. To meet the targeted safety, additional safety features have been added to the FBR-1&2 design. Moreover, few changes have been mandatory based on the safety review and construction experience of PFBR. The certain envisaged changes have been tested and qualified on a possible scale with available facilities under similar reactor conditions. In addition, various R&D activities have to be undertaken to develop confidence in the design. The FBR-1&2 will be constructed, commissioned, and operated by Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI) with support by IGCAR. With all major activities being in progress, beginning of the construction is targeted as medium-term activity, followed by commissioning and power operation.

1.4.3 Development of RML-II for PIE of Fuel & Structural Materials

The objective of the proposed Radio Metallurgical Laboratory-II (RML-II) is for the post irradiation examination (PIE) of larger sub-assemblies and fuel pins of future reactors like PFBR and FBTR II, which cannot be achieved with the existing hot cell facility. The larger dimensions of these fuel sub-assemblies (FSAs) and future PIE requirements include advanced micro-analytical and mechanical testing facilities are factored in the conceptual design of the proposed RML-II. The facility will support the development of special nuclear materials for future reactors such as PFBR and metallic fuelled FBRs, and nuclear materials for societal applications. The main focus of this facility will be in the determination of burn-up limit for the fuel sub-assemblies using indigenously developed fuel and structural materials, determination of the fluence limit for the control rod, blanket, reflector and sub-assemblies, PIE of irradiated candidate materials for in-core shielding such as ferro-boron, W, WC, etc., and study on the evolution of defects in FBR structural materials.

Setting up this facility is being undertaken as a long-term goal. Conceptual design of the proposed RML-II has been carried out. The location and technical requirements would guide in finalization of detailed design. RML-II will contribute towards optimisation of metallic fuel and metal-fuelled test reactor. This will be a significant factor in refining operational parameters and pave the way for commercial metal-fuelled fast reactors.

1.5 Development for Fusion Reactor Programme

1.5.1 Laser Development for Inertial Fusion Energy (IFE)

The laser driven inertial confinement fusion (ICF) reactors are pathway to inertial fusion energy (IFE), which is a sustainable source of energy with no greenhouse gas emissions and with a virtually inexhaustible, widely available fuel supply. RRCAT has long term plan for development of high energy lasers for use in ICF research, shock-physics experiments, laboratory astrophysics etc. It is proposed to bridge the technological gap areas by development of components and subsystems like large aperture Yb:YAG crystals, athermal laser glass, kilojoule class pump diodes, liquid cooled high energy laser amplifiers, etc. for development of high energy (1 kJ) high repetition rate (1 Hz) laser as a technology demonstrator for development of high-power lasers in future for use in IFE during the "Amrit Kaal" period. The inertial fusion energy will augment the total capacity for power generation in future. Along with renewable energy sources, nuclear fission-based reactors play a key role in long term energy security and environment protection. Currently no ICF based reactors or experimental facility available in India and no active research or study is being carried out for development of Laser Inertial Fusion Energy (LIFE) based power plant.

Internationally several efforts had been made to develop the design of a commercial power plant based on ICF concept such as LIFE studies of LLNL USA, SOLASE-H, HYLIFE-II etc. RRCAT plans to develop Nd:Glass based high energy laser for ICF research purpose. The programme will be completed as a long-term goal in stages such as growing 100 mm diameter Yb:YAG crystals, development of a thermal laser glass, design and development of Diode pumped 100 J, ~1 Hz Amplifiers, demonstration of 1kJ, 1 Hz operation of prototype Laser driver for ICF. A high energy (1kJ), high repetition rate (1 Hz) laser will be a technology demonstrator for development of higher power lasers for IFE-based commercial power plants in the future.

1.5.2 Development of Fusion Reactor

Fusion reactors are hope of mankind as future reliable and clean energy source. In the last six decades, there has been considerable progress in this direction worldwide, but a net power generating fusion reactor has not been achieved so far. Department of Atomic Energy has been a significant contributor in this international effort. The development of fusion reactor will be a multi-stage and multi-disciplinary program.

There are several ways to generate fusion power. Magnetic confinement method looks very promising although breakeven has been elusive so far. Under the BARC's Amrit Kaal program, it is proposed to build spherical tokamaks, with the aim to have a compact fusion reactor. Extensive R&D will be carried out on selection of materials to build the fusion reactor. Fast neuron cross-section of these structural materials will be performed at FOTIA, LEHIPA, and upcoming MEHIPA facilities, using quasi-monoenergetic neutron beams. Subsequently, design and construction of prototype fusion reactor shall be carried out. Once the know-how of prototype fusion reactor technology is acquired, design of a commercial fusion reactor will be taken up.

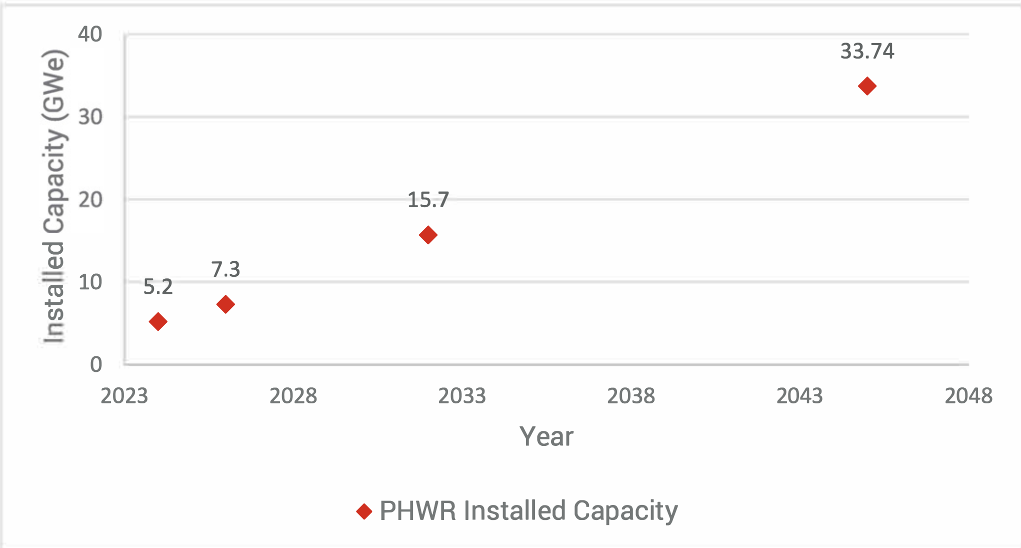
Institute for Plasma Research (IPR) has wide experience in tokamak physics and engineering. Steady state superconducting tokamak (SST-1) at IPR, with a major radius of 1.1m and a minor radius of 0.2m, was able to confine plasma for about 650ms. Under the ITER-India collaboration, the development of many systems including, cryostat, in-wall shielding, cooling water system, cryogenic system, ion-cyclotron RF heating system, electron cyclotron RF heating system, and diagnostics for neutral beam system and power supplies have been carried out. BARC is capable of software development & simulation of plasma, plasma generation & diagnostics for the reactor, and design of breeder and power extraction system.

The Amrit Kaal target to realize a full-scale fusion reactor will be achieved in different stages like feasibility study for fusion reactor, detailed simulation study to fine tune design, measurement of fast neutron cross-section of structural materials, first design of prototype fusion reactor, commissioning of a prototype fusion reactor and scaling up. Software for simulation of fusion reactor, development of materials capable of withstanding high energy high flux neutrons, plasma control & diagnostics and prototype fusion reactor will be developed as a step towards energy security & clean energy source.

1.6 Manufacturing of Components for Reactors and Nuclear Power Plants

1.6.1 Development of PHWR Reactor Components

The Nuclear Power Corporation India Limited (NPCIL) is taking leap in expanding nuclear power generation by erecting several units of pressurised heavy water reactors (PHWRs). NFC is playing key role in meeting this expansion plan by supplying the fuel bundles, and the structural components for 220/700 MWe PHWRs including pressure & calandria tubes, reactivity devices for existing and future reactors. The capacity augmentation of NFC is planned in line with the NPCIL's programme of enhancing the power generation capacity.



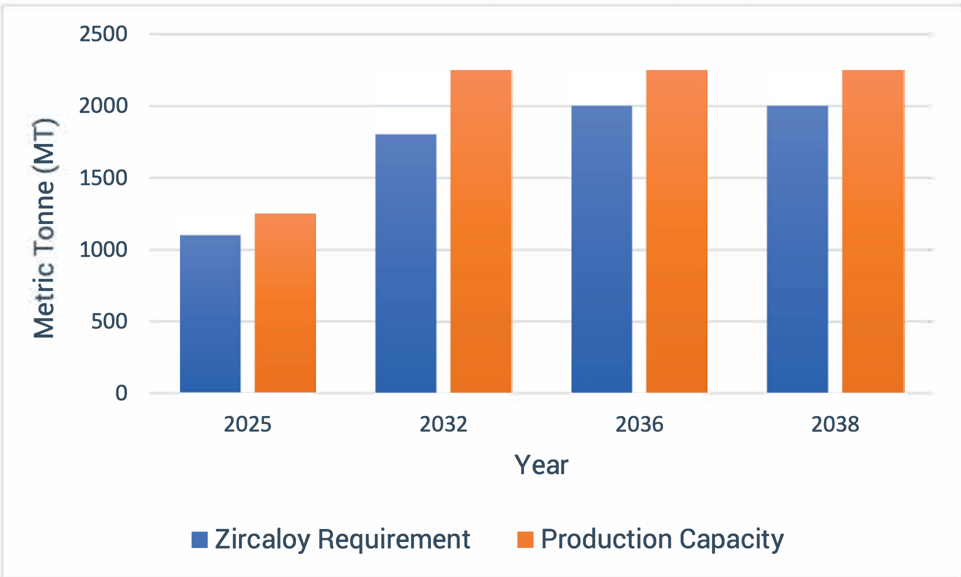
PHWR Installed Capacity Projection

The same will be met through establishment of advanced production & inspection facilities for enhancing recoveries & productivity. This will not only help to cater the requirement of

DAE but also serve as import substitute for various defence, space & other commercial requirements. In addition, development of new technologies to improve the sustainability of zirconium oxide and sponge production will also be taken up in parallel.

Presently, PHWRs, BWRs & VVERs are under commercial operation and more 700 MWe PHWR will be installed in a fleet mode shortly. NFC cater to the requirements of operating PHWRs and BWRs. The entire requirements of core and structural components of zircaloy production are being met by the facilities at NFC, Hyderabad and Kota. To meet this requirement, 15 lakhs fuel tubes per annum is required in addition to various components such as bearing pads, spacer pads, end caps, etc. NPCIL, in phased manner, is increasing installed capacity to 33740 MWe by 2047 by PHWRs. To meet this enhanced requirement, the proposed expansion/ augmentation plan of NFC facilities is given below;

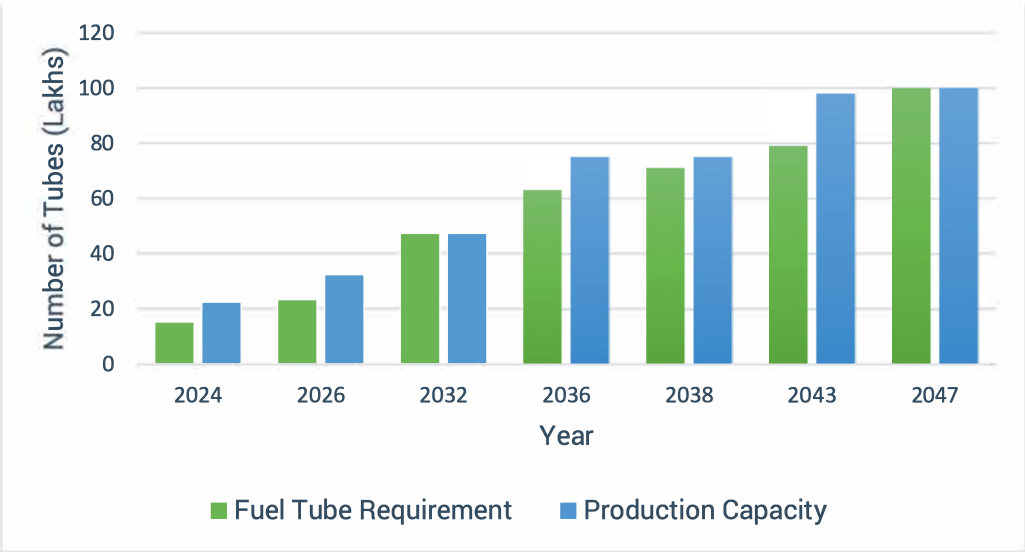
Alloy Production: The projected requirements of alloy production are proposed to be met by setting up of new facility for zirconium oxide, sponge and alloy production.



Zircaloy Requirement and Production Capacity

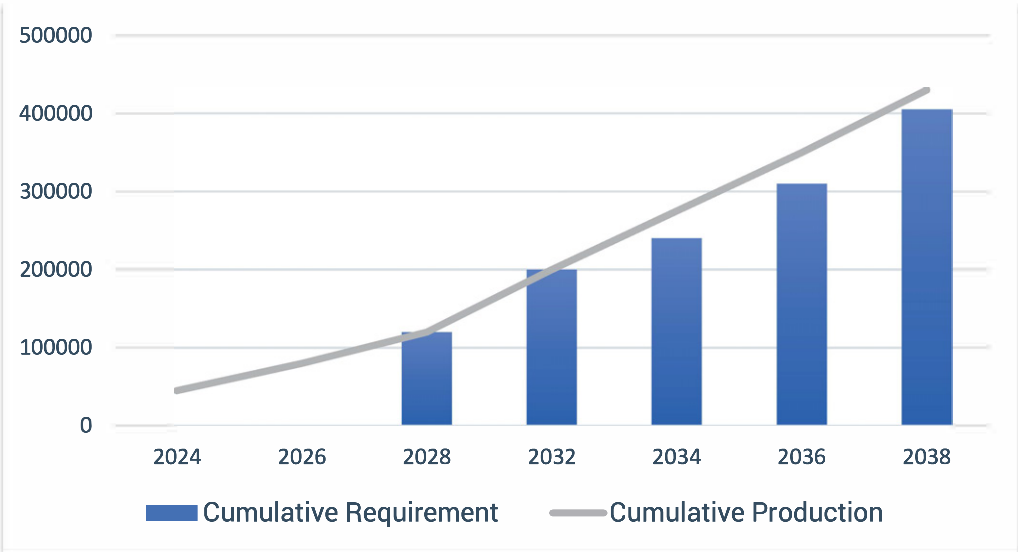
The road map along-with milestones are: augmentation of Zr-sponge and Melting facilities; process development for different grades of zircon sand & pyro-chemical route of zirconium sponge production; and recycle of Mg by electrolysis of $MgCl_2$

Zr-Components and Steam Generator tubes: The road map of NFC to meet the requirements of fuel tubes (FT) and steam generator (SG) tubes is as follows: The present requirement for FT is 15 lakh tubes/annum and will increase to 100 lakh tubes/annum by 2047. The requirement will be taken up by augmentation at NFC Hyderabad & NFC Kota, a new site in line with the site selected by NPCIL.



Fuel Tube Requirement and Production Capacity

4 lakh SG tubes will be required in phased manner. The present capacity is 10,000 SG tubes/annum which is adequate to meet the requirement of SG tubes for fleet mode of reactors 2032. An augmentation to increase the capacity to 20,000 SG tubes/annum is planned to meet the future requirements.



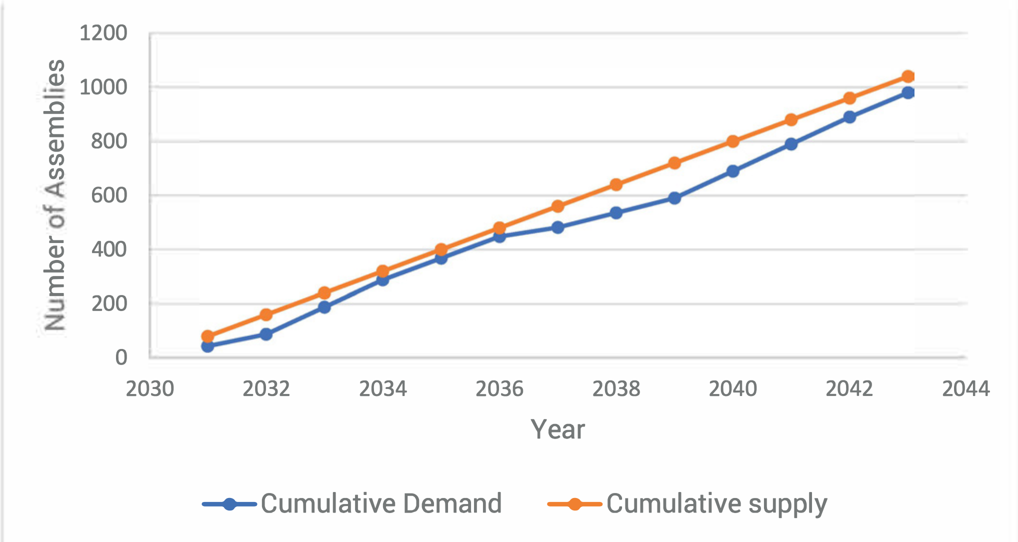
SG Tube Requirement and Production Capacity

Structural capacity augmentation of core structural is planned at NFC, Hyderabad to double the production capacity near future.

1.6.2 Cobalt based Components for PHWR Reactor:

Nuclear Fuel Complex (NFC), Hyderabad is supplying cobalt assemblies for power reactors (220 & 700 MWe PHWRs) and research reactors (Dhruva at BARC). These assemblies serve the function of neutron absorber rods in the reactor and also produce radioactive cobalt-60 which has huge industrial demand due to various applications in food processing, industrial radiography, sewage treatment and health care.

NFC has manufactured cobalt adjuster rod (CoAR) assemblies and zircaloy push tubes for loading CoAR assemblies for 700 MWe PHWR (RAPP-7). To get high specific activity Co-60 in Dhruva reactor, 100 numbers of zircaloy cobalt capsules containing cobalt pellets filled in annular space were supplied by NFC.



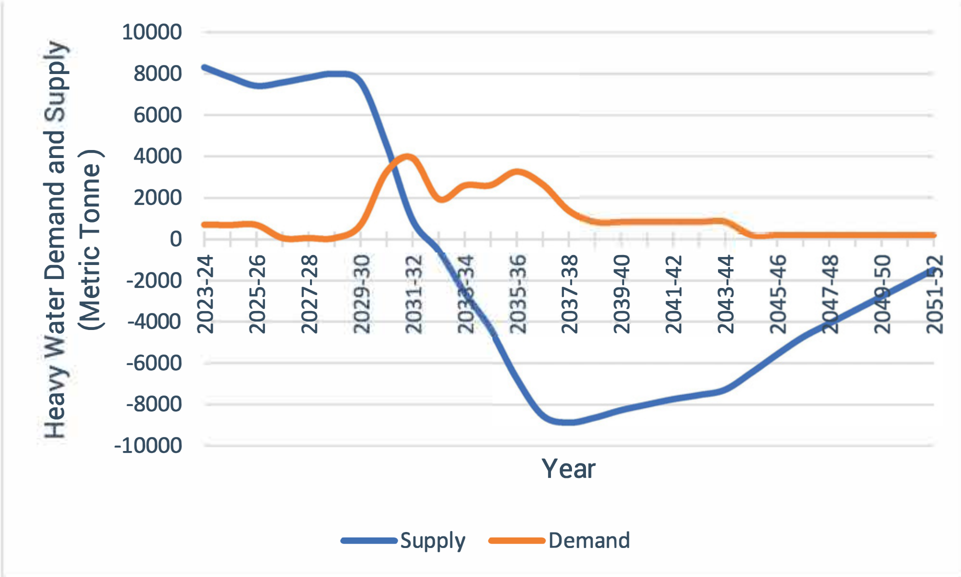
Cobalt Adjuster Rod Cumulative Demand and Cumulative Supply

Future roadmap for supply of cobalt assemblies is based on projected demand from BRIT and expansion plan of NPCIL. Augmentation of manufacturing capacity to 80 nos. of cobalt assemblies/annum as deliverable of medium term is planned at NFC Hyderabad to meet projected demand, including re-loading in existing reactors.

1.6.3 Production of Heavy Water for PHWR's

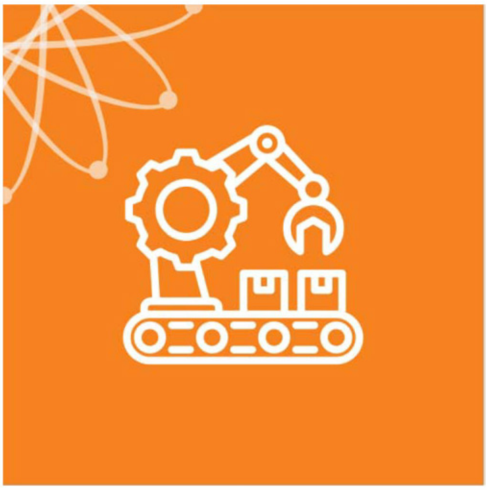
Heavy Water Board (HWB), primarily engaged in production of heavy water required as coolant and moderator for pressurised heavy water reactors (PHWR). It is among the largest heavy water producing entities in the world. Presently, HWB is able to cater the domestic need of heavy water for PHWR programme & non-nuclear applications and also able to export heavy water to countries like US, Japan, Germany, USSR, South Korea, etc. for non-nuclear applications. Capacity augmentation is necessary to match PHWR programme of NPCIL during Amrit Kaal.

With the projected roadmap, HWB can satisfactorily support Indian nuclear power programme while exploiting export potential to support non-nuclear applications of heavy water.



Demand-Supply Scenario for Heavy Water

With present production capacity, HWB can meet the demand of heavy water till 2032 for upcoming PHWRs. Further capacity augmentation is planned to meet the proposed expansion of Indian nuclear power programme during Amrit Kaal. HWB intend to restart HWP-Tuticorin (40 MT/year) and set-up new HWPs to augment heavy water production facility by additional 760 MT/year. As short term and medium-term activity, HWB also plans to augmentation of HW production by adding new streams of 110 MT/year: (a) At HWP-Manuguru and (b) at HWP-Kota. As medium-term activity, production facilities at new sites with total capacity of 500 MT/year (300 MT/year based on Girdler Sulphide (GS) process and 200 MT/year based on NH_3-H_2 exchange process are also planned. Thus, Heavy water capacity augmentation will meet the domestic demand of Indian nuclear power programme and for non-nuclear application.



Vertical 2

NUCLEAR FUEL CYCLE

2.1 Uranium Exploration

2.1.1 Exploration and Resource Augmentation for Uranium and other Atomic Minerals

In the front end of nuclear fuel cycle, AMDER is mandated with exploration and augmentation of mineral resources of uranium (U), thorium (Th), niobium-tantalum (Nb-Ta), lithium (Li), zirconium (Zr), beryllium (Be) and rare earth elements (REE) in diverse geological domains of India to support the nuclear power programme of Department of Atomic Energy (DAE). During the vision Amrit Kaal, AMDER has formulated a robust exploration programme for augmentation of ~ 5,75,000 tonnes (t) uranium oxide, ~300 million tonne (Mt) of beach sand minerals (BSM) containing ~3 Mt monazite, 2.1 Mt RE oxide and 1,60,000 t Nb- oxide from hard rock terrains. Being a premier geoscientific organization of India with pan-India presence, AMDER contemplated to expand its scope of exploration for identifying other necessary strategic elements (B, Ti, V, Mo, Mg) and geomaterials like graphite, serpentinite etc. for supporting the envisaged programmes of DAE. During the Amrit Kaal, exploration efforts for uranium resource augmentation will be intensified in the established brownfield prospects. Subsequently, the greenfield prospects in the Proterozoic and Phanerozoic basins of India, Chhotanagpur granite gneiss complex (CGGC) and iron ore group basins spread over different states of India will be developed for further exploration and resource augmentation.

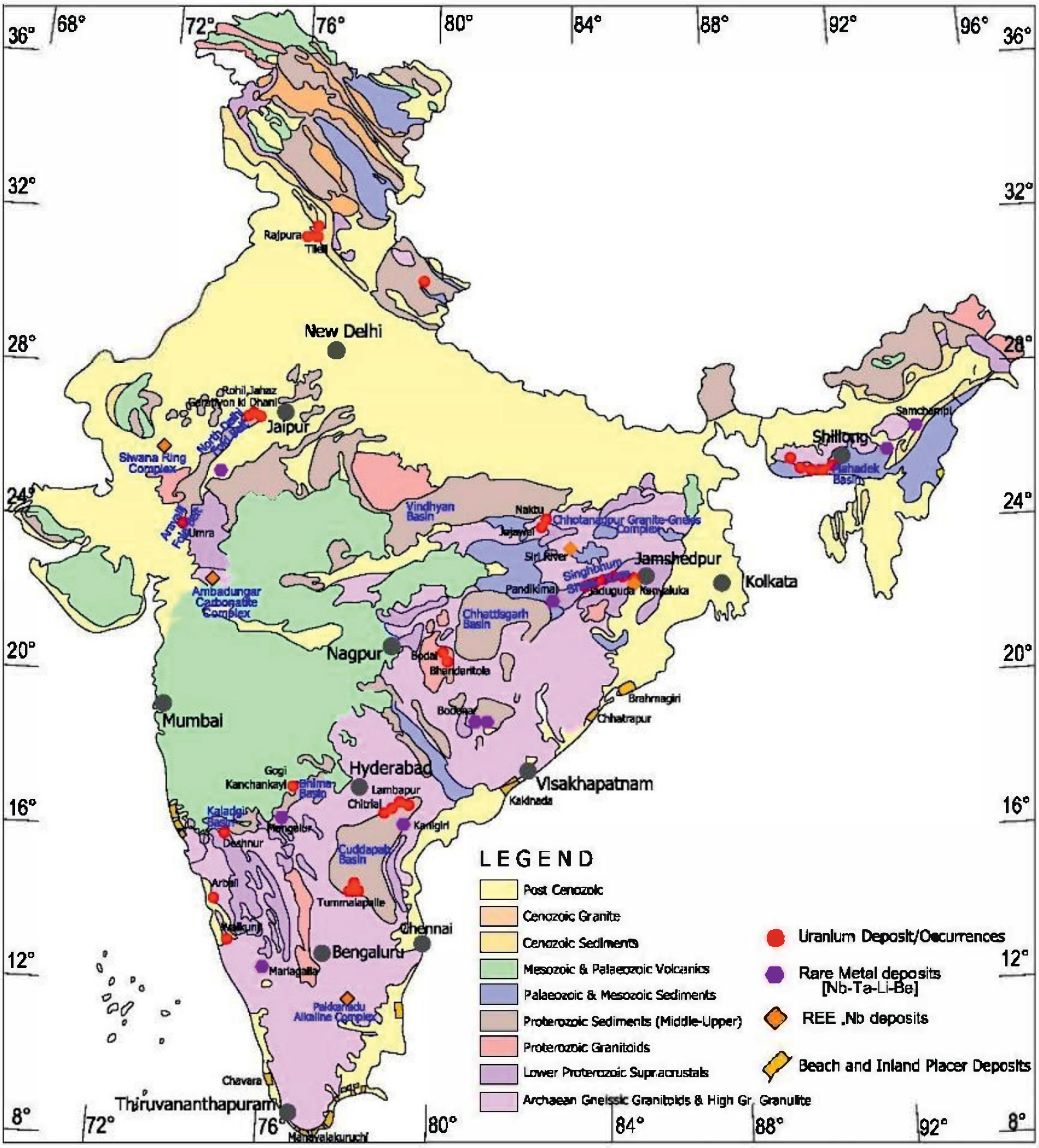
For augmentation of BSM resources, systematic exploration is planned along the shorelines of India, with focus on shorelines, Palaeo-shorelines of Mahanadi Delta, Odisha and Teris/Red sediments in Tamil Nadu and Andhra Pradesh. Besides, sonic drilling in parts of Odisha, Andhra Pradesh and Kerala will augment the resources from the deeper part (~50m) of established deposits.

Exploration strategies have been formulated for exploration and augmentation of REE, Nb and Zr resources from potential hard rock terrains of India. Besides, stockpiling of mineral concentrates of Rare Metals (Nb-Ta, Be and Li) and xenotime will be continued through prospecting operations in the pegmatite belts of India in Odisha, Chhattisgarh and Karnataka and in eastern part of SSZ, Jharkhand. Further, drilling operations for evaluation of Li-resource will be carried out in favourable pegmatite belts of India.

