Evolution of health physics, radiation protection and regulatory framework in India

M. S. Kulkarni[1,]* and G. Nageswara Rao[2]

[1]Health Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
[2]Atomic Energy Regulatory Board, Mumbai 400 094, India

In the early days of India's nuclear energy programme, Homi Bhabha realized the importance of health physics and radiation safety aspects of nuclear facilities. The health physics and radiation protection activities have grown over the years with the multi-dimensional expansion of nuclear fuel cycle facilities and application of radiation in research, medicine and industry. This initiative further helped in laying a strong foundation for a national regulatory framework. AERB has established a multitier system of safety review and assessment to ensure that the use of ionizing radiation and nuclear energy does not pose an undue risk to the public and the environment.

Keywords: Environmental surveillance, health physics, radiation protection, radiological safety analysis, regulatory framework.

Introduction

THE term 'health physics' (physics applied to protection of health from radiation) was coined by Compton during the days when Enrico Fermi demonstrated the chain reaction for the first time in the Chicago Pile (CP1) reactor at the University of Chicago, USA[1]. In India, the rudimentary health physics activities were started in 1952 when S. D. Soman, working with the beta-ray spectroscopy group at the Tata Institute of Fundamental Research (TIFR), Mumbai was identified to provide radiation protection coverage and control radiation exposure to research workers handling radioactive sources. In those early days of the Atomic Energy Establishment, Trombay (AEET), later renamed Bhabha Atomic Research Centre (BARC), Homi Bhabha was scouting around for promising young Indians around the world and identified A. K. Ganguly, who was a research scholar in radiation chemistry in the University of Notre Dame, to work on the health physics and waste management programme in AEET.

Right from the inception of India's nuclear energy programme, Bhabha had realized the importance of radiation safety and health physics aspects of a nuclear facility. An office order in February 1960 from Bhabha expounded it thus: 'Radioactive material and sources of radiation should be handled in AEET in a manner, which not only ensures that no harm can come to workers or anyone else, but in an exemplary manner so as to set a standard which other organizations in the country may be asked to emulate'[2]. The directive became the preamble for the first regulatory document issued in the form of a *Manual for Radiation Protection in AEET* by the Health Physics Division (HPD), AEET in July 1965 (ref. 3).

Activities started under HPD in AEET have expanded and now BARC has a 'Health, Safety and Environment Group' comprising several divisions. In-depth academic and post-academic work done in AEET/BARC has laid the foundation for nurturing a strong regulatory framework for deploying nuclear technology by the Department of Atomic Energy (DAE) in India. The historical background and progress of health physics activities, various radiation protection initiatives and the evolution of the regulatory framework are elaborated in this article.

Evolution of health physics programme in DAE

In the initial years of AEET, Bhabha appointed A. K. Ganguly as Head, Radiation Hazard Control Section (RHC) in HPD under A. S. Rao (a specialist in electronics and instrumentation), who was overall in-charge of the Electronics Division as well as HPD. The HPD consisted of the Radiation Hazard Control (RHC) Section, Environmental Studies Group, Bioassay Group, Industrial Hygiene Section and a group to standardize radiation sources. RHC was responsible for the health physics surveillance for all radiation-related work in AEET. The health physics programme took shape under the leadership of Ganguly. Consequently, in 1963, Bhabha appointed him as Head, HPD, and gave him a free hand to develop a broad-based health physics programme in AEET. Ganguly aptly redefined the role of health physics in AEET to put into practice the radiological safety of the facilities, the personnel, the public and the environment according to the directives issued from time to time by Bhabha[4,5]. He gave a firm and committed direction to health physics activities that transcended into many related branches of science, evolving it into an effective, broad-based radiation protection programme and establishing a multi-faceted R&D programme in health,

*For correspondence. (e-mail: kmukund@barc.gov.in)

safety and environmental discipline. Radiation physics, modelling of radiation transport, radiation ecology, micrometeorology for impact assessment, environmental chemistry, radiation biology, internal and external radiation dosimetry, health physics instrumentation, fission product studies, etc. are some of the important subjects where work was initiated at AEET, which eventually had a great bearing on perfecting a self-reliant radiation safety programme in India. These activities initiated at that time are still important and being pursued by HPD to address radiation protection of occupational workers, the general public, and the environment for the nuclear energy programme of the country. The historical background and progress of health physics initiatives are further described below.

