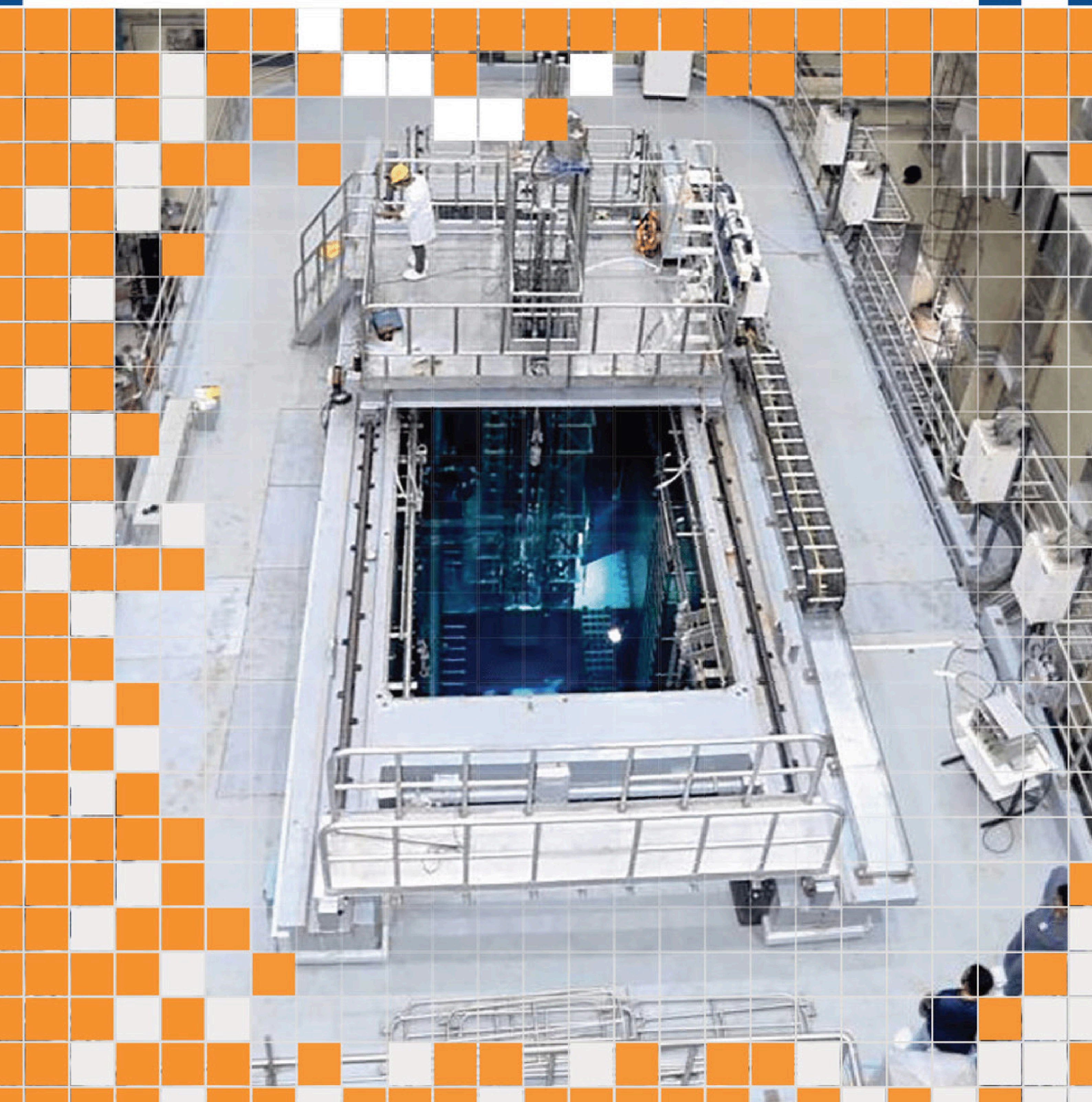
PART A

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

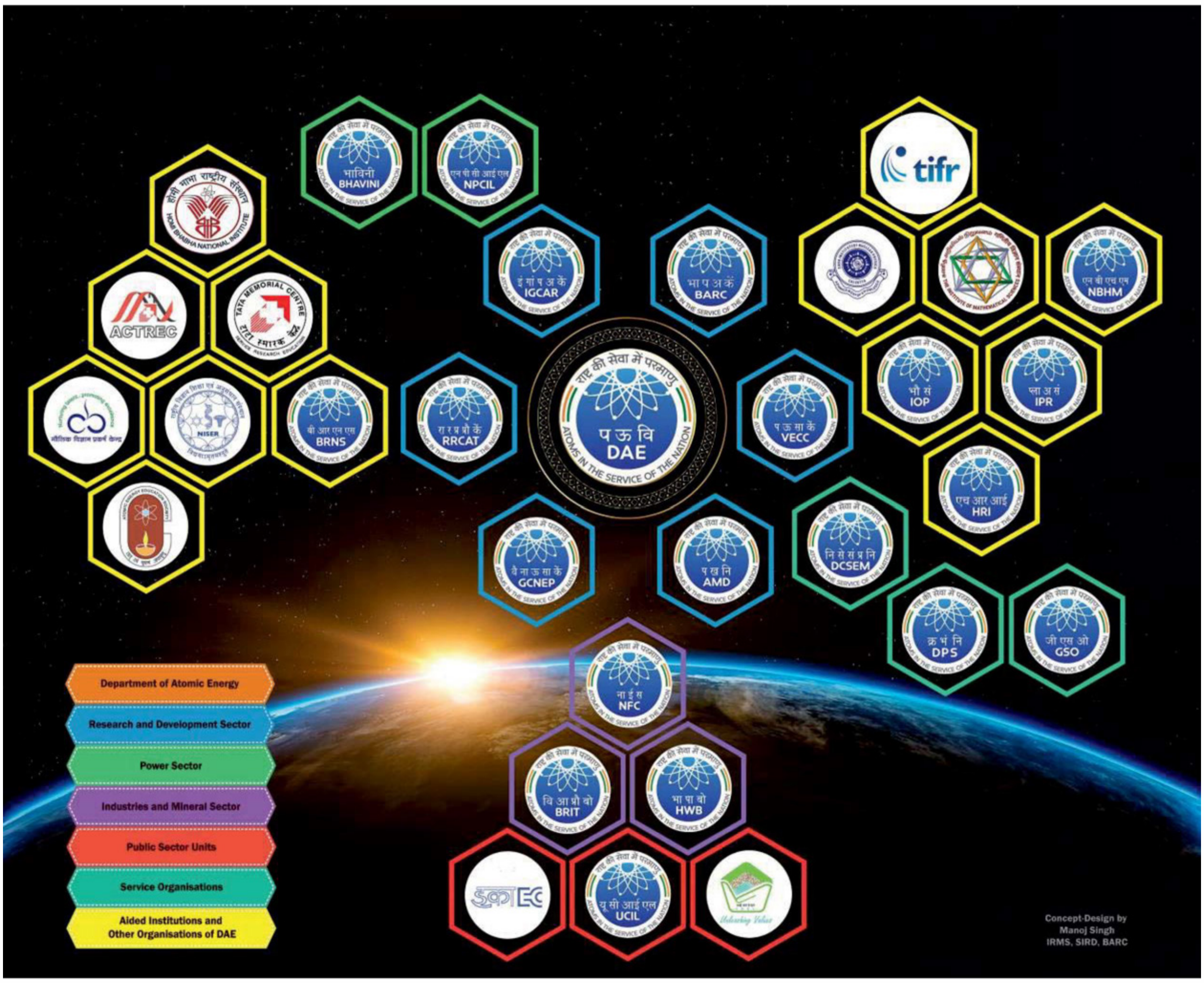
Department of Atomic Energy (DAE), since its inception, has been pursuing a focused mandate for development of indigenous technologies in all the facets of nuclear science and its applications. The core idea is to harness the potential of environmentally benign nuclear energy for achieving long-term 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:

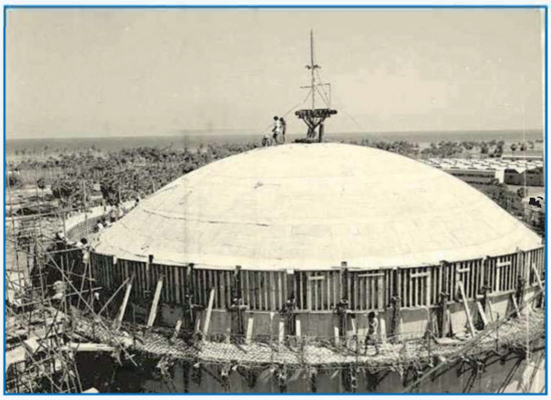
Bhabha Atomic Research Centre (BARC) established in 1954 in Mumbai as India's premier nuclear R&D organisation, has now expanded its multi-disciplinary and multi-scale activities at various places of the country. Its mandate focuses on advancing nuclear science and technology for its peaceful applications 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

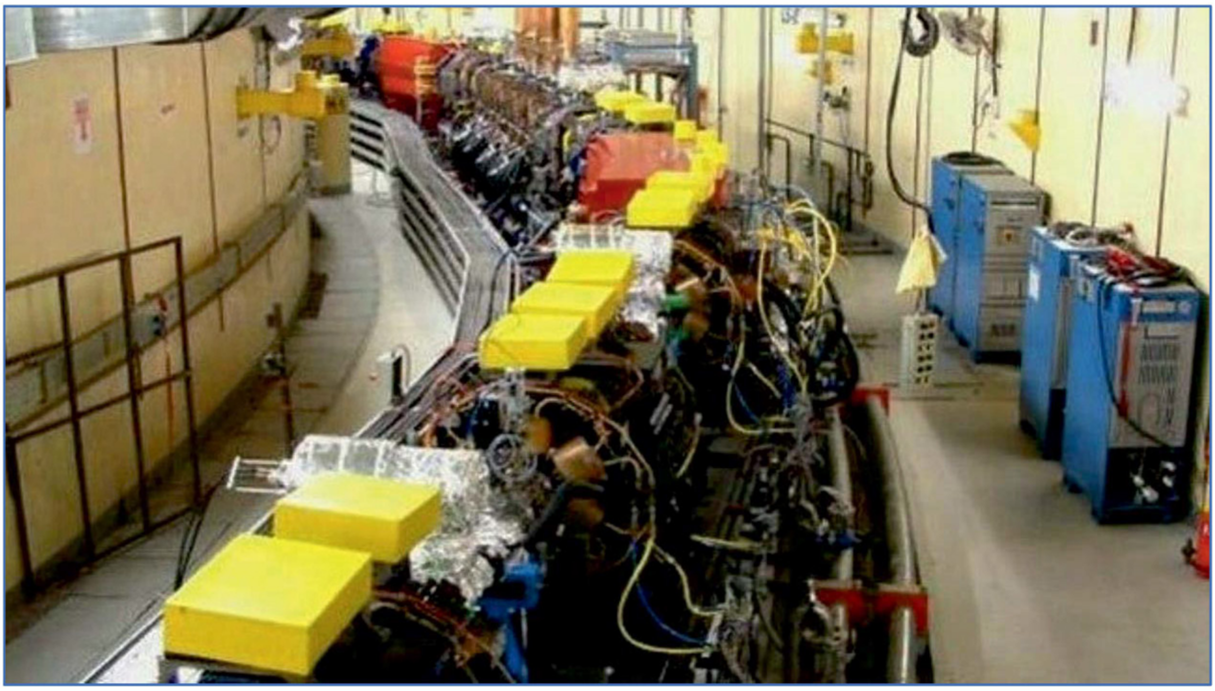
Indira Gandhi Centre for Atomic Research (IGCAR) established in 1971 at Kalpakkam, is the second-largest R&D establishment of DAE. Dedicated for fast reactor technology, its mandate is to carry out multidisciplinary programme of scientific research and advanced engineering to develop sodium-cooled fast 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

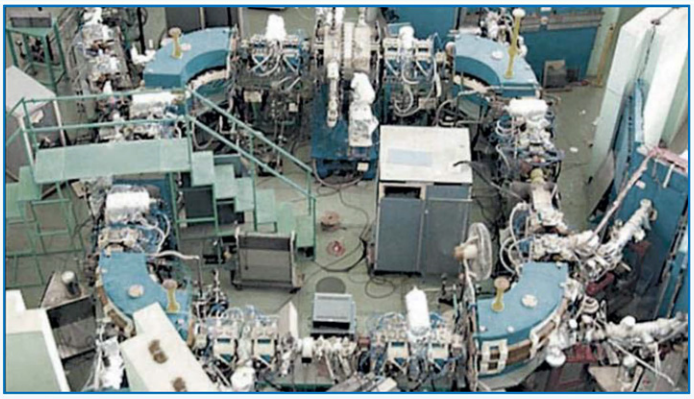


The Fast Breeder Test Reactor (FBTR), breeder reactor located at Kalpakkam, Tamil Nadu, first reached criticality in October 1985 making India the seventh nation to have the technology to build and operate a breeder reactor after United States, UK, France, Japan, Germany, and Russia. IGCAR and BARC jointly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

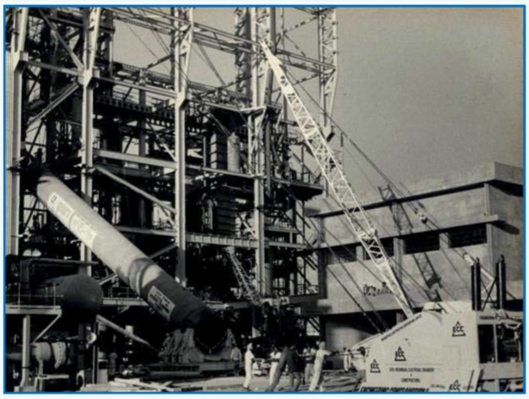
Board of Radiation and Isotope Technology (BRIT) is an industrial unit, established in 1989, to promote the application of radioisotopes and radiation technologies. Its primary mandate is to develop, produce and supply radiopharmaceuticals & isotopes. BRIT also provides a wide range of products and services, 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.

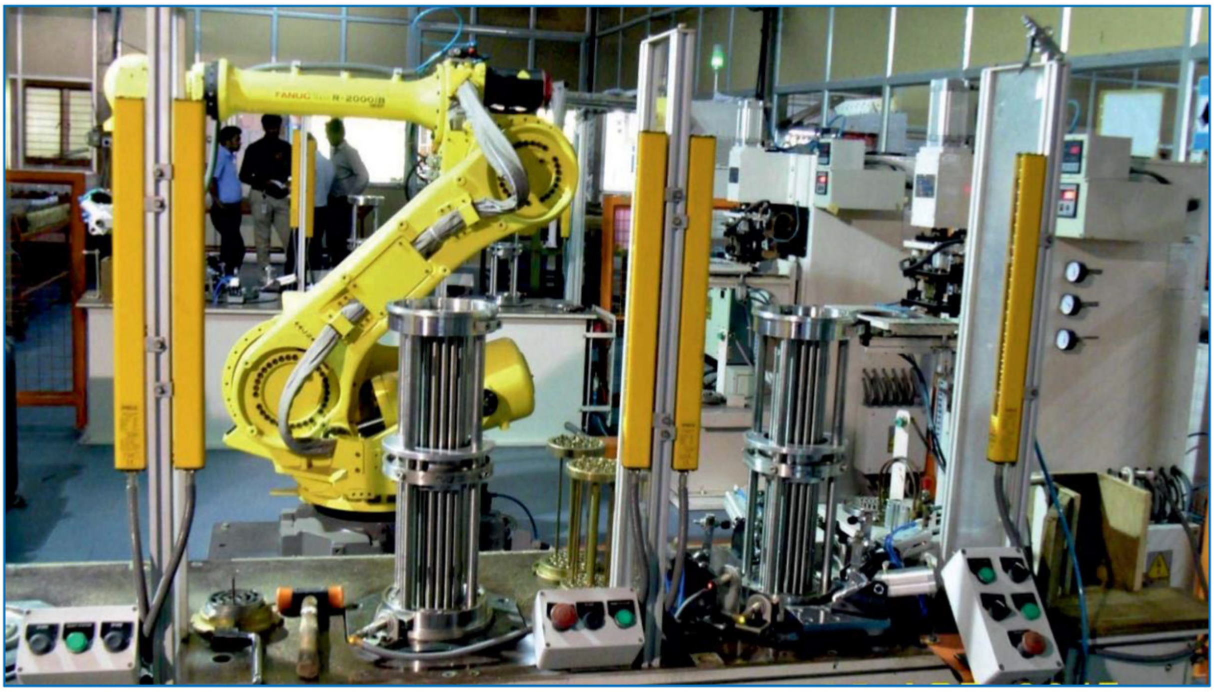
Heavy Water Board (HWB), an industrial unit established in 1962, is responsible for the production and supply of high-quality heavy water (deuterium oxide, D_2O) as well as development and optimization of technologies related to heavy water production. This is essential to meet India's growing nuclear 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

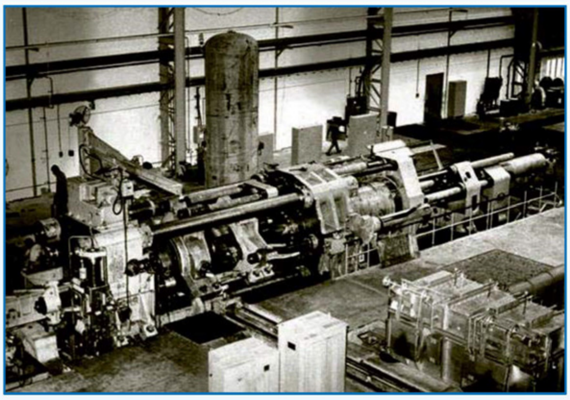


HWB Facilities, Vadodara, started in 1977, produces potassium metal, deuterated compounds, and solvents for in-house use. It also manufactures deuterium gas, which enhances optical fibre performance and aids in chemical synthesis. Deuterium gas is available for sale. Upcoming projects include sodium 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.

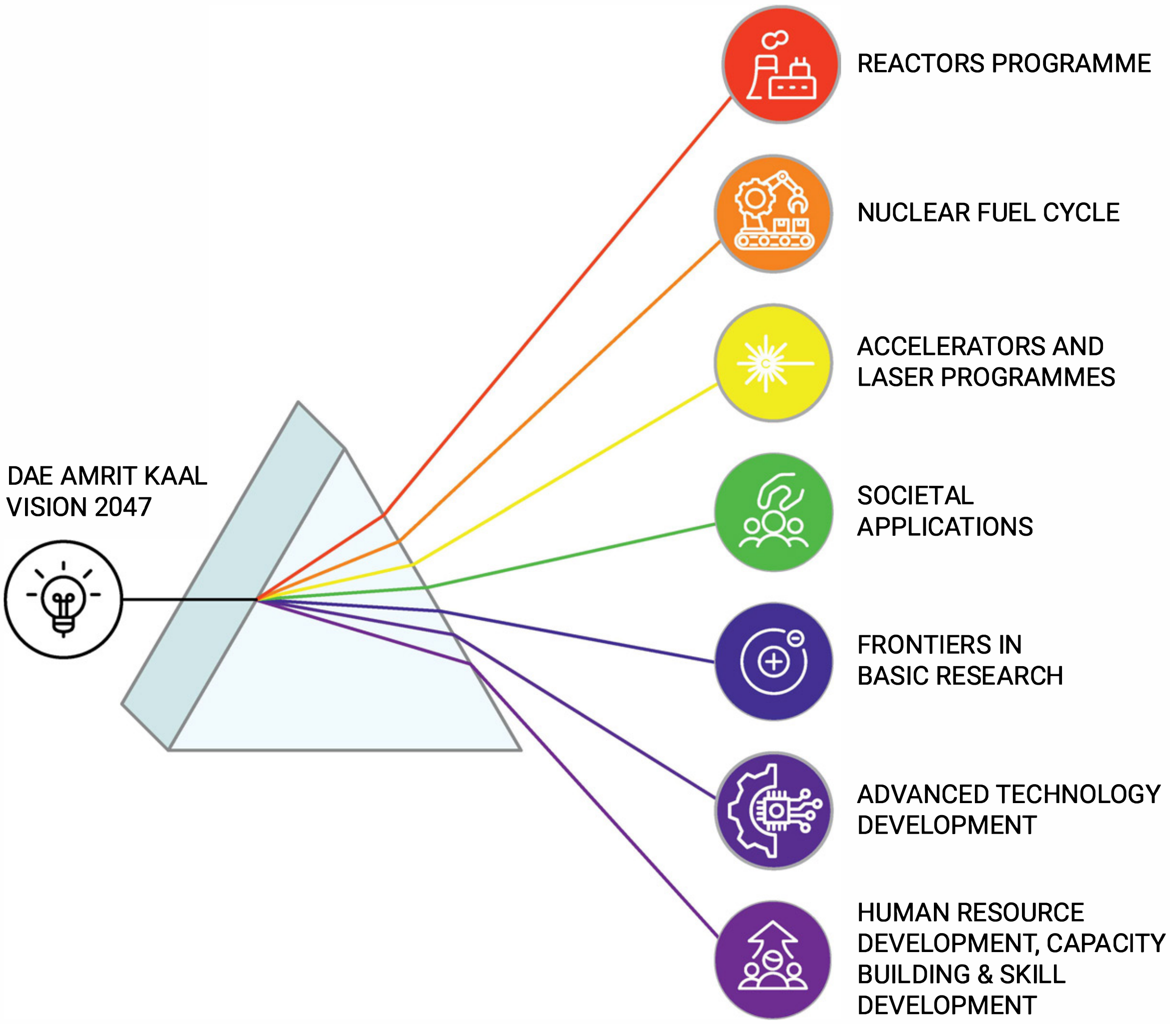
Directorate of Construction, Services, and Estate Management (DCSEM), a service organisation, was established in 1996. DCSEM is responsible for planning, designing, engineering, and executing civil, public health, electrical, air-conditioning, and ventilation works for various DAE units, including housing, 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.



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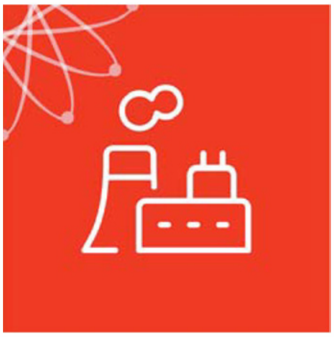
Amrit Kaal Vision 2047 Targets have been divided into seven verticals as described below:



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 1st & 2nd Stage. The programme would as well guide the development of demonstration reactor for realization of 3rd 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:

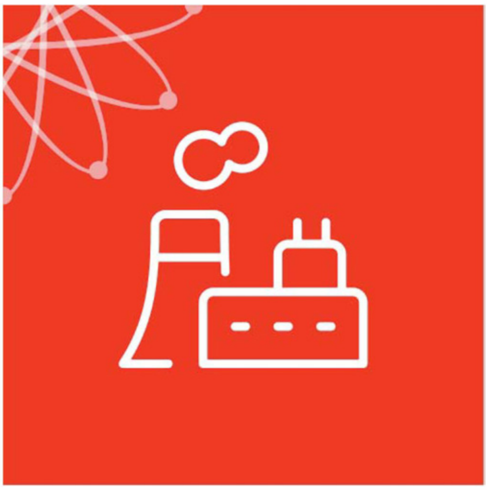
The vision for basic and directed research in the thrust areas of physical sciences, chemical sciences, biological sciences, material sciences are outlined herein. Health physics for reactor programmes, research on nuclear fuel cycle, and physics of accelerator programme are also covered under this vertical,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

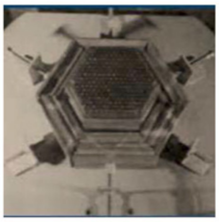
REACTOR PROGRAMME

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.

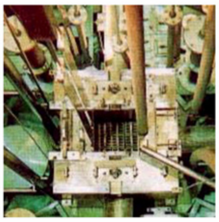
CIRUS A 40-MWth Indo-Canadian research reactor, attained criticality on July 10, 1960. Modelled on Canada's NRX reactor, it used natural uranium fuel and heavy water as a moderator. As Asia's largest research reactor of its time, CIRUS played a key role in nuclear physics research, reactor fuel development,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



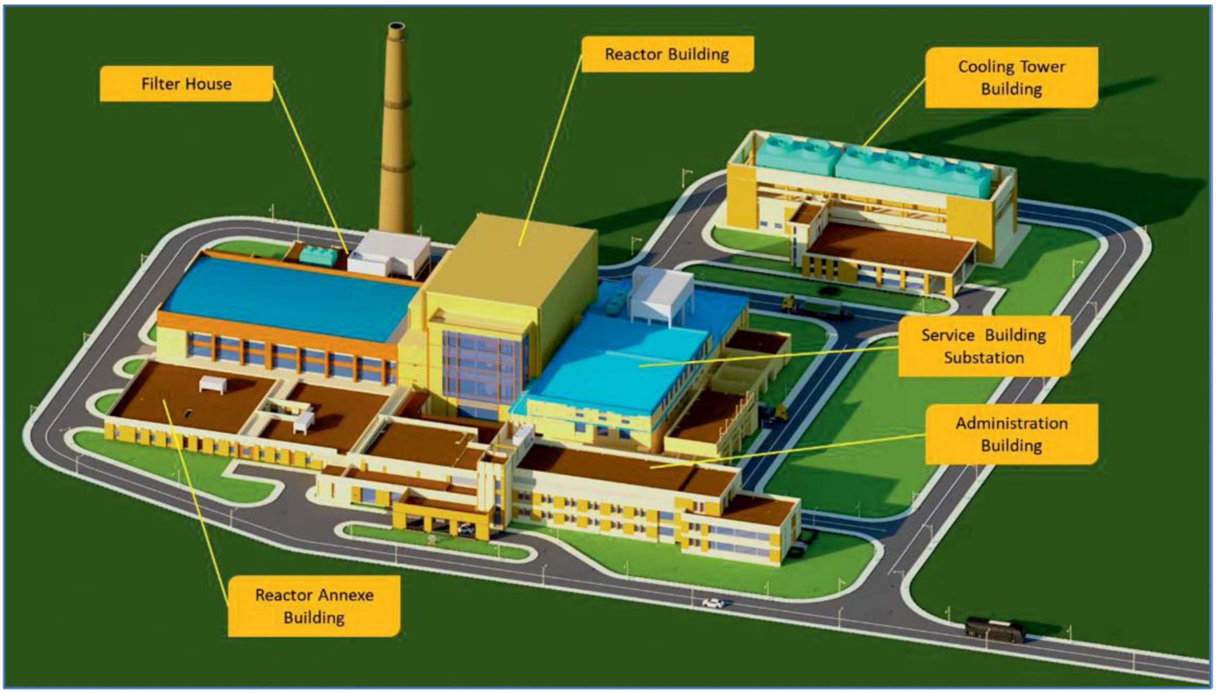
KAMINI A 30 kW-thermal reactor built by BARC and IGCAR, attained criticality on October 29, 1996. Using uranium-233 fuel produced from the thorium cycle, it is the world's only reactor designed specifically for this fuel. Cooled and moderated by light water, KAMINI serves as a precursor to India's three-stage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

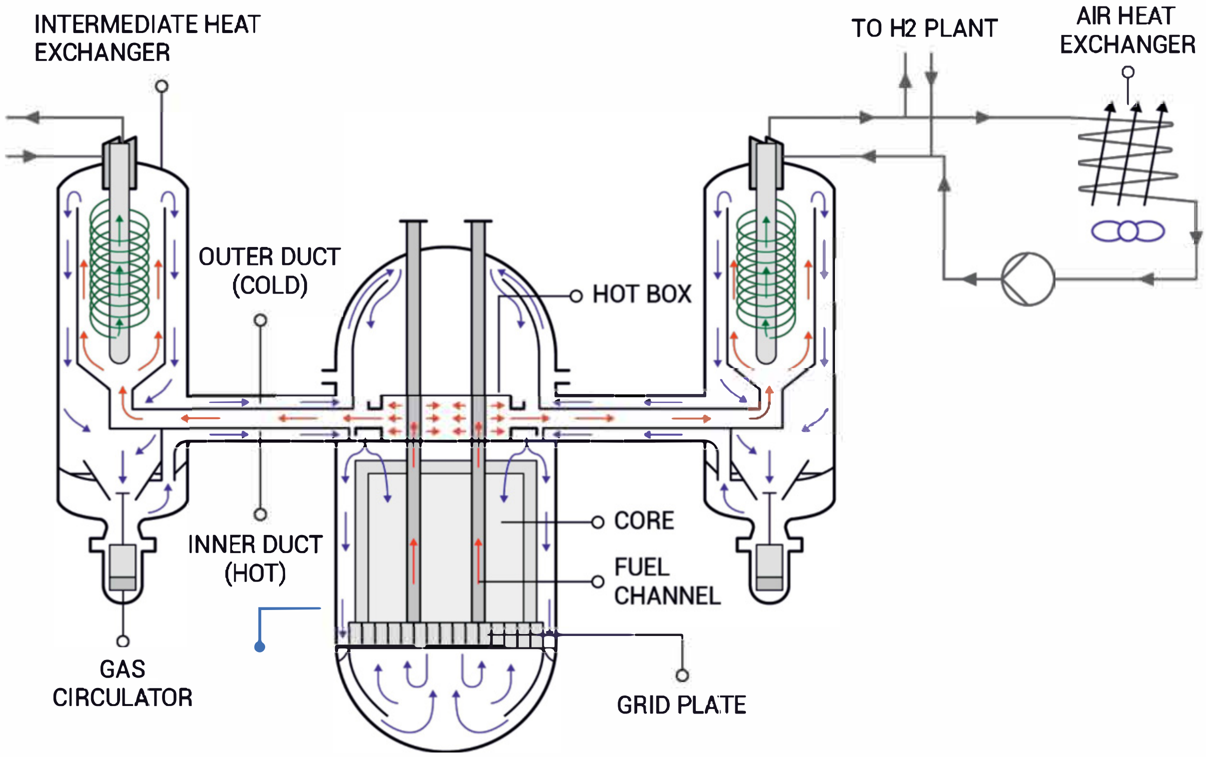
India from the very beginning, conceived the ambitious idea of three stage nuclear power program. This 3-stage program covers building of pressurised heavy water reactors, fast breeder reactors and thorium-based reactors on commercial scale. Obviously, the program also includes technology development 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.

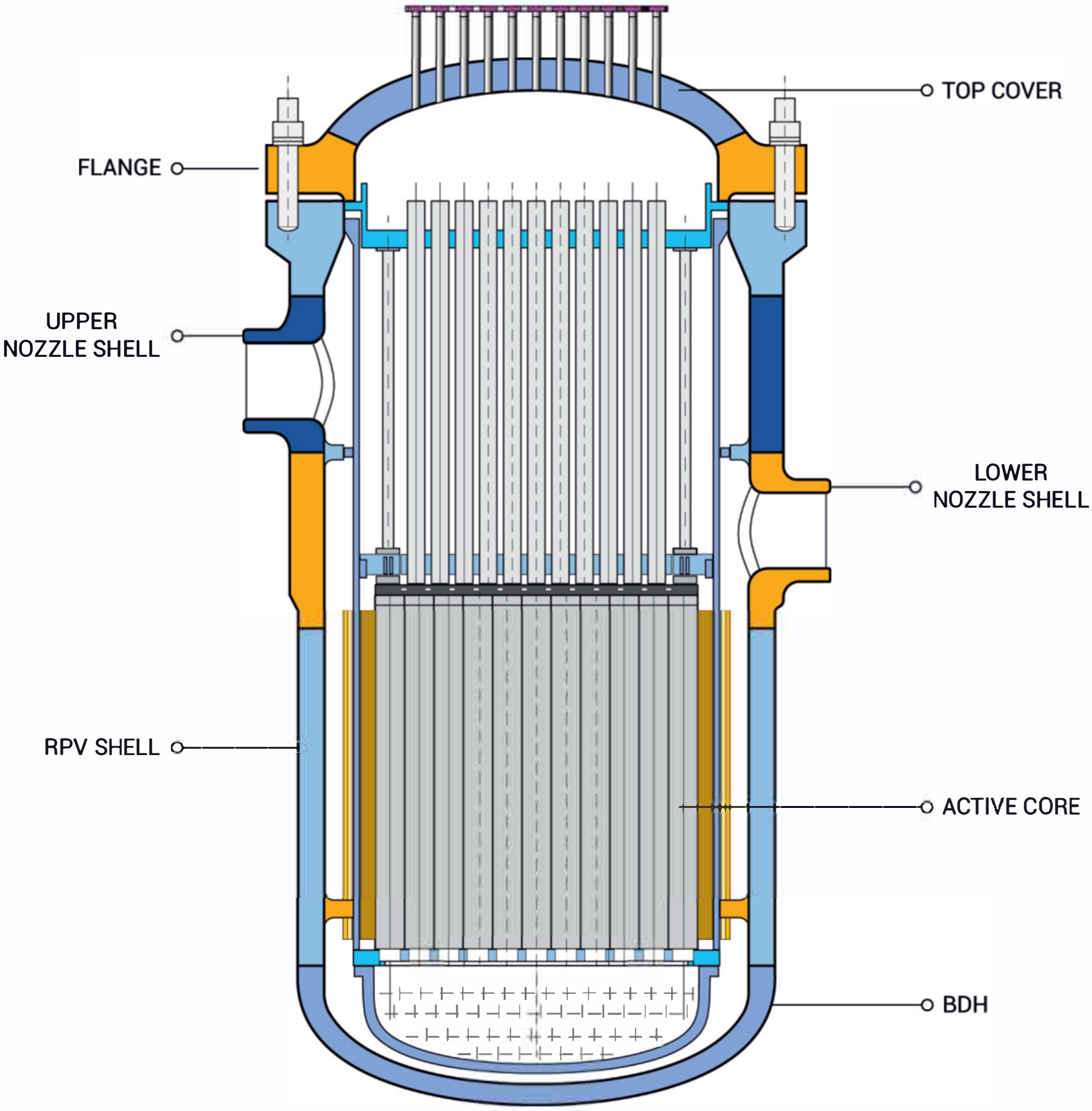
The GCR for hydrogen production promotes Atmanirbhar Bharat in nuclear-based hydrogen production, diminishing reliance on fossil fuels. This initiative is an important step towards fostering a more sustainable future, where nuclear energy plays a key role in addressing energy needs while prioritising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

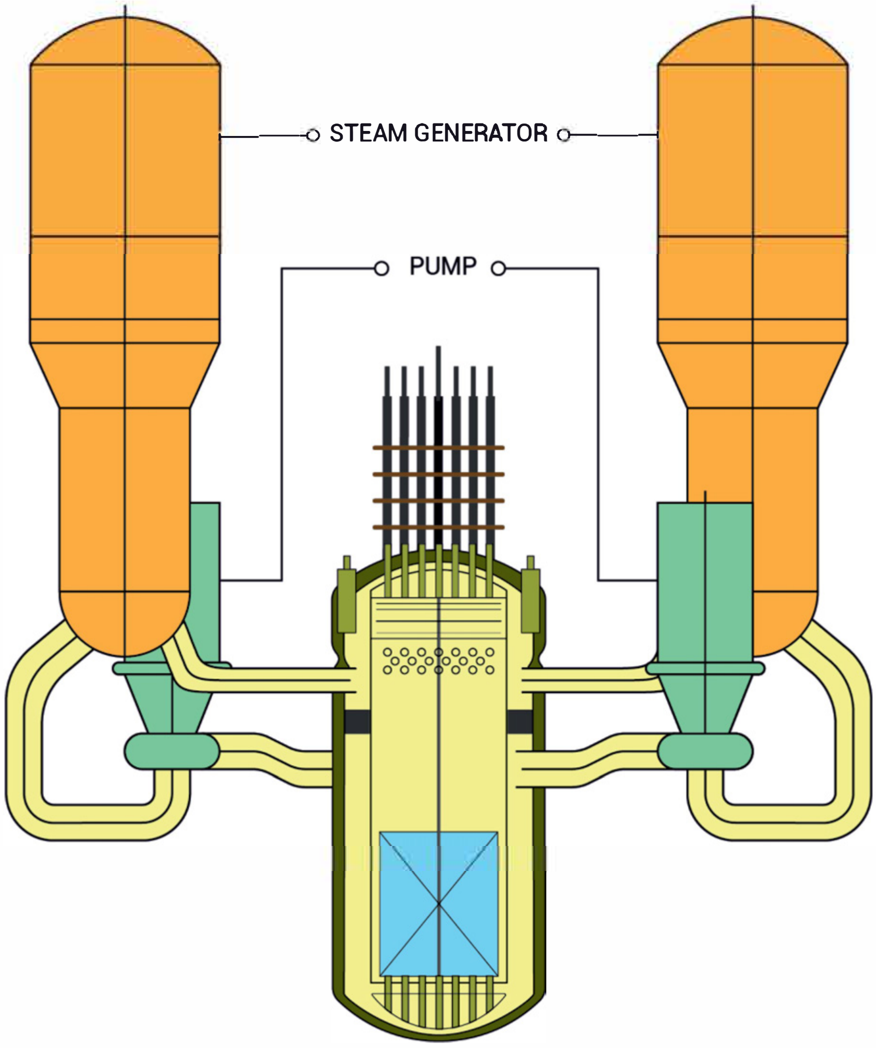
1.3.3 Development of Small Modular Reactor

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.



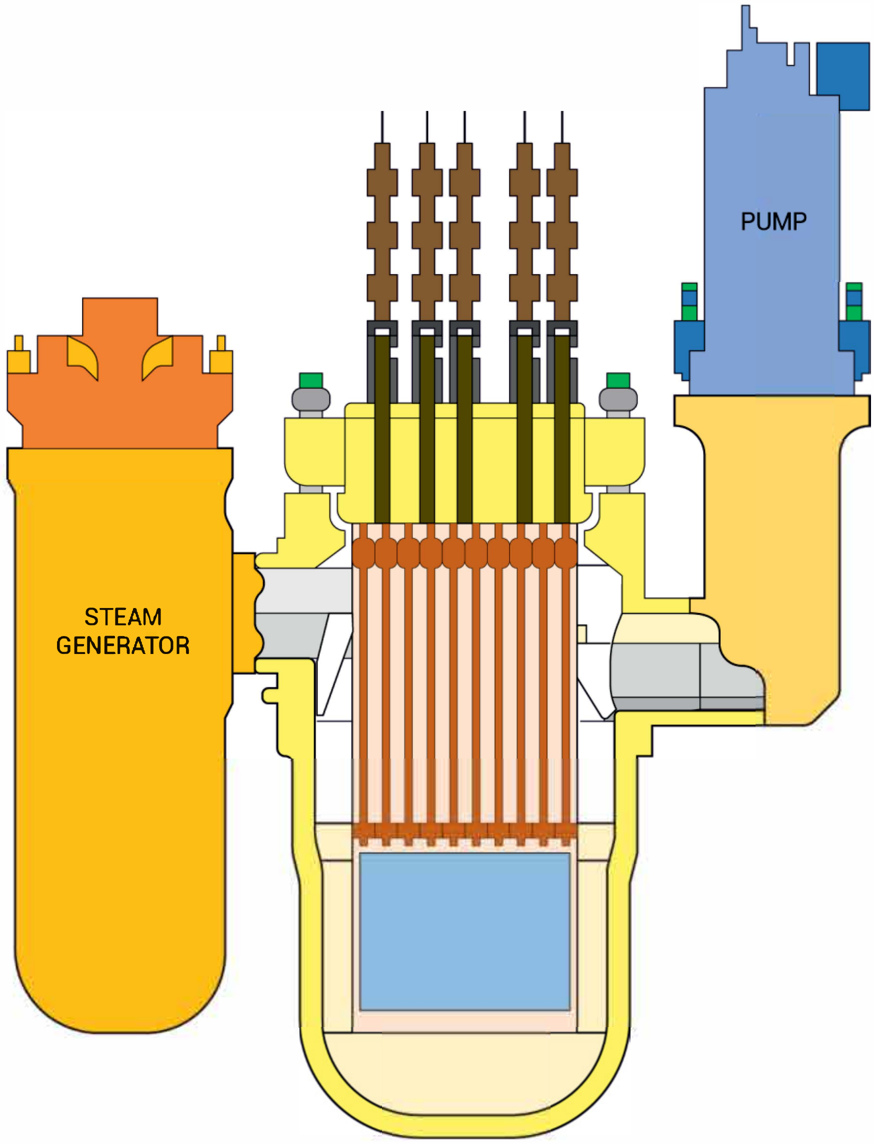
Schematic of Loop Type SMR

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.

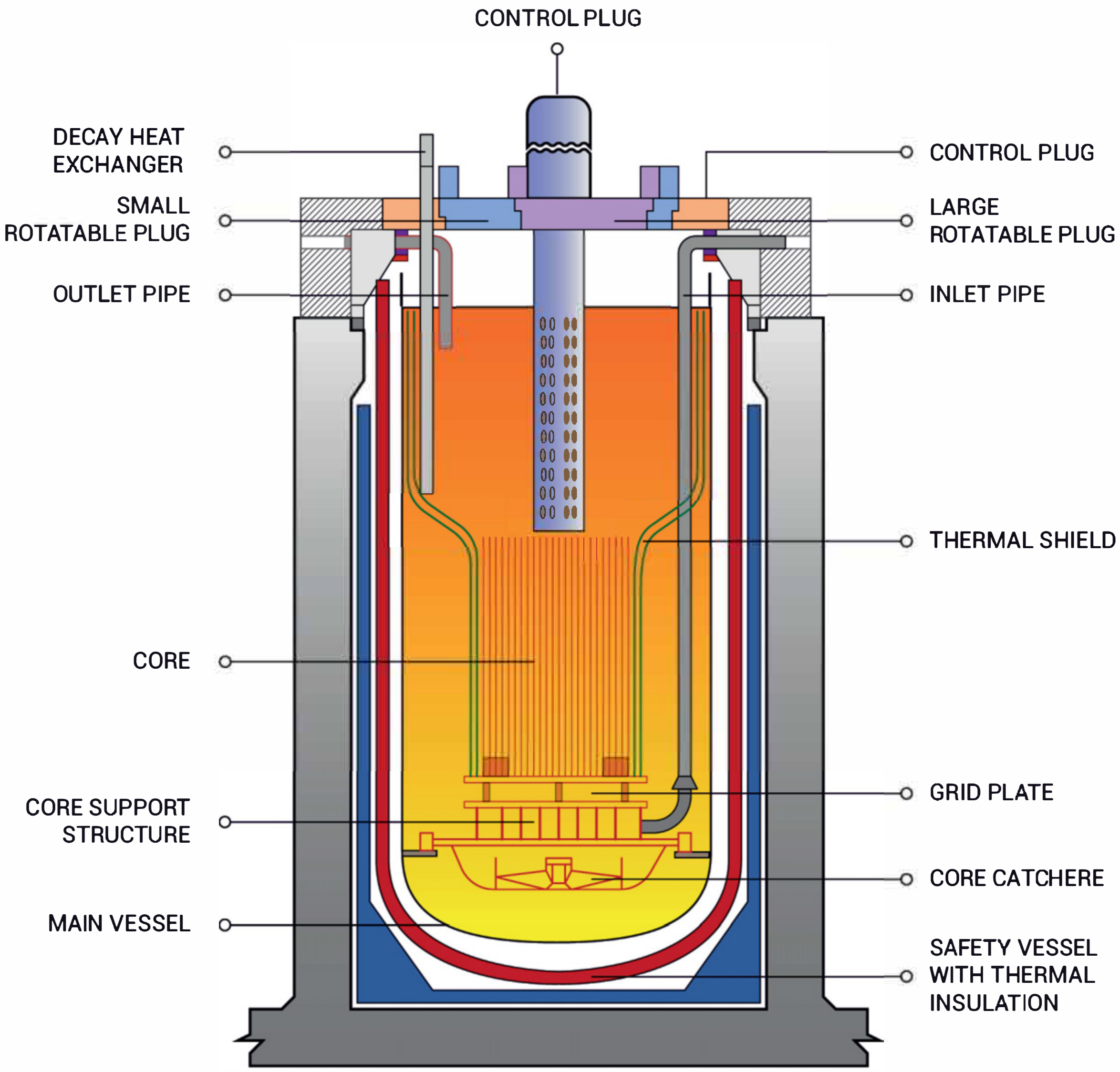


Schematic of Block Type SMR

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.

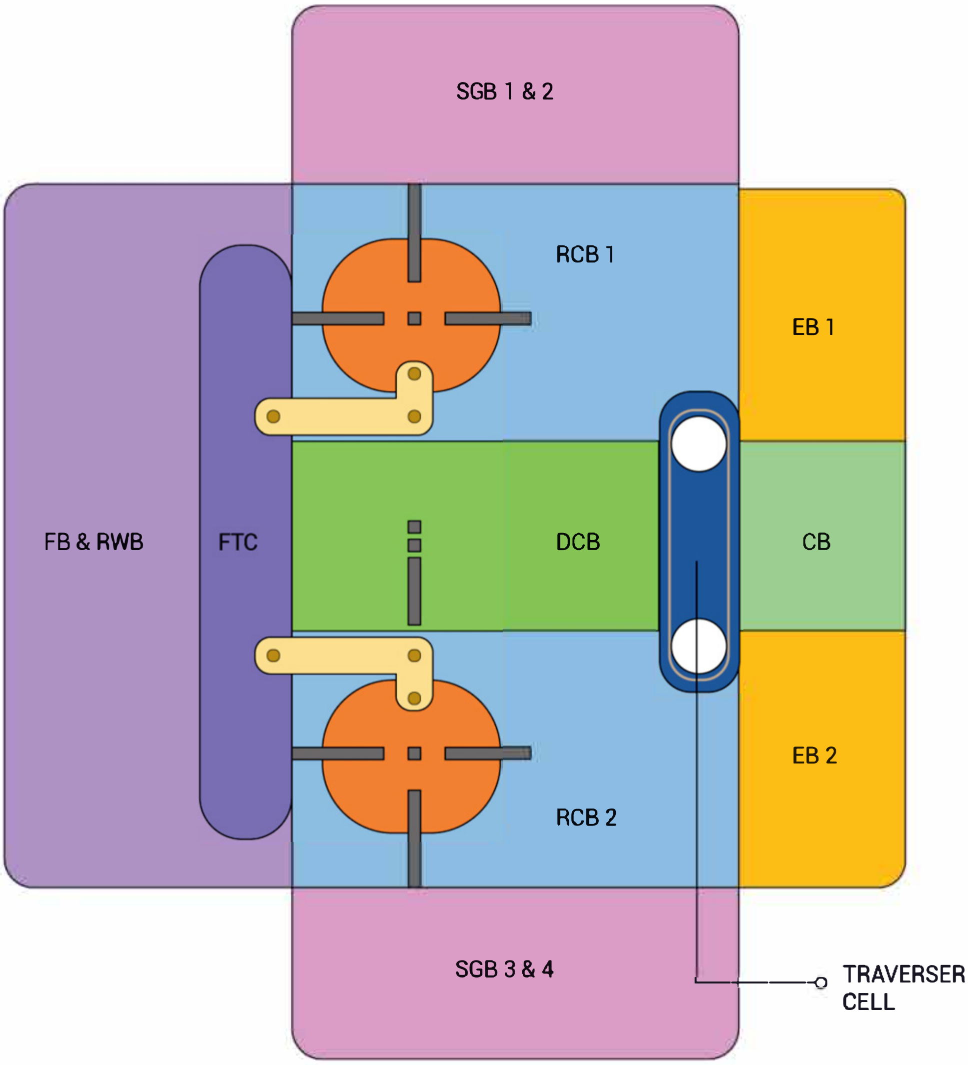


Schematic of FBTR-2

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.

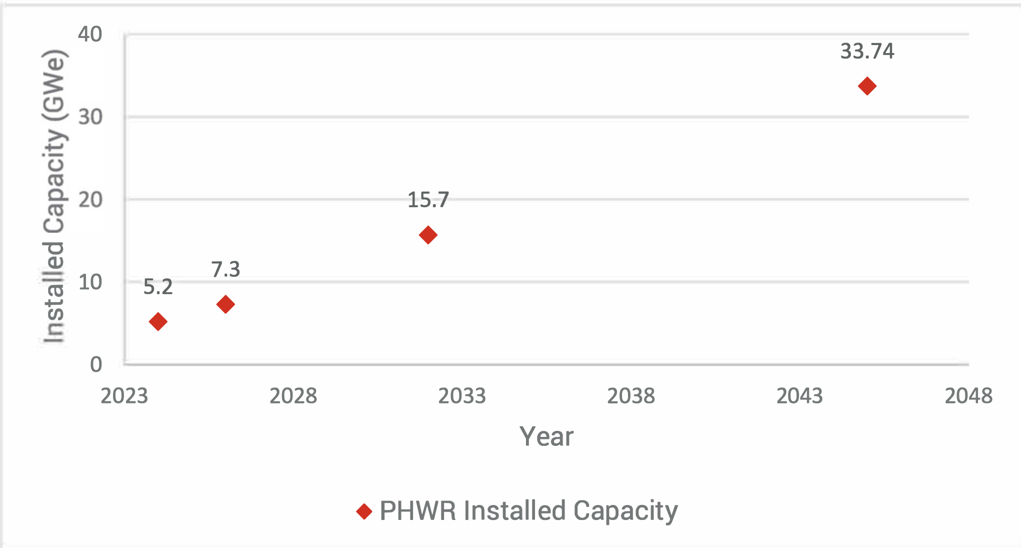
Institute for Plasma Research (IPR) has wide experience in tokamak physics and engineering. Steady state superconducting tokamak (SST-1) at IPR, with a major radius of 1.1m and a minor radius of 0.2m, was able to confine plasma for about 650ms. Under the ITER-India collaboration, the development of many 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.



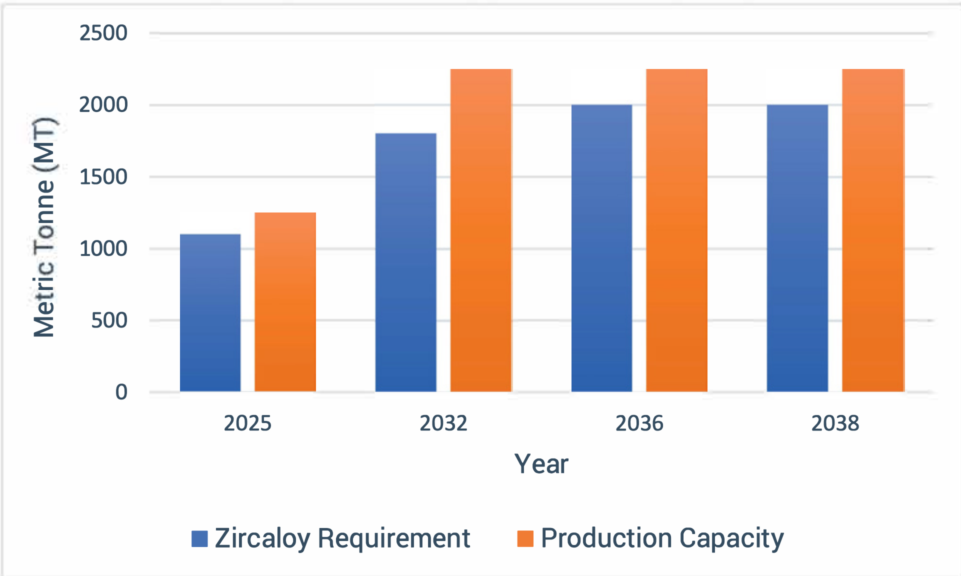
PHWR Installed Capacity Projection

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;

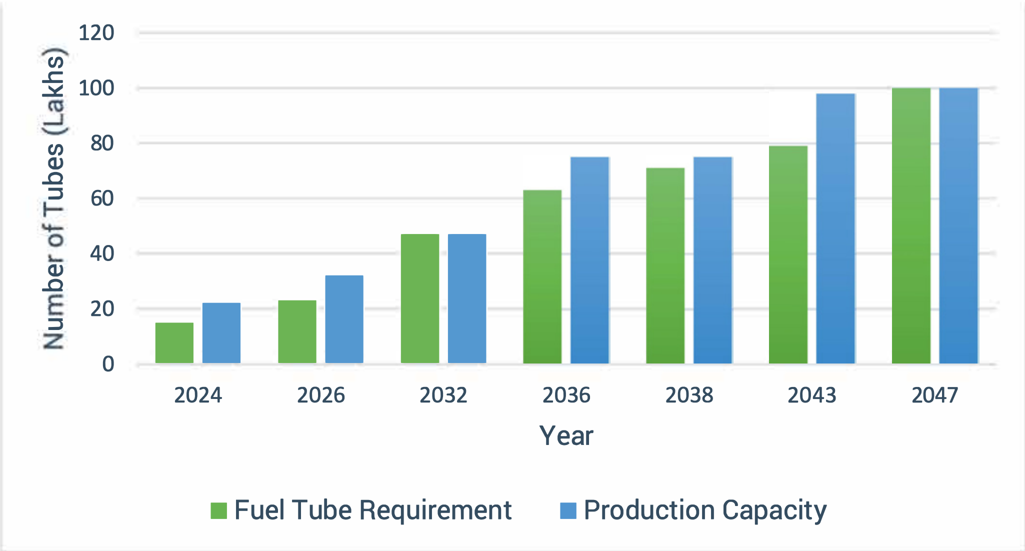
Alloy Production: The projected requirements of alloy production are proposed to be met by setting up of new facility for zirconium oxide, sponge and alloy production.



Zircaloy Requirement and Production Capacity

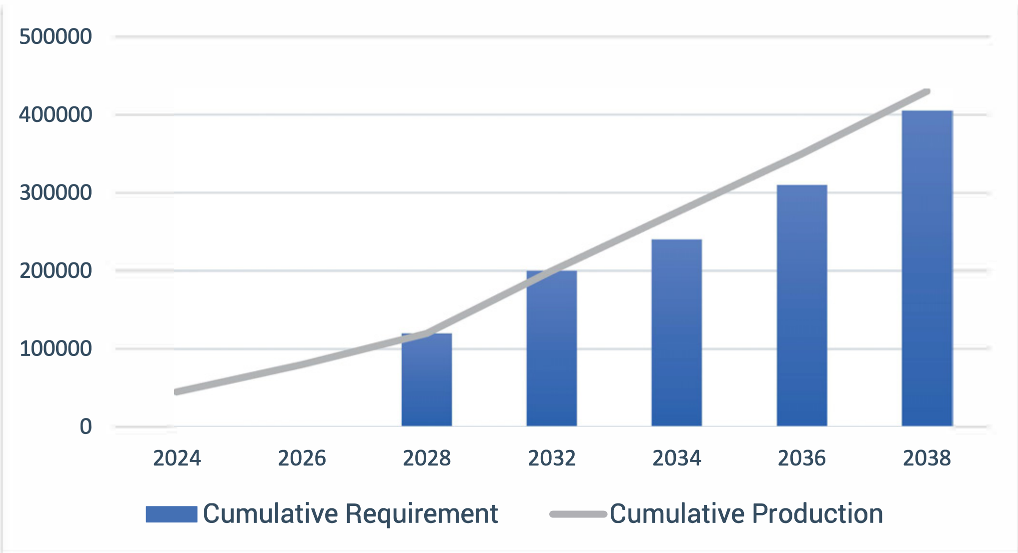
The road map along-with milestones are: augmentation of Zr-sponge and Melting facilities; process development for different grades of zircon sand & pyro-chemical route of zirconium sponge production; and recycle of Mg by electrolysis of $MgCl_2$

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.



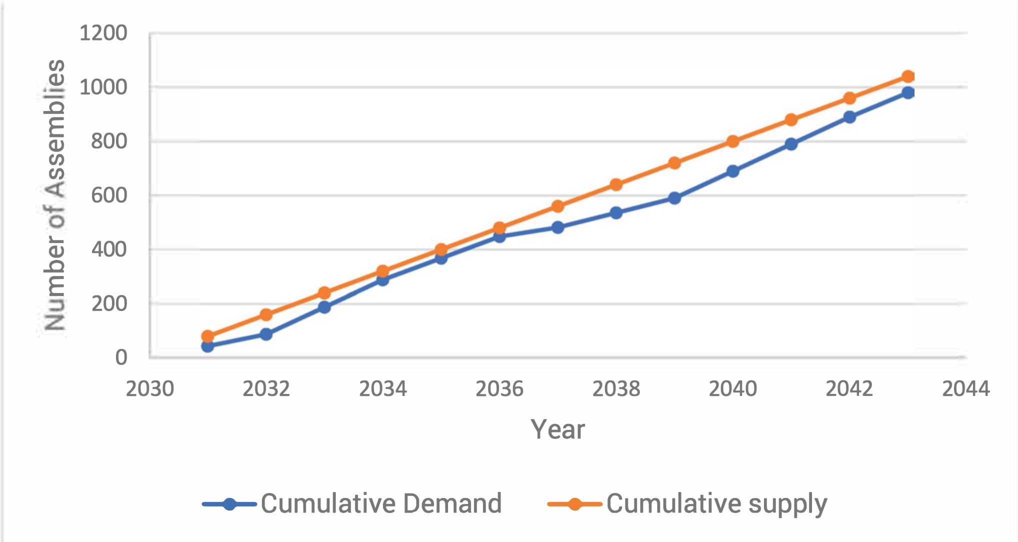
SG Tube Requirement and Production Capacity

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.



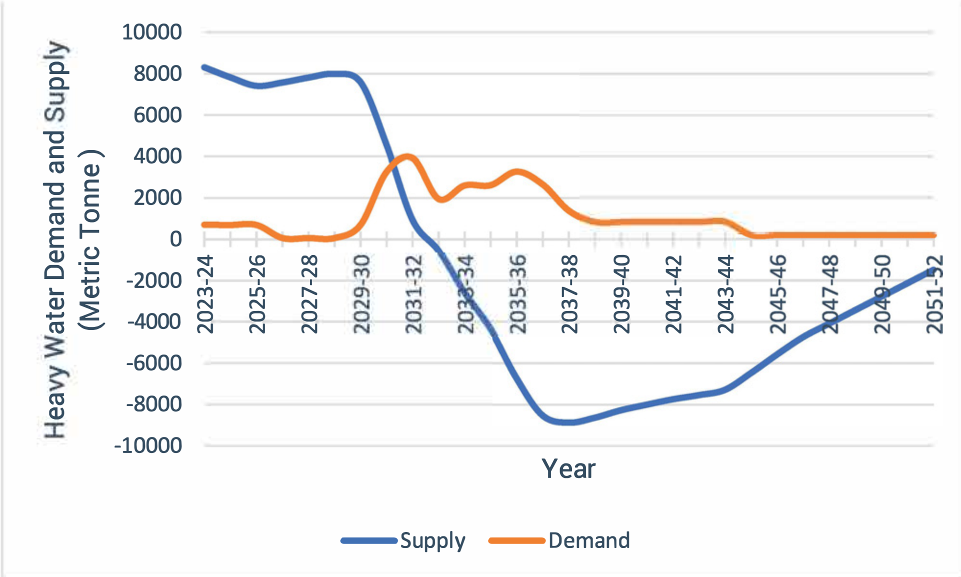
Cobalt Adjuster Rod Cumulative Demand and Cumulative Supply

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

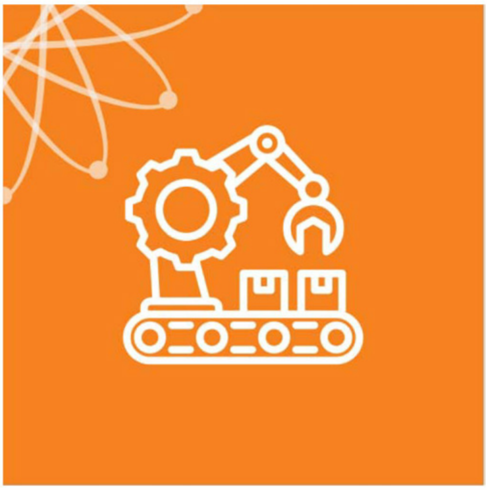
Heavy Water Board (HWB), primarily engaged in production of heavy water required as coolant and moderator for pressurised heavy water reactors (PHWR). It is among the largest heavy water producing entities in the world. Presently, HWB is able to cater the domestic need of heavy water for PHWR programme & 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.

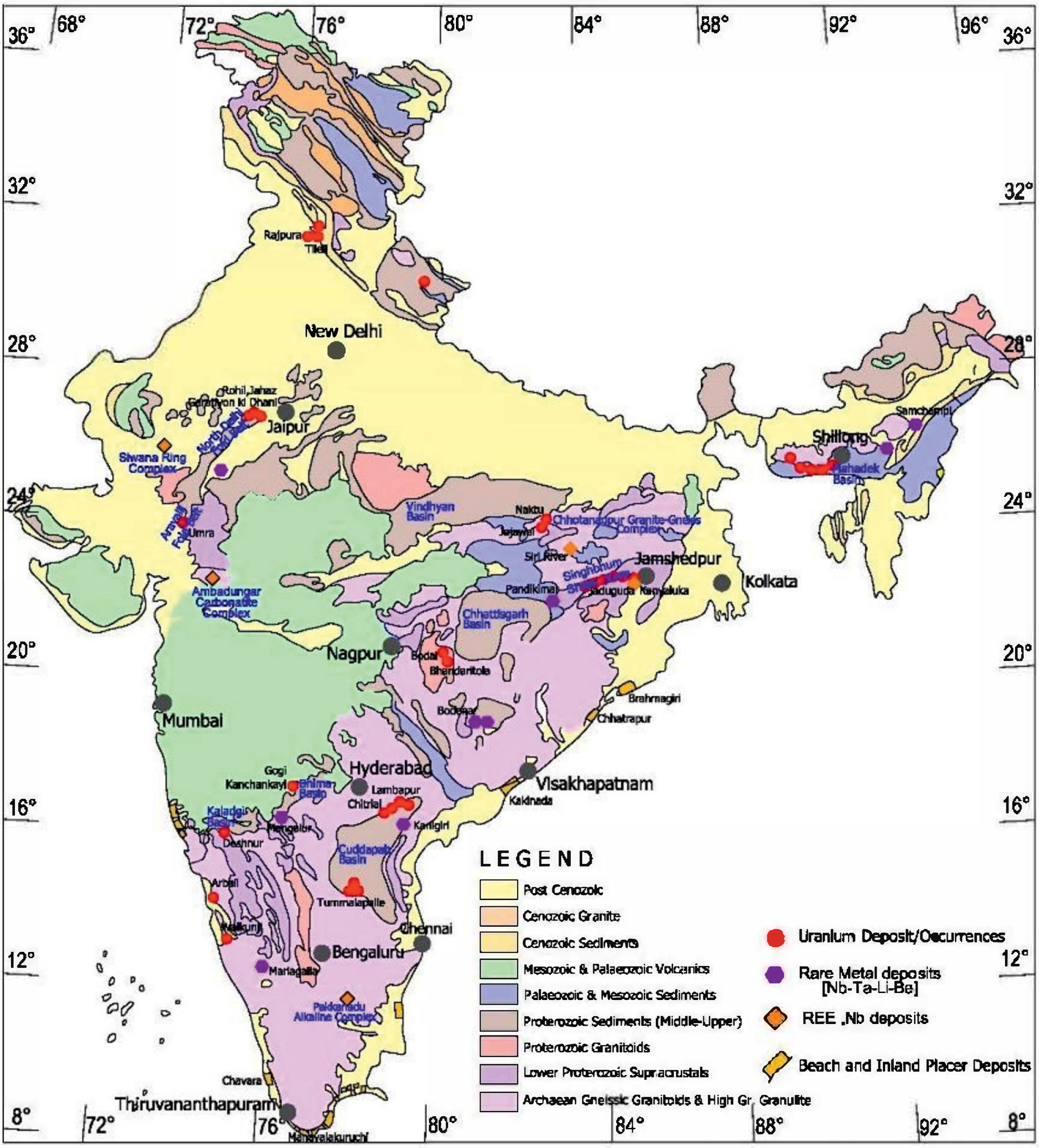
For augmentation of BSM resources, systematic exploration is planned along the shorelines of India, with focus on shorelines, Palaeo-shorelines of Mahanadi Delta, Odisha and Teris/Red sediments in Tamil Nadu and Andhra Pradesh. Besides, sonic drilling in parts of Odisha, Andhra Pradesh and Kerala will 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.

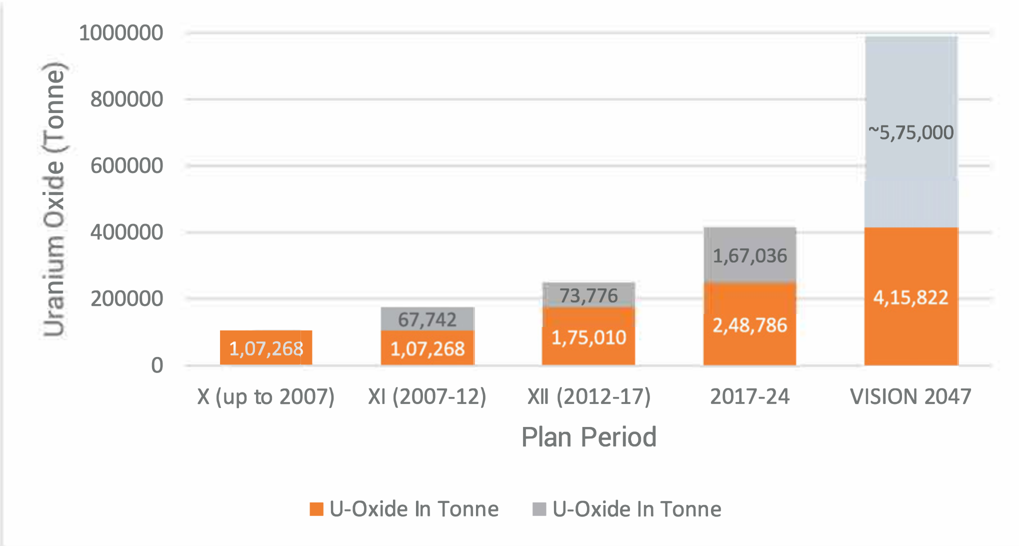
AMDER has established nearly 4,15,000 t in-situ uranium oxide, 1,277 Mt of BSM containing ~13 Mt of monazite resource (~1.17 Mt Th oxide and ~7 Mt REO) and ~1.15 Mt REO in hard rock terrains along with ~1,26,800 Mt Nb-oxide. Besides, collection of mineral concentrates incidental to prospecting operations 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.

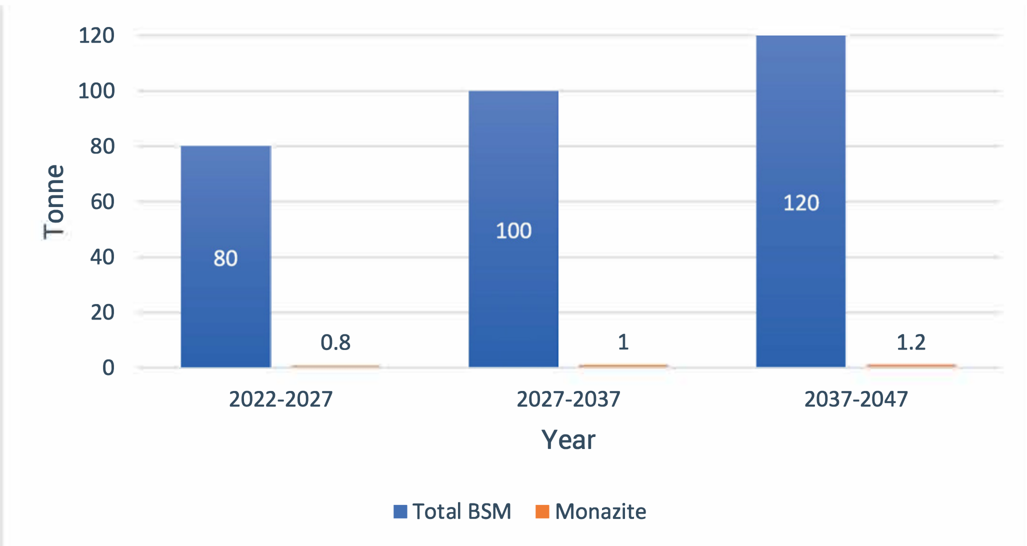


Geological map of India showing important atomic mineral deposits



Envisaged Uranium resource augmentation (2024-2047)

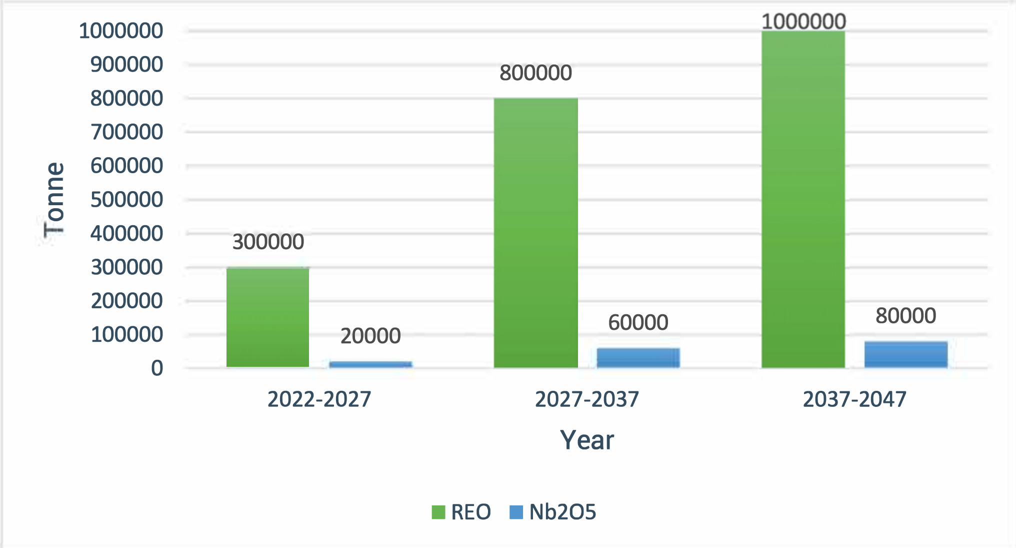
Beach Sand Minerals (BSM): Augmentation of ~300 Mt BSM likely to contain ~3 Mt of monazite (Th+REE) is envisaged during 2022 to 2047. This will comprise ~85 Mt under indicated category from new areas and ~215 Mt under inferred category from deeper part of existing deposits. Accordingly, the BSM resource 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)

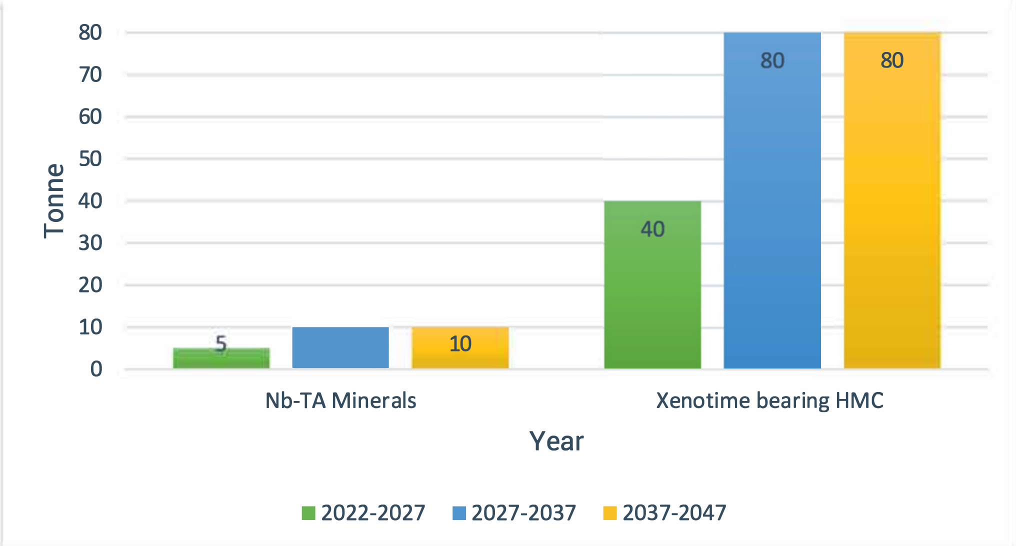
REE and Nb resources in hard rock terrains: Augmentation of ~21,00,000 t RE Oxide and 1,60,000 t Nb- oxide is envisaged during 2022 to 2047 from the carbonatite (Ambadungar & Saidiwasan, Gujarat; Pakkanadu, Tamil Nadu) and alkaline complexes (Siwana Ring

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.

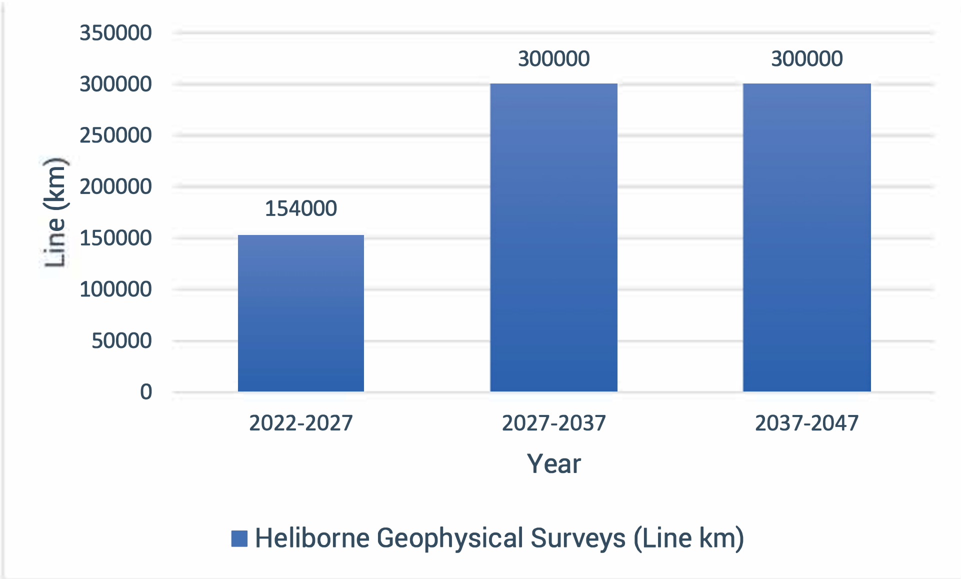


Envisaged Rare Metals, Xenotime bearing HMC resource augmentation (2022-2047)

Envisaged Li-oxide resource augmentation (2022-2047)

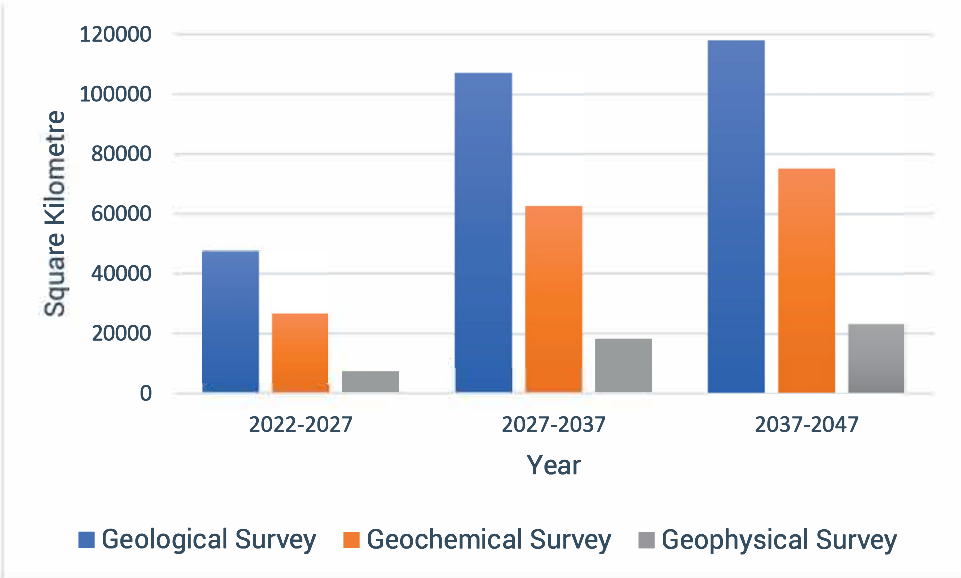
Resource estimates: Substantial quantum of multi-disciplinary exploration inputs viz. heliborne geophysical surveys, ground geological, geophysical and geochemical surveys followed by extensive drilling need to be deployed for augmentation of the envisaged resources. Optimal targets for such exploration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

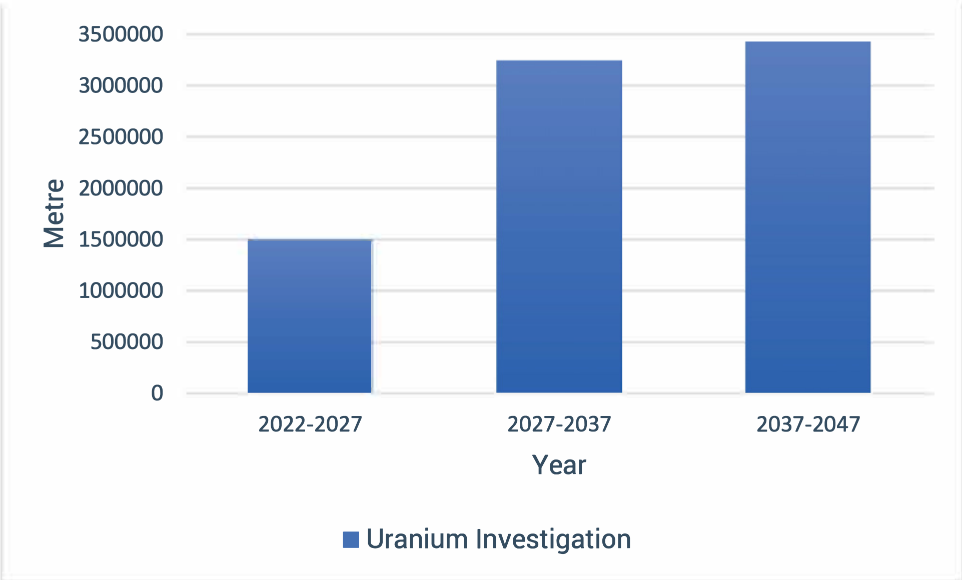
Ground Geological/Geochemical/Geophysical Survey: Ground geological, geochemical and geophysical surveys will further help in narrowing down the targets for subsurface exploration. During the period 2022-2047, 2,72,695 sq. km geological, 1,64,375 sq. km geochemical and 48,750 sq. km geophysical surveys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



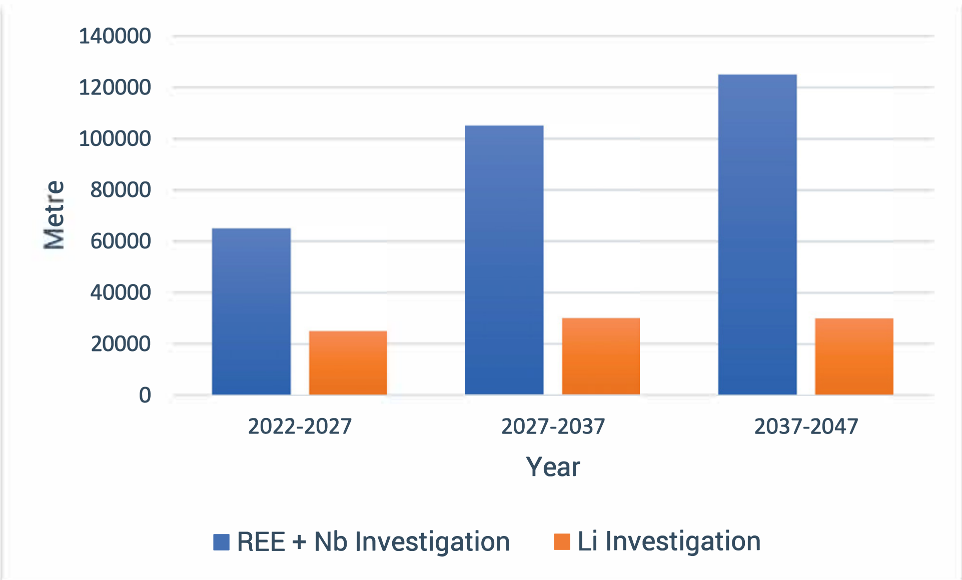
Ground geological/geochemical/geophysical surveys (2022-2047)

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.