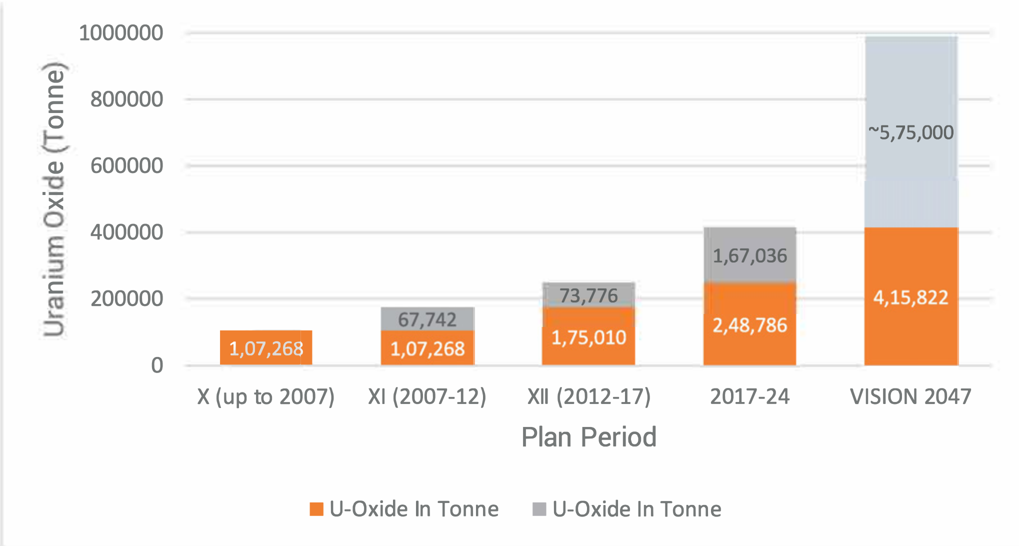
AMDER has established nearly 4,15,000 t in-situ uranium oxide, 1,277 Mt of BSM containing ~13 Mt of monazite resource (~1.17 Mt Th oxide and ~7 Mt REO) and ~1.15 Mt REO in hard rock terrains along with ~1,26,800 Mt Nb-oxide. Besides, collection of mineral concentrates incidental to prospecting operations has led to stockpile of 145 t Columbite-Tantalite, 4,249 t Beryl, 3,372 t Lithium bearing minerals and 108 t Xenotime (Y- mineral) bearing Heavy Mineral Concentrate (HMC).

Steps for Resource augmentation: In order to keep pace with the expansion of the Nuclear Power Programme of DAE, AMDER has laid a roadmap for its programme for exploration and resource augmentation for uranium and other atomic minerals.

Uranium: Augmentation of ~5,75,000 t uranium oxide is envisaged from the brownfield & greenfield geological domains in India from 2024 to 2047. This will comprise 2,25,000 t U-oxide under inferred/prognosticated (resources expected in extension areas and along geological trends of existing deposits) and 3,50,000 t U-oxide under speculative (resources likely to exist based on geological setting/model/extrapolation) categories. Accordingly, the uranium resource of India is expected to stand at ~ 9,90,000 t U- oxide by year 2047.

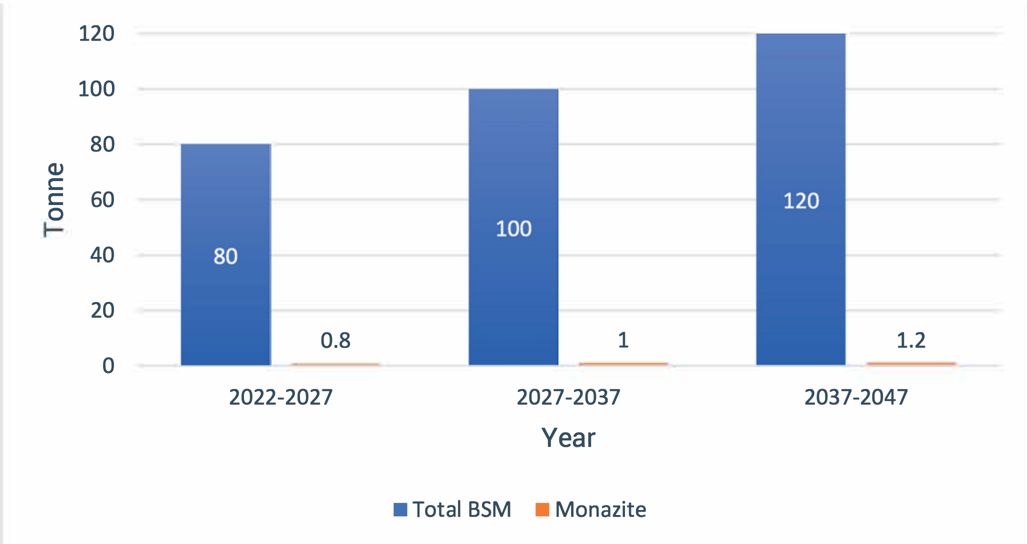


Geological map of India showing important atomic mineral deposits



Envisaged Uranium resource augmentation (2024-2047)

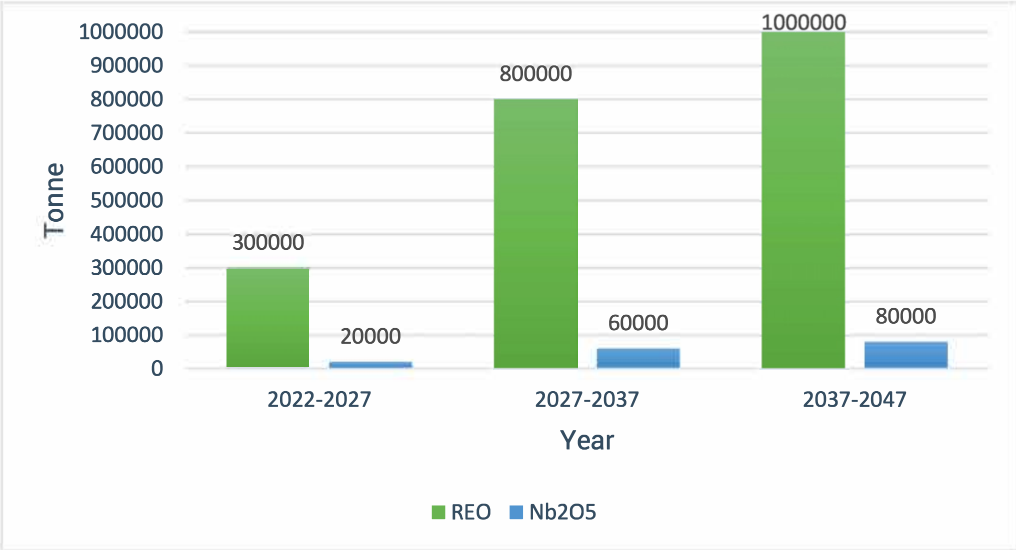
Beach Sand Minerals (BSM): Augmentation of ~300 Mt BSM likely to contain ~3 Mt of monazite (Th+REE) is envisaged during 2022 to 2047. This will comprise ~85 Mt under indicated category from new areas and ~215 Mt under inferred category from deeper part of existing deposits. Accordingly, the BSM resource of India is expected to stand at ~ 1,580 Mt containing approximately 16 Mt Monazite (~8.80Mt REO + ~1.40Mt ThO_2) by year 2047.



Envisaged BSM and Monazite resource augmentation (2022-2047)

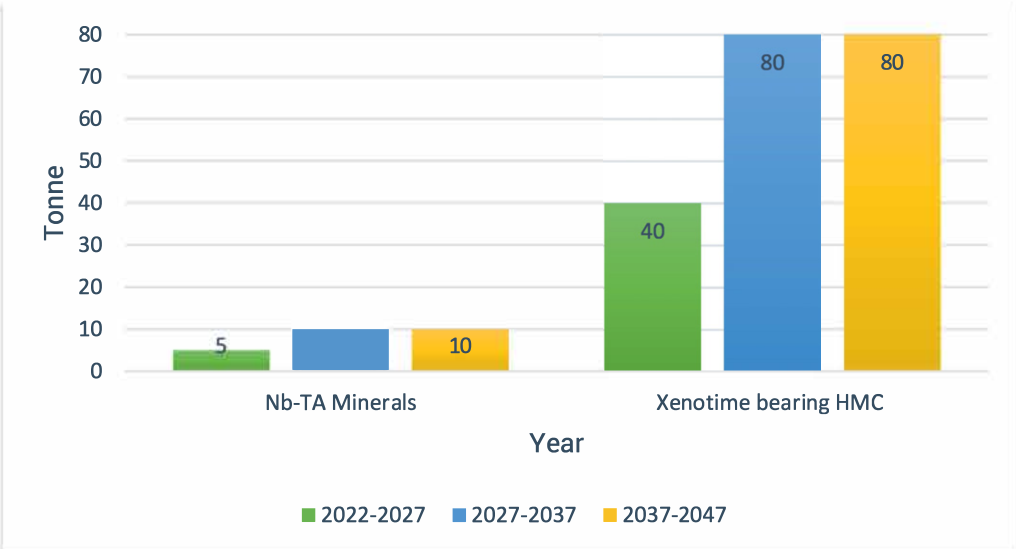
REE and Nb resources in hard rock terrains: Augmentation of ~21,00,000 t RE Oxide and 1,60,000 t Nb- oxide is envisaged during 2022 to 2047 from the carbonatite (Ambadungar & Saidiwasan, Gujarat; Pakkanadu, Tamil Nadu) and alkaline complexes (Siwana Ring

Complex, Rajasthan) of India. This will comprise ~14,50,000 t REO + 1,10,000 Nb_2O_5 under inferred/prognosticated and ~6,50,000 t REO + 50,000 Nb_2O_5 under Speculative categories.



Envisaged REE and Nb resources augmentation (2022-2047)

Rare Metals (Nb-Ta, Be and Li) and Xenotime bearing Heavy Mineral Concentrate (HMC): Evaluation and collection of ~25 tonne Nb-Ta minerals and 200 tonne xenotime bearing HMC incidental to prospecting operations is envisaged during 2022 to 2047. Besides, establishing ~12,000 tonne of Li-oxide resource from hard rocks is also envisaged.

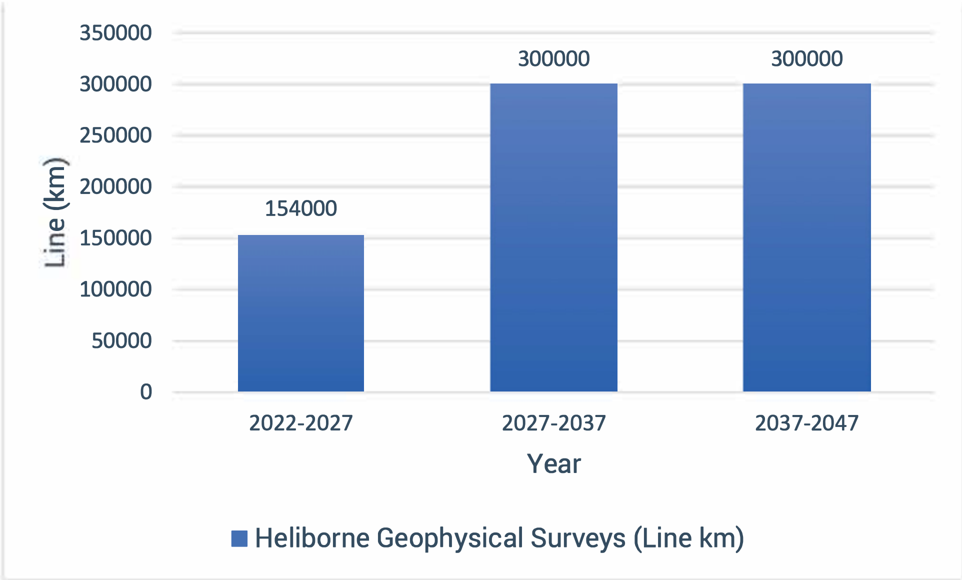


Envisaged Rare Metals, Xenotime bearing HMC resource augmentation (2022-2047)

Envisaged Li-oxide resource augmentation (2022-2047)

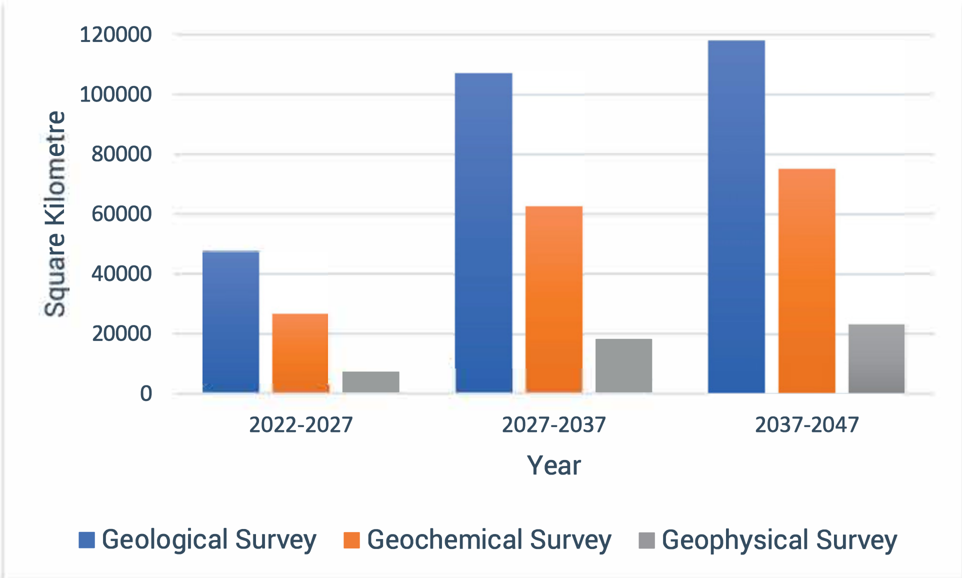
Resource estimates: Substantial quantum of multi-disciplinary exploration inputs viz. heliborne geophysical surveys, ground geological, geophysical and geochemical surveys followed by extensive drilling need to be deployed for augmentation of the envisaged resources. Optimal targets for such exploration inputs are as follows:

Heliborne geophysical surveys: ~7,54,000 Line km of multi-parametric (magnetic, electromagnetic and radiometric) heliborne geophysical surveys have been planned for effective mineral potential mapping and narrowing down of target areas during the period 2022-2047. Further, Geological Survey of India (GSI) and Directorate of Geology & Mining (DGM) of various states are also planning to take up multi-parametric heliborne geophysical surveys for mineral exploration in different parts of India and data will be accessed by AMD. During the vision period focus will be on processing, interpretation & geomodelling of the generated and acquired data after integrating with related ground geological/ geophysical/ geochemical data. Emphasis will be given to the application of Artificial Intelligence (AI) & deep machine learning (DML) coupled with integration of exploration data in 3D-GIS platform.



Heliborne geophysical surveys (2022-2047)

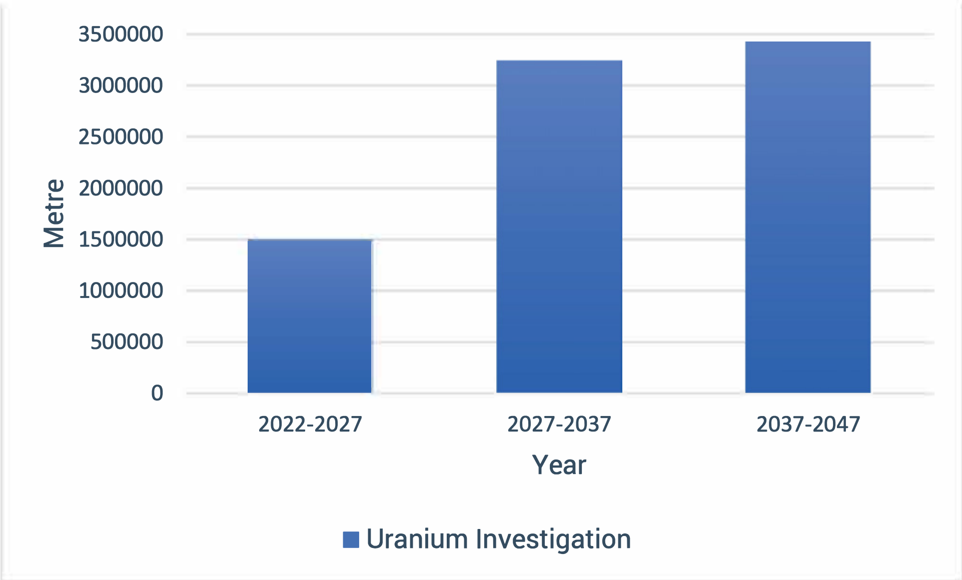
Ground Geological/Geochemical/Geophysical Survey: Ground geological, geochemical and geophysical surveys will further help in narrowing down the targets for subsurface exploration. During the period 2022-2047, 2,72,695 sq. km geological, 1,64,375 sq. km geochemical and 48,750 sq. km geophysical surveys in potential geological domains are conceived to demarcate targets for sub-surface exploration.



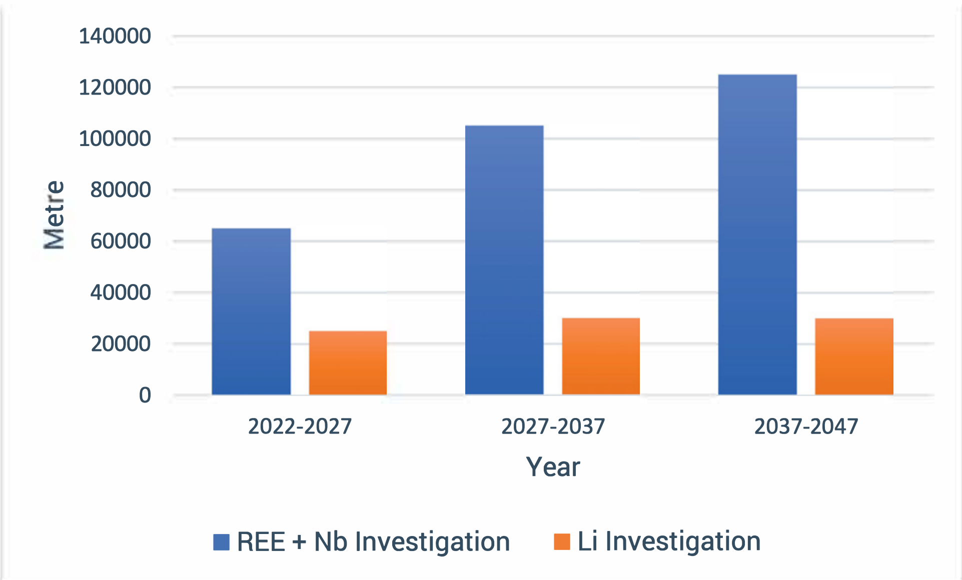
Ground geological/geochemical/geophysical surveys (2022-2047)

Drilling: Subsurface sampling by drilling facilitates delineation of concealed ore body in terms of its geometry, directional continuity and dimensional homogeneity, which has a direct bearing on the assessment of the resource estimate. AMDER deploys modern hydrostatic rigs for achieving greater drilling output and evaluate the potential anomalies, geophysical signatures and conceptual models related to mineralisation. It is contemplated to adopt to latest technologies in line with global developments in the field of drilling.

Phase wise drilling is envisaged to facilitate uranium and Rare Metal – Rare Earth resource evaluation in hard rock terrains of India during the period 2022-2047.



Drilling inputs required for augmentation of Uranium Resources



Drilling inputs required for augmentation of REE and Li-oxide resources

The proposed programme envisages a uranium resource of ~5,75,000 t (uranium oxide), which will support the mining activity by Uranium Corporation of India Limited (UCIL) for a considerable period and so can support ~ 57,500MWe Nuclear Power Production by PHWR for 40 Years. Likewise, the envisaged BSM resources (~300Mt containing ~3Mt Monazite), will support the mining and processing activities of IREL (India) Ltd. to cater to the sustainable supply of Th, Zr, REE, Ti and U for accomplishment of vision plan of DAE.

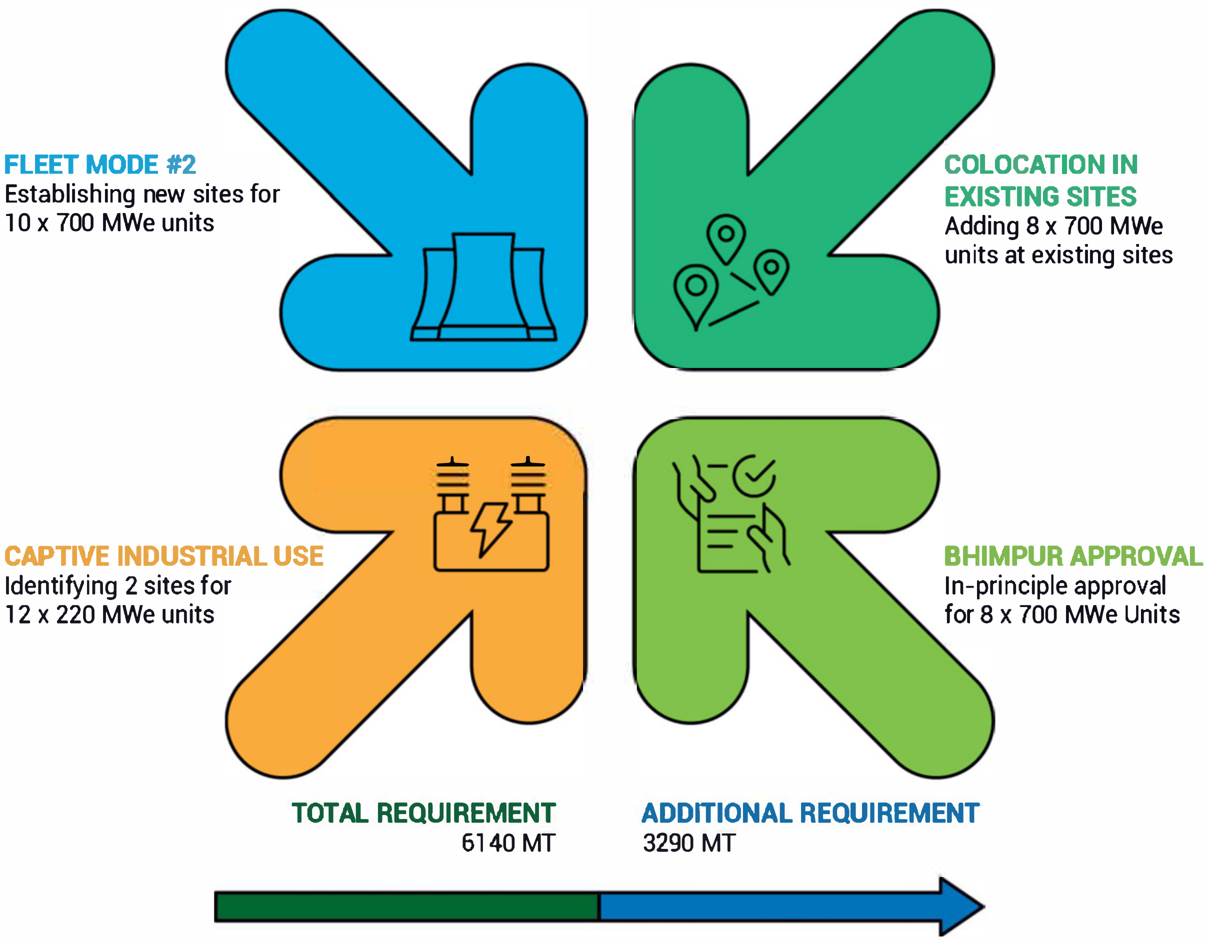
2.2 Nuclear Fuel Fabrication

2.2.1 Uranium Fuel Fabrication for Power Reactors

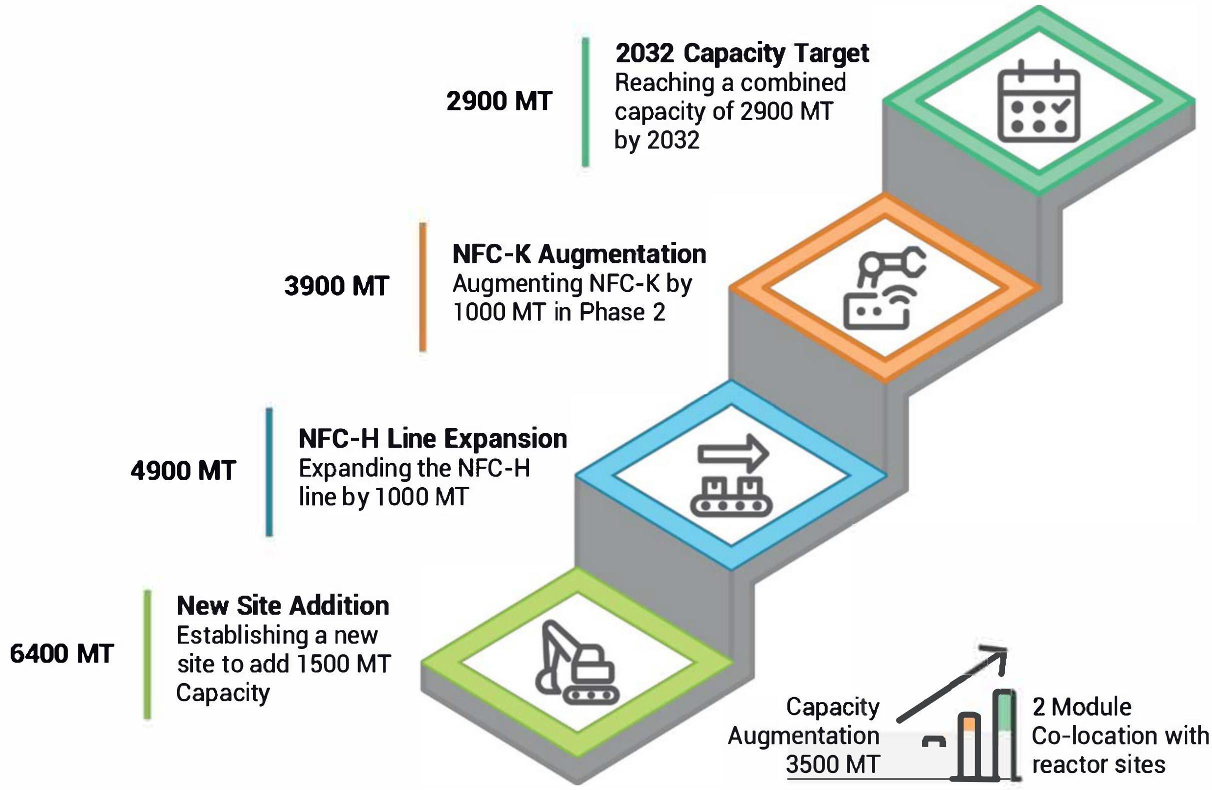
PHWRs are going to play crucial role in expansion of nuclear power in India with several units planned in phased manner till 2032. The installed capacity is expected to increase to 15660 MWe by 2032 through addition of 12 PHWR-700. Beyond 2032, 34 PHWRs (22x700MWe and 12x220MWe) are planned by NPCIL taking the installed capacity to 33740 MWe by 2047. With this reactor deployment plan, present fuel requirement of 975 ton per year will increase to 6140 ton per year by 2047 in line with reactor deployment. Existing production capacities of two production blocks at NFC-Hyderabad is sufficient to meet the present requirement. These two production blocks are required to undergo modification, renovation and augmentation in medium term to achieve total licensed capacity of 1900 ton per year. Total fuel production capacity for future requirements needs to be met from NFC-Hyderabad and NFC-Kota (Rawatbhata, Rajasthan).

The production capacity of NFC-Kota having 500 ton per year capacity can be augmented to 1000 ton per year by 2032 in existing infrastructure through addition of critical equipment. Beyond 2032, NPCIL's projected fuel requirements can be met through setting up of a new module of 1000 ton per year capacity at NFC-Kota comprising of powder, pellet and assembly plants, QC facilities and augmentation of utilities and effluent treatment facilities. Depending on progress of reactor deployment, the production capacity at NFC-Hyderabad can be further augmented through setting up of additional line of 1000 ton per year. The production capacity can be further augmented through setting up of a new facility of 1500 ton per year capacity preferably co-located with a reactor site. Hence, by 2047, fuel production capacity of NFC can be increased to 6400 ton per year against projected requirement of 6140 ton per year.

Fuel supply to operating BWRs will be through the existing enriched fuel fabrication plant using imported finished pellets. NFC can manufacture and supply special fuel bundles for PHWRs – SEU, ReSEU and for in-situ irradiation. Localization of VVER fuel can be carried out through DAE joint venture with original fuel manufacturer in a dedicated facility to be set up. A dedicated facility based on fuel design and production technology can be set up for IPWR.



NPCIL Projection 2047



NFC Roadmap 2047

Timeline for augmentation beyond 2032 will be in-line with NPCIL reactor deployment scenario. The plan for the augmentation of fuel manufacturing is based on implementing in-house and indigenous technologies which has been developed and matured over years of operational experience. The target is to achieve large scale fuel production capacity of 2900 ton per year by 2032 and 6400 ton per year by 2047 in line with NPCIL's fuel demand. The programme is planned to improve energy security for the country through Atmanirbhar Bharat Abhiyan. The localization of VVER fuel assemblies is aimed at achieving cost effectiveness through import-substitute.

2.2.2 Metal Fuel Cycle for Fast Reactors – Fabrication and Irradiation Programme

For rapid growth & sustainability of fast reactors, metal fuel with short doubling time and an integral fuel cycle with Pyro-chemical reprocessing is the option. The technology development work on fabrication of sodium bonded metal fuels and reprocessing by pyro-process route is undertaken by IGCAR. As a prelude to gain experience on metallic fuel, pins of different compositions are being irradiated in FBTR to generate base line performance data. A long-term plan is chalked out to construct FBTR-2 which will be fuelled by metallic fuel. IGCAR has set-up a high purity inert atmosphere glove box train facility for fabrication, characterisation and qualification of sodium bonded metallic fuel pins. IGCAR will be involved in fabrication of sodium bonded metal fuel pins in sub-assembly level and continue irradiation programme in FBTR till its life, to generate data on the distinct advantages of metal fuel such as burn-up, breeding ratio, doubling time, inherent safety features, reactor kinetics etc. The long cycle irradiation studies will help in finalising the fuel design specification for FBTR-2. IGCAR will in parallel reprocess the metal fuel pins & sub-assembly in RCL hot cells till a dedicated shielded pyro-processing facility is established. The shielded facility will reprocess by pyro route & will have a cell to remotely injection cast & fabricate fuel pins using the electro-refined fuel thereby demonstrating the closing of metal fuel cycle.