Radiological safety analysis

Radiological safety analysis is a systematic process that is carried out over the lifetime of a facility to ensure that all the relevant safety requirements are met by the proposed (or actual) design for the protection of the occupational worker, the public and the environment. The HPD was responsible for indoctrinating radiological safety in the Indian nuclear energy programme and carrying out safety analysis right from the early days of AEET. When Asia's first nuclear research reactor 'APSARA' was to be constructed at Trombay in 1955, HPD performed shielding calculations for 1 MW operation for the pool wall, thermal column and taper shape high-density concrete wall of the reactor[6]. In 1956, India decided to build a 40 MW natural-uranium heavy water-moderated research reactor CIRUS, with Canadian collaboration. HPD played a major role in preparing the safety report. It was the first regulatory accident analysis report made for the commissioning of CIRUS. The report had ten chapters, of which three on accident analysis, waste disposal and emergency procedures were prepared by a team led by Ganguly. This was later presented during the IAEA Symposium on 'Reactor Safety and Hazard Evaluation Techniques' in 1962 on the topics 'unusual occurrences', 'accident analysis' and 'administrative procedures'.

HPD played a crucial role in the radiological safety of members of the public residing in the neighbourhood of nuclear facilities by keeping a strict vigil on the releases to ensure that they were within the limits. For the nuclear facilities in India, discharge limits are set on gaseous and liquid effluents discharges to meet the dose limit criteria. Till the setting up of the national regulatory authority, HPD was responsible for laying down the limits for discharges of radioactive effluents to the environment[7]. During 1960s, the dose limits including both internal and external exposures, were apportioned to atmospheric, aquatic and terrestrial environment[7]. This approach was first introduced when limits were being established for environmental discharges during the commissioning of India's first nuclear power plant (NPP) at Tarapur in 1969.

The ICRP Paris statement of 1985 reduced the dose limit from 5 mSv to 1 mSv per year for members of the public[8] and India was first among the countries to adopt the new dose limit. The big task of downward revision of the limits set earlier was taken up for the Kalpakkam site having a multi-facility characteristic and all the operating plants were made to reduce their emission rates to meet the new criteria of 1 mSv per year. The term 'dose apportionment' was coined by T. Subbaratnam for the revision of the discharge limits. The concept of dose apportionment was introduced in India for judicious utilization of the public dose limit. This had the advantage that it controls public exposure at the source rather than in the environment. HPD carried out a detailed radiological impact assessment for the existing and upcoming NPP sites for recommending dose apportionment values. The radiological safety analyses carried out by HPD serve as an important prerequisite for obtaining environmental and regulatory clearances.

Historical development of personnel monitoring programme in India

The personnel radiation monitoring programme in India was started at the Tata Institute of Fundamental Research (TIFR), Mumbai in 1952 using the film badge system[9]. This film badge service established in AEET later developed into a countrywide personnel monitoring programme. The story of transition of personnel dosimeter based on Kodak NTA films to thermoluminescence dosimeter (TLD) is one of the most successful examples of indigenization in any area in India. The story dawned with Ganguly returning in 1963 from an international conference with the information that a new form of dosimeter with dose linearity over six decades is emerging and exhorted K. S. V. Nambi and C. M. Sunta to work on it. Soon, the instrumentation to study TL phosphor was developed and a large team gravitated to R&D in TL materials. Innovative methods to make a coil heater to heat the TL material on a Kanthal strip with a thermal shield resulted in a TL reader which was constantly improved upon from time to time. Initially, the TL glow curve was recorded on a strip chart recorder. Later, standalone TL readers for research applications were developed.