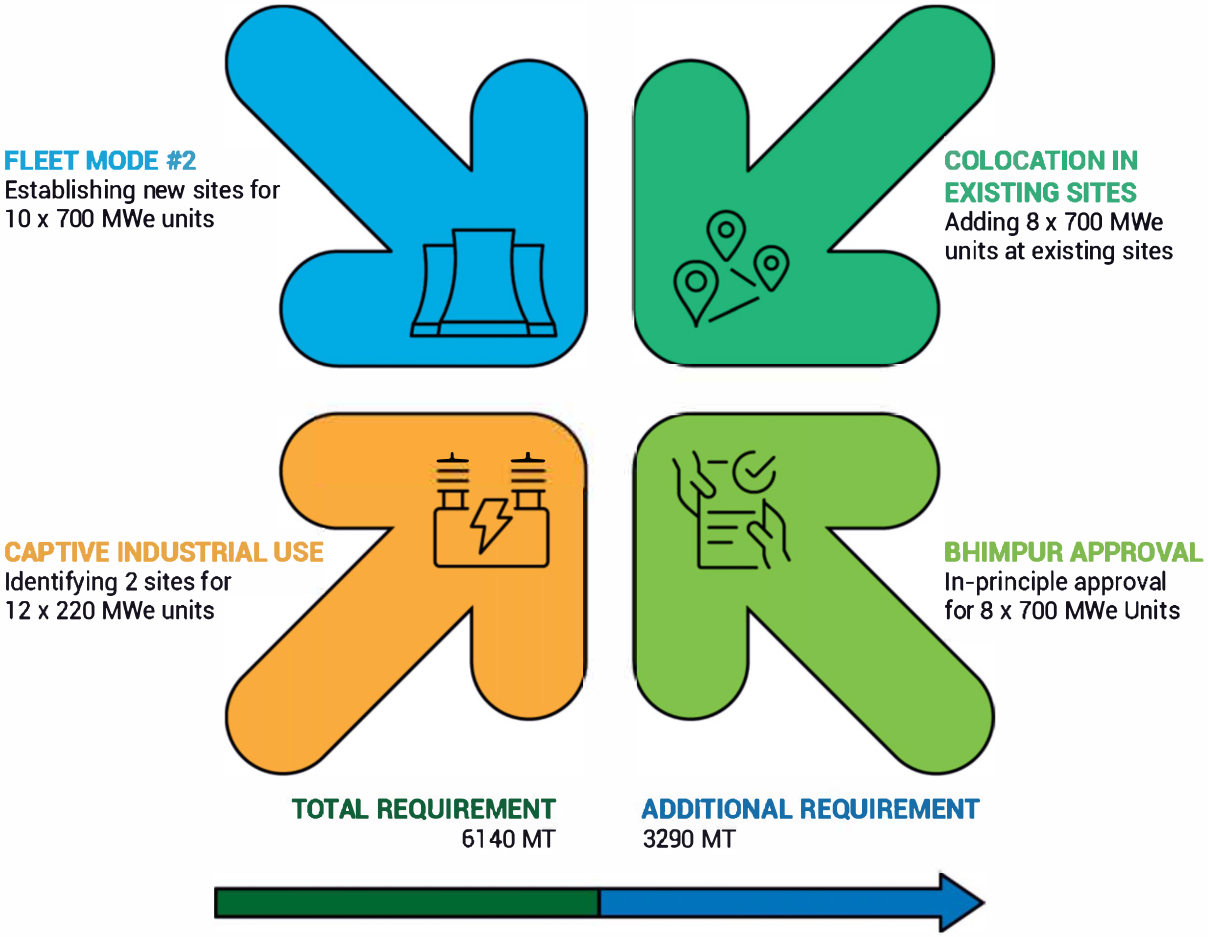
2.2 Nuclear Fuel Fabrication

2.2.1 Uranium Fuel Fabrication for Power Reactors

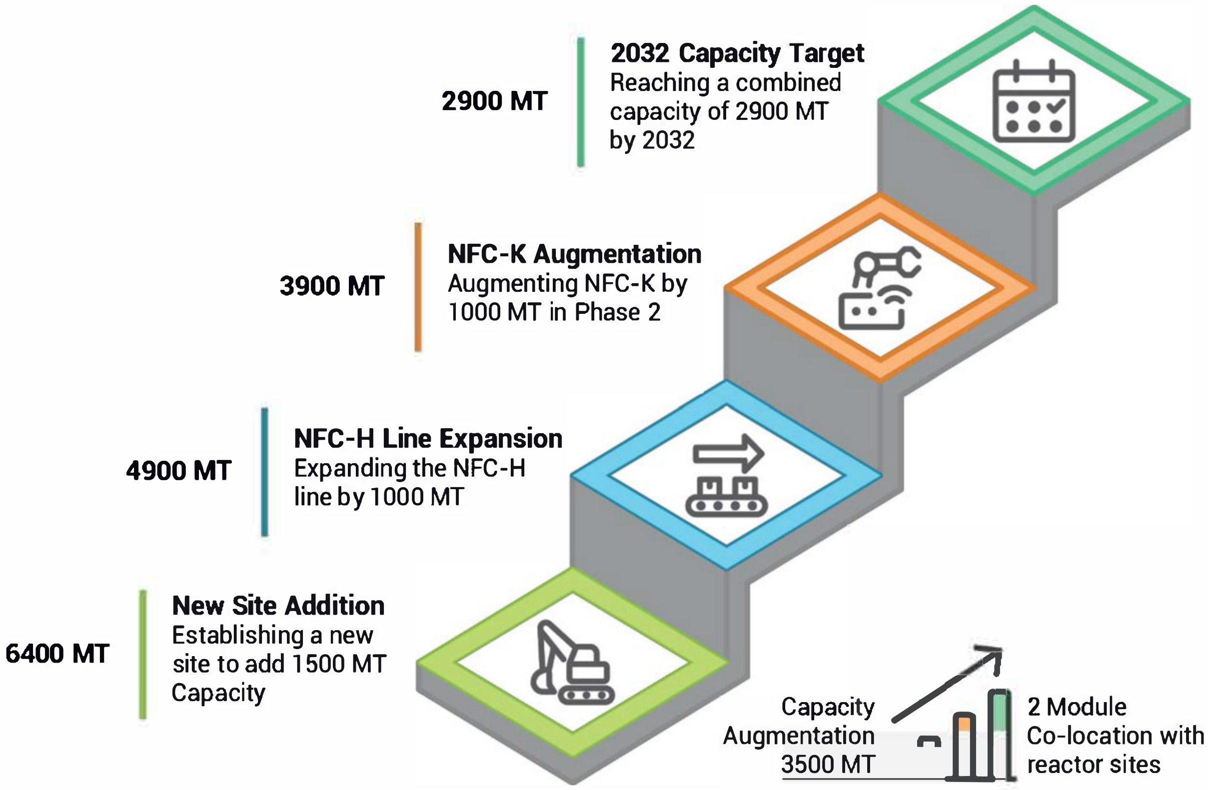
PHWRs are going to play crucial role in expansion of nuclear power in India with several units planned in phased manner till 2032. The installed capacity is expected to increase to 15660 MWe by 2032 through addition of 12 PHWR-700. Beyond 2032, 34 PHWRs (22x700MWe and 12x220MWe) are planned by NPCIL 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.

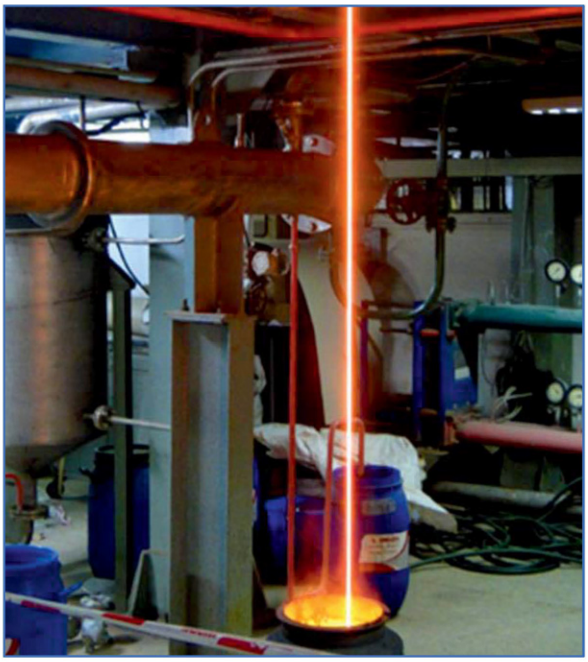
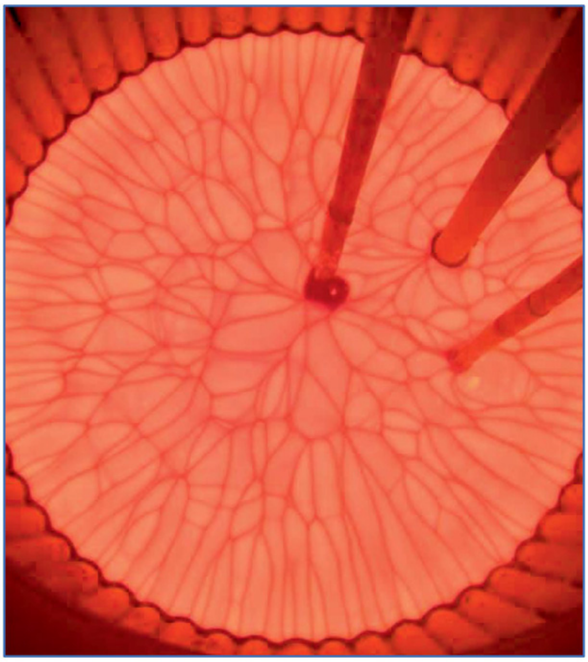
Presently the validation of the technology has been carried out in the pilot facility CORAL (Compact Facility for Reprocessing of Advanced fuel in Lead cell). The facility has been successfully operating for the past 20 years, processing spent fuel discharged from FBTR with very good recovery and decontamination 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

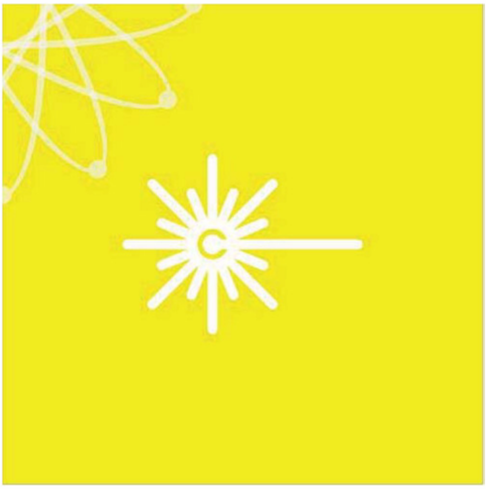
viii. Pre-commissioning commissioning of the prototype facility for regular operation

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

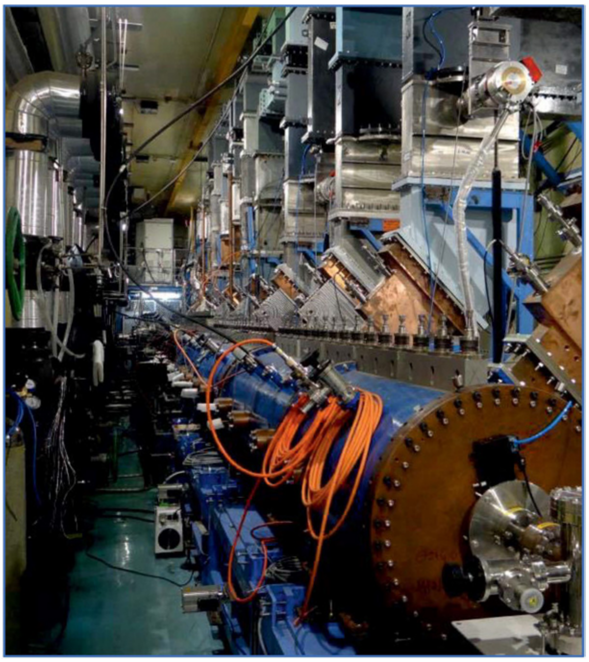
3.1 Linear High Intensity Proton Accelerator

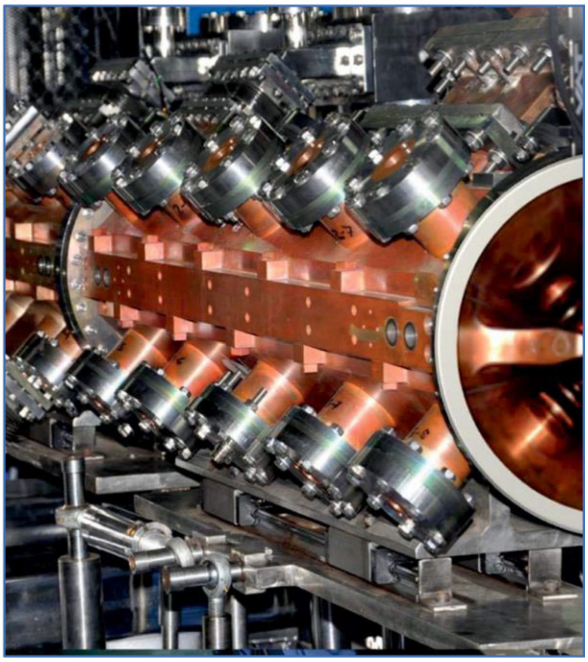
Accelerator driven-subcritical system (ADS) is an advanced nuclear system that could be used for the transmutation/incineration of fission products/minor actinides, thereby eliminating the need of geological repository in near future. Additionally, it can produce electricity as the energy amplifier and 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

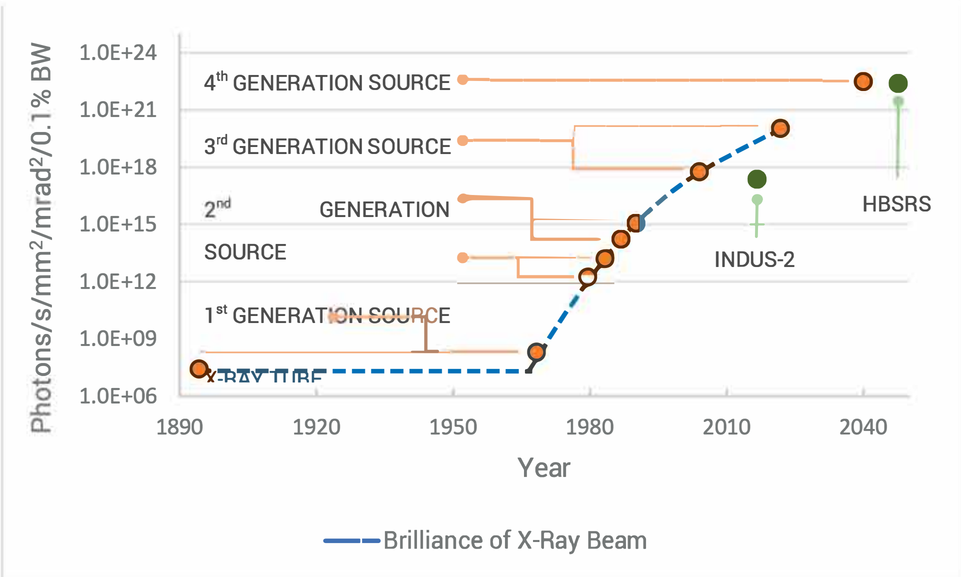
ii. Injector-cyclotron, 4 to 6 sectors up to 80 - 120 MeV

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.

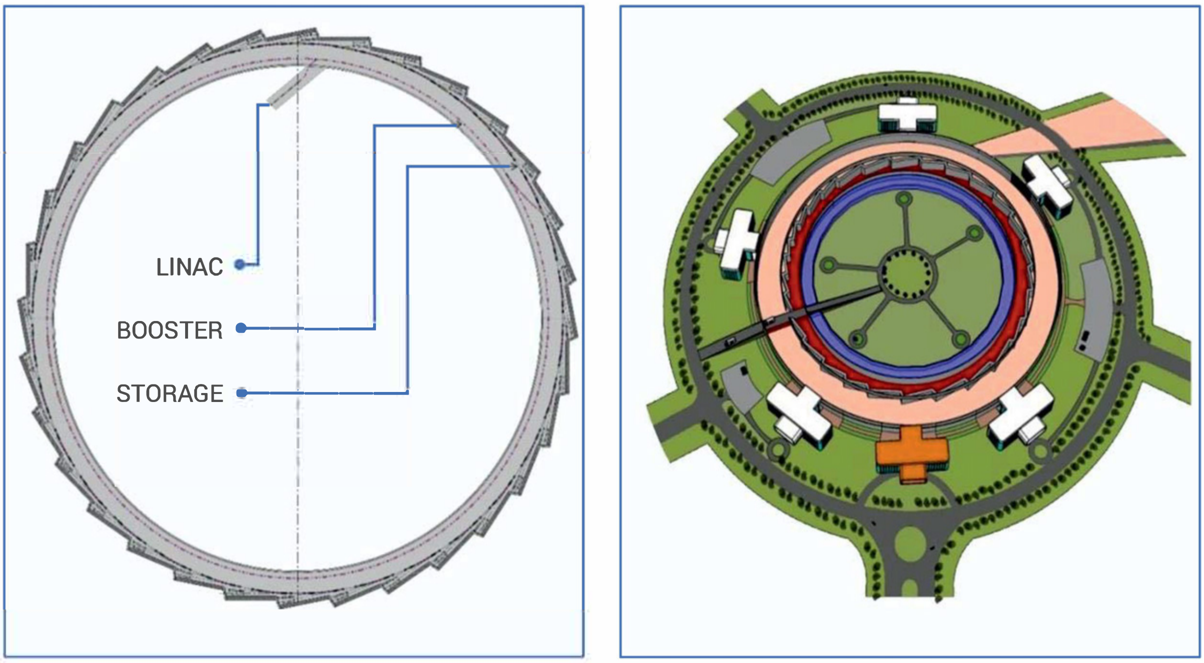
3.3 Establishment of a National High Brilliance Synchrotron Radiation Source: Indus-3

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.

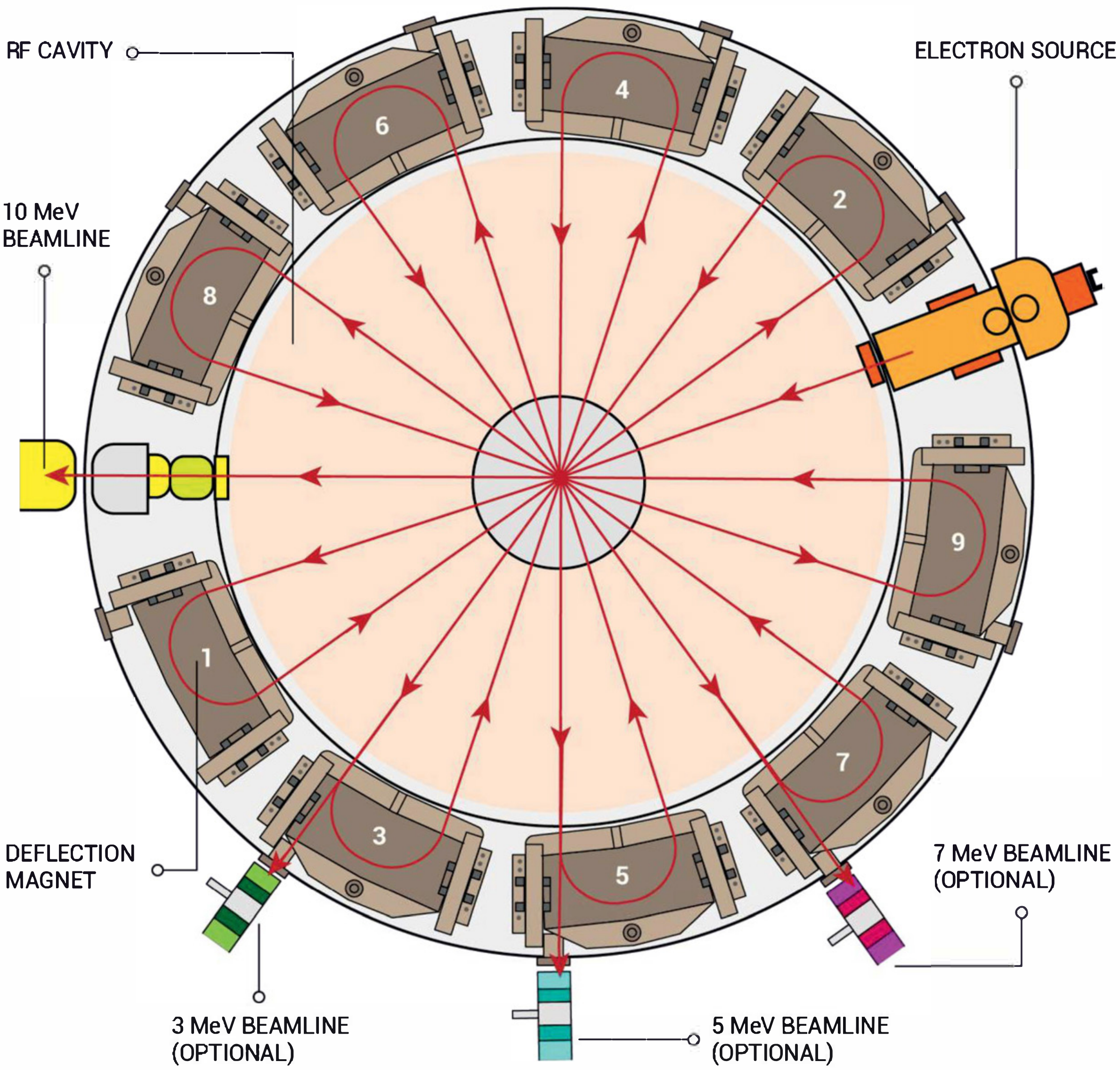


Indus-3 machine layout (left) and its conceptual bird's eye view (right)

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.

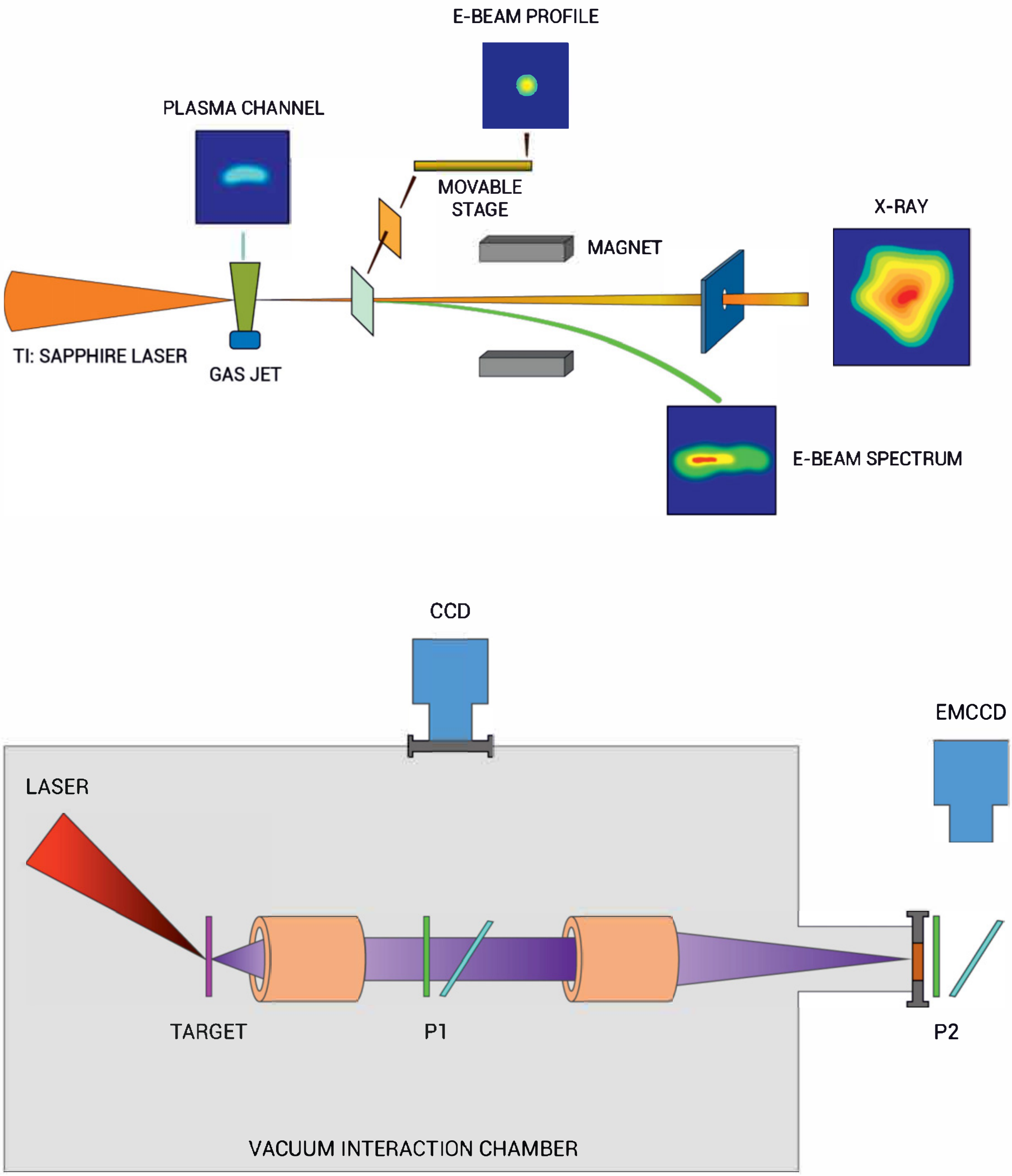
ii. In phase-II, each beamlet will be optimised to get > 635 J so that > 10 kJ can be achieved with 16 such beamlets. The 10 kJ laser will be used for various experiments in shock physics and would be Experimental Test Facility for high energy density physics.

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.

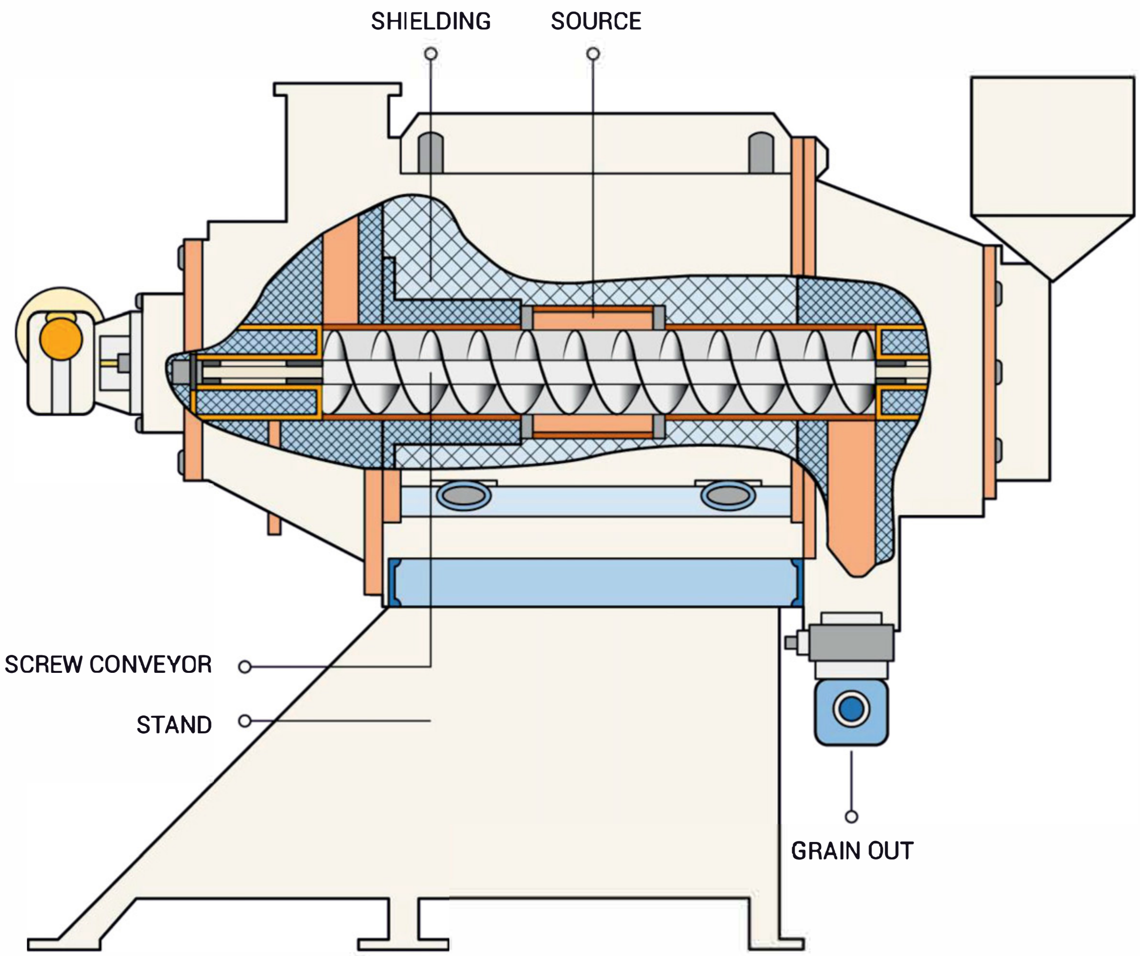
iii. Broadening the host range, e.g., Rhizobium on cereals, mycorrhiza on *Brassica*.

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.

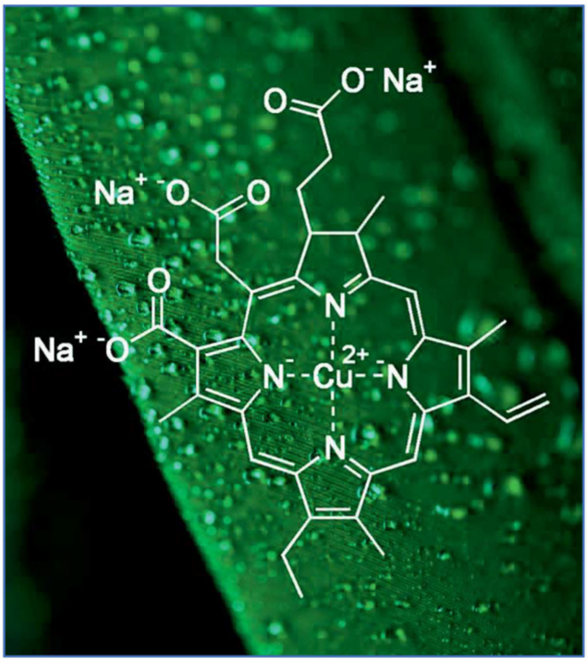
Focus will be laid on the indigenous production and application of ^{225}Ac for targeted α-therapy. Activities to begin for alternative production routes of ^{225}Ac to meet the increasing demand of ^{225}Ac. Another emerging α-emitting radioisotope, ^{211}At, will be produced using the cyclotron at 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.

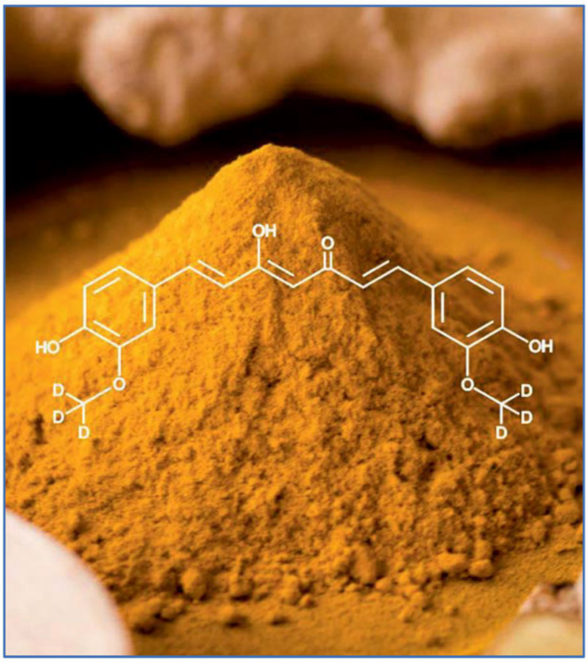
The indigenous production of α-emitters will mitigate import requirements and production of several new radioisotopes meeting the diverse needs of cancer patients while also meeting the goals of making Atmanirbhar Bharat in radioisotope production. This will provide effective and affordable healthcare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

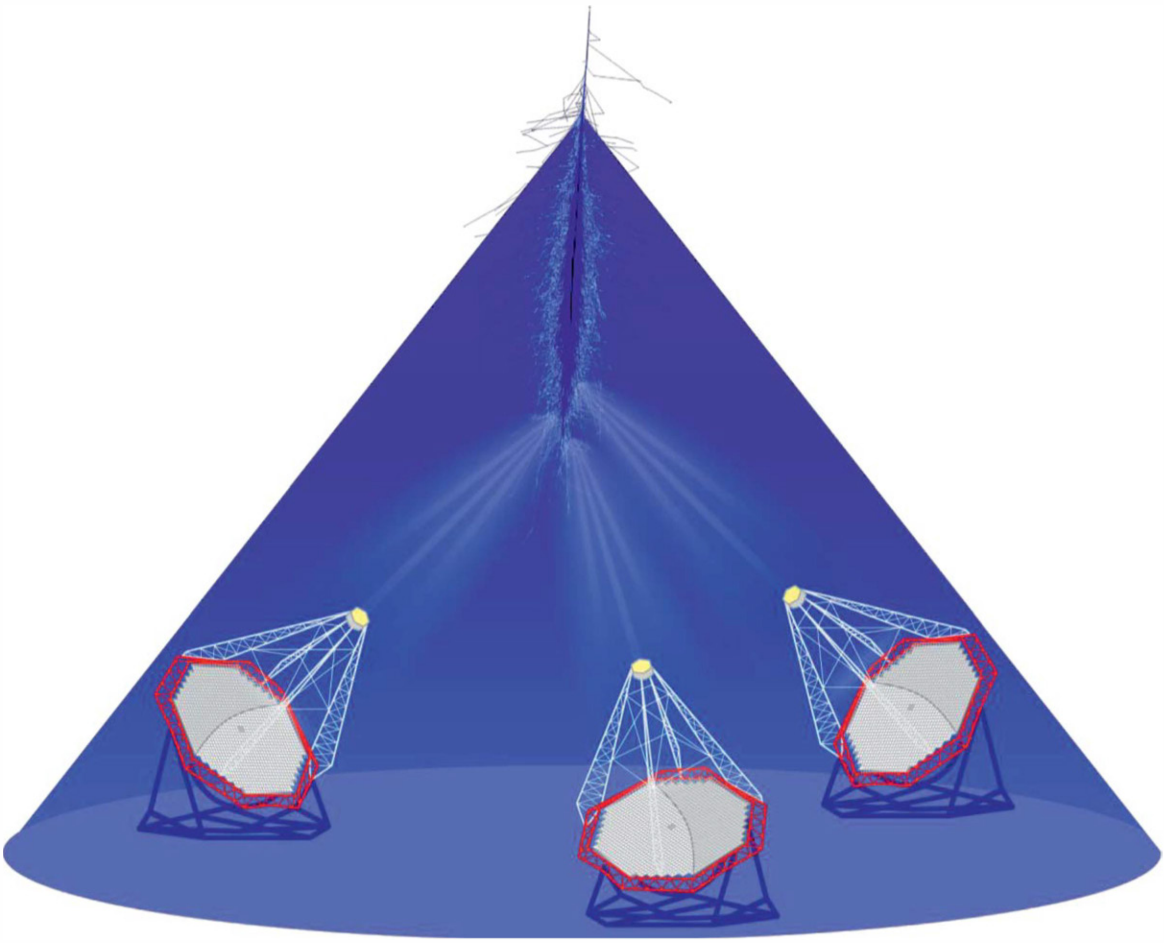
FRONTIERS IN BASIC RESEARCH

5.1 Physics

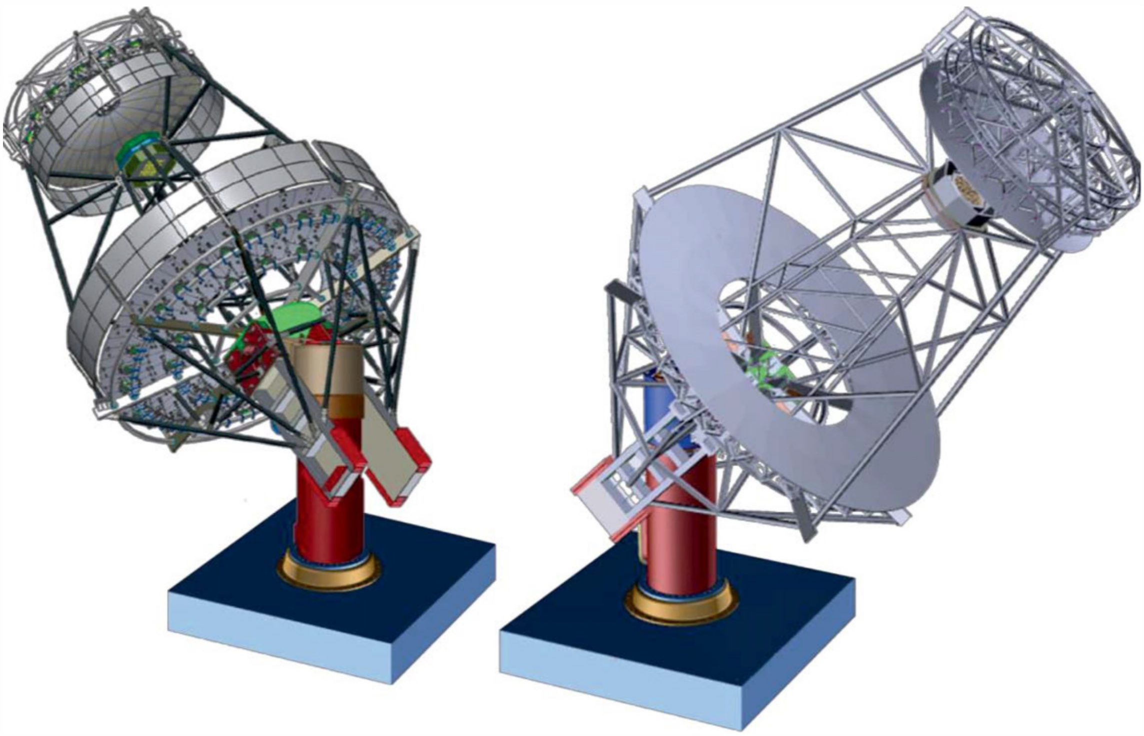
5.1.1 Large Scale Facilities for Physics Research

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.

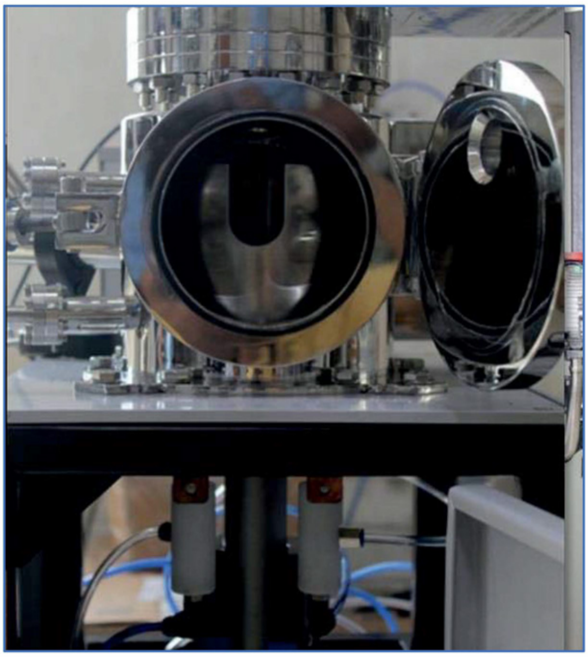
A DAE crystal growth centre for growing large size crystal is proposed at BARC Vizag. A facility for design & fabrication of C_6D_6-based liquid scintillator for detector array for nuclear physics experiments is proposed as a part of this project.

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.

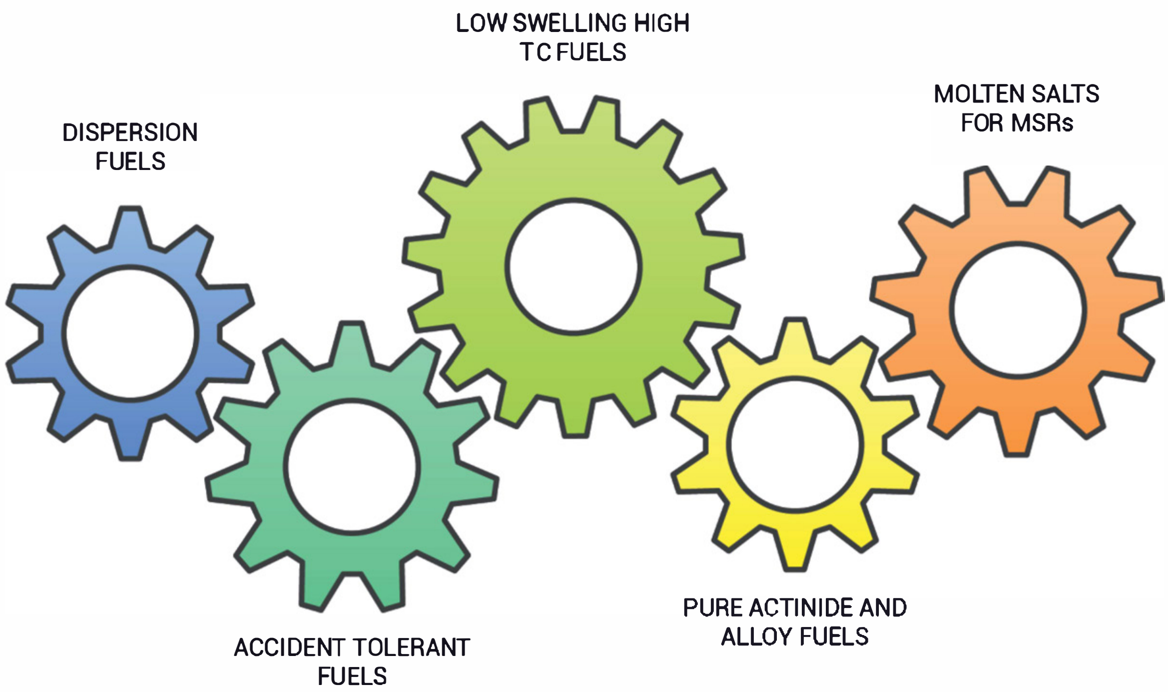
In-house developed capabilities for cold atom trapping will be utilised to trap single atom for preparing quantum qubits. Multiple qubits will be prepared and entanglement among them will be demonstrated by using Rydberg blockade phenomena. In parallel, RRCAT's capabilities in developing advanced lasers 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.

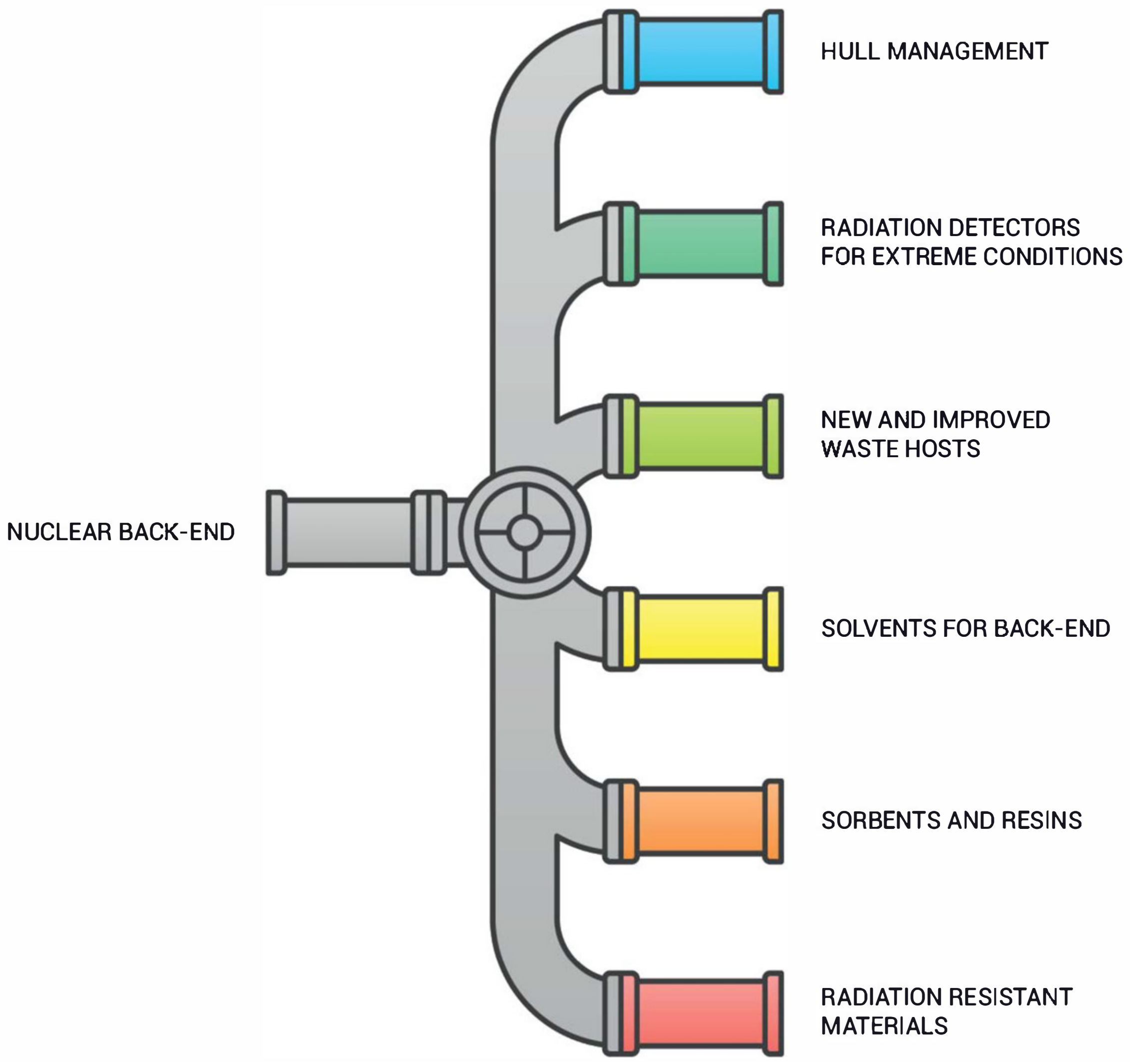
This brings key advantages in terms of

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)

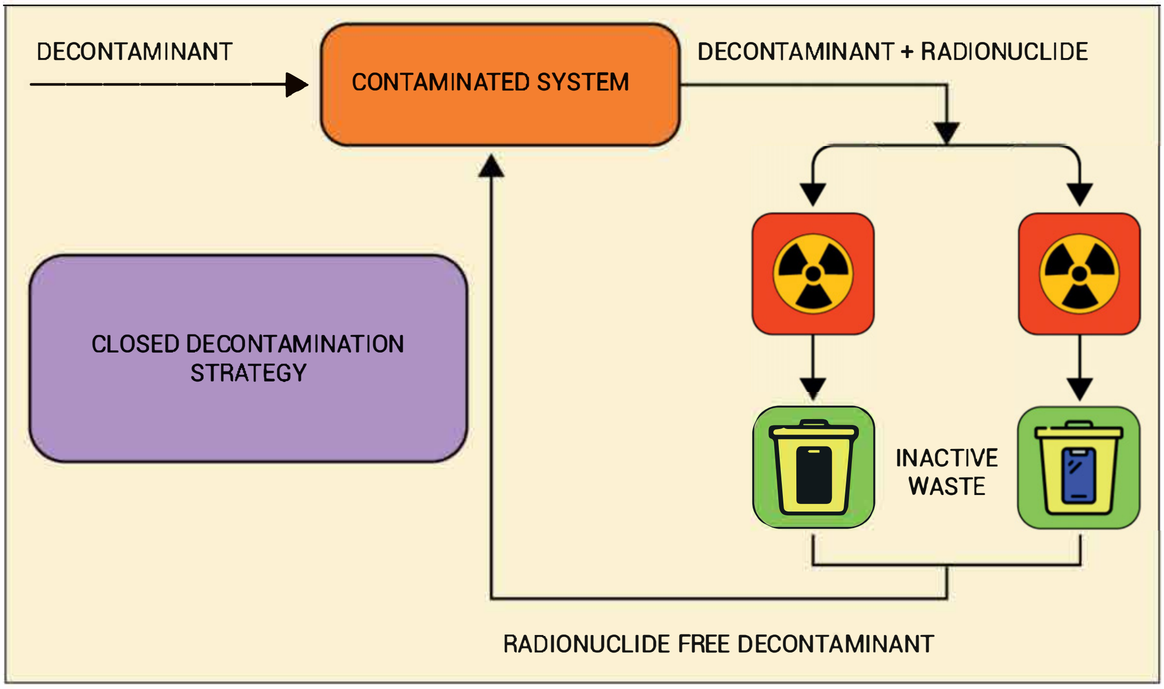
Separation of actinides individually or in group is challenging due to their close and complicated chemistry in the solution phase. Their separation is important for the safe management of the nuclear waste. DGA-based processes (being evaluated worldwide) are promising for group actinide separation but 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.

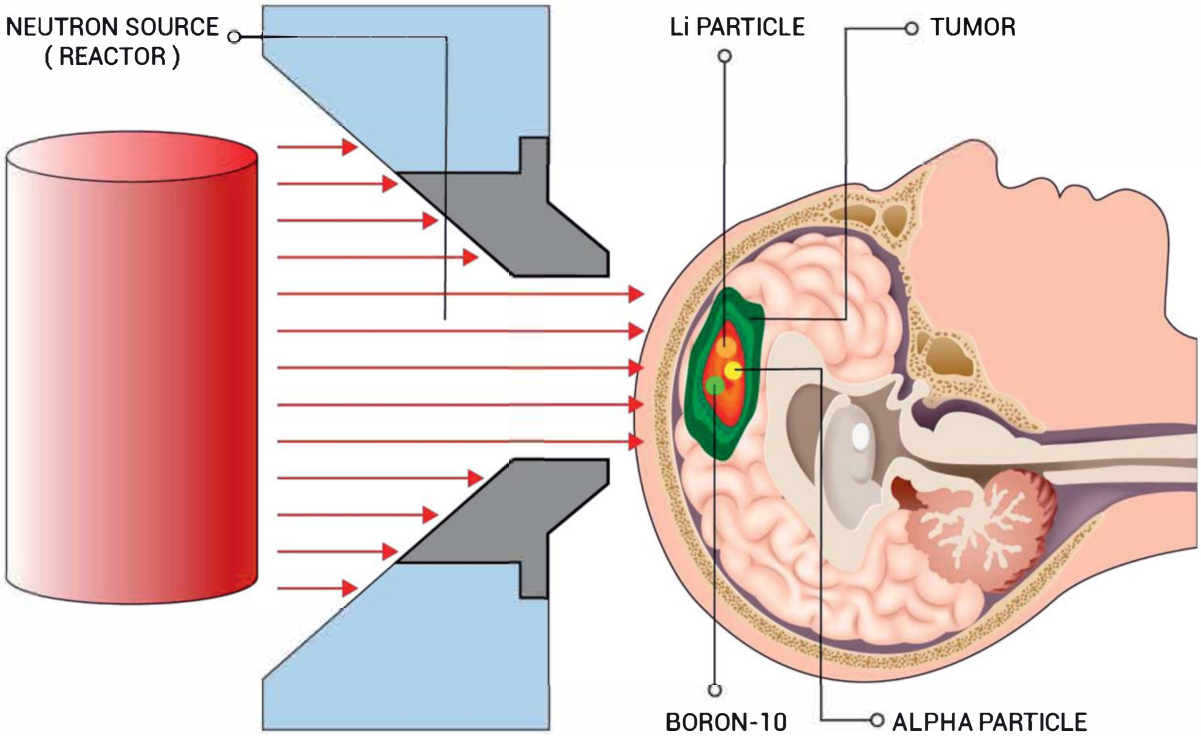
Development of lead-free shielding materials against diagnostic X-rays (30-125 keV) is in progress, where the preliminary screening of silicone polymer as matrix is completed along with the standardisation of nanocomposite preparation. Multi-filler polymer nanocomposites developed here have been compared 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.

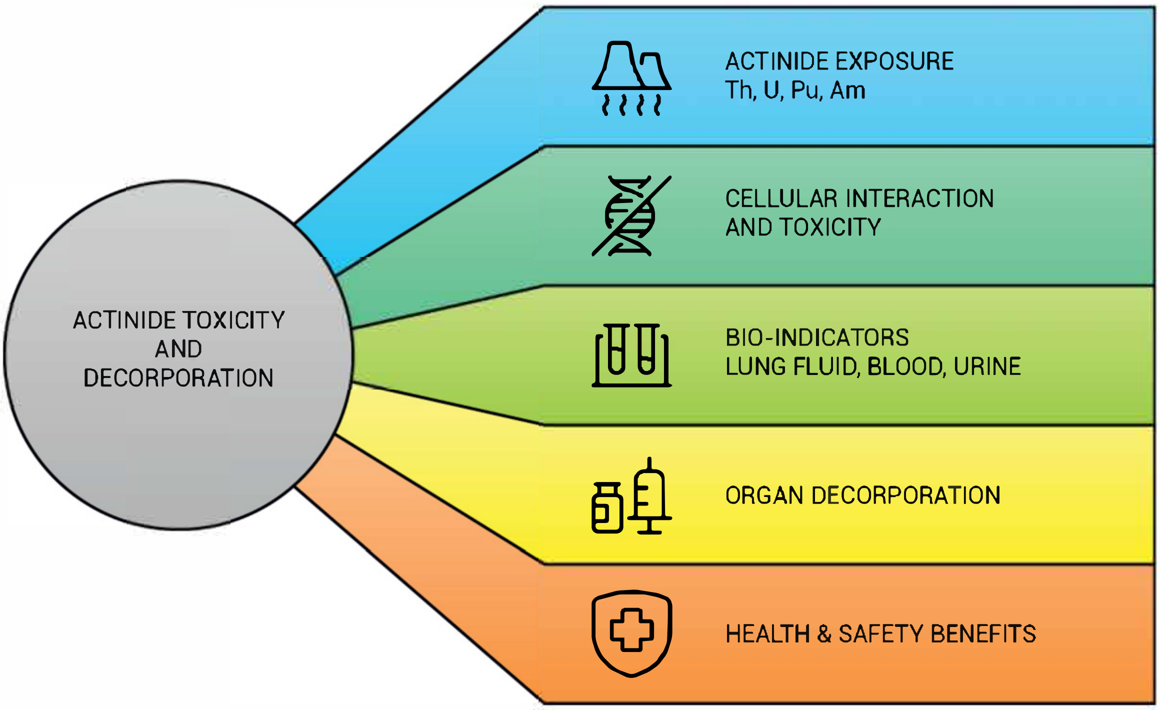
5.3.2 Research and Development towards Advanced Cancer Therapy

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

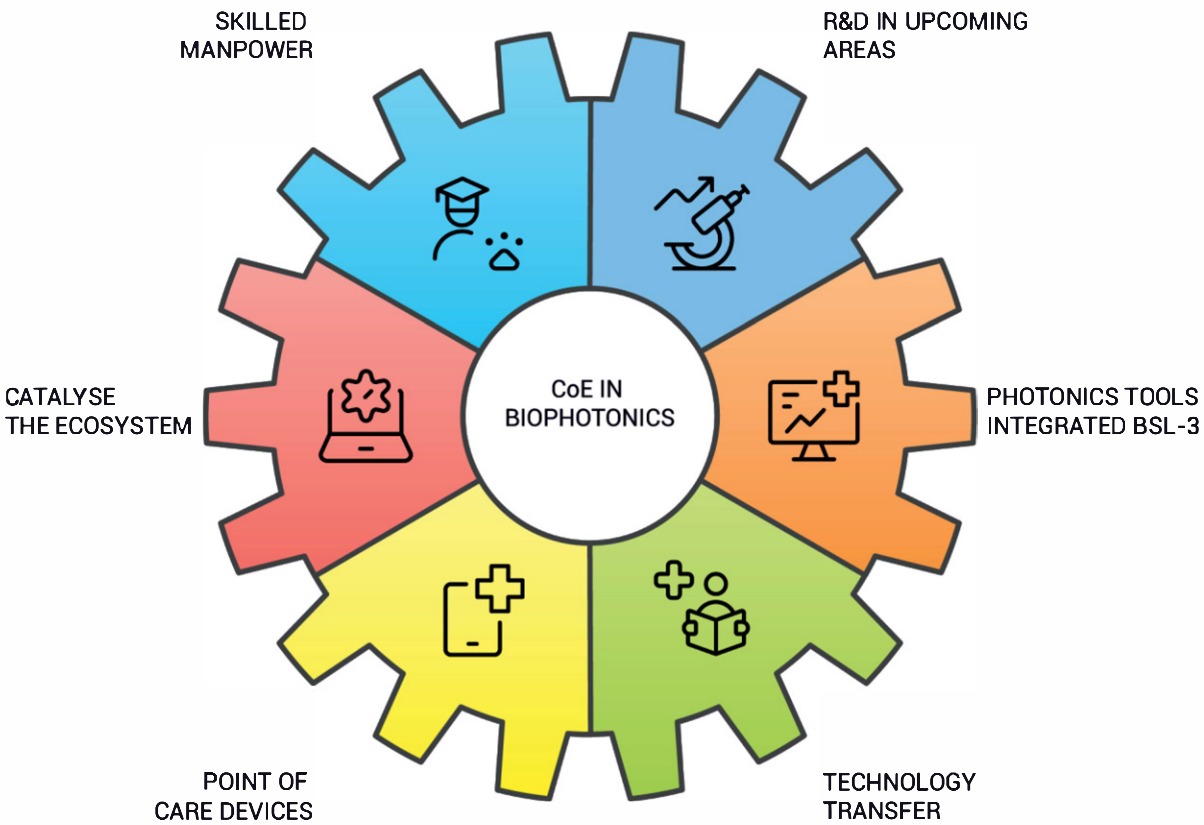
Power plants utilise large volumes of water for cooling purpose, which is sourced from natural reservoir and then released back. Biochemical interactions among source water constituents (minerals, dissolved gases, aquatic biodiversity etc.) under variable temperature and flow conditions cause biofouling, 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”

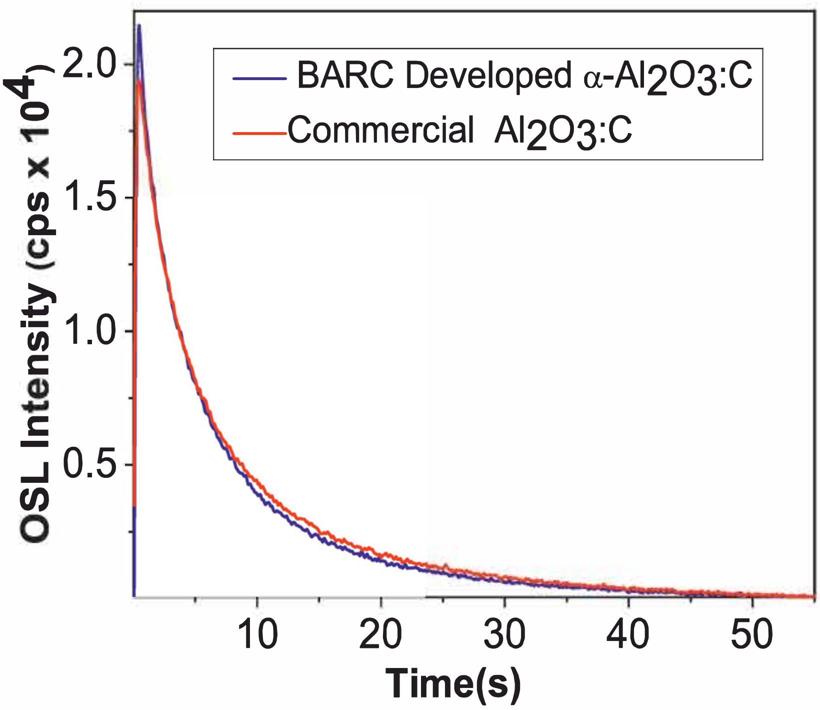
The terms secondary standard dosimetry lab (SSDL) and primary standard dosimetry lab (PSDL) are used by International Atomic Energy Agency to refer to the standards available in a laboratory for measurement of absorbed dose to water. Absorbed dose to water is the quantity of main interest in radiation 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.

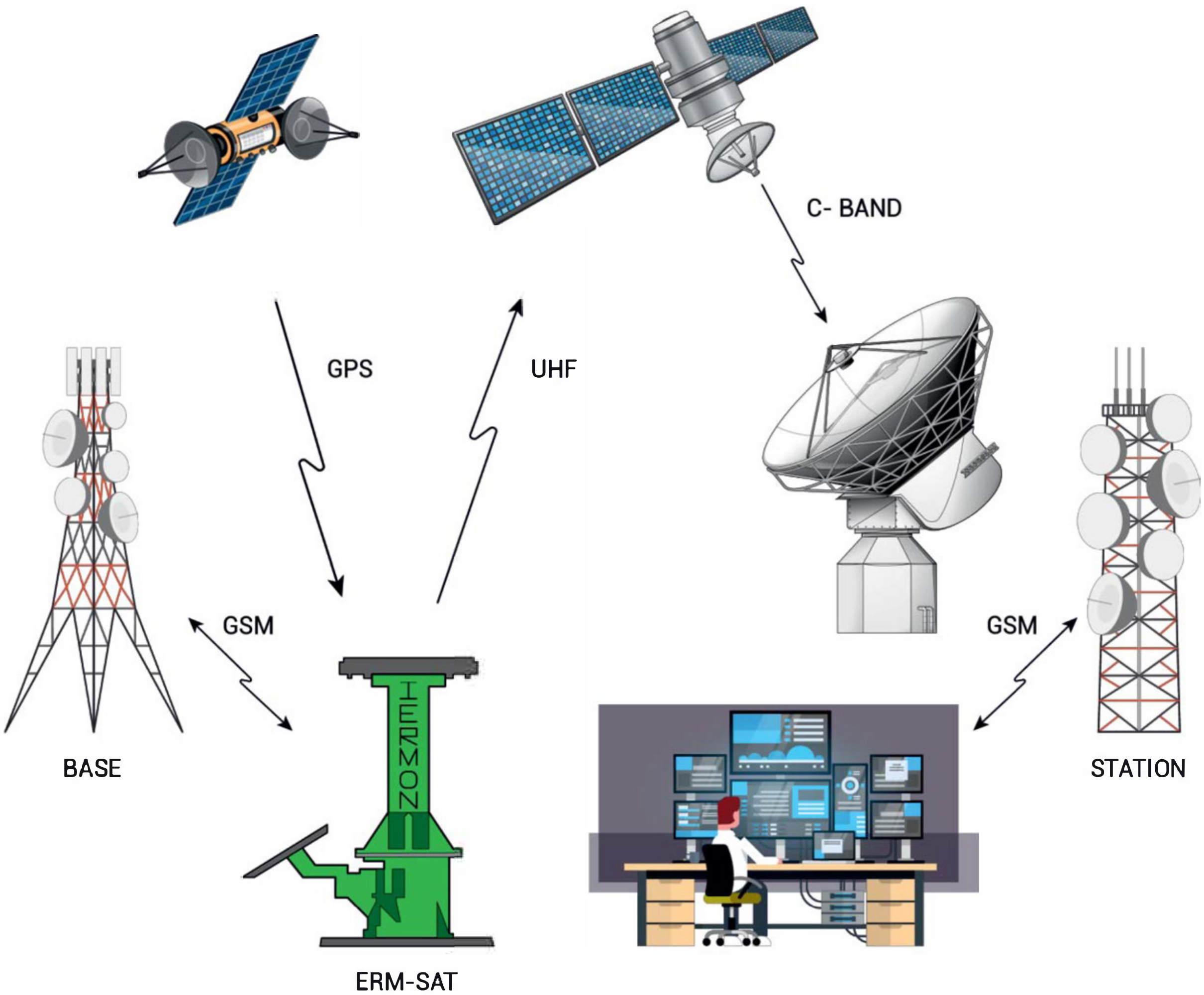
The programme will deliver a comprehensive in-house developed modelling systems for dispersion of radionuclides in different environmental media and radiological impact assessment tools for local to global scale studies. It will result in 100% indigenisation, in hazard mitigation, radiological safety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

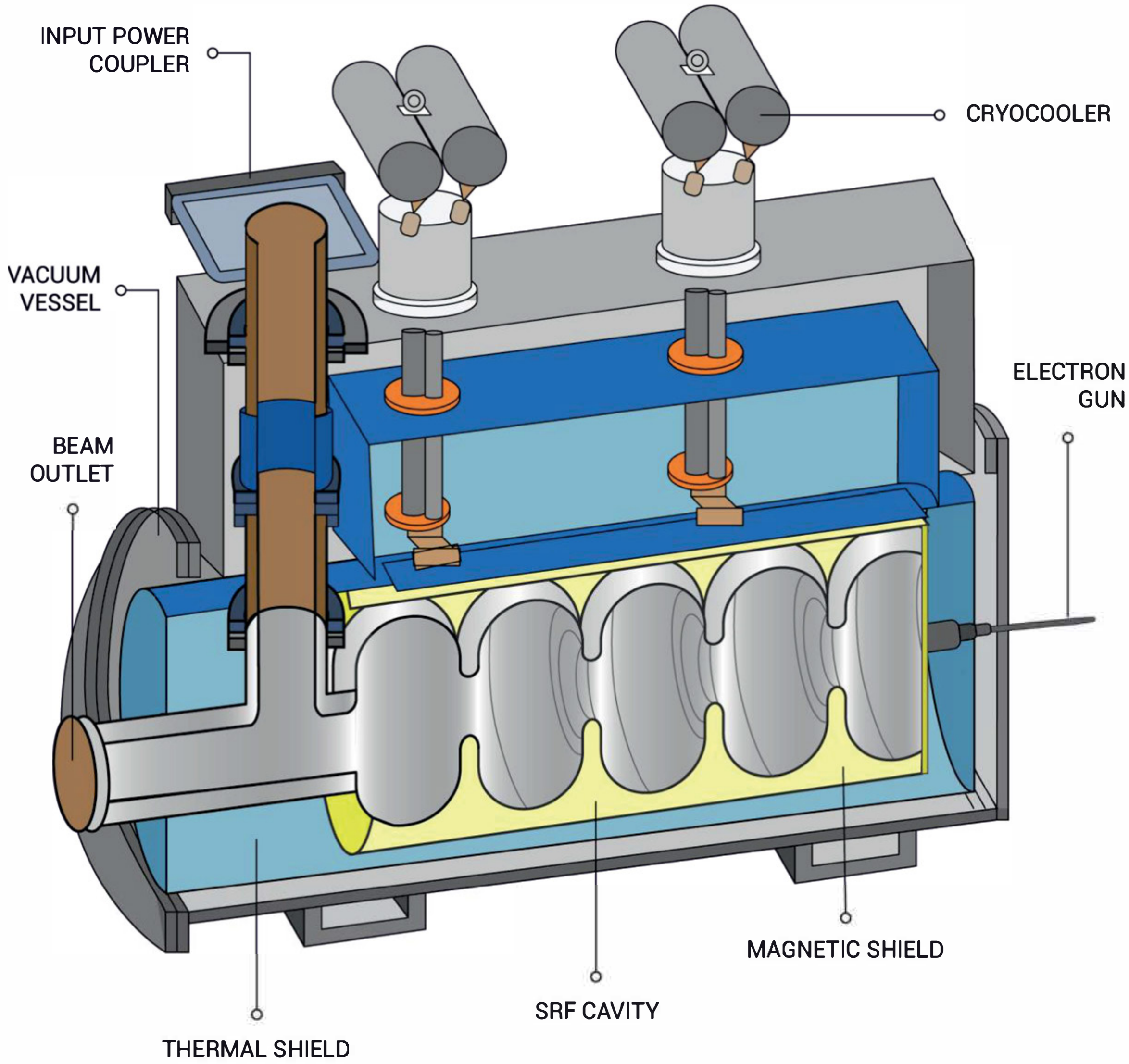
6.7 Development of Superconducting Radiation Detectors

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.

परमाणु ऊर्जा विभाग
DEPARTMENT OF ATOMIC ENERGY

PART B

DEPARTMENT OF ATOMIC ENERGY

PUBLIC SECTOR ENTERPRISES

Driving Growth through Industrial Excellence

AMRIT KAAL VISION DOCUMENT

परमाणु ऊर्जा विभाग

DEPARTMENT OF ATOMIC ENERGY

Content: All Units and Institutions of DAE
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Disclaimer: The data, projections, and other information presented in this document correspond to the year 2024, unless stated otherwise.

अमृत काल AMRIT KAAL

संकल्प प्रलेख VISION DOCUMENT

PART – B

Public Sector Undertakings

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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

Dr. Ajit Kumar Mohanty

August, 2025

Secretary, DAE and Chairman, AEC

1. Introduction

DAE encompasses all the areas related to power and non-power applications of atomic energy which includes exploration, identification and processing of uranium resources and atomic minerals, fabrication of nuclear fuel, production of heavy water, construction and operation of nuclear power plants, nuclear fuel reprocessing and waste management. The vision of the Department of Atomic Energy (DAE) is to empower India through technology, creation of more wealth and providing better quality of life to its citizen. This is to be achieved by making India energy independent, contributing to provision of sufficient, safe and nutritious food and better health care to our people through development and deployment of nuclear and radiation technologies and their applications.

The Public Sector Undertakings of DAE are commercial organisations involved in delivery of products related to atomic energy. The PSUs of DAE at present are Nuclear Power Corporation of India Limited (NPCIL), Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI), Uranium Corporation of India Limited (UCIL), Electronics Corporation of India Limited (ECIL) and Indian Rare Earth Limited (IREL).

NPCIL and BHAVINI are involved in commercial power (electricity) generation using nuclear fuels. UCIL's mandate is to mine and process uranium for production of nuclear fuel. ECIL provides the required support in terms of control and instrumentation required for nuclear power sector, while IREL mines and processes Zircon required for nuclear power plants and monazite for production of thorium. ECIL and IREL are also into other commercial activities – ECIL provides electronics for Defence, Homeland security, Aerospace and IT & E-Governance. IREL produces Rare Earths for industry and other applications.

The five PSUs of DAE primarily serve the clean Energy vertical of the Department of Atomic Energy and have a vital role in providing the country energy security in a sustainable manner. The PSUs Vision Amrit aal (2047) is the integration of the visions of the respective companies in line with the National goals and DAE's vision.

2. India's Nuclear Power Programme

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

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

TAPS 1&2

India's first PHWRs – RAPS 1&2

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

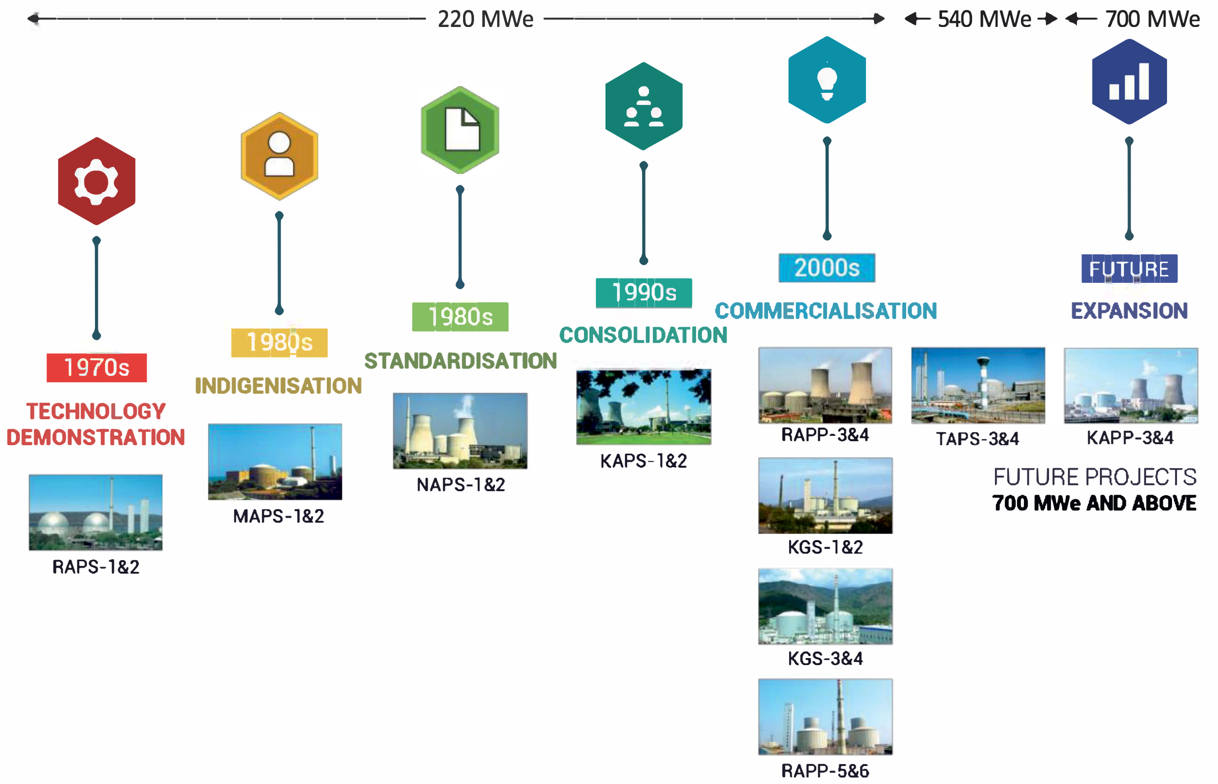
RAPS 1&2

The International Isolation and technology denial Regime

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

Indigenisation and Evolution of PHWR technology

Following the imposition of technology denial regime, Indian scientist and engineers successfully completed RAPS-2 and commissioned the unit in 1981, which continues to operate even today. Following successful operation of RAPS-2, India accomplished full indigenisation of with the design, construction and commissioning of MAPS 1&2. This was followed by standardisation, consolidation, commercialisation and increase in unit size from 220 MW to 540 MW and now to 700 MW. At present, one PHWR of 200 MW, fourteen of 220 MW, two of 540 MW and two of 700 MW are in operation.



PHWR Evolution

Additionalities to the three-stage programme:

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

KKNPP 1&2 (2 x 1000 MW)

International Cooperation in Nuclear Energy

Following the fruition of international cooperation in nuclear energy in 2008, international agreements for cooperation in nuclear energy were concluded to end the country's international isolation and access global markets for nuclear commerce. This opened up the possibility of import of fuel for use in reactors under IAEA safeguards and setting up nuclear power reactors based on technical cooperation with foreign countries. Two 1000 MW Pressurized Water Reactors (PWR) in cooperation with Russian Federation at Kudankulam (KKNPP 1&2) have been set up and are in operation. Four more 1000 MW PWRs (KKNPP- 3 to 6) are being set up at the same site in Tamil Nadu.

The Government has also accorded 'in principle' approval of four sites at Jaitapur in Maharashtra, Kovvada in Andhra Pradesh, Chhaya Mithi Virdi in Gujarat and Haripur in West Bengal for setting up nuclear power reactors with foreign cooperation.

2.1 Energy Demand and Need for Nuclear Power

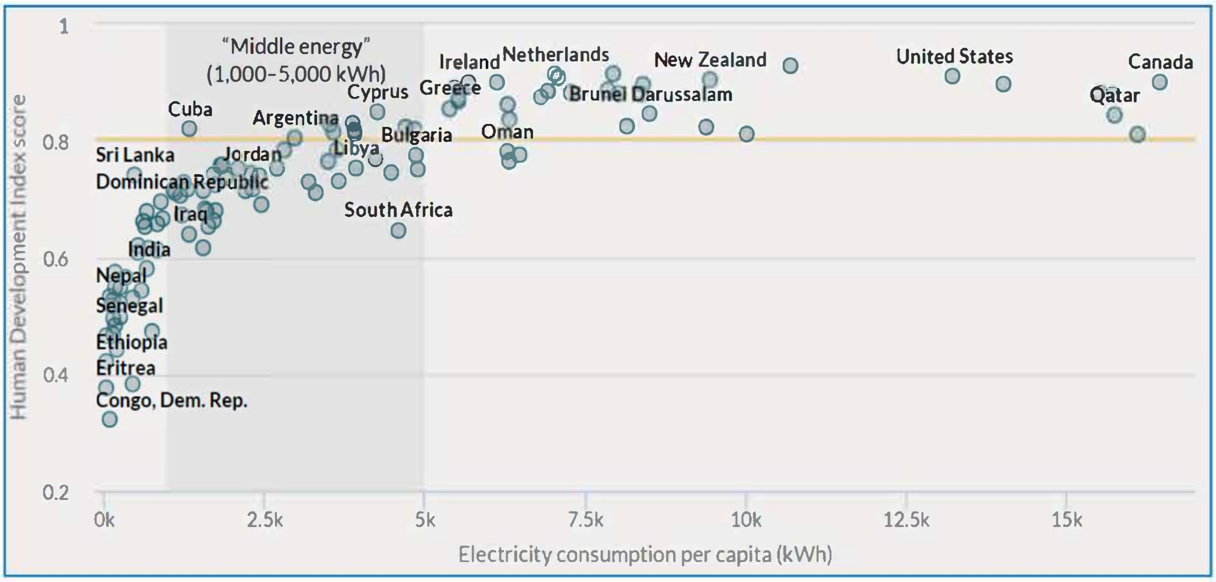
Viksit Bharat

India aspires to be a developed country (Viksit Bharat) by 2047, the 100th year of its independence. The period up to 2047, in which it is to be happened, is Amrit Kaal. The key drivers for developing the Vision are

- Viksit Bharat by 2047,
- Approach to Net Zero by 2070 and
- Atma Nirbhar Bharat

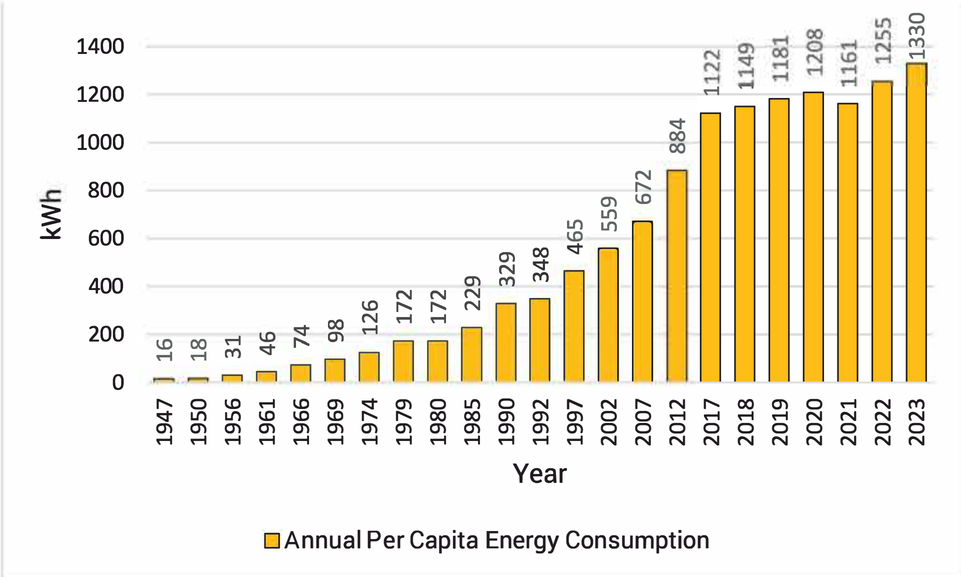
The legitimate aspirations of the country to achieve its development objectives and providing higher standards of living for its people require raising the per capita consumption of energy. Multiple studies over time have shown a positive correlation between the Human Development Index (HDI) and per capita energy / electricity consumption.

A high economic growth is required to achieve the desired HDI of about 0.8. Vision India 2047 also aims to make India a global leader in innovation and technology, a model of human development and social welfare, and a champion of environmental sustainability.