The complete programme is formulated in three phases:

Phase-1: The programme on metal fuel fabrication involves gaining experience in large scale handling of metal alloy, safety features, producing fuel slugs & pins with minimum rejects, accounting the SNM material and closing the gap areas in recycling the fuel rejects.

Phase-2: With inputs from above, an automated facility will produce sodium bonded metal fuel pins in sub-assembly level for FBTR. This facility will handle from starting material master alloy to finished sub-assembly at one place. The phase-2 will supply metal fuel sub-assemblies (~5-10 SAs) to populate in FBTR & irradiate till the life of FBTR. It will fine-tune the technology needed for scaled up facility towards fabrication of metal fuel pins for FBTR-2 in large scale.

Phase-3: This phase will integrate a shielded hot cell for remote metal fuel fabrication in the shielded metal fuel cycle facility comprising pyro-process & remote fuel fabrication to demonstrate the fuel cycle closure. It will develop the flow sheet & technology for FBTR-2 metal fuel cycle and readiness to embark on FBR-3&4 programme.

In continuation to irradiation programme on metallic fuels in sub-assembly level in FBTR, longer metal fuel pins with higher fissile content are being planned. A new glove box line is being setup for 932mm long fuel pins towards fabrication of 37 pin sub-assembly containing higher enrichment of ternary alloy metal fuel. Fuel fabrication processes such as metal alloy melting, solid coil-based heating, injection casting & its automation, alternate casting methods, vision-based cast slug inspection system & data processing etc. have been developed further for mass production. As medium and long-term goals the future steps as foreseen are: pin level & sub-assembly fabrication of sodium bonded metal fuel pins & continue irradiation for long cycles in FBTR; constructing a new integrated shielded metal fuel cycle facility comprising pyro-process cells & remote fuel fabrication cells; and plant layout & proposals for metal fuel fabrication facility for FBTR-2.

This programme will help India becoming Atmanirbhar in several precision manufacturing & automation industries, resulting large scale skilled manpower employment. India is the only country to pursue development of metal fuel technology in large scale, which is indeed the next generation nuclear technology. Development of advanced fuel reprocessing technology will help in achieving energy security, while generating significantly less radioactive waste, establishing India's leadership in this field.

2.3 Back End of Fuel Cycle

2.3.1 Completion of Integrated Nuclear Recycle Plant

In line with closed fuel cycle approach, spent fuel from pressurised heavy water reactors (PHWR) is reprocessed to extract uranium and plutonium. The immobilization of high-level waste arising from reprocessing of spent fuel using vitrification process is well established and the vitrified high-level waste is stored in air cooled vault for safe removal of decay heat. Considering the growth of the nuclear power program, need arises to increase the capacity for spent fuel reprocessing. This enhancement is crucial for the recovery of uranium and plutonium, which will serve as fuel for the next generation of fast reactors. Reprocessing capacities for processing of PHWR spent fuel is being enhanced to meet the future fuelling requirements of FBRs of second stage.

The fuel cycle activities in the first stage have reached a maturity. However, technological developments are being suitably incorporated in the facilities as a part of process intensification, automation, reduction in environmental discharges, occupational exposures etc. Expertise in design, construction, commissioning, operation and maintenance of these radiochemical facilities is available in-house. An integrated nuclear recycle plant (INRP) is being constructed to enhance the PHWR spent fuel reprocessing capabilities with "solid in solid out" concept. This is an innovative concept with spent fuel as the input and mixed oxide (MOX) fuel and solid vitrified waste as the output from the plant. INRP integrates all the facilities operating in the back-end of the fuel cycle i.e., spent fuel storage, reprocessing, waste management and MOX fuel fabrication. MOX fuel will be used in prototype fast breeder reactor (PFBR). As medium-term target, the completion of construction and commissioning of INRP, Tarapur will be achieved.

2.3.2 Setting-up and Commissioning of Fast Reactor Fuel Cycle Facility (FRFCF) for reprocessing of MOX Fuel in Fast Reactor Programme

Multi-recycling of plutonium in fast reactor is feasible. This results in maximum utilization of uranium and plutonium for generation of energy. Hence, recycling strategy adopted in India envisages use of plutonium, recovered from reprocessing of spent nuclear fuel, in uranium-plutonium mixed oxide (MOX) form in fast reactor during second stage of nuclear power programme for generation of energy. A commercial prototype fast breeder reactor (PFBR) is under commissioning at and two additional fast breeder reactors are planned to be constructed at the Kalpakkam site. For optimal utilization of fuel, the spent fuel arising from fast breeder reactor will be reprocessed and recovered plutonium will be recycled back to fast reactor as fuel. This requires reprocessing, waste management as well as fuel fabrication facilities adjacent to fast reactors for enabling of recycling of fuel material in minimum time period.

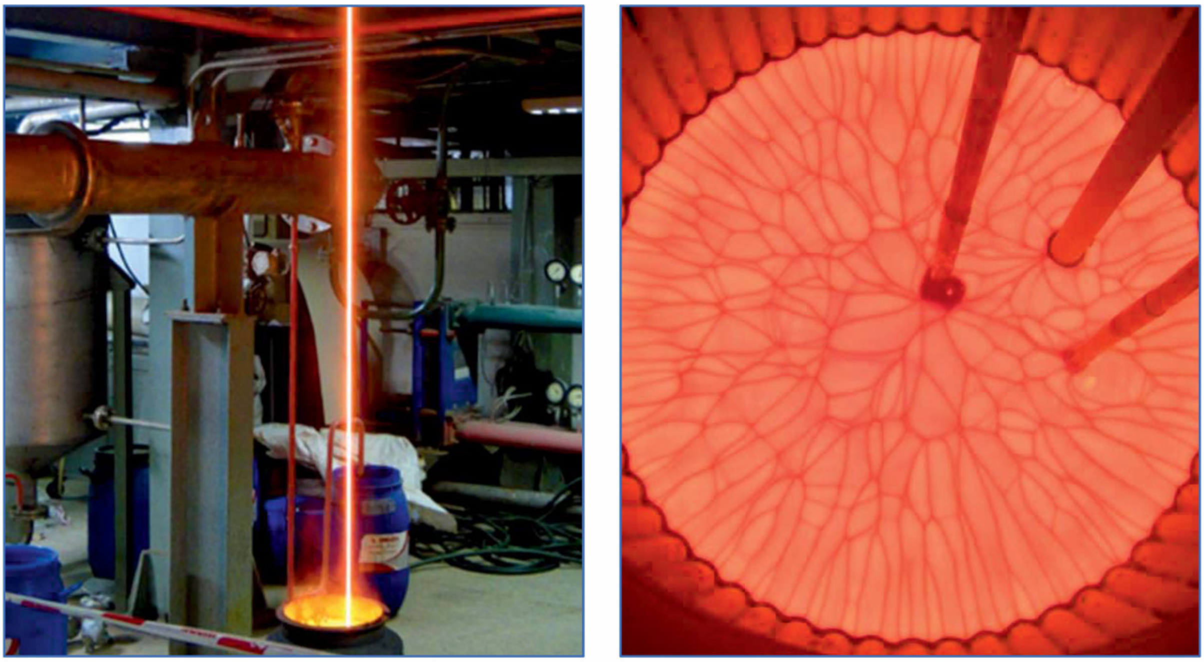
Presently the validation of the technology has been carried out in the pilot facility CORAL (Compact Facility for Reprocessing of Advanced fuel in Lead cell). The facility has been successfully operating for the past 20 years, processing spent fuel discharged from FBTR with very good recovery and decontamination factors. The plant has provided a wealth of operating experience for the design and construction of future plants. Based on this experience, the demonstration fast reactor fuel reprocessing plant (DFRP) has been built, which will serve the purpose of establishing the technology at a plant scale.

As the fast reactor reprocessing plant is to be operated in tandem with the reactor, to process and return the fuel in the shortest possible time, to reduce the doubling time, the availability of the plant becomes critical. Hence, in the DFRP the operation of the plant with the name plate capacity and availability factors will be demonstrated. The facility can handle both FBTR and PFBR fuel pins. The head end facility of DFRP would be commissioned and initially FBTR fuel will be processed. Subsequently processing of the PFBR mixed oxide fuel would be taken up in this facility, which would give valuable input for the design and fine-tuning of equipment for future reprocessing plants. With this operating experience, the design of equipment would be taken up for the reprocessing plants catering to FBR1 and FBR 2. In view of commissioning of PFBR and subsequently augmentation with two more FBRs during the Amrit Kaal, a dedicated FRFCF will be constructed and commissioned for reprocessing of fast reactor spent fuel and recycling back the valuable fuel materials to FBRs. The facility is constructed to attain the objective of self-sustain fuel cycle for fast reactors.

Demonstration of closure of fuel cycle for PFBR would give adequate confidence in taking up of design of future reprocessing plants. The feedback will be vital for the fuel reprocessing plant of FRFCF. The full potential of the fast reactors can be realized only through a robust closed fuel cycle. Successful operation of the fast reactor and its fuel cycle, would lead to large scale deployment of fast reactors which would ensure long term energy security for the country. The construction and operation of the plants would also lead to development of several indigenous technologies and vendors, enabling self-reliance.

2.3.3 Deployment of Partitioning Technology and CCIM for High Level Waste

High level waste (HLW) generated during reprocessing of spent fuel, is characterized by high radioactivity and contains majority of fission products & minor actinides present in spent fuel. Conventionally, liquid HLW is managed by immobilization in to glass matrix (vitrified waste) followed by interim storage in air cooled vault called vitrified waste storage facility (VWSF) for removal of decay heat before its final disposal. Presently, HLW in India is being vitrified at three sites, i.e. Trombay, Tarapur and Kalpakkam, using both metallic and joule heated ceramic melters (JHCM) and stored in a well-engineered passive air-cooled vaults under operation at Tarapur and Kalpakkam sites. Recent developments of partitioning technologies for management of HLW helped towards multi-fold reduction in the volume of the vitrified waste. Partitioning technologies also open up the possibilities for recovery of valuable radionuclides from HLW for societal/industrial applications. Partitioning of HLW, arising from reprocessing of spent fuel of PHWR as well as research reactor, is successfully demonstrated on engineering scale at Tarapur and Trombay sites respectively and the deployment of the technology is planned at Kalpakkam site. A flowsheet has been developed for the complete recovery of useful radionuclides for their deployment in societal applications. The minor actinide (MA) rich stream, generated during partitioning will be immobilised in a glass matrix. Considering the longer life of these radioactive minor actinides, glass matrix (with higher melting point) needs to be specially developed to meet the requirements of higher radiation stability and better chemical durability. Considering the higher melting point glass matrix for immobilisation of minor actinides, cold crucible induction melter (CCIM) based vitrification technology was needed. CCIM based vitrification technology has been successfully developed and demonstrated on an engineering scale and the same will be deployed at Kalpakkam.



Cold Crucible Induction Melter (CCIM)

As far as partitioning of fast reactor high level liquid waste (FR-HLLW) is concerned, the present programme is targeted to design, construct, demonstrate and operate a prototype facility at IGCAR for the separation of trivalent minor actinides from HLLW generated during the reprocessing of FR fuels at CORAL, DFRP and FRP plants on a regular basis. The group extraction trivalent actinides and lanthanides from HLLW is achieved by a tailor made diglycolamide (DGA) ligand and the lanthanide–actinide separation is also accomplished with the use of diglycolamic acid developed at IGCAR. The experience gained in such demonstrations confirmed the technical feasibility of employing these reagents and processes for minor actinide partitioning on industrial scale.

Major activities those have been planned for stepwise systematic execution are:

i. Installation and commissioning of partitioning system; CCIM based vitrification system, and commencement of regular operation of partitioning system and CCIM system

ii. Large-scale production of radionuclide for societal application.

iii. Partitioning and associated technology for HLW from reprocessing of spent fuel of fast reactor (FR-HLLW)

iv. Development of minor actinide laboratory at head-end facility (HEF) of DFRP

v. Bulk scale synthesis of advanced reagents/solvents for the selective separation of trivalent ions from both organic and aqueous phases

vi. Extensive testing and demonstration of the flow-sheet for minor actinide partitioning, Single-cycle separation of trivalent actinides in the laboratory scale and Optimization of flow-sheet

vii. Prototype facility for minor actinide partitioning (both single-cycle and two-cycle process at IGCAR). This includes identification of site annexed to a reprocessing plant, construction of hot cells, fabrication of various equipment, control system etc, and their erection inside the hot cell

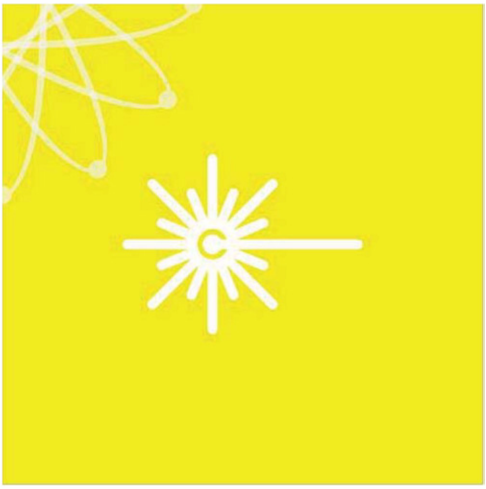
viii. Pre-commissioning commissioning of the prototype facility for regular operation

The Facility for partitioning of HLW arising from reprocessing of PHWR spent fuel will minimise the final waste volume for final disposal. It will also enable the recovery of valuable radionuclide for societal applications. FBR minor actinide partitioning facility at IGCAR could harness the research activities associated with transmutation of minor actinides in fast reactors.

2.3.4 Process & Technology for MSR Fuel Cycle Facility

Indian molten salt breeder reactor (IMSBR) is being developed for effective utilisation of thorium and ensuring long term energy security in a sustainable manner. To start with, a 5 MWth molten salt reactor is proposed. In MSBR fuel cycle, reprocessing has two major roles; firstly, removal of Pa, its decay into ^{233}U and reintroduction of ^{233}U into the molten salt of MSBR, and secondly, removal of fission products and other radionuclides for maintaining desired neutron economy inside reactor. Recovered actinides can be recycled back in the reactor core which results in minimization of radio toxicity of waste and effective utilization of natural resources. The reprocessing requirement, i.e. the rate of reprocessing, depends on the neutron spectrum. Operation in the thermal spectrum requires continuous online reprocessing, while MSBRs operating in the fast spectrum can operate in batch mode reprocessing.

R&D activities are aimed to identify and develop the processes for molten salt fuel reprocessing. The pyro-processing techniques based on relative volatility, reductive extraction, vacuum distillation and electrochemical processes will be pursued. This work involves identification of process scheme, setting up of experimental facilities and associated R&D for process development. The Fluoride volatility process will be pursued for recovery of ^{233}U and other volatile fluoride. Development work will be carried out in the field of reductive extraction using molten metal for selective extraction of first minor actinides followed by lanthanides by controlling redox potential of salt using Li or Th. Vacuum distillation and electro-refining based techniques will be followed for salt purification. Engineering scale development, including materials & equipment has been planned as medium-term target. The expected outcome would be an indigenously developed molten salt based reprocessing scheme, which will further help in making an Atmanirbhar Bharat and promoting optimal utilisation of fuel for self-sustaining energy programme with minimised environmental impact.



Vertical 3

ACCELERATORS AND LASER PROGRAMMES

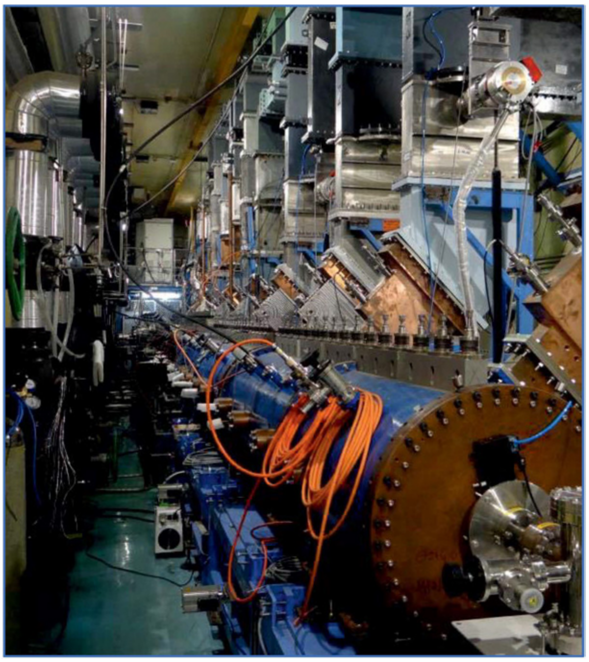
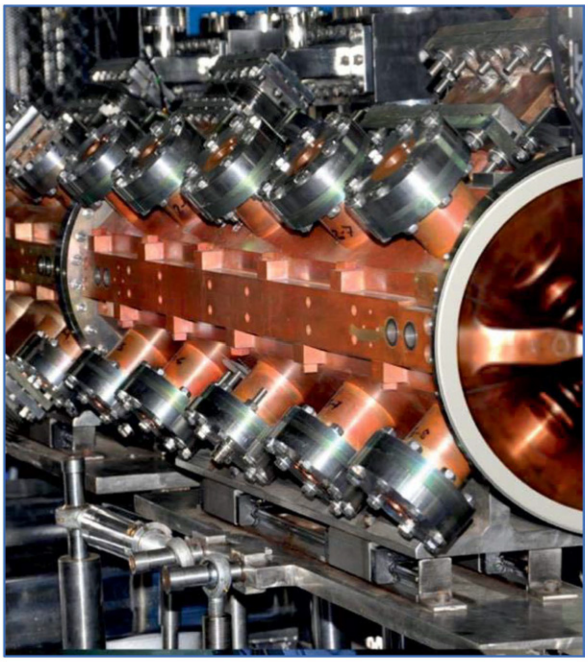
3.1 Linear High Intensity Proton Accelerator

Accelerator driven-subcritical system (ADS) is an advanced nuclear system that could be used for the transmutation/incineration of fission products/minor actinides, thereby eliminating the need of geological repository in near future. Additionally, it can produce electricity as the energy amplifier and conversion of fertile to fissile material as accelerator-based breeding. At present the accelerators for ADS have to expand the intensity frontier and operate with high reliability and stability in the high beam power regime. Proton linear accelerators have a high intrinsic performance capability in terms of beam energy and current, because of their better longitudinal acceptance in terms of beam energies and emittance. They consist of a series of linear accelerating cavities that are excited electromagnetically at microwave frequencies (300 MHz to 1000 MHz) by RF power amplifiers. Each cavity increments the beam energy by a few MeV, so several hundreds of cavities are needed in the accelerator. However, the beam passes only once through the accelerator.

There are active programmes at national as well as international laboratories, to develop, demonstrate and exploit accelerator-driven systems technology for nuclear waste transmutation and power generation. BARC has recently demonstrated acceleration of peak proton beam current of 2 mA (Average Current of 32nA) to 20MeV in LEHIPA facility. R&D is taking place around the world on ADS and the particle accelerator community is pursuing a high-reliability MW (kW seems more appropriate) CW proton operation. RRCAT has built up the infrastructure, such as fabrication, processing, 2K testing etc. required for development of superconducting cavities for high energy accelerators. With this backdrop a 1 GeV, 1 mA average beam current (10mA peak current), high-intensity proton accelerator is proposed to be developed in a phased manner for the Indian ADS program.

The front-end of a high-power proton Linac for ADS applications must meet very challenging requirements, including the delivery of high-current CW beams with high availability. This regime is different from that of existing accelerators which operate with PRFs in the range of few Hz. Final goal of the proton linac would be to increase the average beam current of the Proton beam for increasing the ADS beam power. The planned 1 GeV linac constitutes following major development stages and four different accelerating sections as listed below:

(a) MEHIPA-Phase I: Front-end of 50 keV ECR ion source and a 3 MeV, 325 MHz RFQ, and 10MeV DTL linac. It will attain superconducting after 10 MeV, incorporating cryomodule which houses single spoke resonator (SSR) cavities and superconducting focusing magnets. Beam energy at the exit of this accelerator section would be 40MeV.

Indigenous technologies developed for Proton Linac

(b) MEHIPA-Phase-II: Proton beam acceleration up to energies of 200MeV using SSR cryomodule.

(c) HEHIPA-Phase-I: Proton beam acceleration up to energy level of 400MeV using Low-Beta elliptical superconducting cavities. The linac will incorporate focusing magnets (quadrupole and dipole correctors) outside the cryomodules. In addition, it will consist of Solid-state RF amplifiers to power the Superconducting cavities.

(d) HEHIPA-Phase-II: Final stage of accelerating structures housing high beta elliptical cavity cryomodules taking the proton beam to the energy levels of 1GeV for coupling to the ADS target.

All the above accelerators will be powered by Solid State Radio Frequency Amplifiers (SSRFA).

Finally, a facility of 1MW Proton beam would be built for demonstration of the following capabilities.

a. Transmuting selected isotopes present in nuclear waste (e.g., actinides, fission products) to reduce the burden these isotopes place on geologic repositories.
b. Power generation: Generating electricity and/or process heat.
c. Fissile material breeder: Producing fissile materials for subsequent use in critical or sub-critical systems by irradiating fertile elements.

3.2 High Energy High Intensity Proton Cyclotron

The main characteristic of cyclotrons is a few accelerating structures, fed by continuous-wave radio-frequency (CW RF) generator required to transfer step by step, the full energy to the beam. The beam revolves isochronously with respect to the RF field in multi-turn pass-throughs needed to build up the full energy.

The excellent performance of cyclotrons at high beam intensities makes it a competitive choice in applications such as energy amplifier, accelerator driven transmutation and high-energy physics experiments. High-energy high-intensity cyclotron systems employ two or three cascaded acceleration stages. Proton energy of 1GeV seems to represent a feasible upper limit for such multi stage cyclotron design; a beam current of about 5mA appears attainable, albeit with significant design challenges. A major challenge for a high-energy high-current cyclotron is the beam extraction system. The current limit in a cyclotron is determined by the design requirement for producing a very clean beam at the outer-most orbit of the machine, with a sufficiently large radial separation from the preceding orbit. Nevertheless, the beam power demand required to satisfy the ADS demonstration mission can be met by conventional cyclotron technology or a futuristic superconducting linac. The major technology areas involved in the development of High energy cyclotrons are large room temperature magnet/superconducting magnets, ion-source, injection and extraction system, RF cavities and RF sources. Most of the technology areas have been addressed for indigenous programmes. With the available expertise and research infrastructure at DAE laboratories the cyclotron technology for ADS seems feasible for coupling to spallation target and a Sub-critical reactor core.

The proposed scheme for a three-stage 800 MeV design would employ the following energy ranges and machine types for the individual accelerator stages:

i. DC proton source: 60 keV; DC-pre-accelerator, Cockcroft-Walton/radiofrequency quadrupole (RFQ), DTL up to 15 MeV

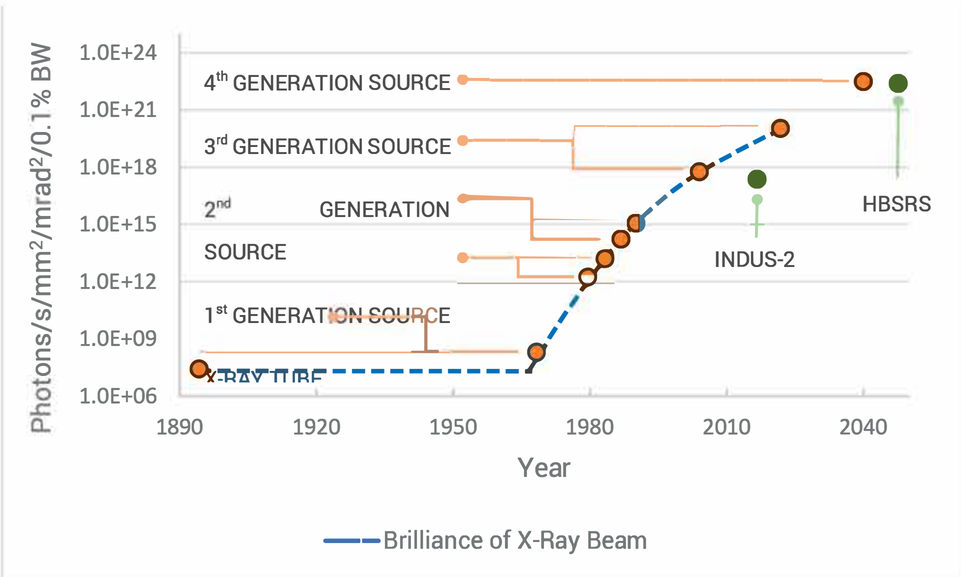
ii. Injector-cyclotron, 4 to 6 sectors up to 80 - 120 MeV

iii. Final stage ring cyclotron, between 8 and 12 sectors up to 800MeV

In addition to injector-I cyclotron technology adoptable for medical applications (hadron therapy), the cyclotron accelerator facility of 1.6 MW proton beam would be able to transmute selected isotopes present in nuclear waste (e.g., actinides, fission products) resulting in reduction of the burden these isotopes place on geologic repositories, generating electricity and/or process heat & fissile material breeding.

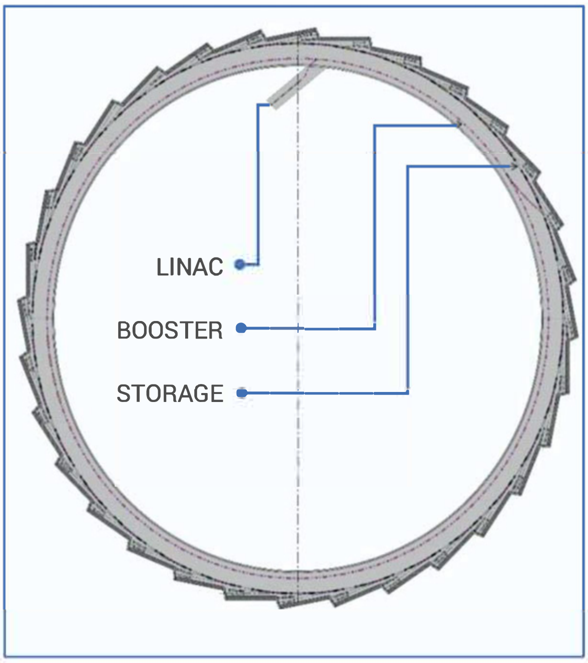
3.3 Establishment of a National High Brilliance Synchrotron Radiation Source: Indus-3

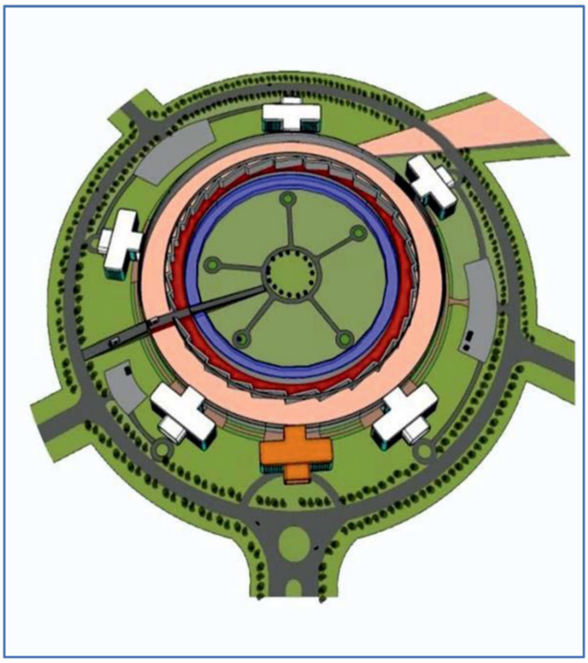
The two Synchrotron Radiation (SR) sources in India, namely Indus-1 and Indus-2 are 3rd generation light sources designed in the 1990's and hence have significantly modest capabilities as compared to the modern 4th generation SR sources. It is now proposed to indigenously develop a state-of-the-art 4th generation high brilliance synchrotron radiation source (HBSRS) named as Indus-3 in India. The urgent need of the facility within the country has been underlined in an inter-agency meeting organized by the Government of India, with the consensus that Indus-3 will be a national project, proposed to be established at RRCAT, Indore with DAE as the lead agency, as a multi-agency governmental effort involving all beneficiary departments. These departments include DST, DBT, DSIR, DRDO, Department of Pharmaceutical and Ministry of Education. The proposed SR source, named Indus-3 with 6GeV, 200mA, emittance ≤ 150pm-rad machine, will provide a significant boost to the national scientific and research community, as well as applied and industrial research, to address national issues like energy security, "Net Zero", food security, affordable health care etc. Indus-3 will also attract a large number of users worldwide, thereby becoming a truly 'International facility on Indian soil'.