Two significant applications of TLD from this homegrown TL development need to be stressed to show its impact on other disciplines during 1965–71. Gopal Ayengar was studying the biological effects of the natural high background radiation areas (HBRAs) of Kerala on the population, and dosimetry was an important component needed. Locket-type TLD was innovatively designed to be worn as a chain by the members of the population to assess the actual dose received by them in 8770 dwellings and on 2338 persons in HBRAs of India[10]. This was deployed in large numbers and for the first time, the population dose to public in high-radiation background areas was assessed. Another was the national radiation map project undertaken by Nambi in deploying TLDs throughout the country and eventually a radiation map of India was prepared, which is accepted even today[11].

During the 1970s $CaSO_4 : Dy$ Teflon-based TLD badge was developed by B. C. Bhatt, A. S. Pradhan and A. R. Lakshmanan for personnel dosimetry[12]. This TLD badge system was first introduced for personnel monitoring service in 1975 at the Tarapur Atomic Power Station using an indigenously developed manual TLD badge reader[13]. Based on the superior performance of the TLD badge system, from 1976 onwards, the film badge service was gradually replaced with the TLD badge system in DAE by 1986 and in non-DAE institutions by 1998. From 2000, the manual TLD badge readers were completely replaced by PC-based, semiautomatic TLD badge readers with several performance improvements[14]. Since the inception of the personnel monitoring services around 1953, maintenance of occupational dose records of all the radiation workers was initiated[15]. A National Occupational Dose Registry was established to maintain a suitable database of occupational dose data of radiation workers. Later this evolved as the National Dose Registry, maintained by the erstwhile Directorate of Radiation Protection (DRP) and currently by the Radiological Physics and Advisory Division. In the last decade, extensive efforts were made to develop indigenous optically stimulated luminescence (OSL) phosphors and dosimetry systems for personnel and environmental monitoring as an alternative to the TLD-based system[16].

Evolution of internal dosimetry activities in India

Internal dosimetry, a branch of radiation protection, deals with the measurement of internal contamination and assessment of internal dose. HPD started internal dosimetry activities in 1957 by setting up a Bioassay laboratory at a naval barrack shed in the TIFR campus with P. R. Kamath as the officer-in-charge. A group led by Soman started working on the development of a methodology for monitoring tritium in environmental and bioassay samples, and established it further using the gas-phase counting technique. The Bioassay Group developed methodologies for the estimation of actinides and fission products in urine samples[17], which were revised in 1961 (ref. 18) and 1964 (ref. 19). Initial bioassay procedures were based on the co-precipitation method and were subsequently updated by Kamala Rudran and her team using the solvent extraction technique. With the availability of the ion exchange technique, the procedures were further updated by the laboratory for ultra-trace level detection of radionuclides, especially actinides in biological samples.

In 1958, when ICRP published a Reference Standard Man, HPD highlighted the differences between ICRP and Indian Standard Man (ISM) in terms of body structure, food, water intake and eating habits. Somasundaram consolidated the data on ISM. The statistical analysis of organ weight led to some changes in the ICRP directives[20]. ICRP changed the norm ‘ICRP Standard Man’ to ‘ICRP Reference Man’, implying that ICRP’s secondary standards are guidelines for national regulatory authorities, which can be modified according to the conditions in the respective countries. The work on the Indian Reference Man was later continued under the IAEA CRP on ‘Asian Reference Man’[21–23].

A Body Burden Measurement Section was formed in HPD, when the CIRUS reactor was being commissioned, for the whole-body monitoring of workers. NaI(Tl) detector-based whole body monitor (WBM) was developed inside a 4-tonne steel shield room[24]. A press wood phantom simulating the human body torso containing ^{137}Cs and ^{60}Co standard sources was fabricated for calibration purposes. Later, a special virgin steel room with graded shielding and phoswich[25] and an array of HPGe detectors were fabricated for the measurement of low-energy photon emitters like Pu and Am. Field-deployable, portable thyroid monitor and portable WBM were also developed for rapid internal contamination monitoring of members of the public in case of any radiation emergency. The lung counting of workers and bioassays remains the backbone of the internal dosimetry programme of HS&EG.