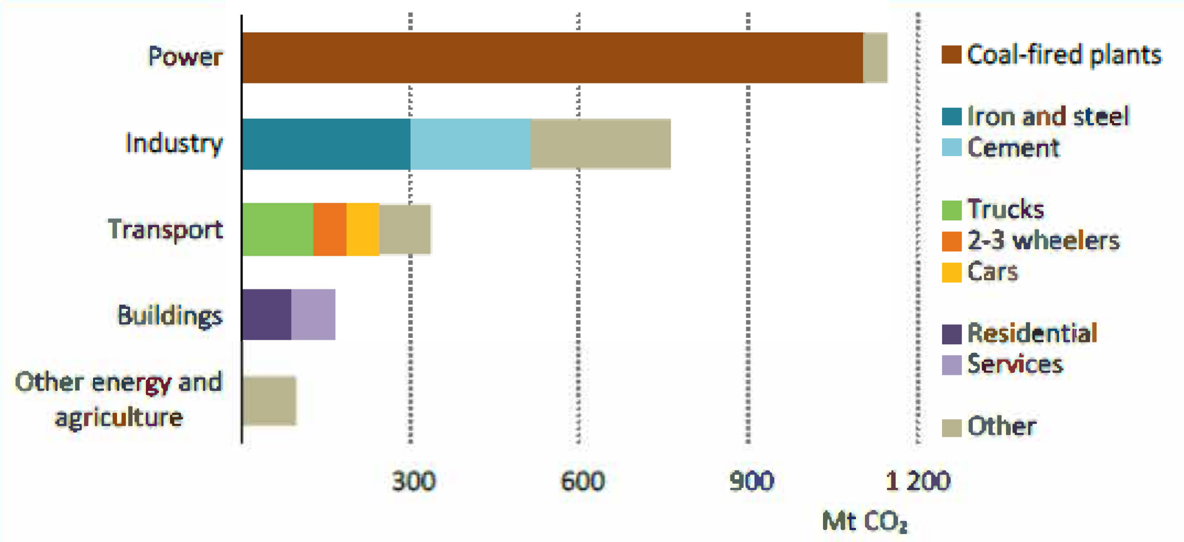
Ref: Center for Global Development

For a Viksit Bharat and meeting the aspirations of our people, providing quality power in the required quantity and at affordable price is essential. The per capita electricity consumption of the country was 1330 kWh in FY 2022-23 against the world average was around 3800kWh. In the last five years, peak demand in India has registered about 5% annual growth. Based on this and considering actual peak demand of 216 GW in 2022-23, the projected peak demand in the year 2046-47 works out to about 700 GW. Projections made in studies by various agencies indicate the need of realization of installed capacity over 1500 GW by 2047 as against the present capacity of about 442 GW.



Another important driver for Vision Amrit Kaal is clean energy transition to Net Zero by 2070. Apart from decarbonising the power generation sector, a huge effort is needed to decarbonise the hard to abate sectors like industries. This would envisage increasing the share of electricity in the energy consumption, and producing clean Hydrogen, which could potentially replace fossils fuels as the energy carrier. Accordingly, India is pursuing energy transition in various sectors including electricity, industry, transport, agriculture, household items etc.

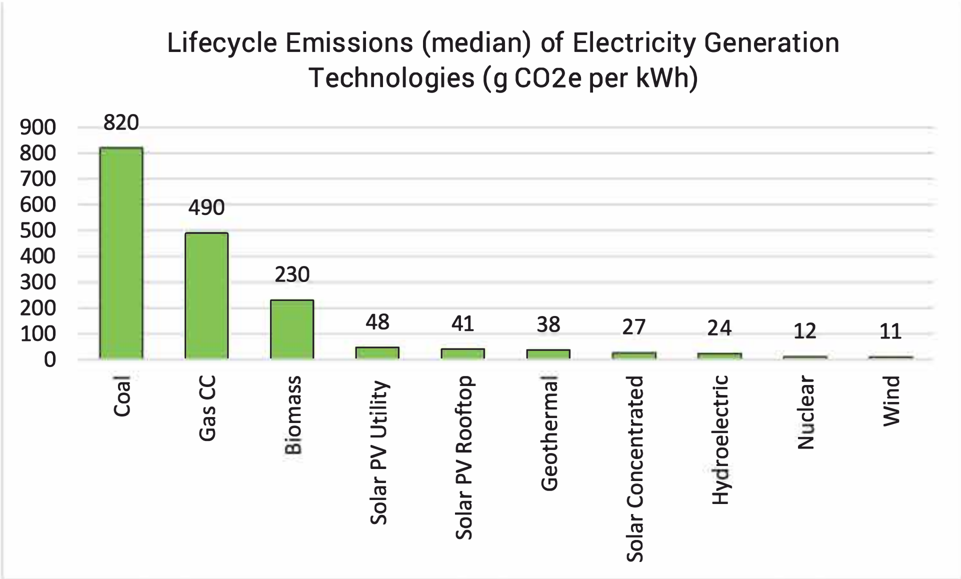
India is a major force in the global energy economy. Energy demand has increased significantly over the last two decades, propelled upwards by a growing population and the industrial growth. Transport sector has also recorded increasing growth trend in terms of distance travelled and consequent energy consumption. Appliances for households are projected to rise manifold. All the above factors have contributed sharp rise in CO_2 emission by various sectors specifically power, Iron & steel, Cement, transport sectors. The energy sector is the major source of greenhouse gas emissions today and holds the key to averting the worst effects of climate change.



India's power sector is the largest contributor to its CO_2 emissions, and coal-fired power plants are responsible for the great majority of power sector emissions.

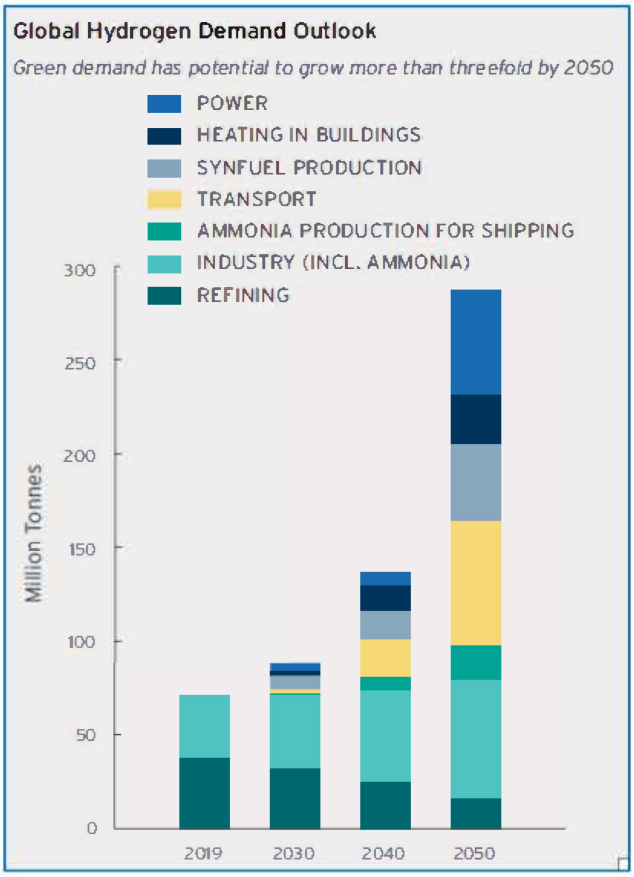
Source: IEA – India Energy Outlook 2021

To meet the anticipated growth in demand for energy in the coming years, technological options need to be chosen which are optimal in the medium as well as long term. There is a need for acceleration of development and deployment of clean technologies such as nuclear, renewable, electrolysers, carbon capture and storage (BECCS), high efficiency fuel cells etc. Net-zero is not possible without substantial nuclear power and Renewable Energy (RE) generation by 2070. Due to its compelling merits as clean energy (CO2 free), 24x7 availability as base load power, safe, reliable, economically viable and having vast operating experience, nuclear power has an important role to play towards India's net-zero target by 2070. There is a need for acceleration of development and deployment of clean technologies such as nuclear, renewables, electrolysers, carbon capture and storage (CCS), high efficiency fuel cells etc.



Source: Annexe III Technology Specific Cost and Performance Parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)

India has to radically transform its energy landscape and prioritise renewable energy, nuclear energy, electrification, hydrogen adoption and carbon removal strategies. Renewable electricity is growing at a faster rate in India than any other major economy. Grid decarbonisation, industrial decarbonisation and transport transition are expected to address nation's current emissions to a large extent.



Source: NITI Aayog–Harnessing Green Hydrogen

Hydrogen demand in India could grow more than fourfold by 2050, representing almost 10% of global hydrogen demand. Initial demand growth is expected from mature markets like refinery, ammonia, and methanol, which are already using hydrogen as industrial feedstock and in chemical processes. In the longer term, steel and heavy-duty trucking are likely to drive the majority of demand growth, accounting for almost 52% of total demand by 2050. The global demand is projected at about 300 million tonnes by 2050.

2.2 India's electricity installed capacity requirements

According to studies conducted by the NITI Aayog, India may be witnessing a steady growth in the share of electricity in its energy demand, which is expected to reach 25% by 2047. The share of electricity in energy demand is estimated to be 20.6% by 2030, which was estimated at 18.3% in 2021. In light of the NZ 2070 commitments, the expected share of electricity in the total energy demand is expected to rise to around 47-52% by 2070.This growth in electricity in view of the Net Zero commitments would have to be primarily met from Nuclear and renewable sources. Coal would necessarily have to be combined with Carbon Capture and sequestration technologies. Various studies by think tanks like NITI Ayog, Vivekananda International Foundation (VIF), Principal Scientific Advisor to Prime Minister (by IIM Ahmedabad) have projected the electricity requirements and sources of electricity generation for achievement of Net Zero by 2070.

The study commissioned by PSA to GoI (carried out by IIM A) indicates that a total Final Energy Consumption (FEC) of 15,400 TWh/y is possible by 2070 and the per-capita electricity consumption in 2070, considering an average HDI of 0.800 may range from 5,100 - 8,400 kWh/capita/year and for HDI of 0.900 between 10,400-13,200 kWh/capita/year across various scenarios.

The study by IIM A projects the requirement of installed nuclear power capacity in various Net Zero scenarios as follows:

Net Zero by 2070 Scenario	Nuclear Installed Capacity (GW)	
	2050	2070
NZ-1 (Thrust on Nuclear)	265	331

NZ-2(Thrust on Fossil fuels with CCUS)	75	78
NZ-3 (Thrust on Renewables)	75	207
NZ-4 (Integrated Scenario)	95	178

The VIF study projects a per capita electricity consumption of 18757 kWh to 15047 kWh by 2070 to cater to a low carbon economy which includes e-mobility, supplying process heat to industry and hydrogen production. It projects a maximum nuclear capacity of 284 GW to 3139 GW by 2070 across various scenarios. Thus, it becomes clear that a minimum installed nuclear power capacity of about 200 GW is needed by 2070 and about half of it i.e. 100 GW by 2047 which is halfway to 2070. Thus, the country needs about 100 GW nuclear power capacity by 2047.

2.3 Nuclear Power Vision 2047

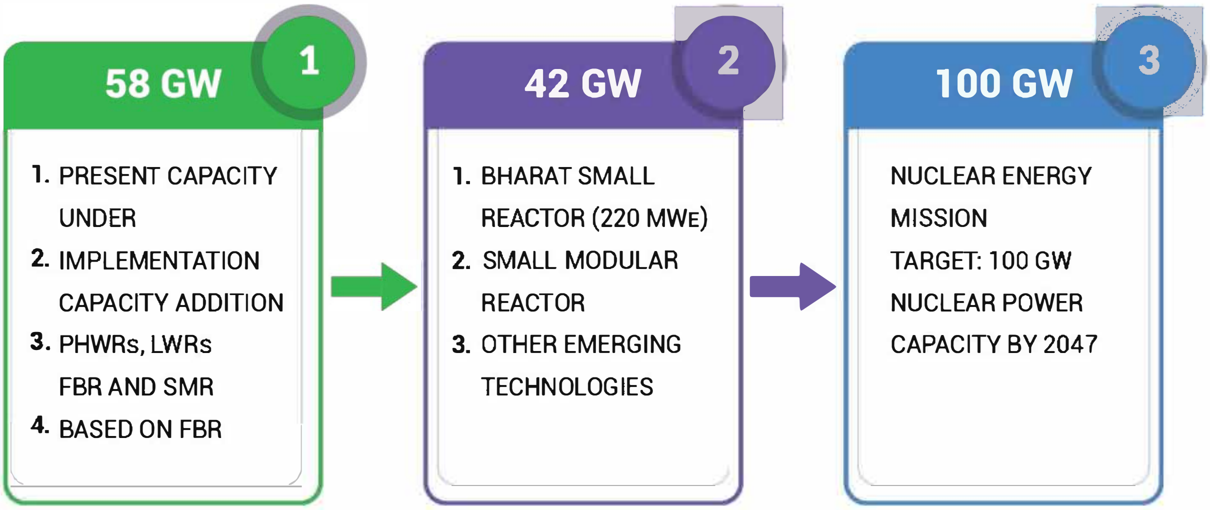
As it becomes clear that the country needs a nuclear power capacity of about 100 GW or 1,00,000 MW by 2047, including for decarbonisation of hard to abate industries like steel, metals, cement etc., necessary roadmap to reach the capacity has to be drawn up. The present installed nuclear power capacity in the country is 8780 MW comprising of 24 reactors (excluding RAPS 1). In addition, 8 reactors with a capacity of 6600 MW are under construction and 10 reactors with a capacity of 7000 MW are under pre-project activities. On progressive completion of these reactors, scheduled by 2031-32, the installed nuclear power capacity is expected to reach 22,380 MW (excluding RAPS 1).

Presently the two PSUs of DAE viz. NPCIL and BHAVINI are engaged in setting up nuclear power plants in the country. While NPCIL is mainly engaged in nuclear power generation from PHWRs and LWRs, BHAVINI is engaged in setting up FBRs. Based on the available sites and technologies and other inputs, it is possible for NPCIL to envision adding about 33,000 MW of additional capacity during the period 2032 to 2047 and BHAVINI, a capacity of about 3300 MW. Thus, reaching a capacity of about 58,000 MW is possible to be set up by NPCIL and BHAVINI, by 2047 based on existing technologies like PHWRs, LWRs and FBRs. There is no specific plan for the balance 42,000 MW needed, which could be set up based on both existing and emerging new technologies, mainly for decarbonistion of hard to abate industries (in captive mode), adopting business models involving private sector, which are being worked out. Further, it is proposed to evolve business models to enable private investment for setting up this capacity by the private sector. Potential for more than 42,000 MW exists in the country for decarbonising of industries presently using captive thermal power plants (most of which run on coal or diesel). Thus, a significant capacity for decarbonisation is expected to be realised through Small Modular Reactors (SMR). While many SMR designs are still under development, NPCIL's standard 220 MW Pressurised Heavy Water Reactors (PHWR) already in operation in the country, upgraded to reduce the land requirement and make it deployable close to the industries for use as a captive power plant is found to be an ideal solution for the purpose. This upgraded 220 MW PHWR is termed as Bharat Small Reactor (BSR) is one of the candidates for large scale deployed in the near future.

In addition, a Bharat Small Modular Reactor (BSMR-200) a small and modular pressurised light water reactor of capacity ~220 MWe which can utilize the balance of plant of 220 PHWRs for augmentation of nuclear capacity in India at a faster rate is being designed. It will have a reactor pressure vessel (RPV) with four loops connecting to pumps and steam generators: a loop type reactor very similar to AP300 of Westinghouse, USA or Rolls Royce SMR of UK in design, but with lower power generation capacity. This will also be a stepping stone in setting up large size indigenous PWR plants in future.

DAE (BARC) is also in the process of development of gas cooled high temperature micro modular reactor. (GCMMR) (<10 MWe), with advanced features. The detailed design is being worked out. The high temperature steam from these reactors will be directly used for carbon free hydrogen production either through chemical reaction like Iodine-Sulphur, Cu-Cl or steam electrolysis. These reactors are also planned to be deployed in the time leading up to 2047.

Thus, possible capacity addition based on technologies is as follows:



Towards realising the Nuclear Energy Mission

While the 58 GW capacity is expected to be implemented by NPCIL, BHAVINI and Joint Ventures of NPCIL, the 42 GW is expected to come largely with public and private sector participation, in evolving business models within the existing legal framework.

3. Nuclear Power Corporation of India Limited (NPCIL)

"To be globally proficient in nuclear power technology, contributing towards long term energy security of the country."

The design, construction and operation of nuclear power plants in the country was started as a departmental activity in the early sixties, by the Department of Atomic Energy (DAE), Government of India. In the year 1967, Power Projects Engineering Division (PPED), a division of the DAE, was formed and entrusted with this responsibility. PPED was converted to Nuclear Power Board (NPB) in the year 1984, with increased delegation of powers. For the planned expansion of nuclear power programme, it was felt necessary to create a framework for faster decision-making and also to tap funds from capital market. Accordingly, NPB was converted into Nuclear Power Corporation of India Limited (NPCIL), a fully owned company of the Government of India, Department of Atomic Energy and registered on 3rd September 1987, under the Companies Act of 1956. The company started functioning from 17th September, 1987. The assets of the Nuclear Power Board excluding Unit-1 of Rajasthan Atomic Power Station (RAPS-1) were transferred to NPCIL on its formation.

NPCIL activities include all aspects of nuclear power reactors. These include Siting, Design, Construction, Commissioning, Operation & Maintenance, Renovation & Modernisation, Life Extension and Waste Management. NPCIL is mainly tasked with implementation of the first stage of nuclear power programme – comprising of Pressurised Heavy Water Reactors (PHWR) and Light Water Reactors (LWR) set up with international cooperation. NPCIL has evolved into an organisation with expertise in all aspects of nuclear power with experience in multiple reactor technologies PHWR and LWRs (BWRs and VVERs).

Growth & Evolution of NPCIL

Established legacy: A CPSE under DAE, incorporated in 1987, to build and operate nuclear power plants. Fully owned by the government of India and has equity participation in BHAVINI for fast breeder reactors.

Robust reactor fleet: Operates nuclear reactors with a capacity of 8180 mw, spanning PHWRs, BWRs, and VVERs, and has 8 reactors (6800 mw) under construction. Engaged in fleet-mode deployment of PHWRs.

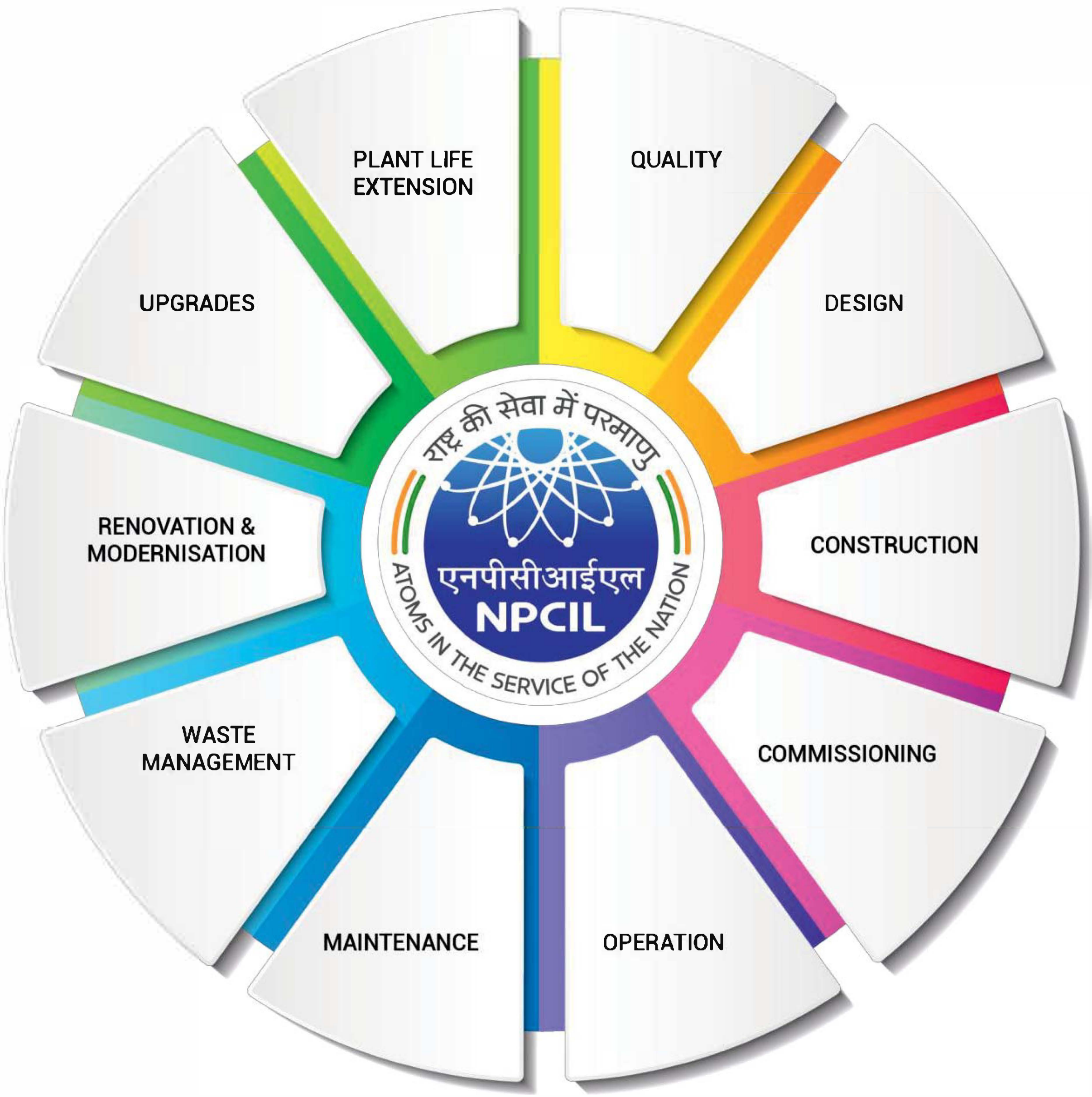
Strong financial backbone: NPCIL is a AAA-rated, consistently profit-making and dividend-paying company. Manages 1,68,235 crore in assets with a net worth of 60,821 crore.

Sustainable development and social commitment: Actively involved in CSR initiatives, neighbourhood welfare, biodiversity conservation and public outreach, engaging with communities around the nuclear power plants.

Global standards and collaboration: Maintains ISO-certified EMS and OHSMS, follows ALARA safety principles & collaborates with WANO, COG and IAEA to enhance global nuclear safety & reliability.

Vision for energy security: Aims to provide safe, eco-friendly and economy viable energy to meet India’s rising electricity demands driven by the vision ' to be globally proficient in nuclear power.

Since its incorporation in September 1987, NPCIL has transformed substantially, growing in all aspects and achieving several landmarks. At the time of its inception, there were six reactors in operation (TAPS 1&2, RAPS 1&2 and MAPS 1&2) and four reactors under construction (NAPP 1&2 and KAPP 1&2). These reactors with the exception of RAPS-1 were transferred to NPCIL. The value of these assets was Rs. 1313 crore. While TAPS 1&2 are Boiling Water Reactors (BWR) of 160 MW each, the others are Pressurised Heavy Water Reactors of 220 MW size.



NPCIL: Many companies in one

3.1 Evolution in Technology

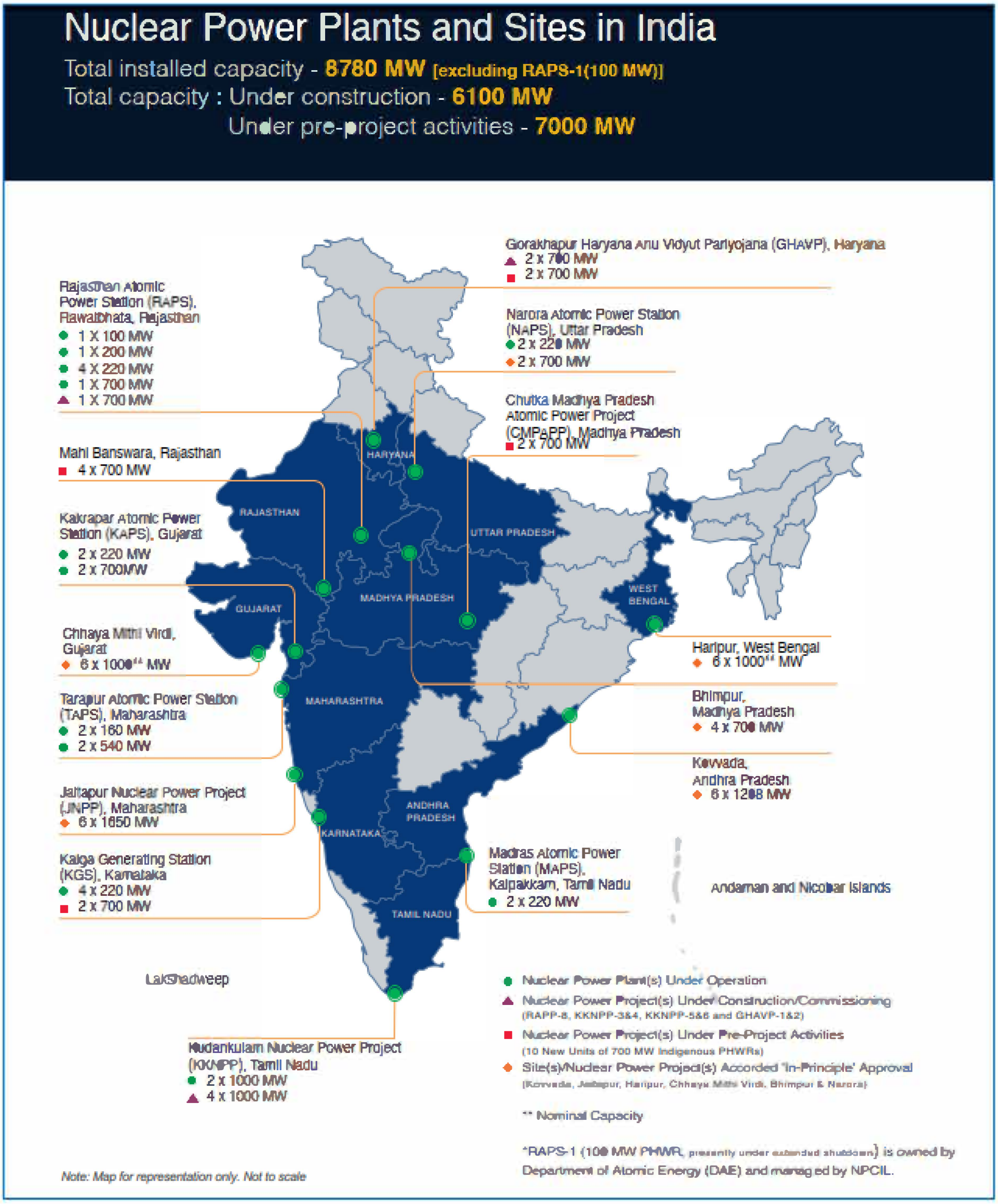
The 220 MW PHWR design which evolved from RAPS 1&2 (AECL Canada) to MAPS 1&2 (first indigenous PHWR) prior to formation of NPCIL was indigenised, improved and standardised with NAPS-1&2 and KAPS-1&2. Eight more 220 MW reactors – Kaiga 1 to 4 and RAPS 3 to 6 of the design were set up by NPCIL. The PHWR design was scaled up to 540 MW capacity and two such units (TAPS-3&4) were set up at Tarapur, Maharashtra Site. This design was further uprated to the state of the art 700 MW with advanced safety features; and the first twin unit of 700 MW PHWR, KAPP-3&4 are in commercial operation. Four more units of 700 MW PHWR are under construction and ten more have been accorded sanction, which are expected to be progressively completed by 2031-32.

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

NPCIL has, over the years, developed comprehensive capabilities in nuclear power technology. This encompasses design of Systems, Structures & Components, Safety analysis, Licensing, manufacturing of nuclear equipment (with Indian industries), Construction and Operation of nuclear power plants. In addition, NPCIL has developed technologies for life management and maintenance, in association with other units of DAE. Adopting these technologies, NPCIL has successfully carried out Enmasse Coolant Channel Replacement (EMCCR), Enmasse Feeder Replacement (EMFR) in several reactors, introduction of Spargers in MAPS-1&2, repair of Calandria Vault in KAPS-1, in situ repair of tri-junction joint in Kaiga-3 Endshield and Over Pressure Relief device in RAPS-1 etc. These jobs were carried out with minimal radiation exposure and at much lower cost than internationally prevalent. Thus, NPCIL has evolved today into an organisation with expertise in PHWRs of different sizes, BWRs, and large capacity PWRs.

3.2 Addition of Capacity

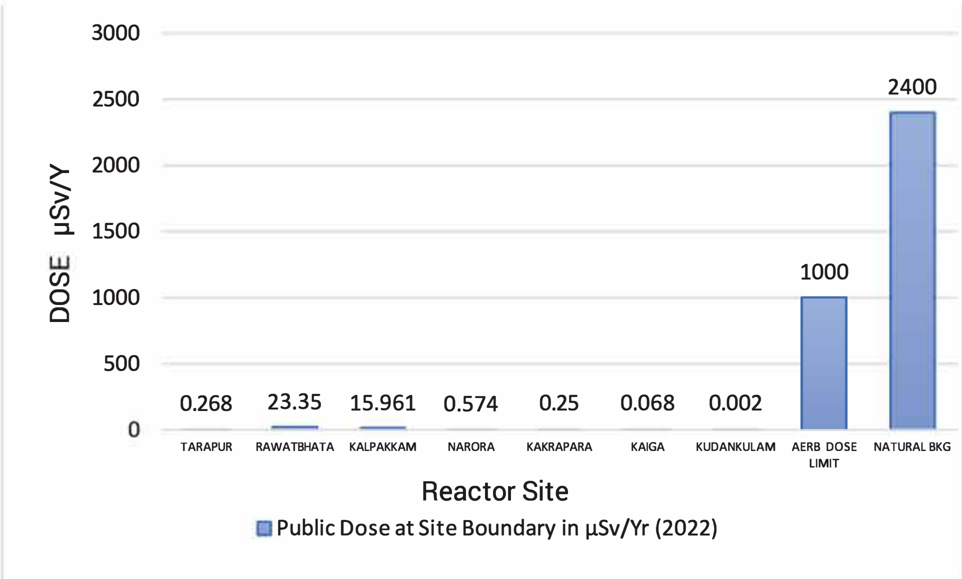
At the time of its incorporation, there were six reactors in operation - TAPS 1&2, RAPS-1&2 and MAPS 1&2 of which five reactors, excluding RAPS-1 were transferred to NPCIL with a capacity of 1010 MW. This capacity has now grown about eight-fold to 8180 MW with 24 reactors in operation. The present locations of NPCIL sites are given below:



3.3 Performance of Operating Plants

Safety Performance Ever since its inception, NPCIL has had an impeccable safety record. There has not been any accident or incident of release of radioactivity in the public domain beyond stipulated limits. Indian nuclear power reactors have registered about 620 reactor-years of safe operation (as of August, 2024).

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



Public Dose at NPP Sites

The radiation dose from NPCIL's nuclear power plants has been found to be a negligible fraction of the limit stipulated by AERB. As against the AERB limit of 1000 micro-Sievert per year at the exclusion zone (site) boundary, the actual value is found to be in the range of 0.004 to 27.72 micro-Sievert per year at NPCIL plant sites. The average natural background radiation in the country is 2400 Micro-Sievert per year. Expert safety reviews, following the Fukushima incident in Japan, found that NPCIL reactors are safe against extreme natural events and have margins and features in design to withstand them. The recommendations made to take the safety to a higher level have also been incorporated in design.

Generation Although NPCIL's installed capacity only grew by about six-fold, NPCIL's annual generation has grown about eight to nine-fold since its inception. The annual generation, which was about 4000 to 5000 MUs per annum in the first five years from 1987-88 to 1991-92, has now grown to over 40000 MUs. The highest generation in 2019-20 was 46472 MUs. It was 43029 MUs in 2020-21 and in the first seven months of the current year, has been 26323 MUs.

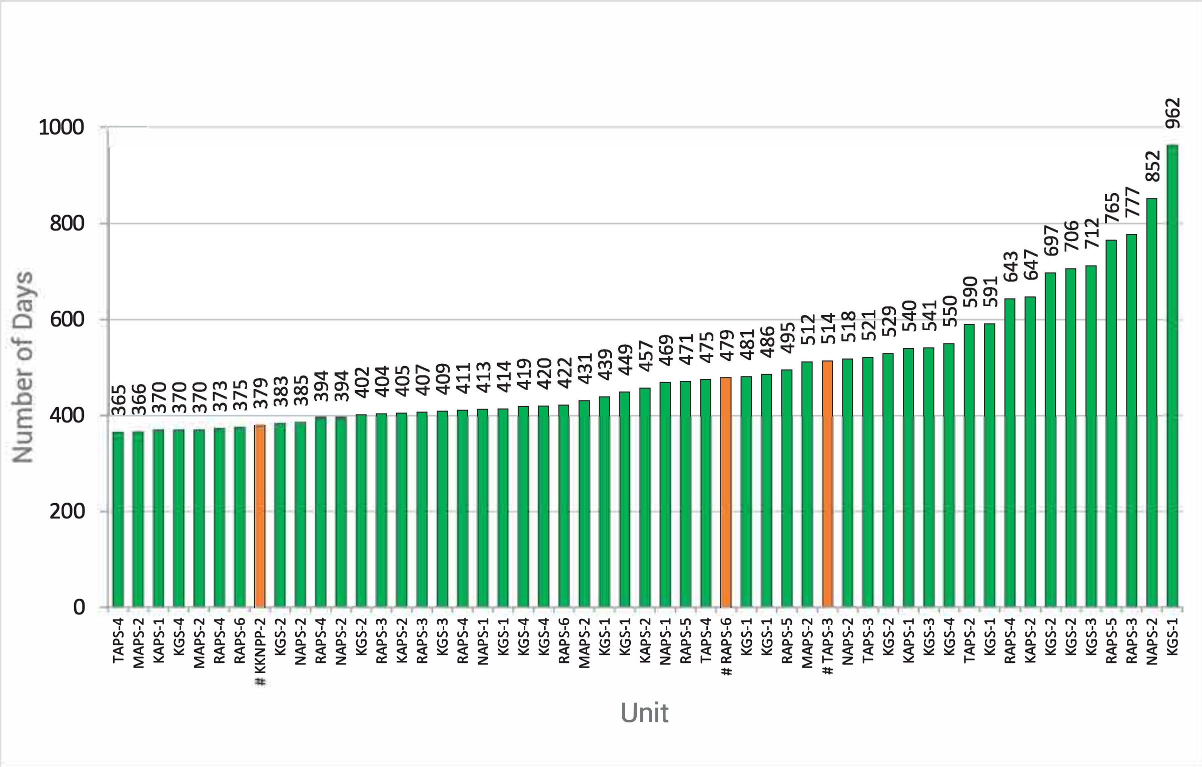
Plant Load Factor NPCIL's Plant Load factor was low in the initial days (around 50% or lower). Resulting out of various improvements made, it steadily increased to over 80% by 2002-03. There was a dip in Capacity Factor from 2003-04 to 2008-09 due to fuel demand-supply mismatch, but it again increased with improved fuel availability and stabilised at about 80%.

Landmark Achievements In addition to several significant achievements by NPCIL over the years, it recently had two world class land mark achievements:

Completion of 50 Years of Safe Operation of TAPS 1&2: These reactors commenced operation in 1969 and were the first nuclear power reactors in India & Asia. They are presently the oldest reactors in operation in the world having completed 50 years of operation in October 2019. These were originally set up by General Electric, USA on turnkey basis. Indigenous technological solutions were developed and implemented to ensure highest level of safety and efficient operation of the units (in an international technology denial and embargo regime prevalent from 1974 to 2008). The units underwent major upgradations in 2005 and 2016. The units are presently undergoing major refurbishment.

3.4 Continuous Operation - World Record of 962 Days By KGS-1

Kaiga Generating Station Unit-1 had set the world record by operating continuously for 962 days before being shutdown on 31st December 2018 for planned surveillance checks and mandatory tests (It now holds the record for the second longest continuous run among nuclear power reactors in world till date). Being a fully Indigenous PHWR fuelled by domestic fuel, this feat bears testimony to the maturity achieved by the country in all aspects of nuclear power technology. In addition, NAPS-2 (852 days), RAPS-3 (777 days) and RAPS-5 (765 days) have operated continuously for more than two years. NPCIL reactors have operated for more than a year 53 times (as of July 2025) so far.



Continuous operation for more than a year registered by NPCIL's Reactors as on 24.07.2025 (53 times), # Unit is continuing to operate

Financial Strength: The value of assets transferred to NPCIL at the time of its formation was Rs. 1313 crore. The total assets have grown manifold and by March 31, 2025 stood at Rs.1,91,607 crore. Its net worth has also grown manifold and stood at Rs.65,475 crore as on March 31, 2025. NPCIL has been a consistent profit making and dividend paying company. In its 37 years of existence, NPCIL has consistently made profit, barring in two years 1993-94 and 1994-95. Its instruments are accorded AAA rating - the highest.

3.5 Capacity Addition & Vision for Amrit Kaal

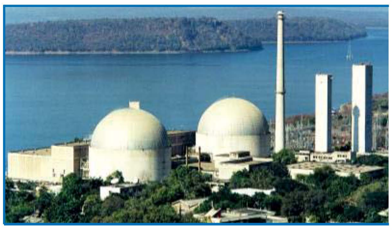
Present Capacity: NPCIL's present installed capacity is 8780 MW comprising of 24 reactors. In addition, it is also responsible for operation of RAPS-1 (100 MW), owned by the Department of Atomic Energy. Thus, it operates 25 reactors with a total capacity of 8880 MW. The technology wise break up of operating reactors is as follows:

Unit Capacity (MW)	No, of Units	Unit Particulars	Total Capacity (MW)
PHWRs			
100	1	RAPS-1	100
200	1	RAPS-2	200
220	14	MAPS 1&2, NAPS 1&2, KAPS 1&2, RAPS 3&4, RAPS 5&6, KGS 1&2, KGS 3&4	3080
540	2	TAPS 3&4	1080
700	3	KAPS 3&4, RAPS 7	2100
PHWRs Total			**6560**
LWRs			
160	2	TAPS 1&2 (BWR)	320
1000	2	KKNPP 1&2	2000
LWRs Total			**2320**

Of these 24 reactors, 8 reactors with a capacity of 2400 MW are fuelled by domestic uranium. The remaining 16 reactors are under IAEA safeguards and are fuelled by imported uranium.

Tarapur 1&2

(2 x 160 MW)



Rajasthan 1 to 6

(100-200; 4 x 220 MW)

Madras 1&2

(2 x 220 MW)

Tarapur 3&4

(2 x 540 MW)

Kakrapar 3&4

(2 x 700 MW)

Kudankulam 1&2

(2 x 1000 MW)

Narora 1&2

(2 x 220 MW)

Kakrapar 1&2

(2 x 220 MW)

Kaiga 1 to 4

(4 x 220 MW)

Nuclear Reactors in Operation

700 MW PHWRs: The 700 MW PHWR design is now well established with the successful operation of KAPS 3&4. These indigenous PHWRs have advanced safety features and are among the safest reactors in the world. While these reactors have been designed, constructed, commissioned and operated by NPCIL, the supply of equipment and execution of contracts have been by Indian industries / companies, and thus the true reflection of the spirit of Atma Nirbhar Bharat. These reactors will be the mainstay of India's nuclear power programme in the Amrit Kaal.

KAPS 3&4 (2X700 MW)

Capacity under construction:

Presently there are eight reactors with a total capacity of 6100 MW by NPCIL comprising of 3 PHWRs and 4 LWRs with foreign cooperation. The details are as follows:

Unit Capacity (MW)	No, of Units	Unit Particulars	Total Capacity (MW)
PHWRs			
700	1	RAPS 8	700
700	2	GHAVP 1&2	1400
PHWRs Total			**2100**
LWRs			
1000	2	KKNPP 3&4	2000
1000	2	KKNPP 5&6	2000
LWRs Total			**4000**

RAPP 7&8

The glimpses of LWRs under construction are shown below:

KKNPP 3&4

KKNPP 5&6

KKNPP 3&4 and KKNPP 5&6 are expected to be completed in 2026 and 2028 respectively. In addition, pre-project activities are in progress in respect of 10 PHWRs of 700 MW accorded sanction at four sites. The details of the locations and capacity are as follows:

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

There projects are scheduled to be completed progressively by 2031-32. Thus, on completion of the projects under construction and accorded sanction, NPCIL's capacity is expected to reach 21980 MW by 2031-32.

Kaiga 5&6

However, in respect of the Mahi Banswara and Chutka projects, while land acquisition process has been completed and R&R Package awarded, physical possession is yet to be fully obtained as the shifting of PAPs has just been initiated by the respective state governments. These projects may therefore spill over beyond 2031-32 though all efforts will be put to complete them on schedule once full access to the land is made available. Mahi Banswara project is proposed to be implemented by Anushakti Vidhyut Nigam Ltd., (ASHVINI), a joint venture of NPCIL & NTPC Ltd. The process of allocation of the project to ASHVINI is under consideration of the Government.

3.6 NPCIL Vision Capacity Addition beyond 2031-32 in Amrit Kaal:

Based on the availability of sites, technologies, supply chain feasibility and other inputs, possibility of setting up another about 33,000 MW by NPCIL is envisioned, apart from participation in the BSR programme to be implemented with private participation. The proposed technology wise capacity addition is as follows:

700 MW PHWRs:

a. **At existing sites:** A committee was constituted in NPCIL to explore feasibility of setting up of additional 2×700 MW PHWR units at existing sites of Kakrapar, Rawabhata, Narora, Jaitapur, Kalpakkam and Tarapur.

Based on the preliminary feasibility study, field survey and plant engineering requirements, setting up of 2x700 MWe PHWR units at Rawatbhata, Karkrapar, Narora and Jaitapur sites (in addition to locating 6X1730 MW EPRs with French cooperation) was found feasible. However, at Tarapur and Kalpakkam sites, it was observed that there is lack of sufficient space for locating new units.

Six PHWRs of 700 MW each are proposed to be set up at following existing sites:

- **Rawatbhata: 2 more units may be set up (RAPP-9&10)**
- **Kakrapar: 2 more units may be set up (KAPP-5&6)**
- **Narora: 2 more units may be set up (NAPP-3&4)**

Further confirmatory studies and analysis is planned at these sites for taking up necessary steps towards setting up projects.

b. **Bhimpur Site in M.P** The Government of India had accorded 'in-principle' approval of site at Bhimpur Madhya Pradesh in August 2011 for setting up 4x700 MHWRs subject to commitment for water which was yet to be confirmed by State government. No progress could be made so far as the state had not given assurance of providing the required quantity of water. However, the recent discussions with the state government have indicated that the water can be made available for the project. Accordingly, pre-project activities are being initiated at the site.

Thus, four PHWRs are proposed to be set up at Bhimpur site in Madhya Pradesh:

Bhimpur 1&2: 2X700 MW

Bhimpur 3&4: 2X700 MW

c. **New Site for Fleet of 10X700 MW PHWRs** The Site Selection Committee of the Government is in the process of identifying new potential sites. A new coastal site is to be identified for setting up a fleet of 10 PHWRs of 700 MW each.

New Site: 10 X700 MW

LWRs: The sites at Jaitapur in Maharashtra and Kovvada in Andhra Pradesh have been accorded in principle approval for setting up 6X1730 MW EPRs with French cooperation and 6X1208 MW AP 1000 reactors with US cooperation respectively. Land has been acquired and presently discussions with technology partners from France and USA are in progress to arrive at a viable project proposal. On finalisation of a project proposal, the same will be put up to the Government for financial sanction and administrative approval. Work on these projects will be initiated after sanction of the Government.

Jaitapur Site: 6 X 1730 MW EPRs

Kovvada Site: 6X1208 MW AP1000 New LWRs proposed to set projected capacity by 2047 based on above envisaged projects works out to be about 23948 MW as summarised below:

Thus, the capacity buildup proposed by 2047 including present capacity, capacity under implementation and new capacity proposed is as follows:

<table>
<tr><th rowspan="2">Technology</th><th rowspan="2">Particulars</th><th colspan="2">Capacity (MW)</th></tr>
<tr><th>Individual</th><th>Total</th></tr>
<tr><td>PHWRs, LWRs, BWRs</td><td colspan="2">Present Capacity (19 PHWRs, 2 LWRs, 2BWRs)</td><td>8180</td></tr>
<tr><td rowspan="3">Indigenous Pressurized Heavy Water Reactor - 700 MW</td><td>Capacity under implementation (14 PHWRs) - target 2031-32</td><td>9800</td><td rowspan="3">23800</td></tr>
<tr><td colspan="2">Possible Capacity Addition</td></tr>
<tr><td>• Additional PHWRs (2X700 MW each) at existing sites of Kakrapar, Rajasthan, Narora</td><td>4200</td></tr>
</table>

	• PHWRs at Bhimpur, M.P approved in principle (4X700)	2800	
	• Fleet of PHWRs at New Site	7000	
Light Water Reactors with International Collaboration	Capacity under implementation (4 LWRs) - target 2031-32	4000	21628
	Possible Capacity Addition		
	• LWRs at Jaitapur (6X1730MW)	10380	
	• LWRs at Kovvada (6X1208 MW)	7248	
Total			53608

3.7 Inputs required for the programme:

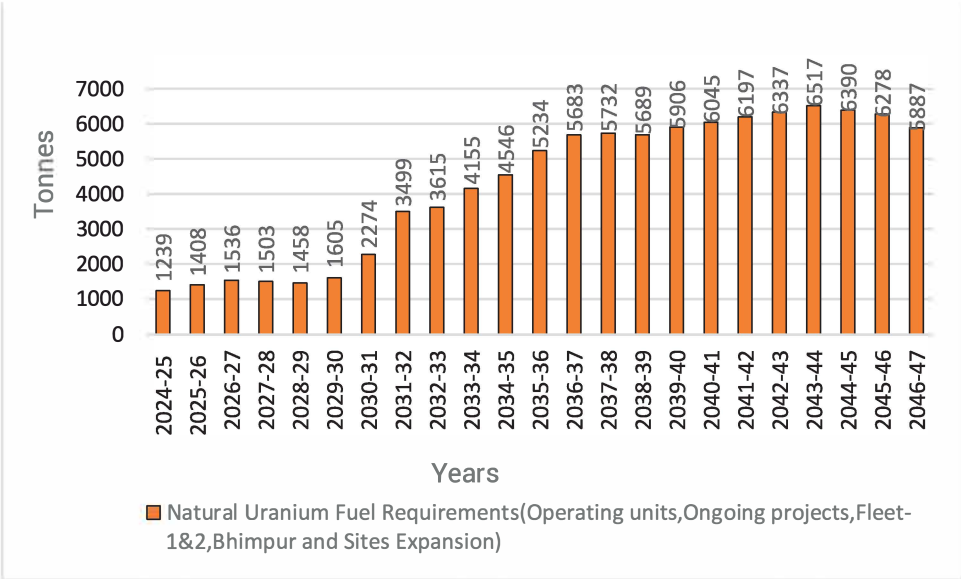
PHWRs:

Major Equipment & Components

32 PHWRs are tentatively to be implemented in the span of about next 20 years. Major long manufacturing cycle equipment and components include Primary Circulation Pumps (PCPs), Steam Generators, Calandria, End Shields, Reactors Headers, Pressurisers, Fuelling Machine etc. A large number of these equipment & components are to be manufactured and supplied in next 20 years progressively. In view of limited number of qualified indigenous vendors, manufacturing and timely supply of these items needs to be planned meticulously and mitigation measures to be evolved in advance to avoid any slippage in supplies. Advance procurement of these long delivery equipment and components are to be planned accordingly.

Fuel

PHWRs fuel require natural Uranium dioxide fuel (UO2). Fuel requirement for operating PHWRs as per tentative implementation schedule is indicated below (PLF for operating units is considered at 90%):



Total requirement up to 2047 works out to be about 98000 tonnes. As requirement of fuel quantity is huge, this is to be met by augmenting indigenous production as well as importing fuel through various routes like direct import, JV for uranium mining abroad, reprocessing of LWR spent fuel, exploring new fuel design etc. Fuel fabrication facility also needs to be matched accordingly. Uranium Corporation of India Limited and Nuclear Fuel Complex activities are to be planned accordingly.

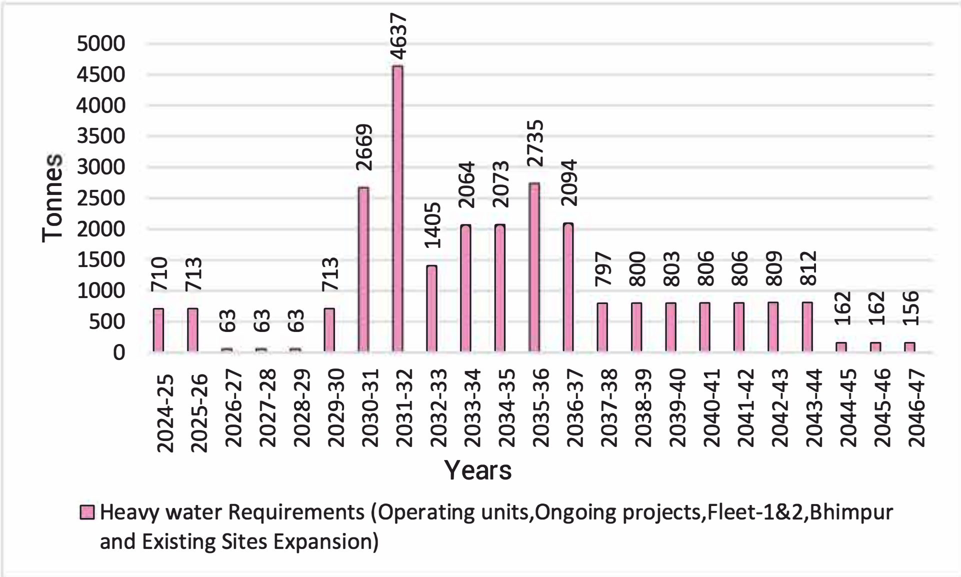
Considering that this would be the most critical input for this entire programme, there is a definite need for creation of strategic reserve (may be for 5-10 years) pool, to mitigate the risk of unavailability of adequate fuel.

Zirconium

In PHWRs, Zirconium is required for structural material calandria tubes and coolant channels as well as for fuel cladding. Zr requirement for constructing and operating PHWRs as per tentative implementation schedule is indicated below (PLF for operating units is considered at 90%). Total requirement up to 2047 works out to be about 12000 tonnes.

Heavy Water

In PHWRs, Heavy Water (D_2O) is required as inventory for moderator system as well as for PHT system. D_2O requirement for initial inventory and make up during operation of PHWRs as per tentative implementation schedule is indicated below:



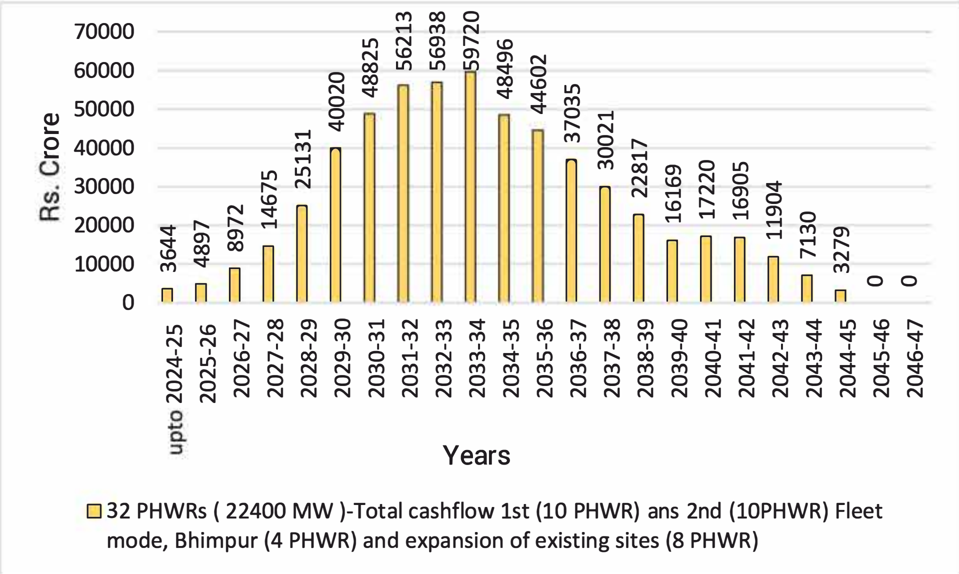
Total requirement up to 2047 works out to be about 26000 tonnes.

However, the accurate estimates and plans for Fuel & Heavy Water are being drawn up by the R&D units vertical.

3.8 Gross Estimated Outlay

In the implementation of nuclear power projects so far, project completion costs have been varying due to several factors including technological development, safety features, delay factors, financial factors etc. As per experience gained so for and considering present and future competitive environment for power sectors, it is envisaged that economy of nuclear power in terms of yearly tariff is going to play an important role. Base cost of nuclear power, thus, is going to be an important area to be optimised to meet the challenges of competitive environment. Considering this, on gross basis, projected cash flows have been worked considering base cost of 2x700 MW project at Rs.20000 Cr at 2024-25 price level. Based on this, economy of PHWRs may be sustainable with a reasonable return on equity. Cash flow is projected with above assumed base cost, interest rate @6.5% p.a., escalation @5% p.a. and Debt-Equity ratio 2:1. Total completion cost works out to be about Rs.5,75,000 Cr. which corresponds to be about Rs. 25 Cr per MW compared to about Rs. 16 Cr per MW for recently completed project KAPP-3&4.

However, these figures are indicative only and need to be fine-tuned considering prevailing several scenarios at the time of actual implementation of respective projects.



In addition to above, balance capital outlays for RAPP-7&8 and GHAVP-1&2 are to be met as per their latest revised cost estimates

LWR Inputs: The fuel and major components for LWRs are expected to be sourced through import in line with the detailed project proposals finalized. As regards cost and funding, these can be determined only on finalization of the project proposals. These will be finalized and the viable project proposals put up for consideration of the Government.

3.9 NPCIL Participation in BSR programme:

The goals for achieving Net Zero of various countries from 2050 to 2070 for addressing impacts of climate change have led to a series of measures to decarbonise the energy sector, particularly the hard to abate industries like steel, aluminium, metals, cement etc. Economic measures like proposed imposition of carbon border taxes on metal products have also brought a sense of urgency to the industry to decarbonise their manufacturing processes by switching to clean energy sources from fossil fuels predominantly coal.

Nuclear is a clean source of baseload electricity available 24X7. It has lifecycle carbon emissions comparable to that of renewables like hydro and wind. These attributes have made nuclear power an attractive candidate for industries wanting to make the switch from coal based captive power plants. This spurred an interest in Small Modular Reactors (SMR). While many SMR designs are still under development, the standard 220 MW Pressurised Heavy Water Reactors (PHWR) already in operation in the country were found to be an ideal solution for the purpose.

The standard 220 MW PHWR though not exactly modular, has a proven safety and generation performance record. Its design is being further upgraded with provision of a steel liner in the inner containment, electrical penetration assemblies, all Fukushima related upgrades and modifications in Instrumentation and Control systems to reduce the land requirement and make it deployable close to the industries for use as a captive power plant. This upgraded 220 MW PHWR is termed as Bharat Small Reactor (BSR).

The business models to enable private funding by the industries seeking these BSRs, within the existing legal framework have been explored and finalised. These are presently under consideration of the Government. The proposals being explored broadly envisage provision of land, cooling water and capital by the private entity, with the design and operation & maintenance by NPCIL (for a consideration). The private entity can have the right to use the electricity produced from such plants for its captive requirements. The construction and procurement of components and equipment could be by the private entity under supervision of NPCIL to ensure the design intent is fully met. The Fuel and Heavy Water, which are strategic materials will continue to be owned by the Government and leased to the entity for a consideration as is being done presently.

Finalising an optimum business model within the existing legal architecture, drafting a suitable Request for Proposal (RFP) in line with the finalised business model and obtaining the approvals of the Government of India for the same have been targeted for the near future. While the exact capacity of BSRs to be set up by 2047 remains to be assessed, it is expected that some capacity of the 42 GW more need by 2047 may come from BSRs.

3.10 Other Technologies:

In addition, Bhabha Atomic Research Centre (BARC) and Nuclear Power Corporation of India Limited (NPCIL) are also working on co-development of a 220 MW SMR based on Light Water Reactor (LWR) technology. It is proposed to use all the other elements of the BSR, with only replacement of the reactor core. Further, NPCIL also proposes to develop a large size Indian LWR in collaboration with BARC, taking off from the 220 MW LWR based SMR. NPCIL will take up other new reactor technologies developed indigenously in the commercial domain once their viability is established.

Hydrogen Production:

To seize the emerging business opportunities in production of Hydrogen from nuclear power, NPCIL has resolved to take enabling steps for entering into the business of clean Hydrogen generation from nuclear power at an appropriate time. In this context, to gain experience in

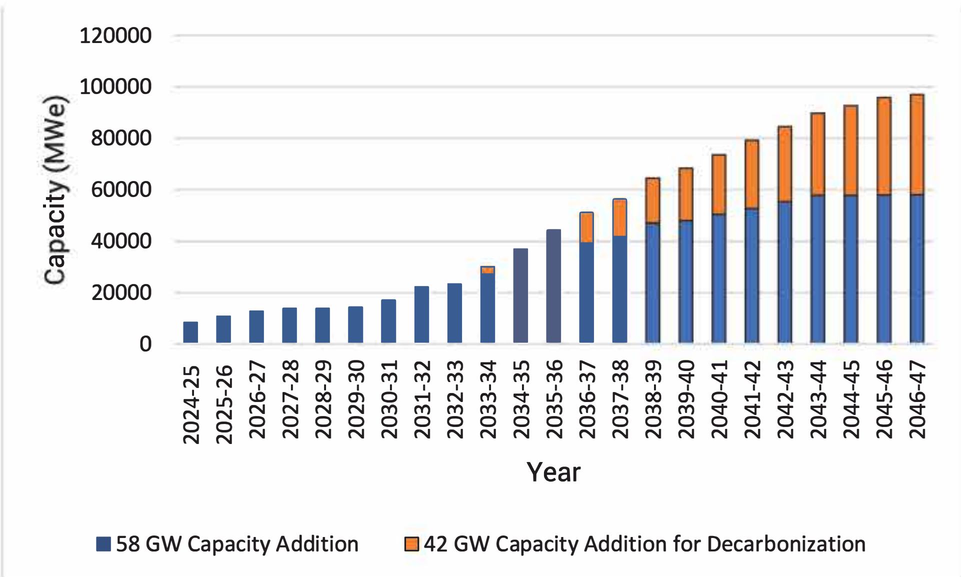
Hydrogen production and related aspects, NPCIL has set up small Hydrogen Generation Plants and associated systems with 10 Nm^3 per hour capacity at Rawatbhata and Tarapur site, mainly to meet in house Hydrogen & Oxygen needs. NPCIL will consider commercially deploying Hydrogen producing reactors being developed by BARC or facilities using electrolysis at an appropriate time depending on evolving market scenarios.

Export of Reactors & Services:

NPCIL has potential to export PHWRs particularly the partially modular BSRs to countries requiring small reactors, particularly those new entrants to nuclear power. Indian PHWRs are among the most economical in the world and thus are competitive. NPCIL also has expertise in carrying out 'in core' jobs like Enmasse Coolant Channel Replacement, Enmasse Feeder Replacement, in core repairs and other Renovation and Modernisation, safety upgrades etc. These activities are carried out at costs that are very competitive. Thus, NPCIL can also export nuclear services, as and when opportunities emerge.

Capacity Buildup Vision:

Based on the doctrine of earliest possible start, availability of land, fuel and resolution of all other constraints / issues, the ambitions capacity addition for Vision Amrit Kaal (including capacity addition by BHAVINI) could be as follows:



4. Bharatiya Nabhikiya Vidyut Nigam (BHAVINI)

"To provide sustainable energy security to Nation".

Bharatiya Nabhikiya Vidyut Nigam (BHAVINI) is mandated for the construction, commissioning and operation of Fast Reactors i.e. the second stage of the three-stage nuclear power programme. Department of Atomic Energy has the mandate for providing energy security to the nation by pursuing the three-stage programme for Nuclear Energy.

The first stage programme with a combination of Pressurised Heavy Water Reactors (PHWRs) and Light Water Reactors (LWRs) have reached a level of maturity. The fuel reprocessing technology for thermal reactor (PHWR) spent fuel has also been established. The reprocessing plants operating presently are giving satisfactory performance and are producing feed material required for the second stage programme.

The second stage programme envisages deployment of Fast Breeder Reactors (FBR) to increase nuclear power generation and thereby increase its share in total electricity generation, with better utilisation of uranium. This requires development of technology i.e. design of Sodium cooled fast reactors, associated fuel cycle and related technologies. Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam is the nodal agency for the development of Fast Reactor technology in the country and Bharatiya Nabhikiya Vidyut Nigam (BHAVINI) is mandated for the construction, commissioning and operation of Fast Reactors.

Large-scale thorium utilisation is envisaged in the third stage of Indian Nuclear Power Programme.

4.1 Prototype Fast Breeder Reactor (PFBR)

BHAVINI has constructed the 500 MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, Tamil Nadu and currently it is at advanced stage of integrated commissioning. The reactor assembly is boxed up and the major milestones of filling of 1150 tons of liquid sodium in the Main Vessel of the reactor, purification of the filled sodium along with Commissioning of Primary Sodium Pumps are completed. The secondary sodium loops are filled and secondary sodium pumps are re-commissioned. All the four SGDHR loops are filled with sodium and commissioned. Currently, isothermal testing at higher temperature has been completed and the plant is poised towards fuel loading activities. Upon obtaining regulatory clearance, start of Fuel loading towards First Approach to Criticality will commence which will take about four months' time to complete. This will be followed by physics experiments and power operation.

Contribution of other DAE units towards FBR programme

IGCAR, Bhabha Atomic Research Centre (BARC), Nuclear Fuel Complex (NFC), Heavy Water Board (HWB) and BHAVINI are contributing significantly towards FBR programme.

PFBR

BARC is contributing towards the technology development, fissile material production, fabrication of fuel, development of alternate/ advanced fuel, special equipment, components, detectors etc. NFC is contributing in the programme by manufacturing core structural components e.g. cladding, hex-cans, other associated hardware, radial blanket fuel pins and assemblies of various types required for the reactor. Heavy Water Board (HWB) has been supplying enriched Boron carbide pellets for PFBR and has developed the process for nuclear grade sodium production for future FBRs. Requirements of solvents for reprocessing are being met by HWB. Spent fuel discharged from PFBR will be processed in a co-located Fast Reactor Fuel Cycle Facility (FRFCF) at Kalpakkam, where all the activities of the fuel cycle such as Fuel reprocessing, Fuel fabrication and waste management will be carried out, there by closing the fuel cycle of PFBR and enable its sustained operation.

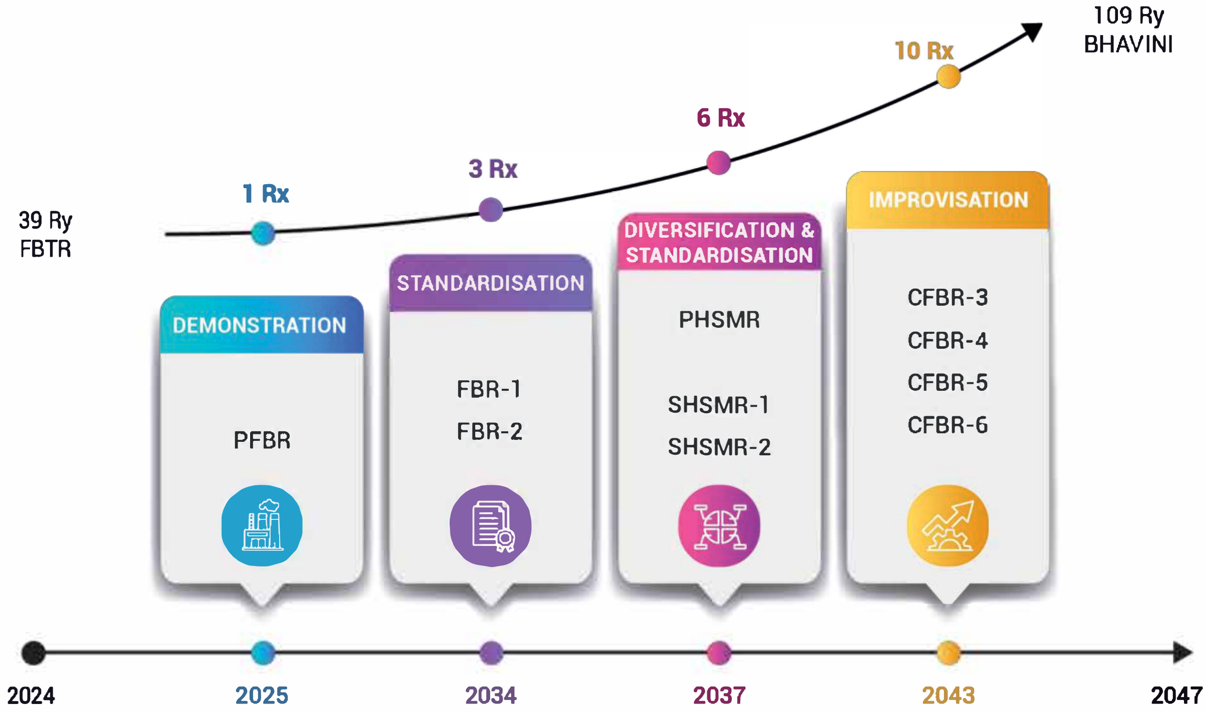
4.2 BHAVINI's Vision – 2047

BHAVINI proposes to make the Fast Reactor technology a mature, economical, sustainable and viable option for energy production by the year 2047. This requires deployment of oxide fuelled FBRs and setting up of fuel cycle facility to cater to the requirement of these reactors. PFBR will be operational in the end of 2025 in which full scale technology development and design validation of PFBR will be demonstrated.

Subsequently, construction of 6 FBRs of 500 MWe capacity (FBR 1 to 6) will be launched during next 20 years. FBR 1&2 will be launched by the year 2025 at Kalpakkam and the project will get completed by 2032-33 confirming the techno commercial viability of Sodium Cooled Fast Reactors.

First fleet of Commercial Fast Breeder Reactors (CFBR 3,4,5 & 6) and its fuel cycle facility (FRFCF-II) will be launched at a new site. Action for site selection will be initiated shortly. This site will also have a Prototype Hybrid Small Modular Reactor of 100 MWe capable of generating both electricity and Hydrogen by the year 2047.

The necessity of deployment of Fast Breeder Reactors was felt in the very early period by founding fathers of Indian nuclear programme. A decision was taken to set up a test reactor FBTR at Kalpakkam. The fuel proposed for this reactor was (U, Pu) O_2 mixed oxide (U enriched to 85%). To begin with, R&D work on MOX fuel for FBTR was initiated. However, because of non-availability of enriched Uranium, a Plutonium rich Mixed Carbide ($U_{0.3}Pu_{0.7}$) C was chosen as the driver fuel. This selection preceded extensive developmental work resulting in setting up of a Mixed Carbide fuel fabrication line at Radio-metallurgy Laboratory, RLG, BARC, Trombay.



FBRs & CFBRs

FBTR is in operation since 1985 and serves as a test bed for irradiation of various fuels, structural materials, components, isotope production and other experiments. Short length PFBR fuel pins containing MOX fuel, sphere-pac fuel, in-core neutron detectors also have been tested. This reactor has given valuable operating experience of over 38 years. A large number of reactor physics and safety related engineering tests were also conducted. The training of operating personnel of PFBR has also been done in FBTR. FBTR has the potential to operate up to 2032 and beyond by carrying out life extension exercise.

The experience gained in the construction, commissioning & operation of FBTR including the focussed R&D programme on related technology e.g., fuel fabrication, cladding/hex-can manufacture, Enriched Boron Carbide production, Sodium handling etc. provided necessary confidence to launch the construction of Prototype Fast Breeder Reactor. Some of the critical equipment like Inclined Fuel Transfer Machine, neutron detectors have been developed by BARC. The fuel supplied for PFBR was manufactured by BARC at an industrial scale fuel fabrication plant, AFFF, Tarapur. The hardware for making fuel pins, manufacture of radial blanket pins, EBC pins, and manufacture of various types of sub-assemblies were done by

NFC. NFC will be able to meet the requirement of core structural components for future FBRs by setting up of new plants at Hyderabad and at a new site. IGCAR has designed 500 MWe PFBR (MoX fuel & Sodium cooled) and it is proposed to deploy 2 such reactors of same design (FBR 1 & 2) at Kalpakkam.

To accelerate the process of multiplying the power generation capacity with Fast Reactors, in comparison to MoX fuel, Metallic fuel (U-23Pu-6Zr) will be more viable with high breeding ratio (1.35-1.4) and low doubling time (9.4 y). Accordingly, the next four similar reactors (CFBR 3,4,5 & 6) with Metallic fuel are proposed to be setup in a new site with collocated Fast Reactor Fuel Reprocessing Facility (FRFCF II). These reactors are proposed to have Thorium as blanket and with advanced safety features meeting Gen-IV reactors.

4.2.1 Prototype Hybrid Small Modular Reactors & Standard Hybrid Small Modular Reactors (PHSMR & SHSMRs 1 & 2)

Prototype Hybrid Small Modular Reactors (PHSMRs) - with multitude of applications including electricity generation, grid integration of renewables, process heat, desalination and hydrogen production which supports de-carbonization of hard-to-abate sectors of the economy are opening up new avenues for deeper and accelerated adoption of nuclear technology. Among the many types of SMRs based on the basic nuclear technology employed in the design, the Sodium Fast Reactors (SFRs) has its own advantages of Plutonium & Minor Actinides burning, longer gap between refuelling due to excess reactivity margin and hydrogen production for decarbonised energy system due to its higher thermal efficiency. Accordingly, it is proposed to construct one 100 MWe PHSMR with SFR technology (for electricity generation & hydrogen production) at the new site that will be identified for constructing CFBRs (3,4,5 & 6). On successful operation of PHSMR for 12 months, two Standard Hybrid Small Modular Reactors (SHSMRs-1 & 2) of 100 MWe each will be constructed.

BARC is already involved in designing the SMRs. LMFRs with lower power production (< 50MWe) and with a core life of 30 years operation without refuelling may also be compactly designed. In absence of refuelling requirement and eliminating rotatable plugs & fuel handling machines will make the reactor more compact in its size and may also prove economical.

4.2.2 Hydrogen Production in PHSMR & SHSMRs

Hydrogen is expected to play important roles in decarbonised energy systems, as an energy source as well as a storage vector to enhance power system flexibility. However, hydrogen is not a primary energy resource and has to be produced using different chemical processes. Compared to conventional Steam Methane Reforming, water electrolysis method, is the cleanest way to produce hydrogen, provided it uses a decarbonised electricity source. Fast Reactor with its higher thermal efficiency would be a viable source for hydrogen production with the later method by water electrolysis.

Important milestones

Facility/ Plant	Site	Start of construction	Commercial operation
FBR-1 (500 MWe)	Kalpakkam	2026	2033
FBR-2 (500 MWe)	Kalpakkam	2026	2034
CFBR-3 (500 MWe)	New site	2033	2041
CFBR-4 (500 MWe)	New site	2033	2042
CFBR-5 (500 MWe)	New site	2034	2042
CFBR-6 (500 MWe)	New site	2034	2043
PHSMR (100 MWe)	New site	2030	2033
SHSMRs-1 (100 MWe)	New site	2033	2036
SHSMRs- 2 (100 MWe)	New site	2033	2036

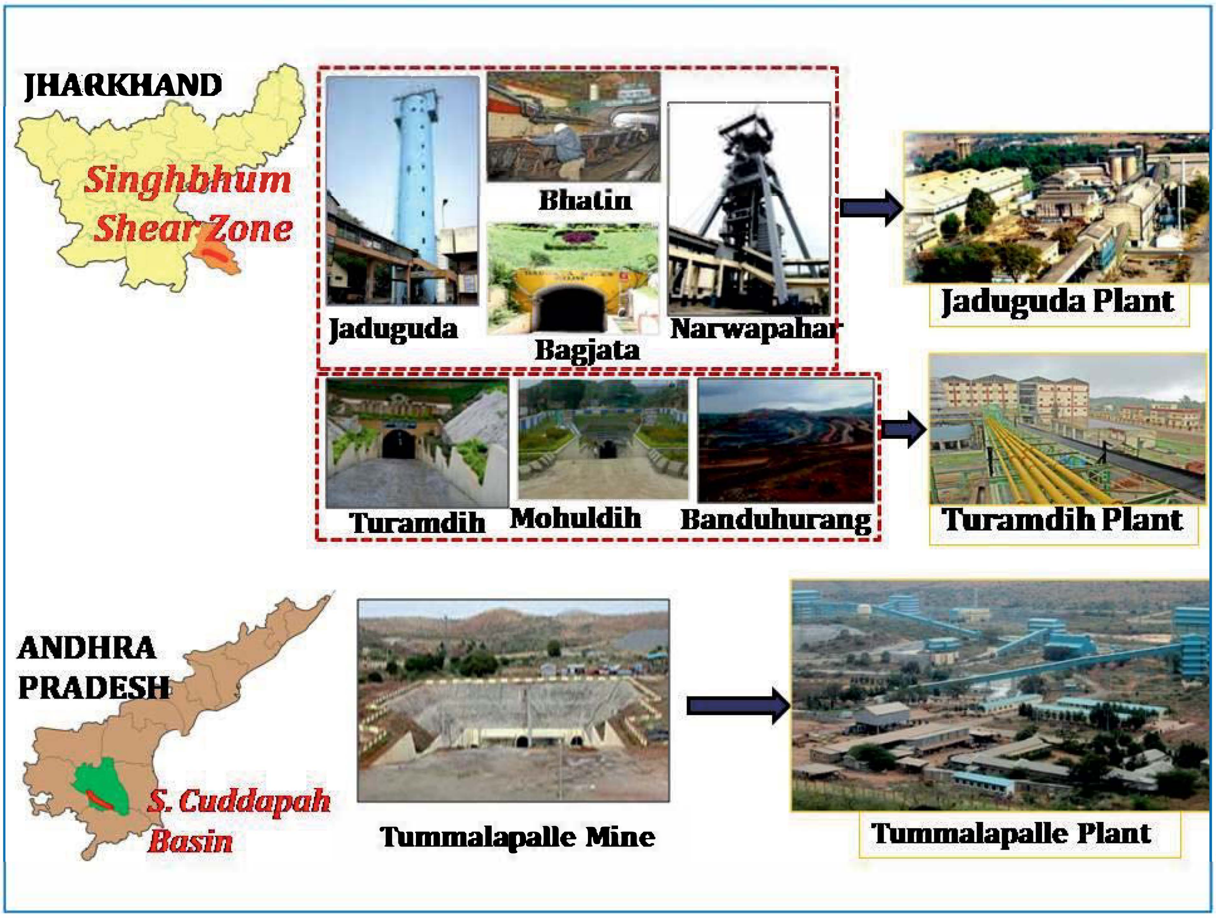
4.3 Conclusion and way forward

The fast reactor programme with closed fuel cycle will increase the nuclear power production capability from our limited uranium resources. Fast breeder reactors will produce sufficient fissile material to support a greater number of FBRs. In due course of time, these FBRs will produce sufficient fissile material to launch the third stage nuclear power programme based on Thorium. Due to SFRs advantages of compact size, longer refuelling interval and other favourable factors, this technology is more viable for constructing SMRs. Additionally, as the FBRs operate at higher thermal efficiency compared to other reactors (PHWR, LWR), it will be more efficient to utilise the heat for hydrogen generation along with electricity generation in Prototype & Standard Hybrid Small Modular Reactors (PHSMR & SHSMRs). The site required for setting up of CFBR 3,4,5 & 6 along with co-located reprocessing plant will be explored either in a coastal site or in an inland site with adequate water supply facility. Construction of FBTR-II with metallic fuel and establishing the reprocessing (Metallic &Thorium) at the earliest will accelerate the usage of Metallic fuel & Thorium blankets in commercial FBRs towards expansion of FBR programme. Similarly, freezing the design & obtaining regulatory clearance of Fast Reactor based SMRs at the earliest will enable the modularisation required for construction of SMRs at minimum time. Accordingly, the existing supply chain may be sensitised and new vendors would be developed for supply of the components in time for the expansion programme. Currently, BHAVINI is constructing the PFBR and planned to construct FBR 1 & 2 with similar specifications as designed by IGCAR. The construction, operation & maintenance experience of these reactors will pave way for a good designer for future FBRs.

5. Uranium Corporation of India Limited – UCIL

"To constantly strive to develop and implement a technology suitable for mining and processing of uranium ore at a competitive cost and to diversify towards mining, tunnelling and process related consultancy and other project implementation ventures."

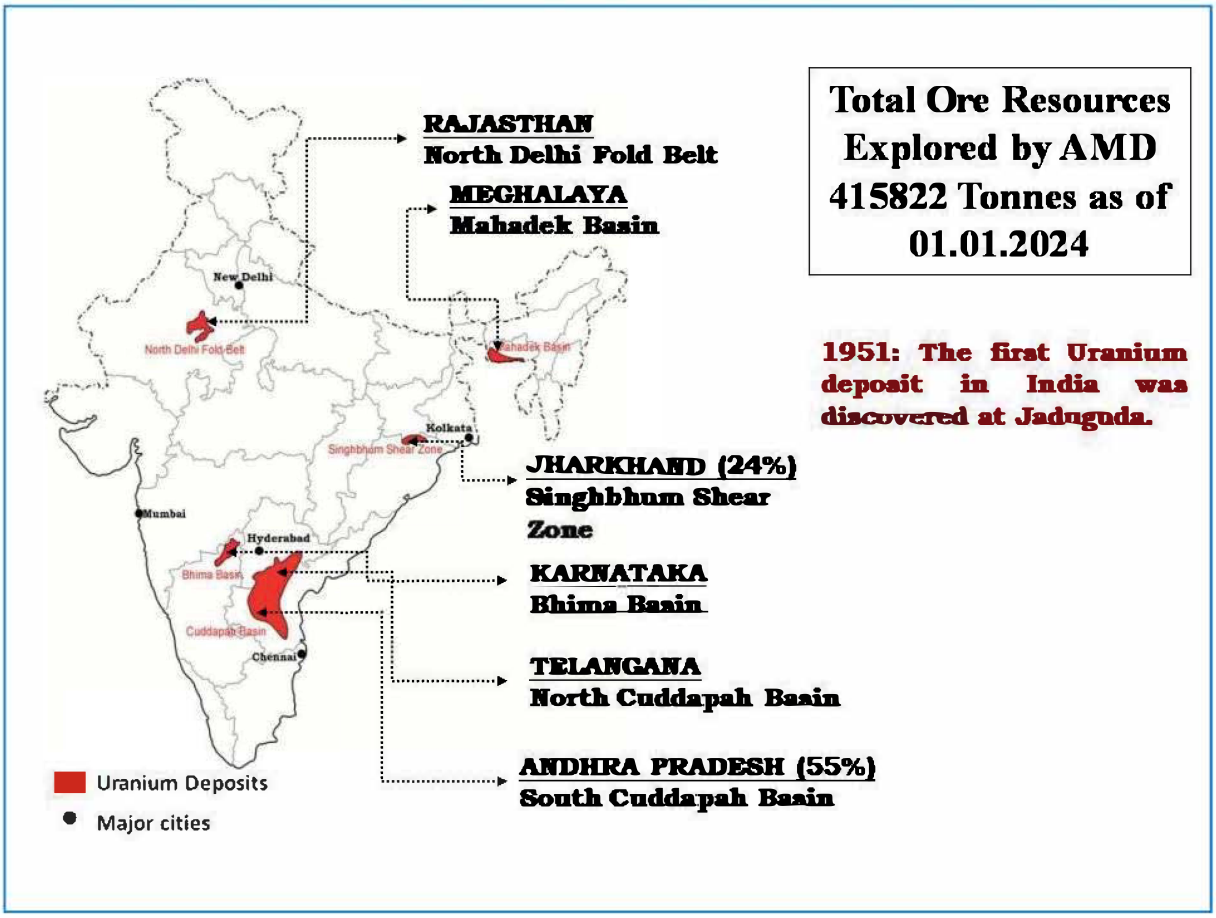
Uranium Corporation of India Limited (UCIL), established on October 16, 1967, is the only uranium mining company in India and has over the years excelled in various fronts with technological advancements in all areas of its operations. Practices of uranium mining, processing and waste management adopted by UCIL are under continuous up-gradation and are in line with eco-friendly global best practices. As of now, UCIL operates six underground mines (Bagjata, Jaduguda, Bhatin, Narwapahar, Turamdih and Mohuldih) and one open pit mine (Banduhurang) in the Singhbhum shear zone in the State of Jharkhand. Ore produced from these mines are processed in two process plants located at Jaduguda and Turamdih in the same region. UCIL is operating a large underground mine and process plant (based on a new indigenous alkaline technology) in Proterozoic Cuddapah basin at Tummalapalle, YSR District in Andhra Pradesh.