Development of High Brilliance Synchrotron Radiation Source

The baseline design for this new 4th generation light source in India, Indus-3, has already been carried out at RRCAT. Indus-3 will consist of a 200 MeV linac with transport line to booster synchrotron, a 200 MeV to 6 GeV booster Synchrotron with transport line to storage ring and a 6 GeV, 200 mA electron storage ring with beam emittance of ≤ 150 pm-rad. A maximum of 50 beamlines on the 6GeV storage ring are possible for user experiments. In the first phase of the programme, the machine will operate at 6GeV, 100 mA, with 12 operational beamlines. These beamlines are planned to cover all the important techniques that are expected in maximum demand among users in India. Some of the important experimental facilities planned in these beamlines include: stress measureaments in large sized engineering components, macromolecular crystallography, micro and nanoscopy using nanosized X-ray beams, coherent diffraction imaging, ptychography, studies of materials at extreme conditions, photon correlation spectroscopy, hard X-ray and atmospheric pressure photoelectron spectroscopy, high resolution X-ray imaging, etc. In addition to these, more routine techniques like X-ray diffraction, small angle X-ray scattering, X-ray absorption etc will also be available. The facilities to develop cutting edge X-ray optics like Multilayer KB optics, Zone plates, refractive lenses and multilayer Laue lenses for applications in X-ray focussing at beamlines of Indus-3 will be established. An important application of multilayer X-ray optics designed for soft gamma rays (~100 keV) is in determining the quantity of actinides in spent nuclear fuel.



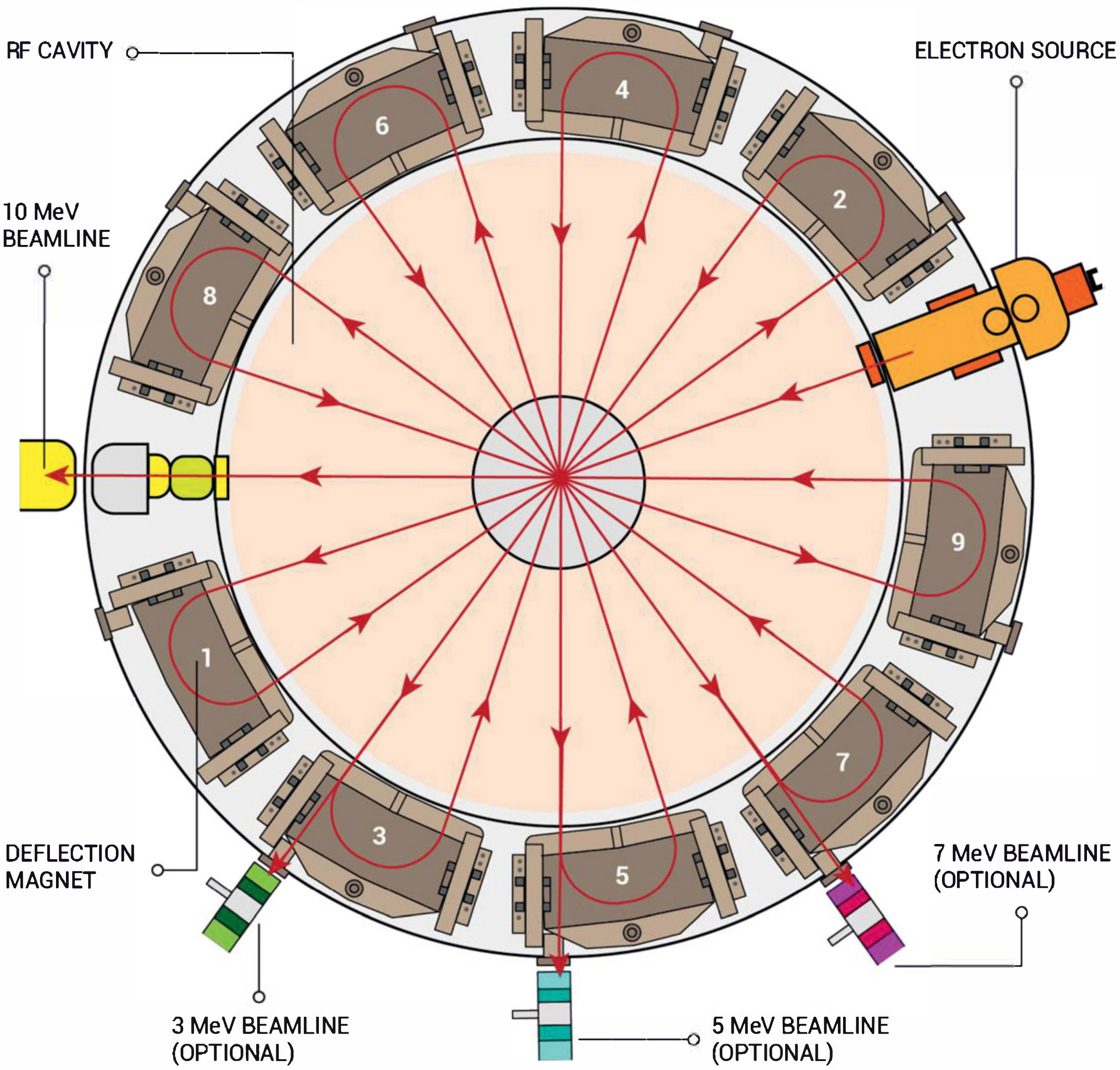


Indus-3 machine layout (left) and its conceptual bird's eye view (right)

Availability of this world-class facility on Indian soil will also attract large-scale participation of Indian industry in utilization of the facility for the industrial research. Indus-3 would serve as enabling tool for science diplomacy as it may attract users' interest from other countries. The significant indigenous component (> 70%) in large-scale manufacturing of high-technology components and systems will contribute towards Atmanirbhar Bharat.

3.4 Development of Linear and Re-circulating Electron Accelerators for Industrial and Food Irradiation Applications

Electron beam accelerators are suitable radiation sources for adoption of the irradiation technology at large scale and offer many advantages as compared to the use of radioactive sources or chemicals. Accelerators can be industrially manufactured and deployed without concern of source security and disposal, and can be operated in switched on/off mode.



Linear and Re-circulating Electron Accelerator

RRCAT has developed and deployed 10 MeV, 6 kW industrial linacs at electron beam radiation processing facility at Indore in 2021. The facility is operating with FDA license for sterilization of medical devices. RRCAT has developed a 10 MeV, 10 kW linac, which is being installed at industry for trials in industrial scale process operations. RRCAT is also set to test a 10 MeV, 15 kW linac. Designs are now being developed for higher power re-circulating industrial accelerator. It is aimed to develop and deploy indigenous high-energy, high-power electron accelerators for irradiation of food and medical products. Emphasis will be given for high level of indigenization, thus enhancing the capability of Indian industries to produce the multi-domain, advanced technology sub-systems, accelerator assemblies, installation, commissioning, qualification, and service expertise for in-service needs.

Three 9.5 MeV, 15 kW industrial linacs for food irradiation applications is planned with an aim to train and enable Indian industry for manufacturing and servicing of high power industrial linacs. RRCAT will provide system integration opportunities to the qualified Indian industries under supervision at RRCAT. After the capability of Indian industries is enhanced to a level where they can develop the industrial accelerators, it will be possible for the industry to quickly absorb the technology of higher power industrial linacs.

(CCW from Top) 10 MeV LINAC, 6 kW LINAC, KIRTI-1010 (10 MeV, 10 kW) LINAC

3.5 High Energy and High Power Lasers

Development of high energy lasers was mooted in the early nineties by DAE. Some of the key components such as long arc-length flash lamps and Nd-doped laser glass have been indigenized. A phase wise programme for development of high energy lasers has now been envisaged. RRCAT proposes to build on its expertise in fibre laser systems to develop 10-100 kW high power fibre lasers by coherent/incoherent combination of several kW-class fibre lasers. These lasers find several applications in all kinds of laser material processing. RRCAT is also pursuing the development of high energy lasers with kilo joules (kJs) of energy and kW class high power lasers. It is proposed to scale-up these activities further with definite steps in terms of energy and power of the lasers and reaching to 1 MJ Nd:Glass laser and 100 kW CW fibre laser. All key technologies, components and systems will be developed in the process.

Laser system design for a 4-pass amplifier & associated components and sub-systems like, amplifier modules, large aperture adaptive optical system, etc. have been developed. Infrastructure is available to house a 1kJ laser system, scalable in the future to 10kJ. Nd-doped phosphate glass discs (optical homogeneity up to 10^{-3}) have been developed, and it is to be further optimised to 10^{-5}.

80 J, 10 ns Nd:Glass laser system test bed developed at RRCAT

Development of monolithic 1 kW single mode and up to 2 kW CW multi-mode fibre lasers have been carried out, which are being utilized for material processing applications. Only a few labs in India are working in the area of fibre lasers. Industries are mostly providing imported systems in India and are not able to tailor these lasers for specific nuclear field or industrial applications

The high energy laser programme will be executed in 3 phases.

i. In phase-I, 1 kJ laser will be demonstrated with 2 beamlets of 500 J each using indigenously developed components which includes 300 mm aperture Nd:glass discs being developed by RRCAT.

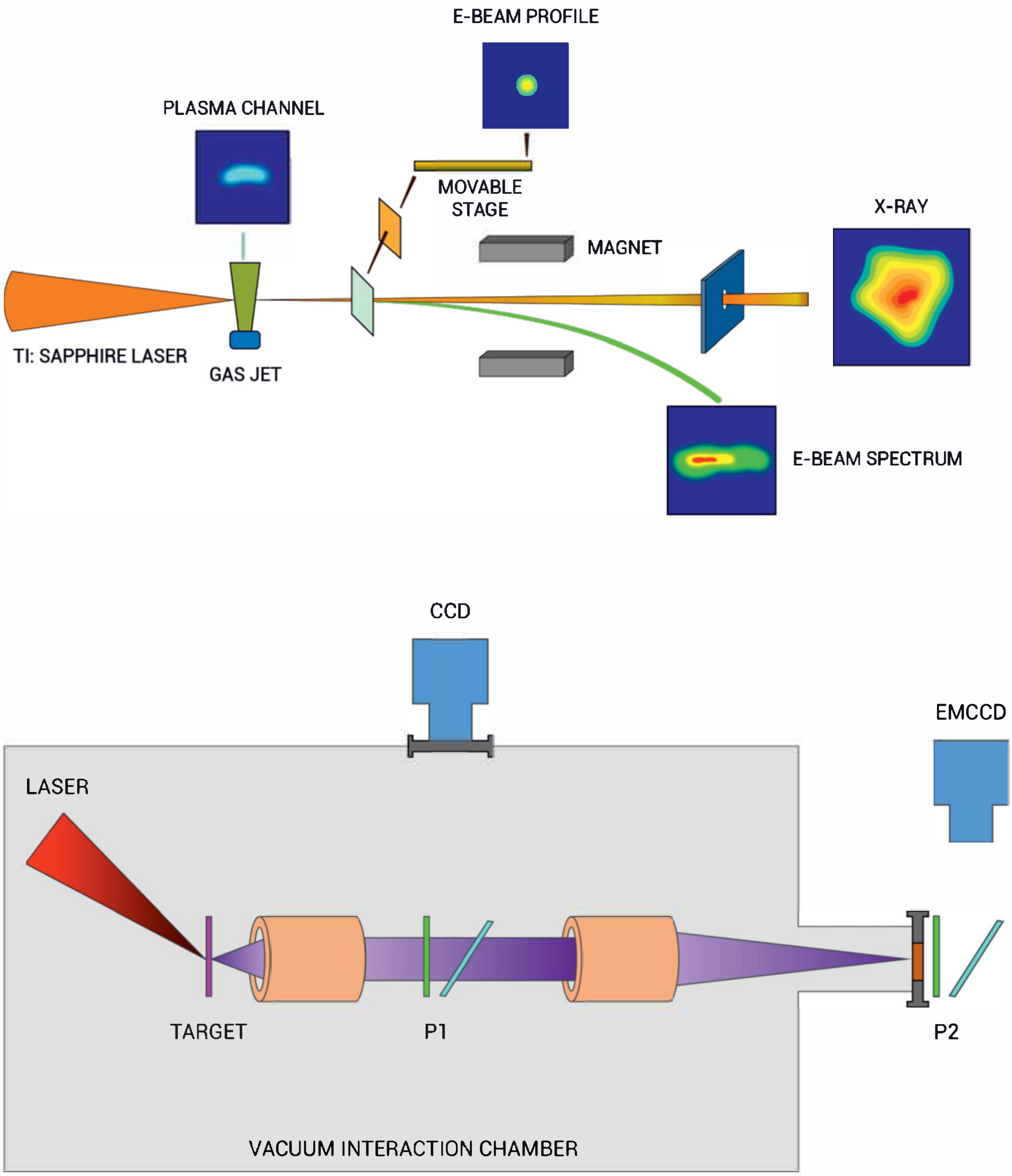
ii. In phase-II, each beamlet will be optimised to get > 635 J so that > 10 kJ can be achieved with 16 such beamlets. The 10 kJ laser will be used for various experiments in shock physics and would be Experimental Test Facility for high energy density physics.

iii. In phase-III, a mega joule laser facility is conceptualized as a four-bay system with each bay consisting of 20 beams, each beam having 4 beamlets. The proposed size of each beamlet is of 400 mm aperture Nd: glass discs. In all there would be 320 beamlets (4 x 20 x 4) each capable of producing > 5 kJ in the fundamental frequency. With a conversion efficiency of >65% from the fundamental to third harmonic, this facility should be able to produce > 1 MJ in the third harmonic. This facility will serve as national test facility for ICF research, laboratory astrophysics etc.

3.6 Laser Plasma Accelerators

RRCAT has worked extensively on advanced particle acceleration schemes using 10 and 150TW Ti:sapphire lasers. Laser wakefield electron acceleration in various gas jets viz. He, Ar, N_2 and mix-gases have been achieved. Various optimisations were done to achieve low divergence stable electron beam relatively of low electron energy (<100 MeV). Maximum electron energy of 500 MeV is demonstrated using 150 TW laser and also betatron radiation is generated from the accelerated electron beam. Proton acceleration in thin foil target (Al, Ni, and Cu) is carried out where maximum proton beam close to 11 MeV is achieved.

It is proposed to develop indigenous technology in the area of advance particle accelerators based on ultra-intense PW Ti:sapphire laser facility at RRCAT. It is proposed to develop electron and proton accelerators of 2 GeV and 30 MeV, respectively (based on advanced laser acceleration scheme). The high energy electron beam will be used to develop high energy betatron and monochromatic IC X-ray source. Further, research and development towards electron and proton particle beam transport system for laser driven accelerators will be taken up. Using these particle beams and X-ray sources, front-line research investigations in nuclear and allied technologies will be carried out.



Schematic of Laser Plasma Accelerator

Finally, ultra-high intensity laser-plasma interaction at 10^{20}–10^{22} W/cm^2 with PW and higher power laser is planned in advanced area of research related to high energy density physics. Continued development is proposed in the development of laser plasma accelerators.

3.7 Development of an XFEL Test Facility with a soft X-ray FEL

Internationally, several laboratories have SRS yet built an X-ray free electron laser (XFEL), which is a complementary facility for studies using short pulse, high brightness, monochromatic X-rays for cutting-edge research not feasible using an SRS. The IR-FEL (a user facility) presently operational at RRCAT, generates far-infra-red radiation with MW peak power in 10 ps pulses. A THz-FEL is in advanced stage of development at IUAC, Delhi. Globally, in addition to several FELs operating in the IR and THz regions as user facilities, seven hard XFELs have been commissioned and one is in advanced stage of commissioning. Soft XFELs (3 nos.), precursors to hard XFELs, use low beam energy and alternate scheme for stable X-ray lasing, have also been demonstrated. Many laboratories are also pursuing this goal as technology demonstrators for XFELs.

This present proposal aims to build a soft XFEL with a 1.5GeV electron beam injector, which will also serve as a test bed for technology demonstration for a future hard XFEL. The seven hard XFELs operating around the world employ femtoseconds (fs) electron bunches with multi-GeV electron beam energy and long undulator sections of around 100m length to generate GW powers in femtoseconds (fs) pulses of hard X-rays using the SASE scheme. Alternate schemes for soft XFELs employ significantly lower electron beam energy and concepts of harmonic generation with short undulators, to generate intense soft X-rays with better reliability of operation. The technologies and the experience generated under this programme will be vital for future light sources. Through this programme, the Atmanirbhar Bharat Abhiyan will be developed in several areas of accelerator technology, with systems like undulators; femtoseconds (fs) beam diagnostics, as import substitutes.

3.8 Multi-Ion Radiotherapy Machine (MIRT)

There is an increasing demand of MIRT machines for treatment of cancer because of its excellent dosimetry parameters and reduced side effects. It is safer and more effective than conventional radiation therapy because proton beam delivers lower dose to healthy tissue and the maximum (“Bragg peak”) energy deposition is near the end of range of the proton beam. Worldwide, more than 135 proton/heavy ion radiotherapy facilities are in clinical operation and more than 35 are under construction. These facilities are either cyclotron based fixed energy machines or synchrotron based variable energy machines. In India there are only two such facilities, one in operation and other under construction and both of these facilities are imported. In order to setup cost effective multiple MIRT facilities in India to meet the demand of cancer treatment and to keep pace with the advances in the ion therapy techniques, it is essential to indigenously develop the technology of synchrotrons for MIRT machines.

Setting-up of MIRT machines involves development, testing & qualification of sub-systems viz., proton / ion accelerator, gantry and beam delivery system, treatment planning system and beam delivery nozzle, regulatory clearances, clinical trials and approvals for clinical use and technology transfer for setting up of multiple MIRT facilities. The major technologies and expertise required for development of proton/ion accelerator for MIRT exists at RRCAT, which is already in the process of development and qualification of a 3 MeV front end test stand. This will act as injector to high energy proton accelerator.

3.9 Accelerator Programme at VECC, Kolkata

VECC envisions a comprehensive and dynamic future in which pioneering research and technological innovations across a spectrum of disciplines drive scientific excellence. From advancing nuclear physics and cyclotron technology to establish world-class accelerator facilities like ANURIB, the commitment extends to the forefront of nuclear physics experiments with stable, as well as exotic nuclei, material science, superconducting magnet, RF technology and cryogenics. VECC aims at discovery of Super Heavy Elements (SHE). With the application of Cyclotron technology VECC aims at enhancing capabilities in nuclear medicine, diagnostics, and scientific research, positioning India as a global leader in these fields. VECC has been leading for last five decades in developing heavy-ion-accelerator facilities in the country. The K130 room-temperature-cyclotron and the K500 superconducting cyclotron provide the maximum energetic heavy ion beams in the country.

To study the domain of exotic nuclei a rare isotope beam (RIB) accelerator facility has been built, consisting of RFQs and LINACs that uses K130 cyclotron as driver accelerator. A superconducting electron LINAC is being added to the RIB facility to generate neutron rich nuclei. This accelerator facility is also being used for material science experiments using stable ion beams. VECC has established a medical cyclotron facility (MCF) using a 30 MeV H^- cyclotron for the production of radiopharmaceuticals. An 18 MeV medical cyclotron is in advanced stage of development at present. Also, an advanced technological know-how is achieved in the field of ECR ion sources and multicusp H^- ion sources. Further progress and major activities include: development of additional beamlines in K500 SCC facility, medical cyclotron: 18 MeV for PET isotopes; 30 MeV (1 mA) for BNCT, cyclotron for SHE facility and finally the ANURIB programme as Amrit Kaal target.

Improved healthcare infrastructure and diagnostic capabilities for cancer treatment is envisaged, while development of high-current cyclotrons for BNCT will contribute to advanced cancer treatment methods, providing more effective and targeted therapies. ANURIB will provide excellent opportunity for research in nuclear physics, as well as in multidisciplinary applied fields, which could lead to spin-off technologies for societal benefits. It is also possible through SHE facility to contribute ground-breaking data to the global scientific community and elevate understanding of the fundamental building blocks of matter.

3.10 Development of High RRR Niobium Production Technology and 2.5 MT Facility

High purity niobium (Nb) is one of the main materials used in the fabrication of Super Conducting Radio Frequency (SCRF) cavities, required for accelerators. Presently, all the high purity Nb (RRR 300) material is imported and the technology of high RRR Nb production is limited to very few countries. Indigenous development of high RRR Nb is essential for particle accelerators to avoid dependence on import of this strategic material.

NFC has taken-up a developmental activity to produce 300 RRR niobium ingots indigenously for DAE's ISNS, ADSS and, other programmes of societal importance in line with the Atmanirbhar Bharat Abhiyan of the Government of India. Worldwide, improving RRR of reactor grade niobium metal by multiple electron beam melt refining is the commonly used method. In the recent trial, NFC could achieve RRR value as high as 334 after refining of reactor grade Nb in an ingot size of 200mm diameter. Future milestones to be achieved as short and medium-term goals are:

i. Setting up a facility of 2.5MT capacity for high RRR Nb ingot production at NFC Hyderabad.

ii. Setting up a dedicate facility to produce 10TPY high RRR Nb products at NFC Hyderabad.

Vertical 4

SOCIETAL APPLICATIONS

4.1 Crop Variety Development

Under the crop variety improvement programme radiation-induced mutagenesis is used to develop novel mutants and varieties having better agronomic traits. Using this approach till date 70 mutant crop varieties of cereals, pulses and oil seeds have been released. The proposed targets herein have been envisaged to benefit the society and for contributing towards the national food security mission. It is proposed to use speed breeding and engineering of crop microbe interactions for enhancement of crop productivity and development of climate resilient crops. In addition, to reduce dependence on chemical fertilisers a programme is undertaken for understanding the plant microbe interactions and engineer the microbes to increase their host-range for enhancing the uptake of major macro-nutrients (such as nitrogen, phosphorus and potassium).

Multiple approaches will be used for success of the program viz-

i. Accelerated crop improvement using gamma rays, electron beam, proton beam, thermal neutron, ion beam followed by mutagenomics, targeted genome editing and speed breeding.

ii. Harnessing plant-microbe interactions for enhancing nutrient-use efficiency in crop plants.

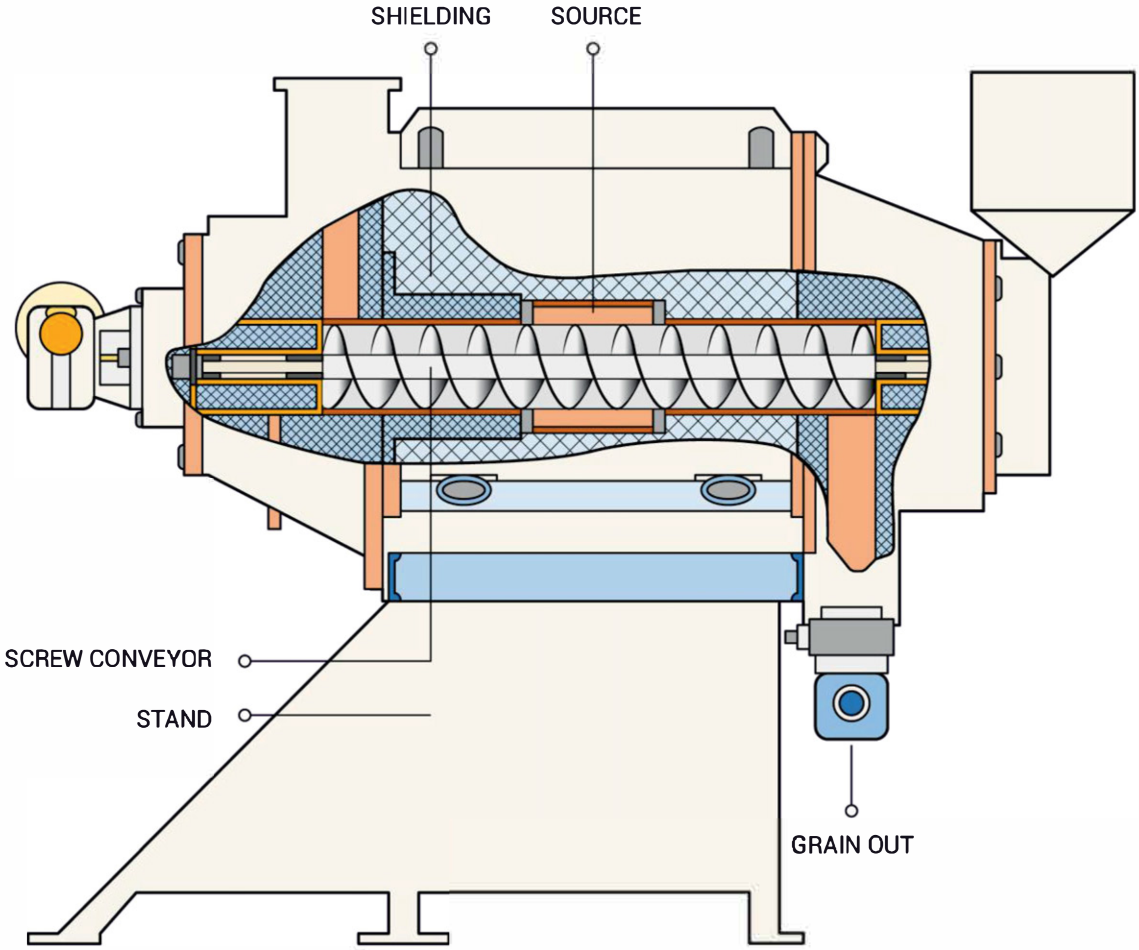
iii. Broadening the host range, e.g., Rhizobium on cereals, mycorrhiza on *Brassica*.

iv. Engineering plant-microbe combination for optimal nutrient mobilisation.

The speed breeding and mutagenomics approach together with engineering the crop microbe interaction would lead to the development of climate resilient crop varieties, increase the crop productivity, and reduced dependence on chemical fertilisers would limit the import of fertilizers in the long run.

4.2 Food Preservation by Irradiation

Food preservation by irradiation is one of the important research programmes for ensuring national food security. Till date, 28 food irradiation facilities (5 Government and 23 private) are operational across India. Five types of customised irradiator designs are being proposed for meeting the needs of the growing agri-produce market. Bi-207 will be explored as an alternative to Co-60/Cs-137 based irradiators and its suitability will be evaluated for food preservation by irradiation. Novel low energy electron/X-ray systems (till 300 keV) for surface treatment of food are to be developed using the concept of e-beam lamp to meet the need of food industries to integrate radiation facility with processing line.



Schematic of Continuous grain irradiator

Conceptualisation, design and deployment of customised radionuclide-based irradiators is planned. Development of innovative product handling system and studies on dosimetry & process control for food will be carried out. Production of Bi-207 using charged particles as residual activity of a lead (Pb) target after irradiation with a high power, 20 MeV proton beam will be explored. The accelerator based and customised irradiator designs would help to meet the need of the growing agri-produce market for food preservation by irradiation, thus contributing to national food security programme.

4.3 Nuclear Medicine and Related Radioisotopes

With recent advances in novel approaches to cancer imaging and therapy, the application of new radioisotopes in nuclear medicine has emerged as a promising avenue. Taking advantage of availability of new radioisotopes, newer radiopharmaceuticals are being proposed to achieve higher targeting efficiency and thus enhanced tumour visualisation. A great deal of research has been focussed towards production of radiometals with diverse and favourable decay characteristics which span the broad spectrum of most cancer imaging and therapeutic applications. Particularly, efforts have been initiated towards the separation and purification of ^{211}At, ^{223}Ra, and ^{225}Ac. Besides, several new diagnostics (^{43}Sc, ^{44}Sc, ^{64}Cu) and therapeutic (^{47}Sc,

^{135}La, ^{169}Yb, ^{169}Er) radioisotopes are produced using the existing research reactors and accelerator facilities in the country.

With an aim to target $\alpha_v\beta_3$ integrin receptor and CD13 receptor, which are concomitantly over-expressed in most of the cancers, bispecific peptide conjugate composed of RGD & NGR peptides are synthesised and evaluated in BARC. Efforts have been directed towards employment of monoclonal antibodies for preparation of radiolabelled antibody-drug conjugates wherein the radioimmunotherapy in combination with chemotherapy will be explored. In the last two decades, multiple PET-based radiopharmaceuticals, e.g., ^{68}Ga-DOTATATE, ^{68}Ga-PSMA, ^{68}Ga-RGD has been employed for diagnostics. Similarly, for therapy, ^{177}Lu-DOTATATE (neuroendocrine tumour), ^{177}Lu-PSMA-617 (prostate cancer) and ^{177}Lu-EDTMP (skeletal metastasis) has been clinically employed for therapy of cancer patients. Work has been undertaken over the last 5 years on the development of integrated omics-based molecular tools for non-invasive diagnosis and prognostication of neuroendocrine tumour (NET) patients. The whole objective in the present program during the Amrit Kaal is Pan-India development of nuclear medicine departments for molecular imaging and targeted treatment of cancer patients, by joint collaboration of BARC/DAE & government medical colleges/hospitals.