Health physics instrumentation

During the early 1950s, there was no electronics industry worth the name in India for the development and supply of radiation monitoring instruments. Bhabha formed a separate Division named Health Physics Instrumentation (HPI) under G. H. Vaze (from TIFR) to design and fabricate radiation-measuring instruments required for surveillance in the newly formed AEET under the direction of A. S. Rao. A portable ionization survey meter with an electrometer amplifier was developed in the early days, popularly known as the gun monitor (due to its resemblance). This became the workhorse of the profession and later, many sensitive GM-based survey meters, contamination monitors, fixed-radiation monitors and highly sensitive pressurized ion chamber-based survey meters with audio-visual alarms were fabricated which catered to the requirement of special monitoring instruments in AEET. Soon afterwards, the HPI division was transformed into the Electronics Division to provide instrumentation support for other applications. There was another unit named Trombay Electronic Instruments (TEI) for the manufacture of instruments required for multidisciplinary research in AEET, which later evolved as ECIL, Hyderabad, in 1967 with Rao as its first chairman.

The RHC Section in HPD had set up an Instrument Maintenance Group to ensure the upkeep of the monitoring instruments in a trim condition. It also undertook limited R&D work and developed alpha contamination monitors, gate monitors, etc. to meet specific requirements. Meanwhile, the R&D group in HPD under M. R. Iyer developed a microprocessor-based Pu waste monitor and a much needed 4-K channel multi-channel analyser (popularly known as HPD 4K MCA) required for the gamma spectrometry. A large number of these MCA units were deployed in various DAE facilities. This expertise in gamma spectrometry found timely help in various research activities and environmental surveillance programme of HPD. These developmental activities led to the formation of a separate Radiation Safety Systems Division (RSSD) under Iyer for carrying out R&D in measurement methodologies and monitoring systems. It enabled the development of an aerial gamma spectrometry system (AGSS) for emergency preparedness to quickly measure and estimate ground concentrations of fission products from an aircraft[26]. The AGSS system was even used in an exercise over Georgia on a request from IAEA.

Tritium monitoring instruments, including a continuous tritium-in-air monitor were developed with a multiline sampling feature for real-time measurement in nuclear facilities[27]. Specialized monitoring systems like portal monitor were also developed and installed at major transport routes, exit points of nuclear installations and airports to prevent unauthorized movement of radioactive materials. The vehicle monitoring systems were developed to locate rogue sources. Many specialized instruments required for radiological emergency preparedness purposes have been developed in the recent past like quad-rotor-based aerial radiation monitors for quick response to radiological emergencies, backpack gamma spectrometry systems, smartphone camera-based dose rate meters, lightweight hand-wearable radiation monitoring watches, etc. The Mobile Radiological Impact Assessment Laboratory was specifically developed for surveying in case of an emergency. In addition to the requirements of nuclear fuel-cycle facilities, a standalone radiation monitor for open-field installation with wireless data communication using a GSM network or satellite communication was developed for the measurement of environmental gamma radiation. Several such units have been deployed across the country under the Indian Environmental Radiation Monitoring Network (IERMON) programme[28].