Operations in Jharkhand and Andhra Pradesh

In order to cater the fuel requirements of upcoming reactors, Atomic Energy Commission has accorded in principle approval for 13 projects which includes capacity expansion of some of its existing units as well as for establishing new projects in various parts of the country. In line with DAE's requirement, UCIL has already outlined a plan for massive expansion which includes maintaining sustained supply from existing facilities, modernization and capacity expansion of some existing units and construction of new production facilities (mines and plants) in different parts of the country.

Indian uranium deposits are small to medium tonnage deep seated deposits and are low grade compared to international deposits. Due to the extremely poor grade of Uranium, cost of mining and processing of Indian uranium bearing ores is higher than international uranium price. Presently, uranium pricing is administered on a cost-plus basis by the Department of Atomic Energy in consultation with Chief Advisor Cost, Department of Expenditure, Ministry of Finance.



Total Ore Resources as of 1st January 2024

5.1 Present status and future plan

Domestic Sources:

The existing production centres of uranium concentrates at Jaduguda, Turamdih and Tummalapalle, in the states of Jharkhand and Andhra Pradesh, may continue to produce at the existing rate i.e., about 7500 Tons per day (TPD) as additional resources have been discovered within the leasehold areas and also in the adjoining areas. The opening up of the deposits in next 10 years (T_0+10) in the adjoining areas will contribute to increase the existing production capacity from 7500 TPD to over 20000 TPD.

UCIL has initiated pre-project activities to open up new green field projects in other states, viz. Rohil in Rajasthan, Kannampalle in Andhra Pradesh, Gogi and Kanchankayi in Karnataka, and Jajawal in Chhattisgarh. UCIL will endeavour to open up deposits in Meghalaya and Telangana as and when a favourable atmosphere for the same prevails. The opening up of these new deposits will contribute to increase the production capacity more than two-fold in the next 25 years.

If the planned projects of UCIL turn into production centres, the additional quantity of Uranium concentrate (Yellow Cake) can contribute significantly to the fuel requirement of the upcoming reactors of NPCIL in next 10 to 15 years subject to the obtaining of statutory clearances.

5.2 Plan for Expansion up to 2047

Up to 2032	2032-2047
Rohil Project (2500 TPD)	Lambapur & Peddagattu
Tummalapalle Expansion (1500 TPD)	Chitrial Project
Kanampalle (6000TPD)	Kanampalle Expansion (6000 TPD)
Gogi (500 TPD)	RKPL East Deposit (6000 TPD)
Kanchankayi (400 TPD)	KPM Project
Jajawal (450 TPD)	More new projects based on discoveries by AMD
Banadungri (1500 TPD)	
Garadih (500 TPD)	

5.3 Import potential with JV abroad for mining

UCIL, in addition to developing domestic resources, is also putting efforts to increase production capacity over the next 10 years from international expansion by forming a JV with a suitable strategic partner to meet the fuel requirement of reactors (12nos.) proposed under DAE safe guards. With respect to identification of suitable assets for acquisition of uranium resources in overseas countries, responses from leading uranium producing companies against floated RFI have been received and due diligence of data is in process. As the next step, an EOI to onboard a reputed Indian firm as a strategic partner to identify/ shortlist firms having the financial and technical capacity to develop and operate overseas uranium assets in partnership with UCIL was floated and the responses received are being evaluated.

5.4 Challenges

Uranium production in the country has always been subjected to various challenges.

- The uranium deposits discovered by AMD over last six decades are of low to medium grade, small in tonnage and also complex in nature (deep seated).
- The country's largest uranium deposit discovered by AMD in the year 1987 in the Proterozoic Cuddapah basin is at Tummalapalle, Andhra Pradesh. This deposit is hosted by carbonate rock having two lodes i.e. Hang wall lode and Footwall lode. The major uranium resources are lying in Hang wall lode. Due to the presence of water bearing weak strata/ rock (Red Shale), the mining of hang wall lode has several issues. The support issues related to mining of hang wall lode have been overcome with intensive scientific studies and mining of hang wall lode is also now being done.
- Also, for the first time in the country, the alkaline processing technology developed by a joint team of BARC, AMD and UCIL was adopted for Tummalapalle plant. However, due to constraints in settling & filtration characteristics of product precipitate, the plant could not achieve its desired capacity. Subsequently, upon detailed research and on-site modifications, the issues were resolved by installing Re-dissolution System facility and plant could start achieving its desired capacity.

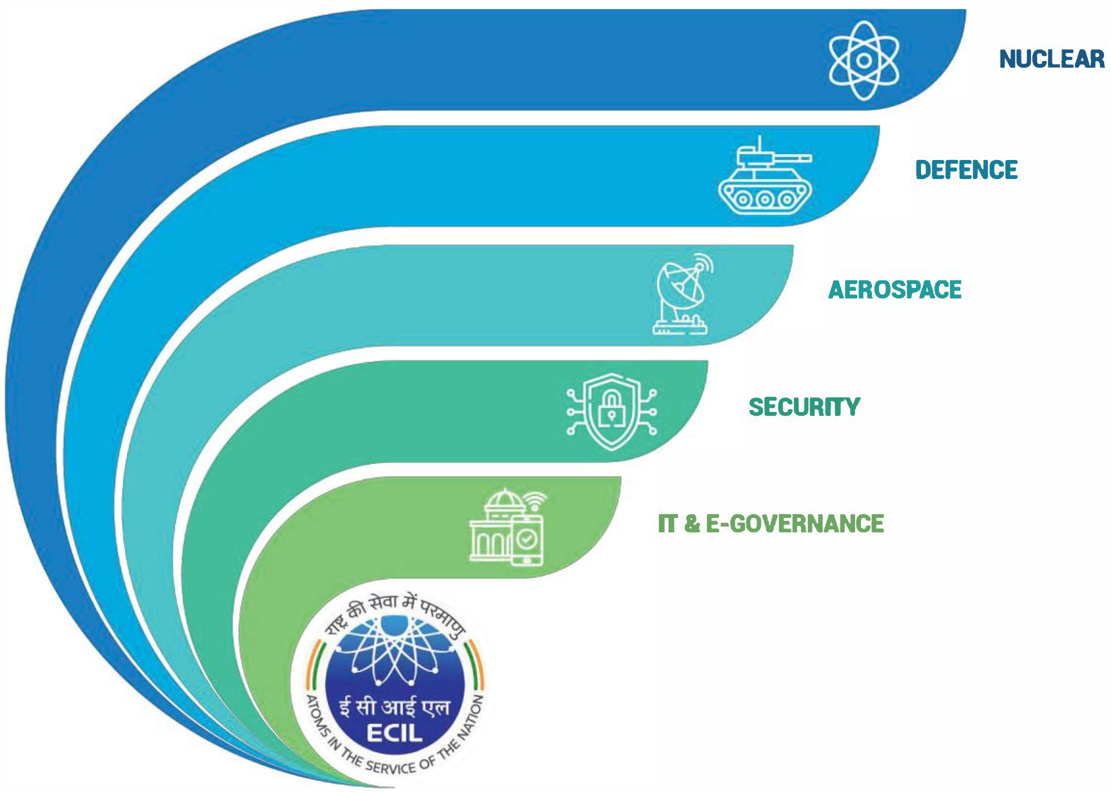
5.5 Conclusion and way forward

Mining of uranium ore from the mines in Jharkhand region is carried out from deeper levels as the ore reserves in the upper levels have almost depleted. In view of this, scope for increasing the production from existing mines in Jharkhand is very less. However, UCIL will continue the operations in Jharkhand & AP at 100% capacity. As setting up of a green-field project often involves acquisition of substantial land from local population, UCIL would acquires the requisite land as per its and resettlement Policy. MOUs/Joint venture with State government, mining PSUs for undertaking mining operations may be initiated. Further, in order to cater any shortfall in production of uranium concentrate to fuel the reactors under domestic safeguards, it is proposed to form a Joint Venture with NPCIL & NTPC to acquire the overseas mines as NTPC has an ambitious plan to venture non-fossil fuel generation to achieve the net zero targets by 2070.

6. Electronics Corporation of India Limited (ECIL)

"To contribute to the country in achieving self-reliance in strategic electronics."

The genesis of Electronics Corporation of India Limited (ECIL) can be traced back to the work undertaken at the Electronics Production Division, Reactor Controls Division, and Computers Group of the Atomic Energy Establishment, Trombay (AEET) since its inception. By the late 1960s, AEET had a significant electronic group, wherein research and development were carried out on silicon crystal, compound semiconductors, ceramics, transistors, diodes, carbon resistors, metal-film resistors, and tantalum capacitors. Additionally, analog and digital computer modules were manufactured and successfully tested. Recognizing the nascent state of the electronics industry in India and its anticipated future requirements, a need was felt to establish an independent entity dedicated to Nuclear Electronic Instruments/systems and Electronic Components.



FOCUS ON HIGH TECHNOLOGY & LOW VOLUME **PROJECTS OF NATIONAL IMPORTANCE**
MULTI-PRODUCT MANUFACTURING / PROJECTS WITH LONG GESTATION PERIODS
CONTRIBUTIONS TO MAJOR INTERNATIONAL **DISCOVERY SCIENCE PROGRAMMES**

Against this backdrop, Electronics Corporation of India Ltd a Schedule- 'A' CPSE under the Department of Atomic Energy was established in April 1967 with the main objective of meeting the requirements of nuclear electronic instruments & systems, nuclear detectors & monitoring systems for Nuclear Power Programme of the country. ECIL has since expanded and diversified into a multi-product, multi-disciplinary and multi-technology organisation providing cutting-edge technology solutions of national importance in Defence, Aerospace, Security, IT & e–Governance sectors besides meeting the core mandate of DAE requirements in nuclear sector.

ECIL pioneered the development of a number of products in India earning it the name and fame as the torch-bearer of Electronics and IT revolution in the country. These products include Black & White TV, Digital Computers, Control and Instrumentation products for Nuclear Power Plants, Automatic Message Switching Systems, Programmable Logic Controllers and Electronic Voting Machines.

Subsequent to the shock of opening up the Indian market for imports during 90's, the company has consciously moved in to projects from products leveraging its multidisciplinary and system integration competencies.

Meanwhile, the outside environment in which ECIL is operating is also undergoing fundamental changes. The Nuclear energy sector is poised for rapid growth. This program will be supported by reprocessing plants and fuel fabrication facilities all of which have a substantial C&I component. This would mean substantial business of C&I equipment over the coming decades. These open up unprecedented opportunities to ECIL – the only fully integrated nuclear C&I company in the country. It also brings in foreign players and increased competition. Similar far-reaching changes are underway in the domestic defence and aerospace electronics sector. Homeland security and information security domains too are set to grow.

ECIL's state-of-the-art infrastructure, manufacturing and quality systems meet all the requirements of products for Defence, Nuclear and Space. The infrastructure includes facilities for CAD, ASIC/VLSI design, Hybrid Microcircuits and PCB manufacture, High Density Interconnect facility, Automatic SMD Insertion Machines, On-line PCB Test Equipment, Secure Manufacturing Facility, calibration and characterization of Radiation Instruments, Compact Antenna Test Range facility, Seeker and C4I systems manufacturing facility, SSRFPA facility, Environmental Testing, Calibration Laboratories and EMI/EMC Test facility.

All the business divisions of ECIL are certified for ISO 9001:2015 Quality Management System and the company is certified for ISO 14001:2015 Environmental Management System and ISO 45001:2018 for Occupational Health and Safety.

The typical business operations of ECIL today involve large, one-of-a-kind projects with long execution periods, high technology content, substantial R&D effort with attendant uncertainties. Most importantly these projects demand a different set of skills and competencies- business development, order booking, system engineering, project management and sub-contracting.

As per Department of Public Enterprises (DPE) guidelines, the Company is grouped in the sectorial category of “Multiproduct manufacturing with long gestation period”. The other PSU’s in the sector include 9 Defence PSUs (BEL, BDL, MIDHANI, MDL, HSL, GRSE, HAL, BEML & GSL), BHEL, HMT Machine Tools under Heavy Industry category and Cochin Shipyard Limited.

6.1 Electronics & Instrumentation (E&I) for Nuclear Sectors

ECIL’s products and capabilities in the nuclear sector span components to systems, all plants of nuclear fuel cycle and C&I systems for every type of nuclear power plant in India (PHWR, FBR, PWR). For all the standard products, ECIL provides life cycle support services from consultancy through design, engineering, manufacturing, qualification, I&C, AMC and refurbishment. The products exemplify a range of capabilities for engineering custom solutions with large indigenous content.

The technology and products developed by ECIL have contributed to the advancement of the country's nuclear power programme which includes a wide range of devices and systems for reactor safety, regulation, radiation monitoring and environmental protection. The key contributions/projects executed are highlighted below: -

- Starting from the design and development of control systems for the Apsara Reactor, the C&I package for all the operating Nuclear Power reactors in the country (except RAPS-1, supplied by Canada and TAPS-1&2 - supplied by USA) were designed by BARC/NPCIL and supplied by ECIL, establishing self-reliance and self-sufficiency in this regard. The restrictions placed and the sanctions imposed on India after the Pokhran Experiments have had minimal impact on this product stream of ECIL. The synergic relationship between BARC-NPCIL-ECIL has been consistently strong and the same is getting extended to IGCAR and BHAVINI in a significant measure

- The products manufactured by ECIL ensure the safe and reliable operations of Indian Pressurized Heavy Water Reactors (PWHRs). This includes systems for reactor control & protection, fuel handling controls and main & emergency air lock systems, among others.

- Utilizing BARC's technology expertise, ECIL has consistently supplied a range of radiation detectors for DAE's nuclear power program for over four decades to use in critical applications like "Start-up," "Reactor Protection," Reactor Power Regulation and Effluents & Area Monitoring systems in Nuclear Power Reactors.

- Reactor instrumentation systems like Neutron Flux mapping system, Neutronic channels, Delayed Neutronic systems etc. were supplied to nuclear power plants, designed to monitor and control various aspects of reactor operation. These systems provide essential data to operators, enabling them to maintain safe and efficient operation of the reactor.

- Different types of radiation monitors were supplied to all nuclear power plants and Reprocessing plants to maintain safe operations, complying with regulatory requirements, and protecting human health and the environment from the potential hazards associated with ionizing radiation.

- Various Health Physics systems supplied assess the radiation exposure levels, identifying potential hazards and implementing necessary measures to mitigate risks to both human health and the environment.

- Instrumentation systems were supplied to nuclear power plants, reprocessing plants and other DAE establishments for fuel handling and nuclear waste handling, treatment, storage, and disposal of radioactive waste generated from various nuclear activities, including nuclear power generation, medical applications, research, and industrial processes.
- ECIL with the technical support of BARC has played a pivotal role in advancing nuclear technology for FBR by supplying precise Control and Instrumentation (C&I) systems for the Prototype Fast Breeder Reactor (PFBR) at Kalpakkam.
- ECIL has undertaken upgrades for various power plants including NAPP-1&2, RAPP-3 to 6, KAIGA-1 to 4, TAPP-3 & 4, and KAPP-1&2.
- Developed new products such as Passive Catalytic Recombiner Devices and Hydrogen Steam Concentration Monitoring System for KAPP-3&4.
- ECIL has also supplied Radiation detection equipment to all Seaports & Airports to prevent illegal flow of nuclear materials in either direction.

The company continues to innovate and supply new products to further enhance the safety and performance of nuclear power plants in India.

6.1.1 Current Projects

The key ongoing activities with regards to Electronics and Instrumentation are appended below: -

- 2x1000 MW Advanced Light Water Reactor at NPCIL, KKNPP-1&2, Kudankulam.
- I&C of entire control instrumentation encompassing erection of 400 main control room panels, 1600 signal processing & I/O cabinets, 1100 local control panels, 2500 junction boxes, calibration and installation of 20,000 process field instruments, 1000 instrument racks, 250 km field routing and cabling, 23 lakhs wire termination etc.

- Commissioning of 10 types of communication systems to ensure routine and emergency communication within the plant.
- Commissioning of Automated Radiation Monitoring System
- Fire alarm system for the entire plant having about 14000 sensors and associated controllers. TPTS(DCS) panels, ULCS workstations & networking, RCD and ESFAS cabinets, reactor protection system etc.
- Total plant Security & Access control system which includes Turnstyle gates, hand geometry readers, control units, control software, about 300 cameras, 60 microwave detectors, 200 intrusion detectors, 250 contact condition monitoring sensors & associated controllers, distress alarm system, guard tour monitoring system, x-ray baggage scanners, Campus-wide fiber optic networking etc.
- Replacement of Russian-supplied delicate HCS fiber optic cables with indigenously customized HCS cables for better pull strength and communication between ESFAS & MCR. Also, review of voluminous Russian drawings & documents for preparation of terminal lists, procedures for erection etc.
- Automated radiation monitoring systems, Fire alarm systems and Access control system are under AMC.
- 1x500 MW Prototype Fast Breeder Reactor at Bhavini, Kalpakkam
- Design, engineering, supply, installation and commissioning of control instrumentation, sodium leak & level detectors, radiation monitoring system and Neutronic instrumentation on EPC basis meeting NPP Quality requirements.
- Main control room panels, 170 signal processing cabinets, 64 remote terminal units, 300 junction boxes, 500 km field cabling, 153 radiation monitors, 60 neutron detectors etc., 200 km fibre optic cabling & networking, PLC based local control panels for fuel handling machine operation etc.

- Automated Radiation Monitoring System (ARMS) for KKNPP-3&4, Kudamkulam. The System is designed and developed for the KKNPP-3&4 radiation safety assurance by means of on-line receiving and processing of the data of the plant parameters, which characterize the NPP radiation condition on all modes of operation including design-basis and beyond design-basis accidents.
- SCADA and Radiation monitors for FRFCF.
- Comprehensive AMC for full scope Simulator for operator training at Bhavini and scaled-down simulator for software testing installed at IGCAR.
- AMC of C&I Systems for TAPS 3&4, KGS 1 to 4, RAPS 3 to 6.
- AMC of NPCNET VSAT communication system for 15 Nuclear Power Plant Sites.
- Various Radiation monitoring systems supplied to FRFCF, Kalpakkam and INRP Tarapur
- Nuclear instrumentation and Radiation Monitoring Systems were supplied to various research reactors of BARC and laboratories of IGCAR.

6.1.2 Near-Term Opportunities

Working together with BARC and NPCIL over the past five decades, ECIL has gained specialized knowledge and expertise in the nuclear domain and has established advanced infrastructure for the production, testing, and quality assurance of these systems. The collaboration between ECIL and NPCIL includes design, development, manufacture, supply, installation, and commissioning of control systems, as well as life cycle support including technology obsolescence management.

The opportunities as envisaged by ECIL include -

- Engineering, manufacture, qualification, test, supply, installation and commissioning of the Control & Instrumentation (C&I) equipment for the operating as well as upcoming indigenous and Nuclear Power Plants established under foreign collaboration. The major equipment includes Main Control Room and Control Equipment Room, Radiation Detectors, Nuclear Instrumentation systems, Radiation Monitoring Systems, Field Instrumentation, Industrial Systems, Simulators for operator training and Security Solutions which includes Physical Protection System, Intrusion detection system, CCTV surveillance system, Access control system, Time & Attendance System & Visitor Management System.

- Design, manufacture, testing, supply, installation and commissioning of Training simulator system and procurement of Simulation Tools for the upcoming indigenous and imported plants.
- Participation in Installation and Commissioning of C&I systems for imported reactors and contribution to gradual indigenisation of these reactors.
- Development Cum Production Partner (DCPP) for futuristic requirements to meet requirements of indigenisation and in-service inspection requirement of NPP including requirements arising from Small Modular Reactors (SMRs).
- Maintenance services under AMC for equipment including the Control Room, environmental monitoring systems, industrial systems, field instruments, simulator systems, integrated security systems, IT and Communication Systems and all mutually agreed upon equipment at the NPPs.

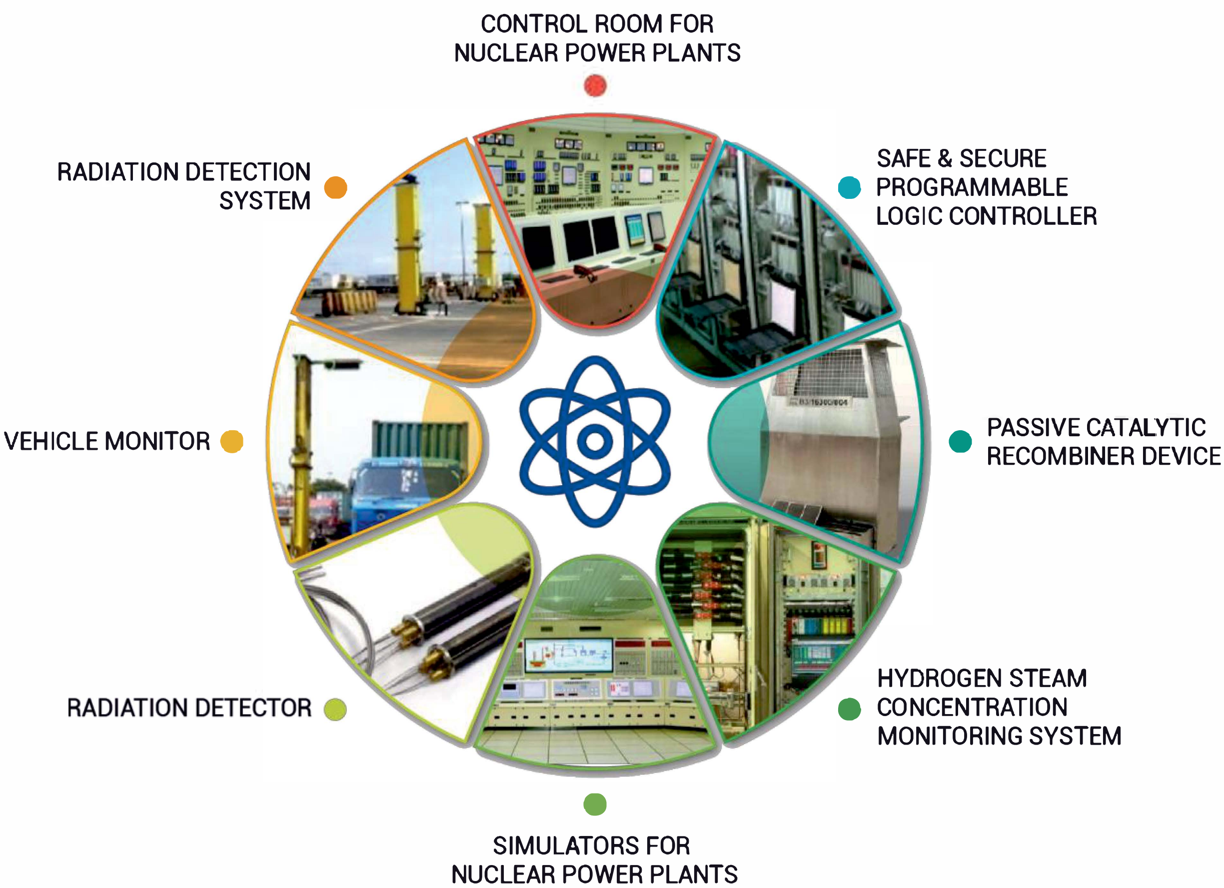
The business opportunities stem from the projected expansion in the Nuclear Power Program, opening up of domestic nuclear power sector for international commerce, the strategic nuclear program including propulsion systems, planned construction of new fuel processing plants, fuel fabrication plants and anticipated contribution to international mega science projects such as ITER and FAIR.

6.1.3 Projected E&I demand as per Vision 2047

The commitments of Government of India towards 'Net zero" highlights the importance of collaboration and innovation in the Nuclear power sector, as well as the potential for significant contributions to India's energy landscape and the global goals for clean energy. Based on the Projected E&I demand emanating from requirements of NPCIL, BHAVINI, Nuclear Recycling Board (NRB) and other activities being undertaken by ECIL in the nuclear domain. The vision of nuclear vertical is summarized in succeeding paragraphs.

6.2 Nuclear Vertical

All the indigenously built nuclear power plants and reactors across the country have the vital Instrumentation and Control (I&C) systems engineered & manufactured by ECIL. ECIL's foot print of I&C systems span diverse reactor technologies and the entire nuclear fuel cycle - pressurized heavy water reactors (PHWR), fast breeder reactors (FBR), compact light water reactors (LWR) and reprocessing plants. All of these I&C systems are based on indigenous system designs.



Nuclear Vertical

The control and automation products which ensure safe and reliable operation of Indian PHWRs include reactor control systems, fuel handling controls, primary and secondary shutdown systems, power supplies, computerized operator information systems and full scope replica simulators. ECIL also develops, manufactures and supplies full range of radiation detectors and nuclear instruments for protection, control, health & environmental monitoring. These include self-powered neutron detectors, uncompensated ion chambers, radiation monitoring systems, health physics instruments etc.

ECIL has commissioned several supervisory control and data acquisition (SCADA) systems for nuclear, oil and gas sector as well as for power management. ECIL is also supplying radiation detection equipment to all seaports and airports to prevent illegal flow of nuclear material.

The yearly revenue of the Nuclear Vertical during the last decade was in the range of Rs 250 Crores to Rs 460 Crore.

The key identified business opportunities, technologies and products to meet the future requirements of Nuclear Sector is tabulated below.

Business Opportunities
• Control & Instrumentation (C&I) systems for Pressurised Heavy Water Reactors • C&I systems for Fast Breeder Reactors • Radiation Detectors for upcoming Reactors • Reactor instrumentation systems for upcoming Reactors • Nuclear and Radiation Monitoring systems for LWRs with foreign collaborations • Electronic equipment for Compact Reactors • Radiation Instruments for reprocessing plants for Nuclear Recycle Board • Control and Instrumentation systems for primary and secondary plants of nuclear submarines • Radiation Detection Equipment for Homeland security • Health Physics instrumentation • SCADA systems for Power, Steel, Oil and Gas sectors

- Training Simulators
- Power Electronics for Discovery Science Programs
- Medical applications

Thrust areas/Product

- Development of new generation Secure PLC, Programmable Logic Controller
- Conventional C&I Systems
- High Sensitivity Neutron Detectors, High range and high energy Gamma Detectors
- Next generation neutronic channels: Delayed Neutron Channels, Pulse Safety Channel, Power Pulse Safety Channel, Wide Range Control Channel, Campbell Safety Channel, Reactivity Safety Channel, Reactivity Control Channel, P/Q Channel, Counting channel etc
- Trip Logic Unit, Portable Tritium in Air Monitor, Gamma Spectroscopic instruments, Low Activity Alpha/Beta Monitor, Low Energy gamma monitors, Iodine-121 monitor
- Nuclear and Radiation monitors of various ranges and sensitivities scaled to compact rector specifications.
- Compact Alpha/Beta Continuous Air Monitors, Radon Monitor, Nuclear Waste Monitoring.
- Radiation and Gas Monitoring Systems
- Nuclear Radiation detection systems for sea ports and airports, Isotope identifiers
- Whole body monitors, Wireless dosimeters
- Accident Mitigation systems for Nuclear Power Plants
- Distributed Digital Control Systems, Supervisory Control and Data Acquisition Systems
- High Voltage Power Converters
- Simulators
- Medical Equipment based on
  - LINAC technology
  - Cyclotron

Future outlook

The government has taken several measures to expedite expansion of nuclear power generation in the country and to fast-track India's domestic nuclear power programme. It has accorded approval for setting up NPPs in fleet mode. To mitigate carbon emissions by 2070, several large sectors, including the steel industry, are considering nuclear power as a viable alternative to power generation. Discussions on Small Modular Reactors (SMRs) are gaining momentum in the country. The company is actively pursuing the opportunities arising from the new NPPs whilst continuing to support the infield systems supplied to various NPPs. The C&I requirement for the upcoming Nuclear Reactors and ongoing up-gradations gives a positive outlook to the nuclear vertical of the company.

Nuclear Power Corporation of India Limited (NPCIL) has a vision for capacity expansion from 7480 MW to 100108 MW by 2070. NPCIL plans to set up Pressurized Heavy Water Reactors (PHWR) and Light Water Reactors (LWR), towards capacity addition of 14500 MW by 2032. Further capacity additions of 35000 MW are planned for implementation by 2047.

Based on the business prospects with regards to upgrades and Vision plan of NPCIL, the estimated value for upgradation of operating reactors, supply of C&I systems for new upcoming reactors and supply of Radiation Instruments & Detectors is likely to result in an annual revenue in the range of 400-600Cr.

BHAVINI is now constructing and commissioning the first 500 MWe Prototype Fast Breeder Reactor (PFBR) at Kalpakkam and the commercial operations are planned from FY 2032. BHAVINI has plans of capacity addition to the tune of 3300 MW by 2040.

Based on vision plan of BHAVINI, ECIL expects to meet the Electronics and Instrumentation requirement to the tune of Rs 100-150 Crore from FY 2026 onwards.

The requirements of Advanced Technology Vessel Program (ATVP) will continue to be stable at an average requirement of systems to the tune of Rs 150-200 Crore.

ECIL anticipates the need for nuclear and radiation monitoring systems for reprocessing plants at INRP Tarapur and FRFCF Kalpakkam. Against this requirement, approximately Rs. 150 Crore in business is expected annually, contingent upon the progress of various phases.

Accordingly, taking into consideration the above major opportunities, service orders and requirements of RDE for sea ports, airports and land borders the company is likely to achieve a yearly revenue in the range of 600- 800 Cr from FY 2026-27 and thereafter grow at an average of 8-10 Percent.

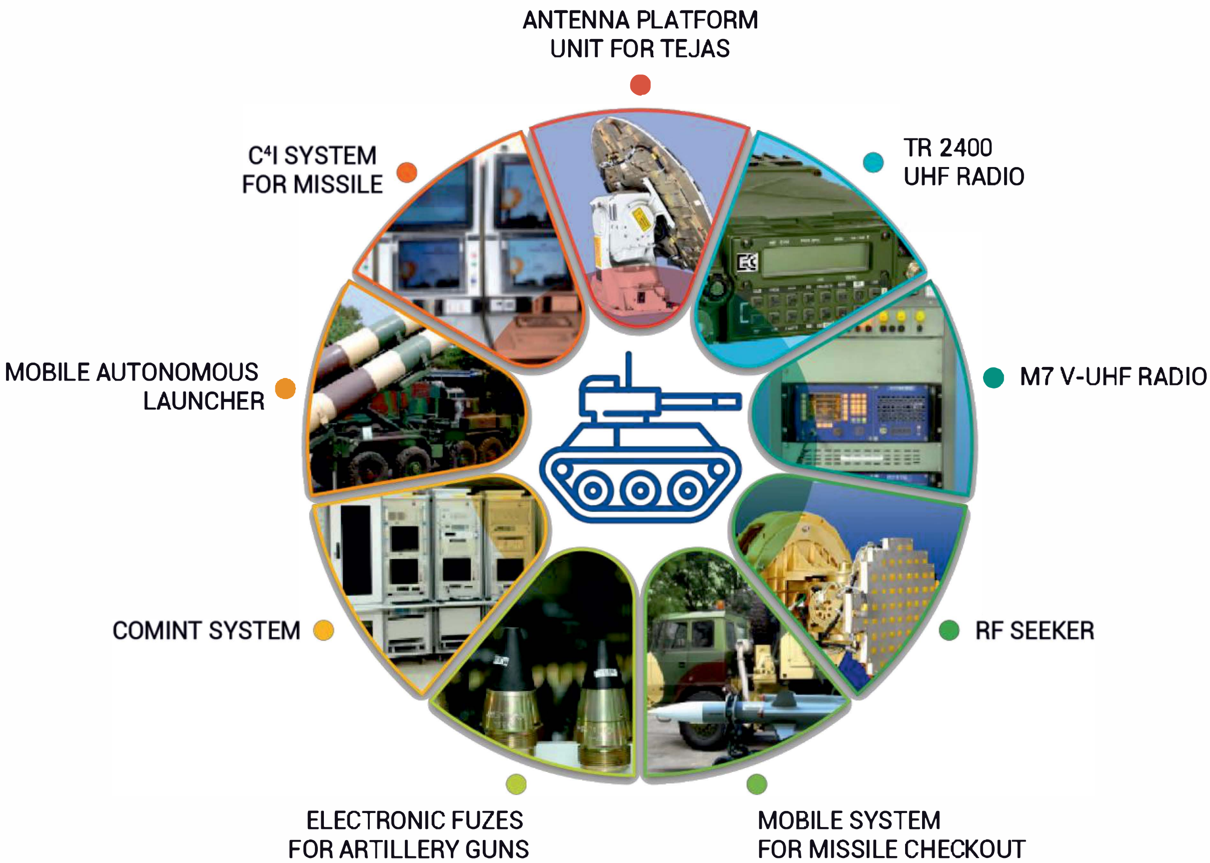
ECIL Verticals -Business Projections

The business outlook and the identified technology domains in the Nuclear Sector are highlighted in the previous chapter, the other verticals of Business operations and the envisaged growth is brought out in the succeeding paragraphs

6.3 Defence Vertical

Defence is key business vertical of ECIL having a range of products viz. Communication Systems, Electronic Warfare Systems, Universal Electronic Fuzes for Artillery, C4I for Missile Systems, RF Seeker for Missiles and Encryption Systems.

ECIL has been supplying a wide range of professional grade components, equipment and integrated strategic systems to all the three wings of the Armed Forces. The contributions of ECIL to Defence Sector span from Secure Communication systems, Electronic Warfare Systems, Simulators, COMINT & Interception Systems, Antenna, SATCOM Systems & Networks, Stabilized platforms for air-borne Radars, C4I & Missile Support Systems, Encryption and Secrecy Systems, Electronic Fuzes, Precision Electro-Mechanical Components, Sensors and Inertial Navigation Systems etc.



Defence Vertical

The yearly revenue of the Defence Vertical during the last decade was in the range of Rs 330 Crores to Rs 790 Crore.

The key identified business opportunities, technologies and products to meet the future requirements of Defence Sector is tabulated below.

Business Opportunities
• Missile Programs • Electronic Warfare Systems and ELINT system for defence sector • Integrated COMINT systems • Electronic Fuzes for Indian Army • Military Communication Systems including Software Defined Radios • Active Radar Seekers for Missile Programs

• Anti-Drone systems • Systems /applications for 5G technology • IOT based systems • Unmanned Underwater vehicles for Naval applications
Thrust areas/Product
• C&I Systems for missiles • On Board Computer for missiles, LRUs. • EW Next Generation Seeker for Missiles • Missile Checkout systems • High Power amplifiers • Smart Jammers for RCIED and Drone applications • Development of Anti Drone systems • Indigenisation of Artillery Fuze Components • Software Defined Radios for Air and Naval applications • Development of Mobile Integrated Network Terminal (MINT) • Development of GPS/GIS based Mine Recording Systems (GBMRS) • AI/ ML based Simulators

Future outlook

Several modernisation and indigenisation programmes are being undertaken by all the three services. The Ministry of Defence has laid out an expansive plan for modernisation of obsolete equipment through the long-term perspective plans, capability plans, capability roadmaps and capital acquisition plans. The vertical is pursuing development of several solutions and actively participating in several Make-II projects. The outlook for the sector is promising and the corporation is likely to see enhanced revenue from this vertical.

The defence vertical is likely to achieve a yearly revenue in the range of 700- 800 Cr from FY 24-25 and thereafter grow at an average of 7-10 percent.

6.4 Homeland Security

Homeland Security Vertical delivers integrated security solutions to vital installations of the country and is engaged in supply of various kinds of jammers to meet the security requirements of government agencies. This vertical is making inroads into providing solutions for Smart & Safe City projects and CBRN solutions.

Security Vertical

The key identified business opportunities, technologies and products to meet the future requirements of Homeland Security Sector is tabulated below.

Business Opportunities
• Integrated Security Systems • Smart & Safe City, Campus Projects • Secure Communication Systems

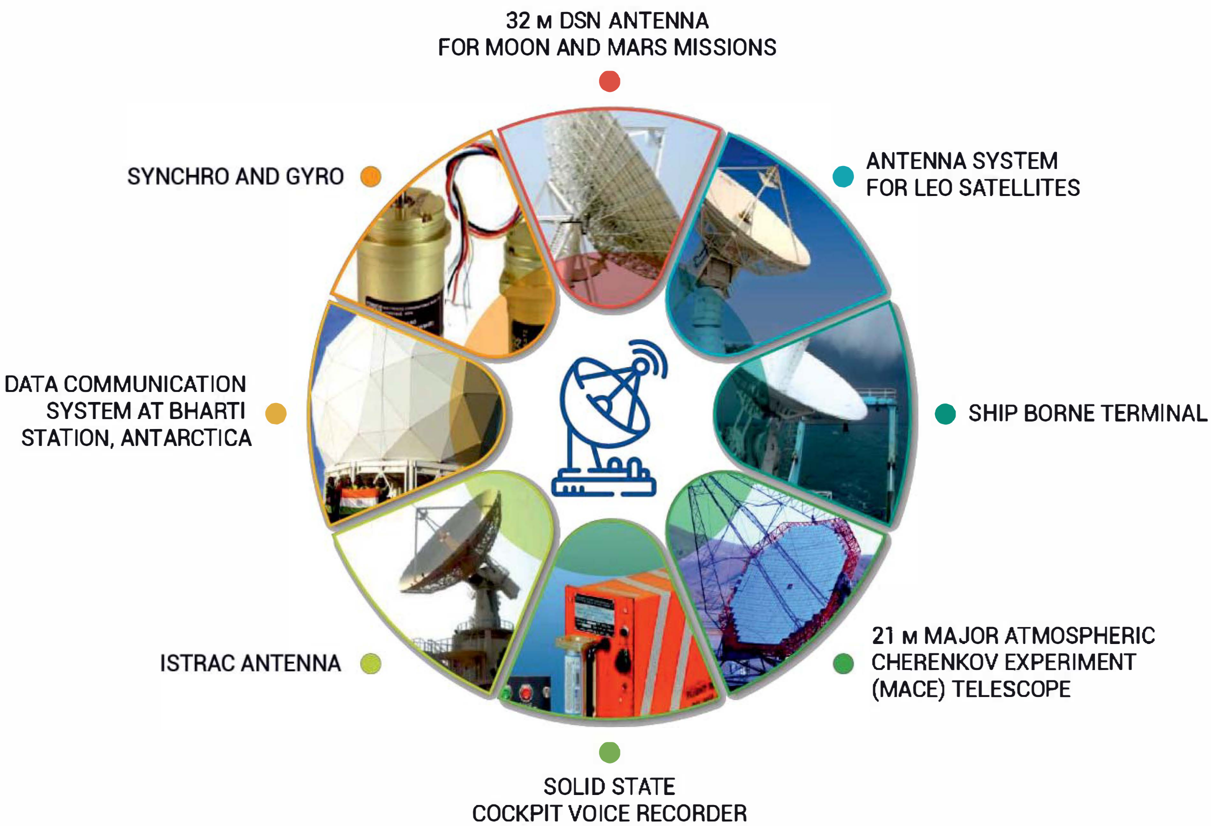
• Cyber security systems • Indigenous Network Switches and routers • CBRN Threat Detection & Mitigation System • AI/ML based security solutions
Thrust areas/Product
• Indigenous Dual view XBIS (X-ray Baggage Inspection system) • X Ray based Container Scanning System • LINAC for multiple applications • AI & Block Chain based Solutions for security technology applications • Radar based Perimeter Intrusion Detection System • Terra Hz & mm Wave based Scanners for application at Airports and Seaports • Integrated Command & Control Centre (ICCC) Applications for Integrated Security Solution • Indigenous Container Scanner System • Physical Protection system for Nuclear Power Plants and strategic assets of the nation • Managed Cyber Security Operation Centre • Web based Enterprise Level Access Control System • Chemical, Biological, Radiological and Nuclear (CBRN) Threat Detection Sensors integration and annunciator systems • Smart Perimeter Protection systems • Vehicle Tracking Systems

Future outlook

The outlook of this segment is positive with numerous opportunities emerging in providing Security Solutions to vital and Strategic installations. The facility towards Chemical, Biological, Radiological & Nuclear (CBRN) threat detection and providing CBRN solutions set up under the vertical will commence execution of projects during the FY 24-25.

6.5 Aerospace

ECIL has supported country's space program by setting up the ground antenna network at all ISRO centres for communication and remote sensing satellites. ECIL has well established core capabilities in the area of design and manufacture of antennas, large reflectors, microwave links and SATCOM networks. Aerospace vertical is engaged in design, development, manufacture of Antenna Systems and providing SATCOM solutions to meet space and defence requirements. It also undertakes manufacture of Electromechanical components such as Gyros, Synchros and Actuators. This vertical is foraying into manufacture of Carbon Fiber-based antenna products.



Aerospace Vertical

The key identified business opportunities, technologies and products to meet the future requirements of Aerospace Sector is tabulated below.

Business Opportunities
• Indian Space Programs • Weather Radars • UAV programs • Light Combat Aircraft Program • VSAT Programs • Military Communication Programs • Discovery Science Programs • Navigation Systems • Carbon Fibre based antennas • Inertial Sensors and Actuators
Thrust areas/Product
• Antennas for Satellite Communication • Electro Mechanical Actuators (Up to 2 T) • Satellite terminal for Nuclear Submarine • Ground station Antennas for Missiles Tracking • Ground Stations for Antarctica • Space Grade Antenna for Satellites. • Antennas for Radio astronomy applications. • Ground Station for Deep Space Networks • Precision components for classified projects • Communication Networks for Strategic Applications • Carbon fibre Antennas

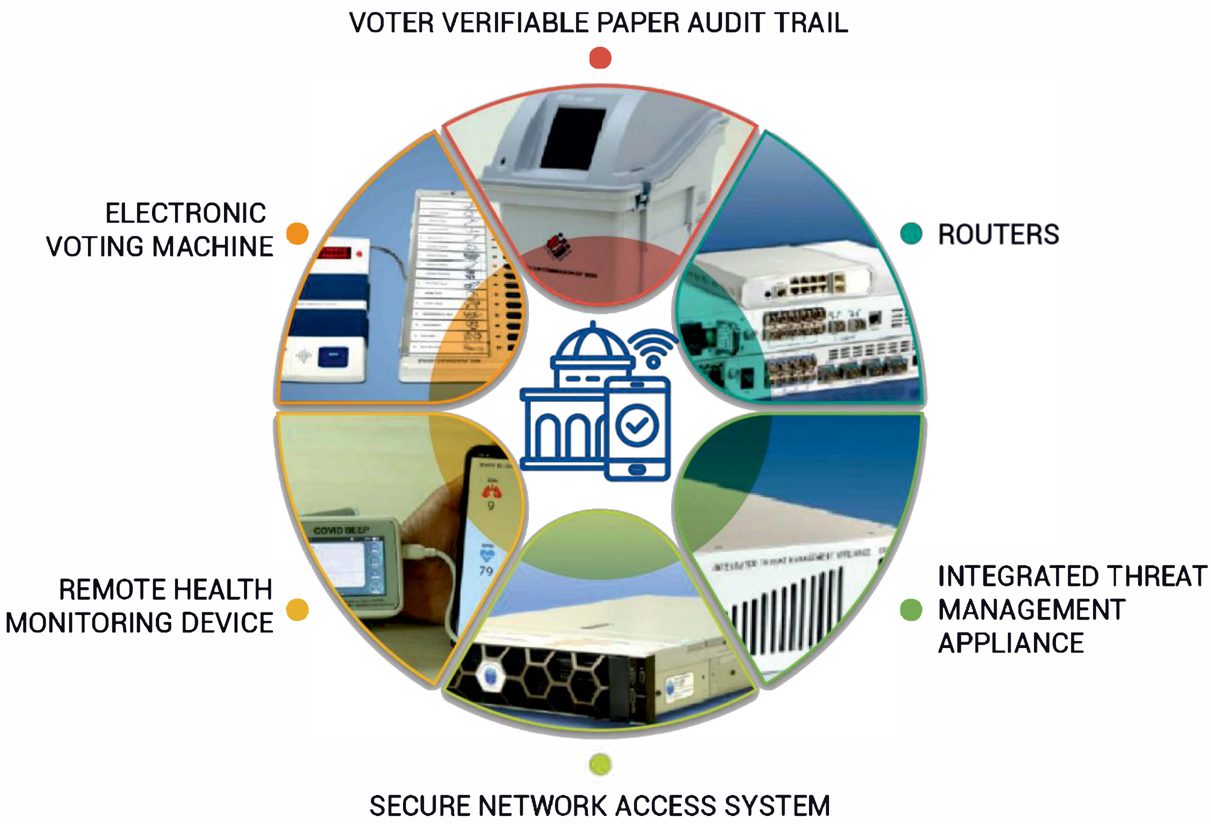
- Stabilized Platforms for aircrafts
- Ship borne Antenna Terminals
- GSAT 7B based SATCOM application for Indian Army.
- SATCOM on the move
- UAV Tracking Antennas
- Export of Satellite Communication Antennas of 11m, 13.5m, 18m & 21m with necessary development
- COTM Antennas for Railway Wagon
- Unfurlable Antennas for Strategic applications
- 21m MACE Telescope for Astro Physics requirements (2Nos)

Future outlook

The company has been building in-house solutions to meet the futuristic requirements. The new infrastructure in terms of Special Component Manufacturing Facility (SCMF) and Carbon Fiber Reinforced polymer (CFRP) facility established in the Aerospace vertical is planned to be put to use towards enhanced value addition and realisation of new products.

6.6 e-Governance

The IT and e-Governance vertical is engaged in manufacture of Routers, Network Switches, EVM & VVPATs and provides IT and Cyber Security Solutions. The revenue of the vertical is cyclical and largely dependent on orders from Election commission of India and state election commissions.



IT, Telecom, and e-Gov Vertical

The key identified business opportunities, technologies and products to meet the future requirements of IT & e-Governance Sector is tabulated below.

Business Opportunities
• Elections for States, Local bodies and Parliament • e-Governance Programs • Public Distribution Programs • Smart City Programs • Telecom network Programs
Thrust areas/Product
• Development of products/ solutions with respect to Crypto products and Cyber

Security

- Secure Network components
- Electronic Voting Machines and VVPAT
- Remote Health Monitoring Systems
- Automatic message switching system for Air traffic applications
- Totalizers for Electronic Voting Machines
- Remote Voting Machines
- EVMs for Physically impaired voters.
- S3 model EVMs for SECs.
- e-Governance solutions
- Telecom Products

Future outlook

Several in-house measures taken in terms of infrastructure augmentation have accelerated the process of mass manufacturing. Several steps taken in terms of technical partnerships have enabled ECIL towards providing IT and Cyber security solutions. Undertaking PCB assembly through contract manufacturing has been identified as one of the focus areas for near future towards full utilization of the state of art facility and to ensure continuous revenue business.

Challenges in Business Operations

The main challenges, and mitigation measures towards sustainability and growth of the corporation have been identified, which are manpower recruitment and retention, lack of marketing, knowledge management, and increased global competition. In consideration of these challenges, the business strategy has been focused on the following:

- Progressive increase in R&D manpower and R&D expenditure.
- Early identification of technological needs and *Suo moto* development of products for envisaged requirements.

- Implement ERP at an early date towards streamlining of processes and clear visibility on operations.
- Increase value addition in all sectors of business.
- Strengthen the collaborations with national laboratories and academic institutes with focus on indigenous technology development. Build capacity for effective technology absorption and assimilation.
- Continuously evaluate the outsourcing decisions against in-house manufacturing.
- Look for technology transfer arrangements with localization opportunities.
- Build-up capacity and capability in technologies and products of strategic importance such as radiation detectors and instruments, inertial sensors, seekers and information security.
- Plan human resource development required for the knowledge-intensive specialised areas by training at induction level and continuous training programs. Implement HR policies which promote talent attraction & retention.
- Leverage IT in all its operations to enhance efficiency, accuracy and transparency.
- Modernize and upgrade infrastructure related to work places, design & engineering, production, testing & qualification so as to improve efficiency, aesthetics, safety, security and environmental objectives.
- Locate "design & engineering centres' in areas nearer to major customer locations or sites so as to reduce cycle times related to requirements capture and engineering.
- Factor in life time support requirement in to the business processes.
- Achieve and maintain rating of 'Very Good' and above for MoU performance

Action plan to meet Future Requirements

Realisation of vision requires comprehensive upgradation of corporate service functions and infrastructure in the areas of Integrated Corporate R&D centre, IT services, business process re-engineering & deployment of ERP, information security, planning & monitoring, safety and HR processes. The envisaged actions on these aspects is enumerated in the succeeding paragraphs.

6.7 Research & Development

(a). ECIL has been a technology driven company right from its inception. The opportunities to engineer and productionise the technologies developed at BARC has generated and nurtured substantial scientific temper within the organization to pioneer a number of technologies and bring out a host of products. The technology handling capability has been providing the Company the flexibility to synergise the efforts in various divisions of the organization to offer customized products and solutions to the clients.

(b). On an average the company has been spending around 3% to 4% of its turnover on R&D. The R&D funding from DAE through the Technology Development Council (TDC) has been a very successful model for product development.

(c). Customer-specific R&D and Technology Management continues to be under the respective divisions and verticals to effectively address the requirements and channelize the resources with focus on time to market/deliver. The key identified technologies have been covered under the respective business verticals.

(d). The company has identified R&D as the key enabler for development of new products and technologies. Accordingly, it intends to enable R&D though in-house expenditure to the tune of 8-10 % of PAT.

6.8 Marketing

(a). In addition to technology strength, the Company has recognized the need to strengthen marketing in order to meet competition both from established Indian players and reputed multinational companies. The product streams of ECIL are re-grouped and a sectoral focus is consciously brought in. The marketing strategies are therefore evolved at the sectoral level based upon the inputs from various agencies and the market research.

(b). The Corporate Business Development Group (CBDG) facilitates the marketing initiatives through positioning the Company at various levels and building its image. A need has been felt to intensify the marketing of business initiatives of the Company and also to facilitate export endeavours of the Company by strengthening CBDG.

6.9 Infrastructure

(a). The infrastructure created at the time of inception of the Company largely catered to the requirements of the plans and programmes of yesteryears. The product profile, the technology mix, revised mission and objectives and above all the endeavours of the Company to negotiate a comprehensive trajectory change necessitated a review of the continued relevance of existing infrastructure.

(b). Considering that Electronics and Instrumentation form a critical element in the strategic programmes of DAE. The R&D programs at BARC are focused to achieve independence in all aspects of enabling technologies such as C&I, including sensors, detectors, drive systems, computation platforms, communication and software. Engineering, prototyping and long-term sustenance of technology developed at BARC require building up of requisite capabilities in the industry to support these programs. Accordingly, through MOU, BARC and ECIL have jointly established technological infrastructure at ECIL for the design, development, prototyping characterization, evaluation, instruments, and systems.

6.10 Human Resources Management.

Considering the age composition and retirement profile of the present employees the manpower requirements over the period have been identified. Concurrent with the efforts to improve the operational performance of the company, several measures are being initiated to raise the quality of Human Resources. This involves training at induction level, skill upgradation programs and project management programs. Taking into account separations the Manpower recruitment is considered vital for the planned growth of the company. In fact, ability to attract the best talents and retain them will be the single most important factor in realizing the vision.

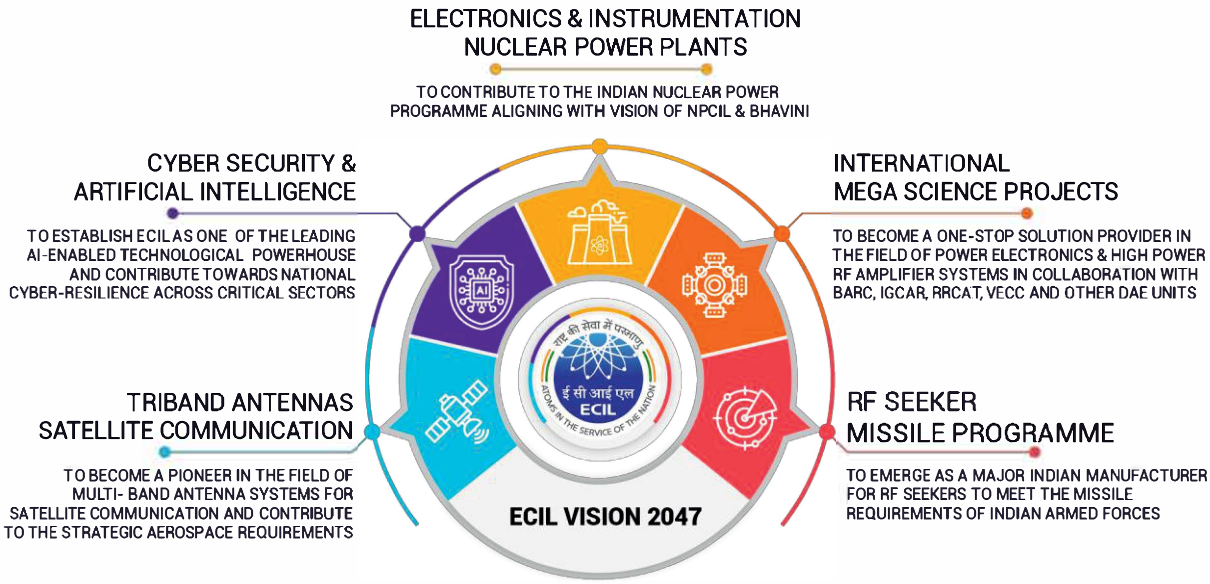
6.11 Conclusion and way forward

Electronics systems are ubiquitous and have far reaching implication in development of new technologies. ECIL, the electronic arm of the DAE over the past five plus decades, not only met the prime objective of becoming self-reliant and self-sufficient in the field of Control & Instrumentation for the Indian Nuclear Power Programme but has also emerged as an important national asset in the field of Electronics. The pioneering spirit displayed by the company with support of BARC and DAE units from its formative period has enabled it to realise several noteworthy products and systems needed in the domains of atomic energy, defence, space and security sectors in addition to few other fields of social or economic significance to the Country.

ECIL is poised to meet the technological challenges involved, given the internal strengths, focus and the springboard of developmental support from premier national R&D institutions of Atomic Energy, Defence and Space. The umbilical connections with BARC and the developmental linkages with other DAE Units like IGCAR, VECC and RRCAT have resulted in a strong technology base for catering to the requirements of the Atomic Energy Sector. Similarly, the development associations with Defence Research and Development Organization (DRDO), Aeronautical Development Authority (ADA) etc. have enabled ECIL to enhance its product base and project execution capabilities in the defence Sector. The strong relationship forged with Indian Space Research Organization (ISRO) is paving the way for executing technologically complex projects of national relevance in the space sector.

Whilst the synergy with BARC and other DAE institutes continues to be strengthened, with the changing business dynamics, ECIL is constantly adopting and collaborating with industry and academic institutes to further 'AtmaNirbhar Bharat' and Make in India Initiatives.

Keeping in view, the enormous opportunities emerging in the nuclear sector, the Company hopes to attain and maintain a significant share of its turnover from nuclear sector. Towards this, the Company has launched many initiatives to synergize the capacities, capabilities, expertise and suitable augmentation of infrastructure. Further, Human resource has been the most valued IP of the company and will continue to be of increased importance considering the high technology area company is operating.



ECIL Amrit Kaal Vision

ECIL's operations are focused on strategic electronic products and niche technologies in the chosen sectors viz., Nuclear, Aerospace, Defence, Homeland Security, IT & e-Governance. The strategic electronics sector globally is expected to grow at a CAGR of 4%-6%. The domestic growth in the strategic electronics sector is likely to be higher than the global growth. Further, the large-scale modernisation of the defence forces with focus on self-reliance with increased local manufacturing are going to boost the strategic electronics sector of the country.

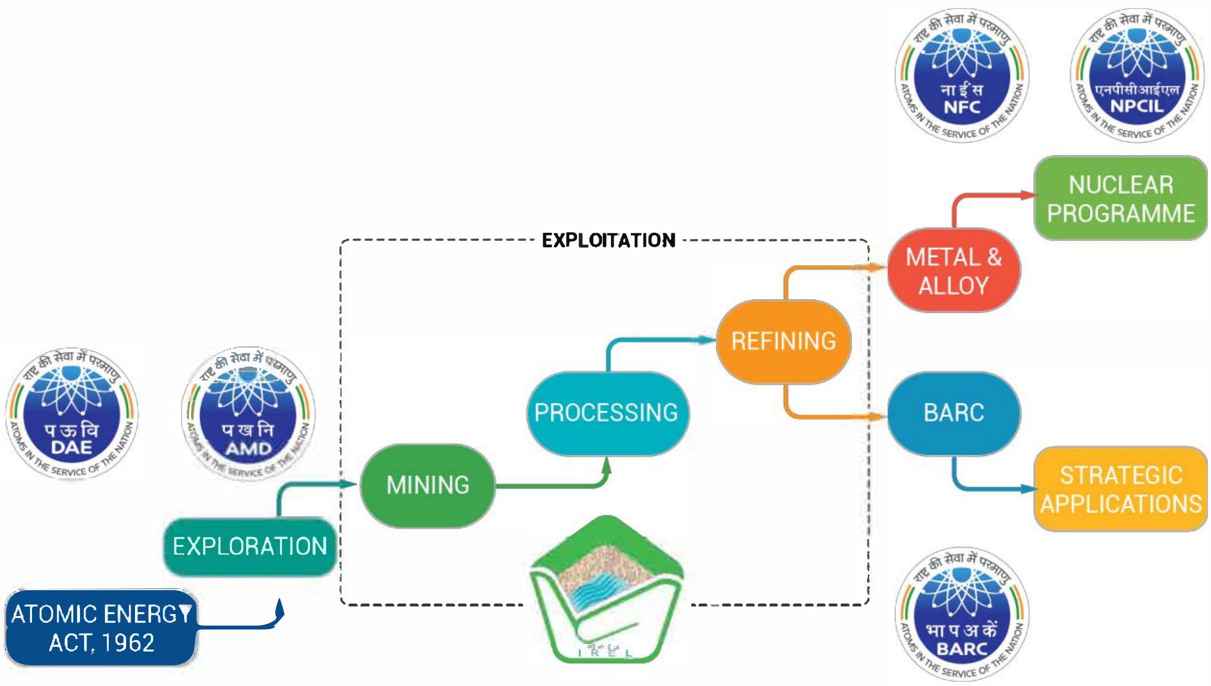
In this backdrop the company revenues are likely to grow at an average of 7 to 8% in the coming decade. This would be achieved by enhancing/ diversifying the Product range through in-house developments, in collaboration with DAE units, DRDO and with strategic partnership with Startups and Private Industries and mitigating challenges. The company aims to achieve a revenue target of Rs 4000 Crores by 2030 and Rs 5000 Crores by 2035.

7. Indian Rare Earths Limited – IREL

"To be a significant contributor to the global clean energy mission by providing high-quality performance-enhancing materials and operating in a socially responsible manner."

IREL (India) Limited, a Mini-Ratna Category-I company, is a Central Public sector undertaking under the administrative control of the Department of Atomic Energy. IREL is engaged in Mining, Concentration and processing of Mineral Sand to produce Processed Minerals. One of the minerals produced which is also a prescribed substance is further cracked to produce strategic compounds and mixed Rare Earth Concentrate. The mixed Rare Earth Concentrate is further refined to produce separated individual High Pure Rare Earths.

IREL has 23 products of 36 different grades with 8 products having value chain within DAE. Some of the essential material supplied to DAE include NGADU, Zircon, Thorium, Samarium, 73Gadolinium Nitrate, Dysprosium.

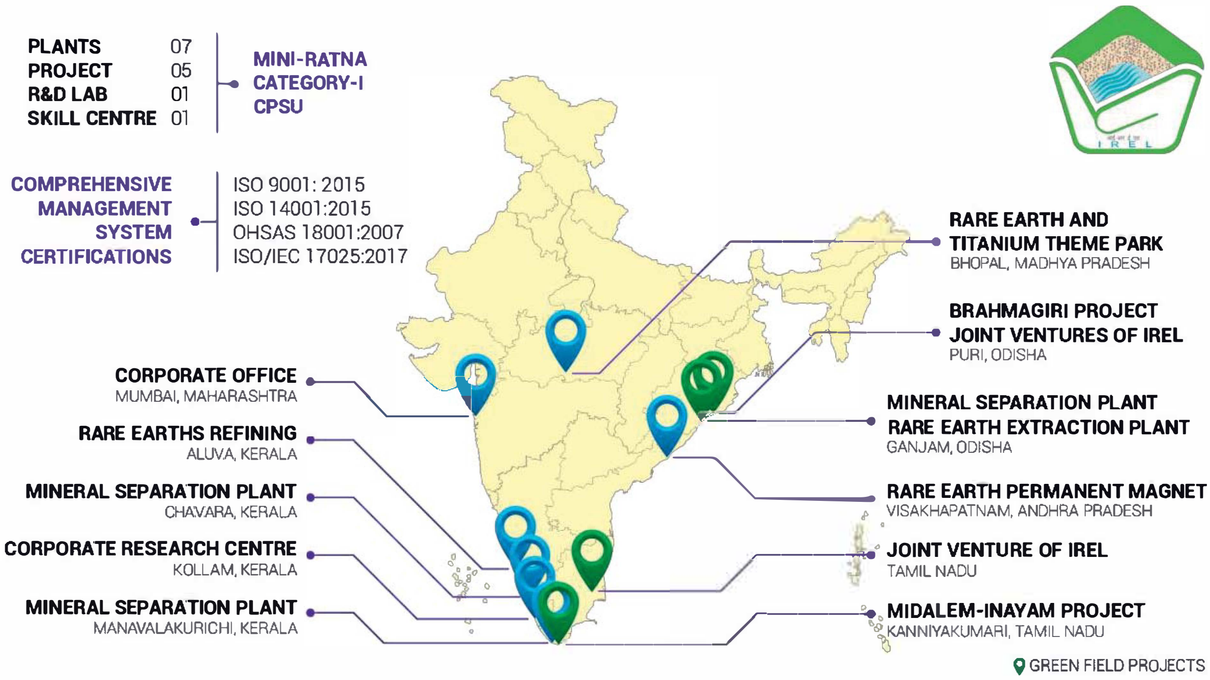


Position of IREL in Indian Atomic Energy Programme

The operating units of the company are located at Chavara, Kerala; Manavalakurichi, Tamil Nadu; Chatrapur, Odisha and Aluva, Kerala. The Corporate Office is located at Mumbai.

IREL's vision for the Amrit Kaal targets are in coherence with DAE's vision plan of 2047 which would be evolving out of the proposed Chintan shivir, i.e., making the country self-reliant by sustained supply of:

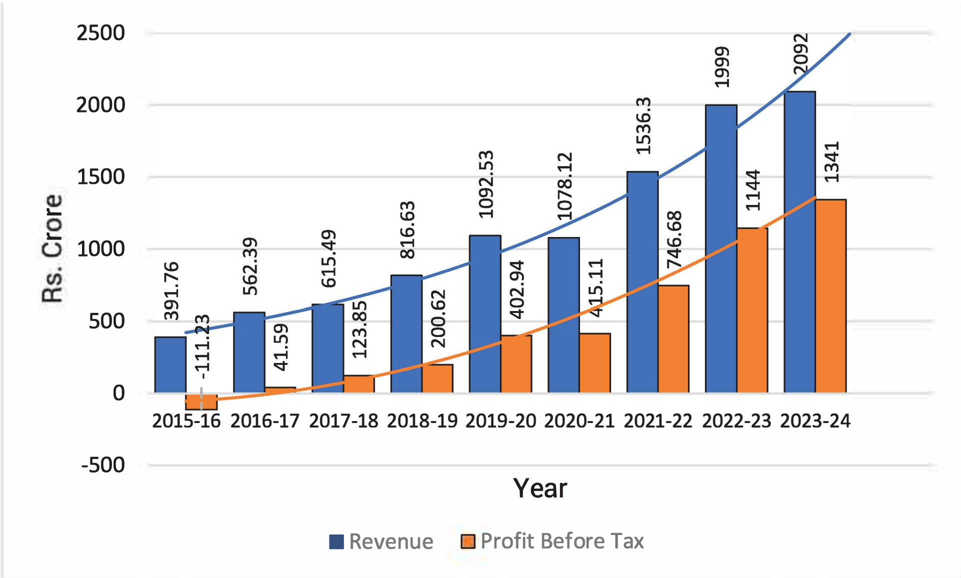
i. Zircon to NFC for the Nuclear Power Program.
ii. Thorium for the Third stage Nuclear Power Program
iii. Strategic Rare Earths and Rare Earth Permanent Magnets (Samarium-Cobalt) to DAE.
iv. Rare Earths to downstream industries involved in the initiatives taken towards Green & Clean Energy.



IREL Overiew

7.1 Performance

The performance of IREL has seen considerable growth in the last nine years growing sustainably at a CAGR of about 30%. The Company has grown over 5.3 times during the period and has obtained "Excellent" MoU rating over the last six years consistently.



The total Dividend paid over the last ten years has surpassed the initial equity infused by more than 14 times. Issued 400% equity bonus shares raising the paid-up equity capital to Rs. 345.46 crore from Rs. 86.37 crore.

7.2 Achievement in Rare Earth Sector

During the period, IREL has established a Rare Earth Extraction Plant in Odisha for extraction of Rare Earths in the form of Mixed Rare Earth Concentrate from a prescribed substance. The NGADU produced during the process is supplied to DAE while Thorium is stored in engineered trenches for future use in the Atomic Power Program of the Country. A facility has also been established for refining the Mixed Rare Earth Concentrate to produce Refined Separated High Pure Rare Earths.

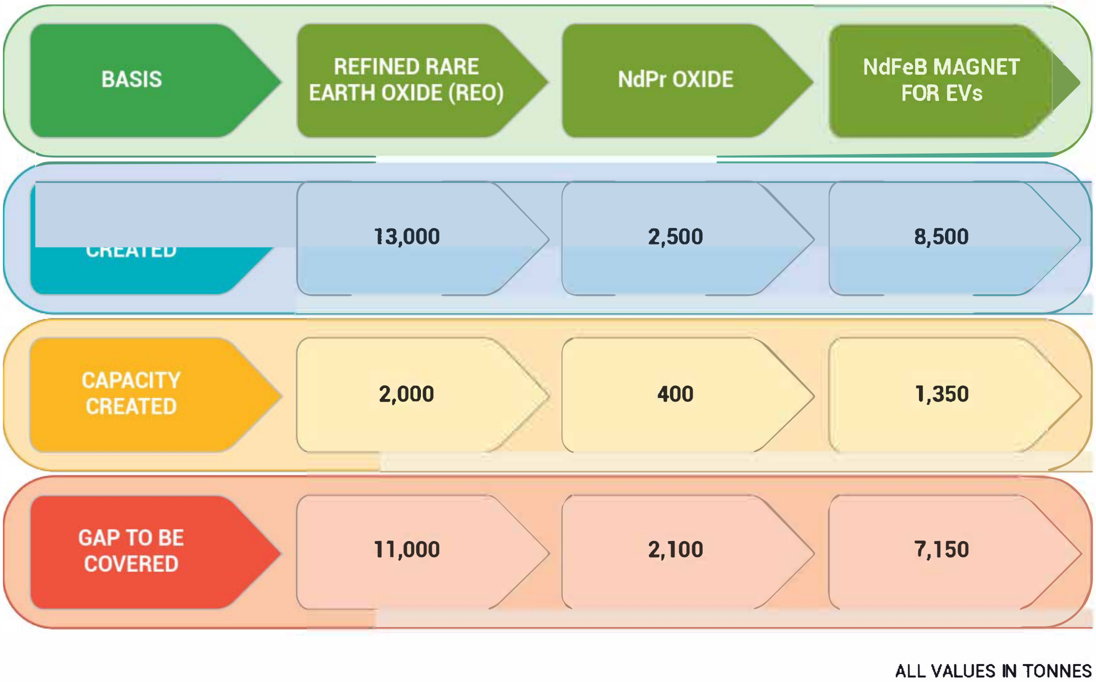
IREL has also set up a Rare Earth Permanent Magnet Plant in BARC Campus, Vizag for the production of Samarium-Cobalt magnets from Indian Rare Earth resources for use by DAE and Defence Sectors.

Rare Earth Permanent Magnet Plant at Visakhapatnam, Andhra Pradesh dedicated to the nation by the Honourable Prime Minister Shri Narendra Modi, May 2023

Rare Earth Permanent Magnet Plant and the Products, Visakhapatnam, Andhra Pradesh

Further, a Rare Earth Metal and Titanium Theme Park has been established in Bhopal for setting up of Mini-Plants to demonstrate production of metals of Lanthanum, Cerium, Neodymium; recovery of Rare Earths from end-of-life magnets; production of LED/ Lamp phosphors and demonstration of Kroll process.

Vision @ 2047 – Rare Earths



Rare Earths Need Statement

For Rare Earths, the Vision Target bestowed on IREL is production of 13,000 tons of Rare Earth Oxides (REO) in the backdrop of Energy Transition aspirations of the Government, which would suffice production of about 8,500 tons of NdFeB magnet for the Clean Energy Initiatives.

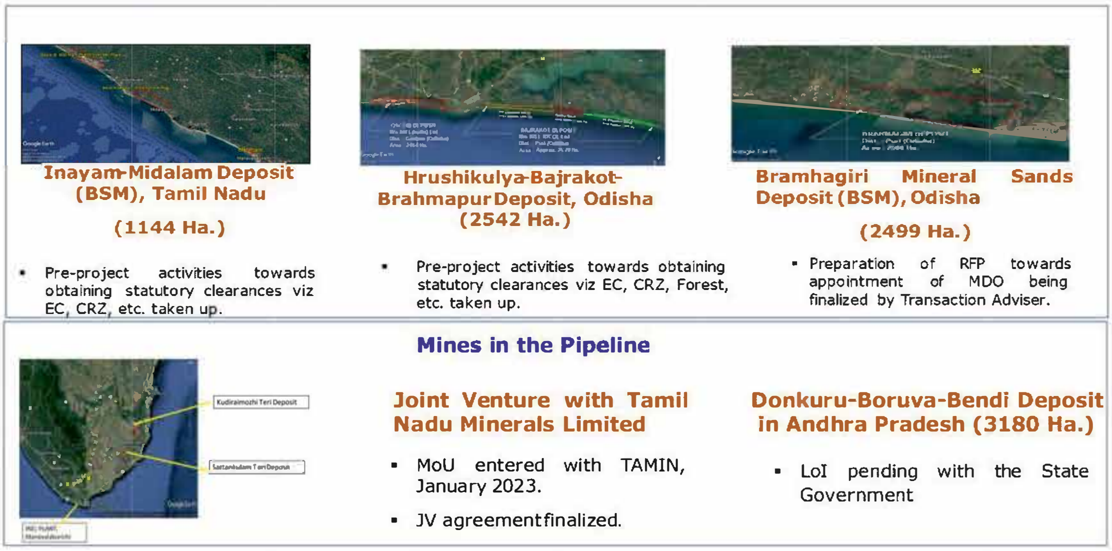
BACKWARD INTEGRATION	MIXED RARE EARTH CONCENTRATE	MONAZITE	MINERAL PROCESSING	CONCENTRATION	MINING
CAPACITY TO BE CREATED	33,000	30,000	32,00,000	50,00,000	5,00,00,000
CAPACITY CREATED	11,000	10,000	7,50,000	10,00,000	1,00,00,000
ESTIMATED PRODUCTION	11,000	10,000	13,50,000	21,00,000	2,10,00,000
GAP TO BE COVERED	22,000	20,000	18,50,000	29,00,000	2,90,00,000

\# INCLUDING NEW LOIs

NOMINATION FOR ADDITIONAL LEASES

IREL Pre-Requisites

IREL has recently obtained three Letter of Intent (LoI) from Government of Odisha and Tamil Nadu.



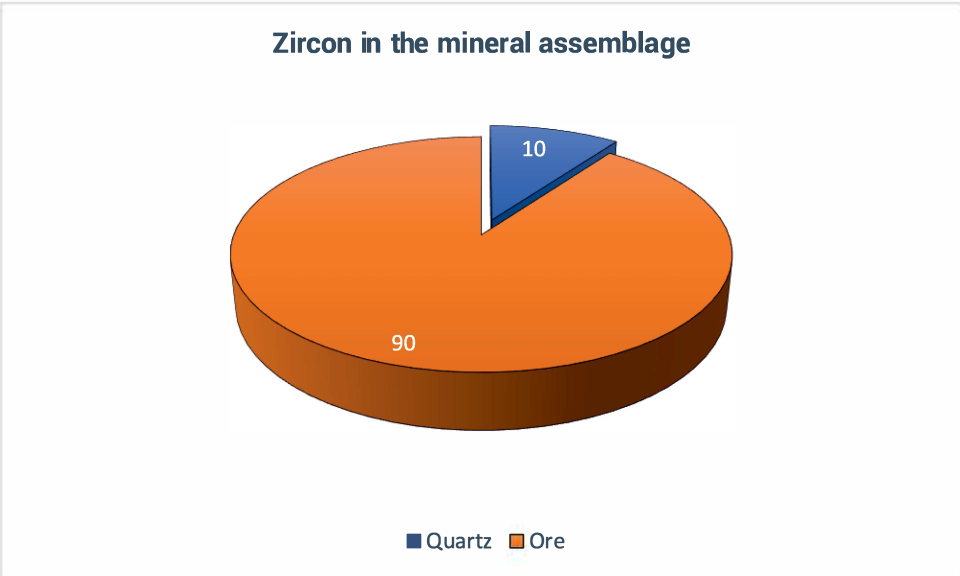
New Project Initiatives

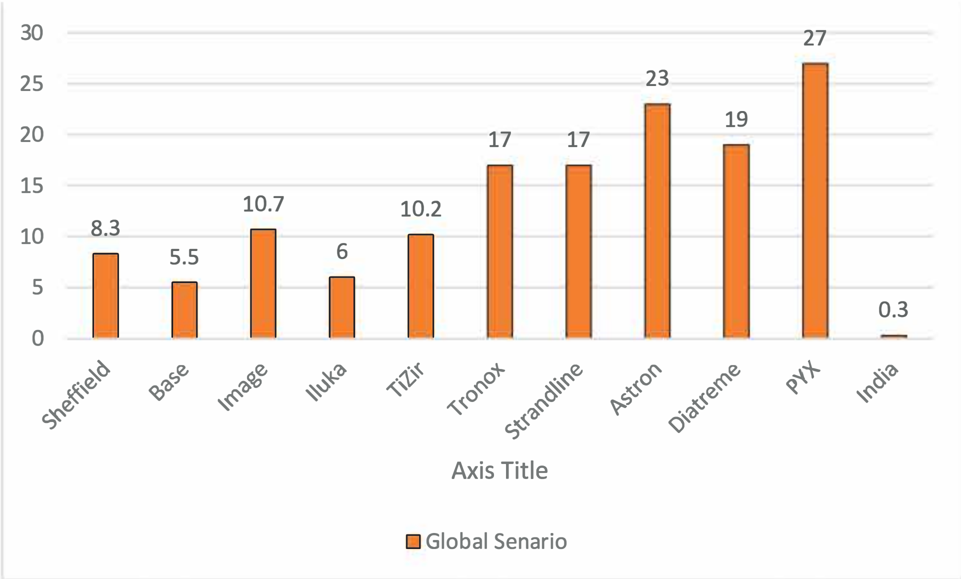
Pre-project activities towards obtaining statutory clearances are underway after which the mines will be operationalized. However, to meet the Vision target additional resources in the form of Mining Leases need to be awarded to IREL. The annual mining capacity from these deposits need to be to the tune of 29 million tons per annum. Considering the quantum of mining to the done, the new leases need to be in different geographies from environment sustainability point of view.

Further, IREL has received directives from the Government of India for co-operation on Rare Earths with Vietnam, Oman and Sri Lanka for which discussions are on at various levels.

7.3 Vision @ 2047 – Zircon

The availability of Zircon in the mineral assemblage in the southern deposits is between 0.5-0.8% while that in eastern deposits is to the tune of 0.20-0.25%. While meeting the Vision target of DAE for Rare Earths, about 32,000 tons of Zircon will be produced of which about 5,000 tons of the grade required by NFC will be set aside. The exact requirement will be worked out in consultation with NFC.





7.4 Vision @ 2047 – Mid-Stream industries in Rare Earths Sector

Rare Earths are considered a niche material since it improves the performance of core/ functional material when added in small quantities. However, this sector is presently absent in the Country due to inverted pricing dynamics. IREL is working closely with DAE/ Government of India to incentivize the aspiring mid-stream industries. Once the same fructifies, the mid-stream sector which deals with converting Rare Earth oxides to metal/ alloy will develop thereby increasing consumption of the niche product within the Country.

7.5 Vision @ 2047 – Technology Demonstration Plant

To meet the requirement of the Department, BARC is developing technology for production of Titanium Sponge and NdFeB Magnets. Once scalable technology is developed, IREL based on funding support from the Government will establish Technology Demonstration cum Production Plant for the production of Titanium Sponge and NdFeB magnets for their requirement in strategic sector.

Availability of Nuclear Fuel (domestic as well as imported) for power projects

In respect of domestic uranium, while modest uranium reserves in the country have been discovered and exploration is on to cover the entire country, with due challenges in establishing mines and extracting the ores.

In respect of imported uranium, the demand for global uranium is expected to grow significantly as, in addition to existing countries having nuclear power planning expansions, several more countries are considering, planning or starting nuclear power programmes, particularly in view of its clean credentials and climate change concerns. With the increase in demand, the prices of uranium are expected to increase over time in the next two decades leading to 2047.

As per IAEA Red Book 2022, reserve, production, demand etc. for nuclear fuel are given below:

Uranium Reserve

(as of 1 January 2021, tonnes U, rounded to nearest 100 tonnes*)

Resource category	2019	2021	Change[a]	% change
Identified (total)				
<USD 260/kgU	8 070 400	7 917 500	-152 900	-1.9
<USD 130/kgU	6 147 800	6 078 500	-69 300	-1.1
<USD 80/kgU	2 007 600	1 990 800	-16 800	-0.8
<USD 40/kgU[b]	1 080 500	775 900	-304 600	-28.2
RAR				
<USD 260/kgU	4 723 700	4 688 300	-35 400	-0.7
<USD 130/kgU	3 791 700	3 814 500	22 800	0.6
<USD 80/kgU	1 243 900	1 211 300	-32 600	-2.6
<USD 40/kgU[b]	744 500	457 200	-287 300	-38.6
Inferred resources				
<USD 260/kgU	3 346 400	3 229 200	-117 200	-3.5
<USD 130/kgU	2 355 700	2 263 900	-91 800	-3.9
<USD 80/kgU	763 600	779 600	16 000	2.1
<USD 40/kgU[b]	335 900	318 700	-17 200	-5.1

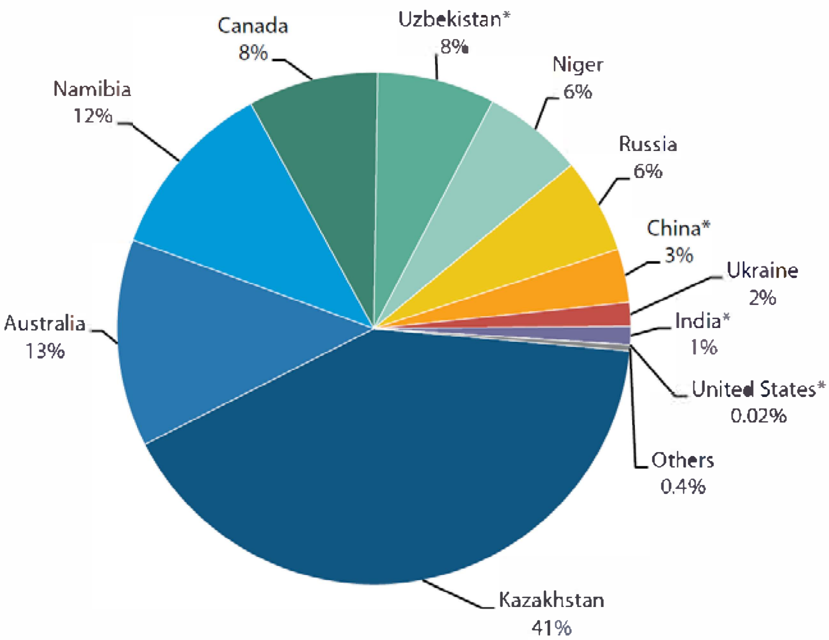
* Note that tonnes U values in this table are rounded to the nearest 100 tonnes, independently, at the country and cost range level. Therefore, these cost range totals do not exactly match totals for these cost ranges as shown in other tables relating to uranium resources in this report. (a) Changes might not equal differences between 2019 and 2021 because of independent rounding. (b) Resources in the cost category of <USD 40/kgU and <USD 80/kgU should be regarded with some caution since some countries do not report low-cost resource estimates, mainly for confidentiality concerns, whereas other countries that have never, or not recently, hosted uranium mining may be underestimating mining costs.