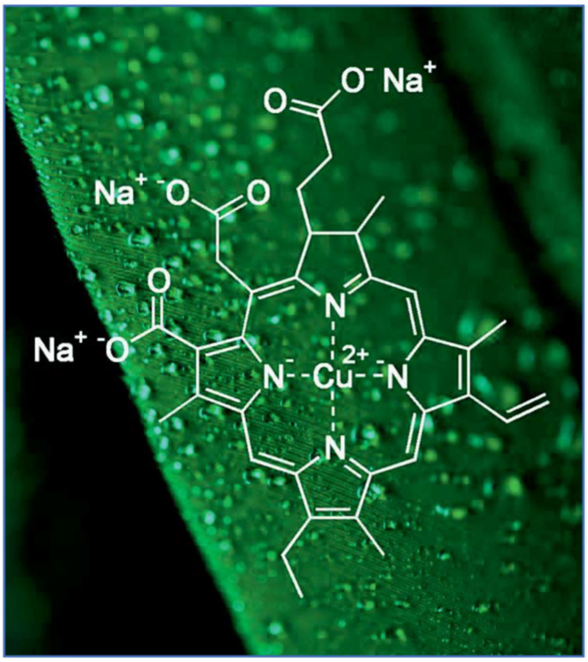
Focus will be laid on the indigenous production and application of ^{225}Ac for targeted α-therapy. Activities to begin for alternative production routes of ^{225}Ac to meet the increasing demand of ^{225}Ac. Another emerging α-emitting radioisotope, ^{211}At, will be produced using the cyclotron at VECC. Several new radiometals such as ^{47}Sc, ^{143}Pr, ^{149}Pm, ^{161}Tb, ^{166}Dy/^{166}Ho, ^{43}Sc, ^{45}Ti, ^{52}Mn and $^{132+135}$La will be produced for imaging, therapy and theranostic purposes. Particular emphasis will be laid on ^{161}Tb, which shows nuclear decay characteristics similar to clinically established ^{177}Lu. In addition, it emits Auger electrons which makes it more efficacious for targeted therapy of various types of cancer. Another interesting theranostic pair of radiometals is ^{43}Sc and ^{47}Sc, which can be used for personalised management of cancer.

Considering the heterogeneity of cancer and possible changes in the expression of the receptors during the progression of the disease, bispecific peptides binding to multiple receptors would be developed for the enhanced visualisation/therapy of cancer. Radiolabelling of porphyrin conjugates with a therapeutic radionuclide will help to investigate the viability of introducing photodynamic therapy and endo radio-nuclidic therapy using the same targeting vector. It is planned to target radiolabelled liposomes encapsulating drugs using antibodies and their fragments to different types of tumours. Developing integrated multi-omics-based molecular tools for non-invasive diagnosis and prognostication of cancer patients will use easy-to-access patients' samples to study the disease-specific biomarkers. A multi-analyte panel would be developed using machine learning for highly accurate diagnosis of the disease & for monitoring treatment response.

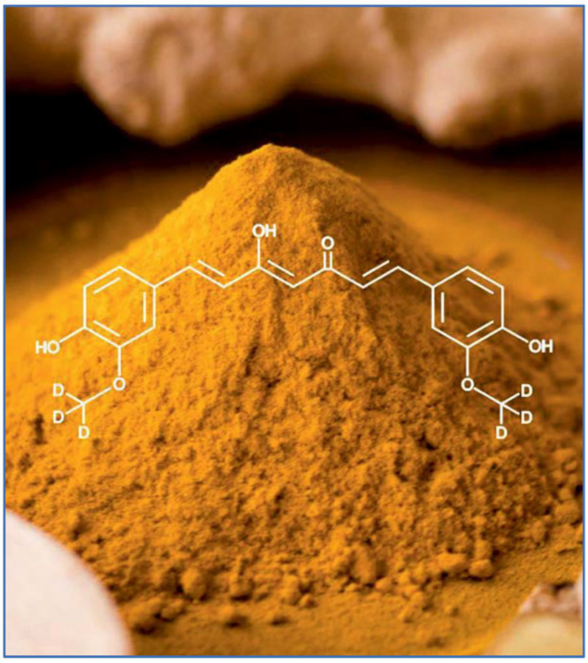
The indigenous production of α-emitters will mitigate import requirements and production of several new radioisotopes meeting the diverse needs of cancer patients while also meeting the goals of making Atmanirbhar Bharat in radioisotope production. This will provide effective and affordable healthcare by the expansion of nuclear medicine activities throughout the country.

4.4. Research for Cancer Medicine

Significant research activities at BARC contribute to healthcare, specifically cancer medicine and diagnostics. Under this research programme, currently two molecules (chlorophyllin and DSePa) are being evaluated for clinical efficacy in cancer patients. The clinical trials are being conducted in TMC. At RRCAT, two diagnostic devices, namely OncoDiagnoScope and OncoVision have been developed as non-invasive optical diagnostic devices for early detection of oral neoplasia in the oral cavity of individuals with history of tobacco consumption.



Chlorophyllin



Mitocurcumin D6

The objectives in totality are focused towards research for cancer medicine encompassing development of approaches for ultra-sensitive and high throughput detection of cancer biomarkers and strategies for improvement of cancer chemo, radio & immunotherapy. It is proposed to evaluate clinical radioprotective and regenerative efficacy of chlorophyllin in pelvic region cancer patients undergoing radiotherapy. Cancer immunotherapy in recent time is leading to durable outcomes in difficult-to-treat cancers but success is highly variable. Biomarker identification to differentiate responders and non-responders of immunotherapy are goals for the future.

To overcome the limitation of non-tumour specific delivery of chemotherapeutic agents and their associated normal tissue toxicity, phage display library technique would be used to identify novel tumour specific peptides. These peptides would be functionalised onto nanoparticles specifically designed for targeted drug delivery, multi-modal (magnetic hyperthermia, photothermal) tumour therapy and improvement of cancer radiation therapy. Secretable and cellular markers would be screened using patient samples for identification of bio-markers for predicting the radio-therapy response and understanding their role in tumour radio-resistance. Currently, research models are not available for prediction of radiation and/or chemo-resistance & sensitivity of tumour in Indian cancer patient scenario. In this regard, rapid prognosis models, based on patient 'tumour-on-CHIP', will be developed for predicting tumour response and personalised therapy. Multi-omic approaches and CRISPR / recombinant DNA techniques will be used for developing methods for early detection of human diseases. Photonics based multiplexed disease diagnostics and simultaneous optical detection of multiple biomarkers linked to oral/cervical neoplasia, infections in biological samples will be developed. Point-of-care (POC) optical device for theranostics of oral cavity abnormalities and non-invasive optical diagnosis, anti-tumour photo dynamic therapy (PDT) & anti-microbial photodynamic therapy (aPDT) will be developed.

Through this programme, clinical evaluation of chemo-radiotherapy efficacy of chlorophyllin and DSePA would be accomplished in cancer patients. Biomarkers would be identified for predicting the clinical response of patients to immuno-radiotherapy. A prediction model based on "Tumour-on-CHIP" for the Indian cancer patients will be developed. Point-of-care diagnostic/theranostic devices for ultra-sensitive detection of biomolecules for early disease detection and predicting therapy response would be accomplished.

4.5 Water Treatment and Waste Management

BARC is working on development of desalination & water purification technologies to recover fresh water from saline or impaired water resources to ensure 'water security' & implement 'Jal Jeevan Mission' goals and wastewater treatment technologies for reuse & recycle and solid & liquid waste treatment & management technologies as a part of 'Swachh Bharat Mission' activities. BARC has developed indigenous multistage flash (MSF), multi effect distillation (MED) and seawater reverse osmosis (SWRO) desalination technologies. BARC has demonstrated nuclear desalination by setting up 6.3 MLD hybrid MSF-SWRO desalination plant at NDDP. Presently, setting up of 5 MLD hybrid MED-SWRO plant at OSCOM, 2 MLD MED plant and 9 MLD SWRO plant at Kalpakkam is underway. BARC has developed membranes such as ultra-filtration (UF), nano-filtration (NF) & reverse osmosis (RO) for desalination & water purifications and transferred these technologies to Indian manufacturer. These technologies are deployed in domestic households as well as on community scale through BARC licensees across India. Novel materials have been developed for advanced oxidation processes such as photo granules, photo catalyst, granular biofiltration & novel methods such as use of DC electron accelerator for wastewater treatment for reuse & recycle and demonstrated these technologies. Three sludge hygienisation plants of capacity 10 tons per day TPD at Baroda and capacity 100 TPD each at Ahmedabad and Indore have been established. These plants employ gamma irradiation technology using Cobalt-60 sources to hygienise the solid sludge.

Desalination & Water Purification Technologies: Under Amrit Kaal targets, BARC will be deploying the matured technologies for setting up large scale hybrid desalination plants in DAE units and nuclear desalination plants in coastal nuclear power plants to ensure 'water security'. BARC is developing solar based humidification dehumidification (HDH) based desalination system and advanced high recovery desalination processes, such as membrane distillation (MD) and counter flow reverse osmosis (CFRO) to implement zero liquid discharge (ZLD).

Membranes and their Applications: High flux fouling resistant nano-composite membranes for water treatment, capillary RO membranes for treatment of low-level nuclear wastewater, hydrophobic polypropylene (PP) membranes for membrane distillation and metal membrane reactor for gas separation & high temperature applications such as CO_2 removal & H_2 production will be developed.

Wastewater Treatment: Novel materials & advanced processes for wastewater treatment, scaleup from lab scale to pilot scale and technology transfer for commercial deployment are envisioned. In particular, deployment of hybrid granular sequential batch reactor (hgSBR) technology to achieve zero discharge of municipal sewer and electron beam technologies to treat textile, tannery, pharmaceuticals & municipal wastewater for reuse or safe disposal to natural sources will be noteworthy.

Solid Waste Management: Radiation hygienisation provides an efficient technique to eliminate pathogenic organisms from waste stream and allow its safe reuse as organic manure. The programme aims to set up more dry sewage sludge hygienisation plants across India based on demand from urban development agencies managing sewage sludge from sewage treatment plants. The product will be further enriched through bio-augmentation using beneficial microbes like *Azotobacter*, *Azospirillum*, P-solubilisers etc.

The significant outcome of this programme would be the following:

i. Large scale hybrid desalination plants in DAE units and nuclear desalination plants in coastal nuclear power plant (NPP) to ensure 'water security.'

ii. Advanced desalination technologies, prototype units and products in advanced membrane & materials.

iii. A model zero wastewater discharge residential colony in DAE township as a part of 'Swachh Bharat Mission' by deploying suitable indigenous wastewater treatment technologies, implementing water reuse & recycling policy.

iv. Realising Atmanirbhar Bharat through development of desalination & water purification technologies for societal applications to ensure cost-effective 'water security'.

v. Import-substitution by development of advanced membranes and materials.

Vertical 5

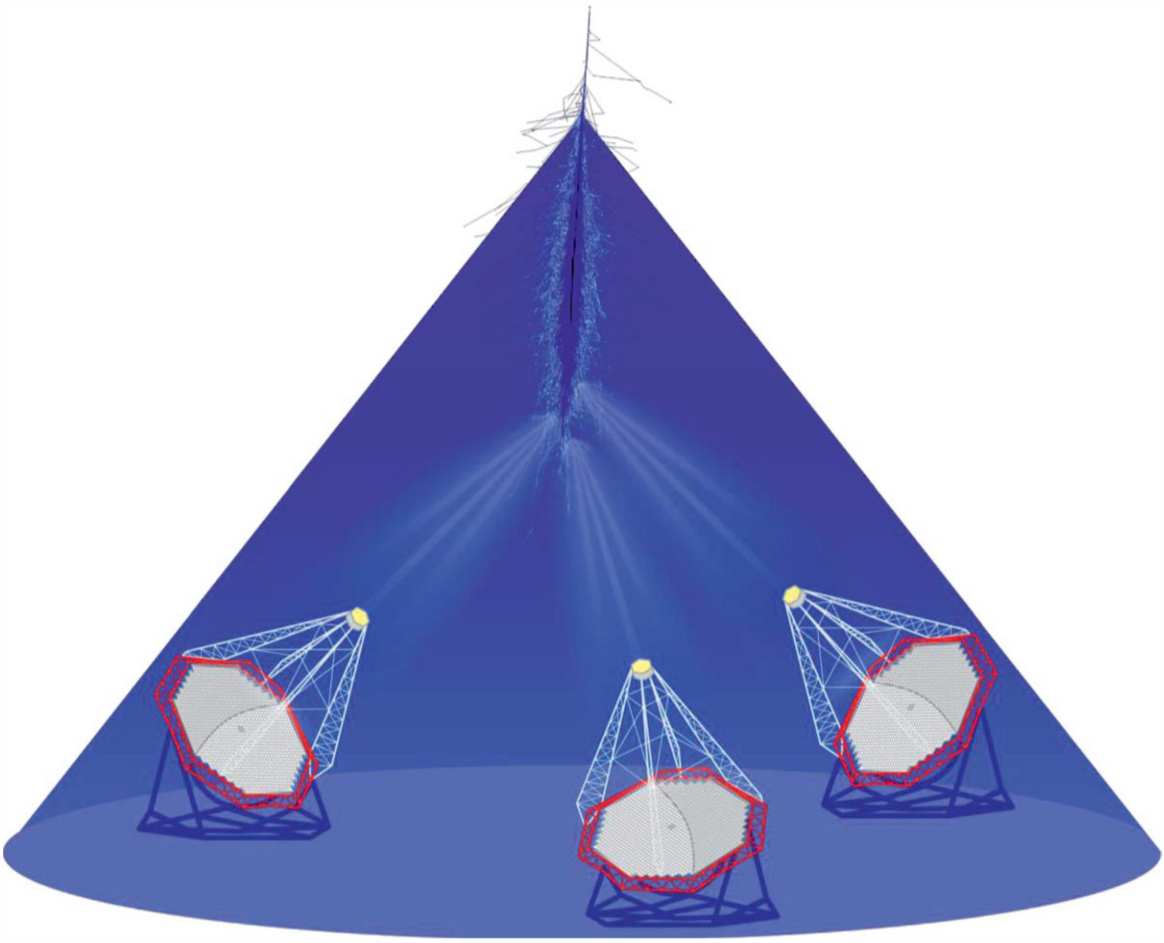
FRONTIERS IN BASIC RESEARCH

5.1 Physics

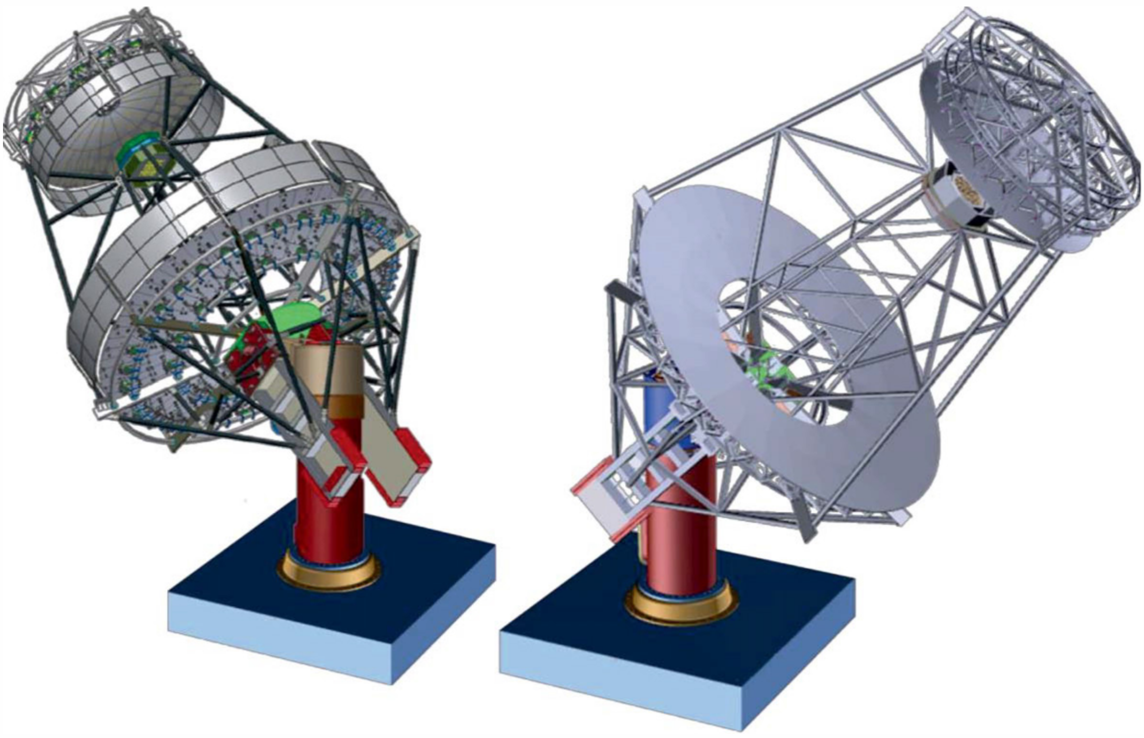
5.1.1 Large Scale Facilities for Physics Research

Large scale facilities are required to carry out fundamental and innovative research in different fields of physics and strategic areas of science. It is proposed to build state-of-the-art facilities to carry out innovative research.

The proposed Stereoscopic MACE System (SMS) is to be established by installing two additional MACE-like telescopes in the vicinity of MACE operating at Hanle in Ladakh. SMS will be integrated with new type of 4 m class Schwarzschild-Couder telescopes (SCTs) array. The geometrical configuration of proposed stereoscopic MACE system (SMS), consisting of three MACE-like telescopes at Hanle, has been finalised. Through this programme, a world-class gamma ray observatory will be established in the country as a unique experimental facility for high energy astrophysics research. Apart from the technology spin offs & scientific endeavours, the observatory will attract astro-tourism and provide employment opportunities to local population in the Ladakh region.



Proposed Stereo MACE System



Schwarzschild-Couder Telescope Array Wide Energy Coverage

A versatile heavy ion accelerator facility will be built at the accelerator complex at BARC-Vizag for accelerating beams of stable and unstable ions of energy up to 10 MeV for frontier research in nuclear science and applications.

Next generation RIB facilities are coming up worldwide. DAE has developed several accelerators and has the capability for developing RIB facility. The proposed radioactive ion beam (RIB) facility is envisaged to provide accelerated beams of both neutron and proton rich radioactive ions. Several radioactive species will be produced utilising the proposed 40 MeV proton and 30 MeV electron accelerators at Vizag complex. The initiative towards RIB facility would make the country self-reliant in the field of RRR niobium production and its utilisation for accelerators.

Measurements of antineutrinos have been carried out using a one-ton large area plastic scintillator ISMRAN (Indian Scintillator Matrix for Reactor Anti-Neutrino) detector at Dhruva reactor, BARC. Large size neutrino detector setups are planned to be developed and installed in the vicinity of high-power reactor complexes for performing neutrino physics studies. The development of neutrino detector setups may lead to discovery of novel phenomena in the realm of particle physics. Large scale neutrino measurement setups will provide a far more comprehensive understanding of the fundamental interactions of nature.

An inverse Compton scattering based X-ray source (CLS) will be constructed to bridge the gap between conventional X-ray sources and synchrotron radiation sources. The state-of-the-art neutron and synchrotron radiation scattering beamlines will be built to carry out research in the strategic areas of science. With the upcoming HFRR reactor at BARC, Vizag, a liquid hydrogen (20K) based cold neutron source will be built with a possibility of high gains (~20) of cold neutron flux.

The national facility for neutron beam research (NFNBR) is operational with 12 beamlines at the Dhruva research reactor, BARC and with 1 beamline in APSARA-U reactor. The neutron residual stress imaging set-up, would provide a non-destructive route for measuring strain and stress deep within engineering components.

At Indus-2, BARC operates 9 beamlines with total 2912 users in last 8 years. Global demand for fourth generation synchrotron with extremely low emittance (~pm rad) & high brightness is increasing and around 3 sources are operational globally at present. An inverse Compton scattering based X-ray source would offer a narrow-band, high flux & tuneable X-ray source that fits into a lab in contrast to large synchrotron sources. Mega facilities of high flux research reactor and 4^{th} generation synchrotron will be game changer for high-end experimental research.

5.1.2 Physics-Based Technologies

Single crystals and liquid scintillator-based radiation detectors, gas sensors, mass-spectrometers & thermoelectric power generators technologies have utilities in various sectors. The full technology for the development of HPGe detector based on Ge single crystal & C_6D_6 based liquid scintillator detector has been taken up to mitigate the requirement of these detectors in DAE. The development of high purity germanium (HPGe) detector is currently in progress. In-house developed NaI:Tl & CsI:Tl single crystal-based detectors were deployed for radiation surveillance during G-20 summit and X-ray baggage scanner, respectively.

Three sensor technologies for H_2, H_2S & a table top static gas sensing unit have been developed & deployed at various user sites including DAE & DRDO and technology is transferred for commercialisation. Various types of mass spectrometers (MS) have been developed in BARC and delivered to users across various DAE units to analyse samples ranging from reactor fuel cycle to heavy water analysis.

The development of micro-electromechanical system (MEMS) technology based, miniaturised quadrupole mass spectrometer aims to provide smaller, faster, cheaper, efficient and portable method of identification of gas/liquids/solids and analysis. A portable miniature quadrupole mass spectrometer through microfabrication techniques is envisaged for in-situ identification of gas/liquids/solids & analysis with wide ranging applications in DAE, medical, space and remote sensing for agriculture. Development of portable miniature mass spectrometers will drastically reduce the time taken for making strategic decisions in the area of isotopic analysis.

Thermoelectric power generator with enhanced efficiency along with a radioactive heat source can be used as a standalone small-scale power source for sensors & detectors located at remote places of strategic importance.

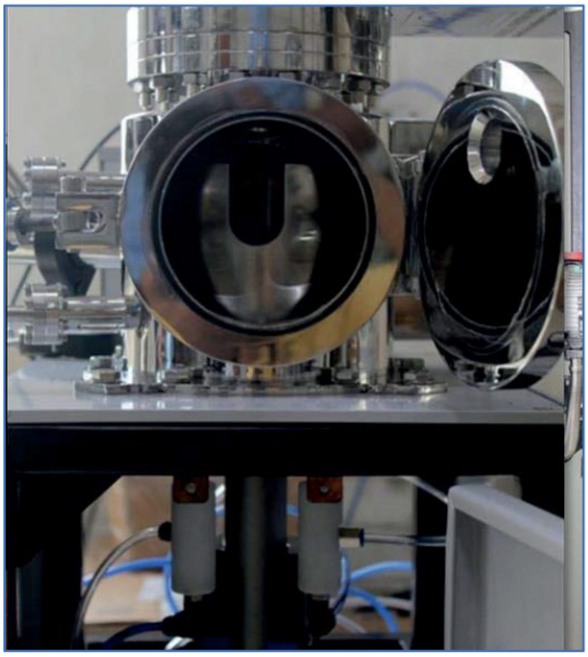
A DAE crystal growth centre for growing large size crystal is proposed at BARC Vizag. A facility for design & fabrication of C_6D_6-based liquid scintillator for detector array for nuclear physics experiments is proposed as a part of this project.

A complete standalone unit is planned for the determination of five gases in mixture present in the environment or the human breath analysis for early disease diagnosis. The indigenously developed electronic nose for gas mixture analysis will be useful for early disease diagnosis and treatment in health care application.

Thermoelectric power generators with high efficiency (≥12%) will be realised through development of high figure-of-merit thermoelectric materials. High efficiency thermoelectric power generators, will save the amount of precious heat sources, such as radioisotopes for niche applications of importance.

5.1.3 Development of Facilities and Technologies for Quantum Computing

Quantum technologies exploit the quantum phenomena, such as quantum entanglement, quantum superposition and quantum state coherence to create new capabilities in quantum computing, communications, and sensing. The ongoing program, "indigenous scalable quantum computing technology" aims to develop a 5-qubit quantum device. Currently 2D and 3D resonators have been fabricated. A design of multi-qubit device based on transmon qubit has been worked out. Setting up of a lab for fabrication of quantum devices and microwave platform equipped with test instruments and electronics is underway. The Government of India announced a national mission covering all areas of quantum technologies. In India, facilities for the development of quantum-computing hardware are located at various places such as, TIFR, Mumbai, which has transman qubits and dilution refrigerator, IIT Mumbai, which has nano scale fabrication facilities, and CeNSE, Bengaluru.



Qubit-Cavity Systems (L) and Double Angle Thermal Evaporation System (R)

Furture activities would include; Quantum material/device development lab, material/device characterisation lab, testing and validation of the qubits, a lab for control line and quantum error corrections and finally a Quantum computer with 100 Qubits. The development of the quantum technologies requires sophisticated tools both in terms of instruments as well as simulations. These include theoretical modelling for the design of qubits coupled with resonators, development of cryogenic systems for quantum technologies and microwave instrumentation.

It is proposed to set up a Centre for Advance Quantum Computing (CAQC) at BARC, Vizag. This centre will have 5 labs (i) quantum material development lab to carry out research on advanced materials relevant for quantum technology, (ii) quantum qubit fabrication lab to fabricate the qubit, (iii) lab for material/device characterisation for the characterisation of quantum materials/devices, (iv) lab for control lines and quantum error corrections for qubit control and error corrections and (v) quantum computer operation lab for the testing, functioning and operation of the developed quantum computer. The plan is to start with aluminium based superconducting transman qubit and then move on to new superconductors such as UTe_2 and hybrid superconductor-based qubit.

Quantum Computing Centre at BARC, Vizag would help significantly in creation of an ecosystem for quantum technologies, research toward quantum computing, communication, and materials research. The development of a quantum computer with 100 qubits will help India to keep pace with the global quantum technology revolution.

5.1.4 Development of Technologies and Facilities for Quantum Information Processing

Photons are considered to be highly attractive option for developing various quantum technologies due to their less sensitivity towards external factors leading to high perseverance of photon qubits over longer time/distance. Development of cold atom qubits, entangled single photon source with high brilliance and purity, and photon qubits is essential for quantum information processing. In India, remarkable progress has been made at research scale, however, only a few photon qubits are yet reported. Development of single photon sources based on SPDC is currently in progress at RRCAT. Fine tuning of the operating characteristics using femtosecond and stabilised CW laser is to be carried out. Cold atoms trapping in optical dipole trap was already demonstrated and trapping of single ^{87}Rb atom in a dipole trap in tweezer geometry is in progress. Studies governed by the quantum mechanical phenomena are reported even on femtosecond timescale. Quantum beating due to the superposition of wave functions of electron and holes in quantum wells is also reported.

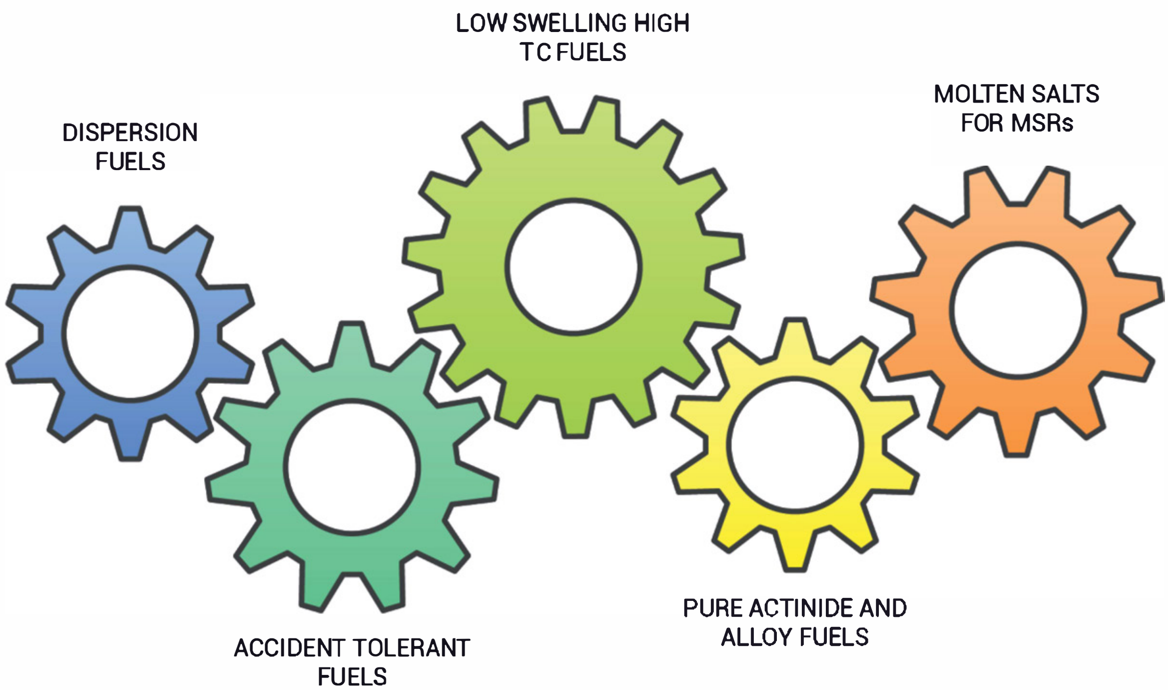
In-house developed capabilities for cold atom trapping will be utilised to trap single atom for preparing quantum qubits. Multiple qubits will be prepared and entanglement among them will be demonstrated by using Rydberg blockade phenomena. In parallel, RRCAT's capabilities in developing advanced lasers and complex optical setups will be exploited for realisation of photon qubits. It is planned to make a quantum computation setup by generating 2 entangled photon pairs. Once the entangled qubits are prepared, quantum gate operations will be performed and testing of quantum algorithm will be explored. Further, preparation, manipulation, and transmission of quantum states will be explored to realise quantum information processing. It is also proposed to build capacity to develop key systems and components such as single longitudinal mode lasers, advanced optics, atom-chips, automation and control systems for the quantum devices. Realisation of quantum gates with unprecedented speed and accuracy, and a successful execution of quantum algorithms are some of the major aims of this programme.