Environmental surveillance around NPP

In 1957, Ganguly initiated work on environmental surveillance of radioactive discharges from nuclear facilities. One of the earliest activities started was the study of the recipient capacity of the Trombay bay due to possible discharges from the laboratories and plants that were fast coming up in AEET starting with the CIRUS reactor and associated nuclear fuel cycle facilities. Innovative methods were adopted to estimate the dilution of the bay water with the main sea and the dispersion pattern using ^{24}Na as a radioactive tracer, and sawdust and dyes as physical markers. During the construction of India's first NPP at Tarapur (TAPS 1 and 2), it was proposed to set up an environmental survey laboratory (ESL) attached to the plant. The project engineers noted that this extra expenditure may not be required at the initial stages. However, Bhabha overruled this reservation on funding the ESL and wrote on the file that 'if there are no funds for ESL let there be no nuclear power stations in India'. Such was the strong support Bhabha provided for the environmental safety programme. Thus, the first ESL attached to Tarapur NPP was started with a separate building for the laboratory located in the residential colony foreseeing the continued use of the laboratory even if some unforeseen accident occurred in the power station that might increase the radiation background in the vicinity affecting the work of ESL. ESLs became an essential feature in all NPP sites in India to assess the environmental impact during the operations of a nuclear facility and ensure that such operations did not have any harmful effects on the environment. In the following years, all the NPPs in the country received a dedicated ESL to carry out routine environmental monitoring and baseline pre-operational surveys. The establishment of an ESL at each of the nuclear installations is a unique feature of the Indian nuclear power programme. While preparing for India's participation in the Stockholm Conference in 1971, the then Prime Minister of India, Indira Gandhi was impressed with the environmental surveillance programme of DAE. The inputs provided by the working group headed by Ganguly later helped her to form a separate Ministry dealing with environmental issues. This was a great contribution from DAE for the protection of the environment from other industrial activities.

Health physics activities at front-end fuel-cycle facilities

The health physics operations for the front-end fuel cycle started with the setting up of the thorium plant in Trombay in 1956, followed by the uranium metal plant to make nuclear-grade uranium metal and a fuel fabrication plant for making fuel for the CIRUS reactor. Basic studies on radon daughter products and nuclear fallout measurements were initiated by K. G. Vohra in 1957 in the Air Monitoring Section. In 1960, Raghavayya[29] initiated measurements on radon daughter products and implemented a programme to quantify radon dose to mine workers. In 1961, he innovatively developed a Lucas-type cell for radon monitoring using a zinc sulphide-coated conical flask with a PM tube known as 'Raghavayya cell'[30]. Many challenges during the initial days were successfully met that resulted in innovative indigenous solutions like sampling mine water for radon and its estimation, radon measuring systems using SSNTD, automation of track counting, radon personnel dosimeter using SSNTD, single- and double-chamber radon personal dosimeters[31], radon breath analyser for radium body burden measurement[32], immobilization of radium and magnesium from tailing pond using pyrolucite, etc. Radon intake dose by mine workers was assessed using group occupancy factors for the first time. Kotrappa who was pursuing aerosol physics studies supported this group and helped them in the refinement of the methods. He developed an electret radon dosimeter, which was later accepted by the Environmental Protection Agency (US-EPA) for clearances of dwellings for radon safety. This is an instance of an innovation made in BARC creating a success story in USA.

Health physics activities at back-end fuel-cycle facilities

Bhabha started work on Pu chemistry with the setting up of a radiochemistry laboratory at Trombay in 1957 and Ganguly initiated health physics activities in this area. K. N. Kirthi, who was identified for this work, concentrated on developing an impactor-based aerosol sampler to monitor Pu-in-air to discriminate against natural radon daughter products activity and tested it with a controlled sampling of the glove-box atmosphere. Later, Kotrappa refined the method and thus the health physics operations in the back-end cycle began. Bhabha had envisaged a closed fuel cycle strategy for the Indian nuclear energy programme. With this foresight, during December 1958, he planned to set up a plant to reprocess irradiated fuel discharged from the CIRUS reactor while it was still under construction. Detailed design of the plant was carried out during the period 1959–1961. HPD was deeply involved in the safety analysis of the plant to guide radiation protection during its operation and maintenance activities[33,34]. Many challenges in designing safety systems for this plant were addressed innovatively, such as containment of airborne Pu and measurement of its concentration in working areas. All these challenges had to be dealt with the hard way as there were no readymade gadgets available. HPD took the initiative to carry out several R&D works in various aspects of radiation protection, such as particle size separation using cyclone separator, aerosol characterization at the workplace using scanning electron microscope (a rare technique in those days), various types of aerosol generators for studying the ventilation pattern, gamma spectroscopic analysis of various sample matrices and so on.