Source: IAEA - Red Book 2022

7.6 Uranium Production

In 2020, 17 countries produced uranium, with the global total amounting to 47342 tU.

(47 342 tU, as of 1 January 2021)



* NEA/IAEA estimate.

7.7 Uranium Requirement

The world Annual requirements by 2040 are given below:

(tonnes U per year)

Region	2020	2025 low	2025 high	2030 low	2030 high	2035 low	2035 high	2040 low	2040 high
Africa	294	304	304	304	304	688	1 392	1 232	1 872
Central and South America	619	560	576	784	784	720	1 056	1 120	1 712
East Asia	16 039	17 408	20 080	19 824	27 056	20 176	33 248	22 560	41 296
Europe (non-EU)	9 244	7 328	7 904	7 904	9 376	8 272	11 232	9 008	14 880
European Union	12 942	15 440	15 584	14 368	15 456	13 696	16 736	12 592	19 360
Middle East, Central and South Asia	1 945	2 816	3 200	3 808	5 728	5 408	8 448	6 032	9 888
North America	19 031	15 552	17 872	13 968	17 888	11 584	18 048	10 336	18 464
Pacific	0	0	0	0	0	0	0	0	0
South Eastern Asia	0	0	0	0	0	0	0	160	800
World Total	60 114	59 408	65 520	60 960	76 592	60 544	90 160	63 040	108 272

* NEA/IAEA estimate.

7.8 Conclusion and way forward

Addressing these challenges and going ahead with the growth as planned will enable actualise the Vision Amrit Kaal and achieving the goals of Viksit Bharat by 2047 & energy transition to Net Zero by 2070. Strong coordination teams involving the union and state governments along with PSU to be established for the entire life cycle of then plants. Improving project management practices to complete projects on time and adopting innovative solutions for reducing gestation period are necessary. Faster development of new technologies by R&D units would enable PSUs to launch them in the commercial domain. Enhanced public outreach by PSUs would ensure genuine apprehensions of stakeholders addressing in a simple, understandable and credible manner. Evolving financing and business models for meeting the funding requirements of the massive expansion programme would be necessary, particularly tapping of private capital.

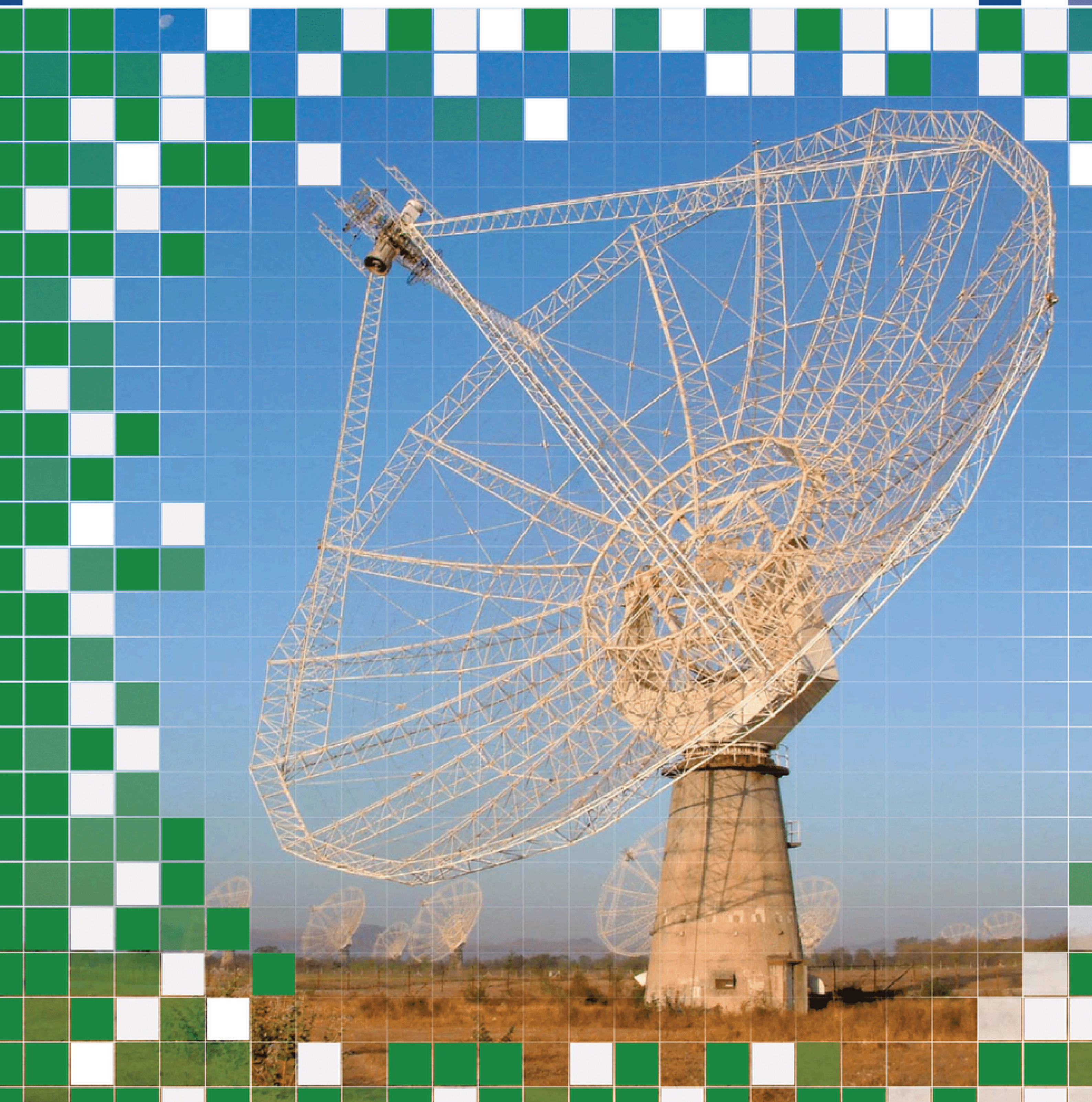
परमाणु ऊर्जा विभाग
DEPARTMENT OF ATOMIC ENERGY

PART C

DEPARTMENT OF ATOMIC ENERGY
AIDED INSTITUTIONS

Fostering Knowledge, Innovation, and Collaboration

AMRIT KAAL VISION DOCUMENT



परमाणु ऊर्जा विभाग

DEPARTMENT OF ATOMIC ENERGY

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Disclaimer: The data, projections, and other information presented in this document correspond to the year 2024, unless stated otherwise.

अमृत काल AMRIT KAAL

संकल्प प्रलेख VISION DOCUMENT

PART – C

Aided Institutes

Table of Content

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

Dr. Ajit Kumar Mohanty

August, 2025

Secretary, DAE and Chairman, AEC

1. Introduction

This document is the outcome of intense discussions carried out among the Aided Institutions of DAE as a part of the “Chintan Shivir” exercises to develop a roadmap for the future. The plans developed as part of this exercise are: (i) astronomy, space sciences and geo-sciences (ii) atomic, molecular and optical physics (iii) high energy physics (iv) laser plasma science (v) chemical sciences (vi) materials for fundamental science energy and environment (vii) quantum science and technology (viii) biology across scales and environments, from molecules to ecosystems (ix) computer science (x) fundamental theoretical physics (xi) mathematical sciences (xii) redesigning the education and HRD ecosystem of the DAE (xiii) high performance computing facilities – the next decade and beyond (xiv) healthcare (xv) nuclear physics (xvi) plasma physics.

The astronomy and astrophysics initiatives aimed at addressing the most fundamental, as well as broad impact and open problems in space and geosciences. These include space weather prediction, earth science, rare earth element exploration, natural disaster management, climate science, solar system exploration, exoplanets, astrophysics and cosmology, instrumentation for ground and space-based observatories, gravitational-wave astronomy, radio astronomy, and theoretical astronomy.

In atomic, molecular and optical physics, the vision includes devising practical methods to control chemical reactions using low-energy electrons, developing a cryogenic storage ring to study the decay of molecular ions, developing a national network of high-altitude platforms and large-area receivers for both quantum as well as free space optical communication and integrating this with the global high-altitude platform/satellite network. Accurate time-keeping is critical for many of these networks and hence the plan also includes for the development of trapped ion or neutral atomic clocks, as well as building collaborating networks for clock comparison.

High energy physics studies lead one of the frontiers of our understanding of fundamental physics. The proposed vision includes the construction of an end-to-end Indian experiment to study the little explored ultra-light hidden sector, the development of a multi-cavern underground laboratory which would serve multiple scientific communities and not just particle physics, as well as the development of a space-borne particle physics detector covering an energy range that is currently unexplored.

In laser and plasma science, the proposed 25-year programme is divided into three Phases. Phase-I, lasting 5 years, will be dedicated for establishing 1PW laser driven GeV class, mono-energetic, highly collimated electron beams. The Phase-II, lasting 10 years, would focus on generation, detection and applications of MeV-scale bright X-ray and Gamma photon beams. In-parallel, the Phase-II would also have equal contribution invested for development of indigenous high-repetition rate multi-PW lasers. The final Phase-III, spanning over 10 years, would focus on delivering industry standard prototypes. Given the scale and scope of these programmes, the task and expertise would be distributed in a collaborative manner with Indian industry/ MSMEs/ startups and academia.

The chemical and material sciences outline a strategic vision for leveraging material innovations to combat climate change, emphasizing the need for ground-breaking research, state-of-the-art infrastructure, and collaborative excellence. The exploration and development of advanced materials for fundamental science and environmental applications are crucial in addressing the pressing challenges of energy efficiency, sustainability, and climate change. The white paper envisages the development of high energy density and power density batteries, alongside the integration of supercapacitors and hydrogen fuel cells, and the development of a fully operational renewable grid.

In quantum science and technology, it envisages developments along four verticals, viz. (a) Quantum Computing & Simulation (b) Quantum Communication (c) Quantum Sensors & Metrology and (d) Quantum Materials & Devices. These in turn will have a wide range of societal impact, ranging from healthcare to clean energy. In quantum computing, the vision includes India emerging as a major supplier as well as user of quantum computing hardware and software.

The computer science roadmap is towards developing quantum as well as post-quantum cryptography algorithms, formal methods and verification methods which are critical in the development of highly safe systems such as nuclear reactors.

Though spanning across wide length and time scales, the study of theoretical physics uses many common techniques and mathematical frameworks. The white paper details a roadmap for research across multiple dimensions, ranging from cosmology at mega-scales, statistical physics and quantum many body physics at macro- and meso-scales, high energy physics and quantum gravity at micro-scales.

The "biology across scales and environment", proposes a holistic approach to biological systems, which would allow one to address critical challenges in public health, environmental sustainability, and technological innovation. This includes understanding microbial biology and mechanisms of antimicrobial resistance. The research integrates fundamental knowledge with clinical solutions, potentially leading to effective cancer therapies and a deeper understanding of resilience across ecosystems.

The DAE Aided Institutes (AIs) have traditionally played a leading role in the development of modern higher mathematics in the country. This includes being instrumental in the training of talented young people across all levels of higher education, via pedagogical schools and workshops organised by the AIs and, under the activities of the National Board for Higher Mathematics and the National Centre for Mathematics, as well as the doctoral programmes of the AIs which are renowned for having the highest standards. The white paper details a vision to soar higher in research aspirations and significantly increase the pedagogical footprint. The research vision also outlines some of the main themes and problems that will be pursued.

The health science white paper lays out an ambitious vision to enhance India's healthcare system by 2047, focusing on improving cancer care, combating infectious diseases, advancing healthcare technology, and fostering innovation. The key goals include expanding access to cancer care services, leveraging artificial intelligence & machine learning (AI-ML) and digital health tools, supporting multidisciplinary research, and strengthening expertise across various medical fields.

2. Astronomy, Space Sciences and Geosciences

Humankind's quest to understand the fundamental rules governing everything from our Earth to the farthest reaches of the observable universe has led to the development of our modern civilization. The long-term visions that have driven the scientific revolution have always emerged from grassroots efforts. This chapter on "Astronomy, Space Sciences and Geosciences" in the Roadmap for DAE Vision for 2047 document, is an attempt to identify our ambitious goals that organically emerged from the Department of Atomic Energy (DAE) family of scientists and engineers.

In this white paper, we have identified sub-areas within this field where we believe we can leverage DAE's existing expertise to leapfrog to cutting-edge capabilities. These advancements will address the most fundamental, high broader impact, and open problems in Space and Geo sciences.

2.1 Space weather prediction

Space weather, characterized by solar phenomena such as solar flares, coronal mass ejections (CMEs), and geomagnetic storms, significantly impacts Earth's magnetic field, affecting satellite operations, communication systems, navigation technology, and power grids. The increasing dependency of modern society on technology that is vulnerable to space weather elevates the need for accurate predictions to mitigate risks. This proposal aimed at developing an advanced predictive model for space weather by leveraging data science and machine learning techniques to enhance the accuracy and timeliness of forecasts.

To succeed, the programme would comprise of developing a comprehensive predictive model by utilizing machine learning algorithms to analyse historical space weather data and to identify patterns that precede major solar events. It is important to implement a system for real-time monitoring of solar activities, enabling prompt forecasting of potential space weather impacts. Finally, the impact of evaluating the potential effects of predicted space weather events on critical infrastructure and technology to provide targeted warnings is to be assessed.

All these would improve the awareness and preparedness by disseminating the findings and predictions to stakeholders and the general public through an accessible platform. The proposed programme stands to significantly advance the capability to predict and prepare for space weather events, safeguarding critical technologies and infrastructure. By applying cutting-edge data science and machine learning techniques to the challenge of space weather prediction, this initiative will not only contribute to scientific knowledge but also enhance societal resilience in the face of solar-induced disturbances.

2.2 Earth Science

Critical minerals are metals and non-metals that are essential for economic development and national security but their supply can be at risk due to geological scarcity, geopolitics, trade policies, monopoly on resources, and other factors. In the near future, the global economy will be underpinned by technologies that depend on these minerals as they are essential for telecommunications, defence, electronics, transport, renewable energy technologies etc. Included in the list of critical minerals for India are Lithium & Rare Earth Elements (REE), which are also of particular interest to the DAE. REEs include lanthanides, Sc and Y, and they are valuable for many sectors including electronics, manufacturing, medical sciences, and renewable energy sector. Lithium is primarily used in batteries, ceramics and glass industries, polymer production etc. Thus, an undisrupted supply of these minerals is one of the most critical requirements for India's transition to clean energy, meeting the 'Net Zero' commitment as well as realizing the vision of "Atma Nirbhar Bharat".

Several studies indicated the presence of abundant resources of these metals in igneous rocks, placers, phosphoritic deposits, and residual (soil/clay) environments, but questions remain about the nature of their distribution and amount of these resources. In particular, alkaline igneous bodies may contain Li and REE resources, but their petrogenesis and extent of Li/REE enrichment remains poorly understood. This programme aims to explore alkaline igneous rocks and pegmatites of India for their potential in hosting REEs and Li minerals, and to understand what controls their formation.

The characterization of alkaline igneous bodies, granitoids, and pegmatites will help in identifying new potential provinces of Li/REE-bearing reserves. The petrogenetic model will help in mapping out the exploration strategies in geological terranes of India that were not studied in the framework of critical minerals so far. Further, the study will focus on characterizing how Li/REE are present in each of the studied rock types and in each phase, which will help in designing the metallurgical extraction.

2.3 Developing an India-specific, physics-based hazard assessment framework for earthquakes and landslides

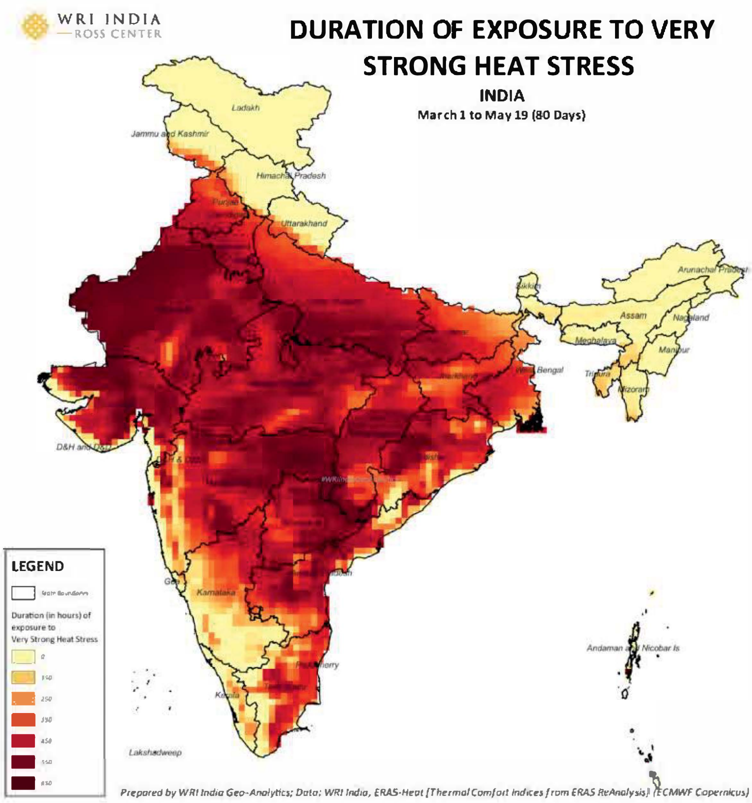
Our knowledge of the earthquake and landslide potentials of Indian fault zones/vulnerable slopes is almost entirely empirical. This makes the assessment of seismic and landslide vulnerabilities of critical infrastructures often uncertain. India is also geologically unique in the sense that even its plate interior is substantially seismically active and its landslide prone areas are not all activated only during monsoon rainfall seasons. The physical processes that control earthquakes and landslides even in the absence of the usual stimuli of such tectonic or climatic forcings are not well understood. Yet, India still does not have a dedicated laboratory setup that can probe and quantify these processes across the many order-of-magnitude variations in strain rates and in-situ conditions that operate during the initiation and culmination of these natural hazards. We propose to establish a state-of-the-art laboratory capable of testing geological samples extracted from fault zones and landslide slopes under in-situ conditions to explore the physics of earthquake and landslide processes at both slow and fast displacement rates. This laboratory will be complemented by field observation/monitoring sites established within regions of active deformation involving both seismic and aseismic fault slip and landslides that will provide in-situ observational constraints and relevant field samples. Using this complementary laboratory-based and in-situ monitoring setup, we are looking to develop India-specific, physics-based, models for earthquake and landslides by integrating field-data, geophysical observations, laboratory experimentation and numerical modelling. These efforts will also align directly with the National Landslide Risk Management Strategy adopted by the National Disaster Management Authority (NDMA) by setting up field-monitoring stations and laboratories that provide micro-scale hazard estimates and developing physics-based early warning models tailored specifically to the geology and hydrology of the region. The proposed facilities will provide vital inputs to physics-based estimation of site-specific earthquake and landslide hazard and early-warning models.

2.4 Climate Science

Process based understanding and vulnerability mapping of the pre-monsoonal heat stress in the Indian subcontinent under global warming is one of the important aspects needs to be attended.

Several important regions in the Indian subcontinent, including the Indo-Gangetic plains, the Ganges and Indus delta and south-eastern India, are projected to witness heat stress at deadly levels under near-future global warming. Pre-monsoonal heat stress is recognized as the most impactful climate change hazard in the subcontinent, already impacting lives, livelihoods and industry. Our understanding of these extreme events is however lacking in tropical regions in contrast to extratropical latitudes where heat-waves are tightly associated with blocking highs controlled by the extratropical dynamics dominated by the Coriolis force. It is proposed herein to analyse the source processes behind pre-monsoon heat stress in the tropics, specifically in the subcontinent, their evolution under global warming and mapping the regions, most vulnerable to these changes under future climate change scenarios. This thematic research area will directly serve the National Action Plan on Climate Change (NAPCC), specifically the National Mission on Strategic Knowledge for Climate Change (NMSKCC). Previous research has identified a key role of near surface atmospheric water vapor in impacting the severity of these heat waves. Following from the existing information and knowledge, the proposed research will explore the role of higher atmospheric water vapor in impacting surface heat stress through a control on atmospheric dynamics and cloud occurrence. The evolution of these processes under global warming will help track the heat wave vulnerability across the subcontinent.

The workflow will include identifying correlations between metrics of heat waves and meteorological conditions, specifically atmospheric water vapor and cloud cover. Tools of ground-based and satellite observations, reanalysis and model data will be employed. A part of such analysis has already been conducted indicating a weak contribution of blocking high events in triggering heat stress conditions as compared to background tropical dynamics which controls the occurrence of mid-level clouds. Also, it is being proposed to establish novel facilities and collaborations with existing ground-based cloud monitoring and atmospheric



Map shows duration of exposure to very strong heat stress (UTCI based) over a period of 80 days.

profiling networks/facilities. Apart from achieving the said objectives, the establishment of ground-based networks will also serve the purpose of general weather monitoring, ground truthing for satellite data retrievals and cyclone monitoring for coastal areas.

2.5 Rising Innovations: Harnessing Balloons for Societal and Scientific Advancements

Balloons have emerged as adaptable tools for advancing societal and scientific goals, serving purposes ranging from disaster relief to pioneering research endeavours. They provide a cost-effective and versatile platform for a multitude of applications. Since its establishment in 1969, the Tata Institute of Fundamental Research's Balloon Facility (TIFR-BF) has played a significant role in crafting zero-pressure (ZP) plastic balloons essential for various scientific endeavours. These balloons are crucial for research in fields such as Astronomy & Astrophysics, Atmospheric Sciences, Astrobiology, and High Energy Physics. Additionally, the facility is also involved in the production of natural-shaped balloons and aerodynamic shape kytoons to meet societal needs.

The objectives of the proposed programmes are to explore the diverse applications of balloons in advancing societal goals, including disaster response, connectivity, and accessibility; and investigating the role of balloons in facilitating scientific research across various disciplines, such as atmospheric studies, environmental monitoring, and space exploration. Important aspects lies in identifying the societal and scientific challenges, conducting surveys, interviews, and literature reviews to understand specific needs and to pinpoint areas where balloons could make significant contributions. Further, collaboration with interdisciplinary teams comprising engineers, scientists and designers is to be considered as advanced modelling and simulation tools is required to optimize balloon designs for various applications.

The utilization of balloons represents a transformative approach to advancing societal welfare and scientific discovery. Through innovative methodologies encompassing design, technology integration, deployment strategies, and interdisciplinary collaboration, balloons have emerged as indispensable assets for addressing diverse societal needs and scientific inquiries. Looking ahead, continued research, investment, and collaboration are essential to further harnessing the potential of balloons and unlocking new opportunities for societal and scientific advancement. By leveraging balloons as versatile platforms for innovation and exploration, we can pave the way towards a more resilient, connected, and informed global community.

2.6 Solar System Exploration

Laboratory study of extraterrestrial materials (e.g. meteorites, micrometeorites, interplanetary dust particles, and samples returned by spacecraft missions) and remote sensing study of different bodies in the solar system provides direct information about the origin of our solar-system and evolution of its constituent bodies (e.g. asteroids, planets). In addition, spacecraft missions give direct insights into planetary habitability and presence of resources. Various past, ongoing and planned solar system exploration missions have provided a wealth of information about different bodies and has also brought back precious pristine extraterrestrial materials for study. Study of these samples and data is changing our understanding about the origin of our solar system and planetary habitability which in turn provides the foundation for future manned, resource utilization and base for planetary missions. The short, medium and long-term objectives of the Indian space mission are also focused in this direction and the present project aims to support this initiative.

Exploration of the Moon, Mars, and other terrestrial planets has garnered a renewed interest among many countries including India. The future plans for lunar habitation, in-situ resource utilization, power generation (nuclear power) and manned mission needs dedicated prior study of data obtained from spacecraft missions. This proposal aims to further expand on the study of remotely sensed data obtained from the Moon, terrestrial planets and from other small bodies by different missions. In addition, the proposal focuses on a dedicated infrastructure facility for study of extraterrestrial samples and samples obtained directly from the Moon, asteroids and comets which is essential for understanding the origin of our solar system, terrestrial planets, Earth and the Moon and in supporting their future exploration.

The objective is to provide confirmed information on the origin & early evolution of the solar protoplanetary disc, asteroids, comets, and planets. Understanding the origin of the Moon and the potential regions for presence of resources (e.g. metal, rare earth elements, uranium and thorium, oxygen, water, hydrogen) for future exploration and manned missions.

Remote sensing study of surfaces of planets and other solar system bodies would be taken up by using data obtained from the upcoming planetary exploration missions.

This proposal will provide the necessary science support to the future manned missions to the Moon, and understanding the origin of Venus, Mars and other terrestrial planets. It will further enhance our understanding about the origin of our solar system and of life on Earth and thereby on habitability of other planetary systems.

Exploration of planetary and solar system bodies is one of the major future goals of the humanity, and India has significant plans in its “National Space Mission.”

2.7 Exoplanets

Over the last 25 years with the advancement in technology, we have been on the path of revolution in astronomy and astrophysics, and this revolution has been the discovery of exoplanets. Discovery of exoplanets has opened an entire new paradigm to explore the Universe. Are we alone in the Universe? Is life on Earth just a mere coincidence, or very common across various other planetary systems out there? Are there many more intelligent civilisations in the Universe? All these are among the most profound questions of humanity and our search for habitable planets has the potential to answer these questions. Moreover, the search for habitable planets will also show us the diversity of exoplanets in our Universe, many of which are unlike anything we have in our solar system. However, this search for habitable planets is very challenging. It consists of finding planets that could be of terrestrial nature, constrain their size and mass, and finally perform atmospheric characterisation to accurately assess their habitability.

Internationally, Kepler and TESS missions have discovered large populations of transiting planets constraining their radius along with detection with many ground-based radial velocity surveys constraining their mass. India has also started making great efforts in being part of this revolution of exoplanets, utilizing the ground-based telescopes like Himalayan Chandra Telescope (HCT) and Devasthal Optical Telescope (DOT) for exoplanet science. However, their capabilities are limited in comparison to other ground-based facilities around the world. Keeping this in mind, we highlight herein the possible areas where India could contribute over multiple time scales, short-term, medium-term and long-term in the search for habitable planets.

The specific objectives of the proposed programme are: how do the properties of exoplanets correlate with the characteristics of their host stars and why? Can we detect and characterize Earth-like terrestrial exoplanets and remotely detect spectroscopic signatures of life or habitability on them? It is to be noted that development of in-house 1D, 2D, and 3D models for exoplanet formation, atmospheres, and interiors, both forward and retrieval would be important step in achieve the goal. In addition, creation of in-house data reduction pipelines and frameworks, establishment of in-house molecular databases are futuristic steps.

The research on exoplanets will help in understanding the diversity of planets and their atmospheres in the Milky Way galaxy. It will also enable understanding of various physical and chemical processes in action in the large range of temperature, pressure and composition that we encounter in these diverse exoplanets. Exoplanet modelling research will help in developing a planetary climate modelling community in India. The said cutting edge research will help bolster the engineering research for developing precision instruments for space and ground-based telescopes.

2.8 Instrumentation for ground, balloon and space-based observatories

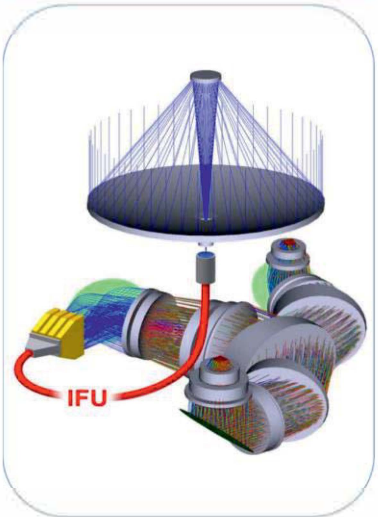
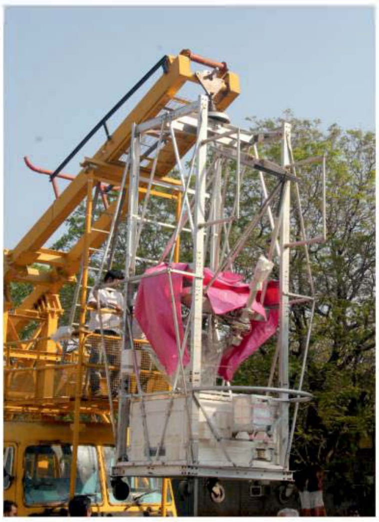
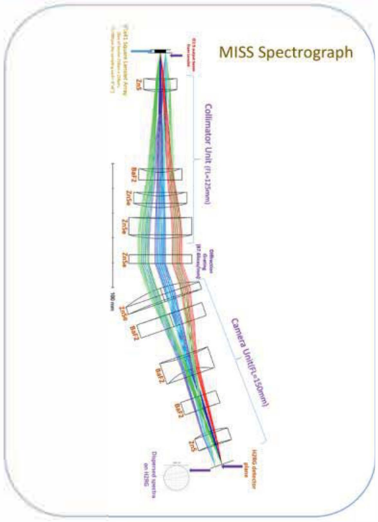
Astronomy instrumentation has always pushed the frontiers of technology in a country. Motivated by the science goals, TIFR has a long heritage of building state of the art cryo infrared instruments for all the ground-based telescopes in the country, and have also developed/developing multiple balloons and space-based observatories.

GROUND-BASED IR ASTRONOMY

TIRCAM2 @3.6m DOT	TIRSPEC @ 2m HCT	TANSPEC @3.6m DOT
		

Ground-based Cryo Infrared Instruments developed for astronomy at TIFR, DAE

SPACE-BASED IR ASTRONOMY

IRSIS LAB MODEL	T100 BALLOON BORNE + FPS	IR PAYLOAD FOR L2 POINT
		

Balloon and Space-based Cryo Infrared Instruments developed for astronomy at TIFR, DAE

On the ground-based instrumentation front, the objective is to develop novel spectroscopic and imaging instruments for the upcoming large telescopes in India (NLOT, 6-m sub-mm telescope) as well as for extremely large telescopes across the world (like TMT). In the balloon frontier, the idea is to deploy UV to Far Infrared telescopes for high precision spectroscopy, photometry and nulling interferometry. In the space frontier, the need is to have large observatory class flagship satellites that will enable probing the origins of planets, stars as well as the universe.

The strategy is to have a continuous development of pathfinder technologies driven by a combination of immediate science requirements as well as long term vision to unlock the mysteries of planet, star and universe formation. For instance, building on our previous instruments like TIRCAM II, TIRSPEC and TANSPEC we are currently developing two novel multi-object spectrograph technologies indigenously (MOIS and TA-MOONS). We are also setting up a digital signal processing laboratory, primarily for building state-of-the-art backend spectrometers both for the upcoming sub-millimetre facility in India as well as for other observatories.

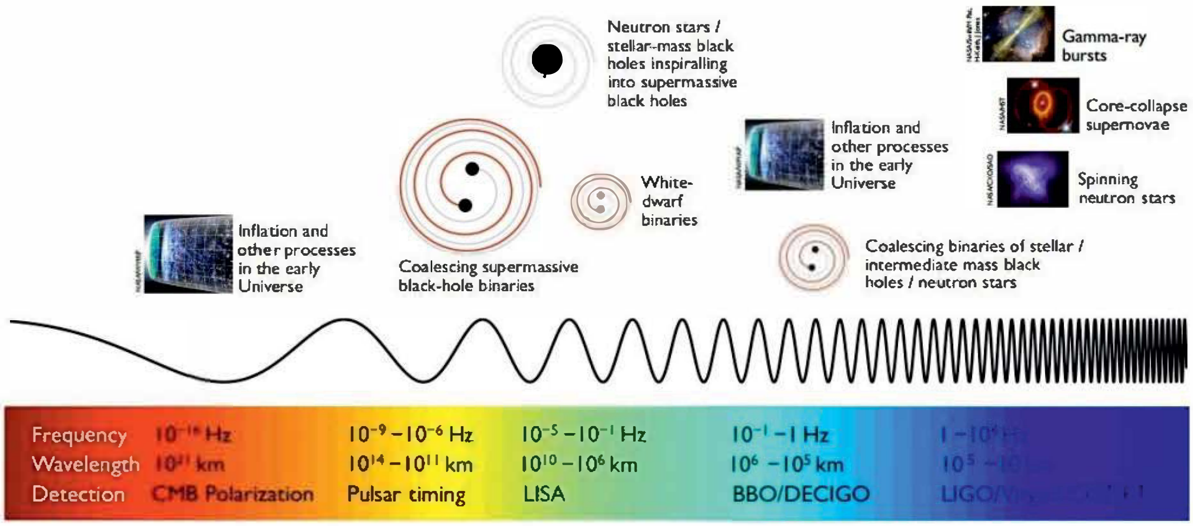
We are also part of the instrumentation team for the upcoming 10 m National Large Optical Telescope. India is also part of the TMT project, and we will contribute to building second generation instruments for the TMT in the next two decades. With the in-house development of key precision optomechanical technologies, we will be able to position ourselves as global leaders in astronomical instrumentation. We also plan to take advantage of our in-house AI/ML expertise to integrate AI capabilities to the instrument design process itself.

The TIFR balloon facility, in Hyderabad, is one of the world's top scientific ballooning facilities. Leveraging on our long legacy and in-house technologies, we are developing highly stabilised 2 m class balloon born telescopes for UV to Far Infared observations. This is to address a plethora of science cases needing deep field imaging, nulling interferometry, and high precision spectroscopy of exoplanets. Scientific ballooning platform offers a very inexpensive, environment-friendly alternative to many of the experiments otherwise possible only from space. Long-term goal is to establish India as a major player in building and operating state-of-the-art astronomical space observatories that will address frontier and foundational questions in astrophysics and space sciences.

Development of novel instruments with capabilities that didn't exist before opens up new discovery spaces. Only by excelling in the instrumentation field, India can become leaders in both basic science research as well as in technology. In-house development of technology will open up avenues for collaborations with international telescopes, which the Indian Astronomy community currently do not have the access. Apart from new astronomy discoveries, the technological spinoffs will greatly benefit Indian Industry and the AtmaNirbhar Bharat Mission.

2.9 Gravitational-Wave Astronomy

Gravitational wave astronomy is gearing into a new field that is capable of exploring physics ranging from astrophysics, cosmology, and fundamental physics from the early epoch of the Universe until the current epoch of the Universe with the aid of multi-band observations of gravitational wave signals ranging from ultra-low frequency (atto-hertz) to ultra-high frequency mega/giga-hertz. Observations accessible from the network of LIGO-Virgo-KAGRA detectors have made it possible to detect several binary gravitational wave sources, starting the era of gravitational wave astronomy over the frequency range of a few tens to nearly up to a kilo-hertz frequency. Also, the observation in the nano-Hertz gravitational wave signal using pulsar timing array observations has made it possible to hint toward the detection of the stochastic gravitational wave background. These observations primarily focus on a limited frequency range and sensitivity. In the future measurement of the signal over a wider frequency range and better sensitivity will open discovery spaces, which are inaccessible from any other observations. These multi-band observations of gravitational waves and in synergy with other probes make it possible to explore the Universe using multi-messenger observations.



The multi-wavelength spectrum of GW signal, which can probe physics from the early Universe to the internal structure of neutron stars, making it feasible to study the Universe with a new cosmic window from the upcoming and planned next-generation GW detectors.

Mission concept

Deci Hertz range gravitational wave detectors: Detection of the GW signal in this range 0.01 Hz to 1 Hz is feasible from the moon using seismometers by measuring the vibration of the moon due to the passing of gravitational waves. An array of seismometers placed on the surface of the moon can measure this signal quadrupolar pattern of the gravitational wave signal in this frequency range. The strength of the moonquakes is weak in this frequency range by orders of magnitude than earth, which makes it possible to detect this signal.

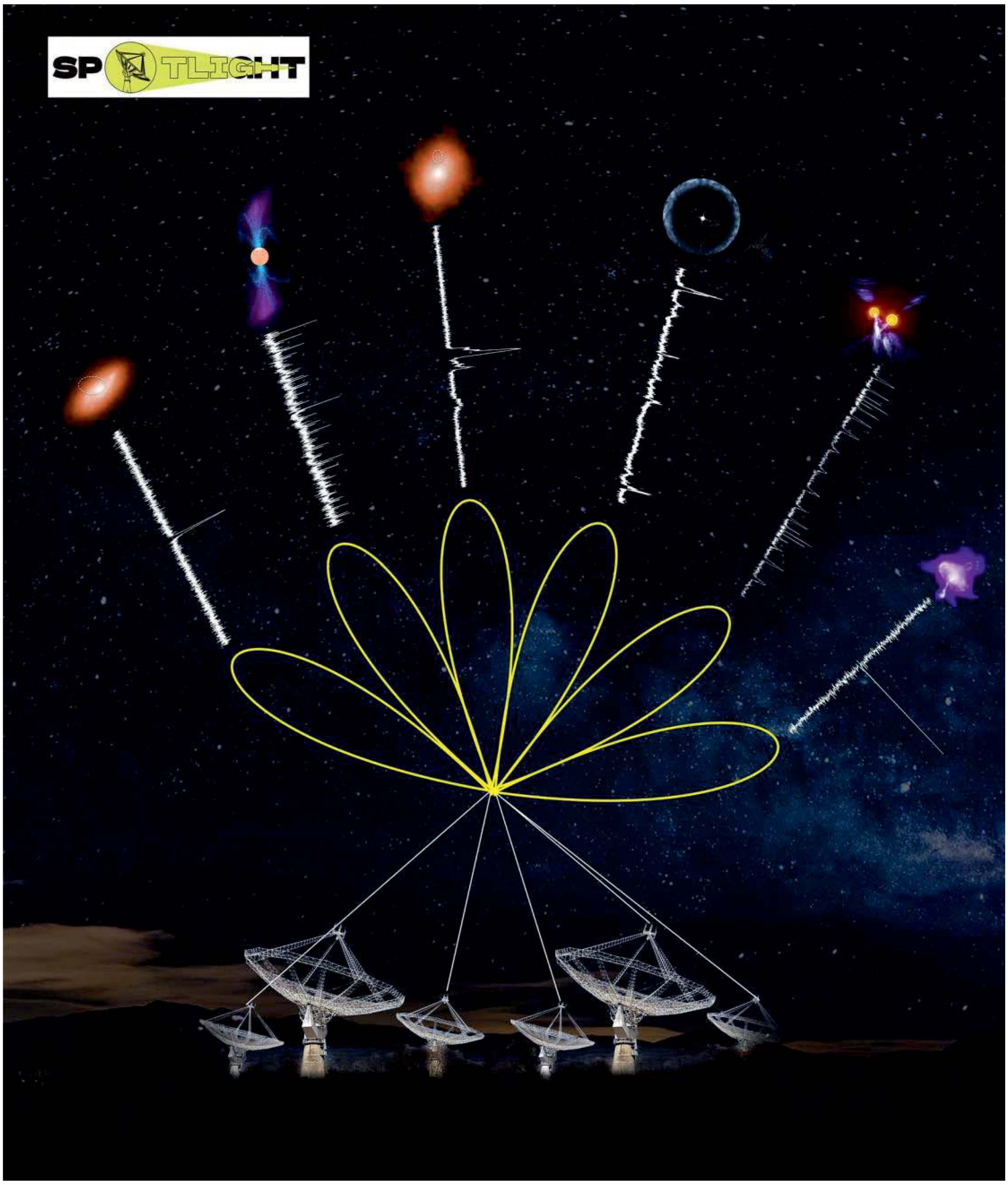
Above kilo hertz range gravitational wave detectors: Detection of above kilo hertz gravitational wave signal is possible from optically levitated dielectric sensors. Dielectric nanoparticles suspended at the anti-node point of a laser standing wave that can measure a passing gravitational wave signal. A cryogenic 100 metre cavity can explore above kilo hertz signal. The expected outcomes would include discovery of the intermediate-mass black holes and cosmological gravitational waves.

Indigenous gravitational wave detectors on the moon and Earth operating from deci-hertz to giga-hertz have the capabilities to discover a plethora of science that can change our understanding of the Universe. Building such experiments in India will bring technological development in the country which will impact several other branches beyond natural science. These experiments will make a strong footing for Indian science in an international community and play a lead role in advancing the frontier of basic science and engineering capabilities in space science and technology.

2.10 Radio Astronomy Research

Radio astronomy, which started in the 1940s, taps into radio signals coming from celestial sources, over the range of the radio spectrum accessible from the Earth (about 30 MHz and higher). India is one of the leading countries in radio astronomy research having facilities like the Giant Metrewave Radio Telescope (GMRT), built and operated by the National Centre for Radio Astrophysics (NCRA). The GMRT is one of the most sensitive instruments in the world for cutting-edge research in low-frequency radio astronomy (110-1450 MHz) in the field of High redshift galaxies, Active Galactic Nucleus (AGN), Clusters, Interstellar medium (ISM), time-domain study for Pulsars and Fast Radio Bursts (FRBs). Along with the emergence of modern astronomical facilities like the GMRT, the international mega-science project, the Square Kilometer Array (SKA), is expected to be a state-of-the-art global facility in the next decade. Looking further ahead, on a horizon beyond 20 years from now, the most important and exciting new frontier would be radio astronomy from space allowing us to escape from the ever-growing problem of radio pollution and accessing radio sky at ultra lower radio frequencies (beyond the ionosphere).

SPOTLIGHT (https://spotlight.ncra.tifr.res.in/), a real-time survey instrument funded by the National Supercomputing Mission (NSM) under MeitY and DST of Govt. of India to explore a completely new programming paradigm both in HPC and in AI to leverage GMRT's potential in delivering cutting-edge time-domain astronomy transient sciences. This multi-beam commensal system, powered by petaflops of computing and petabytes of storage, efficiently probes the transient sky across timescales ranging from nanoseconds to seconds, targeting coherent emitters.



Artistic impression of the SPOTLIGHT system simultaneously spanning the fast transient timescales from nanoseconds to seconds with an energy range of 1027 erg/s to 1042 erg/s

The whole idea is enabling transformational, high-impact science with the GMRT by adding new facilities; expanding the GMRT facility to reach unprecedented sensitivities in hitherto unexplored parameter space; contributing with required science and technology development to support participation in SKA mega-project; and finally working on a roadmap for India to become a leader in space-based radio astronomy.

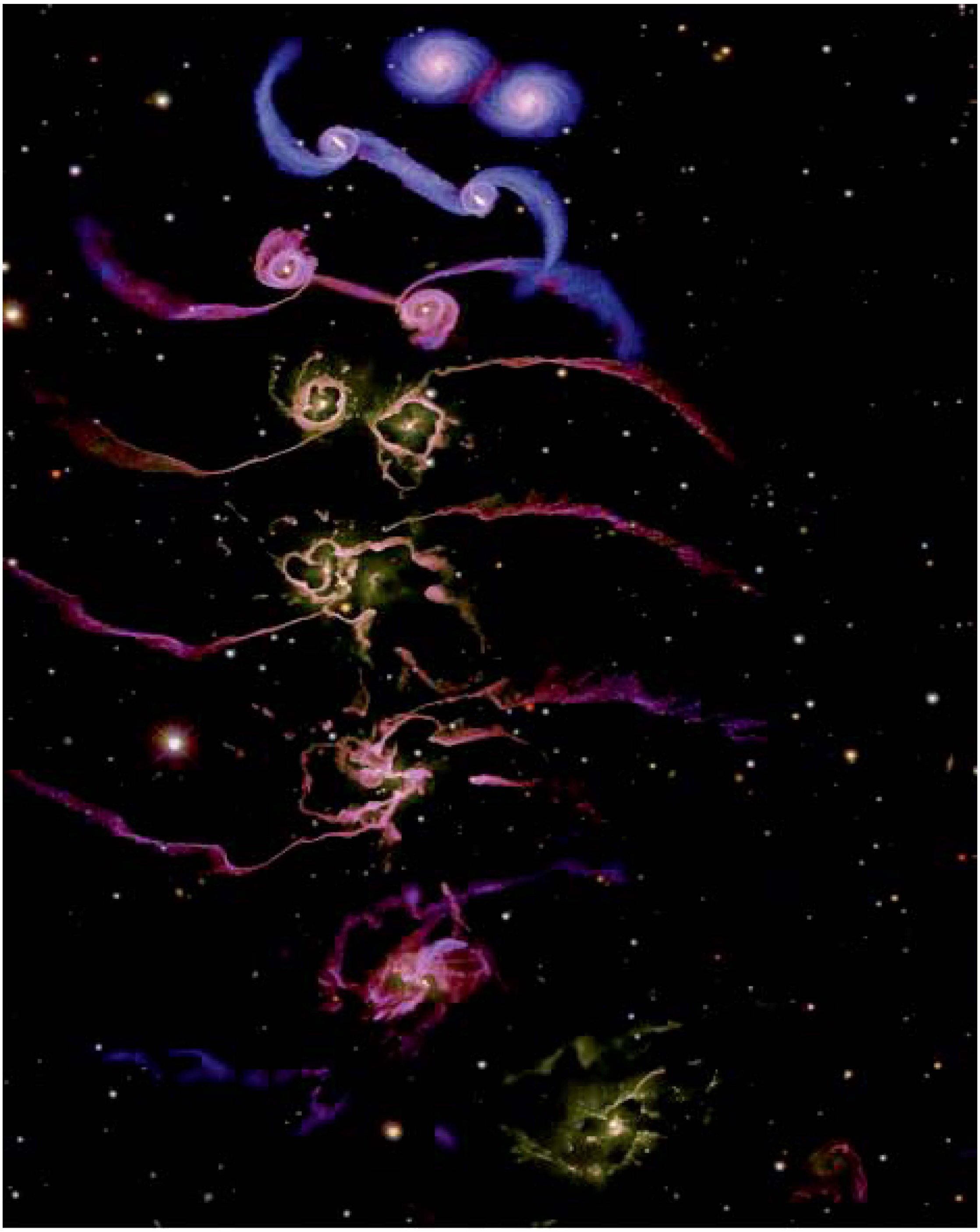
All these radio astronomy instrument developments will further strengthen the unique position of India in the world by rapidly building systems using COTS components largely designed by our Indian scientists/engineers as well as having a timely implementation of AI modules (e.g. ML/DL) to increase GMRT's sensitivity towards genuine cosmological signals. Other specific outcomes of the proposal are the development of GPU-Powered HPC application with Exascale computing in radio astronomy. Working on technology challenges ranging from quantum technology for computing and communication, self-sustaining energy solutions would enable space-based radio astronomy in synergise with other S&T aspirations that India is looking for.

The proposed roadmap will also build facilities for the students and early career researchers with rich resources of astronomical data at unprecedented sensitivity leading to the enhancement of the intellectual property of the nation as well as developing a skilled human resource in the country in the field of high-performance computing, artificial intelligence, networking and energy production.

2.11 Theoretical Astrophysics Using Large-Scale Simulations

Large-scale hydrodynamic (HD) and magnetohydrodynamic (MHD) simulations have become indispensable tools in astrophysics research. However, India lacks the large-scale facilities on which such simulations are being carried out. Thus, while astrophysicists have successfully made use of and contributed to the development of such tools during their previous positions, once working in India they are forced to scale down or change their science objectives or rely on international collaborations to continue this work, which is not always feasible or desirable. Hence, there is a need for vast improvement in computational facilities to help Indian astrophysicists to use their skills and knowledge effectively and help to train the next generation. In particular, DAE scientists at NISER are using such tools to study the following cutting edge fields: (i) the merger of stars in a binary star system, (ii) the evolution and effects of magnetic fields in and around galaxies, (iii) The formation and evolution of the first galaxies and quasars as seen by JWST, (iv) the gravitational wave signal from merging supermassive blackholes, (v) the distribution of metals of different ionization states in gas around galaxies as a probe of galactic feedback, (vi) the role of cold atomic gas in the formation and evolution of galaxies.

One of the specific objectives is to understand the common envelope (CE) phase of binary star evolution, which is responsible for various enigmatic phenomena including luminous red novae and the progenitors of gravitational wave-driven mergers of neutron stars and black holes. The CE phase is extremely challenging to model and still not well-understood owing to the large dynamic range of spatial, temporal and density scales and inherent asymmetry, which necessitates 3D simulations with adaptive spatial resolution.



Source: Tiziana Di Matteo et al. 2005, Energy input from quasars regulates the growth and activity of black holes and their host galaxies, Nature.

Different phases of the merger of two galaxies with central supermassive black holes. From top to bottom, the individual images of the sequence show the gas of two colliding spiral galaxies.

DAE scientists are capable of carrying out excellent research in computational astrophysics related to astrophysical fluids. New discoveries are made when one is able to resolve even larger dynamical scales in the simulation. These days, large-scale simulations are becoming more and more necessary to tackle the most interesting and important problems in the field, but knowledge about and experience in using and developing the leading simulation tools is not enough; computational resources in the form of high-end facilities are also significantly necessary for India to take a leading role and become a place where astrophysicists from around the world want to work.

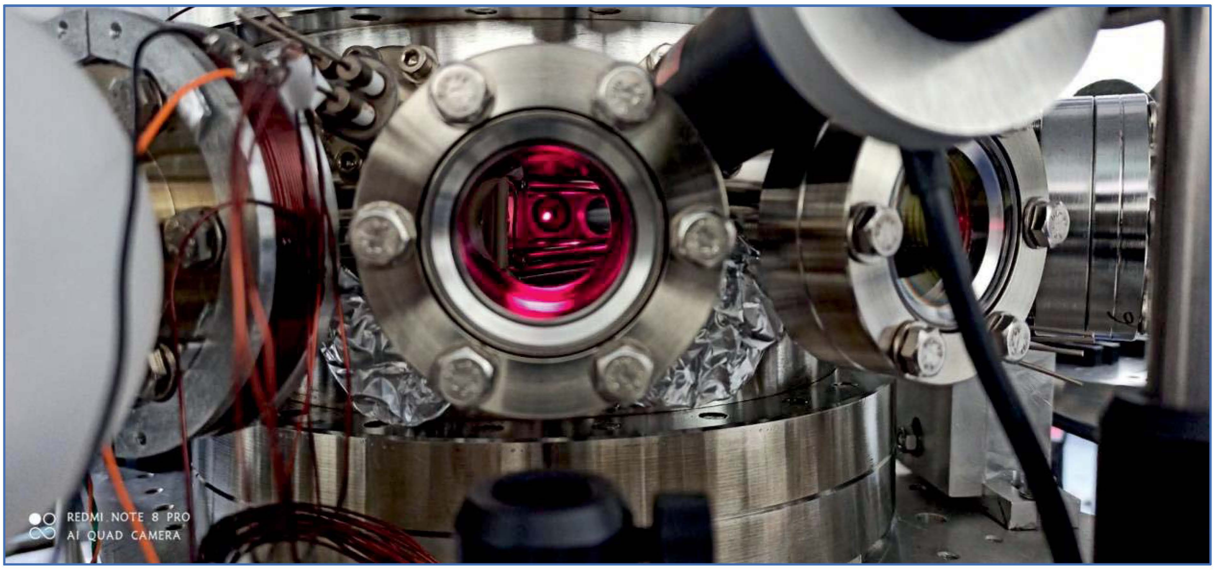
3. Atomic, Molecular and Optical Physics

This white paper describes the vision of TIFR in the broad field of Atomic, Molecular and Optical (AMO) Sciences. The AMO vision-2047 builds on the strong foundation and long tradition of AMO sciences in TIFR Mumbai and, additionally, encompasses the new initiatives and forthcoming opportunities in the TIFR Hyderabad campus. Following are the key areas which shape the AMO science vision:

3.1 Ultralow energy (<1 meV) and low energy (~eV) collisions

Studies of collisions at ultralow energies (< 1 meV) are possible using the techniques of laser cooling, supersonic expansion and a combination thereof. Atomic and molecular collisions at such low energies allow precise control over the quantum state of the particles and enable detailed understanding of molecular structure and dynamics. We propose to develop experiments towards these goals, making use of existing expertise as well as hiring new members. In the low energy (~eV) regime, we propose to focus on electron induced chemistry on surfaces and in high pressure gases which are actively pursued by groups within TIFR. Of particular interest are devising methods to control chemical reactions using low energy electrons, developing new techniques of imaging surfaces based on atom scattering, build predictive models and develop techniques for surface characterization.

For collisions between atoms or between atoms and molecules at ultralow energies (<1 meV), the collision cross section is dominated by only a few partial waves and at extremely low energies by a single partial wave, known as the s-wave collision regime. This implies that classical treatments of collisions breakdown and full understanding of the experimental outcomes is possible only through a quantum mechanical treatment. Such calculations are sensitive to the underlying long-range interaction potential between the colliding partners and therefore, a joint experimental-theoretical approach provides precise knowledge about the interaction potential. In many cases this enhances our understanding of collisions and chemical processes, some of which may result in uncovering of new fundamental physical phenomenon. Another important aspect of extremely low energy particles is that they can be trapped and their quantum state can be manipulated with exquisite precision, therefore enabling studies of quantum-state resolved molecular dynamics. A complementary approach is implemented for collisions between molecules and electrons at low energies (~eV). Here effusive or supersonically cooled molecular beams interact with the low energy electrons whose energy can be tuned to break molecular bonds and the resulting fragments can be imaged to reveal the underlying molecular potentials and dynamics. The approach allows selective breaking of bonds and has been instrumental in revealing underlying symmetries, electron correlation or new mechanisms. Another area which remains relatively unexplored is the interaction of electrons and molecules with surfaces. It is well known that surfaces alter chemical reactions (e.g. in catalysis) but the detailed molecular level understanding is lacking partly because of challenges in surface preparation and probing techniques. Exploration in these directions further, are being proposed herein.



Setup for laser-cooled lithium atoms in TIFR Mumbai.

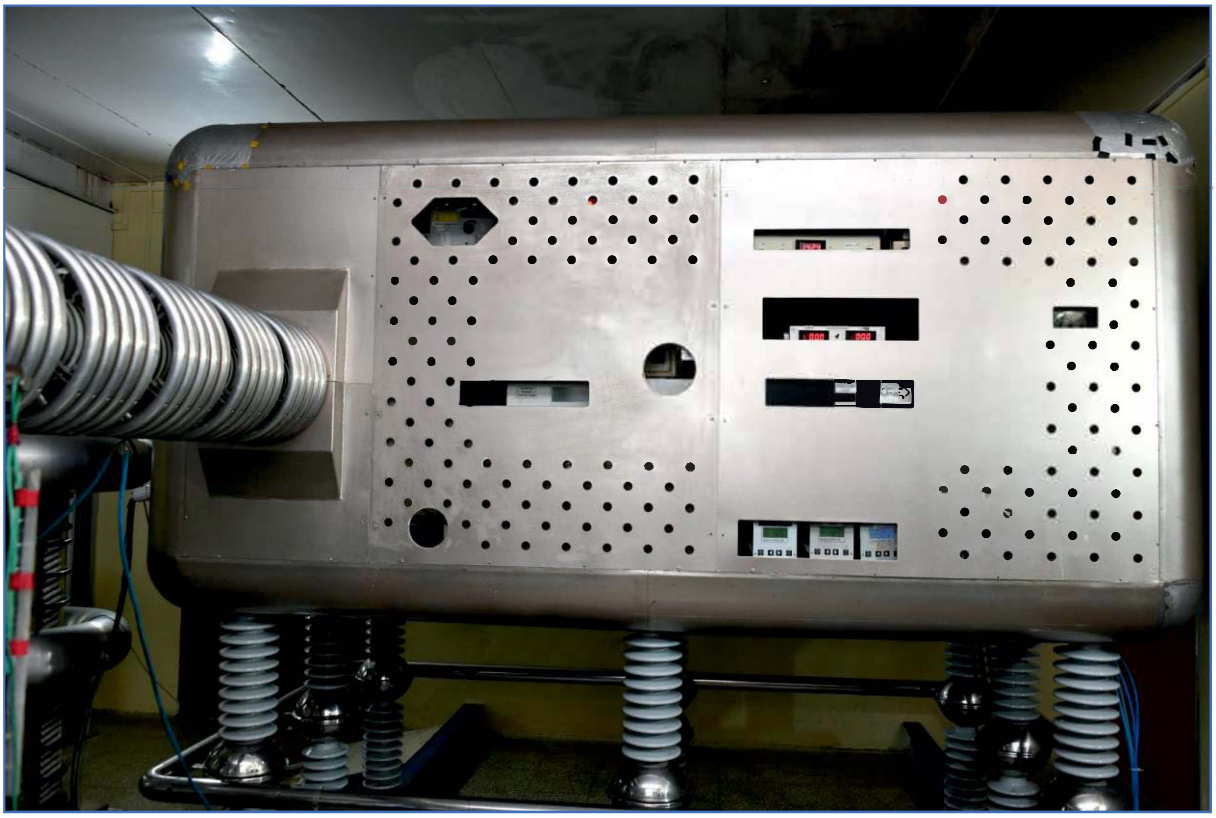
The short term (0-5 years) goals are to produce ultracold polar molecules, study quantum-state controlled collisions and reactions and surface induced chemistry.

The long term (5-15 years) goals are to study dynamics of long-range interacting systems, Insights into cluster formation, devising methods to control chemical reactions using low energy electrons.

3.2 Accelerator-based atomic and molecular physics

The relatively unique facilities such as the Electron Cyclotron Resonance Ion Accelerator (ECRIA) and the Pelletron makes TIFR Mumbai suited to carry out experiments involving highly charged ions and ions with energies ranging from keV to MeV.

The interaction of highly charged ions with molecules, in particular molecules of astrophysical and biological relevance is important from the view point of interaction of solar wind with PAH molecules and for the biological molecules it is important from the radiation therapy point of view. Interaction of highly charged ions with PAHs sheds light on the formation of smaller hydrocarbons and hydrogen in the interaction of PAHs with cosmic rays and solar wind. The measurement of absolute cross sections gives insight into the chemistry happening in the interstellar medium. The measurement of absolute cross section of biologically relevant molecules provides input for the dose calculation in the hadron therapy. Besides, the study of fragmentation dynamics of small molecules is important to gain knowledge about fundamental interaction of highly charged ions with molecules. Another important aspect is the electron capture by highly charged ions from He atoms and H_2 molecules which is important in the role of electron capture in TOKAMAK plasma.



The Electron Cyclotron Resonance Ion Accelerator in TIFR Mumbai.

The specific road map has been drawn, which include studies on breakup of PAH molecules due to collisions and relevance to production of molecular hydrogen in space, biomolecular breakup, cancer therapy.

Participating in building a High Energy Accelerator for GeV ion beam (e.g. GSI type), Developing a Cryogenic Storage Ring, Rare decay of molecular ions using the CSR, Study structure and dynamics of larger PAH molecules are chosen further as long-term goals.

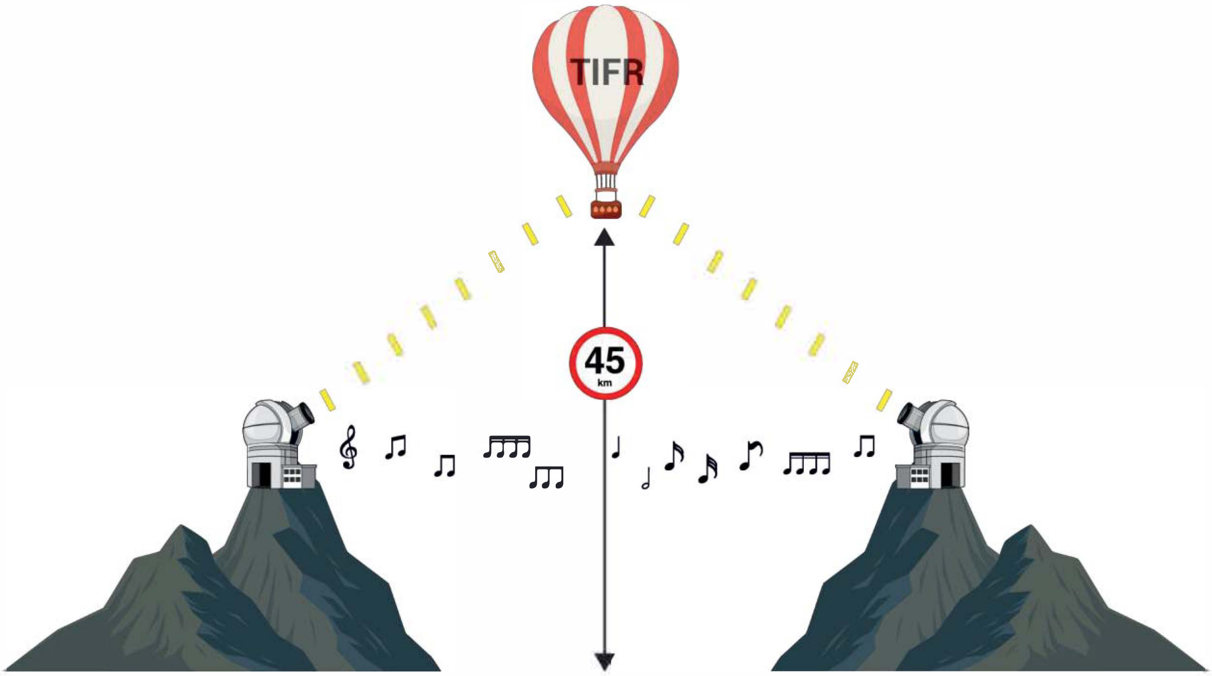
3.3 Quantum and Optical Communication

Investing in long distance quantum communication and optical communication using the TIFR Balloon Facility in Hyderabad and designing and developing the necessary hardware are proposed in this programme. High altitude platform (HAP) node for quantum communication over 800-1000 km is proposed also. Further, the eventual handshake with the Indian Satellite Program, expansion of LAN to national length-scales by adding nodes and large area receivers and integration of the National HAP/Satellite network with the global HAP/Satellite network is envisioned.

Establishment of communication facilities from local to global scales has shrunk the world to its effective size today. The security of communication has become a vital aspect in communication in regard to financial organizations, government offices, or strategic locations. Currently, technological advancements are happening over increase in the speed or bandwidth of the carrier, and augmentation of the security thereof. Towards secure communication, an indomitable solution that has been uncovered is quantum communication. In this technology, principles of quantum physics are exploited to realize a hard-to-break protocol of communication, with the additional security layer in which any attempts to break the protocol are detected. Long-distance free-space quantum communication is perceived as a global solution by creating a quantum network consisting of satellites, drones, aerostats etc. It is, therefore, advisable to be part of this effort by launching indigenous technologies. In the domain of high-speed communication, maximum effort is being invested in optical communication. Several advantages exist in free-space optical communication, particularly with regards to accessibility to difficult areas. With advanced optical, optomechanical and optoelectronic technologies, free-space optical communication has the potential to become the mainstream technology connecting any two locations on the globe and thus global efforts are mounting where a communications network is being envisioned. Interestingly, the very same vehicles such as satellites, drones, aerostats etc. are being evaluated for the high-speed optical network and there are several overlaps in the hardware and software aspects of quantum communication and free-space optical communication. Investing in the indigenous efforts using similar high-altitude vehicles will place India perfectly to harness and exploit the technological advancements happening globally.

The entire programme is ambitious and may be achieved in stages. Initially, design and development of hardware for quantum and optical communication, wide area optical receivers, and high-altitude platform (HAP) node for quantum communication over 800-1000 km are important.

In the second stage, demonstration of a network of HAP nodes and large area receivers (≥3) towards both quantum / FSO communication, is planned.



Concept of high-altitude platform for free space optical communication

A long-term goal, LAN is to be expanded to national length-scales by adding nodes and large area receivers and thus, integration of the National HAP/Satellite network with the global HAP/Satellite network would be attained.

3.4 New Initiatives in Precision Measurements

Historically, precision measurements have played a pivotal role in expanding our understanding of physics e.g. the observation of Lamb shift that led to the development of quantum electrodynamics. In recent years, precision measurements in atomic and molecular systems have focused on two, broad but somewhat interlinked, fields. The first is to do with improvement of "optical clocks" which includes optical clocks based on atomic systems (e.g. strontium lattice clock) as well trapped ion systems (e.g. aluminium ion clock). These optical clocks have demonstrated staggering frequency stability at the level of 10^{-18} or better, surpassing the current SI standards (based on caesium microwave transition) by several orders of magnitude. It is only a matter of time before the SI unit of time is redefined using optical clocks. In India, there are no optical clocks in operation although efforts have just begun in a couple of places. It is of immense strategic and social importance that India develops its own optical clocks within the next decade and demonstrate operation at the level which is commensurate with the global standards. The second focus of precision measurement is on uncovering new physics including physics beyond the standard model of particle physics, search for dark matter etc. The idea is to replace the high energy in collider-based experiments with extreme precision in low energy atomic physics experiments. Recently, optical clocks based on highly charged ions have been proposed as good candidates to study new physics and TIFR, with the ECRIA source for highly charged ions, is particularly well suited to take up such a program. In addition, the interdisciplinary expertise in both nuclear physics and atomic physics makes TIFR a great place to initiate laser spectroscopic studies on radioactive isotopes and measure isotope shifts.

3.5 New Initiatives in Quantum Computing using Atomic Systems

Quantum computing has the potential to solve problems that are intractable using classical computers. It is expected to have a huge impact in several fields including financial modelling, drug discovery, materials discovery, cybersecurity and so on. Trapped ions and, separately, ultracold atoms have emerged as the leading platforms for quantum computing. These systems rival, and in some cases outperform, other platforms such as those based on superconducting qubits. The advantage of atoms as qubits is that atoms are identical, resulting in qubits that are identical, and that they have long coherence times. Recent developments in the field include the demonstration of >50 qubits trapped ion quantum computer and >1000 qubits in trapped neutral atomic arrays. Very recently, the operation of a logical quantum processor with error corrected logical qubits based on reconfigurable atom arrays has been demonstrated. The progress in this field has been rapid and has attracted significant commercial attention. Taking cognizance of these developments, the Government of India has launched the National Quantum Mission with a Vertical dedicated to Quantum Computing. TIFR and DAE institutes would contribute toward this, especially since some relevant expertise, e.g. in laser cooling and trapping of atoms and ions, already exist.

Within a short period, setting up experiments on trapped ions and/or trapped atom quantum computing with up to 8 qubits and performing single qubit gate operations and measure fidelities would be completed. However, the challenges in expanding it to higher number of qubits, demonstration of two-qubit gate operation with high fidelity, a fully operational quantum machine capable of implementing quantum algorithms are envisaged to be addressed in the next step.

4. High Energy Physics

In the past few decades, physicists working in the field of High Energy Physics (HEP) have devoted their efforts in understanding the Standard Model (SM) of particle physics. With the discovery of the Higgs boson in 2012, the remaining puzzle of mass generation was solved SM and it remains the best theory describing the fundamentals laws of particle physics up to a few hundred GeVs till now. However, few open-ended fundamental questions that SM does not describe are: origin of the neutrino mass, matter-antimatter asymmetry in the universe, the nature of dark matter and dark energy, to name a few. Thus, search for beyond the SM (BSM) has become the focal point for the last few years. The vision is to have a full-fledged particle physics program that is conceived, built, maintained and run by the Indian particle physics community to carry forward future international experiments in a substantial way.

4.1 Collider Physics

For more than half of a century, the principal focus of the particle physics community has been geared towards finding new degrees of freedom (particles) and learning about these by relying on measurements that directly/indirectly depend on the couplings of these new particles. However, one critical aspect of all these strategies generically relies on reasonably large couplings. Even the most elusive of all known particles, namely neutrinos, have quite large couplings to the electroweak bosons, which paved the way for their detection. The same principle has also dictated the construction and design of detectors, search strategies for high energy colliders such as the LHC at CERN, KEKB at KEK, RHIC at BNL, USA etc. Even the decades-long search for dark matter primarily focused on the so-called WIMPs, with weak strength interactions to the visible sector. While this scenario could be the truth of the nature, data from direct observation of dark matter hints that infinitesimal strength couplings scenarios could well be the case. The programme thus needs to have a two prong approach to search for these likely scenarios.

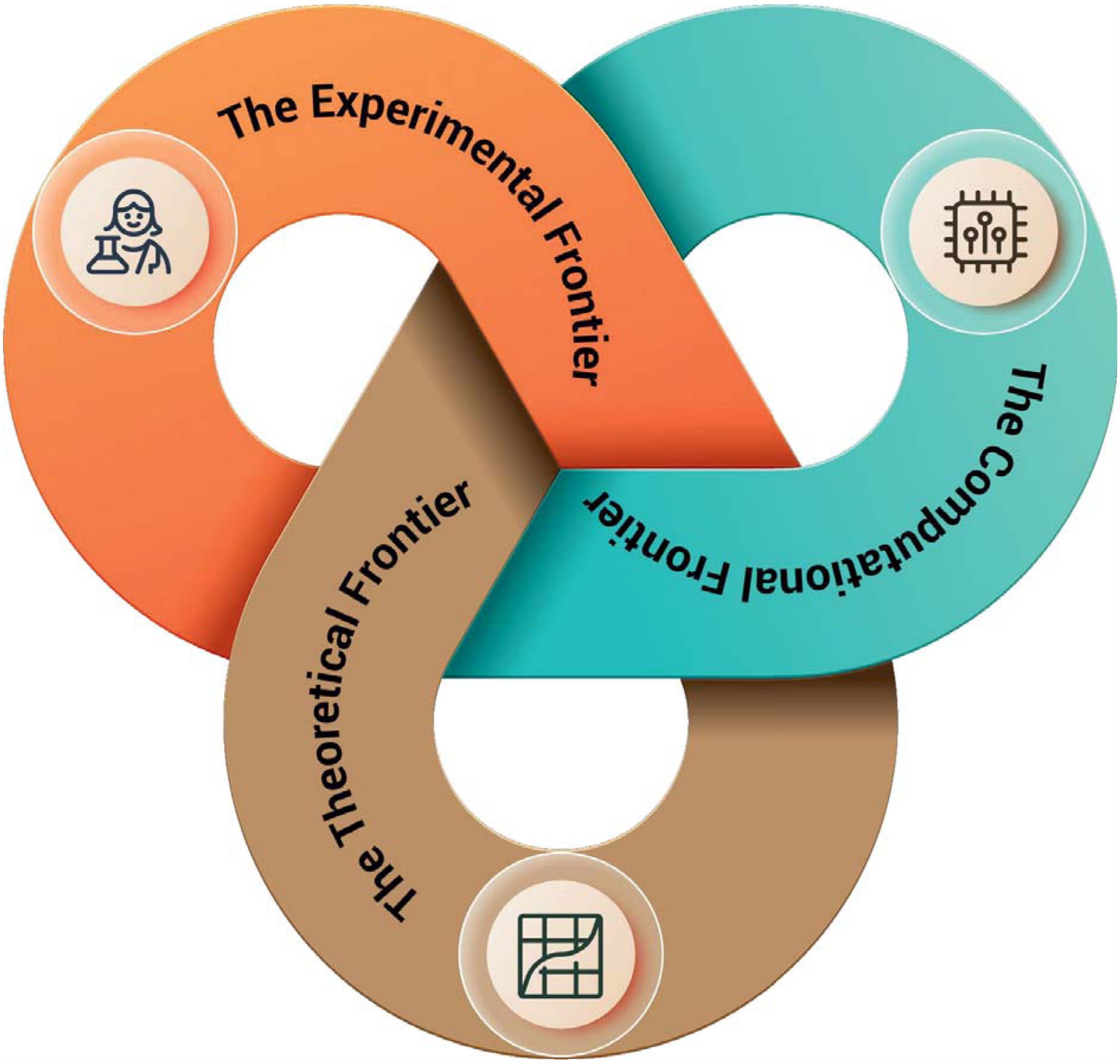
4.1.1 Future collider experiments

Exploration of scenarios that require high energy and high luminosity experiments are only possible when many international collaborations come together as in the case of LHC at CERN, BELLE etc. India is currently involved in the CMS and ALICE experiments at the Large Hadron Collider in CERN, Switzerland, KEKB at KEK, Japan; and the STAR experiment at the Relativistic Heavy Ion Collider (RHIC), US. In addition to it, Indian scientists have been involved in the experiments related to precision measurements of neutrino related parameters at NOvA, and Minerva in Fermilab, USA. Participation in leading experiments around the world gives India the opportunity to play a role in new scientific discoveries and provides exposure to cutting-edge technology.

Apart from providing novel physics opportunities where an end-to-end Indian experiment can potentially deliver competitive results. It also provides opportunities for building specialised expertise to tackle the physics of the light/ultralight hidden sector in the experimental, theoretical, and computational frontiers. While we engage with the global physics by carrying out research in various high energy colliders, building and running a low energy HEP experiment will allow us to have a fully Indian end-to-end HEP program that can be competitive. Moreover, it will pave the way forward for developing capabilities towards setting up and running a world class facility.

Several beam dump experiments around the world including ones at CERN that use electron, muon and proton beams with different absorber materials are available to study various low energy physics. In addition, there is an upcoming LUXE experiment proposed in DESY, Germany to study the non-perturbative effects of QED. The goal of this roadmap is not just being able to establish such facilities in India but achieving more in terms of higher energies, higher magnetic field and higher luminosity down the line.

The program will have a clear roadmap with incremental goals, which at every stage will identify niche areas of R&D, generate expertise all aimed towards attaining the final objective and would engage in verticals ranging from low energy beam related experiments to designing/developing table top experiments, exploring and developing new ideas in improving the existing detector technologies, developing specialized hardware including quantum sensors, to building specialized simulations and algorithms (particularly, AI and quantum machine learning), etc. The developments on the experimental fronts need to have an overarching theoretical support, which would require large roles to be carried out by phenomenologists and theorists. Clearly, in order to face the enormity of this challenge, we need to develop a multi-dimensional approach; bringing three frontiers together:



The multi-pronged approach to the Indian end-to-end HEP Program

Theoretical Frontier: The challenges in the theoretical domains can be broadly classified into the following categories: Charting the space of theories systematically in high energy to be explored in the experimental setup we plan/construct. Deriving observables from these theories at low energies requires techniques of Effective Field Theories, which can give a clear line of connection between high energy operators between quarks/gluons and new physics coupling to nuclear form factors. There has been substantial development in the context of neutrinoless double beta decays, however the program needs to be broadened substantially in the context of our set-up and target theories. Understanding the detector – because of the very nature of the detectors to be built, physics ventures into the subject of material science. Collaborations need to be established in order to bring in the knowledge base to HEP. Understanding the flux and the background – again, the very scale of energy is to be attempted to probe requires collaborations with experts in nuclear and atomic-molecular physics where sources involve collisions. Collaborations with cosmologists and astrophysicists for understanding detectors facing the sky is also very important.

Experimental Frontier: The basic premise of the end-to-end HEP program is to prepare for a diverse set of sources and generate expertise with a myriad of detector technologies.

***Beam dump experiments*:** These experiments are fixed target experiments where the achievable luminosities can be higher compared to the collider type of experiments. These are relatively easier to arrange compared to a collider-based experiment.

***Light shining behind a wall class of experiments*:** The basic principle behind such experiments is that in the presence of a strong magnetic field photon could be transformed into light particles which could well be dark matter candidates and then those particles again transfer back to light.

Physics from electron - photon collisions: Such experiments can probe non-perturbative effects of QED.

***Low energy electron-positron collider*:** Beam energies of the order of few GeVs (10 GeV or so) can be used to search for various low energy new physics and to study several rare decay channels of mesons. If future R&D allows, this can become a possibility given that electron beam of several GeVs is expected to be available in the near future.

Terrestrial detectors to study cosmic particles:

Large area multi-detector arrays to comprehensively study cosmic rays, their sources and composition targeting the highest energy and Ultra-sensitive haloscope class of detectors

***Space based experiments*:**

- Detectors similar to Fermi-LAT optimized for high energy gamma ray detection
- Scaled down versions of general-purpose HEP detectors similar to what has been implemented by the AMS Collaboration

Computational Frontier:

In order to extract "more from less", a key focus of the "frugal" HEP program, specialized AI based tools and algorithms for maximizing the extraction of information from a given amount of data to be developed. In fact, the use of AI tools can't just be limited to data analysis but must be extended to all aspects of the program and particularly to the hardware aspects of the programme.

4.1.2 Contributions in future collider experiments

Collaborations in future collider experiments are very important not only because of their potential to discover new physics if it lies at high mass or large couplings but also because of other factors, e.g., exchange of knowledge and ideas, novel detector technologies, etc. Future colliders bring a completely new era of detector challenge we should be ready in terms of concrete contributions which are not only related to data analyses but need to be augmented by building an end-to-end detector/sub-detector in India for a collider experiment starting from laying down the foundations of the detector concept to its construction, installation and its running for the full data taking period. In addition, the ability to handle very large volume of data throughput has undergone a paradigm shift over the last decade and is expected to keep evolving in the future colliders. The software and computing demands will also increase manifolds by then. This includes the stringent requirements for more accurate simulations in various aspects e.g. for the detector or the machine-detector interface. This is again a good place where we can carve our niche by building a software ecosystem adaptable to any future collider.

4.2 Cosmic Physics

4.2.1 Dark Matter Searches

There is now overwhelming evidence for dark matter at more or less all astrophysical scales, starting from the galactic scale to galactic clusters to the truly cosmological scales. The evidence is extremely strong for the existence of a non-collisional, electrically neutral, non-baryonic tenuous fluid which encompasses most of the matter density of the universe. Within the Standard Model of cosmology, dark matter constitutes about 24% of all the energy density of the Universe. The biggest conundrum of the present time is the lack of any observable evidence or any clue about the particle nature of dark matter. Over the past decade or so, there has been an explosive rise in the study of dark matter through various experimental, astrophysical and theoretical channels. The principal probes of dark matter are done through relic density measurements, direct detection experiments and indirect detection experiments. The relic density is a cosmological observation determined predominantly by the measurements of tiny anisotropies in the Cosmic Microwave Background Radiation (CMBR). These measurements are most accurately done by satellite-based experiments like COBE, WMAP and PLANCK. Together with optical and other probes of Type 1A Supernovae, the dark matter relic density of the Universe is now quite accurately estimated. The direct detection experiments, on the other hand, are ground-based, typically employing large detectors housed in underground laboratories. These can identify direct interactions of dark matter with the ordinary matter in the detector. Such experiments have already produced very high-quality results by putting strong constraints on thermal dark matter cross-sections.

Indirect detection of dark matter is the attempt to measure dark matter properties within the galaxy or nearby, by looking at the indirect products of dark matter decay or annihilation. There are both ground-based and satellite-based probes which look for signatures either in cosmic rays, gamma-rays or neutrinos. In future, ground-based experiments like Cherenkov Telescope Array (CTA) and Tibet AS-γ would also lead to significant constraints on indirect detection of dark matter or even have the potential to provide clues to the nature of the dark matter. Most of the work in order to find the nature of dark matter has been centred on Weakly Interacting Massive Particles (WIMPs), however, in recent times, other forms of dark matter are being explored too. These particles could be detected in high-energy collisions, such as those at the LHC (collider searches), or via annihilation products of particle-antiparticle pairs (indirect detection), or via their elastic scattering with matter showing up as nuclear recoil signals (direct detection). Another set of candidates for the dark matter particles are axions or axion-like particles (ALPs), light pseudoscalars that couples weakly with photons. The study of DM forms a very important bridge between high energy physics and astrophysics. Overall, the future of dark matter research has the potential of opening up an entirely new sector of particles and interactions to study.