Development of single photon source, cold atom qubits, photon qubits and quantum gates will lead towards Atmanirbhar Bharat in quantum information processing. The development of quantum gates with large number of qubits will lay the foundation for quantum computing technologies and associated applications. Some components such as single longitudinal mode lasers, advanced optics, improvised atom-chips, automation and control systems for quantum devices will be developed as import substitutes. Outcome of this exercise will set the foundation for the realisation of quantum systems involving 50-1000 qubits.

5.2 Chemistry & Material Science

5.2.1 Studies on Advanced Nuclear Materials

Advanced basic research on variety of nuclear materials including nuclear fuels will be of paramount importance for upcoming nuclear reactors during Amrit Kaal. Fundamental studies on these materials at extreme thermal and irradiation regimes will be required to assess their potential as high burn-up safe fuels. Development of innovative nuclear fuels has been among the core competencies of researchers in DAE. Some of the landmark achievements in this direction have been successful deployment of mixed carbide fuels in FBTR, global leadership in thorium-based nuclear fuels development, thorium-based innovative MOX fuels for LWRs etc. With the present thrust on (i) attaining higher burn-ups, (ii) developing accident tolerant fuels and (iii) innovative metallic alloy fuels, generation of indigenous database on physico-chemical properties of these fuel systems continues to be an essential activity.



Emerging fuel systems for futuristic nuclear reactors

The proposed programme focuses on lab-scale development of innovative nuclear materials and in-house generation of reliable database on their physico-chemical properties as a function of temperature, composition, microstructure and porosity. The programme would encompass probing virgin fuels, fuel-fission product interaction phases, SIMFUELS, clad materials and structural materials. A variety of advanced fuel systems namely, accident tolerant fuels, molten salts, metallic alloys, low swelling high thermal conductivity fuels and dispersion fuels will be investigated. Several experimental techniques for probing these fuel systems will be developed during the course of this programme.

Major activities to be taken systematically as targets are:

i. Indigenous standards for H & D estimation in Zr-alloys.

ii. Advanced facilities for chemical quality control in nuclear materials.

iii. Methods for preparation & purification of fluoride salts for MSRs.

iv. Establishment of state-of-the-art laboratory for studies on ultra-high temperature materials (UHTMs).

v. Development of methods for chemical quality control of high burn-up irradiated fuels.

An indigenous database on physico-chemical properties of nuclear materials also will be documented.

The programme will benefit timely and in-house development of advanced nuclear materials in synchronisation with department's pursuit of setting up innovative nuclear reactors and related technologies. Database generated through advanced fundamental research will aid reactor physicists & engineers to develop and assess reliable fuel performance codes for predicting the behaviour of nuclear fuels & related materials under normal & transient reactor operating scenarios. The programme would aid towards attaining a complete Atmanirbhar Bharat in the front-end of the nuclear fuel cycle.

5.2.2 Chemistry of Materials for Molten Salt Reactor Programme

Molten salt reactors (MSRs), which are one of the Generation-IV nuclear energy systems, are among the most attractive options for safe, efficient and sustainable utilisation of thorium. They are now considered as the gateway to the 3rd stage of Indian nuclear programme. Considered as a 'chemist's reactor system,' thorough understanding of chemistry of molten salts reactor materials is crucial for timely demonstration of 5 MWth IMSBR experimental reactor. This first-of-a-kind indigenous development would crucially depend on detailed understanding of chemistry of MSR materials under thermal, chemical and radiative stress conditions that may prevail during IMSBR operation. Early studies on actinide-based fluoride salts and related materials commenced in India during late seventies. It led to pioneering works on preparation, purification and physico-chemical assessment of actinide fluorides, candidate fuel and coolant salt systems in BARC. Valuable indigenous database has been generated on potential fuel and coolant salt systems.

The programme focuses on applied research on fluoride-based salts (fuel, blanket and coolant) and salt-alloy systems. It is also planned to develop in-house experimental techniques to probe various materials envisaged to be used in IMSBR development programme with the objective of minimisation of efforts towards lithium enrichment as well as reduced use of beryllium fluoride (due to its chemical toxicity), invention of Be and Li-lean salt systems for IMSBR is aimed. The programme involves lab-scale preparation & purification of nuclear-grade salt systems, assessment of their physico-chemical properties as a function of temperature and composition, electrochemical studies on salts containing simulated fission products to understand online fuel reprocessing behaviour, development of on-line real-time chemical assay of flowing/static molten salt streams, chemical interaction of such salts with candidate structural alloys (Hastelloy, Inconel, D9, HT9, etc.) and inventing protective coatings to enhance the salt-alloy compatibility. The stage wise developments that would take place are: identification of Be & Li-lean salt systems for IMSBR; determination of solubility limits of actinides in molten salts; demonstration of on-line monitoring in molten salts; indigenous database (thermal, thermodynamic, thermophysical & electrochemical properties) on IMSBR salt systems, and development and assessment of alloys & coatings for IMSBR. The proposed programme will lead to identification of cost-effective fluoride-based salt systems for IMSBR

5.2.3 Materials and Methods for Efficient Back End

The closed fuel cycle approach adopted in Indian nuclear programme involves chemical reprocessing of spent fuel in the back end of fuel cycle to recover fissile & fertile materials as well as valuable radioisotopes.

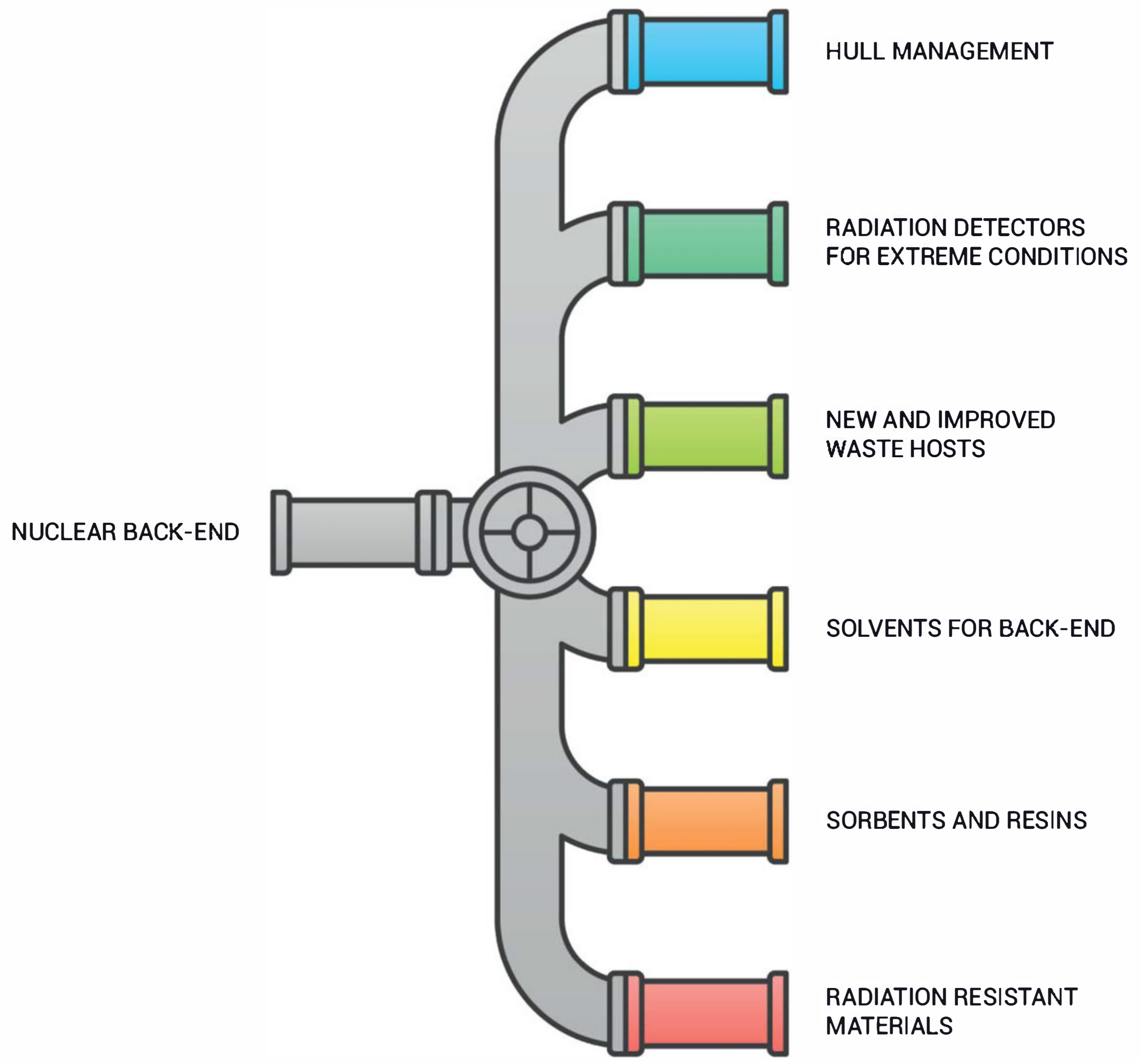
This brings key advantages in terms of

i. Optimum utilisation of fissile and fertile resources

ii. Minimisation of radioactive waste that requires long-term safe storage/disposal

iii. Harnessing the non-power applications of radioisotopes extracted by reprocessing the spent nuclear fuel (SNF).

An efficient back end is therefore essential for closed fuel cycle approach and calls for development of novel materials. Globally, DAE is among the front runners in implementation of back-end technologies at industrial scale. This includes fuel reprocessing, partitioning & separation of actinides, extraction of valuable radioisotopes (^{137}Cs, ^{90}Sr, ^{106}Ru, etc.) and minor actinides (MAs) from nuclear waste, development of suitable chemical forms for their utilisation (in healthcare, industrial and advanced technologies) and, safe management of residual nuclear waste. Embarking on development of chemical processes that aim to separate most of the long-lived radioisotopes, Indian programme on back-end activities is advancing towards ‘minimum waste-maximum wealth’ approach.



Various facets of back-end fuel cycle materials & Technologies

This programme is aimed towards development of chemical for emerging back-end applications and implementation of these in nuclear fuel cycle facilities. It would also address timely development of matrices for zirconium-based hull management. With the objective of minimum radioactivity release in the environment, novel chemical hosts will be developed and implemented. Solvent extraction for efficient and selective separation of various radionuclides, high performance durable solvent systems and glasses, ceramics & glass-ceramic composites will be developed. The future road map consists of thoughtfully structured activities as short term, medium term and long-term targets as appropriate and necessary. These include, indigenous ceramics (castable & machinable) for high temperature application; indigenous host materials for immobilisation of minor actinides; simultaneous extraction (SIMEX) for Cs, Sr & Mas, database on sorption of actinides & FPs in geopolymers and demonstration of radionuclides retention in geopolymers; indigenous glassy waste forms for vitrification of high alpha waste; demonstration of chemical hosts to recover radionuclides (I, Xe, Kr etc.); indigenously developed ceramic core-catcher materials for Indian NPPs; large-scale implementation of developed sorbents; development of matrices for hull management; durable solvents & processes for their environment-friendly degradation; and phosphate waste hosts for high burn-up fuels and fluoride-based nuclear waste.

The major benefit of this programme will be realised in terms of development of new materials and relevant to emerging back-end requirements of Indian nuclear programme. Identification of suitable hull management strategy is envisaged to be one of the major anticipated outcomes. Advancements in back-end technologies will be governed by innovations in related materials and would take us towards near-zero release of artificial radioactivity emanating from overall nuclear fuel cycle and related facilities. Enhanced indigenisation of back-end technologies would help attaining Atmanirbhar Bharat in core sectors such as energy security and sustainability.

5.2.4 Group Actinide Separation (GANSEP) with High Level Waste (HLW)

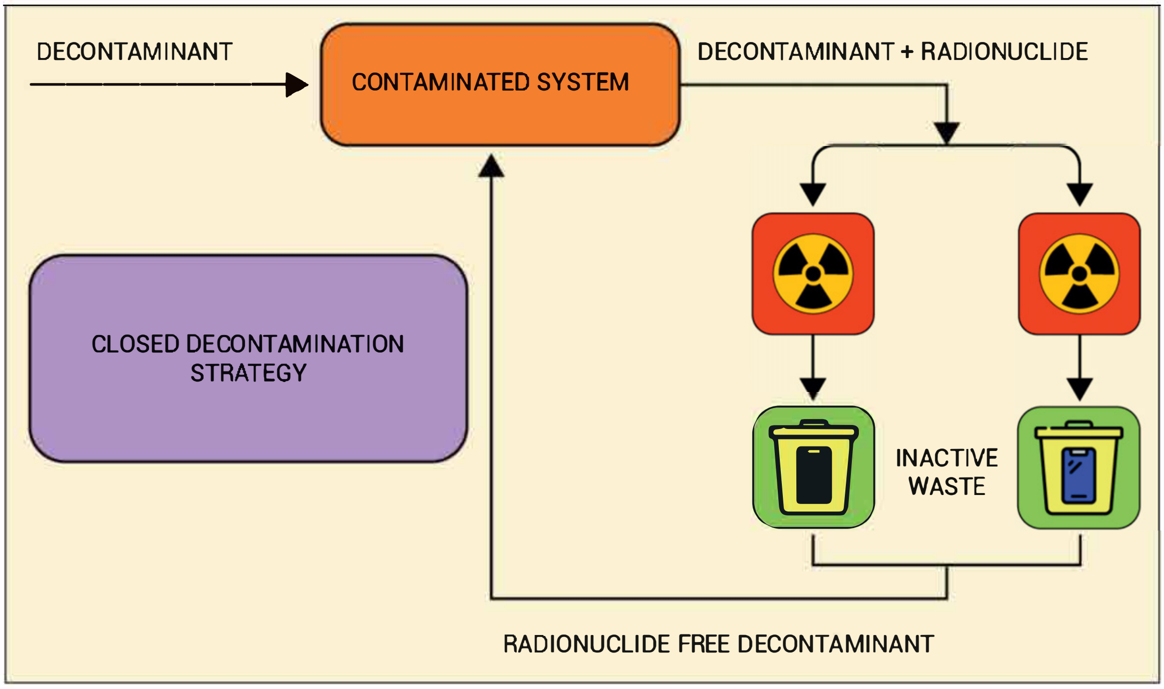
Separation of actinides individually or in group is challenging due to their close and complicated chemistry in the solution phase. Their separation is important for the safe management of the nuclear waste. DGA-based processes (being evaluated worldwide) are promising for group actinide separation but still not implemented due to number of issues, including choice of phase modifier and radiation stability. Moreover, they cannot extract fission products such as Cs or Sr. Individual actinide separation, more specifically Am/Cm separation, is still challenging where poor selectivity is reported with various class of ligands. Selective oxidation-based separation of Am and Cm shows promise with respect to selectivity, but choice of oxidant is an issue for the process suitability. Herein, it is proposed that new materials will be synthesised and explored for selective oxidation and complexation for targeted actinide ion thereby increasing the selectivity.

Extractants will be designed and developed for the extraction of actinides as a group or individually (GANSEP or GIAS) or simultaneous extraction of actinides and troublesome fission products (SIMEX) through computational and experimental studies at the lab scale. New materials will be explored for selective oxidation/reduction of a targeted actinide to achieve improved selectivity. Extractants with promising separation behaviour will be synthesised at larger scale for the development of the flow sheet for the separation from the actual waste solution. Efforts will be directed towards the understanding of unusual oxidation states of actinides to achieve higher selectivity for a targeted actinide ion. Lab-scale studies on complexation and separation to optimise the process parameters, radiation stability and flow sheet development will be followed by large scale synthesis and demonstration with actual HLW.

R&D for the GANSEP, GIAS and SIMEX will benefit the management of long-term radioactive waste, more specifically minor actinides, which is unavoidable for the sustainability of the nuclear power programme and for the long-term energy security. Moreover, some of the actinide isotopes when separated individually can be useful for other specific and important national programmes.

5.2.5 Development of Decontamination: Current Status and Way Forward

With 22 operational NPPs and 19 NPPs under implementation, the Amrit Kaal period would witness progressive efforts towards lifecycle management of NPPs and associated nuclear facilities. While decommissioning campaigns of large-scale NPPs would begin beyond Amrit Kaal, timely development of decommissioning strategies is the need of the hour for national decommissioning policy. It is envisaged to develop decommissioning strategies in closed-cycle with retrieval of valuables and minimum generation of waste. Notable experience has been gained over past five decades on chemical decontamination of coolant circuitries as well as research-scale nuclear facilities. Lab-scale R&D efforts have been directed towards various decontamination strategies. Decontamination of complex shaped radioactive surfaces has also been explored with the use of foams and gels as well as plasma-based methods.



Envisaged closed decontamination strategy

The programme will focus on lab-scale development of decontamination strategies, which will combine physico-chemical, electrochemical, laser- and plasma-based methods. Matrices & sorbents will be developed for selective & specific uptake of radionuclide contaminants. Based on the results of lab-scale studies, decontamination campaigns on small nuclear facilities, whose lifecycle is over, will be carried out to generate database on the extent of recovery of valuables & waste volume generated. Such database will help in laying down the roadmap for

India specific decommissioning policy for nuclear facilities. However, the long-term goal is to development and demonstration of closed decontamination strategy.

Directed lab-scale R&D activities on chemical decontamination will benefit in terms of generation of valuable database on the efficiency of different decontamination methods. Indigenous process will be available and overall outcome of this programme will aid towards laying out a roadmap for national decommissioning policy for large-scale nuclear facilities in India.

5.2.6 Water Chemistry under Extreme Conditions

Chemistry of water at elevated temperatures & pressures in presence of ionising radiation fields, and water-structural alloy interaction is of paramount importance in nuclear technology. With future reactors aimed to operate under super-critical water (SCW) conditions, it is utmost important to carry out systematic research to understand material behaviour under these conditions. Chemistry of materials under SCW conditions has been less understood and directed research towards this aspect is essential to develop materials that are compatible under high temperature-high pressure regimes close to SCW. Studies on material behaviour under high temperature water & steam environment has a rich legacy in BARC. Extensive research on this subject, focused on currently operating PHWRs and LWRs in India, have led to reliable evaluation of materials used in coolant circuitry (both primary and secondary). It has also led to the development of suitable materials and coatings, which can passivate the coolant flow alloy surfaces and prevent / slow-down their corrosion under high temperature-high pressure water/steam environment.

A dedicated research facility that can attain SCW conditions as well as to in-situ simulate the effect of ionising radiations on water/stream chemistry is envisaged in this programme, wherein behaviour of large number of materials can be investigated to assess their performance potential under SCW conditions. The setup will also be equipped with (i) provisions to in-situ generate oxidants & radicals (thereby approaching the effect of reactor irradiation on water chemistry), (ii) partial boiling facility (to mimic 700 MWe PHWR scenario) and to study the material behaviour in presence of both SCW and oxidants and/or radicals. Based on the results obtained on presently used structural materials (e.g., coolant tubes) under SCW conditions, passive coatings as well as modified alloys will be developed for future NPPs. Extensive scientific database will be generated on physico-chemical properties of coolant circuit alloys under SCW conditions.

Results obtained from proposed studies on nuclear reactor alloys under SCW conditions will benefit in terms of enhanced performance and extended material life-cycles. Coatings developed to passivate such alloys from corrosion under SCW conditions will also help towards improved aging management of SCW-based fossil-fuelled thermal power plants.

5.2.7 Development of Materials for Laser and Accelerator Technology

Indigenous development of single crystals and special, electron emitter, variety of radiation detection materials for X-ray, electron, proton & H^-, X-ray monochromator and materials for non-evaporable getter pumps are important for the accelerator development programmes. Similarly, devices for second harmonic generation and electro-optical modulation and gain medium are crucial for laser development programmes. In view of this, several technologically important materials to be used for laser gain medium, harmonic generation, electro-optic modulation, electron generation, high energy radiation detection, actuation and non-evaporable Getter pumps are to be developed. RRCAT has been involved in the development of single crystals and ceramics since its inception. It has designed and developed multi-zone furnaces, water-bath with extremely high thermal homogeneity and stability, accelerated rotation unit, automatic diameter controlling crystal pull-head. The required state of the art crystal growth technologies like solution growth, Czochralski, Bridgman and float zone method have been developed and are being used to grow single crystals of conventional and deuterated potassium dihydrogen phosphate (KDP and DKDP), ortho-vandates, potassium titanyl phosphate, etc. The proposed programme focuses on development of technology for growth / fabrication of single crystals and ceramics for applications related to on-going and proposed activities of laser and accelerated programmes.

Development of the materials are integral to the in-house laser and accelerator programme at RRCAT. Growing of the largest KDP crystal (160 mm × 155 mm × 120 mm; 5.5 kg) has been carried out at RRCAT. In addition, several functional ceramics like Ce-doped YAG, PZT, etc. have also been developed. For the high energy laser program, large size electro-optic and SHG elements of KDP crystal are indispensable, which must be grown indigenously. For development of solid-state lasers, Ti-sapphire, Nd, Yb-doped garnets and vandates, etc. will be grown by Czochralski method. LaB_6 & CsB_6 single crystal will be grown by floating zone technique. For radiation detection application in accelerator technology, single crystals of Ce-doped garnet, 3PB along with trans-stilbene crystals/composites will be developed. Technology for development of bent acid phthalate crystals for X-ray monochromator & plasma diagnostics, DAST & periodically poled niobate crystals for integrated opto-electronics & THz generation, lead zirconate & lead-free piezoelectric for actuation, and materials for non-evaporable getter pumps will be developed. This programme will help to make Indian laser and accelerator programmes Atmanirbhar. Further, the development of lead-free piezoelectric will reduce the environmental impact of lead-based material by substituting them with a better choice in terms of lead pollution.

5.2.8 Development of Technology for Recovery of Helium

Worldwide helium is recovered from natural gas where concentration is as high as 2.7% (by vol.). However, in India helium concentration in natural gas is as low as 400 ppm and its recovery directly from natural gas may not be economical. Therefore, alternate sources of helium, such as purge gas of ammonia-based fertiliser plant, have been explored by HWB across the country with encouraging results. HWB has analysed helium in purge gas stream and concentration as high as 1.5% has been obtained. Helium gas was not detected in the purge gas of fertiliser plants, which use imported natural gas. Therefore, fertiliser plants operating with Indian natural gas are targeted to be potential secondary source of Helium. KRIBHCO and HAZIRA fertiliser plant has untapped potential to supply enough Helium gas to meet the annual demand of DAE. Further, other ammonia-based fertiliser plants, which are operating with Indian natural gas, can contribute to supply of Helium gas for commercial requirement. It is proposed to set up a technology demonstration plant for helium recovery at HWB facility, Manuguru with a feed flow rate of 5 Nm^3/hr. A technology demonstration plant of 2 Nm^3/day capacity is being set up at HWBF-M for He recovery from purge gas. In the proposed facility, artificial gas mixture (similar to purge gas composition of KRIBHCO and HAZIRA plants) will be prepared to demonstrate the technology for recovery of helium from purge gas stream. After successful demonstration, the facility will be shifted to KRIBCHO, HAZIRA for process validation with original purge gas.

A first of its kind technology demonstration plant for recovery of helium from purge gas, which includes separation of hydrogen and helium using cryogenic adsorption will be operated. This programme will reduce helium imports in the country. Such industrial scale facilities will meet commercial helium demands of the nation to a significant extent.

5.2.9 Development of Lead-Free Polymer Nanocomposite-Based Radiation Shielding Materials

This programme envisages the development of shielding materials against X-rays, gamma rays and neutrons for the personal protection of radiation workers. It would help in enhancing the technical know-how of the development of lead-free hybrid shielding materials and commercialisation of indigenous products, with wide applications in the medical and other fields. The objective of this programme is to replace the existing lead-based shielding materials with lead-free polymer based shielding materials for personnel protection. The programme would involve the study of the suitability of multi-filler nanocomposites as personel protective garments and as cable sheathing. In-house synthesis of nanomaterials, development of polymer-based nanocomposites and optimisation studies are of high importance.

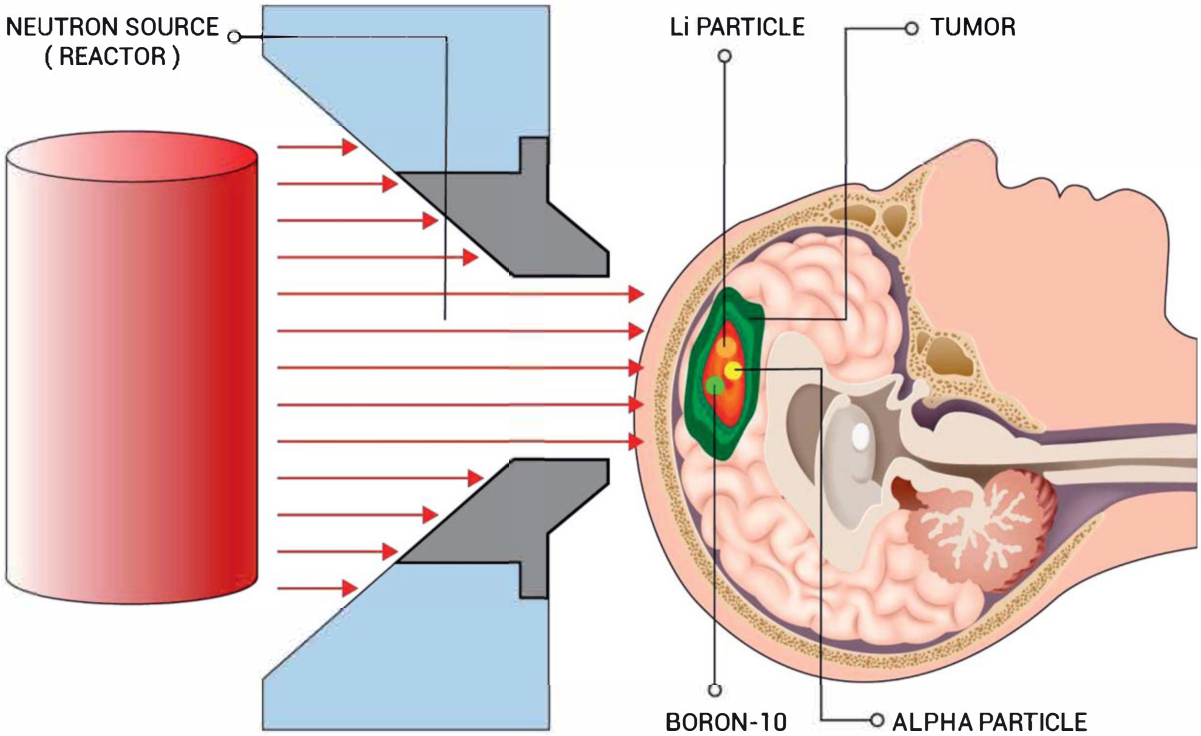
Development of lead-free shielding materials against diagnostic X-rays (30-125 keV) is in progress, where the preliminary screening of silicone polymer as matrix is completed along with the standardisation of nanocomposite preparation. Multi-filler polymer nanocomposites developed here have been compared with standard lead specimen to estimate the suitability of these lead-free materials for practical applications. Material characterisation, dermal compatibility studies and the fabrication of these nanocomposites into the desired end-product would also be carried-out. Comparative studies with existing shielding materials would be performed. Stepwise road map include large scale development of nanocomposite sheets for diagnostic X-rays and dermal toxicity and sensitisation studies; multifiller nanocomposites for shielding of gamma rays and neutrons; and demonstration & deployment of multi-filler polymer nanocomposite for effective shielding of multiple radiation

Successful completion of the above projects would lead to the indigenous development of materials and processes for the preparation of lead-free polymer nanocomposites for radiation shielding applications. Specific benefits are indigenous development of materials and processes leading to import-substitute, and cost-effectiveness.

5.3 Biology

5.3.1 Novel Strategies for Cancer Radiotherapy

Utilisation of ionising radiation is one of the prominent ways towards healthcare applications in general and advanced cancer care in particular. Targeted irradiation of cancerous region is emerging as one of the most promising approaches that have minimal impact on non-cancerous regions. Boron neutron capture therapy (BNCT) is among such options, which is distinct from conventional radiotherapy and is being developed as a next generation cancer treatment option. For BNCT's success, targeting boron-based materials to the tumour site is essential and development of clinical-grade neutron sensitisers is required. Inventing clinical-grade therapeutic formulations utilising the blend of B/Gd-based compounds with conjugating receptor-based ligands is the need-of-the hour for success of targeted radiotherapy options such as BNCT or gadolinium neutron capture therapy (GNCT). Boron-based materials, and their clinical-grade formulations that can be targeted to specific tumour site, will be developed. These targeted neutron radiosensitisers, which will primarily be based on conjugating receptor-based ligands with boron-doped materials will be developed. Based on radiation biology studies, these materials and therapeutic formulations will be optimised in a manner so as to minimise their uptake by the non-cancerous (normal) cells. Development of therapeutic solutions will be demonstrated for clinical usage.



BNCT (Boron Neutron Capture Therapy)

Lab-scale studies are presently underway to develop various nanoparticle-based as well as other formulations for the purpose of effective BNCT for different types of cancer. Development of therapeutic solutions for brain tumour is being given major emphasis owing to inability of conventional therapeutic approaches to easily cross the blood-brain barrier. Comprehensive radiation biology studies, information on which, are relatively scarce at present, are also essential towards this emerging approach of cancer care. Development of targeted "neutron radiosensitisers" based on conjugating receptor-based ligands with B-doped materials that have minimum uptake by normal cells is the final goal of the program. Indigenous clinical-grade therapeutic formulations for targeted cancer care will be a major outcome of the programme.