India has had a very long and rich history in the field of cosmic rays (CR) and high energy gamma-ray astrophysics. In India, the Atmospheric Cherenkov Radiation (ACR) was first detected by the TIFR group in the early seventies by using search light mirrors and fast photomultiplier tubes. Several technological improvements in the design led to the establishment of an array of 25 distributed Cherenkov telescopes, namely, Pachmarhi Array of Cherenkov Telescopes (PACT) at Pachmarhi in Madhya Pradesh. Later, in the year 2002, a seven telescopes array was set up at Hanle to observe high energy gamma rays from celestial objects at lower energies. BARC group started its VHE gamma-ray astronomy program at Mt. Abu by setting up an imaging telescope called TACTIC. Buoyed by the success brought by these installations which detected very high energy gamma rays from different classes of galactic and extragalactic sources, the BARC group has now installed a new large telescope of 21 m diameter, MACE, at Hanle, which is the currently the world's largest high altitude imaging telescope. GRAPES-3 is a major high-altitude, near-equator Astroparticle Physics experiment at Ooty led by TIFR and operated by an international consortium of several institutions in India and Japan. It is an expanded version of the original GRAPES experiment, which started running more than 30 years ago. It consists of 400 large-area detectors made from scintillators, as well as 4000 massive sealed proportional-counters, making it the world's largest muon telescope. It is well suited for exploring the "knee" region in the energy spectrum of CRs as well as for observing accelerated particles in atmospheric, solar, galactic and extragalactic domains. In addition to the cosmic ray spectrum and composition studies over 1013 to 1017 eV, GRAPES-3 is sensitive to particle acceleration by electric potentials generated in thunderstorms, and performs measurements relevant for space weather and heliospheric studies. Additionally, it looks for gamma ray sources in the multi-TeV to PeV range, diffuse gamma ray emission from the galactic disk, and can also look for decaying dark matter in the galaxy. GRAPES-3 scientists have also demonstrated that cosmic-ray muons can be a powerful tool to measure arrival time of solar storms at Earth with great precision. Such studies are vital for protecting worldwide telecommunication and electrical-grids from disruption.

GRAPES detector array at Ooty

4.2.2 Astroparticle Physics with cosmic rays and gamma rays

Even after a century of intense research, a complete understanding of cosmic rays (CR) is still lacking. Nevertheless, various properties of cosmic rays as regards to their spectrum, elemental composition and angular distributions have been studied extensively. However, one of the major difficulties in identifying sources of cosmic rays is that they are charged particles and are therefore deflected in the interstellar magnetic field. Therefore, cosmic rays cannot be traced back to their sources, the so-called cosmic particle accelerators, except for energies beyond 1020 eV, where the bending effects of galactic magnetic fields become minimal. Thus, much of the current effort goes into identifying and quantitatively describing these cosmic accelerators. Shocks in supernova remnants and/or pulsar wind nebulae systems are thought to be the dominant sources of Galactic cosmic rays.

At energies below 1014 eV, cosmic rays have been primarily studied using space- based instruments where detectors used are magnetic spectrometers and/or calorimeters for momentum/energy determination along with transition radiation detectors and Cherenkov detectors. While direct detection mechanisms in space provided many important results on elemental and isotopic composition, the steep fall in flux of cosmic rays with energy, along with the limited size of space-based detectors, restricts the energy range of detection. Thus, at higher energies, ground-based instruments have a distinct advantage where the Earth's atmosphere acts as a calorimeter in which particle cascades are created when a primary particle or a photon interacts with the atmosphere. Some of the important ground-based cosmic ray experiments are KASKADE, Pierre Auger Observatory, IceTop, GRAPES-3, Telescope Array (TA), Tibet AS-γ and LHAASO. GRAPES-3 represents the only major operational facility in India. Even though many interesting and ground-breaking results have been obtained from the above-mentioned experiments, it is very difficult to identify the sources of charged cosmic ray particles as explained above. Therefore, high energy gamma-ray observations both from space and ground and neutrino observations from the ground are of prime importance in order to establish the directionality of cosmic-ray sources. With a very modest beginning in 1989, the field of very high energy (VHE) gamma-ray astronomy grew rapidly in the last two decades owing to tremendous technological progress and currently, more than 200 high energy gamma ray sources of various classes have been discovered in the last decade.

The most sensitive satellite-based gamma-ray detector currently operating is the Fermi Large Area Telescope (LAT) which has discovered hundreds of high energy sources including several new source classes. However, at higher energies beyond a few tens of GeV photon statistics drops and one needs to start observing from the ground. The most sensitive ground-based approach is the Imaging Atmospheric Cherenkov Technique (IACT), which uses the Cherenkov light produced by the electromagnetic cascade of electrons and positrons in the atmosphere to establish the properties of the primary gamma-ray photon. The current generation of IACT instruments include MAGIC, H.E.S.S. and VERITAS and these have already yielded many ground-breaking results in the field of very high energy gamma-ray astrophysics. These space and ground-based instruments have shown the abundance and indeed ubiquity of cosmic particle accelerators. The BARC group has recently installed a new telescope, MACE, at Hanle. MACE will add to the impressive list of current generation of imaging telescope and its longitude allows it to make observations that are complementary to most other telescopes in the world.

The future proposals can be broadly categorized into three main areas:

- Experiments where we clearly have an advantage over the rest of the world, from the point of view of existing expertise in technology and human resource, availability of material, geography or topology, or new niche ideas that have not been tried out yet elsewhere. In such projects, we can be extremely competitive with the rest of the world and may even be the first ones to discover new phenomena or resolve long-standing scientific puzzles.

- Projects where Indian scientists are a part of international collaborations based elsewhere and would like to perform R&D / prototype testing in the country. This would enable the Indian scientists to play significant roles in the international projects at the forefront of knowledge and fulfil the in-kind commitments of the country in these projects. Over the long run, this would lead to technology-building, and prepare the foundation for the future generations of Indian scientists to lead major projects in these areas.

- New ambitious and challenging ideas, some of which are still in the inception phase that need a clean environment, free of cosmic-ray background. The availability of an underground facility is of paramount importance as it would allow the Indian scientific community to conceive and implement such projects. Once the infrastructure of an underground facility is available, the marginal investment needed for implementing these projects would be much smaller and performing these niche experiments in a timely fashion will be feasible.

A few of these ideas (not exhaustive though) are enumerated below:

Deuterated Liquid Scintillator for solar and supernova neutrinos:

The Deuterated Liquid Scintillator (DLS) project proposes a 1 kt-class detector with either a hydrocarbon-based liquid scintillator with the hydrogen replaced by deuterium, or water-based liquid scintillator dissolved in heavy water (D_2O), instrumented with a few thousand PMTs. This would allow neutrino and antineutrino detection, with sensitivity to all flavours. And low energy, high resolution measurements using the scintillator light along with Cherenkov radiation, to reduce threshold and increase light yield.

Dark Matter Searches: As explained above, dark matter (DM) is the dominant component of mass in the Universe. The fundamental scientific question that remains unanswered is the nature and type of particles DM is composed of. A direct detection experiment involves the interaction of DM particles with detector material. They must be located in deep underground laboratories to avoid the effects of cosmic ray interactions that produce energetic neutrons that could mimic DM particles. Indian groups, several of them already participating in international projects like SuperCDMS, PICO and others, are interested in setting up DM search experiments in India and using the facility to carry out detector R&D in the area. This R&D would focus on the development of technology to enable the improvements in backgrounds and detector performance required to achieve these ever-growing compelling science goals. Such an experiment has been set up in Jaduguda Underground Science Laboratory (JUSL) and has been taking data since last year. This facility will need augmentation and upgradation in the next few years in order to set up detectors of larger masses in order to improve the sensitivity of the instrument. A clear observation of fractional charge would be very important since depending on the type of particle observed, it might mean that confinement breaks down under some circumstances or that entirely new classes of particles exist.

Multimessenger Astroparticle Physics using cosmic rays, gamma rays and neutrinos:

In order to understand the acceleration of particles to very very high energies (way beyond that can be achieved in the laboratories), it is important to combine messengers of different species to understand and probe the key questions that have remained unsolved for many years now. On the neutrino front, Indian physicists are involved in two international MSPs that will study neutrino oscillation physics, the Deep Underground Neutrino Experiment (DUNE) in the USA and the Hyper-Kamiokande (HK) experiment in Japan, both of which are expected to start within the next decade. The DUNE participation of Indian scientists could be a continuation of that in the NOvA and Minerva projects, with further possible contributions to the construction of the near detector. In addition, the IceCube detector at the South Pole, which detects ultrahigh- energy neutrinos, will soon be upgraded to IceCube-Gen2, for which the contribution from Indian scientists in the form of detector assembly, integration and testing is being envisaged. The Cherenkov Telescope Array (CTA) would be the most sensitive very high energy gamma ray astrophysics experiment in the world in the decades. Some Indian institutions have already been participating in CTA, hence a formally coordinated participation is highly desirable. At the same time, the home-grown facilities like GRAPES-3 and MACE need to be upgraded vigorously. Hanle especially has a longitudinal advantage as there are no gamma-ray telescopes operating at this longitude and would thus compliment the observations carried out at other existing facilities around the world. Similarly, GRAPES-3 is located at near the Equator which makes it possible to view both the hemispheres for cosmic-ray studies. Below a few GeV, gamma rays cannot penetrate deep into the Earth's atmosphere and so they cannot be detected. Instead, one has to rely on detectors flown in satellites or balloons to perform such observations. Hence there is a growing need to build and commission a particle physics detector in space which would carry out observations of astrophysical sources from several hundred keV to a few GeV as currently there is no such detector operational in this energy range. This would involve strong inter-agency cooperation with possible multinational partners with India taking a lead role in the design and development of such a detector in space.

4.2.3 Neutrino properties and Neutrino astronomy

Neutrinos are perhaps the most difficult and challenging particles to study in the Standard Model, as well as some of the most intriguing objects in the Universe. One of the most fundamental open questions in neutrino physics is the absolute mass scale of neutrinos. The oscillation experiments determine the mass-squared differences among neutrinos and guarantee that all the neutrinos are within 0.1 eV of each other. The Standard Model of Cosmology puts reasonable limits on the sum of neutrino masses to be less than 1 eV. The absolute scale for neutrino masses is expected to be partially addressed by the ongoing KATRIN experiment which is trying to measure the effective neutrino mass in tritium beta decay. Several international experiments such as GERDA, CUORE, MAJORANA etc. are planning to address the issue of Dirac or Majorana nature of neutrinos. In the precision sector of oscillation experiments, several experiments like Hyper-K, DUNE, NOvA would be probing oscillation observables at a high precision. Within India, the India-based Neutrino observatory (INO) was conceived to take a major step in that direction, unfortunately the project is currently stalled due to reasons beyond the scope of this document. Apart from measuring the neutrino properties, the neutrinos coming from astrophysical objects or phenomena can give us information about the processes taking place inside stars, or inside dense media like AGNs, from where light cannot reach us directly. Precision measurements of solar neutrinos can help us monitor the nuclear reactions taking place inside the Sun, and thus directly probe the solar core. Experiments like Hyper-K and DUNE are sensitive also to supernova neutrinos. Detection of these neutrinos would lead to a deeper understanding of the stellar life cycle. Additionally, neutrino tomography of the Earth can reveal the size and composition of the core of the Earth.

5. Laser Plasma Science

This white paper describes the roadmap for studies and applications of multi-petawatt laser–matter interactions in the TIFR Hyderabad campus. Followings are the key areas based on which the Vision for extreme field science has been prepared.

Developing the design and manufacturing capabilities for making next generation high-repetition rate Multi-PW lasers. The Petawatt lasers have revolutionized the field of high-energy-density science, compact particle accelerators and MeV photon sources. However, for any practical applications, a fundamental transformation is required in increasing the average power of these laser systems, by making them operate at kHz or higher repetition rate compared to current standard of 0.1 Hz. A few possible directions will be coherently combining many fiber lasers, thin-disk lasers or bulk thulium-doped crystals. These high repetition rate lasers would improve the data collection efficiency with the help of machine learning techniques and statistical and big-data analytical approaches to explore weakest interaction physics.

Bright energetic MeV photon source driven by multi-PW lasers. As an alternative to synchrotron, "Inverse Compton Scattering (ICS)" can be a mechanism of generating bright photon beam by scattering of high-energy electrons with low-energy photons. In the traditional collider scheme of ICS, the electron beam comes from LINAC accelerator, and gets scattered from a laser beam. However, we are proposing a more compact and ultra-short version by opting for an all-optically-driven high-energy source of X-rays where a 1.5 eV NIR photon beam will scatter from a GeV electron beam, and produces MeV peak energy photon beam. The generated ICS photon beam can have divergence of ~ 10 mrad, source size of few µm scale and peak brightness can be 10^{19} photons s^{-1} mm^{-2} $mrad^{-2}$ (in 0.1% BW).

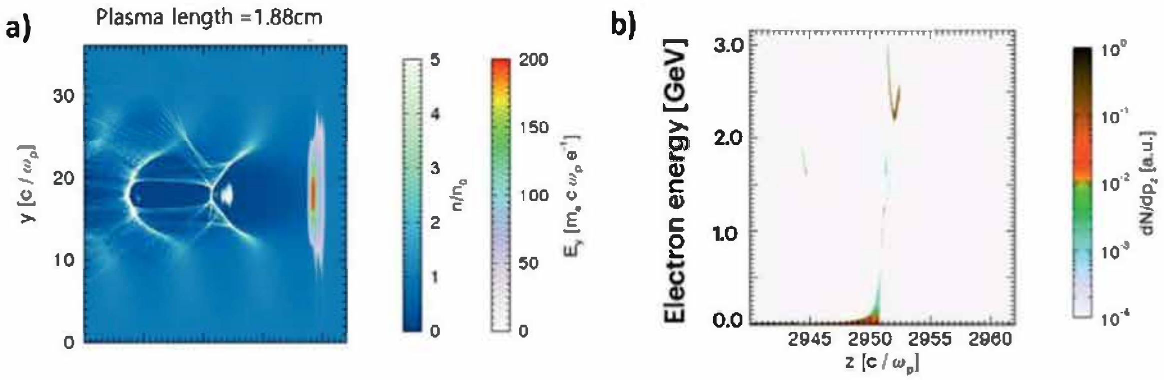
Laser based exploration of Strong-Field QED (SF-QED). The interaction of extreme lasers field with electrons, positrons, and photons may lead to a number of SF-QED effects including vacuum "breakdown" and polarization, light by light scattering, vacuum birefringence 4-wave mixing, high harmonics generation from vacuum, and EM cascades of different types. The multi-Petawatt laser will be used to explore new frontiers of converting a large part of the laser energy into electron-positron pairs, and consequently facilitate the generation of dense neutral gamma-electron-positron plasmas. This would enable access to a new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics.

Gamma ray beam for Nuclear Photonics. The availability of high spectral brilliance laser Compton sources opens a new possibility of basic research in nuclear physics, also known as "Nuclear Photonics". The few prominent areas to explore would be electromagnetic dipole response of nuclei with nuclear resonance fluorescence (NRF), heavy elements synthesis in the Universe and photo-fission phenomena.

5.1 Science/technology/societal goals

Development of ultra-compact, multi-Petawatt laser driven particle accelerators for fundamental discovery science and practical applications:

In 1979, T. Tajima and J. M. Dawson, proposed the theoretical idea of laser wake-field acceleration (LWFA) where a plasma medium can be used to transform laser pulse energy into the kinetic energy of accelerated electrons. The LWFA can operate at plasma wavelength typically around 10 to 100 μm, which is several orders of magnitude shorter than the typical RF period used in conventional accelerators. Similarly, the strength of the electric field can reach 100 GV/m, three orders of magnitude greater than with conventional technology. These features allow the electron beam to reach the same particle energy, in a distance three orders of magnitude shorter than their conventional counterparts. The current Petawatt laser pulses in the relativistic regime can excite plasma waves, which, in turn, can accelerate the electrons to the GeV energy range within a length scale of few centimetres. This can serve as the basis for a compact electron accelerator and future particle colliders.

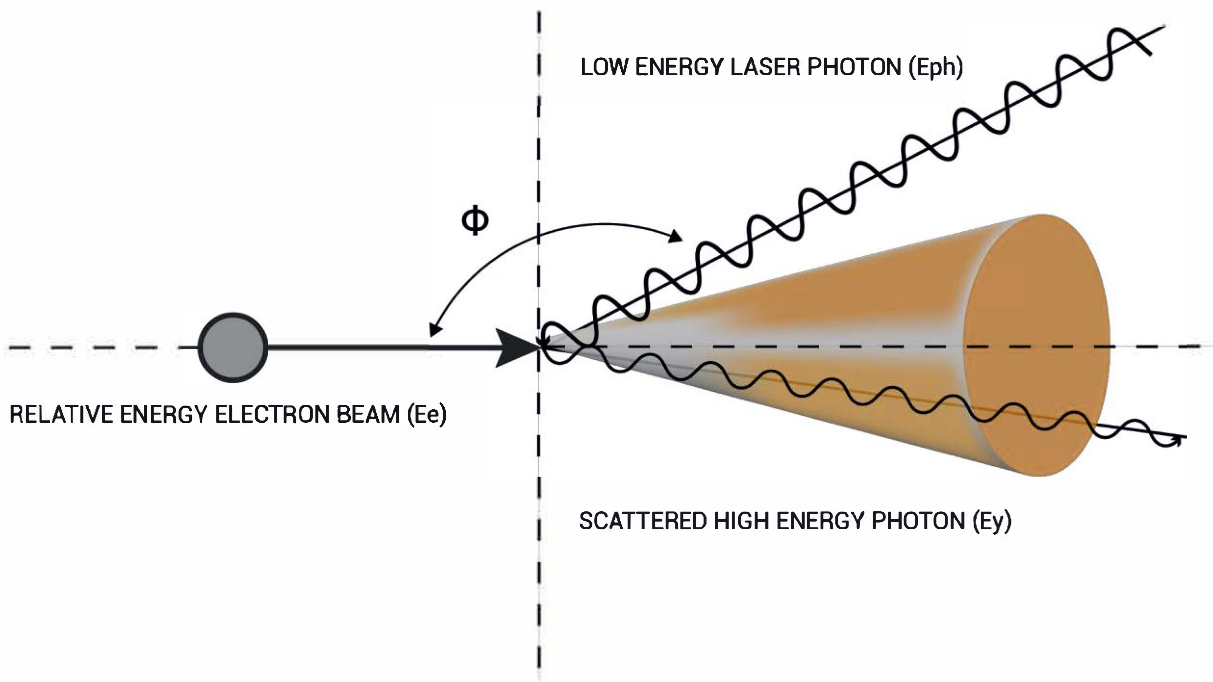


Relativistic intense laser drives a nonlinear plasma wake in an under-dense medium (a) The quasi-static electric field created in the wake-field bubble traps the electron (b) Accelerates them to 3.0 GeV (Simulations: Vishwa Bandhu (VIT, India) & Osiris 3.0)

From the application perspective, the secondary sources, produced by GeV-class electrons from LWFA, can span the broad electromagnetic spectrum (from THz to gamma rays)). These photon sources have relevance in medical science, high-energy-density and material sciences, and national security. Processes including betatron emission, Thomson/Compton scattering, bremsstrahlung, free-electron laser generation, and coherent transition/THz radiation are all outcomes of LWFA providing near-term applications. A particularly attractive feature of LWFA is the intrinsic synchronization between the drive laser beam, the generated particle bunch, and any secondary radiation. High-energy-density science and other areas of plasma physics need but do not have routine access to advanced photon probes that could offer greater resolution for precision in the spectral, temporal, and spatial domains.

Laser based Inverse Compton scattering source:

Ever since the discovery of X-rays over a century ago, the high-energy photon sources have become an indispensable tool in fundamental science, medical imaging, and non-destructive testing of high-opacity objects in industry. The broad applicability of this source has been a continuous drive for seeking novel ways of X-ray generation methods, and the field is still looking for compact, bright high-energy X-ray and gamma-ray radiation sources delivering femtosecond pulses with μm scale spatial resolution. One of the methods of generating bright photon beam is via Synchrotron radiation where a high-energy charged particles follows a curved trajectory. Within India, Department of Atomic Energy (DAE) currently runs two Synchrotron facility located in RRCAT, Indore. The first one is Indus-1, an electron storage ring of 450 MeV for VUV radiation source and another one is Indus-2, a 2.5 GeV electron storage ring for X-ray radiation.



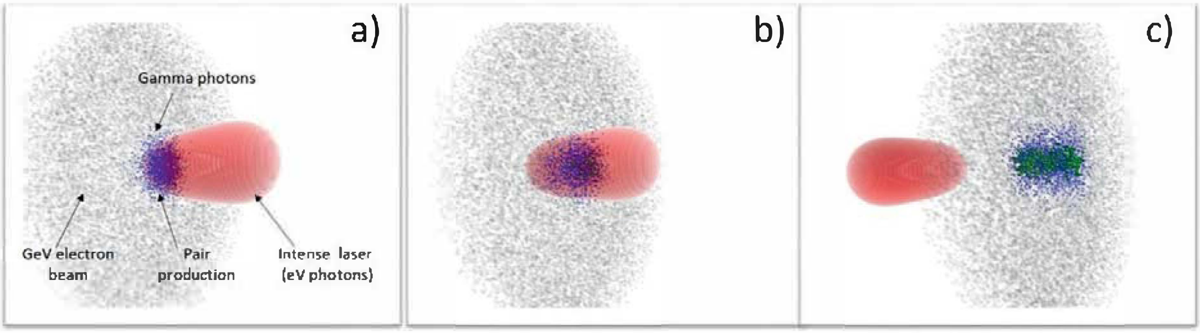
Geometry of inverse Compton scattering between relativistic electron and low energy photon.

Besides synchrotron, "Inverse Compton Scattering (ICS)" can be thought of another mechanism of generating bright photon beam by scattering of high-energy electrons with low-energy photons. In the context of astrophysical scenario this was first investigated as a process by which cosmic-ray particles such as electrons and protons would lose energy during their passage through the galaxy. The Compton sources usually have large spatial foot-print (>100 m) as they are driven by rely on large conventional electron accelerators. However, in contrast to the radio-frequency (RF) cavity, the accelerators can be made more compact and yet generate bright X-rays by laser-Wakefield electron accelerator (LWFA) scheme, which can accelerate electrons to GeV energy in a distance of only a few centimetres.

X-ray free electron laser (XFEL):

X-ray free electron lasers (XFELs), an intense coherent radiation source of sub-angstrom wavelength are indispensable tool to probe ultrafast and ultra-small phenomena across STEM fields. The conventional XFEL facilities in operation, require kilometre-scale radio-frequency electron accelerators, which limits their availability due to size and expense. On the contrary, laser wake-field accelerators can provide accelerating gradients three orders of magnitude higher than those of RF accelerators, and therefore are regarded as a candidate for compact XFEL. Along this direction a proof-of-principle (W. Wang et al, Nature, 595, 516 (2021)) experimental demonstration has been shown where the amplified undulator radiation centred at 27 nm was generated from 490 MeV energy LWFA electrons. Furthermore, the magnetic undulator can also be replaced by electromagnetic fields of a laser pulse, which reduces the undulator period to the laser wavelength and consequently shrinks the overall size of the FEL. These all-optical scheme for FEL uses traveling-wave Thomson Scattering, where the electron-laser overlap by passing the electron beam at angle to a laser pulse with a compensating phase-front tilt. Furthermore, an immediate challenge for LWFA driven XFELs is increasing the repetition rate to match with the conventional facilities. This bottleneck has to be resolve by developing high-repetition rate lasers.

Laser based exploration of Strong-field QED (SF-QED):



Electron-positron pair production in multi-GeV electron beam collision with an ultra-intense short laser pulse. The grey colour represents the energetic electron beam. During the head-on collision between the electron beam (gray) and laser pulse (red), due to the strong-field QED effects, gamma beam (in blue) and electron-positron pairs (in green) are generated (Simulations from: Vishwa Bandhu (VIT, India) and Osiris 3.0).

On a single particle level, the classical electrodynamics and quantum electrodynamics (QED) are one of the best verified theories so far. However, interaction of electrons, positrons, and photons in the presence of strong electromagnetic fields, are not yet well understood. As the fields strength approach or exceed the QED critical field strength (E_{crit}= 1.3 × 10^{18} V/m or B_{crit} = 4.4 × 10^{9} T), the interactions become highly nonlinear. Using most powerful lasers, the highest electric field achieved so far are several orders of magnitude lower than the E_{crit}. However, as the electric field is not a Lorentz invariant, these subcritical electric field strengths may be boosted to the E_{crit} and beyond while going in the rest frame of an ultra-relativistic particle. Therefore, SF-QED processes such as multi-photon Breit-Wheeler electron-positron pair production or multi-photon Compton emission of photons can be realize at much lower field strengths than E_{crit}. The interaction of lasers with electrons, positrons, and photons, whether they act as single particles or plasma constituents, may lead to a number of SF-QED effects including vacuum "breakdown" and polarization, light by light scattering, vacuum birefringence 4-wave mixing, high harmonics generation from vacuum, and EM cascades of different types. The multi-Petawatt laser systems will open up the new frontiers of converting a large part of the laser energy into electron-positron pairs, and consequently facilitate the generation of dense neutral gamma-electron-positron plasmas. This would enable access to a new regime dominated by the interplay between strong-field QED effects and collective plasma dynamics.

Multi-PW Laser driven Gamma ray beam for Nuclear Photonics:

The high spectral brilliance of all optical, multi-PW laser driven MeV Compton sources makes an attractive tool for pursuing basic research in nuclear physics. Intense lasers driven bright beams of energetic photons or particles and nuclear reactions can be used to probe samples, provide quantitative, isotopic composition of large objects, verify the security of cargo, assess the integrity of bridges, buildings, turbines and heal deep tumours in patients. Further a more relevant application to be pursued will be Laser-induced nuclear transmutation and radioactive clean-up. To handle the radioactive waste, common transmutation strategy involves bombardment with neutrons from a reactor or from particle accelerators. Off late, laser-driven high-brightness gamma generation for photo-transmutation has also been suggested as an alternative way. One of the first demonstration being the long-lived I^{129} ($t_{1/2}$ = 15.7 million years) was photo-transmuted to I^{128} ($t_{1/2}$ = 25 min).

The proposed 25-year programme will be divided into three Phases. Phase-I, lasting 5 years, will be dedicated for establishing 1PW laser driven GeV class, mono-energetic, highly collimated electron beam. The Phase-II, lasting 10 years would be focus towards generation, detection and application with MeV scale bright X-ray and Gamma Photon beam. In-parallel, the Phase-II would also have equal contribution invested for development of indigenous high-repetition rate multi-PW lasers. The final Phase-III, spanning over 10 years would focus on delivering industry standard prototypes. Societal benefits span a wide range of applications from national security to diagnostic and therapeutic medicine, and will enable new technologies for the energy security of mankind. Given the scale and scope of these programmes, the task and expertise would be distributed in a collaboration manner with Indian Industry/ MSMEs/ Startups and Academia.

6. Chemical Sciences

6.1 ENERGY and ENVIRONMENT: *Innovations for a Sustainable Future Against Climate Change*

This ambitious goal to achieve net zero by 2070 necessitates the development of not only innovative materials capable of solar energy harvesting, green hydrogen production through watersplitting, and the conversion of CO_2 into valuable products, all using sustainable and efficient all-in-one materials, but also in principle, to take a holistic approach as to how to take these new materials and utilize them effectively in devices at a viable technological scale and do so at a relatively faster pace than what is currently being practised. Addressing the urgent challenge of climate change necessitates significant advancements in chemical science, aiming to create innovative molecules to materials and technologies capable of reducing greenhouse gas emissions, promoting renewable energy sources, and enhancing sustainability across diverse sectors.

Fundamental Breakthroughs and Discovery of Novel Molecules and Materials: Realizing this vision necessitates a comprehensive overhaul not only the goals and objectives, but also of our scientific methodologies and the development of adequate infrastructure. It is noteworthy that most of the groundbreaking achievements in materials science have originated outside India, including the development of aerogels, shape memory alloys, quantum dots, nanocrystals, high-temperature superconductors, metal- and covalent organic frameworks (MOFs, COFs), carbon nanotubes, perovskite solar cells, graphene, two-dimensional (2D) materials beyond graphene like MXenes, quantum materials for computing qubits like nitrogen-vacancy centres, and flexible and stretchable electronics. Even none of the catalysts currently used in industrial processes have been discovered in India.

To realize the aforementioned objectives, the vision, is to establish an Institute of Scientific Excellence dedicated to materials and solar energy, as the National Centre of Solar Energy (NCSE).

Mirroring the success of institutions like the National Centre for Biological Sciences (NCBS), the National Centre for Radio Astrophysics (NCRA), this centre would serve as a focal point for solar energy research, uniting experts from various fields under a single mission to harness the power of the sun for India's energy needs.

The proposed NCRA signifies the strategic importance of solar energy technologies for India's sustainable development. By leveraging advancements in chemical science to improve solar energy harvesting and utilization, this centre will play a crucial role in propelling India towards a sustainable and energy-secure future.

The complexity of materials science and solar energy research necessitates the collaboration of synthetic chemists, spectroscopists, theorists, and chemical engineers. By bringing together the best minds in these fields, the centre will foster an environment of interdisciplinary collaborative excellence. The proposed national centre will serve as a focal point for conducting high-quality fundamental and translational research in solar energy, materials and CO_2 capture-conversion, aimed at combating climate change.

The centre can concentrate its efforts on various research topics, including: *All-in-One Solar Harvesting and Catalytic Transformation Materials; Advanced Energy Storage Materials; Next-Generation Solar Photovoltaics; Biodegradable and Recyclable Plastics; Water Purification and Desalination Materials*.

By focusing on these research areas, the centre would be able to contribute significantly to advancing sustainable energy technologies and addressing the challenges posed by climate change. Additionally, collaboration with academia, industry, and international partners can enhance the centre's impact and foster innovation in this crucial field. NCSE is poised to deliver a multitude benefits, including:

- Cutting-edge Research: NCSE will serve as a hub for cutting-edge research in chemical and materials science and solar energy technology, fostering innovation and pushing the boundaries of scientific knowledge.

- Technology Incubation Centre: The outcome of basic research must help in the developmentof commercial products and technology to help resolve societal challenges. In order to translate such potential into a reality, technology parks/incubators geographically embedded inside the campus need to be built. The policies for such a Centre will be based along with the more "open" consultancy and start-up guidelines to fulfil the "Invent-in-India" and "Make-in-India" dreams.

- Skill Development: By offering specialized training programs and academic courses, NCSE will nurture the next generation of scientists and engineers, equipping them with the skills and expertise needed to excel in the fields of materials and solar energy.

- Industry Partnerships: Through strategic partnerships with industry stakeholders, NCSE will facilitate technology transfer and commercialization of research outcomes, driving economic growth and fostering a vibrant ecosystem for solar energy innovation.

This proposal is a strategic vision for leveraging material innovations to combat climate change, emphasizing the need for ground-breaking research, state-of-the-art infrastructure, and collaborative excellence.

6.2 Beyond Exascale: Leading the Nation Towards Higher Performance Computing

Research in the Chemical Sciences across DAE units aims to further our fundamental understanding of how nature works at electronic and molecular scales and apply such understanding to tackle problems of societal relevance such as the development of clean/sustainable energy solutions and the diagnosis/treatment of diseases. Computational research in the Chemical Sciences is used in both deductive and predictive fashions. Computational modelsare used to rationalize experimental observations and develop design principles for molecular design. The design of molecules which can self-assemble into desired architectures, absorb solar energy efficiently, convert light excitations into charge flow, and electronically couple to inorganic substrates is a requirement in the quest for clean sustainable energy solutions. Computational drug design, on the other hand, aims to design molecules which can shut down orturn on the activity of specific proteins/enzymes while avoiding non-specific interactions with therest of the cellular machinery. Researchers in the chemical sciences at DAE units are today well poised to spearhead both fundamental and applied aspects of Chemical Science research. However,development of a globally competitive high-performance computational infrastructure is asignificant milestone in this effort. DAE has an opportunity to develop a unique andglobally competitive computational facility which will catapult the nation into the forefront of computing technologies.

We envision a DAE-wide computing centre which possesses state-of-art commercial hardware tech in terms CPUs, GPUs, field programmable gate arrays (FPGAs), and Tensor Processing Units (TPUs) along with cutting-edge software technology which is AI/ML enabled. A unique aspect of the centre in enabling the indigenous development and deployment of emerging technology to provide an edge over global competition. Researchers in the chemical sciences are well suited to lead these efforts with emerging technologies with specialized expertise in developing molecular qubits based on electron-paramagnetic/spin resonance spectroscopy, molecular electronic integrated circuits with components such as resistors, diodes, switches, and transistors, and quantum computing algorithms tailored to specific applications in quantum chemistry. Some of this expertise is already present within the DAE system and can be augmented by focused hiring in aligned areas. This facility will serve as a hub for research and applications of cutting-edge hardware and software technologies, providing us with a globally competitive edge in delivering impactful research:

- Artificial intelligence and machine learning tools: This has taken the world by storm over the last decade. With continuous theoretical developments in the field, we are at a crossroads where the applications of this field can be varied and limited only by our imagination. In a completely different application, deep neural networks are now being used to successfully understand atomic interactions. Fitting and predicting the interactions between atoms in a complex chemical system at high levels of accuracy are being made possible through frameworks like DeepMD. This enables for the first time the prospect of simulating reactive chemistry at an atomistic level for large systems.

- Quantum Computing: The vision is to lead research and development efforts in quantum algorithms, hardware, and software frameworks to unlock the transformative potential of quantum technologies. Quantum technologies can influence areas of chemistry such as sensing and computing. While fundamental breakthroughs have occurred in areas of superconducting qubits, it is unclear how these will be scaled up. Researchers in the chemical sciences at DAE units can provide a bottom-up approach towards the scalable design of qubits.

- Molecular Electronics for Next-Gen Hardware: A major challenge in this field is to fit in the molecular componentsto create an integrated circuit which actually performs useful computations. TIFR chemists have for the first time translated the concept of an electronic breadboard to the molecular scale. The researchers have shown a way to combine five molecular circuits within the same scaffold. At present, it is imperative to generate a technological setting wherein researchers can screen molecular scaffold libraries and test them for their computing capabilities and integrate molecular electronics into the existing computing hardware infrastructure.

- Long-Time Scale Simulations: Researchers in the chemical sciences at TIFR have expertise in developing high-performance algorithms for studying the motion of quantum particles like electrons and excitons, and for understanding the motion of large biomolecules like proteins and DNA. A fundamental understanding of these motions and subsequent structural changes iscritical for designing energy-harvesting molecules & materials and discovering chemical, biological, as well as opto-electronic properties of biomolecules

  The DAE Centre would thus fast-forward millisecond simulation for molecular dynamics of biomolecules and nano-second ab initio simulations of electronic motions and energy transfer. The Centre would enable much-needed virtual solutions to nations' health, energy and technology needs.

7. Materials for Fundamental Science Energy and Environment

India's materials research initiatives are strategically aligned with the Sustainable Development Goals (SDGs), playing a crucial role in driving the nation's economic growth and environmental sustainability. By fostering collaborations across academic institutions, government agencies, and industrial sectors, India is poised to make significant strides in key priority areas. A major focus of this research is expanding renewable energy capacity to 450 GW by 2030, a vital step towards achieving net-zero carbon emissions by 2070. This involves developing advanced materials for solar cells, wind turbines, and energy storage systems to enhance efficiency and affordability. Additionally, India aims to reduce emissions by 45% by 2030 through the transition to low-carbon technologies and the adoption of hydrogen technologies. The country also targets a semiconductor revenue of $300 billion by 2026 and a quantum technology industry worth $90 billion by 2030. Materials research is essential for developing cutting-edge semiconductors and quantum devices, which underpin advancements in computing, communication, and defense.

Advancing Sustainable Development Goals through innovative material research in India

Moreover, materials research is vital for creating sustainable infrastructure and manufacturing processes. This includes designing lightweight, durable materials for construction, developing smart cities with advanced materials for energy efficiency and waste management, and creating eco-friendly materials for manufacturing. To achieve these ambitious goals, India must invest in its R&D workforce, streamline policies, and foster collaborations to establish a materials-based economy. By enhancing individual-centric research with large-scale material networks aligned with technology deliverables, India can drive innovation and economic growth.

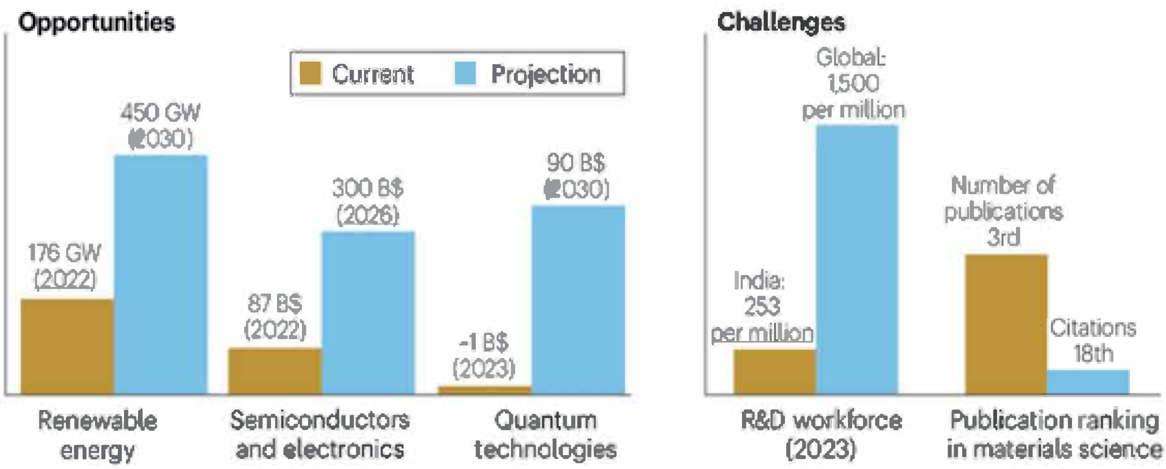
The critical role of materials research in India's economic development underscores the need for strategic partnerships and a cohesive ecosystem to bridge the gap between academic, government, and industrial sectors. Streamlined and transparent policies in areas such as equipment purchase, project funding, and engagement with overseas experts are crucial for maximizing research efficiency and supporting India's goal of becoming the third-largest economy globally.

Transforming the nation’s future through materials research focuses on two key objectives: exploring abundant materials for sustainable development; and promoting a circular economy.

According to Nature Review Materials 2024, the power generated from renewable energy sources is expected to increase from 176 GW to 450 GW by 2030, while semiconductor and electronics revenue is projected to rise from $87 billion in 2022 to $300 billion by 2026. In the realm of quantum technologies, revenue is anticipated to grow from less than $1 billion in 2023 to $90 billion by 2030. The vision for 2047 in materials science emphasizes the exploration of the country's energy resources, including nuclear materials, multifunctional materials, and materials for healthcare and sustainable living. Achieving these objectives requires a deep understanding of materials, extensive characterization, application, and benchmarking. India can unlock its full potential and contribute to a more sustainable future for all.

The proposed energy materials research theme aims to accelerate developing, testing, and deploying advanced materials for various energy applications, supporting India's transition towards a sustainable, low-carbon future. The key elements of this research theme include:

Semiconductor Fabrication Hub: Establishing a dedicated semiconductor fabrication hub equipped with state-of-the-art device and interface engineering facilities is critical to advancing the development of next-generation solar cell technologies. This hub will focus on enhancing the entire solar cell production process, including crystal growth, wafer processing, thin-film deposition, and device fabrication. By concentrating expertise in these areas, the hub will facilitate the innovation of more efficient solar cells, which are essential for meeting the growing global demand for renewable energy.

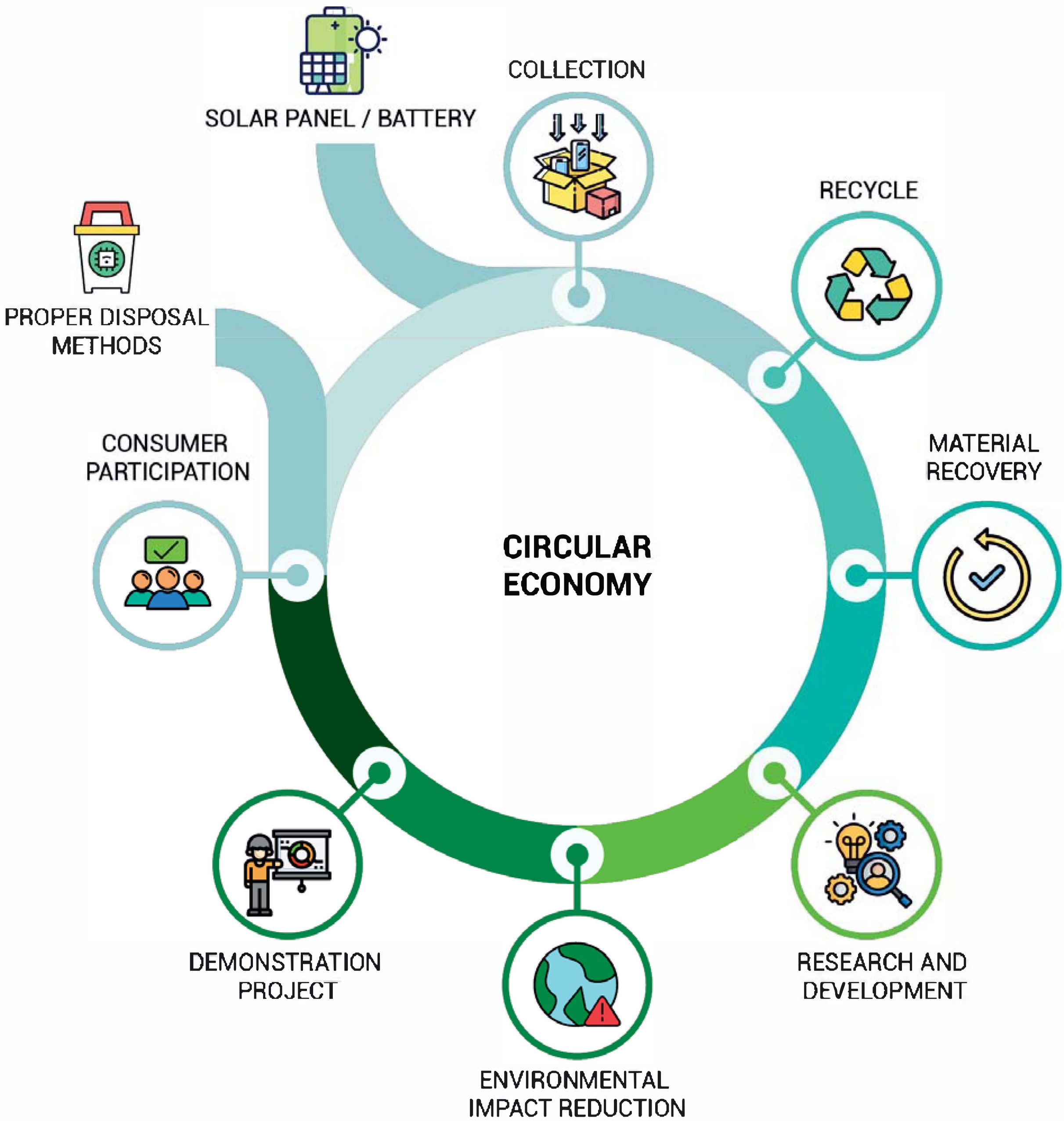


Opportunities and Challenges in the semiconductor manufacturing and quantum sectors in India. Data from SJR - International Science Ranking and the UNESCO science report.

The integration of advanced technologies and methodologies will allow for the production of solar cells with improved efficiency and lower production costs, ultimately contributing to a more sustainable energy future. Central to the hub's operations will be the development of cutting-edge techniques in crystal growth to create large, defect-free crystals for solar cell fabrication. Wafer processing will involve advanced methods like plasma etching and chemical vapor deposition (CVD) to ensure optimal surface quality and electrical properties. Thin-film deposition techniques, including sputtering and atomic layer deposition, will be utilized to create innovative solar cell architectures that enhance light absorption and conversion efficiency. Furthermore, the hub will focus on device fabrication processes that integrate these advanced materials into functional solar cells, ensuring that the final products meet industry standards for performance and reliability. To support this initiative, collaboration with academic institutions, research organizations, and industry leaders will be essential, leveraging collective expertise and resources to drive innovation and accelerate the commercialization of new solar technologies. As the solar energy market expands, the semiconductor fabrication hub will play a pivotal role in positioning the region as a leader in solar cell technology, contributing significantly to global efforts in renewable energy production and sustainability.

Incubation Centres: Creation of incubation centres to nurture the translation of research outcomes into practical applications, fostering collaborations between academia, research institutions, and industry. These centres will help bridge the gap between laboratory prototypes and commercially viable products.

Recycling Program: The initiation of a dedicated program for recycling batteries and solar cells is crucial to address the growing need for sustainable end-of-life management of these components. As the use of batteries, particularly lithium-ion types, and solar panels increases, managing their disposal becomes a significant challenge. This program aims to develop innovative technologies and processes for the efficient recovery and reuse of valuable materials from spent batteries and solar panels, including metals like lithium, cobalt, and nickel, as well as critical materials from solar cells, thereby reducing environmental impact. To implement this program effectively, a comprehensive approach will involve research, development, and demonstration projects.



Socio-economic depiction of circular and Make-use-dispose economy

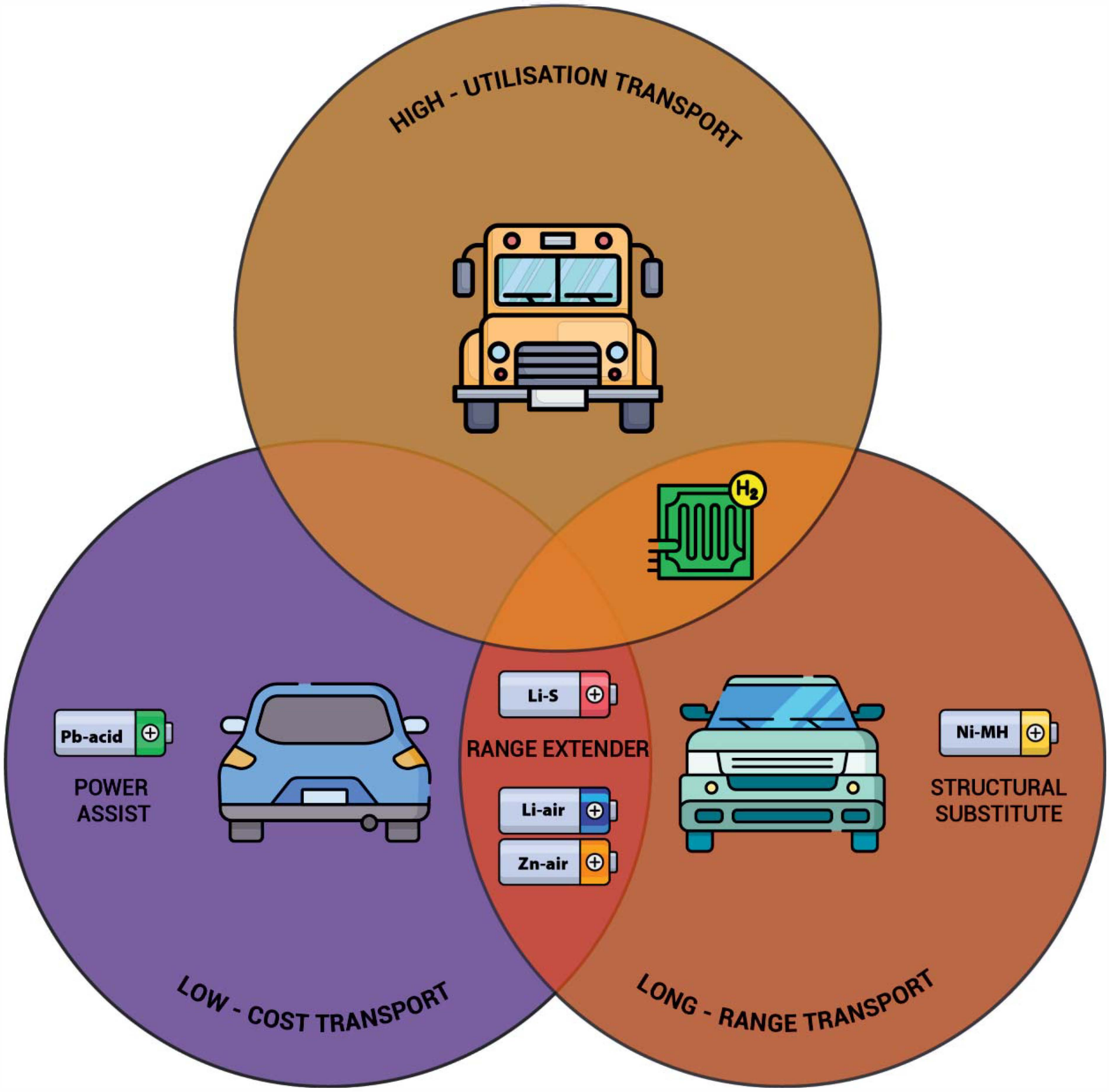
Funding will support initiatives that promote designing batteries and solar cells with recycling in mind, ensuring easier dismantling and material recovery. Strategies will also be developed to enhance consumer participation in recycling programs, addressing barriers to recycling and raising awareness about proper disposal methods. The program will prioritize integrating recycled materials back into production, fostering a circular economy that minimizes waste and maximizes resource efficiency. Collaborations with academic institutions, research agencies, and industry stakeholders will help create a robust infrastructure for recycling, including collection points and processing plants. Ultimately, this initiative represents a significant step toward sustainable management of battery and solar cell waste, contributing to a greener future and supporting global climate change efforts.

7.1 Advanced Energy Storage Systems

Development of high-energy and high-power density electrochemical batteries, including novel concepts like solar batteries and nuclear batteries, high-power density supercapacitors, and waste heat management systems. The focus will be on indigenous materials-based solutions, leveraging the expertise across DAE institutions.

Rechargeable electrochemical energy storage, particularly batteries, stands out as a highly efficient method for storing electric energy, a crucial and versatile form of energy, in the form of chemical energy. Currently, lithium-ion batteries (LIBs) dominate the electronics market; however, their limited gravimetric energy density (~250 Whkg-1) compared to fossil fuels like gasoline (~13000 Whkg-1) restricts their use in high-energy applications such as electric vehicles (EVs). To address this, the development of alternative battery technologies, including metal-air batteries (MABs) and fuel cells, is essential. MABs, leveraging gas as an electrode component, offer ultra-high energy densities comparable to gasoline, making them promising for long-range EVs.

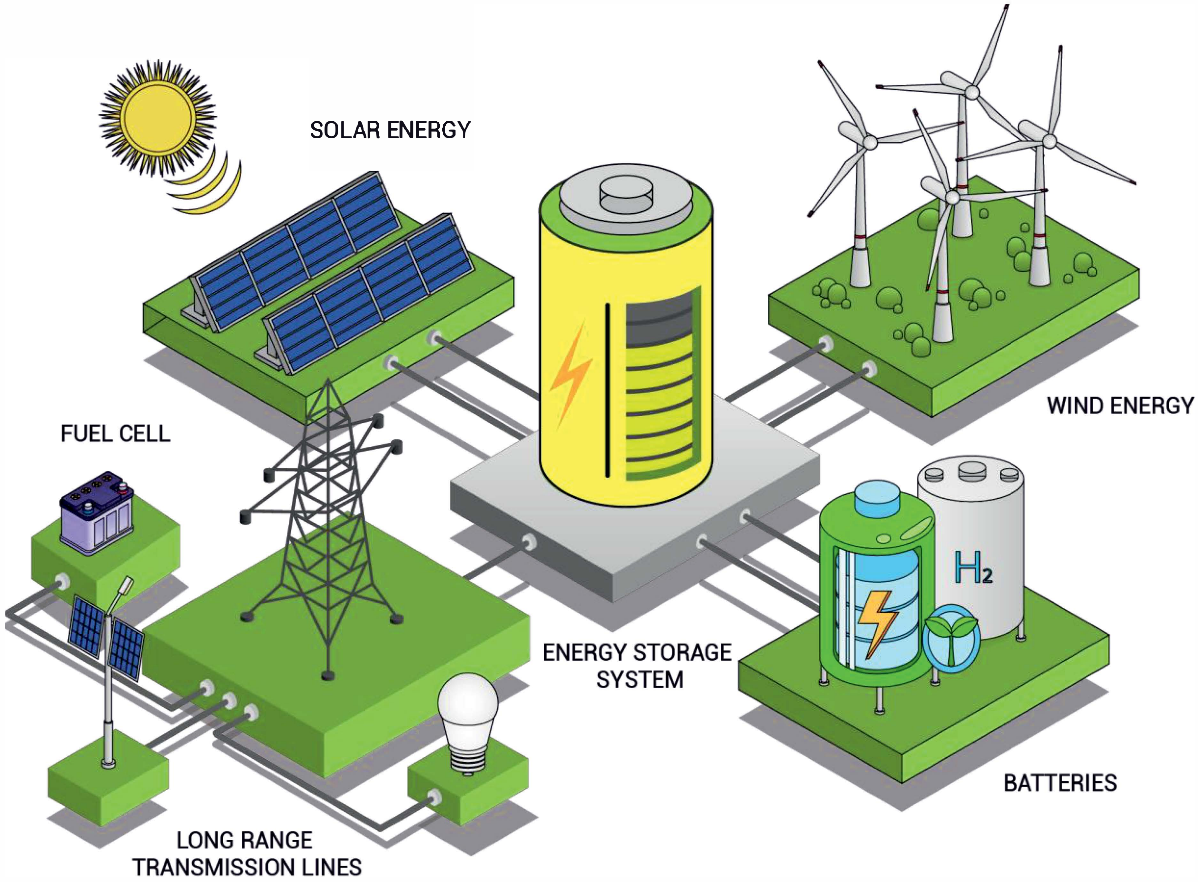
Overcoming challenges like self-discharge, extended cyclability, and suppressing parasitic reactions is crucial for successfully developing high-performance MAB systems, which also hold potential for mini-grid energy storage, replacing existing Pb acid-based systems. The proposal aims to develop a 10kWh capacity MAB (Zn-based) battery pack, highlighting the importance of integrating MABs with higher power density systems like supercapacitors for mini-grid applications, ensuring the utilization of Indigenous materials-based technologies. This comprehensive plan involves fundamental chemistry, physics, and electrical engineering studies, emphasizing collaborative efforts across different institutions to advance electrochemical battery technologies. The electrochemical battery plans encompass a range of advancements beyond lithium-ion batteries, exploring alternatives like sodium (Na), potassium (K), aluminium (Al), and others. The focus extends to developing safer, high-energy density metal batteries, particularly lithium-based systems, high-energy density metal-air batteries utilising materials like zinc (Zn), aluminium (Al), and iron (Fe), high-power density supercapacitors, fuel cell technologies, piezoelectric generator development, thermoelectric energy harvester development, and the creation of highly efficient and durable catalysts. This multifaceted approach aims to revolutionise energy storage technologies, enhancing efficiency, safety, and sustainability across various applications.



Suitability of alternative batteries and fuel cells to emerging EV markets.

Renewable Energy Harvesting: Advancement of stable and efficient semiconductor technologies for solar cells, optimisation of materials, understanding interfaces, effectively coupling harvesting and storage systems, and evaluating carbon footprints. This will involve device and interface engineering to overcome the Shockley-Queisser limit and improve the efficiency of photovoltaic technologies.

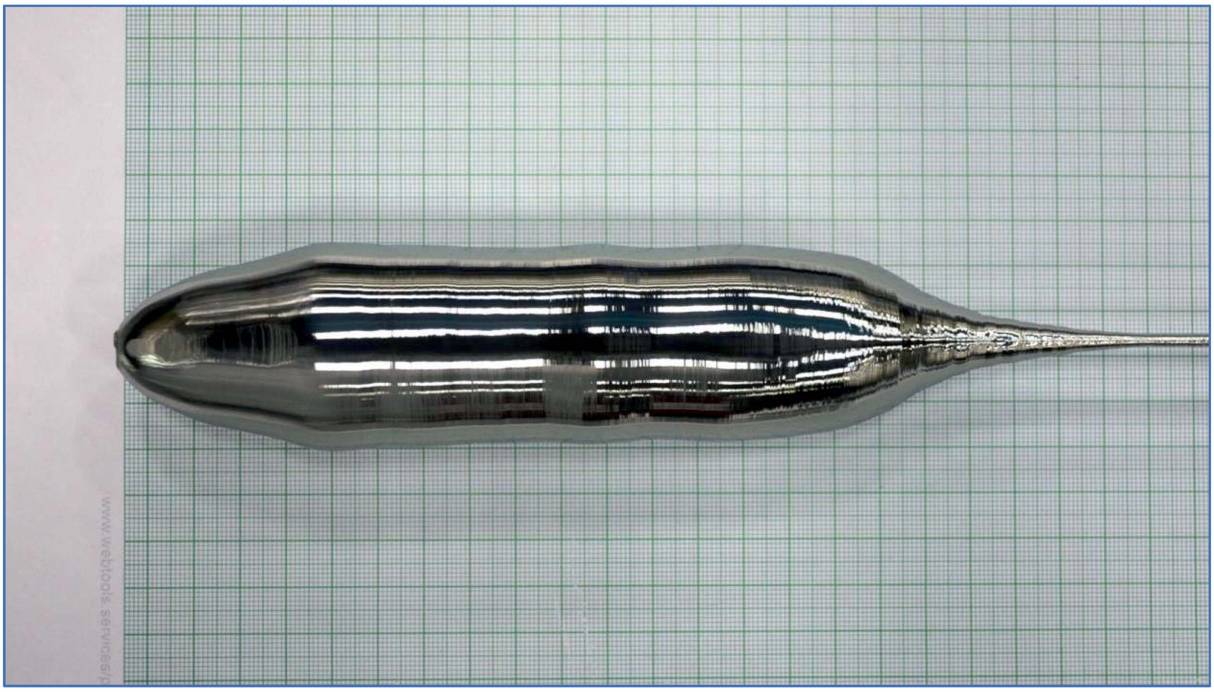
Decentralised Energy Platform: Development of a decentralised energy harvesting and storage platform to identify and implement micro- to megawatt energy storage system solutions, including waste heat management and recycling technology. The aim is to support the transition towards a distributed, sustainable energy ecosystem.



Integrated renewable-decentralized energy systems

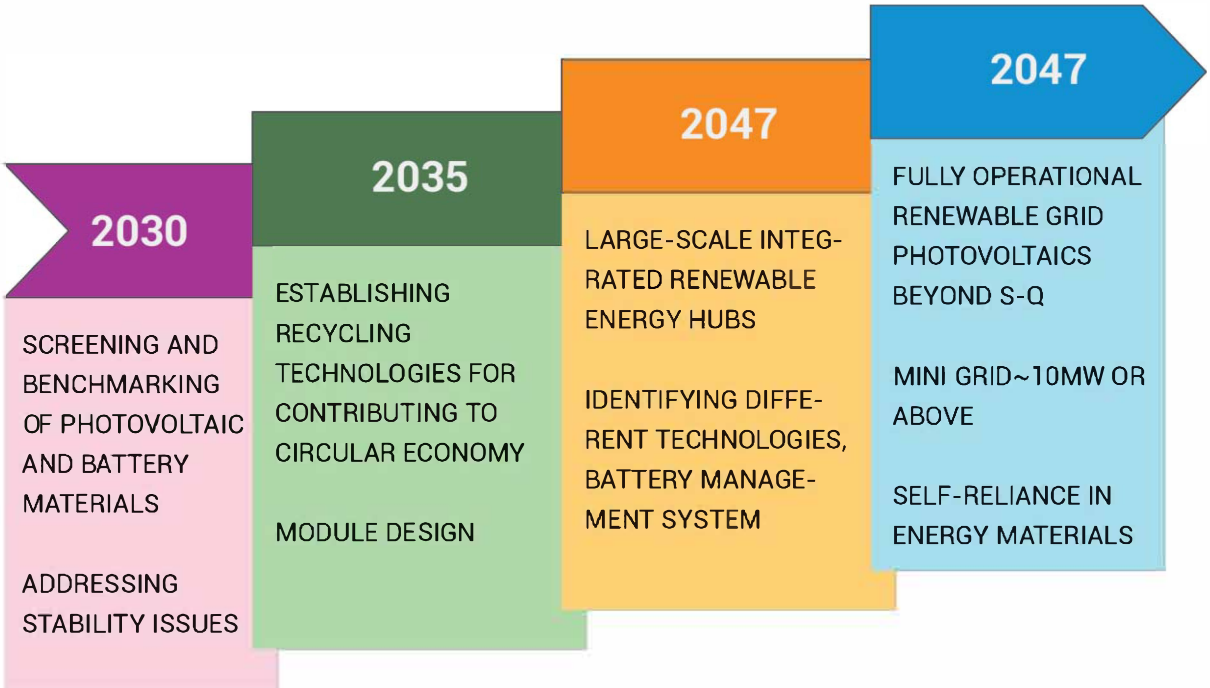
7.2 Radiation detectors:

Gamma-ray detectors are vital across various fields, such as medical imaging, nuclear physics, and environmental monitoring. Developing these detectors involves refining fabrication processes to ensure high quality consistent detector crystals. Additionally, there is significant research into semiconductor-based detectors, particularly high-purity germanium and silicon, which offer superior energy resolution but face challenges in producing large crystals. Advanced crystal growth techniques are being employed to enhance the availability of high-performance detectors for precise gamma radiation measurements. Recent advancements in gamma-ray detector technology have focused on enhancing the performance characteristics of existing materials while also exploring novel compounds. Researchers are investigating new scintillator materials that could potentially offer better light output and faster response times. For example, materials like perovskite crystals and organic scintillators are being studied for their promising properties, which could lead to improved detection capabilities in various applications.



High Purity Ge single crystal for radiation detectors developed by BARC

Additionally, hybrid detectors that combine scintillation and semiconductor technologies are being developed to leverage the strengths of both detectors, aiming to achieve higher sensitivity and better energy resolution. The applications of gamma-ray detectors are continually expanding, driven by advancements in technology and increasing demands for safety and security. In medical imaging, these detectors are crucial for improving the accuracy of diagnostic procedures such as PET scans and SPECT imaging. In the realm of nuclear security, enhanced gamma-ray detection capabilities are essential for monitoring and preventing illicit trafficking of radioactive materials. Ongoing research is expected to focus on miniaturization and integration of gamma-ray detectors into portable devices, enabling real-time monitoring and analysis in diverse environments. As the need for precise radiation detection grows, the future of gamma-ray detectors promises exciting developments that will enhance their effectiveness across multiple domains.

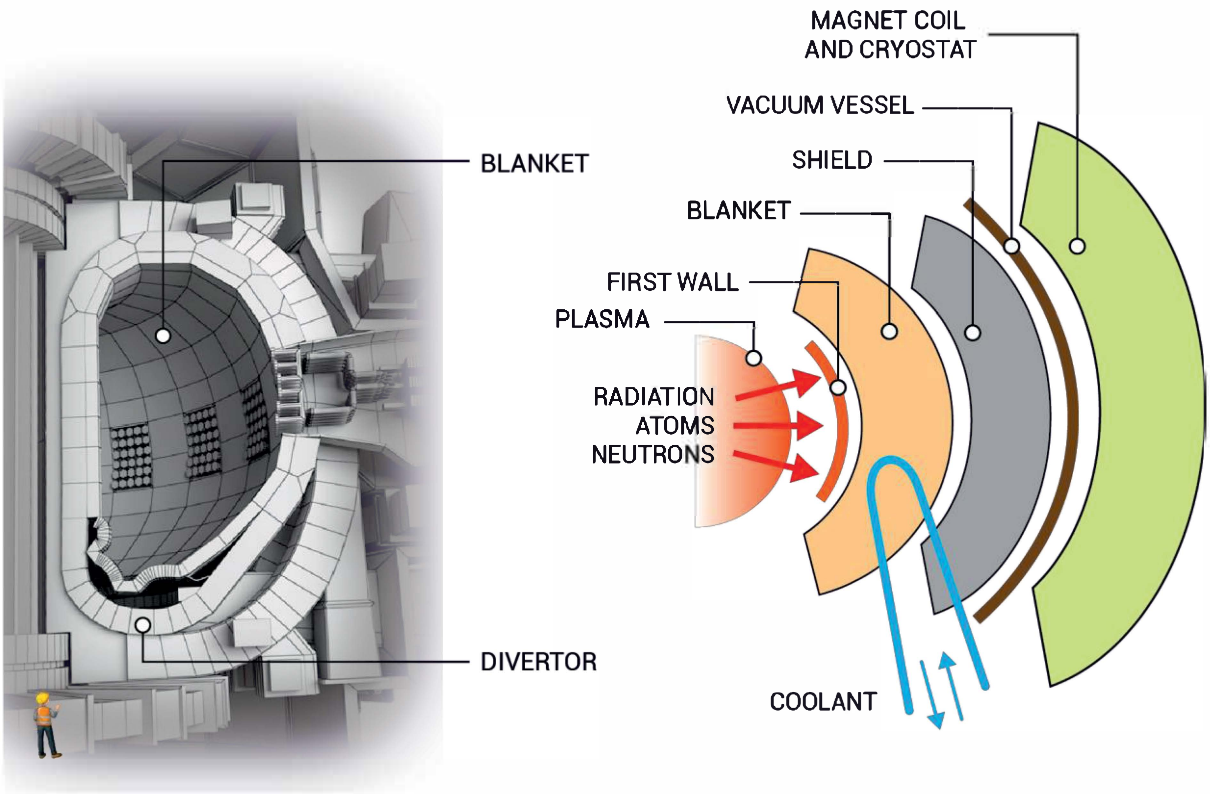


Vision for Energy Materials Research

7.3 Fusion Reactor Materials Research

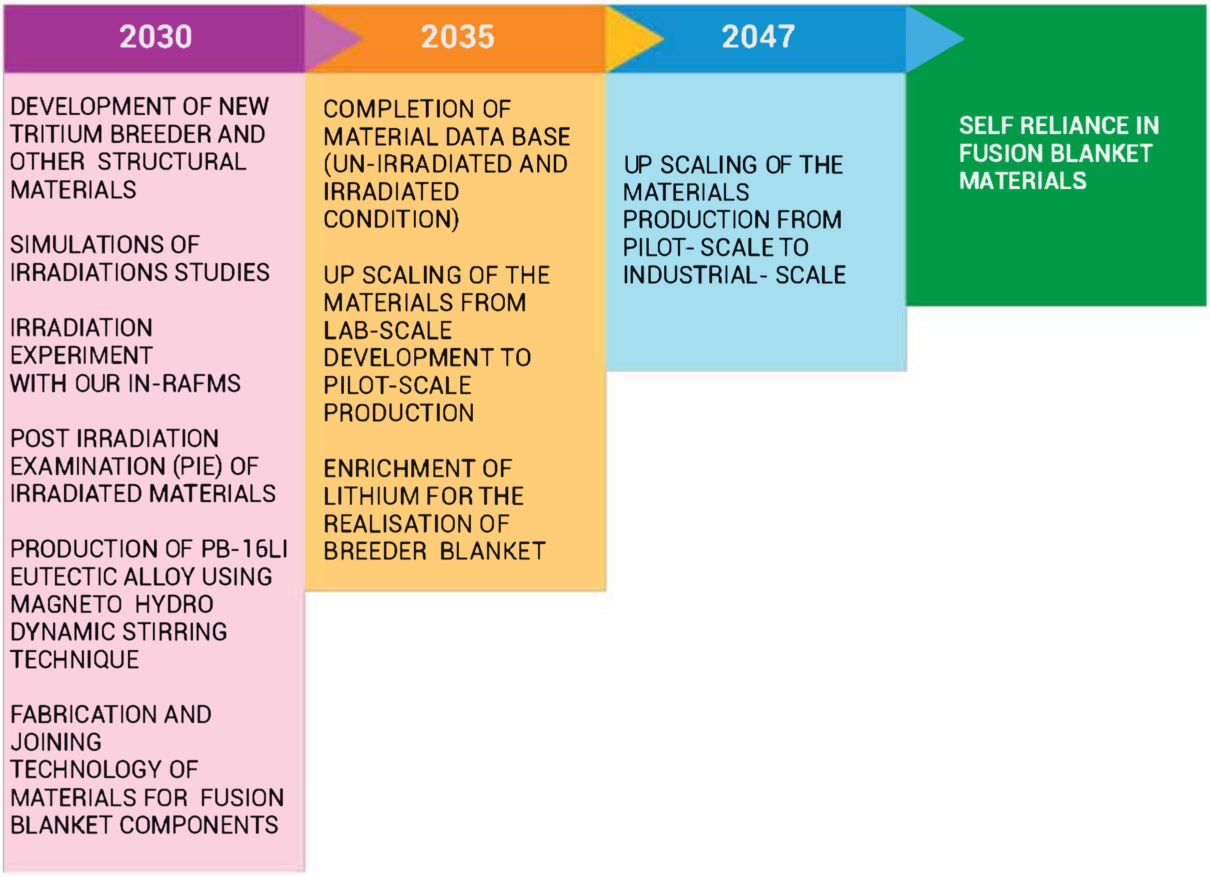
This section highlights the critical requirements for various activities to achieve readiness by 2047 for commencing the construction of a DEMO fusion reactor in India. The key focus areas include:

Fusion Blanket and Plasma Facing Materials: Development, characterization, material joining technologies, fabrication technologies, irradiation studies, post-irradiation examination studies, materials modelling, and simulations to produce large-scale materials and fusion studies, materials modelling, and simulations to produce large-scale materials and fusion reactor components. This involves expertise and facilities to study material interactions with neutrons, develop tritium breeders, neutron multipliers, tritium permeation barriers, and neutron shielding, while minimising activation and transmutation.



Schematic of the Fusion Reactor

Liquid Metal Plasma Facing Components (PFCs): Development, characterization, and testing of Liquid Metal alloys, fabrication and testing of Liquid Metal PFCs, and the establishment of experimental facilities to test these components under thermal, electromagnetic, and plasma loads.



Vision for Fusion Blanket Materials

This requires expertise and facilities for high-temperature loops, high-pressure high-temperature pumping systems, and characterization under plasma conditions.

High Power Electron Beam System: Development of a 200kW/50kV Dual Electron Beam Guns system, including dry type-high voltage transformer, low and high voltage power supplies, beam deflection system, data acquisition and control system, and software for beam scan pattern programming. This enables the simulation of high heat flux conditions on PFCs to study material behaviour and advanced PFC designs.

High Temperature Superconductor and Prototype Magnet: Activities involving HTS tape design and fabrication, quench detection and protection systems, current leads for high currents, nano-ohm resistance joints, coil winding technology, and neutron irradiation studies on relevant materials. This initiative requires raw materials, major fabrication facilities, and a skilled workforce to develop and characterize HTS tapes.

7.4 Sustainable technology for purification

Materials play a vital role in addressing global health and sustainability challenges, particularly in energy-efficient filtration, desalination processes, and water harvesting.

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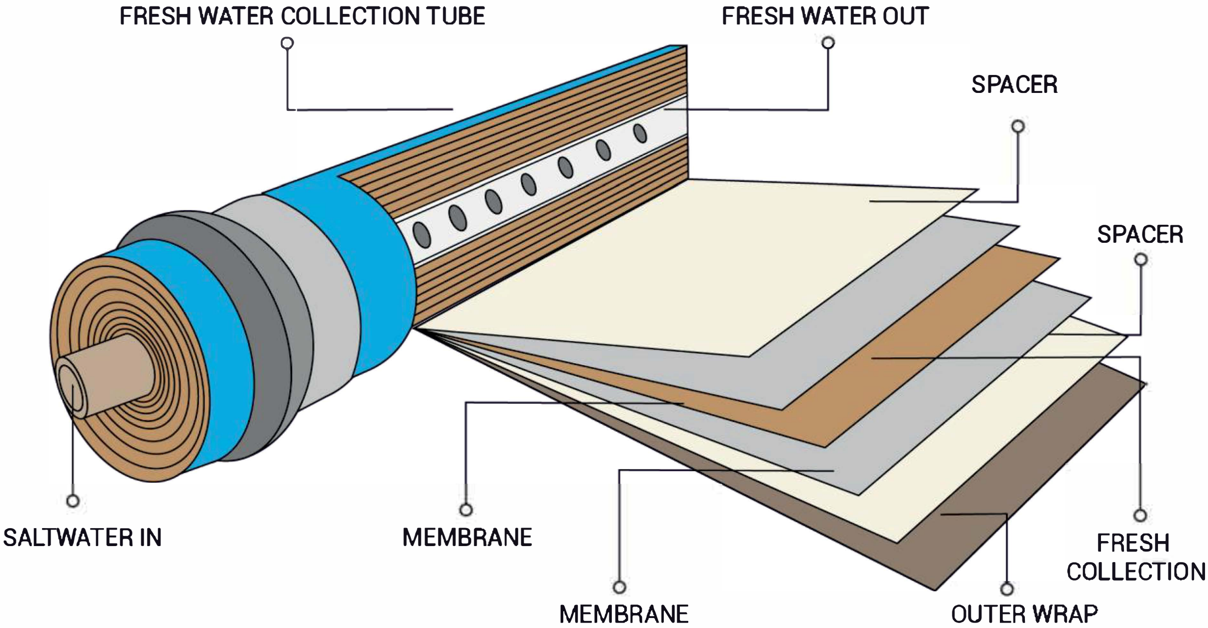


Membrane based sustainable water purification system

Energy-efficient filters are critical for removing contaminants and pollutants from air and water while minimizing energy consumption. Advanced filtration materials, such as nanoporous membranes, activated carbon, and graphene-based filters, offer high surface area and selective adsorption properties, allowing for the efficient removal of particles, gases, and organic compounds from fluids. These materials can be tailored to target specific pollutants, including fine particulate matter, volatile organic compounds (VOCs), and heavy metals, contributing to improved air and water quality in both indoor and outdoor environments.

Desalination technologies are essential for addressing water scarcity by converting seawater or brackish water into potable water. Energy-efficient desalination processes, such as reverse osmosis (RO) and membrane distillation (MD), rely on specialized membranes and materials to separate salt and other impurities from water while minimizing energy consumption. Thin-film composite membranes, forward osmosis membranes, and novel nanostructured materials enable higher water permeability and salt rejection, improving desalination efficiency and reducing energy requirements. Additionally, innovations in renewable energy integration, such as solar-powered desalination systems, further enhance the sustainability of desalination processes by reducing reliance on fossil fuels.

Water harvesting technologies capture and store rainwater or moisture from the atmosphere for various uses, including irrigation, drinking water supply, and ecosystem restoration. Porous materials, such as hydrogels, zeolites, and metal-organic frameworks (MOFs), exhibit high water absorption capacities and can be incorporated into passive or active water harvesting systems. These materials selectively adsorb water vapor from the air under ambient conditions and release it upon heating or exposure to lower humidity, enabling efficient water capture in arid and semi-arid regions. Additionally, biomimetic materials inspired by natural water collection mechanisms, such as fog-harvesting surfaces and dew condensation devices, offer innovative solutions for harvesting water from fog, dew, and humid air, contributing to sustainable water management practices worldwide.

7.5 Computational methods for Material Science

Computational methods have become an indispensable tool in materials science, as it allows for better understanding, selection, design, optimization, and integration of materials with engineering applications. We can utilise computational methods for material science by leveraging the Inorganic Crystal Structure Database (ICSD) and selecting the optimal combination from data fed into Artificial Intelligence (AI) systems. The integration of artificial intelligence (AI), especially machine learning, into computational materials science research has become a new trend, enhancing materials design, synthesis, property predictions, and accelerating materials development. The use of computational methods, such as density functional theory (DFT), molecular dynamics (MD), and phase-field methods, allows for a deeper understanding of material behaviour across different length and time scales, enabling the prediction of material properties and the optimization of synthesis processes. Additionally, the availability of powerful computing resources has facilitated the application of complex computational techniques in materials science, leading to advancements in materials design and optimization.

Utilizing advanced supercomputing capabilities and cutting-edge methodologies, the Materials Project offers accessible web-based resources containing computed data on existing and potential materials, alongside robust analysis tools aimed at stimulating the innovation and creation of novel materials. Emphasizing the critical role of strategic partnerships and a cohesive ecosystem to bridge the gap between academic, government, and industrial sectors, and to support India's goal of becoming the third largest economy globally.

Pathways for propose Material Research

In summary, the exploration and development of advanced materials for fundamental science and environmental applications are crucial in addressing the pressing challenges of energy efficiency, sustainability, and climate. Collectively, these efforts in material science not only drive technological innovation but also align with global sustainability initiatives, fostering a more resilient and environmentally friendly future. The integration of these advanced materials and technologies will play a pivotal role in achieving energy independence, enhancing public health, and promoting societal well-being through cleaner and more efficient energy solutions.

8. Quantum Science & Technology

Quantum technology has emerged as a frontier in the realms of physics and engineering, embodying an array of technologies derived from the tenets of quantum mechanics. These technologies seek to exploit the ideas of quantum entanglement, quantum superposition, and quantum tunneling, where control is exerted over single quantum entities such as single photons, single spins etc. This burgeoning domain encompasses a diverse spectrum of advanced applications spanning quantum computing, sensors, cryptography, simulation, measurement, imaging, energy harvesting, and space navigation. Quantum technologies promise to bring about transformative changes in the technology landscape, casting profound influences on established domains such as space exploration, cryptography and data privacy, defense and internal security, sustainable energy innovations, nanofabrication, semiconductor advancements, and laser technologies.

Intersections with other themes: The subject of quantum science & technology has a wide overlap with other themes such as biology, materials for fundamental science etc. For example, these days scientists aim to work at the intersection between biology and quantum technology, seeking to deepen our comprehension of biological systems and enhance medical practices. This interdisciplinary pursuit holds promise for illuminating immunology, metabolism and other facets of medical science. Beyond its conventional roots in physics, selected branches of quantum technology may venture into realms such as biophysics, bio-imaging and microbiology, thereby broadening the horizons of its applications and fostering potential contributions across diverse scientific disciplines. Quantum technologies are expected to accelerate design and discovery of new materials for wide-ranging applications from nuclear reactor technologies to novel drugs and pharmaceutical products, which are the topics of interest under the themes of materials for fundamental science, energy, and environment, health sciences, and biology across scale and environments.

The field of quantum science and technology (QST) can primarily be divided into four verticals

A. Quantum computing & simulation
B. Quantum communication (discussed earlier in detail)
C. Quantum sensors and metrology
D. Quantum Materials & devices

In the Indian context the field of QST has already seen a significant attention and several achievements have been obtained. Herein the aim is to lay down a proposed roadmap that we hope would propel India at the forefront of research in quantum science and technologies.