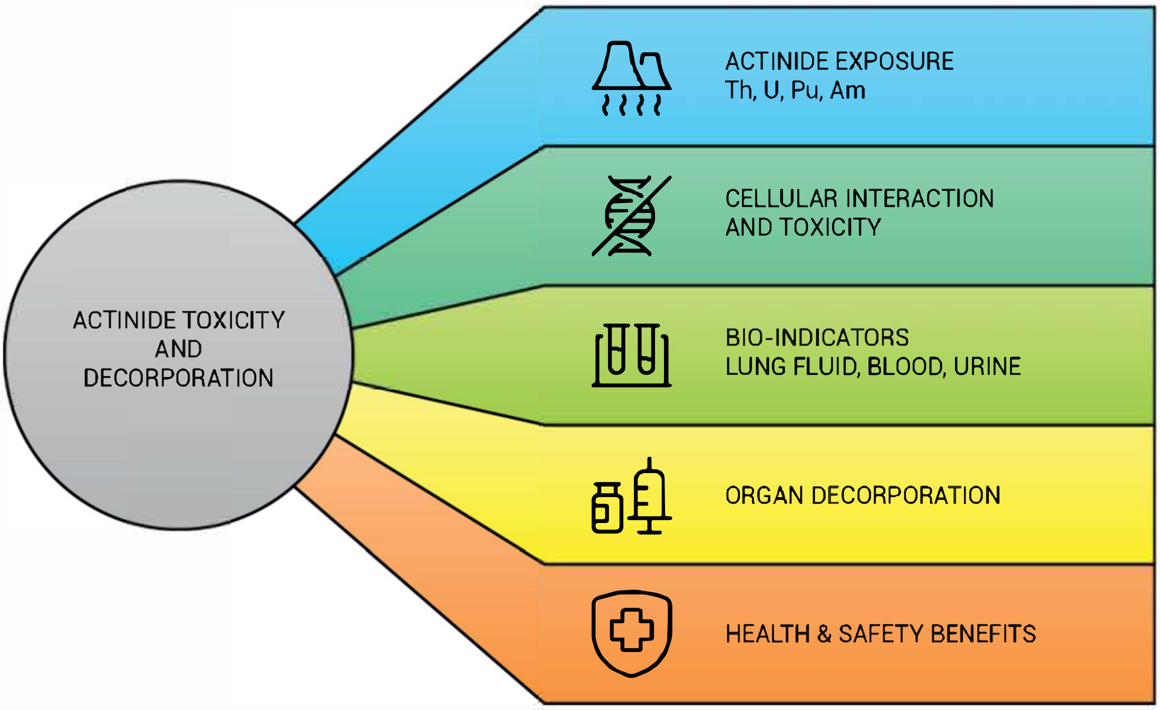
5.3.2 Research and Development towards Advanced Cancer Therapy

Cancer is rapidly emerging as a significant health concern both, in India as well as globally. Early detection, accurate stage-diagnostic and strategizing optimum treatment protocol through combinatorial chemo- and radiotherapy approaches is currently being followed for cancer treatment. While ionising radiations are being used for cancer diagnostics as well as therapy, the mechanism of cancers' radiation resistance is poorly understood. Study of cancer specific epitranscriptome signatures and its role in cancer progression and radiation resistance can help further such understanding and is therefore, the central aim of this research programme. Research on cancer specific epigenetic dysregulation is an important step needs to be addressed.

Fundamental studies are being carried out currently that are aimed to understand the epigenetic response of cancerous cells towards ionising radiations. Advanced research will be carried out herein by epigenetic remodelling and enhancer reprogramming associated with cancer and radiation resistance. The insights obtained from such studies will be utilised for developing improved breakthrough therapeutics and cancer care strategies. Major goal is to establish the epitranscriptome signatures in cancer radio resistance and identification of probable therapeutic potential. Breakthrough therapeutics development on the basis of fundamental understanding of radiation resistance mechanism of cancer cells is expected through this directed research programme.

5.3.3 High LET Radiobiology in Healthcare

Energetic charged particles, collectively referred to as hadrons are rapidly being explored for targeted radiation therapy of cancer. These particles have high linear energy transfer (LET), which imparts distinct radiobiological effects upon interaction with living cells. Studies on radiobiology of high LET radiation-living cell systems is important for advanced cancer care, as well as understanding the effect of such radiation on space astronauts. Such studies also provide valuable basis on the potential of actinide (^{227}Th)-based alpha radiotherapy. The programme will include development of proton microbeam and biomarkers for actinide exposure & countermeasures. The existing infrastructure will be used for radiobiological studies on charged particle-living cell interaction systems.



Bio-indicators of Actinide Toxicity & Decorporation

While fundamental studies on the effect of high LET radiations on biological systems have been ongoing for few years, state-of-the-art proton microbeams are yet to be established to specifically understand the radiobiological responses of living cells. Thus, indigenous proton microbeam and biomarkers for actinide exposure will be developed for implementation of high LET radiation-based in cancer therapy. The research will result in fundamental understanding of radiobiology of charged particles on cancer cells and affordable healthcare & societal benefits of atomic energy technologies.

5.3.4 Anti-biofilm Agents for Nuclear Technologies

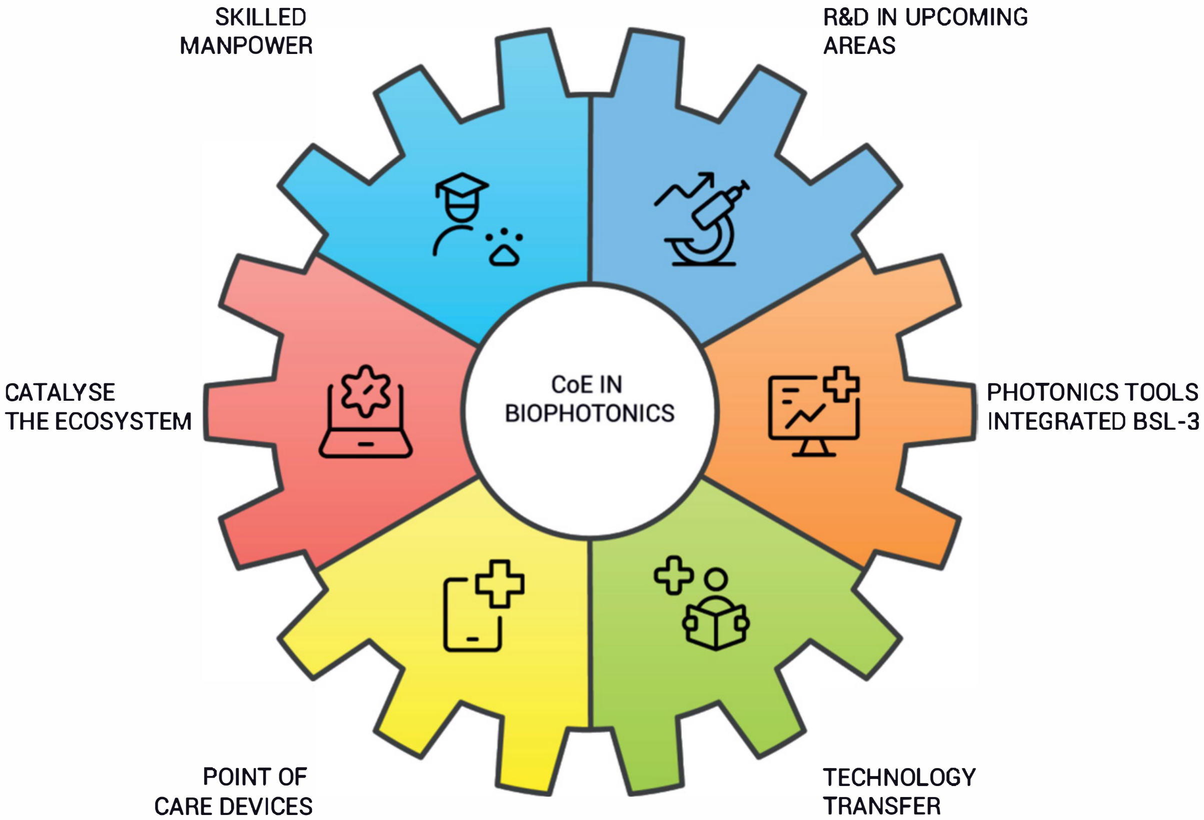
Power plants utilise large volumes of water for cooling purpose, which is sourced from natural reservoir and then released back. Biochemical interactions among source water constituents (minerals, dissolved gases, aquatic biodiversity etc.) under variable temperature and flow conditions cause biofouling, which leads to formation of biofilms as well as macro-fouling. Biofilms can be both, detrimental (industrial and medical biofilms) and beneficial in nature. Biofilms are the dominant microbial lifestyle, and the microbes present in such biofilms show much greater (>10 times) tolerance to antimicrobials. To minimise biofouling in secondary (or tertiary) cooling streams of NPPs, anti-biofilm (AB) formulations are required. The proposed activity aims to indigenously develop novel anti-biofilms and related materials for futuristic nuclear technologies and spin-off societal benefits.

Extensive research over past few decades have led to notable progress in understanding of biofouling, its causes and strategies to minimise it for normal operation of NPPs. This has led to significant progress in minimisation of steam generator fouling to maintain better heat transfer efficiency in secondary circuits, understanding biofouling and its control in tertiary cooling water circuits to avoid condenser tube material failure. Such studies have also advanced environmental sustainability of operational NPPs.

As part of this programme, anti-biofilms (AB) and anti-larval formulations will be developed and deployed at various NPP sites. AB coatings will be developed for both, nuclear reactors, fossil-fuel based thermal power plants and maritime applications. Utilising the research outcome of this programme for societal benefits, AB materials and formulations will be developed for wound healing and topical applications, etc. through biofouling research and deployment of spinoff technologies for societal benefits. The major goals are: demonstration and deployment of AB-based solutions for power plants and establishing the phage bank of India, providing database for research and clinical applications throughout India.

5.3.5 Establishment of Centre of Excellence in Biophotonics Research and Development

Ongoing extensive research on biophotonics has translated to various photonics-based point-of-care (PoC) devices for disease diagnosis and therapy worldwide. However, in India, biophotonics related research is scattered in various universities and research organisations. Currently, there is no dedicated centre for focused research on biophotonics in the country. The proposed centre of excellence (CoE) will aid to generate multi-disciplinary facility and expertise under one roof for carrying out globally competitive research in thrust areas of biophotonics. Establishment of a CoE will strengthen biophotonics R&D, for deeper understanding of diseases & infections directed towards the development of novel diagnostics & therapeutics, in upcoming areas like optogenetics, regenerative photomedicine, and photonics based multiplex diagnosis, etc. for lab-to-clinic translation for healthcare and societal applications.



Planned Activities for Centre of Excellence in Biophotonics

Development of cost-effective, hand-held, personalised optical theranostics devices for fluorescence-based detection and concurrent photodynamic therapy of oral cavity pathologies and drug resistant pathogen wound infections prevalent in the country will be undertaken at the CoE. The developed know-how and technology of the PoC devices will be transferred to Indian industries. This CoE will serve to catalyse the ecosystem for development of skilled manpower and industry-academia collaboration by providing access to advanced biophotonics facilities. Establishment of CoE in Biophotonics Research and Development (CBRD) will ensure globally competitive research in emerging fields of biophotonics for a deeper understanding of diseases and infections directed towards development of novel diagnostics and therapeutics. One of the major scope of activities under CoE involves development of a bio-safety level-3 (BSL-3) laboratory integrated with animal house, optical spectroscopy and optical micromanipulation, phototherapy facilities, which will cater to research on infections caused by multidrug-resistant and newly emerging pathogens.

The multidisciplinary R&D efforts thus far have resulted in the development of PoC photonics devices for cancer diagnosis, namely oncodiagnoscope, tuberculoscope and oncovision. Various PoC devices for photodynamic therapeutic applications in nasal, oral and wound infections have also been developed in collaborative incubation with industrial partners. One such device "Nasolight™," is currently available at an online webstore. Further, field deployable devices like *in-situ* Raman measurement probe have been developed.

The various stages of activities include:

i. Development of biosafety level-3 laboratory, optical theranostics, development of edible and/or inhalable light-activable drugs.
ii. Integration of optical technologies with BSL-3 facility and clinical validation of optical theranostics prototypes.
iii. R&D on multiplex diagnostics, optogenetics, and regenerative photomedicine, technology transfer, certification and field deployment of optical theranostics devices, development of phototherapeutic approaches/ devices for management of lower respiratory tract infections and clinical validation of edible and/or inhalable light-activable drugs.
iv. Technology transfer & field deployment of multiplex diagnostics devices.
v. Photonic biomaterials and clinical translation.
vi. Multi-centre clinical trials of PoC devices and/or drug formulations.

5.4 Health Physics

5.4.1 Fundamental studies on effect of low dose at low dose rates on living systems with a special focus on quantum processes

At low levels of radiation doses, there is uncertainty regarding the purported health effects. At present linear no threshold (LNT) theory is used to explain these health effects from radiation dose, which essentially states that every radiation dose has a certain health risk and there is no threshold. This is in-spite of adaptive biological processes contrary to this theory. However, arguments supporting adaptive responses encounters limitations similar to those of LNT principles - namely small cohort sizes and a focus on lower organisms. Here quantum biology presents a promising framework to understand these biological responses. This could bolster empirical evidence for adaptive responses, and advocate for a hormetic or threshold radiation paradigm, which in turn would have beneficial applications for the nuclear industry. The proposed programme will be a pioneering exploration into the molecular complexities of adaptive responses and hormesis under chronic low doses of radiation exposures.

Quantum biology is a nascent field with only a handful of researchers globally. The current focus in this domain is on understanding various biological phenomena such as photosynthesis, olfaction, magnetoreception etc. There is no concerted research in this domain towards understanding biological processes arising out of chronic low dose radiation exposure. Leveraging state-of-the-art quantum mechanical models, this programme aims to adopt an open quantum systems approach to decode experimental observations. Molecular investigation into low-dose radiation effects, including cellular dynamics, antioxidant status, DNA repair/mis-repair etc will be carried out and open quantum systems approach will be employed to understand experimental findings. The programme will result in creation of a reduced environmental dose rate laboratory that may be used even for other low background studies, not related to quantum biology. One of the direct outcomes expected from this research are new insights into cellular-level mechanics of adaptive response. Indirect outcome expected is the creation of a potential dose threshold, which in-turn would lead to optimised regulatory requirements.

5.4.2 Up-gradation of existing "Secondary Standard Dosimeter Lab, SSDL" to the "Primary Standard Dosimeter Lab, PSDL”

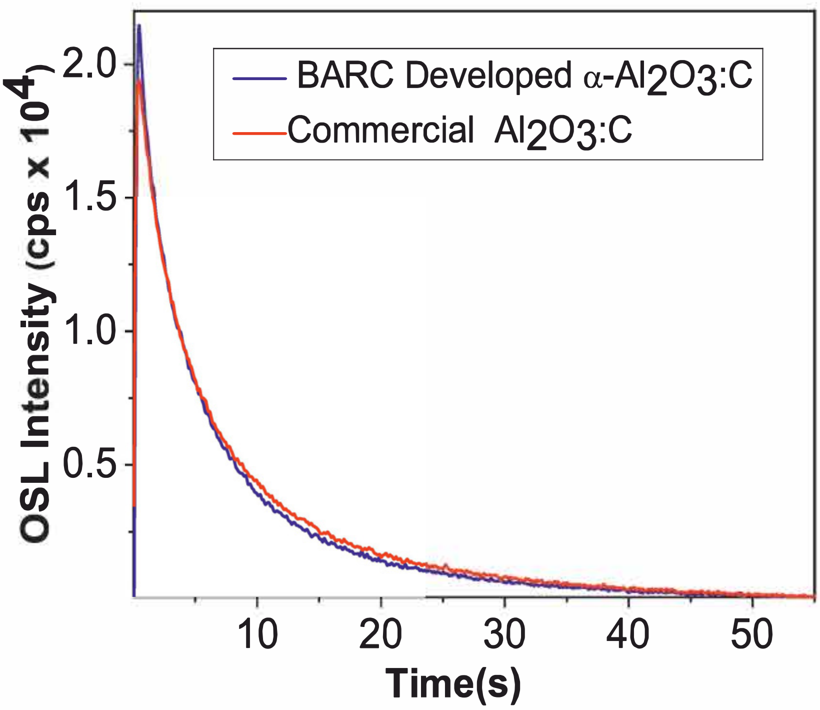
The terms secondary standard dosimetry lab (SSDL) and primary standard dosimetry lab (PSDL) are used by International Atomic Energy Agency to refer to the standards available in a laboratory for measurement of absorbed dose to water. Absorbed dose to water is the quantity of main interest in radiation therapy, since this quantity relates closely to the absorbed dose to human body. PSDL uses a well-established procedure for measurement of absorbed dose to water using measurement standards either using ionometry method or calorimetry (water or graphite calorimetry). Whereas, at SSDLs, standard ionisation chambers are used as secondary standards which is calibrated against a primary standard, maintained by a PSDL or the Bureau International des Poids et Mesures (BIPM) whose calibration is thereafter transferred to hospital users by means of unbroken chain of calibrations.

The programme focuses on the establishment of a standard for the measurement of absorbed dose to water using appropriate base or derived quantities. The establishment of the standard along with participation in intercomparisons with other PSDLs will make the laboratory eligible to be recognised as a PSDL. The activity has to be peer-reviewed and approved by APMP approved technical and quality system experts for the publication of calibration and measurement capability (CMC) in KCDB, according to the provisions of the CIPM mutual recognition arrangement (CIPM MRA).

The graphite calorimeter developed by Domen and Lamperti, NIST with certain modifications, is used to determine the absorbed dose to graphite in a graphite phantom. The conversion to absorbed dose to water at the reference point in a water phantom can be performed by application of direct Monte Carlo calculations. The ionometry primary standard consists of an air-filled graphite cavity chamber with known cavity volume, designed to fulfil as far as possible the requirements of a Bragg–Gray detector. The chamber is placed in a water phantom and the absorbed dose to water at the reference point derived from the mean specific energy imparted to the air of the cavity. The infrastructure of the laboratory has to be augmented to allow establishment of new state of the art facilities. This will obviate the dependency of BARC on BIPM for periodic calibration of BARC's secondary standard dosimeter. In addition, BARC will be able to provide traceable calibration to radiotherapy centres of India and SSDLs of other countries.

5.4.3 Migration to OSLD-based Individual Monitoring of Radiation Workers

Optically stimulated luminescence (OSL) is a phenomenon observed in crystalline solids, which can be either insulators or semiconductors. In this process, these materials emit light when stimulated after being previously excited by ionising radiation. The development of the highly sensitive dosimetric material α-Al_2O_3:C has significantly advanced OSL technology, making it widely utilised in various dosimetric applications like personnel monitoring, environmental monitoring, clinical dosimetry etc.



OSL Decay Curve for Al_2O_3:C

OSLD Badge

This has led to a global transition from thermoluminescence (TL) to OSL-based dosimetry. In India, indigenously developed $CaSO_4$:Dy based TL dosimetry technique is being used for personnel monitoring. This programme is about migration to OSLD from TLD based individual monitoring of radiation workers. Migration to OSL-based PM programmes promise increased throughput, crucial for expanding nuclear technology. Introduction of OSL discs under a metallic mesh distinguishes static or dynamic exposures, elevating radiation monitoring accuracy. OSLD badge has four elements with different filter combinations to discriminate between beta, X-ray and gamma components. Dose evaluation algorithm for estimation of Hp (10) and Hp (0.07) for OSLD badge has been chalked out. The system has promising features that offers fast readout, high throughput and inherent simplicity. OSL dosimeters' cost-effectiveness, owing to better reusability, positions BARC's innovation as a sustainable solution.

In the past, Landauer Incorporation, US had the exclusive expertise for synthesis of OSL grade Al_2O_3:C crystals. BARC has developed Al_2O_3:C with sensitivity at par with commercially available material using melt processing technique that is protected through a US patent. To achieve successful personnel monitoring (PM) programmes, 100% indigenisation and self-reliance are crucial criteria. BARC has developed expertise in development of highly sensitive Al_2O_3:C powder, dosimeter discs, OSLD badges, and associated instrumentation like badge reader system, bleaching set up etc. These are essential components of OSLD based PM program. Major steps as conceived for the success of this program are:

i. Synthesis of Al_2O_3:C phosphor, formulation of dose estimation algorithm and field trials of OSLD badge system (including regulatory clearances).
ii. Demonstration of large-scale synthesis of Al_2O_3:C for technology transfer.
iii. Implementation of OSLD based PMS in DAE & non-DAE facilities.
iv. other applications of OSLD (space, medical, etc.).

Migrating from TL to an OSL-based PM programme promises increased throughput, ensuring precise and rapid dosimetry for a substantial number of radiation workers. This becomes especially crucial during the expansion of nuclear energy programme. Further, owing to the avoidance of heating, OSL dosimeters exhibit superior reusability, establishing this method as a cost-effective solution in the long run. The integration of OSL discs beneath a metallic mesh introduces a capability to discern whether radiation exposure is static or dynamic, making the programme more versatile.

5.4.4 Space Radiation Dosimetry

In the challenging realm of space dosimetry, individual dose monitoring for astronauts becomes essential due to the intricate radiation environment they face. Galactic cosmic rays (GCR), solar particle events (SPEs), and Earth's radiation belts contribute to this complex field. Secondary particles, originating from nuclear interactions, further impact individual doses. Evaluating the total absorbed dose proves challenging, necessitating consideration of relative biological effectiveness (RBE) or quality factor (Q). The goal is to estimate absorbed doses for various forthcoming and future Indian missions by ISRO using indigenously developed passive dosimeters and tissue equivalent proportional counters (TEPC). Using indigenously developed TL/OSL-based dosimeters and CR-39 solid-state nuclear track detectors (SSNTDs), the programme assesses low and high LET radiations. Simulation work using FLUKA and HZETRN codes estimates critical doses in low earth orbit.

Prototype TEPC Assembly 1.5 Kg full weight

The space dosimetry programme represents a pioneering effort in developing advanced dosimetry solutions for space missions, addressing the complex radiation environment faced by astronauts. Through multifaceted approaches, the programme aims to enhance understanding of space radiations, ensuring accurate assessment and safeguarding the health of astronauts during their missions.

Simulation work has been initiated using FLUKA and HZETRN transport codes as per Badhwar-O'Neil 2014 model for estimation of critical organ dose and effective dose for human. The simulation is carried out by mimicking cosmic ray environment at low earth orbit (LEO) for astronaut typically at 300-400 km from earth surface for both low LET and high LET particles. The wall material of spacecraft is considered as aluminium and thicknesses were chosen in the range of 2.5 to 7.5 cm. Preliminary study indicates that total effective dose were in the range of 0.40 to 0.57 mSv/day depending upon the thickness of the spacecraft body. For heavy charged particle, experimental work has been initiated to correlate the track parameter of CR-39 detector with LET of charged ions using the accelerator facilities available in India.

The space dosimetry programme yields advanced dosimetry technology, developing TL/OSL-based dosimeters and utilising CR-39 SSNTDs for precise assessment of low and high LET radiations in space. Creation of calibration and response curves ensures tool reliability, enhancing dose measurement accuracy. A robust dose assessment is formulated, applicable to individual and cumulative astronaut doses. The program's outcomes include the development of active dosimeters, improving real-time monitoring, and ultimately enhancing safety measures for astronauts during space missions.

5.4.5 Development of Advanced Simulating Tools for Predicting Spread of Radioactivity through Air, Surface Water and Ground Water

Environmental models to predict dispersion of radionuclides in different environmental media are essential tools for a nuclear facility. It helps in deriving authorised discharge limits for the facility, and support as well as guide in case of accidental releases. The models used for authorisation purposes are simple and conservative, whereas models required in case of accidental releases are complex and account for spatial and temporal variability of governing parameters which could be very important in optimising the counter measures and handling the emergency situation in a better way. For such applications, it is proposed to develop multi-scale atmospheric dispersion modelling system which will cover local, regional and global scale. Proposal also aims at developing numerical models for surface water and groundwater modelling studies.

The Lagrangian modelling approach for atmospheric dispersion modelling is quite popular and many such models are available internationally such are CALPUFF, RIMPUFF, FLEXPART, HYSPLIT etc. At BARC also, Lagrangian based models have been developed such as EDPUFF, Particle Trajectory Model, and ADOCT. However, some of these models are not specifically developed for radionuclides, and almost none of these models provide comprehensive radiological impact assessment. Under this programme, initially, Lagrangian puff based atmospheric dispersion model will be developed for local scale atmospheric dispersion studies. This developmental activity will be followed by development of Lagrangian particle trajectory-based model utilising NWP model data for regional atmospheric dispersion studies. Subsequently, a particle trajectory-based model will be developed for global dispersion of radionuclides/pollutants. Finally, it is envisaged to have auto mode operation, as well as radiological and meteorological data assimilation in the developed modelling system.

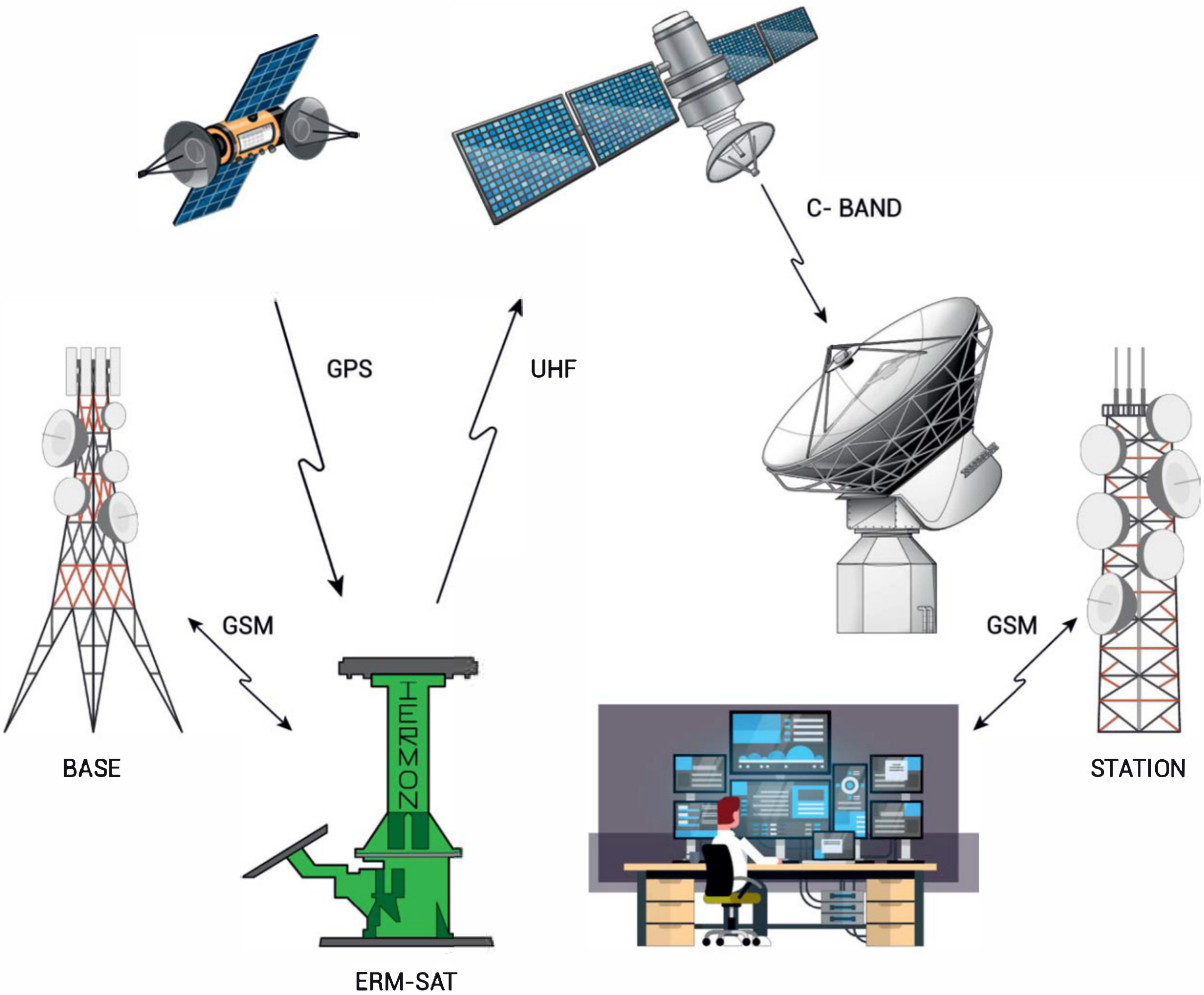
The programme will deliver a comprehensive in-house developed modelling systems for dispersion of radionuclides in different environmental media and radiological impact assessment tools for local to global scale studies. It will result in 100% indigenisation, in hazard mitigation, radiological safety of population and environmental safety.

5.4.6 Expansion of Countrywide Network of Radiation Monitoring

A countrywide network of standalone, solar-powered, battery operated, field-installed environmental radiation monitors (ERMs), capable of measuring gamma absorbed dose rate in outdoor air and wireless communication of the measured dose rate values in near-real time to central data receiving stations, serves as the backbone of a country’s early-warning infrastructure to detect any nuclear or radiological emergency happening anywhere in the country/ trans boundary migration. This also facilitates nationwide continuous and long-term environmental gamma dose rate monitoring. Establishment of such vast network requires dedicated resources, efforts and infrastructure. The programme aims to deploy 2000 ERMs in the long run, ensuring at least one ERM in every 100×100 km^2 area. Integration of AI/ML tools for data analysis will further enhance the monitoring capabilities, offering a robust national early-warning infrastructure to safeguard against radiological threats. The existing GSM based communication is proposed to be improved by introducing more & more ERMs with stable satellite-based communication (ERM-SAT).

ERM and ERM-SAT

The Indian environmental radiation monitoring network (IERMON) serves the said purpose in India, presently with its 556 ERMs spread across the country. The ERMs are equipped with Geiger-Mueller (GM) detectors and GSM as well as satellite based wireless communication channels. The measured dose rate values are received at three geographically separated, redundant data receiving stations.



IERMON Network

Large-scale production and installation of import-substitute ERMs, will bring the entire country, into the coverage of IERMON. This would strengthen the national early-warning infrastructure for detection of any radiological or nuclear emergency anywhere in the country / trans-boundary migration.

Vertical 6

ADVANCED TECHNOLOGY DEVELOPMENT

6.1 New Cryogenic Technology Development at BARC

Cryogenic technologies are the backbone of the superconducting (SC) accelerator programmes envisaged by DAE. Accordingly, cryogenic technology development and its refrigeration capacities are planned in sync with the SC accelerator programme of DAE. A 30 W at 2 K cold box (SHP20) is conceived for R&D on superconducting radio-frequency (SCRF) cavities. The 2 K would be generated and maintained through bath evacuation using a small capacity warm vacuum pumping system (WPS) or an innovative reciprocating cold compressor system (RCS) in conjunction with LHP100/LHP50. SC accelerator with 40 MeV beam energy would require a refrigeration capacity of 100-200 W at 2 K for which LHP100 can be utilised along with a 2 K cold box serviced by larger WPS or RCS. For enhanced beam energy of 200 MeV, the cryogenic refrigeration requirement is estimated to be about 1000 W at 2 K for which an integral cold compressor (CC) based 500 W at 2 K refrigerator will be developed followed by another of the same type.

The technology of integral 2 K helium plants with turboexpanders and centrifugal cold compressors (CC) is scalable so that the next plant in the series will have a designed refrigeration capacity of 2000 W at 2 K. It is envisaged to develop two such plants to be installed in a phased manner in order to serve the extended and enhanced superconducting accelerator requirements.

As an extension to this program, development of dilution refrigerator (DR) for supporting research on large qubit array sizes is proposed to be taken up along with R&D activities on micro heat exchangers, matrix heat exchangers, printed circuit heat exchangers and other special types of heat exchangers.

Following the development of key component technologies such as that of ultra-high speed cryogenic turboexpanders, high effectiveness plate fin heat exchangers and Dewar, the first turboexpander based Indian helium liquefier (LHP50) was successfully developed in-house by BARC. A larger capacity helium liquefier (LHP100) is developed on a turnkey basis through local industry with the successful completion of first commissioning run. The 2 K operation with LHP50 coupled with a helium Dewar and a vacuum pumping system, is also demonstrated. It is planned to develop a helium refrigeration system of capacity 30 W at 2 K with warm vacuum pumping system (WPS)/reciprocating cold compressor system (RCS) for super conducting radio frequency (SCRF) cavities performance evaluation & design of DR. The technology will be scaled up to the capacity of 100-200 W at 2 K. As long-term target, helium refrigeration system of capacity 2000 W at 2 K for SC accelerator beam energy up to 400 MeV and DR design improvements will be taken up. Further goal is to develop helium refrigeration system of capacity 4000 W at 2 K for super conducting accelerator of beam energy up to 1 GeV. The technologies described would be entirely developed in India through local vendors leading to substitution of expensive and often unreliable imports and making an Atmanirbhar Bharat in the cryogenic technology.

6.2 Hydrogen Related Technologies

Bhabha Atomic Research Centre has a very prominent programme for development of indigenous state-of-the-art hydrogen technologies pertaining to production and storage centred around nuclear energy for contribution, towards achieving the target of net-zero by 2070. The hydrogen production technologies can be classified into electrochemical methods which include alkaline water electrolysis (AWE), polymer electrolyte membrane electrolysis (PEM) & high temperature steam electrolysis (HTSE) and the second category being thermochemical technologies which include iodine-sulphur (I-S) and copper-chlorine (Cu-Cl) processes.

50 kW AWE stack developed at BARC

Technologies for hydrogen storage based on metal hydrides & metal nanocomposites and devices for hydrogen hazard mitigation are also actively being developed. Further, IGCAR is pursuing research and development of solid hydrogen storage materials with efficient hydrogen storage and recovery capabilities.

All the pertinent technologies are at different levels of maturity as described below:

i. *Alkaline Water Electrolysis (AWE)*: Completely indigenous 50kW stack having 10 Nm^3/h H_2 throughput developed in-house with technology readiness level (TRL) of 10. Further, stack capacity augmentation process, through industry partnership, with 0.15 MW (30 Nm^3/h) and 0.5 MW (100 Nm^3/h) are under evaluation. Zirfon equivalent membrane used in the electrolyser is also under development.

ii. *Polymer Electrolyte Membrane Electrolysis (PEM)*: Indigenous SPEEK membrane developed for PEM electrolyser, as a substitute to imported membranes and PEM electrolysis demonstrated at 18 NL/h.

iii. *High Temperature Steam Electrolysis (HTSE)*: Indigenous HTSE cells fabricated and HTSE technology demonstrated at 800 ºC at a hydrogen throughput of 4 NL/h for 150 hours.

iv. *Iodine-Sulphur Cycle*: The iodine-sulphur technology has been demonstrated at 150 NL/h in engineering materials, making India the first country to achieve this unique feat.

v. *Copper-Chlorine Cycle*: Novel first of its kind integrated facility demonstrated in metallic systems at 5 NL/h for 170 hours making it the highest recorded duration for any thermochemical cycle globally.

vi. *Solid State Storage*: Metal hydride storage device based on MgH_2 and Ti_2-Cr-V systems demonstrated at 150 NL capacity by BARC.

vii. R&D on different types of hydrogen storage materials have been carried out by IGCAR like rare earths, Mg-, Ti-, Zr-, V-based alloys, inter-metallics, metal hydrides, transition metal borohydrides, metal aluminium hydrides and high entropy alloys.

viii. ***Metal Nano-Composites for Metal Water Reaction***: Under conceptualisation stage

ix. ***Passive Catalytic Recombiner Device***: Prototype device has been fabricated and supplied to NPCIL for performance evaluation.

The expansive hydrogen programme of BARC & IGCAR is driven by domain expertise for fostering development of indigenous hydrogen ecosystem centred on nuclear power

The pertinent technologies following a sequential approach for expedited scale-up and deployment are listed below:

i. ***Alkaline Water Electrolysis (AWE):***

a. Development and commercialisation of MW scale AWE stack with indigenous membrane.

b. Coupling with green energy source is planned.

ii. ***Polymer Electrolyte Membrane Electrolysis (PEM):***

a. Indigenisation of the membranes having similar performance to imported PEMs and development of membrane-electrode (Pt/Ir)-assemblies (MEA) & PEM electrolyser components is planned.

b. Staged scale-up of PEM technology is planned with demonstration of 0.5 kW stack and subsequent capacity augmentation to 5 KW and 100 kW

iii. ***High Temperature Steam Electrolysis (HTSE):***

a. Development and demonstration of HTSE stack at 150 NL/h as a short-term goal with subsequent scaled-up demonstration at 3 Nm^3/h through industrial partnership.

b. Demonstration of HTSE technology integrated with nuclear plants.

iv. ***Iodine-Sulphur Cycle:***

a. Demonstration of 3 Nm^3/h plant in collaboration with Heavy Water Board in short term. Catalyst development for lowering temperature requirement.

b. Setting up of a semi-commercial plant through incubation and technology transfer. A scale of >100 Nm^3/h is envisaged through incubation route.

v. ***Copper-Chlorine Cycle:***

a. Demonstration of pilot scale facility at 150 NL/h in short term and subsequent prototype facility demonstration at 3 Nm^3/h, which will be followed by staged scale-up to TRL-8.

b. Demonstration of hydrogen production at 1000 Nm^3/h coupled with gas cooled reactors (GCRs)

vi. ***Solid State Storage:***

a. Demonstration of kilogram scale MgH_2 production facility.

b. Development of large scale H_2 storage following transfer of technology.

vii. ***Passive Catalytic Recombiner Device:***

a. Device is undergoing testing at NPCIL for qualification, subsequent to which deployment in Indian NPPs is targeted.

The hydrogen production technologies being pursued will foster a wide spectrum of tangible benefits. The electrochemical technologies viz. AWE, PEM and HTSE and the thermochemical technologies viz. I-S and Cu-Cl cycles are envisaged for large scale production of clean hydrogen using nuclear and renewable energy sources. The indigenisation of hydrogen technologies being developed encompassing production, storage and hazard mitigation will result in import substitute of cutting-edge technologies for fostering energy security to the nation.

6.3 Indigenous Technology Development for FBR Applications

Advanced technology development is the keystone to ensuring an independent and self-reliant FBR program. A technology road map is chalked out to meet the anticipated challenges as the country plans to expand its FBR program. The Amrit Kaal targets are derived based on the experience gained in the design, construction, and commissioning of FBTR and PFBR. Several targets have been identified to meet the technology requirements of FBR program. They include (i) establishing infrastructure for full scale FBR equipment testing (ii) indigenisation of critical components such as bearings, seals, valves, electromagnetic devices etc., (iii) developing automated vehicles for remote inspection of reactor internals and augmented reality-based tools for precise control & manipulation in unstructured environments, and (v) indigenisation of critical components The strategy is to identify crucial technological gap areas and find indigenous solutions through collaboration with Indian industry and R&D organisations. Additionally, in house infrastructure development is also outlined to facilitate in-house development and testing in specialised areas.

Work is already initiated in many thrust areas. This includes conceptualisation, proof of concept validation, small scale testing, initiating collaboration with industry and R&D organisations. Some important areas include design of remotely operated vehicles for viewing and inspection of reactor internals, development of oil less bearings and seals, design of large sodium pump test facility, development of valves, sodium pressure sensors, etc. Emphasis will be given to indigenization of Pump test facility, Oil free pumps, EM devices, critical components such as seals, valves, forgings, and bearings, remote inspection system and its controls.

The facilities planned will provide in-house infrastructure to garner experience in development, testing, troubleshooting, operation experience of critical equipment. This, coupled with indigenous technology development will significantly propel the drive towards achieving Atmanirbhar Bharat.

6.4 Facility for Severe Accident Management

NPPs are built with several inherent and engineered design safety features. However, as a part of plant safety analysis, consequences of severe accidents are evaluated towards demonstration of safe mitigation. Severe accident management guidelines (SAMG) are developed and implemented in all reactor designs with a focus on containing the molten fuel (corium) in a sub-critical and coolable state. Investigation of various phenomena associated with accident progression is important for designing passive safety devices such as core catchers, decay heat removal systems etc., towards effective implementation of SAMG. A comprehensive research programme is underway at IGCAR for addressing various issues related to SAMG. The programme focuses on design and development of first of a kind world class indigenous facility with integrated efforts from DAE consortium to cater for severe accident research of all Indian NPPs. A benchmark test facility is planned to be set up at IGCAR for demonstration of advanced safety features of Indian NPPs.

IGCAR has undertaken various experimental and numerical studies for investigating severe accidents from initiating events to the corium management. Facilities were developed for generating simulated corium using induction melting and thermite reaction. Numerical analysis was carried out using few inhouse developed codes and commercial software. Various large-scale experiments such as fuel slumping/melting, molten fuel coolant interaction and corium interaction with core catcher materials will be studied using prototypic corium representing the various fuel for reactors such as FBRs and advanced LWRs. Further, short term and medium-term goals are: detailed design, regulatory clearance of experimental facilities; construction of the facility building, initiation of metal fuel safety experiments, and testing of various core catchers.

The experimental data will be vital for validation of advanced numerical models and qualification of passive safety systems towards enhancing the public acceptance. The facility will be indigenously developed with component manufacturing envisaged by Indian industry. Through demonstration of robust safety of NPPs, the programme would support rapid expansion of clean energy in India towards achieving Net Zero carbon emission.

6.5 Development of Semiconductor based Radiation Detectors and Transducers for NDE Applications

Radiation detectors are vital for ensuring safety during the operation of nuclear reactor and its associated fuel cycle facilities. Currently most of these radiation detectors are being imported for various nuclear applications and maintenance of these detectors becomes a challenge. HPGe based semiconductor detectors are being used for varied application including in vivo monitoring and non-destructive assay, owing to its high resolution. But these detectors need liquid nitrogen for its operation and hence portability of these detectors for field measurements adds additional challenge. This has led to the development of room temperature semiconductor detectors based on CdZnTe (CZT). CZT bridges the gap between scintillator-based detectors at one end and high-maintenance germanium detectors at the other, with its high energy resolution. Further the objective it to focus on development of lead niobate – lead titanate piezo-electric transducers for NDE evaluation of materials like flaw detection, under water measurements and ultrasonic imaging.

At present there are around six commercial players supplying CZT detectors in the international market. In India, IGCAR has also ventured into the development of these gamma detectors. The crystal growth technology, etching, passivation and electroding of CZT detector have been standardised and a portable gamma ray detector with 4% resolution at 662 keV of ^{137}Cs has been demonstrated successfully. Further improvements in the development are in progress. Also, the development of novel bottom cooling high temperature solution growth setup led to the growth of large-sized PZN-PT crystals with high piezo-coefficient (2000 pm/V) and whose characteristics led to demonstration of SAW devices and hydrophones on par with international standards. The program needs and efforts will be made to develop room temperature semiconductor / scintillation based single crystals for radiation detectors suitable for nuclear reactors and associated fuel cycle facilities. Next CZT array detector will be developed for non-destructive assay and medical imaging applications. Development of piezo-electric sensors and ultrasonic transducers for NDE applications like in-sodium inspection of reactor components and SONAR applications is planned as medium-term goal.

The proposed programme will be the indigenous development of large volume CZT detector for hand held identification of radionuclides in nuclear reactors and array of CZT detectors for industrial and medical imaging applications. It also envisages large scale production of CZT detectors for varied applications in nuclear industry including non-destructive assay. Indigenous development of CZT based detectors for varied applications will be an import substitute and support the 'Make in India' programme in health care applications and for nuclear energy security.

The development of PZN-PT and PMN-PT crystals with high piezo-coefficient (2000 pm/V) can be widely used in high sensitivity SONARS, ultrasound imaging and SAW devices. These piezo-electric based transducers can also be used in NDE applications under sodium studies in fast reactors.

6.6 Development of Semiconductor Based X-ray and Gamma-ray Detector Arrays

Semiconductor based X-ray and gamma-ray detector arrays are crucial electronic components for several scientific, industrial and societal applications. GaAs, CdTe, InP, GaN, and SiC materials are commonly used as radiation-hard photodetectors. The detection efficiency of GaAs is higher than silicon, which makes it ideal for X-ray and gamma-ray pixel detectors under intense radiation environments at room temperature. Further, in comparison to silicon, GaAs and GaN are more radiation-hard for gamma rays, electrons, low-energy protons and neutrons. Such attributes make GaAs, and GaN promising candidates for the development of X-ray and gamma-ray pixel detectors.

Compound semiconductors like GaAs, GaN are promising materials for the development of X-ray and gamma-ray pixel detectors, in particular under intense radiation environments. In India, though the technology for the fabrication of such devices is available in a few R&D labs, yet there is no industry which can produce the devices locally and such devices are imported even today. In view of this, fabrication of high-resolution pixel detectors for X-ray and gamma-ray imaging is being pursued. It comprises of setting-up of an epitaxial growth facility for the growth of layers with reduced background carrier concentration typically lower than $<10^{14}/cm^3$, detector fabrication facility for developing high-resolution pixel detectors with a single pixel size of 75×75 μm and consisting of 1028×1028 pixels. A suitable preamplifierbased readout electronic device with high signal-to-noise ratios will then be developed for real-time image processing. The pixel detectors along with readout electronics can find useful applications, in high-energy physics experiments, astrophysics, nuclear reactors, synchrotrons, intense light sources and societal domain, leading to self-reliance.

In India, fabrication of GaAs based semiconductor devices is limited to a few R&D labs and those too are imported. In this context, RRCAT has developed a complete technology for the fabrication of radiation hard GaAs and GaN based photodetectors. Few detectors have been deployed for early arc fault detection in RF circulators. The devices can detect gamma rays, X-rays, UV-VIS-IR radiation, and have a high charge conversion efficiency for x-ray photons with a dynamic range of up to 10^6 at 12 keV along with a low dark current of 5 pA. Development of quadrant and linear arrays based on GaAs, GaN detectors expected to be achieved in near future. Development of high-resolution pixel (1028 × 1028 pixels) detectors for X-ray and gamma-ray imaging is planned as medium-term target. In the long run potential applications of these devices in high-energy physics experiments, astrophysics research, medicine, nuclear reactors, synchrotron and intense light sources will be explored.

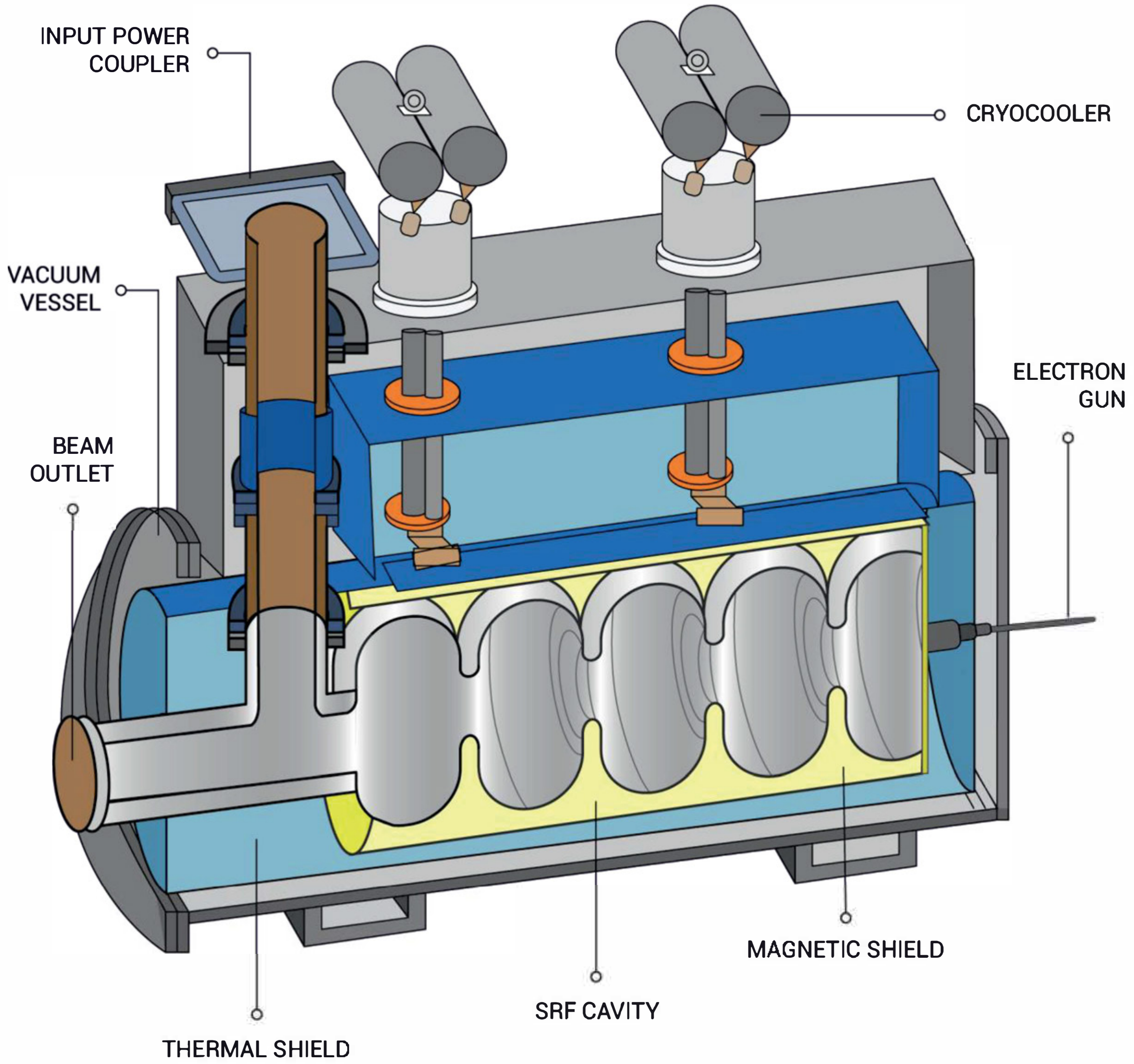
6.7 Development of Superconducting Radiation Detectors

Superconducting films can be designed to form extremely sensitive radiation detectors for any frequency/wavelength range. The kinetic inductance detectors (KID) are one such class of superconducting cryogenic detectors. They can be easily multiplexed for making large detector arrays, which is suitable for achieving high sensitivity. The low temperatures of operation of superconducting detectors boosts their signal to noise ratio. An R&D programme is envisaged for developing KIDs and superconducting nanowire single-photon detectors (SNSPDs, for quantum computing) for IR/THz range and KIDs for X-ray and γ-ray wavelengths. For the qualification of detector structures, an ultra-low temperature test facility will also be developed.

Research and development of superconductor-based radiation detectors is in its nascent stage in the country. Some attempts at developing superconducting detectors are underway at TIFR, Mumbai and NPL, New Delhi. Internationally, superconducting radiation detectors have been developed across the electromagnetic spectrum and are employed for analysing the spent nuclear reactor fuel, performing sensitive experiments at synchrotron beam lines and astronomical observations ranging from IR/THz to gamma rays. As the choice of sensitive detectors for 12.5-50 microns wavelengths is very limited, initial work on the development of superconducting detectors for the IR/THz range is being done for studies using the IR-FEL radiation. For the qualification of detector structures in different wavelength ranges, an ultra-low temperature (50 mK or lower) optical cryostat-based facility shall be developed and as an off-shoot of the fabrication techniques developed, development of thermal sensors for extreme environments is also envisaged.

6.8 Conduction-Cooled Cavity and Cryo-Cooler Technology Development for Portable Accelerators

Presently niobium (Nb) is used as a construction material of superconducting radio-frequency (SRF) cavities for the particle accelerators. The typical operating temperature of Nb cavities is 2 K, which puts high load on the cryogenic system. The quest of development of conduction cooled, niobium-3-tin (Nb_3Sn) SRF cavity, as an alternative technology for niobium SRF cavities, is being pursued at leading accelerator labs for achieving higher particle energies with better power efficiency at a lower capital cost. The higher operating temperature allows for cooling the cavities with a small device called a cryocooler instead of a large, complex and difficult-to-maintain cryogenic plant.



Portable Accelerator

This results ease in development of portable particle accelerator technology for industrial and societal uses. Due to above reasons, conduction cooled Nb_3Sn cavities is an attractive choice and promising option to replace conventional niobium in constructing SRF cavities. Implementing Nb_3Sn technology in SRF cavities poses challenges due to its complex fabrication process and sensitivity to defects. Achieving uniform and reproducible properties is crucial. The material's sensitivity to imperfections necessitates strict quality control. Cavity development work needs setup of coating/deposition facilities, film characterization, cavity fabrication, processing, testing, cryo-coolers technology & RF source with industrial participation after in-house qualification of the technology.

RRCAT is involved in establishing technology & infrastructure for fabrication, testing and dressing of superconducting RF (SCRF) cavities using high residual resistivity ratio (RRR) niobium material. Recently, work on Nb_3Sn films deposition and design and development of conduction-based cooling system on niobium (Nb) has been taken up at RRCAT. Cryocooler for temperatures up to 5 K has been developed by RRCAT for future applications. The technique for the deposition of Nb_3Sn films on niobium substrates samples will be established in near future. In parallel, development of Cryo-cooler with cooling capacity of 1.8 W at 4.2 K shall begin. Industrial participation and qualification of technology for broader application is also envisaged.

Traditional accelerator technology is bulky and energy-intensive. Next-generation superconducting RF cavities offer a portable and efficient cost-effective alternative for accelerator applications. Development and qualification of conduction-cooled advanced superconducting cavities would be beneficial for societal applications (such as advanced medical treatment, sludge treatment and various industrial applications). Compact accelerators have the potential to revolutionise healthcare, irradiation applications and improved industrial processes.

6.9 Development of Vacuum Tube Devices and Circulators for High-power RF Systems

In accelerators high frequency (UHF to S band) RF system is most critical system that is dependent on costly imported RF devices. Furthermore, being high by capital intensive and consumable, they increase the affordability bar, processing cost and uncertainty in the deployment plan for societal applications. Vacuum tube devices like klystrons and inductive output tubes and high-power RF circulator are critical technology devices. Multi-beam and multi-cavity vacuum tube devices are used as medium or high-power amplifiers in UHF and microwave ranges for both continuous and pulsed operations. The circulator is used to protect the costly RF amplifying devices against the reflection from load. The programme proposes to develop these components indigenously. Rugged, commercial vacuum tube devices in India have not been developed. CEERI (Pilani) pursued a programme for development of klystrons. Worldwide, there are very limited klystron manufacturers. Therefore, availability is quite uncertain from suppliers. Development of klystron (6.5 MW/50 kW, S band Pulsed), IOT (80 kW, UHF, CW) and circulators (150 kW CW at ~500 MHz, 250 kW, pulsed/CW at 650 MHz, 6.5 MW/50 kW pulsed at S band) is envisaged in a phased manner.

This State-of-the-art, critical RF technology base is essential for implementing irradiation application for societal benefit (medical, industrial) and scientific accelerators like linacs, synchrotrons and ADSS at scale.

Vertical 7

HUMAN RESOURCE DEVELOPMENT, CAPACITY BUILDING & SKILL DEVELOPMENT

7.1 Human Resource Development: Capacity Building & Skill Development

Dr. Homi Jehangir Bhabha strongly professed for building a sustained pool of highly skilled human resources to achieve self-reliance in the nuclear energy sector. In view of this, a super specialised training school was established in the Trombay campus in 1956, within three years from inception of the then Atomic Energy Establishment. The training programme conducted in the training school is enduring with a holistic approach of providing quality training & education using best practices prevailing in the educational sectors and striving to unceasingly upgrade & improve curriculum, infrastructure and training facilities. Eyeing at extensive expansion in the future for nuclear energy programme of the country, the department has framed a meticulous vision towards human resource development and capacity building, this include creating a combined training centre in Vizag. The training centre will work towards capacity building by consolidated training programmes at one place for all scientific officers, CAT- I & II trainees and administrative trainees joining the DAE institutes.

The department will continue to share its human resource for international collaborations and mega projects such as LIGO-India Project; LHC (EU), ILC (Japan); CLIC (CERN), FCC (CERN), Fermi-Lab collaboration, which would further help in capacity building.

To boost the growth and capabilities of industries for achieving complete self-reliance for the country, dissemination and transfer of DAE developed spin-off technologies is one of the thrust areas and will be given priority. Atal incubation centres in four units of DAE will play a big role in linking India's robust start-up eco-system to nuclear/non-nuclear sectors by setting-up of technology development cum incubation centres. Deployment of societal technologies through universities, NGOs, MSME is the major goal of the Advanced Knowledge and RUrban Technology Implementation (AKRUTI) program. Finally, through different awareness programmes, the department will continue its endeavour to educate and inform the public about various aspects of nuclear technology, its benefits, risks, and safety measures; foster understanding, dispel misconceptions, and build trust among the common Indian people.

The BARC Training School over the years has grown into an internationally acclaimed school of excellence with more 10,000 scientists and engineers graduated-from it with flying colours. DAE has been licensing knowhow of spin off technologies since last forty years and has at present about 250 technologies available for Transfer. Around 800 licenses have been issued to the industrial and rural sector. It has also worked in technology development activity under the technology incubation scheme at BARC, wherein industries are mentored to scale up or upgrade the existing DAE technologies. The future activities in the proposed program are as following:

i. Creation of infrastructure for a consolidated training centre at BARC, Vizag.

ii. According to the proposed expansion of nuclear energy program, plan is for yearly increase in the number of trainee officers will start prior to the functioning of the Vizag facilities.

iii. In the technology development front, department has started working with Government and non-Government agencies to create start-ups, employment, and technology wealth creation.

iv. Large-scale public outreach programmes will include: Parmanu-Vigyan Mela in metros and other cities, public talks and lecture by serving and retired employees, showcasing documentaries and films, publishing cartoon books on DAE social media and YouTube, and Parmanu Jyoti (school outreach) programme covering all possible schools in states and union territories.

Development of infrastructure for an all-inclusive training centre with state of art facilities in the new campus at BARC-Vizag will help in creation of augmented human resource and capacity building. Through Atal incubation centre, several start-ups will be started which in turn would generate large scale employment. In addition, it is proposed to engage a large number of entrepreneurs through AKRUTI centres. DAE, while involved in national development of nuclear technologies, also emphasised in advanced and radiation technologies for societal applications; together which has created a large pool of spinoff technologies for deployment in the Indian market. The Department would focus in multiplying the efforts in achieving further heights in this direction.

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DEPARTMENT OF ATOMIC ENERGY