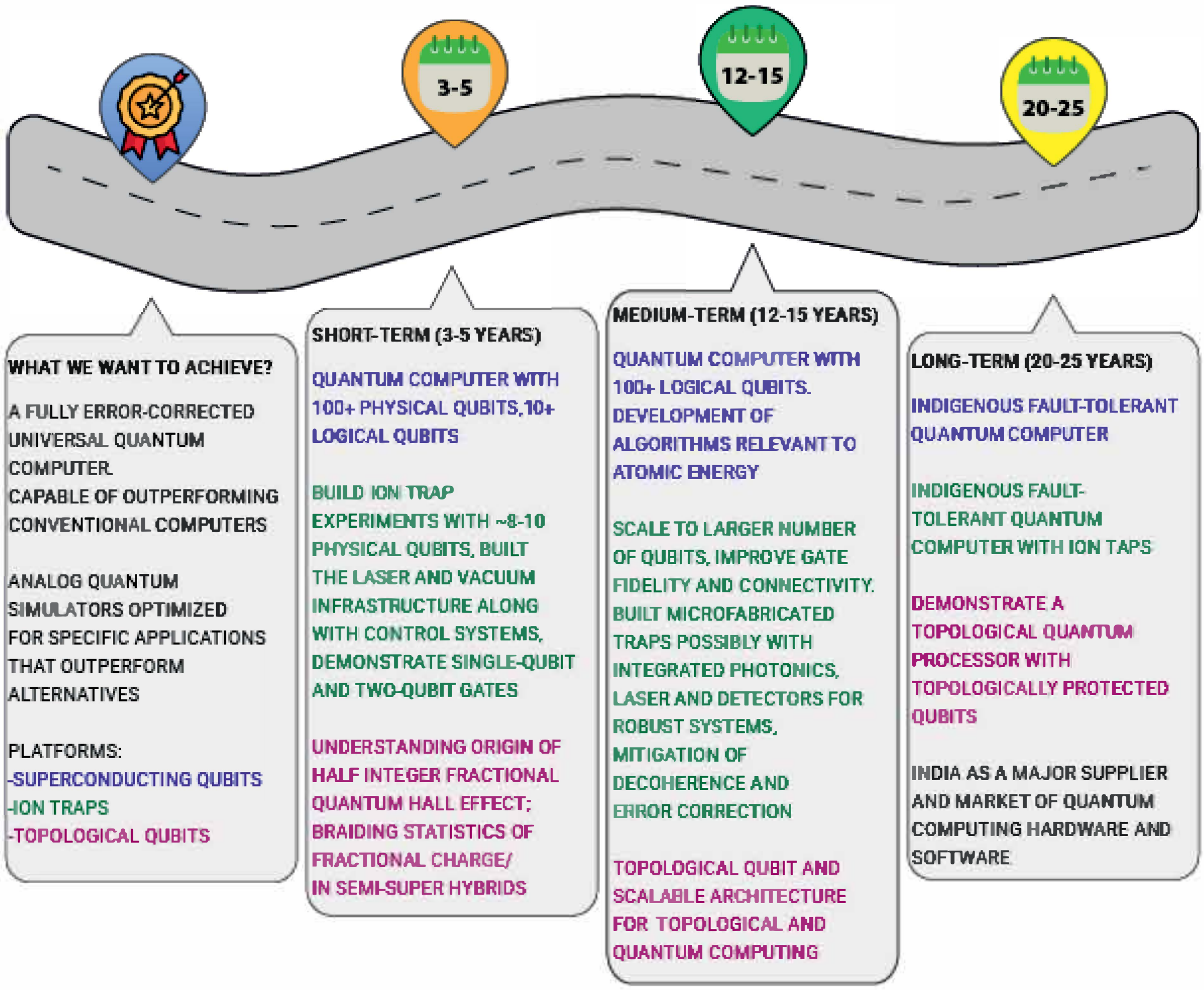
The four-thrust area of Quantum Science and Technology

The scientific, technology, healthcare and societal goals are, *Healthcare; Climate Change; Clean Energy; Novel Materials; Communication & Connectivity; and Fundamental Science and Technology.*

8.1 Quantum Computing and Simulation:

Quantum computers store and process information using quantum two level systems (quantum bits or qubits) which unlike classical bits, can be prepared in superposition states. This key ability makes quantum computers extremely powerful compared to conventional computers when solving certain kinds of problems like finding prime factors of large numbers and searching large databases. The prime factorization quantum algorithm has important implications for security as it can be used to break (Rivest-Shamir-Adleman) RSA encryption, a popular method for secure communication. In addition, quantum computers can be used to efficiently solve quantum mechanical problems which are otherwise intractable on a conventional computer. Since quantum mechanics is at the heart of most physical, chemical and biological phenomena, a quantum computer promises to revolutionize these fields by enabling us to model nature at a very fundamental level. This will potentially lead to the discovery of new molecules, novel materials, clean energy, effective medicines and a deeper understanding of nature. Some of these have been already listed in the previous section.

While several platforms for quantum computing are being pursued, superconducting electronic circuits operating at millikelvin temperatures have emerged as a leading candidate for a scalable quantum processor architecture. This architecture is also the most pursued approach in the world with major efforts in the United States, Europe, China, and Japan, including significant industrial efforts by companies like IBM, Google, Intel and Amazon to name a few. Ion-traps and cold atoms-based quantum computers have also emerged as a strong candidate for building practical quantum processors. On the other hand, topological qubits potentially offer an exciting platform that would not need error correction and hence would be simpler to scale up and expected to be more robust that other competing platforms. This platform is also being actively pursued in several leading research institutes and Microsoft. However, this technology is still in its infancy.

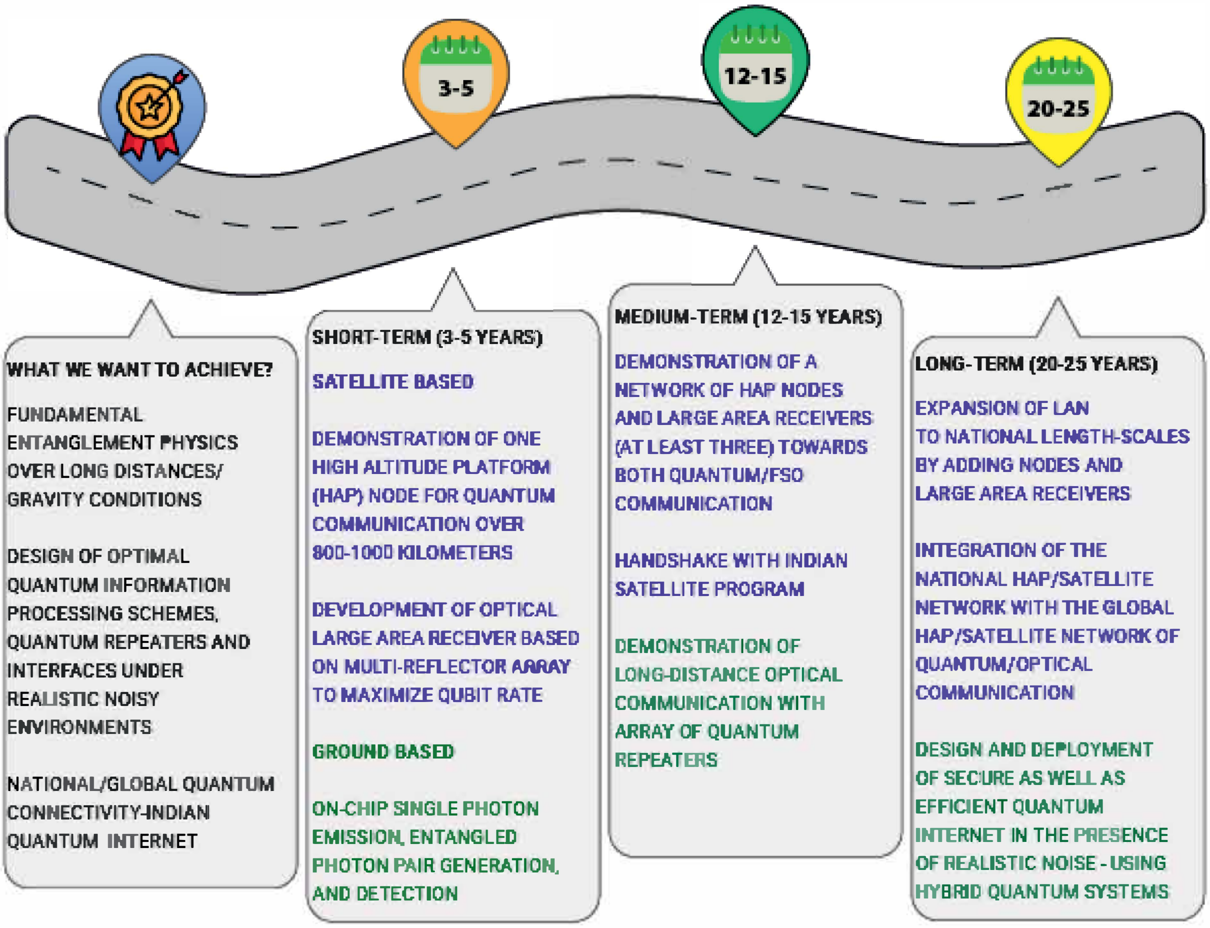


The Quantum Computing Roadmap

Within DAE, the development of a new type of ultra-low noise broadband quantum parametric amplifier for quantum measurements have been developed. Very recently, a fully functional six-qubit quantum processor based on transmon qubits has been developed. This is a joint work between institutes of DAE, DRDO, and TCS, where the quantum hardware, peripheral electronics, and cloud-based platform from where this quantum computer could be accessible has been developed by institutes of DAE, DRDO, and TCS, respectively. There is also work in progress on spin ensemble-based quantum memories for superconducting qubits. This can provide an alternative method to boost performance of quantum processors by combining long lived quantum memories with the fast-superconducting qubit-based processing elements. In addition, collaborations have been initiated between members of aided institutes and DAE core units on quantum control electronics and software, microwave components, and multi-qubit chip design.

8.2 Quantum Communication

This programme lays down the anticipated roadmap towards the development of a powerful high-speed national communications network that has the potential to connect any terrestrial location to any other within the country, with no restrictions on terrain, atmospheric conditions etc. The national network will be based on high-altitude platforms based on stratospheric balloons relaying data to and receiving data from wide-area optical receivers on the ground. The hardware on the payloads will be multi-pronged, a part of which will be aimed at quantum data, while the other part will cater to classical optical communication. This network will also be aimed at plugging into an envisaged global network created using dedicated satellites.

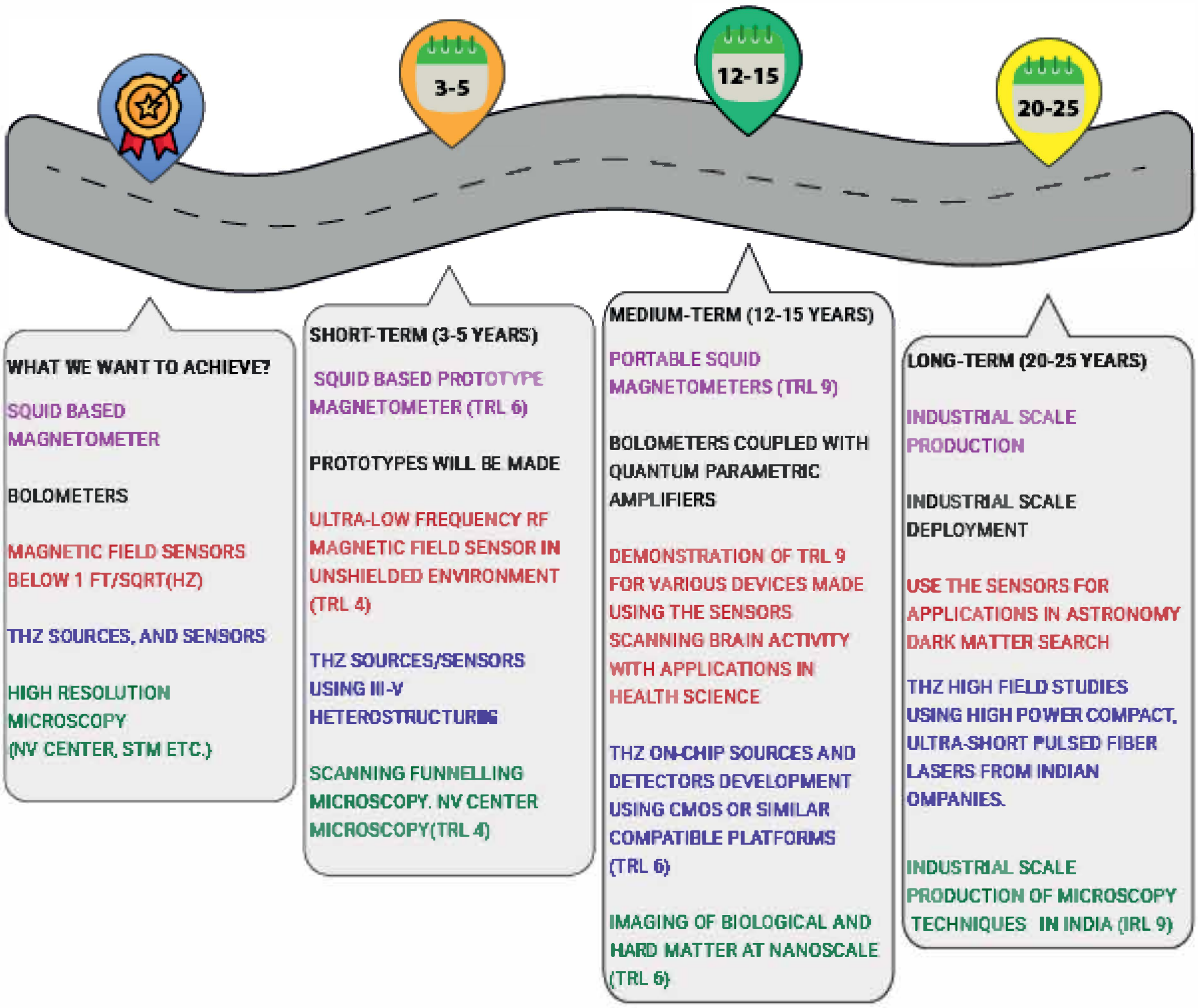


The quantum communication roadmap

8.3 Quantum Sensing and metrology:

Quantum sensing is one of the significant areas which uses quantum protocols of estimation and discrimination to outperform classical sensing strategies. The development of compact quantum sensing systems is crucial for their integration into portable devices for real-world applications. Miniaturization of components, efficient signal processing algorithms, and integration of multiple functionalities into a compact design are essential aspects of advancing quantum sensing technologies for widespread adoption in diverse fields. The focus of this roadmap is to look ahead to the next 25 years and beyond, where exploratory research and technology translation in quantum sensing and metrology both from a generic perspective as well as across specific areas of quantum sensing will be considered.

Researchers across DAE institutions are working on several theoretical and experimental aspects of quantum sensors/metrology including quantum advantage, development of realistic noise models etc. The roadmap for quantum metrology and sensing along specific research directions (but not limited to) are as follows:



The quantum Sensing and metrology roadmap

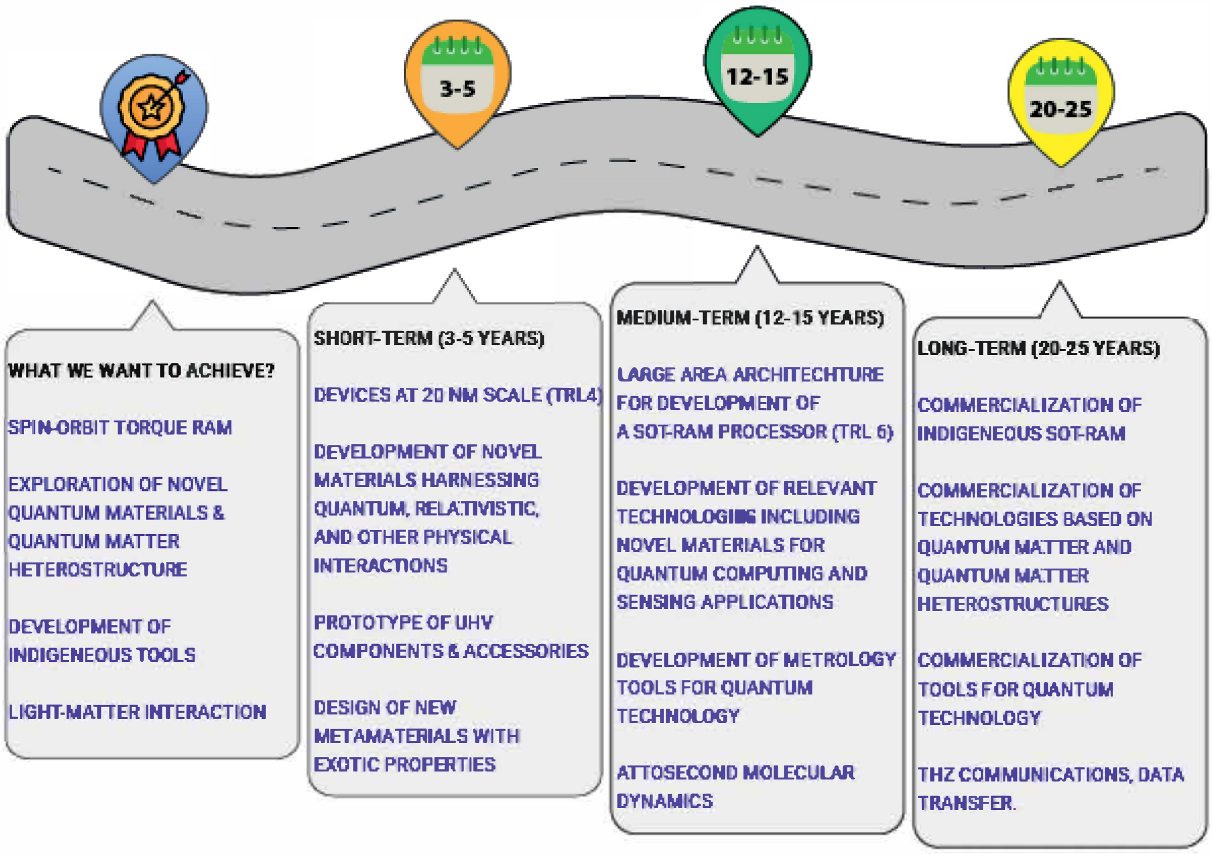
Apart from these specific directions, researchers are working on various other theoretical and practical aspects of quantum sensors and metrological devices, including quantum advantage, realistic noise models, breaking the Heisenberg limit, etc. In this context there is already collaboration between theory and experimentalists within DAE and more such exchange of ideas is envisioned.

8.4 Quantum Materials & Devices:

Quantum materials and devices form the foundational bedrock of advanced quantum technologies, serving as building blocks for groundbreaking innovations. These materials possess unconventional properties due to reduced dimensionality and strong electron interactions, resulting in quasiparticle excitations. The electronic properties of these materials are influenced by electron wavefunctions and their superpositions, leading to a variety of quantum states and phases, which are less classically described than conventional ordered states. Moreover, the role of intrinsic spin-orbit coupling (SOC) effects led to the prediction of materials like topological insulators and superconductors, and the experimental discovery of a new class of quantum materials characterized by topologically protected massless Dirac surface states. The convergence of research areas in the context of quantum technology is best exemplified by the coexistence of strong correlation, quantum criticality, and superconductivity in Moiré materials such as twisted bilayer graphene (TBG). Leveraging these materials, scientists craft sophisticated quantum devices, including qubits, quantum sensors, and quantum transducers. As researchers continue to push the boundaries of quantum materials and devices, they unlock new frontiers in technology, propelling us toward a quantum-enabled future. Research in quantum materials present significant opportunities in controlling and manipulating quantum states at the level of single quantum entities such as electron spin, single photons etc., necessitating extensive research to achieve stable and reproducible quantum properties.

Selected list of quantum materials that have drawn significant attention over last few decades. The materials listed on the right side are emerging materials and possess a lot of potential for quantum technology. Other materials shown with an asterisk (*) are also being studied in the theme of materials for fundamental science

Selected quantum materials for the proposed roadmap have been identified.



The quantum materials roadmap

The world of quantum materials consists of many more candidates under study and new quantum materials are expected to be discovered in time to come. In these materials many interesting and novel physical phenomena relevant to quantum materials and devices can be experimentally and theoretically observed such as, Majorana fermions; Spin Hall effect; Anomalous Hall effect; Quantum Correlations & fluctuations; Many body interactions; Entanglement; Topology; and Non-equilibrium quantum matter

In recent years, among these there is a new field of research called as “Spintronics” has emerged over the last few decades. The read-write head of computers are primarily a gift of spintronics. This field has been sub-divided into several sub-fields, which have their own merits for different types of applications.

An overview of different sub-topics of the emerging field of spintronics. These subject areas have a lot of potential applications.

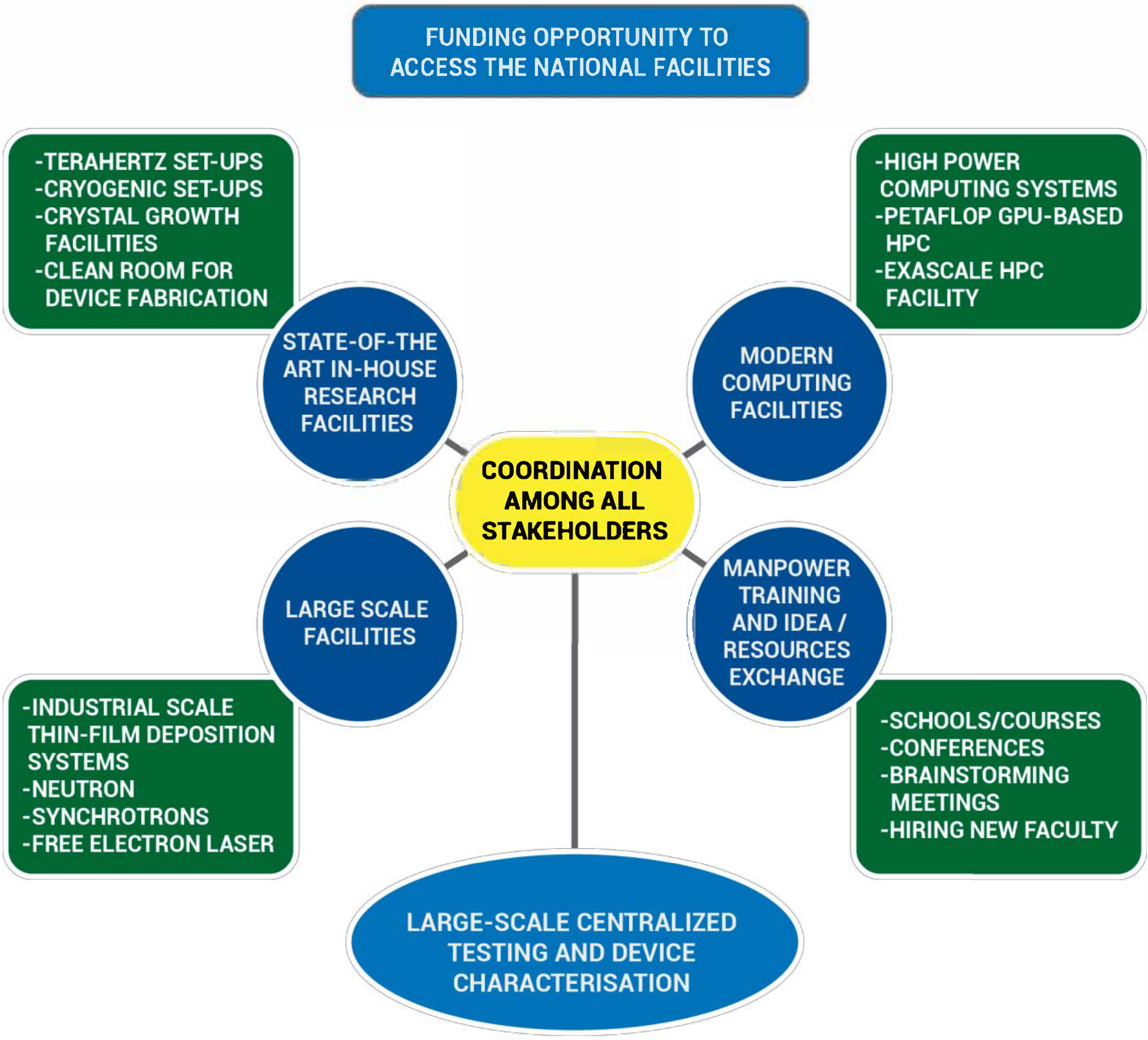
In the field of spintronics, several novel phenomena/effects are the timely topics, which need intense attention include Spin Hall effect; Anomalous Hall effect; Spin Seebeck effect; Spin Peltier Effect; Spin Nernst effect; Rashba-Edelstein effect; Topological Hall effect; Terahertz dynamics; and Magnon Hall effect.

8.5 A proposed centre for "Quantum Science and Technology":

Many researchers in India working on Quantum Science & Technology opined that a big research centre should be opened. In this centre we can hire new faculty and PhD students.

But most importantly in this centre a huge technical support may be incorporated who can help the scientists to improvise the technology readiness levels (TRL) from 2 or 3 to TRL level about 7. The centre should have a state-of-the-art workshop, a dedicated section consisting of engineers who can help in making devices and testing its performance. The new centre can be housed in any of the DAE units/aided institutions or may be established at a new place.

It is desired to have adequate scope for hiring new manpower and training of existing manpower in this emerging technology. We need to hire at the level of scientists, engineers, senior technicians at different DAE units and institutions who can dedicatedly work in the project related to quantum science and technology. At the same there will be opportunity for PhD students and postdocs who can be involved in various projects of quantum science & technology and on occasions can move to scientist positions. We need to develop an ecosystem which will offer a platform for developing our knowhow and at the same time will be able to generate sufficient trained and skilled manpower to innovate, generate and maintain the applications related to quantum technology. This goes in line to the concept of "AtmaNirbhar Bharat". In this context, summarizes our approaches which will be highly required for a sustainable ecosystem in the field of quantum materials & devices.



A chart depicting the requirements to achieve remarkable progress and obtain significant deliverables in the field of Quantum Materials & Devices.

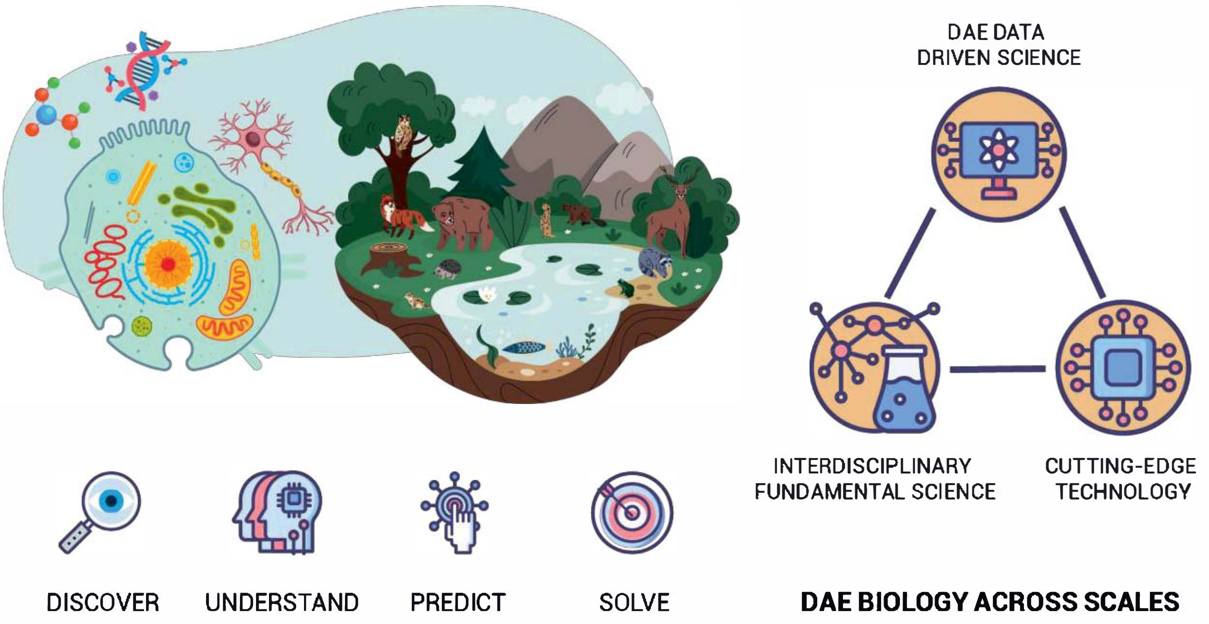
9. Biology across scales and environments: From molecules to ecosystems

Starting from studies to understand radiation resistance in biological systems, biology supported by DAE has expanded significantly and made impacts nationally and globally, from single molecules to entire ecosystems. Examples include novel fundamental discoveries such as the genes for olfaction, memory formation in the brain, and the physical principles of cell membrane organization. Biological scientists have discovered new Indian biodiversity, built databases such as those dedicated to the cataloguing of natural compounds systematically, and have studied the genomics of native plants such as tulsi and moringa. This research has shaped government policy, including but not restricted to aspects of biodiversity conservation. All this has been possible due to the scales and disciplines covered by biological science research at the fundamental level in the DAE, from molecules to entire ecosystems across acres of forest. Such fundamental biological sciences research supported by DAE has already shown real-world and immediate impact during the global challenge of the COVID-19 pandemic. AI centers worked across all levels to mitigate the effects of this disease. From developing testing protocols and capacity building to enabling the application of the same across the country to innovate on new diagnostic kits, sero surveys, and drug discovery, fundamental biological sciences met the essential needs of our country and will continue to do so. Thus, the pursuit of research at this level is critical.

1. ADVANCED CENTRE FOR TREATMENT, RESEARCH AND EDUCATION IN CANCER (ACTREC)
2. SAHA INSTITUTE OF NUCLEAR PHYSICS (SINP)
3. UM-DAE CENTRE FOR EXCELLENCE IN BASIC SCIENCES (UM-DAE CEBS)
4. THE INSTITUTE OF MATHEMATICAL SCIENCES (IMSc)
5. INSTITUTE OF PHYSICS (IOP)
6. NATIONAL INSTITUTE OF SCIENCE EDUCATION AND RESEARCH (NISER)
7. TATA INSTITUTE OF FUNDAMENTAL RESEARCH (TIFR)

- DEPARTMENT OF BIOLOGICAL SCIENCES
- TIFR-HYDERABAD
- INTERNATIONAL CENTRE FOR THEORETICAL SCIENCES
- NATIONAL CENTRE FOR BIOLOGICAL SCIENCES

This proposal covers the following DAE institutes engaged in biological research: TIFR (Mumbai, Hyderabad, NCBS, ICTS), ACTREC, IoP, IMSc, NISER, SINP, and CEBS. Their aims span biological scales from single molecules to single cells, a collection of cells, organisms and environments. The objectives span four key pillars: to discover, understand, predict and solve. This will be achieved by bridging the interdisciplinary expertise in the DAE with big data-driven science and cutting-edge indigenously developed technologies. Thus, these four pillars combine research, development, and new technology innovations to fundamental biological studies.



Executive summary - Biology across scales and environments. From molecules to ecosystems

Specific aims:

DECODE: Resilience in biology. How does life adapt to changing environments? Aim is to understand the mechanism of adaptation and change in biological systems from single-cell organisms, to plants and ecosystems.

***SCALE and TRANSLATE*:** Biological complexity from molecules to organisms. Aim to uncover the laws of biological complexity: how do you go from single molecules to entire organisms interacting in ecosystems?

BUILD: New technology development

9.1 DECODE – *Resilience in biology*

9.1.1 Understanding mechanisms of microbial adaptation

Predicting evolution in antimicrobial resistance and emerging infectious diseases

Microbes (such as bacteria and fungi) are among the most abundant and successful organisms on the planet. They have significant impacts on human health and disease and are ecologically important. It is proposed to develop a thrust area focussed on understanding microbial physiology, adaptation and evolution under changing and stressful environments. Via fundamental approaches, we will discover and understand the basis of microbial resilience and adaptation, thus allowing us to predict evolutionary outcomes.

- Microbial genomes: We propose investigating two new routes for bacterial adaptation via genome modifications: a. horizontal and/ or vertical gene transfer b. stress-induced mutagenesis (SIM). These strategies (recombination and SIM) are contingent on the action of pathways that can modify the bacterial genomes (such as DNA repair mechanisms). We will employ high-throughput computational studies with whole genome sequencing technologies, bacterial genetics and molecular biology as well as biochemistry and cell biology of bacteria to gain molecular mechanistic insights into the pathways contributing to genome modification under stress, understand how these pathways are regulated, and based on this understanding, predict the course taken by the organism to gain resistance to new environments.

- Microbial metabolism: While the need for newer antibiotics is ever-increasing, the target space to develop novel antimicrobials is shrinking. This paradox and the central importance of bacterial metabolism in stress physiology have made metabolic pathways an alternative and attractive target. However, bacterial metabolism is highly plastic and robust. Thus, translational progress in this direction requires a holistic understanding of metabolic adaptabilities. Our existing and proposed requirements put us in an advantageous position to explore this area innovatively, including multi-omics integration, modeling, and simulation of clinical outcomes in laboratory conditions. We propose to investigate the mechanistic details of the emergence of antimicrobial resistance, develop novel targets, and increase the rationality of combination therapy.

- Structure-function studies for new drug discovery: To combat threats of AMR, in the short term (next 5 years), we urgently need to bolster our knowledge base regarding structure-function relationships of potential antibacterial drug targets that are unexplored so far. After such targets are figured out, we will first aim to deduce the high-resolution structures of these entities in apo and ligand-bound forms and complex forms along with their interacting partners. In the long term, we plan to employ this strategy to combat antibacterial resistance and address the challenge posed by antimicrobial resistance arising in viruses, fungi, and unicellular parasites. The structural information from these biological targets would be used to design precision therapeutics based on synthetic bio-conjugated nanomaterials.

9.1.2 Mechanism of Stress Tolerance in Cancer Cells - Understanding and Taming Resilience to Therapy

Cancer Research across DAE institutes covers all aspects of tumour biology, ranging from understanding the molecular basis of cancer epidemiology to uncovering the basis of disease in the Indian population, structure-based drug design and translation of these discoveries to clinics. Cancer research spans all biological scales in space and time. In this context, cancer must be recognised as an 'ecosystem' and treated as an evolving 'organism'. Reliance or resistance to treatment at the primary and metastatic sites remains a formidable challenge and a bottleneck in oncology. The proposed programme focuses the following objectives.

- Investigate/develop model systems, including humanized and genetic mouse models, across scales to test and understand the role of mutations, molecular alterations, TME such as hypoxia, CAFs, mediators of immune response, nutrient deprivation, and mechanobiology of ECM on therapy resistance and disease aggression.
- Collect large longitudinal multi-omics data from bulk and single cells from Indian patients (breast, lung, ovarian, cervical, head and neck, hematolymphoid, and GI).
- Analyse data using informatic tools and computational methods and develop new mathematical models and theoretical concepts for prediction and hypothesis testing.
- Use of model systems to validate computational predictions in a 'closed loop format' until predictions match data and provide probable solutions.
- Discover and validate new biomarkers of early disease, prognosis and resistance using novel de novo chemical tools and activity probes.
- Identify new vulnerabilities that can be validated and targeted using high throughput screening strategies and structure-guided ML-trained algorithms.
- Generate new molecular scaffolds emanating from traditional knowledge systems for preclinical studies.
- Test some of the alternative resilience theories and those originating from the study of Integrated Stress Response in other DAE settings.
- Develop therapeutic vaccines, cellular therapies, and innovative strategies to overcome immune exhaustion.
-

9.1.3 Ecology and biodiversity studies towards a biodiverse and sustainable future

A thrust area to discover, understand, predict and address biodiversity loss and climate change-associated problems to safeguard our future is proposed herein. Scientists at DAE-AIs would work together towards the vision that allows resilience and adaptation to secure India's biodiverse and sustainable future. Much remains to explore, explain, and understand India's biodiversity in terms of species, genetics, behaviours and physiological mechanisms.

Organismal responses across biological scales (molecular, cellular, organismal, populations, communities) to climate stressors, unveiling the underlying mechanisms influencing adaptation, resilience, and vulnerability will be explored. This can be done by leveraging insights from biology, physics, chemistry, and engineering to develop innovative technologies for monitoring, analysing, and mitigating the effects of climate change on biological systems. Species occur in communities, and interactions between communities (predator-prey, host microbiome, etc.) remain poorly understood in the Indian subcontinent. Especially important is how anthropogenic impacts can affect these relationships, potentially resulting in zoonotic spillover. For example, scientists at TIFR-NCBS have previously investigated reservoir dynamics and spillover from bats and rodents. DAE-AI scientists will investigate communities and species relationships and how human habitat modifications impact them. Characterizing ecosystems is critical in understanding how people benefit from nature through ecosystem services. Wide-ranging species invasions, global change and habitat fragmentation have unprecedented impacts on biodiversity, ecosystem, and services. These unprecedented impacts can be mitigated through science-based and action-oriented restoration and conservation. DAE-AI scientists will work with partners to enable restoration and preservation. A specific focus area likely to be developed is urbanization and its impact on ecology, global change and resilience. Projections suggest that 80% of Indians will live in cities by 2050. Collaborative interagency efforts will be expanded across Mumbai, Hyderabad, Bangalore and Bhubaneswar.

The proposed aim will have the following impact.

A. Fundamental research: deep scientific understanding and knowledge generation on

(1) biodiversity and ecosystems of the Indian subcontinent,

(2) how habitat change, fragmentation and contemporary rapid climate change affect different biodiversity assemblages, and how global change will affect biodiversity.

B. Resilience through scientific knowledge: A new centre on Mitigating human impacts on biodiversity.

C. Innovation for an unprecedented future: A working group called 'Urban Futures' on urban ecosystems, projects, and working plans will allow sustainable development in India's urban settings.

9.1.4 Mechanism of Stress Tolerance in Plants - towards climate resistant crops

Food insecurity is a severe problem worldwide. Reducing crop damage and enhancing the overall agricultural yield and productivity is essential to tackle this ever-growing food demand. Thus, it is important to make judicious use of resources (including fertilizers and pesticides) before the disease occurs and employ modern technologies to improve agricultural productivity. Here, we propose to (i) develop an artificial intelligence-based solution for early detection of plant stress (due to biotic and abiotic factors) and use appropriate strategies to combat it and (ii) use genetic and system biology approaches to understand genes regulating responses to biotic, abiotic, yield and development associated traits towards generating climate resilient and disease resistant plants. The former includes using information and electronic technologies to develop wireless sensor networks, robotics, and machine learning with automated technologies to monitor agricultural farms with intelligent solutions. The latter involves recombinant DNA technology to create mutants or epigenetic variants of genes associated with defence, abiotic stress tolerance, yield, fruit development and pigmentation in important crop plants in Indian agriculture, such as rice, banana, tomato and mung bean.

The ideas are to:

- Develop an artificial intelligence-based solution for early detection of plant stresses.
- Screen for natural variations of different crops (varieties, landraces) in field conditions and identify robust accessions resilient to temperature, light, pathogen, etc. Identify the resistance genes/epigenetic variations and evaluate their effectiveness under environmental conditions.
- Identify naturally occurring, nutritionally enriched crops/species and edit signal transduction mechanisms for temperature, light and pathogen sensing with delicate precision.
- Manipulate fruit development and ripening to identify the regulators of stress tolerance associated with pigment accumulation under variable conditions of light and drought.
- Genomic (ATAC-seq, RNAseq) and epigenomic (miRNAs, siRNAs, histone modifications) studies to identify clusters and modules of developmentally, diurnally and stress-associated genes that can be used in crop engineering.
- Use micro gas sensors as readouts in pathogen attack situations, and develop a prototype to combat pathogen and disease spreading much before the disease causes damage.

- Elucidate the impact of the rhizosphere microbiome on the general fitness and defence of the host and anticipate engineering a universal resilient microbiota that could determine the growth defence trade-off by acting as probiotics.

9.2 SCALE AND TRANSLATE – *Biological complexity from molecules to organisms. We aim to uncover the laws of biological complexity. How do you go from single molecules to entire organisms interacting in ecosystems?*

9.2.1 Principles of organismal development

Developmental biology stands at the forefront of scientific inquiry, seeking to unravel the mysteries of how a single fertilised egg transforms into a complex multicellular organism. This proposal aims to delve into the intricate principles governing the development of tissues, organs, and organisms, focusing on the following themes: gene *to geometry*, developmental diversity across an organism, evolution, and developmental diseases. By understanding the mechanics and molecular mechanisms driving morphogenesis and comprehending gene regulatory networks underpinning the developmental processes, we aim to uncover fundamental insights into the development process and potentially engineer novel solutions for gene therapy, regenerative medicine, and biotechnology.

The focus is to elucidate the mechanisms underlying morphogenesis, combining insights from cellular signaling and metabolic state with the mechanics of cells and tissues. Building upon foundational insights gained in the immediate future, organoids and engineered tissue systems will be further developed to recapitulate complex developmental processes in vitro, enabling high-throughput screening of genetic, metabolic, environmental, altered climate changes and pharmacological interventions for developmental defects. Synthetic biology approaches will be harnessed to engineer precise spatial and temporal control over gene expression, allowing for the construction of synthetic morphogen gradients and patterning cues. Moreover, manipulating the extracellular matrix using bioengineering strategies will sculpt tissue architecture and mechanical properties, facilitating the assembly of functional tissue constructs that can be used for regenerative medicine and therapies.

By unravelling the principles of development, this initiative aims to advance our understanding of morphogenesis, and it will pave the way for innovative approaches in regenerative medicine and biotechnology. We aspire to make transformative contributions to scientific knowledge and societal well-being through collaborative efforts and sustained investment. Ultimately, this research endeavour holds the promise of unlocking the full potential of developmental biology to address pressing healthcare challenges and drive economic growth through biotechnological innovation.

9.2.2 Brain and mind

The brain at all levels, will be investigated from the single cell and molecule to microcircuits and networks, to understand cognition, emotion, and behaviour. In parallel, investigation on brain diseases of neurodevelopmental, neurodegenerative, psychiatric and cancerous origin in model organisms and iPSC-derived brain organoids will be carried out.

First step of investigations would be at the single cell and microcircuit level for unbiased insights into the brain's cellular subtypes and intercellular interactions. We will delve into deciphering heterogeneity and its functional relevance during brain development, function and pathologies. The last few years have seen a transformational shift in the ability to define large-scale connectome of the brain. We will integrate our ongoing investigations with new revelations of brain connectome for a more accurate understanding of synaptic, dendritic and neuronal computations. We will employ this to gain insights into the neural regulation of breathing, sleep, memory, emotion and motor regulation. We will leverage the power to manipulate neural circuits using genetic, chemo-genetic, optical and magnetic systems to study the mechanistic underpinnings of normal physiological processes and behaviour and use this to decipher specific cellular and circuit dysfunction evoked pathophysiological states. We intend to study the signalling mechanisms and their ncRNA-mediated molecular regulations through the establishment of a 3D co-culture of glioma cells with neurons.

In the next phase, we will work for large-scale efforts towards a) an atlas for synaptic signalling, b) catalogue for subpopulation level identity & function of brain cells, c) neuro-glia interactome for brain function and resilience, and d) consortia projects for longitudinal human data. To leverage the knowledge acquired through the above programs, we will explore translational opportunities through collaborative and consortium projects between basic researchers in the DAE system and clinicians. New methodologies will be developed to achieve such readouts for basic, translational and diagnostic applications. Integrating this research with the proposed new pipelines for big data and AI/Modelling, new pharmacological targets and combinatorial therapies will be proposed.

Three significant developments have converged to make this an exciting time for neuroscience research. First, the tools for recording, imaging, controlling, and analysing brain activity have recently leapt forward with new genetic reporters, optogenetics, and high-throughput omics. Second, AI brings new concepts to the field and vastly increases analysis capacity. Third, mental health and neurodegeneration are now forefront concerns, and the latest tools provide untapped opportunities to treat them, especially in the context of the Indian spectrum of disease. The next few decades hold unprecedented promise for making significant breakthroughs in understanding of the brain to figure out how the brain works. In this regard, DAE is uniquely positioned within the scientific ecosystem in our country to lead the effort with the power of interdisciplinary expertise and the ability to capitalize on high-precision, big-data pipelines to drive quantum leaps in understanding the brain. The above-mentioned scientific goals and the roadmap can potentially develop "RNA therapeutics" modalities in the long run.

9.2.3 Decoding genetic landscape and genetic underpinning of diseases Indian context

It is proposed to undertake functional underpinning of the susceptibility of the Indian population to metabolic, cardio-vascular and rare-genetic diseases and cancers of young adults by mapping the mutational landscape of selected inbred populations. We propose integrating our efforts across DAE institutions and hospitals, and in collaboration with clinical geneticists, to generate a comprehensive reference genetic map of these populations through a large-scale WGS to identify mutations causing undiagnosed rare and orphan diseases using a consortial-based approach. It is also important identifying epigenomic alterations and epidemiologic and clinical factors associated with cancers in young adults and age-related metabolic diseases. In the first phase, the focus will be on ciliopathy, mitochondrial-metabolic disease, brain and eye development disorders, blood-related disorders, aging and cancer and the burden of pre-disposition/emerging comorbidity – for young who live long and the elderly.

The outcome of this programme would be followed up with patients with the help of clinical partners in this study. Further, using a subset of candidate genes, characterizing the function of genes to understand basic biology and pathogenic mechanisms will be carried out. India should be a leader in human genetics and rare disease diagnosis, as we will also be a most populated nation. We would like to develop a comprehensive knowledge of genotype and phenotype relations using WES and fundamental and clinical investigations. The understanding generated by these goals can also lead to the design of an assay for drug screening geared towards therapy or prevention.

9.3 BUILD – *New technology development*

9.3.1 Engineering Biology and Designing Living Systems

Governments and the public worldwide, including India are advocating for replacing and minimizing animal testing for investigational drugs and encouraging researchers to innovate effective non-animal methods. Such effective non-animal methods could increase the speed and success of drug discovery and acceptance. In cancer research, the existing organoid models cannot truly mimic the tumour microenvironment and surrounding physiology and, hence, cannot be used as alternatives to animal models for studying or drug testing. To bridge this gap in this thematic area, incorporation of bioengineering approaches with novel synthetic platforms to enhance the possibility of learning new biology by exploring living organisms in biomimetic 3D settings and building new technologies including complex 3D tumour models as an alternative to animal drug testing and cell-based computers is envisioned.

This thematic area will enable pushing the boundaries of 3D culturing capabilities and probe cells with unprecedented resolution using biomimetic in vitro platforms. By precisely tuning the systemic properties and accurately recreating in vivo parameters, the use of animal models will be minimized. Further, scaling up these systems for high-throughput applications such as drug screening will be undertaken. Overall, this thematic area would provide new methods to investigate various fundamental questions in biology and build new technologies using 3D systems.

9.3.2 Integrative imaging and therapeutic modulation across large length scales:

The aim is to spearhead a paradigm shift in biomedical microscopy and biomodulation in India by indigenously developing cutting-edge imaging techniques across length scales, from single molecules to whole organisms. Central to our initiative is the design and development of novel imaging solutions, focusing on tool development using chemical and synthetic biology approaches to democratize advanced imaging technologies across the country, particularly super-resolution microscopy, through innovative AI and ML approaches for pathologists.

Pioneering the development and implementation of advanced non-linear optical imaging technologies, bridging the gap between conventional microscopy and IR-based imaging modalities, development of new imaging tools and drugs based on peptides, small molecules, and designer cells for precision imaging and correction of cellular pathology, developing and refining AI/ML algorithms to enhance conventional microscopes' resolution, making super-resolution imaging accessible for pathologists and researchers alike are the goals to achieve. This proposal represents a bold and ambitious endeavour to redefine the landscape of biomedical imaging and research.

In summary, this proposal on health reflects a broad spectrum of scientific research directions, each aiming to address critical challenges in public health, environmental sustainability, and technological innovation such as:

1. **Microbial Biology and Antimicrobial Resistance:** The proposed research emphasises understanding microbial biology and mechanisms of antimicrobial resistance. These studies aim to develop effective infection prevention and treatment strategies, contributing to significant healthcare cost savings and better public health outcomes.

2. **Biodiversity and Ecosystem Resilience**: The study aims to generate knowledge on biodiversity and ecosystems in the Indian subcontinent, focusing on how habitat changes and climate change impact biodiversity. The proposed research seeks to foster sustainable urban development in India.

3. **Climate-Resilient Agriculture:** This proposed initiative targets food security in a changing climate by developing climate-resilient and disease-resistant plants. The proposed research involves using AI to enhance farm management and sustainability, identifying genes and epigenetic factors that regulate crop traits, and improving major Indian crops like rice, banana, tomato, and mung bean.

4. **Developmental Biology and Regenerative Medicine:** The proposed research aims to advance the understanding of morphogenesis, paving the way for innovations in regenerative medicine and biotechnology. It aspires to make transformative contributions to scientific knowledge and societal well-being by unlocking the potential of developmental biology to address healthcare challenges and drive economic growth.

5. **Neuroscience Research:** This proposed research highlights the convergence of new tools in neuroscience, such as genetic reporters, optogenetics, and AI, to advance the understanding of the brain. It focuses on treating mental health and neurodegenerative diseases, particularly in the Indian context. The proposal aims to inspire technological advancements in neural networks and robotics and understand the molecular mechanisms behind conditions like "Chemo Brain."

6. **Cell Biology:** This proposal involves using cryo-tomography and other advanced techniques to study cellular macromolecular assemblies, aiming to develop detailed cellular atlases. This research provides insights into cancer progression and aids in developing disease therapies by understanding the altered ultrastructure of cancer cells.

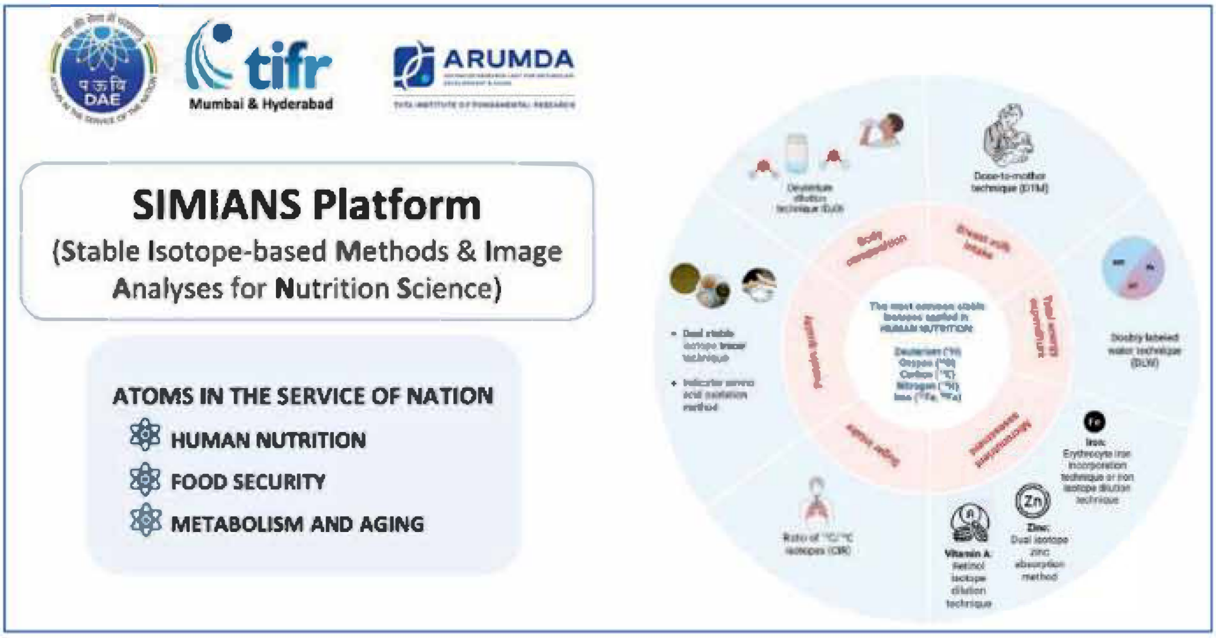
7. **Rare Diseases and Genetic Research:** The proposed research addresses the burden of genetic diseases and rare diseases in India. It aligns with the National Health Mission to improve diagnostics, treatment, and precision medicine strategies through interdisciplinary research and advanced molecular techniques.

8. **3D Culturing and In Vitro Platforms:** The thematic area explores pushing the boundaries of 3D culturing capabilities, allowing for precise cell probing and minimising animal model use. This research has potential applications in drug screening and fundamental biological investigations, aiming to develop new technologies using 3D systems.

9. **Biomedical Imaging and Research:** The proposal seeks to revolutionise biomedical imaging by making advanced microscopy techniques accessible and pioneering innovative imaging methodologies. The research envisions establishing an Advanced Bioimaging Centre as a hub for interdisciplinary collaboration, driving advancements in healthcare and contributing to national innovation and self-reliance.

9.4 Enhancing National Capacity in Stable Isotope Applications

India faces high prevalence of double and triple burdens of malnutrition, compounded by rising lifestyle diseases such as diabetes, obesity, and metabolic syndromes. These challenges are exacerbated by socio-economic disparities, genetic diversity, and rapidly changing dietary habits. The Advanced Research Unit on Metabolism, Development and Ageing (ARUMDA) at the Tata Institute of Fundamental Research (TIFR) represents a ground-breaking initiative aimed at addressing India's complex nutritional health challenges. By integrating stable isotope technologies with multidisciplinary research, ARUMDA seeks to revolutionize the understanding, management and alleviation of malnutrition, metabolic disorders, and aging-related diseases. This vision document outlines TIFR-ARUMDA's strategic roadmap for leveraging nuclear science in collaboration with other DAE organisations, to achieve transformative nutritional health outcomes using stable isotopes by 2030 and 2047. Stable isotopes offer a unique advantage as non-invasive, precise, and safe tools for studying nutrient metabolism, body composition, and energy expenditure. As India approaches the centenary of its independence in 2047, this TIFR-ARUMDA initiative under the DAE umbrella should aim to redefine the country's position in global health and scientific innovation.



The vision for Amritkaal Bharat should include India as a pioneer in stable isotope applications, transforming healthcare, nutrition, and aging research through cutting-edge nuclear science, primarily a resultant of interactions between ARUMDA and DAE units. By 2047, India should not only achieve self-reliance in stable-isotope production but also emerge as a global leader, exporting knowledge, technologies, and solutions to address pressing health challenges worldwide, driven by TIFR-ARUMDA in partnership with the other DAE units.

Foundational Infrastructure and Achievements: ARUMDA has established state-of-the-art facilities to support its mission. The National Analytical Facility for Nutrition and Metabolism Research, equipped with state-of-the-art metabolomics platform and Isotope Ratio Mass Spectrometry (IRMS), enables advanced metabolic studies. The SIMIANS Platform, embedded within the National Facility, is dedicated to using stable isotope-based methods and imaging analytics for addressing nutritional health challenges. Additionally, the ongoing installation of India's first human metabolic chambers at CMC-Vellore marks a significant milestone in controlled metabolic research. Ongoing collaborations with DAE institutions, such as the Heavy Water Board (HWB) and BARC, ensure a steady supply of critical stable isotopes like deuterium oxide (D_2O), doubly labelled water (DLW), Iron and others for research and interventions.

Strategic Goals and Future Initiatives: The vision for 2030 and 2047 is anchored in five key pillars: scaling stable-isotope production and utilisation in nutritional health, advancing research and innovation, building human capital, integrating findings into public health policy, and enabling the Global South to mitigate nutritional crises (initiatives like 'Nutrisotope Maitri').

To enhance isotope accessibility, ARUMDA with DAE organisation like BARC and HWB will focus on enriching stable isotopes of iron, carbon, and nitrogen while strengthening supply chains of these isotopes and D2O and DLW. Grassroots-level implementation of D_2O and DLW techniques will enable large-scale studies on assessing body composition and total energy expenditure across diverse populations.

Research and innovation will prioritize the development of new stable-isotope techniques for studying metabolic diseases such as diabetes and metabolic dysfunction-associated steatotic liver disease (MASLD). The procurement of advanced GC-MS systems will expand lipid metabolism research, while pilot cohort studies will generate data to refine national nutrition programs.

Capacity building is critical to sustaining the progress. An M.Sc. Program in Isotope and Nuclear Imaging Techniques will be launched to train the next generation of professionals, drawing expertise from TIFR, DAE and the International Atomic Energy Agency (IAEA) network of experts. Workshops and fellowships in collaboration with DAE institutions will further enhance expertise among researchers and clinicians.

Policy integration will ensure that stable-isotope-based evidence informs national health strategies. By collaborating with ICMR, MoHFW, and NITI Aayog, ARUMDA aims to refine programs like Anaemia Mukt Bharat and help develop dietary guidelines grounded in robust scientific data.

9.4.1 Roadmap to 2030 & 2047

The journey to 2030 is structured into two phases. From 2025 to 2028, the focus will be on scaling infrastructure, formalizing isotope supply chains, and launching pilot studies. Key milestones include completing the human metabolic chambers at CMC-Vellore, initiating the design of the M.Sc. Program, and deploying iron isotope techniques in high-anemia-burden states/populations.

> **Strategic Significance for DAE**
>
> - **Adding a new dimension to its mandate** to apply nuclear science for societal welfare.
> - **Positioning India as a global hub** for stable isotope research.
> - **Supporting SDGs** (e.g., Zero Hunger, Good Health) through innovation.
> - **Global health diplomacy** through the **"Isotope Maitri"** initiative
>
> ***Atomic Precision for Nutritional Security***

Between 2028 and 2030, the emphasis will shift to human capital development and policy integration. The M.Sc. program will be rolled out, and the DAE-TIFR/ARUMDA Centre for Metabolic Innovations will be established to prototype new diagnostic tools. Isotope techniques would be integrated into national health programs, and domestic production of critical stable isotopes would reduce reliance on imports.

India's battle against anemia and childhood stunting will reach its culmination, with iron-isotope-based interventions ensuring significant decrease in deficiency diseases by 2032-2035. Mitigation of diabetes, obesity & cardiovascular disease epidemics would be a reality through nationwide deployment of 13C/2H metabolic flux diagnostics, cutting incidence rates drastically. These achievements will position India as a model for other nations grappling with similar health challenges.

Expected Outcomes and Global Leadership: By 2030, ARUMDA with DAE organisation aims to achieve significant milestones, including the formulation of over ten evidence-based nutrition policies/publications and the training of 100 professionals in isotope applications. A 30% reduction in research costs through domestic isotope production will enhance affordability, while the establishment of a National Repository of Isotope Data will facilitate open-access research.

By 2047, stable isotopes would be deeply embedded in India's healthcare ecosystem. The widespread adoption of isotope-mapped metabolic profiles will allow for AI-driven dietary recommendations, tailored to individual genetic and lifestyle factors. This precision nutrition approach will significantly reduce the burden of diabetes, obesity, and micronutrient deficiencies. The National Metabolic Health Grid, powered by decentralized SIMIANS nodes, will provide real-time monitoring of population health, enabling timely interventions and policy adjustments.

India's leadership in stable isotope applications would be recognized globally, with frameworks exported to low- and middle-income countries through WHO partnerships. This vision underscores the transformative potential of the DAE-ARUMDA partnership in addressing India's health challenges and positioning the nation as a hub for metabolic health innovation.

Conclusion: The ARUMDA is DAE's bold step toward a healthier future. By investing in stable isotope technologies, fostering interdisciplinary collaboration, and aligning research with national health priorities, this initiative will pave the way for sustainable solutions to malnutrition, metabolic diseases, and aging. The vision for 2047 is not just about scientific advancement but also about ensuring equitable health outcomes for all, reinforcing India's role as a global leader in nuclear applications for societal welfare.

10. Computer Science

The Computer Science groups in the Department of Atomic Energy (DAE) aided institutes are located at Tata Institute of Fundamental Research (TIFR, Mumbai), The Institute of Mathematical Sciences (IMSc, Chennai), and National Institute of Science Education and Research (NISER, Bhubaneswar). The focus of CS groups at TIFR and IMSc is on understanding fundamental or foundational questions in algorithms and complexity, quantum computing, information and communication, machine learning, cryptography, formal methods and verification; equivalently, the mathematical underpinnings of computation. The vision of the school of computer sciences at NISER is to set up a Centre for Artificial Intelligence (CAI) that will attempt to create an indigenous “Make in India” large scale General Intelligence System as well as tackle problems such as bias, trustworthiness and privacy of machine learning models. Furthermore, the Centre for Artificial Intelligence will attempt to solve challenges across all sciences including biology, chemistry, physics along with earth & planetary sciences using AI. The worthy goal to aspire to for 2047 would be to create conditions in which the Computer Science groups at DAE aided institutes have the ability not only to keep the country abreast of latest scientific advances, but to also have a good chance of creating those advances right here.

Algorithms and Complexity: The Computer Science groups at TIFR and IMSc are currently engaged in developing conceptual and foundational ideas concerned with computing, communication and learning, in the tradition of Turing and Shannon. Just as exploiting and living harmoniously with nature would be impossible without grasping its basic laws, so is the case with these three areas. Basic laws manifest not only in what is possible, such as the construction of a steam engine or a supercomputer, but also, in perhaps a more profound way, in what is not possible, such as the second law of thermodynamics or the impossibility of building a universal debugger for computer programs.

Theoretical Computer Science (TCS) is centered around some of the deepest and most fascinating questions in Computer Science and Mathematics. TCS is expected to play a crucial role in various important areas such as data-driven computation, the algorithmic basis of the contemporary economy, secure computation, the utilization of quantum computing, and the study of deep learning. The core strength of the Computer Science faculty in DAE aided institutes lies in not only designing algorithms, communication protocols for basic problems, but also in discovering fundamental limitations of such algorithms if they are to be realized on models obeying the laws of physics.

Quantum computing, information and communication: The Computer Science groups in DAE aided institutes (in particular, TIFR) have been at the forefront of theoretical foundations of quantum information and communication complexity for the last two decades. TIFR provides an excellent environment for a healthy exchange of ideas between the physicists and computer scientists and is the testing ground for India's first digital computer, TIFRAC. It is by now widely believed that novel ideas from quantum information and quantum error-correction not only aid quantum computing but might also throw light on some unresolved questions in physics. We believe the Computer Science groups at DAE aided institutes are uniquely placed to play a larger role in this in the upcoming years.

The Computer Science group at IMSc seeks to look for practical applications of quantum computing and quantum information theory that are relevant to the current computing scenario such as learning theory, data analytics, and coding theory. Furthermore, the limitations of classical computation are etched in the area of computational complexity theory. Understanding the theoretical limitations of quantum algorithms is an essential and tangible goal towards analysing the applicability of quantum techniques to problems arising in computer science.

Machine learning: Advances in machine learning in the last few decades have prompted a revisit of several foundational notions in statistics and optimization. The School of Technology and Computer Science (TIFR) already has substantial research activity addressing questions of this sort: these include, for example, learning in changing environments, or learning in the presence of large noise when what is being learnt has some structure. Given the school's traditional strengths in algorithms, information theory and applied probability, the school is in a good position to grow further and emerge as a leading centre of research on these questions.

Cryptography: Cryptography, which provides the mathematical foundations and systems for securing digital communications, financial transactions, personal data, critical infrastructure, etc. by ensuring the confidentiality, integrity, and authenticity of information, fosters trust in online interactions and facilitates the widespread adoption of digital technologies that underpin modern society. Future research in the area will be driven by technological developments, emerging threats, and the need for more robust systems. The Computer Science groups at DAE aided institutes expect to build on their current strengths in other areas of computation such as complexity theory and algorithms to grow in this critical area.

Formal methods and verification: With the growing increase in computational power, we expect to see a surge in complex software and cyber physical systems which often work concurrently in parallel. These systems work in real-time and are also often stochastic in nature. It is imperative to ensure correctness of these systems since otherwise their failures can be catastrophic. Globally, formal methods tools are widely used in academia and in industry and there is an ever-increasing demand for their scalability due to increased complexity in software. Algorithmic verification aims to automate the process of ensuring correct behaviour of these complex systems. A fundamental research challenge is to consider mathematical models to capture systems that are stochastic and show real-time behaviour while also capturing corresponding requirements through logic. This can lead to automatic verification under these increased expressiveness scales for systems with huge state space. Over the years, the Computer Science groups at TIFR and IMSc have contributed fundamentally to specify real time requirements and establishing the decidability and complexity of these logics, and we expect it to further strengthen over the subsequent years leading to real-time verification of large and complex systems.

Algorithms with societal impact: These are algorithms taking societal considerations such as fairness, energy efficiency, and environmental considerations such as responsible scaling and sustainability of large computing infrastructures. The design of an algorithm that “minimizes the carbon footprint” is desirable. Heavy computing is energy-expensive, and thus explicit bounds on energy expenditure will become the norm. Given the proliferation of cloud computing, the general ideas that underlie distributed computing, such as scalability, fault tolerance, should be re-examined. Usually, these things come at a cost, and what exactly they are and what the adverse effects should/will be quantified. The Computer Science groups at DAE aided institutes will revisit and build new algorithms that are also socially efficient, i.e., that maximize social welfare.

Artificial Intelligence: The crucial aspects of artificial intelligence that will shape our medium and long-term goals.

- *Indigenous Large Scale General Intelligence System:* General intelligence would directly lead to solving problems with both decision and execution parts in the machine learning system. It is imperative that we move to future open instruction set architectures such as RISC-V.
- *Trustworthy and Private AI:* AI is shaping our world and will have a major impact on our daily lives in the near future. It is thus absolutely crucial to make sure that the AI is behaving as promised. Currently, we don't have any robust tools to validate the workings of these AI models.
- *Bias and Fairness in AI:* Artificial Intelligence technologies are revolutionizing various domains, but concerns about fairness in AI-generated results have surfaced. This problem revolves around understanding how biases are introduced, why they occur, and what consequences they entail. AI systems learn from data, and biased training data can perpetuate societal prejudices. The design and coding of algorithms may inadvertently introduce biases, leading to unfair outcomes.

10.1 Short and medium-term roadmap:

Algorithms, complexity, and verification: In these areas the goal would be to continue with the ongoing research programs in areas such as computational game theory, computational number theory and algebra, communication complexity, combinatorial, geometric and sampling algorithms, coding theory, reactive systems etc. Some of these results also overlap with areas such as machine learning and formal methods mentioned below. In particular, our short-term roadmap is to focus on the following sub-projects.

1. *Learning and optimization.*

Recent successes of large and successful neural networks have a far larger number of parameters than the number of data-points on which these networks are trained. This challenges the recommendation suggested by classical statistical theory that when fitting a function to a dataset, the number of parameters of the function to be estimated from the dataset should typically be much smaller than the number of samples in the dataset. We seek to obtain a theoretical understanding of this phenomenon of neural network models.

2. *Proof verification in the age of blockchain.*

We seek to use the recent advances in algebraic error-correcting codes, especially, the multiplicity variants of polynomial-based codes and high-dimensional expanders to obtain better proof- checkers both in theory and practice and to pursue various cryptographic applications of such checkers.

3. *Algorithmic coding theory.*

Several of the natural and fundamental problems related to codes based on polynomial evaluations (such as Reed-Solomon codes, Reed-Muller codes, Algebraic-Geometric codes) have continued to remain open. Our goal in this project is to investigate some of these problems.

4. *Algorithms for sampling.*

Sampling from subsets of n-dimensional Euclidean space that are defined by a set of constraints is an important primitive useful for applications such as volume estimation or (more generally) Monte Carlo integration. We seek to give sharper bounds on the number of steps a given random walk has to take before its distribution is sufficiently close to the uniform distribution on K.

5. *Computational algebra.*

Low degree polynomials are objects of central importance in discrete mathematics and computer science with numerous surprising applications to many sub-areas including, combinatorics, discrete geometry, complexity theory, coding theory, pseudo-randomness and algorithm design. The main focus would be on the design of faster and more efficient algorithms for fundamental computational questions about polynomials.

6. Fair division algorithms.

As algorithmic decision making becomes more prevalent, the issue of fairness of these algorithms becomes very important. In various fields such as clustering, advertising, resource allocation, and machine learning, there has been a significant amount of work on both defining relevant fairness objectives, as well as coming up with algorithms that achieve these objectives. Our work focuses on the foundational issue of fairness in particular, envy-freeness and equity in resource allocation. Our project aims to significantly extend the set of instances for which fair allocations can be obtained, as well as address the question of combining fairness and efficiency. While the literature so far has mostly addressed the case of additive goods, this class of valuations is highly restrictive, and we would like to extend existing results to more general valuations.

7. Secure computation in the quantum age and information theoretic limits.

Quantum computation has revolutionized Computer Science in general, and cryptography in particular. The leading agencies such as the National Institute of Standards (NIST) have already called for the standardization of cryptographic schemes such as public-key encryption and digital signatures that are believed to withstand quantum computers. The rise of near-term quantum devices (NISQ) also provides us with a fascinating opportunity to use the power of quantum information and computation to achieve tasks we believe to be impossible in the classical world. The main aim of this proposal is to explore the power of quantum computers in the area of secure computation and build new protocols that are provably, or believed to be impossible in the classical world and are resilient against the looming threat of quantum computers.

9. Stochastic reactive synthesis.

While traditionally reactive synthesis has focussed on qualitative objectives which require functional requirements to be satisfied, a more interesting, useful, and technically challenging problem is to consider specifications that combine both qualitative and quantitative objectives where the quantitative objectives are used to specify resource consumption, cost, energy among others which are important parameters in safety-critical embedded applications. Our focus will be on the study of solving Markov decision processes and stochastic games with a combination of objectives.

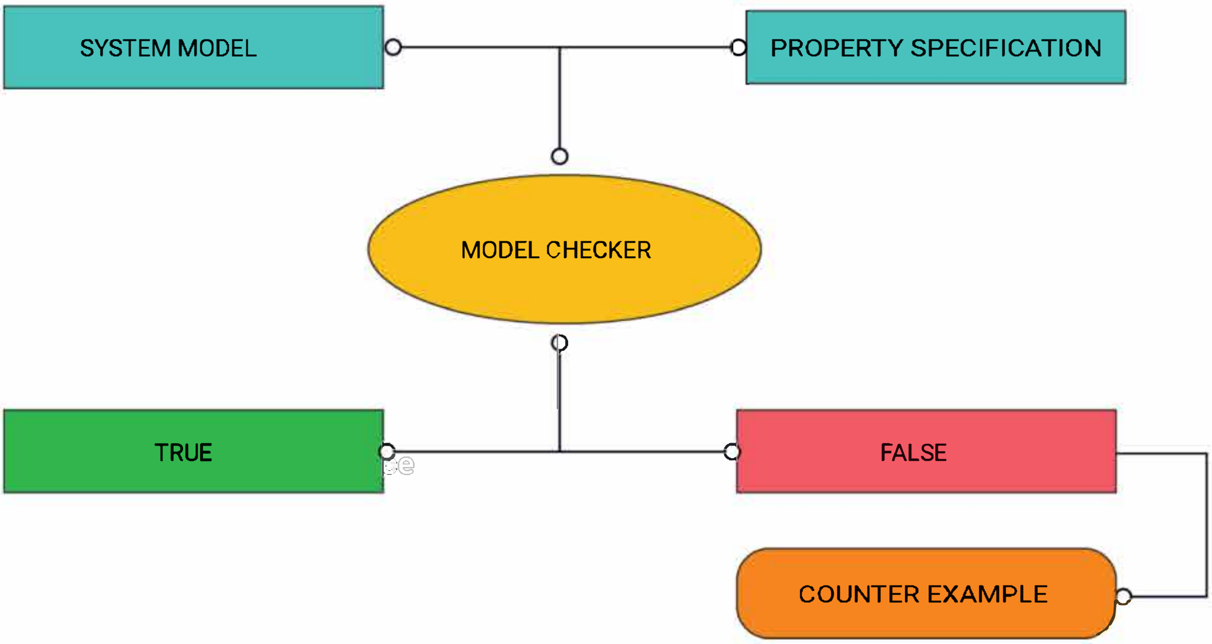
10. Communication complexity.

We seek to explore and find answers to some of these questions. What is the exact nature of communication complexity? Is it information theoretic, algebraic or combinatorial or all three?

Multivariate Algorithmic Analysis: There is a real need for a mathematical framework that allows us to express the running time of algorithms in terms of both input size and the structural properties of the input instances. Such a framework would not only be a breakthrough in understanding the nature of computing, it would also drive the design of efficient algorithms in practice. A particularly successful attempt at creating such a mathematical model is the field of parameterized complexity. This field was created in order to improve over worst-case analysis for NP-hard problems; problems whose worst-case running time is conjectured to be at least exponential in the input size. However, so far, the success of fixed-parameter tractability has been limited to applications with NP-hard optimization problems, mostly on graphs and networks. There is no inherent reason why this should be the case. This idea of a multivariate algorithm analysis has the potential to address the need for a framework for refined algorithm analysis for all kinds of problems across all domains and subfields of computer science. Our ultimate goal is to unlock this potential. We will develop toolkits for designing and analysing multivariate algorithms for every relevant class of input instances, including, but not limited to set systems, matrices, matroids, polytopes, lattices, as well as algebraic, topological and geometric objects. We also aim to create a multivariate theory of approximation algorithms, of machine learning algorithms, of pre-processing heuristics, of dynamic algorithms, of distributed algorithms and even of polynomial time algorithms.

Machine learning: An important direction for future progress is suggested by the spectacular, and often baffling, recent successes of large machine learning models in a variety of application domains. The ultimate goal of a hypothetical "theory of large ML models" would of course be to predict reasonably precisely and accurately the expected performance of any proposed model architecture and learning procedure, but such a theory appears to be far away. Ongoing recent activities noticed in STCS (TIFR, Mumbai) in these directions in the setting of understanding what biases might be inherent in various learning algorithms and the school could attempt to further enhance activity in this and related directions over the coming decade.

Formal methods and Verification: Research in model checking aims at expanding the scope of automated techniques for program reasoning, both in the scale of programs handled and in the richness of system and properties that can be checked. We note here that though testing allows us to find bugs, it does not certify absence of bugs. Also, for most practical systems exhaustive testing may not be practically feasible.



Algorithmic model-checking

Formal verification is also used in the Electronic Design Automation (EDA) industry. Formal verification plays a significant role to boost productivity by an order of magnitude in the chip design and implementation cycles including functional, safety and security verification, logic optimization at various levels of design abstractions starting from architectural levels and up to implementation of both software and hardware models.

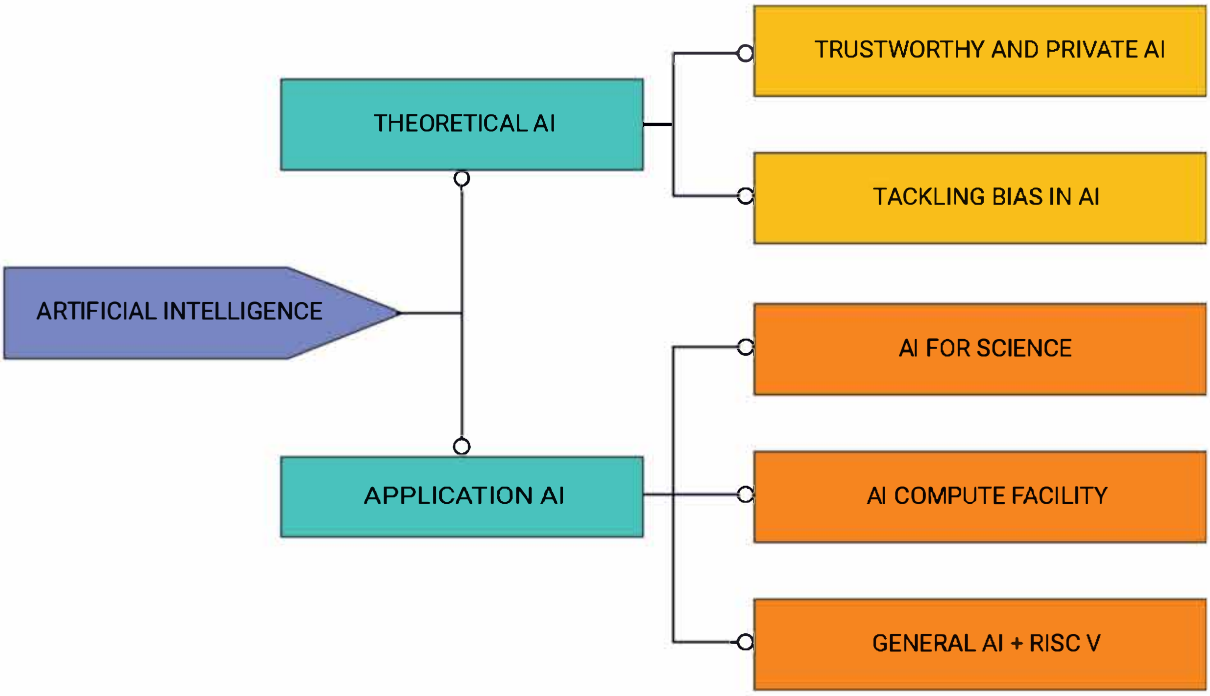
Artificial Intelligence:

- *Indigenous Large Scale General Intelligence System.*

  The goal is to set up a large-scale general intelligence system built on efficient and lower parameter custom models and integration into model operating systems to form the general intelligence system.

- *Bias and Fairness in AI.*

  We can envision a future in which AI systems develop algorithms, so any kind of quality control may not even be possible. Hence, we specifically want to develop algorithm design mechanisms where transparency and control are built in.



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- *Trustworthy and Private AI.*

  The focus of this line of work would be to build tools to check the validity of the output of AI models. Since the scope of this area will be enormous in the future, we aim to restrict our attention to the specific tasks for which the input and output behavior can be defined explicitly. This line of research falls at the intersection of property testing, sublinear algorithms and machine learning.

- *AI for Science*.

  One of the goals here is to address challenges in biology and predict intrinsic microbial metabolites that regulate host physiology. Other fields that we desire to explore include (i) Smart Agriculture; (ii) Early detection of eye diseases and hemoglobinopathies; (iii) Nucleic acid and Peptides-based therapeutic drugs for anticancer; (iv) Challenges in Chemistry - Clean, error free, easily interpretable NMR spectra, Machine Learning in Chemical Dynamics; (v) Challenges in Earth and Planetary Science - Earthquake detection; (vi) Challenges in Physics - Quantum many-body techniques, Weather and climate modeling, and Dynamic temperature evolution.

10.2 Long-term road map

Post-quantum cryptography: Much of current cryptography is based on problems which are believed to be difficult for classical computers to solve. However, quantum computers hold the potential for efficiently solving such problems and breaking the cryptography. Several new/additional problems which are expected to be resistant to quantum computers and on which post-quantum cryptography can be built are being considered with some of these being standardized. Given the need for cryptography which remains secure far into the future, post-quantum cryptography research and standardization efforts is an active area. As our understanding of the capabilities of quantum computing improves with time, this nascent area is expected to mature and remain highly relevant.

Quantum cryptography: It has been recognized from the early days of quantum computing that basing cryptography on quantum mechanical phenomena has the potential for delivering unconditional cryptography (i.e., cryptography which does not rely on assumptions of computational abilities of adversaries). Quantum cryptographic algorithms are expected to play important roles in a future Quantum Internet and is one of the fastest growing areas of research in quantum information science.

Formal methods and verification:

Most of the newer nuclear power plants have systems and equipment that are software controlled. The analog devices are being replaced by digital, software-based devices. Safety in these plants is of paramount importance and can include reactor protection or safety feature actuation. A conscious effort to deal with possible failures of these software systems and components operating on the nuclear power plants is necessary. Unlike some of the other domains where software is used, in nuclear reactors, the safety levels and requirements are very demanding.

Also as noted earlier, the soft landing of Chandrayaan-2 mission failed due to a software glitch. The Indian Space Research Organisation too can be keen on the use of formal methods to ensure correctness guarantees for the various software modules used in space research. The formal methods community in TIFR and IMSc would contribute in providing guidance to these requirements.

10.3 High Performance Computing Facilities – the next decade and beyond

High Performance Computing (HPC) related scientific research of DAE scientists spans over a very diverse range of sciences including: astrophysics and cosmology, biological sciences, chemical sciences, quantum many body physics, statistical physics, complex systems, nuclear and high energy physics, applicable mathematics, and even for string theory. In recent years, high performance computing has become an integral part of each of these subjects. For the fruitful implementation of big-science projects that Indian scientists are participating, one would anticipate a large demand for high performance computing. Moreover, recently Artificial Intelligence (AI) with Machine-Learning (ML) and Deep-Learning (DL) is becoming an important component in most of the above areas. It is highly anticipated that in the coming days there will be rapid expansion in computing intensive and data-driven field of research through these new directions.

Based on the experiences of peer institutions and R & D establishments worldwide, it appears that such allocation of individual resources is not necessarily optimal, since it misses out on the synergies that are derived from a unified computing resource centre. In view of this we envisage for a large data centre. This large data centre will be connected to all DAE institutes through dedicated fastest possible bandwidth lines.

Scientific areas that need HPC facilities:

Astrophysics and Cosmology

Astrophysics research in DAE is spread over almost all DAE-aided institutions including National Centre for Radio Astrophysics, Pune. The research areas also cover a broad spectrum-- from the nearby solar system to celestial objects in our Milky Way galaxy to the farthest corners of our Universe. This diversity in research topics has led to involvement in several observational mega-projects, such as Square Kilometre Array (SKA), LIGO India, and Thirty Meter Telescope (TMT).

Nuclear and Particle Physics:

Indian physicists are engaged in various nuclear and high energy physics experiments around the world including many inside India. These experiments collect a large amount of data that need to be analysed in the framework of numerical analysis utilizing a large computational resource. For example, often it is essential to have grid computing resources comprising a fast connection along with a large data-storage space and faster processors.

Theory: Strong Interactions Physics:

The computing usage of theoretical nuclear physics is mainly to investigate strong interaction physics. It has different components: first principles method of lattice gauge theory, hydrodynamical simulations, nuclear shell structure calculations, plasma simulations and the emerging field of machine learning. There is substantial presence of Indian physicists in these areas and they have made very important contributions to understand strong interactions physics.

Quantum many-body physics

Quantum Many-body Physics (QMP) encompasses the study of emergent phenomena in interacting quantum systems with a large number of degrees of freedom. Problems in quantum many-body physics require a wide range of tools, from analytical quantum field theory-based approaches, variational wavefunctions, large scale HPC with numerical methods like quantum Monte Carlo, exact diagonalization, DMFT, DMRG, Tensor Networks etc.

11. Fundamental Theoretical Physics

Traditionally, DAE has strongly supported fundamental theoretical physics, with its grant-in-aid institutions like

Harish-Chandra Research Institute, Institute of Mathematical Sciences,

Institute of Physics, National Institute of Science Education and Research, Saha Institute of Nuclear Physics, and Tata Institute of Fundamental Research

are carrying out theoretical research in many subareas of physics.

Fundamental theoretical physics plays a crucial role in understanding natural phenomena and contributes to various areas of science and technology. It studies Nature at widely different length scales, starting from sub-microscopic scales of femtometers to cosmological distances of gigaparsecs. It also spans time scales from beyond attoseconds to billions of years. Herein, some of the key visions of theoretical physicists in the DAE grant-in-aid institutions, for the next 25 years is presented.

- **Mega-scale:**
  - **Cosmology:** Deciphering the initial conditions of the Universe, discovering non-gravitational interactions of dark matter, nature of dark energy, formation of first stars and galaxies, testing the fundamental assumptions of the standard model of cosmology.
  - **Complex Flows and turbulence:** Analysing atmospheric and oceanic flows to understand the Indian monsoon and rainfall formation; understanding the role of turbulence in solar physics, supernova explosions and accretion disks.
- **Macroscale/Mesoscale:**
  - **Statistical Physics & Complex Systems:** Understanding the performance of living complex systems, e.g., enzymes, gene expression, active systems; designing new disordered and soft material functions via simulations and providing statistical physics tools to interdisciplinary applications.
  - **Quantum many-body physics:** Integrating quantum many body theory with computing tools, including quantum computing and AI-ML, for predicting the properties of interacting quantum systems.

- **Microscale:**
  - **High energy physics:** Establishing an end-to-end high energy physics program in India, focused on ``exploring the light hidden universe'' of weakly interacting particles.
  - **Strong interaction physics:** Simulating nuclear scattering processes from first principles, understanding dense matter such as neutron stars, phase transitions in the early Universe, controlling QCD uncertainties in high energy scatterings.
  - **Quantum gravity:** Understanding microstates of non-supersymmetric black holes, quantum dynamics of black holes, holography in AdS, flat and cosmological space times, reformulation of quantum field theory which makes the hidden global symmetries more manifest, string theory on cosmological space times.

The roadmap towards pursuing the above goals will include (i) generation of creative ideas and development of unified mathematical frameworks, (ii) analysing data from ongoing experiments efficiently and conceptualising future experiments, (iii) using large-scale numerical simulations for solving problems that are intractable by analytic means. In order to progress towards the fulfilment of the vision, one will need to facilitate the exchange of ideas within and across theoretical disciplines, close collaborations between theorists and experimentalists, availability of adequate computing resources, and training of next generation of young scientists. Investment in collaboration hubs, visitor programmes, high-performance computing data centres, and short-term advanced training schools is therefore crucial for achieving the goals stated in this document.

11.1 Scientific goals:

11.1.1 Cosmology:

Cosmology has seen tremendous breakthroughs and fundamental discoveries about the Universe over the last 100 years. The birth of modern cosmology can be traced to the *Great Debate* between Curtis and Shapley in 1920 about the scale or size of the Universe. The measurement of distances to the nearby galaxies by Hubble settled the debate and discovered the expansion of the Universe as predicted by Friedmann's solutions to Einstein's equations of general relativity. We have mapped the observable Universe in great detail from radio to X-ray wavelengths. The precise measurements of the cosmic microwave background, large scale structure in galaxy surveys, and measurement of distances to the distant galaxies using the Supernovae of type 1a has led to the establishment of the standard model of cosmology also called the ΛCDM model. The Λ and CDM (cold dark matter) in the name stand for two *confirmed* new constituents of the Universe (beyond the standard model of particle physics) discovered by cosmologists, namely dark energy and dark matter, respectively.

While we have made tremendous progress in understanding the origin and evolution of the Universe, Nature has also thrown up intriguing new questions about the Universe. There are numerous international experiments being planned in the next 25 years which should help in answering some of these questions. New theoretical understanding and data analysis tools would be needed to understand and interpret the deluge of data from the next generation of experiments. Some of the most important questions in cosmology are the following:

- **Early Universe:** What is the nature of the big bang? Was there Inflation in the beginning? The standard model of cosmology is consistent with the simplest models of inflation but details about the high energy theory of inflation and initial conditions before inflation remain elusive.

- **Dark Ages to Cosmic Dawn**: When and how did the First Stars form and ionize the Universe? How can we use the observations of this epoch to learn about fundamental physics?

- **Late-time Universe:** How do galaxies and the Cosmic Web form and evolve? What is the current accelerated expansion phase of the Universe telling us about fundamental physics? Is it due to the cosmological constant, a new fundamental particle field, or modification of gravity? Does Nature follow Einstein Gravity on large scales?

- **Cosmological Tensions:** There are many ways to measure the same cosmological parameters, e.g. using the cosmic microwave background, directly measuring the expansion history of the Universe, mapping the galaxy distribution in the Universe (large scale structure of the Universe), looking at absorption of light by intervening matter in the spectrum of distant quasars, etc. If the standard cosmological model is consistent and correct, all experiments should give the same values for these cosmological parameters. A disagreement between the different ways of measuring the same cosmological parameter then provides a clue to the physics and processes beyond the standard model of cosmology. Future experiments will also begin to test the fundamental assumptions of the Standard Model of Cosmology such as the cosmological principle.

- **Black Holes:** What is the origin of the stellar mass black holes in the universe observed in gravitational waves, and of the super massive black holes observed in radio, infra-red, x-ray and optical telescopes at high redshifts? How do the black holes evolve with time? Recent observations have shown that the supermassive black holes with masses higher than million solar masses exist at redshift $z \sim 10$, or when the age of the Universe was of order 100 million years. This poses an interesting problem of how such massive black holes are formed at such an early phase of the Universe. In particular, whether the existence of these black holes is consistent with the standard model of cosmology, or whether we need to invoke new physics is still an important open question.

- **The Local Universe:** What is the distribution of dark matter in the Milky Way and how does it affect the interpretation of data from the direct detection experiments? Since all efforts to detect dark matter have so far given negative results, we need to come up with new experiments for direct detection in laboratories and new signals for indirect detection of dark matter in astronomical observations. What role do neutrinos play in astronomical phenomena such as supernovae? How to use the next generation of neutrinos observatories to learn about the fundamental laws and astrophysical phenomena?

11.1.2 Complex Flows: atmospheric, oceanic and astrophysical:

Fluid flows drive physics at scales ranging from a few micrometres to galactic scales. The examples include atmospheric and geophysical flows as well as Astrophysical flows. Remarkably, in most cases, the governing equations are well-known but their solutions remain rather elusive. A key complication appears from the fact that when the inertial forces become dominant, the flow dynamics becomes turbulent wherein all length and timescales are excited. Thus, understanding turbulent flows in a variety of settings has been a central issue of interest in the last century. Thanks to recent advances in experimental techniques and the advent of high-performance computing, several questions of importance in this domain are now being addressed.

The expertise to tackle may of the above issues already exists in many parts of the DAE system. This may be brought together to address the following challenging questions:

- **Physics of droplet growth in warm clouds:** A warm tropical cloud is a turbulent suspension of aerosol and tiny water droplets in its simplest formulation. Rain initiation is an outcome of the dynamics of this suspension when the seed droplets grow to sizes of a 100 micron or so. Recent studies have underlined the importance of turbulence in accelerated growth of droplets in the coalescence phase. However, the bottleneck between the condensation (early phase) and the coalescence (late phase) growth is still poorly understood. This, along with the dynamics of ice crystals in higher latitude clouds, is a critical ingredient in not only understanding the microphysics of clouds but also in providing key inputs to large scale modelling of weather where the clouds form a building block. This is the right time to tackle this problem in all its complexity.

- **Interaction between turbulence and suspended micro-particles:** Typical studies of turbulent suspension focus on the one-way coupling of the effect of the flow on microparticles. With recent concerns on the fate of suspended micro-particles -- both in the ocean (marine snow and microplastics) and the atmosphere (pollutants) -- more detailed studies and predictions of their motion by factoring in every facet of their dynamics is critical. These would include the exploration of how such particles may affect flows, which in turn may lead to a different sampling of the flow by such particles. They would also address questions of transport of anisotropic particles, filaments and polymers.

- **Predicting the state of the atmosphere from sparse observations**: A mathematical framework may be built to address the question of state-estimation in dynamical systems associated with geophysical applications. In state-estimation, one tries to estimate the state of a system given (1) the dynamical equations, (2) observations of the system (functions of a trajectory). The latter nowadays includes high-resolution satellite imagery. This study will blend ideas from various disciplines including dynamical systems, control theory, machine learning and scientific computing.

- **Cyclone Diagnostics -- estimating the velocity-field from a cyclone track:** Cyclone-tracking methods often simulate the trajectory of a cyclone by assuming the state of the neighbouring air-ocean system (or some suitable approximation). Instead, we ask, to what extent does the trajectory of a cyclone determine the surrounding velocity field? This can be posed as a state-estimation problem which fits into the framework described above. The eventual goal is to infer the vertical vorticity distribution from other datasets (SST, cloud cover, etc.) and use these to drive the observer problem.

- **Bubbly flows:** Bubbles play a crucial role in mixing and heat transfer in various industrial and oceanic flows. Nevertheless, the fundamental understanding of the mechanisms governing mass and energy transfer in these systems remains elusive. The key challenge is to understand the turbulence generated in these flows and how it alters mass transfer.

- **Turbulent emulsions:** A catastrophic example of turbulent emulsions is the oil spills in oceans. How turbulent transport spreads oil, and what controls the size of oil droplets are some questions that have garnered the attention of scientists for the past few decades. However, with the advent of large-scale computing, the phenomenology of these processes is now being tested. A detailed understanding of the underlying multiphase flows remains elusive.

- **Jet formation in accretion disks:** Coherent magnetic fields in accretion disks facilitate angular momentum transport and formation of jets. They are thought to be generated and maintained by a turbulent dynamo, i.e. a mechanism that converts kinetic energy to magnetic energy. The open questions include how the dynamos operating in accretion disks help in jet formation and whether there are large-scale features that depict a correspondence between disk and jet mediated by dynamos. This will have a bearing on the interpretation of the observations from the Event Horizon Telescope.

- **Turbulent transport in weakly collisional plasmas like solar corona:** In spite of being extremely tenuous, hot and hence weakly collisional, the solar corona shows turbulent behaviour. The understanding of turbulent transport in such weakly collisional systems is one of the central problems in the field of plasma turbulence.

- **Turbulence in supernova explosions and neutrino physics:** After the shock wave formation and subsequent neutrino heating, the propagation of shock wave inside a core-collapse supernova leads to turbulence that can affect the explosion itself, as well as the flavour conversions of neutrinos that carry out almost 99% of the energy of the core collapse. Attacking this problem needs collaborations among astrophysicists and neutrino physicists.

11.1.3 Statistical Physics & Complex Systems:

At its core, statistical physics relies on the principles of probability theory and statistical analysis to study the collective behaviour of particles in systems that may contain trillions upon trillions of them. This approach allows us to tackle complex systems that would be otherwise impossible to analyse using traditional classical mechanics or quantum mechanics alone. Contemporary research on complex systems include the themes of emergence, complexity and organization that were mentioned by P. W. Andesron in his seminal paper ``More Is Different''. Over the years, there has been a paradigm shift from the traditional view to more towards neo-emergentism, a shift driven by the observations and phenomena from nature and largely made possible by innovative tools of empirical research and experimental design, as well as an impressive array of sophisticated mathematical and computational perspectives.

Some of the key questions in this area, that can help us identify the unifying principles and general truths in natural phenomena, are the following:

- **Fundamental nature of non-equilibrium phenomena:** While the formalism of equilibrium physics is established elegantly within the canonical Boltzmannian description, a unified understanding of non-equilibrium systems remains elusive although they appear ubiquitously in nature. For example, nonequilibrium processes are essential for fluid motions or sustaining life in a single cell, colloids, interacting particles, glasses to living systems such as bacteria, enzymes, macromolecules such as polymers and strongly interacting quantum matter. The major quest is for identifying universal physical and mathematical laws that may dictate fundamental limits and trade-offs governing the pattern and binding the performance of non-equilibrium systems. The questions to be addressed are how systems far from equilibrium approach their ordered steady state, or What the universality classes of non-equilibrium systems are?

- **Soft Condensed Matter, Chemical and Biological Systems:** The study of statistical mechanics of disordered and complex systems explores the emergent behaviours of systems with many interacting degrees of freedom, subjected to random interactions, or being immersed in a complex, chaotic or stochastic medium. These include aggregation, fragmentation, evaporation; diffusive and active transport phenomena; nonequilibrium thermodynamics of many body systems; dissipation in active matter and the living systems; charged polymers in solution, or polyelectrolytes; and structural & dynamical properties of water.

- **Disordered Systems and Amorphous Materials:** Understanding the dynamical and mechanical properties of amorphous materials, such as supercooled liquids, glasses, jammed materials, gels, and granular systems, is not only theoretically interesting, but also has applications in industry. Research on these materials involves studying the behaviour of glass-forming liquids, the structural relaxation and plastic response of a range of soft condensed materials, as well as granular materials and other amorphous solids in equilibrium and under external driving.

- **Emergent behaviour:** In some systems with a large number of components, the system-level properties cannot be predicted with knowledge of only the properties of its constituents; their emergence can only be understood with reference to interactions amongst the constituents. This emergent behaviour is observed in systems of interest in a wide range of disciplines: the cell, the brain, ecosystems, individual cognitive performance, markets, urban traffic flow, etc. the advent of affordable high-performance computing has made the exploration of such systems possible, with agent-based modelling having millions of interacting agents.

- **Synchrony:** Some networks of interacting systems with a range of frequencies are observed to undergo a transition to a state of synchronized behaviour. This emergent synchrony might help us to understand power-grid/communication-network failure and resilience, chimera states observed in neural/brain circuits, etc. From the point of view of statistical physics, the important questions is whether a unified framework can be developed by combining methods of non-equilibrium statistical physics and kinetic theory. Atomic ensembles interacting with the mode of a high-finesse resonator offer a unique platform to study the physics of long-range interacting systems, through the phenomena of optomechanical bistability, spontaneous spatial ordering, collective lasing, etc. Envisaged applications for these systems range from sensors to quantum enhanced metrology, quantum simulators and quantum optics.
- **Stochastic modelling of income dynamics:** Developing methods for studying the temporal properties of income dynamics, for example whether individuals can improve their income profiles within the socio-economic ladder in times comparable to their working life, is a fundamental question in the literature of economic inequality and mobility. This is where analytic frameworks built on stochastic modelling of income dynamics could be useful, for example, using the labour office data, one may try to answer questions such as: What is the time needed for a low-wage worker to spend in the

workforce in order to reach a reasonable income level? Which proportion of workers are able to reach the highest status during their working life? How easy it is for the workers to reach certain income targets? The methodology and the results emanating from such studies would be of wide interest to practitioners for developing policy interventions aimed at optimizing the time in the Indian economy. It would also motivate new multidisciplinary research focused on creating even more comprehensive methods that could be applied to economies all across the globe.

- **Interdisciplinary hub for complex systems:** The activities in the growing field of complex systems in India may be taken to the next level by establishing a key hub of research in complex systems. This unique centre is envisaged to carry out research on diverse topics such as intracellular signalling networks and their role during infection through pathogen invasion, social networks of individual contact and their role in the spreading of infectious diseases such as COVID, detecting rising systemic risk prior to a major financial crises or ecological catastrophe mediated by climate change, as well as, spatio-temporal pattern formation and its regulation that is crucial for development and functioning of many biological, ecological or social systems.

11.1.4 Quantum Many-body Physics

Quantum Many-body Physics (QMP) encompasses the study of emergent phenomena in interacting quantum systems with a large number of degrees of freedom. Historically QMP has been the birthplace of new ideas like symmetry breaking, Higgs-Anderson mechanism etc. which have impacted physics across scales. It has also been the generator of phenomena which have formed a crucial backbone of technology, from microprocessors to superconducting magnets to platforms for quantum computing. Traditionally phenomena in quantum materials have provided both the inspiration and the most versatile testing ground for new ideas in QMP. However, more recent platforms like ultracold atomic systems and quantum circuits have enlarged the ambit of the subject, bringing with them new phenomena and new paradigms.

Problems in QMP require a wide range of tools, from analytical quantum field theory-based approaches, variational wavefunctions, to numerical methods like quantum Monte Carlo, exact diagonalization, DMFT, DMRG, Tensor Network based methods etc. The DAE system has a versatile group of scientists with wide research interests and deep expertise in these areas. However, it is important to keep in mind that this is an arena where new phenomena are uncovered in experiments frequently. As a result, the “interesting” problems change, and this often requires new expertise. The quantum many-body theorists in DAE aided institutions would like to focus their future research on the following areas.

- **Topological Phases of Matter:** The traditional notion of classifying phases of matter by their symmetries has been updated with inclusion of their topological properties, leading to diverse topological phases of matter. These states are characterized by protected edge modes, robust quantized responses, fractionalized excitations with non-standard mutual statistics (in systems with topological order). In future, the research of DAE scientists would focus on

- o The interplay between symmetries and entanglement in topological phases of matter.
- o Analogues of topological order in classical systems using topological gauge theory.
- o Protocols for 'smoking-gun' detection of SPT phases (e.g. in curved space-time).
- o Non-hermiticity as a route to new topological phases in open quantum systems.

The long-term objective of this research would be to produce a complete framework for classification of phases of matter (even in strongly interacting systems) involving symmetry, topology and entanglement.

- **Heterostructures and Quantum Devices:** The experimental ability to create heterostructures, which creates boundaries between materials with different bulk properties, is the key to making devices for quantum technologies. It is thus imperative to study junctions of quantum many body systems in their own right. Some interesting heterostructures we propose to study are
  - o Junctions between recently discovered anomalous fractional quantum Hall systems (without magnetic field) and superconductors, which can exhibit parafermionic excitations.
  - o Interfaces of magnetic and non-magnetic materials leading to valleytronics, anomalous Hall effects etc.
  - o Interface of magnetic materials to enhance coercive fields and transition temperatures
  - o Interface of insulating materials (e.g. $LaAlO_3$-$SrTiO_3$) which shows metallic and even superconducting behaviour.

The goal of this research is to predict heterostructures with interesting properties relevant to quantum technologies, sometimes by mixing the properties of the materials forming the interface, sometimes by creating a junction with new properties not inherited from the parent materials.

- **Quantum Information:** A new paradigm is gradually evolving in quantum many-body physics where quantum information (QI) theoretic quantities like entanglement entropy, negativity etc. are used to characterize the many body states of matter. As the 2nd quantum revolution winds its way, we expect these connections to get deeper and provide a more fine-grained non-local description of states of matter. Some key issues of immediate interest are:

The connection between correlation functions and entanglement entropy, negativity etc; entanglement of excited states, and many-body localization in disordered systems; evolution of entanglement in closed and open quantum systems, driven floquet systems. This has implication for thermalization, dynamical phases of matter in ultracold atomic systems and NISQ computations; evolution of QI measures (entanglement, quantum magic etc.) in quantum circuits under hybrid dynamics involving unitary gates and projective measurements, relevant to preparation of quantum states with large resources; quantum error correction by storing information non-locally in states with large entanglement and entanglement phase transition.

- **Non-Equilibrium Quantum Dynamics** Non-equilibrium dynamics of quantum many body systems is a relatively virgin field with very few universal paradigms. Ultracold atoms, quantum materials in pump-probe setting and random circuits provide a versatile setup to study non equilibrium quantum dynamics. Our proposed research would use multiple techniques from large scale numeric to non-equilibrium field theories to
  - Classify dynamics where the system fails to thermalize at long times. What is the long-time fate of such a system? How does it depend on initial conditions?
  - Develop a general framework for understanding pump-probe spectroscopies. What are the signatures/features one should follow? How does one interpret these features?
  - Classify Floquet phases of matter in driven quantum systems.
  - Find general conditions for existence of long-lived prethermal phases of matter under quantum quenches. Classify non-equilibrium steady states which show larger versatility than equilibrium phases.
  - Study dynamics of open quantum systems. An important goal is to find sectors/properties of systems which are protected from runaway heating in these systems. This can be used for quantum state preparation in NISQs settings.

The long-term goal of this research is twofold: a theoretical goal to develop a framework where interesting dynamics can be described systematically by a few variables/degrees of freedom (akin to renormalization in equilibrium systems), and a practical/technological goal of developing protocols to temporally control bulk properties of many body systems to perform particular tasks.

The melange of problems in quantum many body physics cover a broad range of topics with import on fundamental physics as well as new quantum technologies. These dual goals will drive the efforts of the quantum many-body physics community in the DAE aided institutions in the years to come.

11.1.5 Physics of Strong Interactions

Strong interactions between quarks and gluons is a fundamental force in our universe. It is behind the emergence of almost all of the visible mass in the universe, and may also hold clues to understanding of dark matter. Comprehension of subatomic particle properties including much of nuclear physics and its full potential hinges on a deep understanding of this force. From the deconfined quark-gluon-plasma during the universe's early stages to its transition into subatomic particles via complex dynamics, and from the nuclear force shaping all nuclei to matter under extreme densities in astrophysical objects like neutron stars, a thorough comprehension of strong interactions is essential. A large class of experiments at several high energy laboratories, including the Large Hadron Collider and the future Facility for Antiproton and Ion Research as well as future Electron-Ion-Collider are linked to various aspects of strong interactions physics.

Quantum chromodynamics (QCD), an asymptotically free local non-abelian quantum gauge field theory, is the theory of strong interactions of nature. The strength of the interactions of the strong force changes with the energy being probed which has implications in wide ranges of physics.

QCD at high energy:

In high energy domain, where the coupling constant of QCD is small, analytical calculations based on QCD have been proved to be accurate enough to explain numerous experimental data. However, inclusion of predictions of higher-order quantum effects at fixed order in a perturbative expansion, and re-summation to all orders of specific classes of corrections are necessary to reach an accuracy at the 1% level for many important measured observables. Use of improved predictions will allow to extract the value of several SM parameters, such as the masses of the W and Higgs bosons or the couplings of the Higgs boson to all the other elementary particles and also its self-coupling with higher precision. In turn, the value of these parameters will provide guidance to understand the mechanism of spontaneous breaking of the electroweak symmetry. In addition, these predictions will help to explore any new physics. Our physics goals in these areas involve:

- Interpreting high-precision data at the colliders
- Multi-loop gluonic processes, calculations at higher orders in the strong coupling constant.

- Higher order QCD corrections to differential cross-sections in Higgs, Drell-Yan, semi-inclusive Deep Inelastic Scattering.
- Precision Higgs measurement at current and future colliders (LH, HLLHC and FCC).
- Study of jets and their substructures.

QCD at Low energy:

QCD in its low energy domain is non-perturbative and so far, there is no first principle analytical solution. Euclidean formulation of quantum field theory on space-time lattices, so called lattice gauge theory, has emerged as a very powerful method to solve QCD by using large scale computation. Such numerical computations, assisted by formalism of effective field theory, has become integral to understand the physics of strong interactions.

Our future research will comprise of a judicious use of the theoretical tools, supplemented with insights from experiments in order to understand the strong interaction physics in its various aspects, starting from the early universe to constructing tomography of nucleons. Using large scale high-performance scientific computing, new algorithms and analysis techniques will be constructed and predictions on strong interactions physics as well as other quantum systems will be made. Some of the investigations will comprise machine learning. Moreover, development of algorithms for study of this physics on quantum computers is a part of our strategy in that. Below are some of our physics goals.

Physics of early universe, quark-gluon-plasma, and dense matter: Here key questions involve the study of high-density phase of the strongly interacting matter, in particular, the existence of a critical point in the phase diagram of hadronic matter, as well as the role of symmetry breaking at different phases of matter, their dynamical properties, through a synergy of large-scale numerical studies, exploration of new algorithms, and the formalism of effective field theory. The dense matter such as neutron star as well as the hypothesised colour-glass-condensate are also subject of interests. State-of-the-art hydrodynamical numerical codes including large scale ML utilities will be employed for the study of quark-gluon-plasma.

Nuclear astrophysics: A vast area of cosmology and astrophysics are deeply connected to nuclear physics. Starting from QGP at early universe, big-bang nucleosynthesis to star-burning and formation of neutron star requires deeper understanding in nuclear physics. Formation of exotic nuclei such as hyper-triton and their implications in astrophysics also need to be understood. A strong collaboration between nuclear physics, astrophysics and cosmology is expected in the next decades.

Nuclear Physics from first-principles: A first principles study of the first few nuclei is also crucial to understand the formation of nuclei in the early universe, particularly to understand the carbon cycle. Study of nuclear scatterings, particularly involving light nuclei, employing lattice QCD frameworks, will be of immense importance to understand the nuclear reactions of light as well higher nuclei. Information on polarized fusion using lattice QCD could be helpful for energy production in fusion processes. With current expertise in DAE institutes, an immense progress can be made provided adequate computing resources are available.

Emergence of mass and spin, and tomography of proton: The emergence of mass and spin in subatomic particles is a fundamental question in our understanding of nature. In fact, the future Electron-Ion-Collider will investigate these aspects. Detailed theoretical studies comprising lattice QCD calculations are very much necessary along with the EIC experiments to obtain the tomography of nucleons and other hadrons, which may also lead to new technological developments including their applications to medical sciences.

Heavy hadrons, exotics, and beyond the standard model: A large number of exotic subatomic particles have recently been discovered with the valence quark content beyond the normal mesons and baryons. Our focus will be predicting more such states aiding their discovery. A crucial step involves the understanding of their structures and bindings with a broader goal of deciphering strong interactions at multiple scales and unlocking its full potential. Likewise, precision studies based on lattice QCD are essential for investigating new physics phenomena, including lepton flavour violation, the anomalous magnetic moment of the muon, neutrino less double beta-decay, and dark matter, among others.

Sign problem, algorithmic developments for quantum computers: For systems where dynamics is involved (e.g., equilibration of the quark-gluon-plasma produced in the heavy ion colliders or at early universe), or at high densities (properties of the matter inside neutron stars), the numerical methods based on classical computers require an exponentially large time with increment of sizes. To solve the impasse, known as *sign problem*, novel conceptual works, in conjunction with the development of quantum algorithms, will be one of the main focuses of our research.

Computing Resources: The most essential part for carrying out calculations in this area is the access to large-scale high-performance computing of the order of 100s of Petaflops.

11.1.6 High Energy Theory

India boasts a strong and diverse community of particle physicists, who have made significant contributions in varied topics ranging from formal theoretical physics to collider physics, to flavour physics; from neutrino physics to astroparticle physics. Particle physics, however, was and remains a subject dominated by large experiments, big facilities, and often develops/shapes/utilizes the very frontier of technological developments. Even though India has a healthy population of physicists who are world experts in many corners of the field and contribute non-trivially to efforts led by mainly Americans, Europeans, and Japanese collaborations, we do not currently have the overarching depth or the breath in experimental, technical, and theoretical topics which would allow us to have one such major facility and lead the world of research in the fundamental physics of nature. The main goal of this program would be to pave the path forward so that by 2047 we generate such capabilities in all these frontiers. Clearly, in order to face the enormity of this challenge, we need to develop a multi-dimensional approach.

The overall programme has to seamlessly intertwine experiments and theory / phenomenology. The detailed vision of this ``Indian End2End HEP programme'' has been presented in the White Paper for the HEP vision 2047 that has emerged out of the Chintan Shivirs of the Department of Atomic Energy, Government of India. In this document, we include specific points relevant specifically to theory and phenomenology.

The physics goal: Exploring the light hidden universe

The visible matter contributes less than 5% to the energy of our universe. Finding and exploring light/ultralight hidden sectors, which are feebly connected to our visible universe, represents the new frontier in particle physics. One can envision building on the current expertise of Indian scientists in this area to tackle this issue along the experimental, theoretical, as well as in the computational frontiers.

The Theoretical Frontier

The theoretical exploration of the light and/or hidden (semi-visible) sector involves building models to solve non-trivial problems such as the strong CP problem of QCD, the observed discrepancies in measurements of neutron lifetime, the observed vs. estimated measurements of (g-2) of muon and electron, anomalies observed in collider experiments, the yet-to-be pinned down particle physics properties of the dark matter, etc., as well as studying phenomenological consequences of these scenarios in the myriad of low energy experiments and in various astrophysical measurements. The challenges in the theoretical domain that are crucial for the ``light hidden universe'' programme include:

- systematically charting the space of high energy theories to be explored at the experimental setup(s) constructed,
- developing effective field theory techniques to derive low-energy observables from these theories,
- bringing in the material science knowledge base needed for understanding and constructing novel detectors,
- collaborations with experts in nuclear and atomic-molecular physics where sources involve collisions, and with those in cosmology and astrophysics for understanding detectors facing the sky, for understanding the flux and the background.

Deepening the talent pool in HEP

One of the biggest efforts to be taken by the program in this regard would be to increase the depth of the talent pool in the Indian HEP community by means of providing training at various levels as summarized below:

- A HEP database: A database of pedagogical HEP resources will be built, which will include courses taught by various experts as well as supplementary materials/resources that can help prepare students.
- A regularly recurring school for beginning HEP graduate students in experiment as well as theory, based on the model of the highly successful SERC/SERB schools, will be re-initiated.
- Recurring schools for highly specialized training, which will provide advanced and focussed training aimed at postdocs and advanced graduate students, will be initiated.

The Indian end-to-end HEP Programme

The programme exploring the light hidden universe will rely on the expertise and talents of the current state-of-the-art facilities such as the BARC, RRCAT, IUAC, IMSC, SINP, RRI, TIFR etc., will bring together experimentalists, theorists, and engineers from varying fields of high energy physics, nuclear physics, astrophysics, condensed-matter and atomic-molecular physics, and even experts from industries. The programme will have a clear roadmap with incremental goals, which at every stage will identify niche areas of R&D, take steps to generate expertise aimed towards attaining the final objective, and will engage in verticals ranging from designing/developing table top experiments, to designing and developing specialized hardware including quantum sensors, to building specialized simulations and algorithms (particularly, AI and quantum machine learning), etc. The developments on the experimental fronts need to have an overarching theoretical support, which would require large roles to be carried out by phenomenologists and theorists. The culmination of these efforts would be in having a world-leading HEP experiment on Indian soil, spearheaded as well as implemented from beginning to end by Indian scientists (with possible international collaboration), which will also help nurture, build and focus the talent pool in the area of high energy physics.

11.1.7 Quantum Gravity and String Theory

A fundamental problem in theoretical physics is the unification of the two foundational theories of modern physics, namely general relativity and quantum mechanics. The problem of quantum gravity has important implications to a wide variety of subjects, ranging from black holes to cosmology. Over the years, research in string theory has led to significant progress on this longstanding question. The AdS/CFT correspondence -- a framework for quantum gravity in asymptotically Anti-de Sitter spacetimes, which grew out of string theory, has led to a paradigm shift, where spacetime and gravity are viewed not as fundamental, but as emergent phenomena from the dynamics of a dual, microscopic quantum system. The next few decades of research in string theory hold great promise in terms of solving the problem of quantum gravity, building a new quantum picture of spacetime and making contact with cosmology. Some of these promising directions are detailed below:

Black Holes and String Theory

The Bekenstein-Hawking formula -- a remarkable formula which assigns an entropy to a macroscopic black hole proportional to the geometric area of the black hole horizon -- is at the heart of quantum gravity. General relativity shows that this entropy satisfies the laws of thermodynamics, but does not explain its statistical origin in terms of underlying microstates. One of the success stories of string theory is an explanation of this Bekenstein-Hawking entropy in the special case of certain supersymmetric extremal black holes in terms of the underlying quantum degrees of freedom corresponding to branes and strings. The macroscopic calculation involves finding a (charged, extremal) black hole solution in supergravity/string theory and computing its area, while the microscopic calculation involves counting quantum states of a system of branes and strings in flat spacetime with the same charges as the black hole. Actually, more is true -- in string theory, the Bekenstein-Hawking formula receives classical stringy corrections, as well as quantum corrections, thus making the matching between the microscopic and macroscopic computations highly non-trivial. Nevertheless, in some special cases, this matching has been accomplished with great precision[2]. Furthermore, the AdS/CFT correspondence has led to a vast generalization of black hole entropy formula via the celebrated Ryu-Takayanagi formula. This has resulted in, among other things, a modern understanding of the structure of quantum information in gravity in terms of quantum error correction, and a resolution of the long-standing black hole information problem.

Black holes hold a lot of promise for important developments in the near future. The interplay between the mathematics of modular forms and the physics of supersymmetric black holes will remain a fertile subject in the coming years. Exact calculations in supergravity using localization and insights from low-dimensional quantum gravity on the one hand, and on the other hand precision-counting of microstates via the supersymmetric index are very active areas of research and will likely lead to an increasingly precise understanding of the microstructure of black holes in string theory in the near future. However, much of the progress in understanding black holes in string theory so far has been in the context of supersymmetric extremal black holes. The next few decades of research on black holes will have to include a major effort to understand non-extremal black holes. Finally, the interplay between quantum information, computational complexity theory and black hole physics within the AdS/CFT.

In such cases, the supersymmetric index can be obtained in terms of modular forms and related objects. The most well-known example of this are quarter BPS black holes in N=4 string theories. In this case, the index is given by Fourier coefficients of Siegel Modular forms. On the macroscopic side, classical higher derivative corrections can be taken into account using Wald's formula. Sen's Quantum Entropy function is a proposal to include the quantum corrections.

Correspondence is a very active area of research, with the goal of achieving an increasingly precise quantum picture of spacetime. So far, this effort has largely focused on semi-classical gravity; in the coming years, it needs to be extended to included stringy and non-perturbative quantum corrections, with the long-term goal of having a quantum resolution of the black hole singularity.

Scattering Amplitudes and bootstrap

Scattering amplitude is a basic quantity used to study properties of elementary particles in collider experiments. The method for computing these amplitudes was discovered by Richard Feynman more than seventy years ago and even today, this is the state-of-the-art. However, summing over Feynman diagrams is not a simple job in most cases. The number of diagrams for even six or seven gluon tree-level amplitudes grows dramatically, and so calculating these amplitudes in QCD is a daunting task. In spite of these physicists have computed such amplitudes and the final answer is amazingly simple! One of the reasons for this is that the Feynman diagram technique often hides the underlying symmetries of a theory. For example, the mysterious relation between the scattering amplitudes of gravitons and gluons, known as the KLT relation, does not have any simple explanation in terms of field theory Feynman diagrams. This has led many people to believe that perhaps Feynman diagrams is not the best way of organizing the perturbative expansion in quantum field theory, and that a more efficient reformulation must exist.

In the last two decades a lot of progress has been made in understanding the structure of this putative reformulation; no coherent picture has emerged so far, but this remains an active area of work. Research in string scattering amplitudes, and in particular construction of twistor strings or other ``toy string theories'' which capture a sub-sector of gauge theory or gravity is one promising avenue to be pursued. Secondly, flat-space holography is a very active area of research which seeks to reformulate gauge and gravitational amplitudes in flat spacetime as correlation functions in a lower-dimensional quantum theory. One of the lessons to come out of this effort is that these amplitudes are invariant under large (infinite-dimensional) symmetry algebras, a powerful tool which can be used to constrain these amplitudes significantly. A relatively short-term goal will be to find the complete set of symmetries of tree level scattering amplitudes in gauge theories and gravity, to understand their representation theory, and to then apply this technique to loop amplitudes. A long-term goal will be to reformulate gravity in flat space as a lower-dimensional quantum system, thus also solving the problem of quantum gravity in flat spacetime. Finally, significant recent progress has also been made by trying to solve for amplitudes from general principles such as analyticity, unitarity and crossing symmetry under the bootstrap program, which promises to yield increasingly precise results in the coming years.

Cosmology and String Theory

We are currently living in a golden age for cosmology. The precise measurements of the power spectrum of density perturbations of the cosmic microwave background and the distribution of galaxies over the past 25 years has revealed striking patterns. The surprising discovery of the accelerated expansion of the universe in the present epoch has given rise to one of the the biggest puzzle in physics: dark energy. The standard model of cosmology together with inflation has been successful in providing fits to the data. At the same time, many fundamental questions remain, such as for instance the resolution of the big bang singularity, an explanation for the initial state of the universe, the structure of quantum mechanics in an accelerating universe, etc. Quantum gravity lies at the heart of many of these questions. A large number of new experiments probing the very earliest epoch of the universe will become operational in the next 25 years, likely ushering in a new wave of progress in the subject.

The big open question in this field is to study phases of early universe in quantum gravity and understand implications for the big bang singularity. In the absence of a complete theory of quantum gravity, toy models will play an important role. Lessons from the study of black-holes will also likely be important. Inflation has emerged as the leading explanation for the nature of the inhomogeneities in our Universe. Since it is well-appreciated that inflationary physics is sensitive to quantum gravity, embedding inflationary models in quantum gravity and its implications will be pursued. String theory provides a concrete framework to address some of the puzzles in cosmology. Compactifications, de Sitter vacua in string theory (the KKLT and related constructions), symmetries, time dependence and the role of quantum entanglement are all active areas of research. Finally, the observation of gravitational waves by the LIGO experiment has given us a completely new tool to probe nature. There are proposed experiments in a wide range of frequencies which will allow us to probe the cosmic history of the universe. Gravitational wave production from inflation, phase transitions in the early universe, cosmic strings and exotic phases of the very early universe and their phenomenological implications are some directions of research along these lines.

11.1.8 Quantum Field Theories on Quantum Computers

Quantum computing is emerging as the next major frontier of research and development. An integral part of that involves the development of algorithms which can be executed on quantum hardware. DAE family has a large number of scientists, along with strong presence in computer science and mathematics, whose expertise can be utilized in this endeavour benefiting the nation in the long run and also in achieving the goals of National Quantum Mission.

As quantum technology worldwide is undergoing outstanding development, parallel efforts are underway to identify classes of problems that can benefit from the so-called Quantum advantage. Strongly interacting systems in particle and condensed matter physics are natural candidates in this class, necessary not only to understand how our Universe works but also in the design of novel technology for the benefit of the society. Analytical understanding of such theories is limited, while numerical studies using classical computers face roadblocks and impede progress, especially while exploring physics at finite densities or in real times. The new paradigm of quantum computation is known to be free of conceptual roadblocks faced with classical methods, and limited only by the corresponding technological development. Over the last decade, global efforts have been put towards developing quantum algorithms (for both near-term and far-term devices) for simulating gauge theories on quantum platforms. This includes developing novel frameworks for such theories, proposing and implementing system on analog quantum architecture, developing algorithms for universal quantum computers and benchmarking the same on NISQ era devices as well as developing algorithms for benchmarking the same on state-of-the-art classical computational tools such as tensor network methods and novel Monte Carlo methods.

Our initial aim will be to explore and exploit quantum algorithms for addressing relevant problems in the NISQ era . Simultaneously we will be developing algorithms which we intend to employ for technology development. In DAE family we have experts from different areas of the theoretical sciences, namely computer sciences, condensed matter and statistical physics, nuclear and high energy physics, mathematical physics and string theory. We will also closely collaborate with our experimental colleagues to establish a quantum hub within DAE.

The activities in our vision are designed to bring together the collective wisdom and advancements in diverse areas of the theoretical sciences to advance specific end goals. Some of the activities that we envisaged are described below:

Structure and complexity of quantum states, their preparation and measurement:

An important step that must precede any quantum computation is the understanding of the structure and complexity of different states. Here we plan to go beyond the commonly used measures based on bipartite entanglement entropies and develop new measures such as multipartite entanglement entropies and departure from stabilizer states. These tools will help construct a ``heat map" of the Hilbert space showing the strength of the quantum resources (e.g. entanglement, coherence). This will be followed by exploration of different techniques based on projective measurements as well as unitary counterdiabatic evolution for accessing desirable states with greater quantum resources. This programme will be ultimately implemented with NISQ era processors with the goal of bettering entangled state preparation on classical simulators.

Error correcting codes from condensed matter, gravity and field theory:

A number of condensed matter systems such as those endowed with topological order (e.g., the Toric Code, quantum spin liquids) or others such as Sachdev-Ye-Kitaev model allow the realization of quantum qubits that are robust against local environmental perturbations. Lessons learnt from gravity and quantum field theories have enormously advanced our general understanding of quantum error correction and fault tolerant platforms. A key effort here is an interdisciplinary one of consolidating developments in these disparate areas and designing new robust error correcting codes.

Optimization strategies with quantum circuits:

Besides state characterization, preparation and measurement, the final ingredient in a quantum computation scheme concerns state manipulation. We will explore different strategies to optimize transport (with relevant constraints) of an initial state to a desired final one using local constraints and/or projections. This will include statistical inference schemes for learning random quantum circuits with specified end results.

Application - Quantum emulation:

The above proposed activities seek to advance our ability to study quantum states using ideas developed in different areas of physical sciences. Conversely, quantum processors will provide an ideal platform to advance the knowledge in the physical sciences. Some of the topics we will pursue are (a) simulation of entangled phases of matter, (b) study of string dynamics and topological qubits in gauge theory, (c) simulating scattering with quantum circuits, (d) simulating emergent spacetime with SYK model implementation, (e) studying measurement induced entanglement transitions, and (f) studies of topological states.

Commercialization - Quantum Linear Solvers:

One of our main goals would be to design and implement linear solvers on quantum processors and systematically scale up taking advantage of the progress we hope to make in state preparation, measurement and manipulation. Practical implementation on scale will require hybrid classical-quantum strategies whose relative proportions will be determined by the complexity of the linear system being studied. We will closely work with our industrial partner to commercialize the linear solver.

11.2 Proposed roadmap and expected outcomes

Though spanning across wide length and time scales, the study of theoretical physics uses many common techniques and mathematical frameworks. Indeed, questions at the cosmological scales often find their answers in the subatomic processes. The visions in different areas described in this document are therefore interwoven with each other and are interdependent in many instances.

12. Mathematical Sciences

The DAE mathematics portfolio has historical strengths in the areas of algebra, algebraic geometry, analysis, number theory, partial differential equations, representation theory, and Lie groups. Recently, we have added expertise in new subjects like probability and mathematical modelling. Several striking results and monumental achievements have been attained in the past decades. A very small sample of highlights include the study of vector bundles, algebraic groups including structural and arithmetic aspects, index theory for elliptic operators, and Diophantine questions innumber theory, especially Waring's problem. It is worth mentioning that India's strength in modern mathematics, especially in the early stages, has largely grown out of DAE AI's. In addition to forming the backbone of mathematical research in India, the DAE community has also been instrumental in the training of talented young people, across all levels of higher education. These efforts have already borne fruit a significant number of the mathematics faculty across the IIT's, IISER's and other leading institutions of the country have received their doctoral training at DAE institutions.

Our vision in this document, seeks to buttress, and amplify these two basic ideas. Namely, we wish to soar higher in our research aspirations and significantly increase our pedagogical footprint. Our research vision outlines some of the main themes and problems that will be pursued. We aim to add new areas of research to the DAE portfolio as well as engage with emerging technology such as Artificial Intelligence. Our training vision includes several new ideas, including a scaling up of 'Math Circles' as well as a new centre for women students, particularly from disadvantaged areas of the country.

12.1 Research Vision:

Algebra and Representation theory

The broad areas include Advanced Group theory, Infinite dimensional Lie algebras, Algebraic Combinatorics, (Galois) representation theory, and Langlands program

Advancing the theory of skew braces as a tool for classifying solutions of the Yang-Baxter equation, and as an independent subject encompassing several mathematical topics.

- Classification of irreducible integrable modules over infinite dimensional Lie algebras.
- Applying combinatorial methods to study problems in algebra, representation theory, and special functions.

The long-term goal is to understand different types of representation theories via a diverse set of methodologies along with several applications and interplay with different branches in Mathematics like Number theory, Geometry, etc.

Algebraic and Arithmetic Geometry

The broad Areas include Moduli Stacks, Algebraic K-theory, Motivic homotopy theory, Derived algebraic geometry, and enumerative geometry. Topics planned to study are: Period index problem over number fields; Understanding Brauer groups of algebraic stacks, Quiver varieties, and their moduli spaces Developments on Chern-Simons theory and their algebraic versions; Computing Gromov-Witten invariants of the quintic threefold by interpreting it as a relative Gromov-Witten invariant in enumerative geometry; A good theory of the Arithmetic cycles of a smooth open variety, Constructing mirrors of moduli spaces via cluster charts and applications to the Atiyah-Floer conjecture, and Constructing new homology theories for algebraic varieties using unstable motivic algebraic topology. Expertise to be developed are Algebraic K-theory, Algebraic stacks, Cohomological methods in algebraic geometry, Enumerative geometry, and Motivic homotopy theory

The long-term aim is to study fundamental questions and conjectures in algebraic and arithmetic geometry using homological and homotopical methods.

Analysis of Partial differential equations (PDE)

PDE arise in various models in engineering, natural sciences, and other branches of mathematics like geometry. Most of these equations are highly nonlinear and complex and finding an explicit solution to these problems is almost impossible. In view of this, the analysis of partial differential equations becomes extremely important especially due to their applications and various mathematical challenges it poses. There is no unified theory about PDEs and the mathematical tools needed to analyse equations vary quite a bit from one to the other. Based on the expertise available in DAE institutions at present some of the topics planned for study are:

- Fluid dynamics Equations, Fluid solid Interactions, and homogenization
- Elliptic and Parabolic equations, PDEs from Geometry
- Control Theory, Inverse Problems

The main focus of research will be to resolve major open questions in many of the subareas. The other focus will be to scale up the training and research programs to address the shortage of manpower for research in these areas.

Scientific computation and Applications

Scientific computation of PDEs addresses the issue of developing numerical schemes preserving the essential features of the model involved. It is also important to develop numerical schemes which are computationally less expensive. The aim is to develop novel, accurate, and robust algorithms for various non-linear PDE models that arise in modelling flow problems.

On the application front, we plan to focus on some of the relevant topics like Oceanic flows, weather, data problems, etc. Some of the future goals are:

- Developing models for oceanographic flows capturing turbulent multiscale flows in the ocean.
- Oceanic flows transfer energy from 1000 km scales to cm scales. This energy transfer is difficult to resolve with existing partial differential equation models. The plan is to develop stochastic reduced models using wave turbulence phenomenological understanding to decipher energy transfer across so many spatial scales.
- Develop a mathematical framework to combine observational data and dynamical systems to solve problems in state and parameter estimation. The broader goal of developing mathematics is to "learn dynamical systems from data"
- Establishing the mathematics of parameterizations used in weather and climate models using the Koopman operator framework.

Dynamics

The strengths include Ergodic theory, holomorphic dynamics, and homogeneous dynamics.

Research highlights and goals are:

- Investigation of Teichmüller spaces from several complex variable viewpoint.
- Developing a unified theory of various branches of conformal dynamics: rationalmaps, Kleinian groups, and algebraic correspondences.

- Studying geometric and ergodic-theoretic properties of thin subgroups of semi-simple Lie groups, enlarging on the class of lattice subgroups.
- Periodic tilings.
- Study of irreversible non-commutative dynamical systems with possible applications to quantum information theory, physics, and computer science.
- Classify q-Araki-Woods von Neumann algebras and study of the von Neumann algebras associated with locally compact groups.

Geometry

The strengths include Differential, Riemannian, symplectic, hyperbolic, complex,and geometric group theory.

Research highlights and goals are:

- Various topics in Riemannian and Finsler geometry.
- Questions in geometric analysis, gauge theory, and calibrated geometries, Existence and classification of symplectic structures, and their interactions with contact and symplectic topology, enumerative geometry, Gromov-Witteninvariants, etc.
- New areas at the interface of algebra and analysis including CAT (0) cube complexes, generalizations of hyperbolicity, and measured group theory.
- Automorphisms of free groups.
- Study of groups in low-dimensional topology using techniques from combinatorial group theory.
- Questions in complex geometry and Geometric PDEs

Number theory

The strengths include Algebraic, Analytic, Arithmetic, combinatorial Transcendence and Modular forms.

Ongoing/Upcoming research highlights are:

- Class number problem and its link to Artin's primitive root conjecture, Brauer-Siegel conjecture and Lenstra's work on Euclidean ideal classes.

- Growth, non-vanishing, periods as special values and distribution of zeros of *L*-functions in their various avatars.
- Studying arithmetic of Fourier-coefficients of modular functions through Atkin - Serre conjecture, Lehmer's conjecture, differential operators.
- Studying values of elliptic curves using quasi-periodic functions.
- Analytic methods like Poissonian correlations among various interesting arith-metic sequences or discrepancies in the prime number theorem.
- Exploring Diophantine geometry via the recent work of Pila-Tsimerman on Singular Moduli or via Lehmer's conjecture.
- Studying the Langlands programme in all its varied aspects (global, local and geometric).
- Exploring the Iwasawa theory of higher dimensional Galois representations.
- Studying (integral) *p*-adic Hodge theory and *p*-adic Galois representations using Prismatic co-homology and analytic geometry.

The long-term goal is to understand and explore the interplay between arithmetic,analytic and transcendental aspects of number theory to address some of the long-standing open problems as well as to strive for applications in real life.

Probability

The strengths include Percolation theory, random matrix theory, and stochasticanalysis.

Research highlights and goals are:

- Various topics in random geometry, random polynomials, rough path theory, Gaussian multiplicative chaos, and branching Brownian motion.
- Quantum field theories as continuum limits of lattice spin models from thepoint of view of probability theory.
- Understanding of stochastic processes on braided compact quantum groups; and potential connections between Anyonic quantum permutation groups andnon-local games.

One of the long-term goals is "Gender imbalance improvement". This is one of the major existing pressing issues inthe current mathematical community is gender imbalance. To address this complicated issue, we plan to implement several strategies in multiple fonts.The idea of having the program "Vigyan Vidushi" is a step towards this direction.

We also plan to approach the problem from the ground-root level by creating a center for women in Chennai to train underprivileged female students from rural and remote areas. The main focus will be to offer a 4-year BS program in Mathematics in cognizance of the new NEP.

13. Health Science Research

Researchers from DAE-aided institutions working in the field of health sciences gathered at the DAE Chintan Shivir, to deliberate on a roadmap for health sciences. This initiative aims to contribute towards achieving the goal of a Swasth and Viksit Bharat by 2047. DAE-aided institutions are engaged in cutting-edge basic and translational research in the field of health sciences. Building on the achievements of the multidisciplinary expertise across other institutions, the health science theme proposes this roadmap towards a Viksit Bharat by 2047.

A major focus will remain on research, capacity building, and technology development to ensure affordable, high-quality, pan-India health particularly by leveraging digital technology. A central theme will be affordable, holistic healthcare based on the "One Health, One Solution" paradigm. In the health sector, DAE institutions have also proposed several other initiatives that can be developed to deliver affordable health outcomes for every resident of India. With the existing infrastructure and past achievements, we propose new programs, such as establishing centres for Infectious Diseases and Metabolic Syndromes (IDMS) and drug discovery.

The aforementioned vision is based on established national wisdom, expertise, and a robust knowledge base. Evolutionary or Darwinian medicine is a crucial aspect of medicine that should be incorporated into curricula. Many diseases and most physiological reactions we observe exist because of natural selection's role in protecting us. For example, responses like fever or vomiting are precautionary measures to clear infections or foreign objects. Similarly, possessing a single genetic variant for thalassemia may offer protection against malaria, making it advantageous. Furthermore, conditions such as insulin resistance, type-2 diabetes, or obesity may have emerged and become endemic due to rapid lifestyle changes and the inability of our physiology to adapt quickly. Addressing these diseases requires a different approach, one that can only be understood through the lens of natural selection. The dichotomy between traditional diagnostic and intervention strategies is counterproductive in light of natural selection. This programme has been developed by striking a balance between evolutionary medicine and traditional therapeutic approaches.

13.1 A Centre (IDMS) for Infectious Diseases (ID) and Metabolic Syndromes (MS)

Establishment of a clinical and therapeutic centre dedicated to research and treatment in Infectious Diseases (ID) and Metabolic Syndromes (MS) is proposed herein. The outbreak of COVID-19 highlighted the need for a more critical focus on infectious diseases beyond the traditionally recognized conditions like malaria, TB, and dengue. The pandemic also revealed that individuals with comorbidities such as lung conditions or cardiovascular diseases (CVD) were at a higher risk, underscoring the importance of addressing these factors.

Globally, CVD remains the leading cause of morbidity and mortality, and many of these conditions, including metabolic syndrome, play a crucial role in determining disease outcomes and mortality. Similarly, morbidity and mortality in cancer patients are often influenced by comorbidities like obesity and type 2 diabetes (T2D). A systematic analysis, supported by state-of-the-art facilities, is necessary to understand the aetiology of these conditions and develop effective interventions.

NISER is well-positioned with the technical know-how and facilities to undertake this initiative. Still, it will need to recruit clinicians specializing in ID and MS. Just as DAE pioneered the development of a robust system for cancer therapy, we now propose the establishment of an IDMS clinic and research centre. This centre will be staffed with world-renowned clinicians and researchers and will start with ten clinicians, 20 nurses, and other auxiliary staff members for a 200-bed facility. The centre will feature state-of-the-art diagnostic and care facilities.

13.2 Big Data and Digital Healthcare

In the rapidly evolving landscape of health research and treatment, harnessing the power of big data is essential for advancing our understanding of diseases and improving patient outcomes. Electronic Medical Records (EMR) are crucial for capturing and maintaining individuals' health and clinical treatment records over time. There is a pressing need for indigenous and advanced software-based management systems to systematically compile electronic records of patients in public hospitals. As these medical records are created, gathered, managed, and accessed by authorized clinicians and staff within or across healthcare organizations, EMR software must be designed to meet the specific needs of medical professionals. A cloud-based EMR system holds the potential to benefit patients, clinicians, and healthcare facilities within and across organizations, all while ensuring patient privacy and data security. This indigenous EMR solution could be commercialized to healthcare providers across India, generating revenue streams to support self-sufficiency. Simultaneously, the de-identified data collected could promote research and enable computational/AI projects to derive insights that improve cancer diagnosis, treatment, and outcomes. It is crucial that EMR data strictly adhere to the principles of being Findable, Accessible, Interoperable, and Reusable (FAIR). Significant effort will be needed to transform existing unstructured health records in government hospitals into FAIR-compliant EMR data. Researchers from ICTS-TIFR, IMSc, and IPR, who have experience handling Big Data and AI-ML, propose collaborating with TMC to create this comprehensive EMR database of cancer patients also. Once fully functional, the compiled data will be invaluable for AI-based health analytics research, helping to uncover genetic susceptibility, predict risk and prognosis, and prioritize healthcare resources.

13.3 Artificial Intelligence (AI) and Computational Biology

Artificial Intelligence (AI), Machine Learning (ML), and Computational Biology are poised to play increasingly critical roles in health sciences. Integrating AI into the Indian healthcare system is advantageous and essential to address the unique challenges posed by the country's diverse population, occupations, and regions. Specific areas where AI and Computational Biology will contribute include:

Data Entry and Documentation: AI-assisted tools can automate the manual entry process by extracting relevant patient information from printed documents.

Natural Language Processing (NLP): Large Language Models (LLMs) are increasingly used to extract and summarize texts/notes in various domains. Similarly, these models can extract valuable medical information from clinical notes, pathology reports, and other unstructured text data within EMRs.

Telemedicine: AI-assisted applications can enhance telemedicine services, particularly in situations where the patient and doctor do not share a common language, by facilitating communication and understanding.

Clinical Decision Support: AI-ML-powered tools can analyse real-time patient data, such as blood pressure, sugar levels, and other critical indicators, to provide clinical decision support to healthcare providers. For example, by leveraging patient EMRs, AI can alert clinicians to potential drug interactions.

Predictive Analytics: AI-ML tools can predict patient outcomes when trained on large EMR datasets. These tools can help identify individuals at risk of developing certain conditions, monitor disease progression, and more.

Image Analytics for Digital Pathology and Radiology: AI tools can assist in efficiently and accurately interpreting medical images. For instance, researchers at IPR have developed DeepCxR, an AI-based software in collaboration with ICMR Delhi that performs automated detection of pulmonary tuberculosis and other chest ailments using chest X-ray images. Soon, such predictive tools will be instrumental in screening and diagnosing cancer.

Drug Discovery: Computational methods, including AI, are expected to play an increasingly significant role in drug discovery, particularly in identifying new small molecules and peptides, as will be elaborated in a later section on drug discovery.

Researchers at IMSc, IPR, NISER, and TIFR possess Computational Biology and Data Science expertise, including AI-ML. We anticipate significant collaboration between these computational biologists, data scientists, chemists developing drugs and diagnostics, and clinicians at TMC in advancing this research area.

13.4 Accurate and Affordable Diagnostics

- **Biomolecular- and Microbiome-based diagnostics**

  Tumour-derived exosomes present a promising avenue for cancer diagnostics and therapeutics due to their numerous advantages. These include their high abundance, stability, diverse molecular cargo, and the ability to isolate them from any biological fluid multiple times during treatment in a non-invasive manner, thereby overcoming the limitations of traditional solid biopsies. Moreover, by leveraging the unique properties of exosomes—such as their structure and cargo—they can be further engineered for cancer theragnostic, offering high targeting specificity and efficacy.

  Researchers at NISER have developed a prototype test known as the **Gut Function Test (GFT)**, which requires only a single finger prick, like a glucometer test for diabetes, to provide a blood spot on a DBS card. The sample is then analysed using ultra-sensitive methodologies to generate a list of molecular markers that can reveal the status of various physiological functions and predict the entire gut microbiome. By employing an AI-ML-based training set, the results can categorize an individual for one or multiple diseases and recommend plausible interventions or supplemental strategies for clinical decision-making. This test is cost-effective and affordable for the general population in India and eliminates the need for faecal material collection.

- **Molecular probes for rapid diagnostics:** The development of multiplexed diagnostics will be a key focus area. Molecular scaffolds for multi-biomarker detection will be invaluable in diagnosing complex diseases where a single biomarker is insufficient for guiding therapeutic intervention. TIFR Chemical Science researchers are working on novel tools for multiplexed diagnostics within this context. Complex diseases like cancer, which exhibit numerous variants, also require companion diagnostics to assist clinicians in determining therapeutic routes, performing rapid and robust drug screening assays, and identifying the most relevant patient sub-groups during clinical trials. A diagnostic agent would rely on identifying metabolites and proteins; hence, computational tools for proteins can guide effective design.

- **Large-scale imaging-based early detection tools:** Over the coming years, we aim to develop and test prototypes of silicon (Si) and gaseous detectors for medical imaging applications. The long-term goal is to create indigenous, cost-effective imaging modalities that can be deployed in rural and urban hospitals across India. This initiative will be phased according to every five-year plan: (i) the research and development phase, (ii) the system optimization phase, (iii) the pre-clinical prototype development and testing phase, and (iv) the clinical prototype phase.

13.5 Drug Discovery and Repurposing

India has long been a global leader in producing affordable generic drugs and making medicines accessible worldwide. The COVID-19 pandemic demonstrated how inclusive programs that harness India's vast scientific community can unite industry and government to achieve formidable goals. For an AtmaNirbhar and Swasth Bharat in the face of emerging diseases, rising cancer incidence, and antimicrobial resistance, it is crucial to establish collaborative drug discovery initiatives that incorporate repurposing and intelligent design, leveraging traditional knowledge from Ayurveda and other Indian systems of medicine.

A primary approach will involve employing AI-ML-based de novo drug design methods. A Network Pharmacology approach across DAE institutions (e.g., TIFR, IMSc, CEBS) would collaboratively use computational biology and chemistry to screen natural products from traditional Indian medicinal formulations and laboratory-synthesized therapeutically active compounds. This approach not only facilitates the prediction of novel lead molecules or the repurposing of existing ones (including phytocompounds) to treat various diseases but also provides insights into the probable mechanisms of action and toxicity of drug candidates. IMSc has developed a comprehensive resource, IMPPAT, which compiles phytochemical constituents from over 4,000 Indian medicinal plants used in traditional medicine, serving as a precursor to these efforts. The predictions derived from these methods must be validated in disease models.

A key focus area in novel drug development will be creating multi-targeted drugs for managing diseases with complex pathologies, particularly cancers. Researchers at TIFR, Mumbai, are developing clinically viable novel candidate drugs to counter multiple pathological processes, overcome chemoresistance in cancers, and reduce the side effects of current cancer therapies. Multifactorial diseases like cancer are often resilient to single-target drugs due to resistance mechanisms that either pre-exist or are activated as a compensatory response. Drug resistance is responsible for most relapses and cancer-related deaths. The shift from mono-target therapy to multi-target therapy in cancer treatment represents a pivotal strategy for enhancing the efficacy of anticancer chemotherapy. TIFR, Mumbai, proposes to establish a rapid drug and diagnostics development and preclinical screening facility within its Chemical Sciences division to support the creation of indigenous and affordable drugs and diagnostics.

To effectively screen the vast diversity of natural products available through Indian knowledge systems, CEBS proposes a Networked Drug Discovery (NeDD) model. This model will merge efforts across the country's university ecosystems with DAE facilities. CEBS and NISER have already developed frugal, cost-effective disease models in organisms such as yeast, algae (Chlamydomonas), and Drosophila, using principles of sequence conservation or by humanizing simple transgenic models. These models, which are inexpensive to culture in common laboratory settings, could enable university-college laboratories and start-ups to participate in high-throughput drug screens, fostering a sense of ownership and national pride.

Additionally, SINP plans to develop complex, hierarchical, high-precision, and highly controllable 3D bioprinted tissue structures of tumours. These models aim to replace animal testing with more physiologically relevant in vitro models, allowing for the assessment of tumour invasiveness, metastatic potential, and the therapeutic efficacy of drugs. This approach will also aid in developing methods for biomarker identification and creating metabolic sensors for other cancer-related studies. ACTREC-TMC, through its Anti-Cancer Drug Screening Facility (ACDSF), has established a wide range of human tumour cell lines, murine tumour models, and xenograft models for small molecule screening. However, a critical limitation is the absence of Indian patient-derived cell lines. To address this gap, ACTREC-TMC plans to establish a state-of-the-art drug discovery centre, the 'Centre for Innovation in Emerging Medicines (CIEM).'

There are several existing inexpensive drugs (e.g., aspirin, metformin, propranolol, progesterone, statins) that exhibit potential anti-cancer activities in various common cancers, including breast, cervical, oral, lung, and gastrointestinal cancers. These drugs could contribute to a 4-5% improvement in eligible patients' long-term survival. If about 250,000 non-metastatic and 100,000 metastatic patients could benefit from 5-6 such drugs, there would be significant cost savings and an extension of lives. In addition to preclinical facilities, TMC units plan to establish highly sophisticated centres capable of planning, initiating, executing, and analysing large, definitive clinical trials.

13.6 Indigenous Technology for AtmaNirbhar Bharat

- **Biomedical waste management:** Plasma pyrolysis-based biomedical waste disposal plants will cover all 100 smart cities by 2047 through technology transfer partners. Plant capacity will be calculated at 5 TPD for a town the size of Varanasi (~50 lakhs population).

- **Plasma-based Air Sanitization:** The plasma application for air sanitization involves generating reactive species that can effectively deactivate or destroy airborne pathogens. IPR, in collaboration with the Centre for Cellular and Molecular Platforms (C-CAMP), has co-developed a cold atmospheric plasma (CAP) based air disinfection device.

- **Indigenous Nuclear radiation detectors**

  TMC will collaborate with TIFR to develop next-generation radiation detectors, leveraging TMC's clinical expertise and TIFR's cutting-edge research capabilities. The partnership is expected to yield innovative detectors with enhanced sensitivity and spatial resolution, potentially transforming cancer diagnostics and treatment monitoring at an affordable cost. Integrating artificial intelligence into detector systems could enable real-time data processing and adaptive imaging protocols.

- **Indigenous production of high-grade medical equipment**

  DAE may aim to revolutionize India's healthcare technology sector by focusing on the indigenous development of advanced medical equipment. This ambitious initiative aims to create indigenous radiotherapy machines, CT scanners, MRI systems, Surgical robots and ventilators, among other crucial devices (dual-energy linear accelerator costs around 25 crores, dual-energy CT scan costs around eight crores, and MRI machine costs around 16 crores). This will significantly reduce the cost of diagnosis and treatment, making advanced healthcare more accessible to our population. Customized solutions better suited to local needs and conditions will be developed, potentially improving patient outcomes while reducing healthcare costs across the board.

13.7 Environment and Health

- **Linking Exposome, including Air Pollution and Climate to Human Diseases:** With the significant increase in pollution and the effects of climate change, it has become essential to understand better the impact of environmental exposures—the "exposome"—on human health. The Institute of Mathematical Sciences (IMSc) has substantially contributed to compiling, curating, and exploring environmental chemical spaces implicated in endocrine disruption, cancer, neurotoxicity, and vitiligo. It is aimed to identify and characterize environmental factors specific to India that contribute to diseases such as cancer, diabetes, and reproductive disorders. By leveraging toxico-genomics and AI-ML, it is planned to develop adverse outcome pathways and predictive toxicity models for environmental chemicals (e.g., pesticides, heavy metals, microplastics) and non-chemical stressors such as viruses and radiation. Researchers from IMSc, TMC, NISER, and SINP will collaborate to advance this critical research.

- **Nutrition and Health:** As globalization progresses, there is a renewed interest in plant-based protein sources, particularly sustainable and nutritious options like legumes. We are currently working on improving the mung bean for sustainability in the context of climate change, screening approximately 214 genotypes. Additionally, we aim to identify and assess the health benefits of under-recognized, nutritionally enriched legumes of tribal origin. Our expertise in this area will be further applied to manipulating light signalling to enhance nutrient content. Moreover, we plan to increase anthocyanins and vitamins in tomato fruits to promote human health.

- **Epidemiology:** The growing burden of cancer in India represents a significant healthcare challenge. According to the International Agency for Research on Cancer's GLOBOCAN project, the incidence of cancer in India is projected to rise from 1.3 million cases in 2018 to approximately 1.7 million by 2035. Although age-adjusted cancer rates in urban and rural India have remained constant over the decades, the absolute number of new cancer diagnoses continues to rise. This increase is primarily due to population growth, longer life expectancy, and lifestyle changes transforming rural populations into semi-urban and semi-urban populations into urban populations. Equally concerning is the projected rise in cancer deaths, expected to increase from 0.88 million in 2018 to 1.3 million by 2035. As a result, India must prepare itself to address the escalating cancer burden.

14. Cancer Care

Health is a crucial pillar for the maintenance and sustainable development of the country. A nation can only thrive if its population is healthy, which is a significant challenge for a country like India being the most populous in the world. Through the Tata Memorial Centre (TMC), DAE has substantially contributed in providing affordable, high-quality cancer care to the Indian population across various strata of the society.

14.1 High-Quality and Affordable Cancer Care Across Bharat

(a) National Cancer Control Program

In 2022, the projected number of new cancer cases in India was 1.46 million, with a crude incidence rate of 100.4 per 100,000 individuals. Cancer deaths are expected to rise from 0.88 million in 2018 to 1.83 million by 2047, making it imperative for India to prepare itself to address this significant healthcare challenge. The Tata Memorial Centre (TMC), India's oldest and largest cancer centre, has spearheaded the systematic National Cancer Control Program to ensure high-quality, affordable, and standardized cancer care across the country.

A key focus remains on preventing common cancers, particularly those affecting the oral cavity, cervix, and lungs. Tobacco usages and obesity are significant contributors to cancer, both of which are preventable. It is crucial to prioritize early cancer detection by raising awareness among the public and primary care physicians, including alternative medicine practitioners and traditional healers. Currently, the private sector provides over two-thirds of cancer care in India. To make quality cancer care accessible to all sections of society, it is important to expand cancer treatment facilities across different regions of India and establish additional government-run centres. Further attention is needed in palliative care, survivorship, and patient advocacy. A dual approach is required for planning a systematic national cancer control program. Firstly, there is a need to ensure uniform standards of cancer care across India by strengthening existing centres. Secondly, additional government-run cancer centres must be established to address gaps in access across various regions. TMC would lead the creation of a national network of palliative care departments within its hospitals and other institutions. This network will promote evidence-based practice, training, education, research, and access to services throughout India.

The National Cancer Grid (NCG), a DAE initiative launched in 2012, successfully implemented the first approach. NCG's broad vision includes establishing uniform standards of patient care for preventing, diagnosing, and treating cancer, creating adequately trained human resources, and facilitating collaborative basic, translational, and clinical research in cancer. NCG has revolutionized cancer care in India by establishing the world's largest cancer network, comprising over 200 cancer centres, research institutes, patient advocacy groups, charitable organizations, and professional societies. The organizations associated with NCG provide treatment to over 700,000 new cancer patients annually, which accounts for over 60% of India's cancer burden. Uniform standards of patient care are being implemented nationwide by adopting evidence-based treatment guidelines. NCG also evaluates adherence to these guidelines through institutional peer reviews of the participating centres. Quality assurance programs in surgical pathology and radiation oncology are also being planned. By incorporating all cancer care stakeholders in India, NCG has become a strong, unified, and powerful voice in the fight against cancer. Further expansion and deeper integration of the National Cancer Grid to ensure uniform standards of cancer care is being proposed, aiming to cover more than 90% of cancer patients across India

The second approach involves the Hub and Spoke healthcare delivery model, which ensures high-quality cancer care is accessible to people close to their homes. This model provides familiar and less complex cancer care at local centres ('spokes'), while uncommon cancers and those requiring complex treatment protocols are managed at expert centres of excellence ('hubs'). To avoid overburdening the hubs, the spokes must be adequately equipped to handle common and less complex cancer types prevalent in the region. This strategy effectively minimises costs and reduces inconvenience for patients and their families. Care delivery would be carried out at the spokes as much as possible, with treatment planning, even for uncommon cancers, done at the hubs and actual treatment delivered at the spokes. Hubs will be comprehensive cancer facilities with state-of-the-art equipment, infrastructure, and expert human resources capable of treating all types of cancer. Each hub is envisioned as a 300-bed facility, with an estimated cost of Rs. 750 crores and an annual recurring expenditure of Rs. 120 crores, covering a population of approximately 4 crores, i.e., an estimated cancer burden of around 40,000 new patients annually. A spoke is envisioned as a 100-bed facility, built at an estimated cost of Rs. 300 crores and an annual recurring expenditure of Rs. 40 crores, covering a population of approximately one crore, i.e., an estimated cancer burden of around 10,000 new patients annually. Highly complex treatments, such as bone marrow transplants, complex surgical interventions, and high-end radiation, will not be available at the spokes. All existing TMC centres should act as hubs, guiding neighbouring states in developing spokes.

The proposed Hub and Spoke model would ensure that the entire Indian population can access affordable, high-quality cancer care. This model will establish sufficient hubs in all Indian states equipped with advanced cancer treatment facilities. These facilities will be designed to handle approximately 2.1 to 2.5 million new cancer cases annually, with a prevalence of 3 to 4 times that number, which is the projected cancer incidence and prevalence in India over the next 15-25 years.

(b) Therapeutic Nuclear Medicine in Oncology

Significant gap exists between the demand for, and availability of dose isotope therapy beds, which are crucial for treating cancers such as neuroendocrine tumours, thyroid cancer, and neuroblastoma. Additionally, innovative radio-tagged monoclonal antibodies can potentially treat common cancers such as breast and head and neck cancers. If one-third of common cancers could benefit from this treatment, it is estimated that approximately 200,000 patients could be treated annually with these beds. Currently, only 75 beds are available across 30 centres in the country, with most centres having just 1-2 beds. Need for 25-30 large centres in ideal locations, each with 35-40 nuclear medicine beds and sufficient space to accommodate large delay tanks is envisioned. Another limitation of existing facilities is the inability to synthesize ready-to-use therapeutic radiopharmaceuticals. There is a pressing need for a large isotope therapy facility with a comprehensive hospital radio-pharmacy capable of producing ready-to-use therapeutic radiopharmaceuticals that meet Good Manufacturing Practice (GMP) standards. Additionally, these facilities require specialized medical support from oncologists and physicians. Establishment of 5-6 nuclear medicine centres across the TMC hubs is being proposed, each equipped with 35-40 nuclear medicine beds. These units would develop systems and processes to establish best practices that can be emulated by non-TMC healthcare institutions.

(c) Centres of excellence in cellular therapy, including immunotherapy, supported by GMP facilities

Recent advancements have shown that many cancers traditionally difficult to treat such as prostate cancer, acute leukaemia, chronic leukaemia, melanoma, and renal cancers, are now responsive to cellular therapy, including various forms of adoptive immunotherapy. These forms of cellular therapy require highly sophisticated, GMP-grade, scalable laboratory setups and highly trained multidisciplinary teams. In the next 15 years, there is need to build capacity in this frontier area of cancer treatment. Within the Tata Memorial Centre (TMC), 5-6 highly sophisticated and self-contained cellular therapy units may be established to produce tailored cellular therapy products ready for human use in treating 5-6 niche cancers. These public sector units will offer treatment at nominal costs to patients, ensuring access to cutting-edge therapies. It is being proposed to set up 4-5 highly sophisticated and self-contained cellular therapy units, including immunotherapy, in selected TMC hubs. These units will also enable research on novel technologies for next-generation CAR therapies, including nanotechnologies, NK-cell therapy, and oncolytic immune-virotherapy.

(d) State-of-science Biobanks in all TMC units

The cancer incidence rate in India is significantly lower compared to more developed countries, with a gradient in incidence observed from rural India to urban India to Western countries, approximately at a ratio of 1:3:9. This suggests that certain elements of the traditional Indian lifestyle may protect against cancer. However, these factors are not yet fully understood. These protective elements could be related to environmental factors (such as diet, exercise, and hygiene) as well as the genetic makeup of the Indian population. Following geographically well-defined population cohorts over time, with meticulous baseline characterization, will be crucial in identifying the specific protective and risk factors for various cancers in the Indian population. This will also help in devising appropriate primary and secondary preventive strategies. The establishment of state-of-the-art biobanks in all TMC units will enable such studies. TMC aims to set up and coordinate at least four well-defined and meticulously followed population cohorts across India's rural, semi-urban, and urban centres.

14.2 Prevention of Cancer

Cancer prevention is a critical component in the fight against this devastating disease. Cancer is a complex condition requiring a multifaceted approach that addresses various risk factors and promotes healthy behaviours to reduce its incidence and impact. At its core, cancer prevention involves a comprehensive strategy targeting multiple aspects: minimizing the risk of developing cancer, ensuring early detection, and improving outcomes for those affected. This holistic approach includes several key components: addressing obesity, promoting proper nutrition and hygiene, encouraging lifestyle changes, combating smoking and tobacco use, limiting alcohol consumption, raising awareness, and empowering individuals to take responsibility for their health. Comprehensive research to be undertaken to identify dietary patterns and nutrients that may modify cancer risk, thereby enabling the development of evidence-based guidelines for cancer prevention. Beyond addressing individual risk factors, cancer prevention efforts also focus on raising public awareness and empowering individuals to take proactive steps to protect their health. This includes educating the public about the importance of cancer screening and early detection and promoting healthy behaviours and lifestyle choices through community-based programs, public health campaigns, and school-based initiatives.

Early detection is a cornerstone of cancer prevention, as it allows for prompt diagnosis and treatment, significantly improving outcomes and reducing mortality rates. Screening tests, such as mammograms, Pap smears, and VIA tests, are instrumental in detecting cancer at an early, more treatable stage. Increasing access to screening services is essential for downstaging the disease. TMC, through all its centres, will ensure the development of preventive oncology departments to address these issues in their respective regions.

A key initiative would be the creation of a DAE cohort focused on understanding the environmental, genetic, and lifestyle factors contributing to cancer risk. This cohort could provide valuable insights into prevention strategies tailored to the Indian population.

Additionally, establishing an epidemiological long-term cohort across different TMC centres could shed light on geographical variations in cancer prevalence and the potential influence of regional factors such as environmental exposures, cultural practices, and socioeconomic determinants. The Department of Atomic Energy (DAE), through TMC, would provide technical assistance to state and central health agencies to develop cancer infrastructure following the Hub & Spoke model.

TMC's Centre for Cancer Epidemiology (CCE) is unique among Indian institutions, collecting population-level data, conducting interventions, and researching cancer incidence and burden. TMC proposes establishing a network of CCEs within its units and collaborating with non-TMC institutions to provide large-scale quantitative data to policymakers. Additionally, TMC will collaborate with ICMR to enhance complementary capacity in this domain.

14.3 Integrative medicine

Traditional AYUSH systems of medicine, particularly Ayurveda, take a holistic approach to healthcare, emphasizing disease prevention, personalized treatment, and addressing the root cause of disease rather than just the symptoms. Combining traditional and modern medical practices, integrative medicine offers a promising avenue for developing new and affordable treatments for various diseases, including emerging conditions. TMC has embarked on an ambitious project in Khopoli, where an integrative medicine approach will be employed to treat cancer. As part of this initiative, TMC plans to establish a facility for cultivating and conserving medicinal plants and developing herbal formulations for integrative medicine. For integrative medicine to succeed, there is a need for rigorous basic research in AYUSH systems for oncology, transforming experience- and reason-based traditional Indian medicine into an evidence-based science. In the coming years, TMC units will harness digital technologies to provide cancer care to a broader section of the population, potentially linking with Ayushman Arogya Mandirs. By utilizing these technologies, TMC would mitigate the impact of the shortage of healthcare professionals and ensure more equitable access to cancer care across India.

In coming few years, a 100-bed hospital-cum-research facility, ACTREC-TMC, will become operational in Khopoli, dedicated to treating cancer patients using integrative medicine approaches. Over the following decade and half, it is being proposed to establish ten state-of-art integrative medicine departments across selected TMC units.

15. HRD ecosystem of Aided Institutes of DAE

This white paper presents the vision on redesigning the education and the human resources development (HRD) ecosystem of the Aided Institutes (AIs) of DAE. The proposed redesign and revamping is necessitated by three ongoing changes; a) The rapidly changing nature of scientific research practices; b) The changing nature of the world, and c) Our changing aspirations as a nation.

DAE has affiliated institutes that work in most frontier areas, related UG programs, a research centre for science education (Homi Bhabha Centre for Science Education - HBCSE, TIFR), and a school system (Atomic Energy Education Society - AEES). DAE is the only establishment in the country with such range and diverse strengths. This ecosystem can be leveraged to address the practice-education gap. This unique braiding of research backgrounds would allow them to translate the frontier practices into educational models of compelling quality, for the country and the world to follow. Having identified the broad nature of the crisis and a potential way out of it, the aided institutions came up with a set of proposals. As a systematic investigation of frontier science and technology practices and human learning/education practices, in tandem, is a requirement for the proposed redesign, the need for establishing more centres of science education research (similar to HBCSE, TIFR) has been identified.

At the school level, the proposals were centred around AEES. Ongoing national and multi-AI programs, such as *Vigyan Pratibha* and the Science Olympiads, could be leveraged for wider nurture and dissemination. At the UG level, a world class 4-year program, with emphasis on advanced experimentation and instrumentation was proposed by Tata Institute of Fundamental Research (TIFR). Replication of the Centre for Excellence in Basic Sciences (CEBS) model, expansion of programs at NISER, CEBS and Homi Bhabha National Institute (HBNI) were among other highlights. Saha Institute of Nuclear Physics (SINP) proposed a research associateship and internship program for UG students and faculties. At the master's level, programs in cutting edge areas, involving a multi- institute collaboration, were outlined. The Tata Memorial Centre (TMC), in association with Institute of Mathematical Sciences (IMSc), proposed a program in data science, with a focus on health informatics. At the master's level, programs on bio-analytical sciences and sustainable energy (jointly by HRI, SINP, NISER, IMSc) were some highlights. At the Ph.D. level, targeted industrial collaboration and MD-Ph D programs to produce clinician researchers (TMC-SINP, other AIs) were proposed. Proposals on outreach, equity and inclusiveness include expansion of the *Vigyan Vidushi* model, and a regional focus by concerned AIs (for e. g. HRI catering to north India and SINP focusing on north east).

In summary, this proposal outlines an action plan in three broad phases: initiation/expansion, consolidation, and excellence. These denote short-term, medium-term and long-term plans, respectively.

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DEPARTMENT OF ATOMIC ENERGY