Ventilation systems are important barriers against the possible escape of Pu from glove boxes to laboratory areas. To detect any release of Pu into the working environment, continuous air monitors were developed by the Air Monitoring Section. Criticality monitors and radiation zone monitors were designed, developed and installed in the Pu laboratory and the plant areas. Personnel protective equipment such as airline respirators and plastic suits were designed and used to prevent intake and personal contamination. Methods for testing high-efficiency particulate filters were established to further improve the safety systems. The Bioassay Laboratory provided effective support in checking for any possible Pu intake by the workers. Whole-body counting for *in vivo* measurement of gamma emitters and lung counting technique for actinides using a special steel room equipped with phoswich detectors were also established. Within a few years of operation, the Health Physics Group could establish all the finer details of radiation safety of spent fuel reprocessing[35]. The safety guides prepared by HPD delineated all radiological safety aspects such as maximum permissible exposure limits, zoning of plant areas, procedures for external and internal radiation monitoring of workers, area and air monitoring, criticality control, radioactive waste management, issuing a radiation work permit, decontamination, radiation emergency handling, exposure investigation procedures and maximum permissible contamination on the surface, air and water during plant operation. The robustness of the health physics surveillance programme initially established was sufficient for the design and operation of larger reprocessing and waste management facilities at Tarapur and Kalpakkam in the later years.

Biological dosimetry programme in BARC

Exposure to ionizing radiations results in several biological responses such as biochemical, biophysical, physiological and cytogenetic changes. Many of these responses can serve as biological indicators. The changes which show consistent quantitative variation with dose can serve as biological dosimeters. The induction of chromosomal dicentrics in human peripheral lymphocytes has served as a reliable biological dosimeter during the last five decades. In 1992, B. S. Rao in the erstwhile DRP, set up the Biodosimetry Laboratory and initiated extensive research activity in biodosimetry. Chromosomal aberration analysis (CAA) was validated for assessing the dose in the case of partial body exposures. A method to assess the dose by applying decay corrections based on the half-life of different subsets of lymphocytes was established. Calibration curves for exposure at different dose rates were also established. Rao standardized an additional technique of scoring micronuclei in cytochalasin-blocked lymphocytes (MN assay). In 1995, the Biodosimetry Group established a technique for retrospective biological dosimetry by fluorescence *in situ* hybridization (FISH) to score translocation and validated it by analysing the past exposure cases[36]. More recently, the CAA technique has been automated to handle and process a large number of samples simultaneously. The Laboratory has successfully demonstrated the ability to score 100 samples in a day in an emergency scenario.

Radiation standards

The history of radiation standards in India closely follows that of the International Bureau of Weights and Measures (BIPM). Radiation standards were identified as one of the key areas. A small group of scientists was formed during 1957–58 to develop radioactivity standards which established a $4\pi\beta\gamma$

coincidence system for activity measurement. The laboratory also participated in the first international inter-comparison of radioactivity measurements organized by BIPM in 1961 (ref. 37). The group was later renamed as Radioactivity Standards Section (RSS). RSS slowly expanded the radiation standards activities, and established the primary and secondary standards for radioactivity, exposure and neutron fluence measurements. In 1976, this laboratory was designated as a WHO collaborating centre for secondary standard radiation dosimetry in collaboration with IAEA. RSS augmented the calibration facilities and disseminated the standards to the users in medical and industrial fields, which helped in the enhancement of the quality of treatment of cancer patients in India and ensured the safety of radiation workers. The Laboratory evolved to become the 'Designated Institute' for ionizing radiation metrology in India in July 2003.

Radiological surveillance at accelerator facilities in India

The first high-energy accelerator Van-de-Graff having protons up to 5.5 MeV was commissioned at AEET in 1962 and work on the accelerator radiation safety was formally begun by Kirthi. Radiation safety requirements like monitoring of prompt and residual radiation were formalized by his team. The Variable Energy Cyclotron in Calcutta (VECC) started its regular operation in 1981. In the accelerator installations, health physicists face many challenges as the radiation environment is different from other nuclear fuel cycle facilities due to different measurement techniques and their theoretical evaluations. The health physics team led by Muthukrishnan carried out many experimental investigations for characterizing the neutron radiation generated from different nuclear reactions for a deep understanding of the characteristics of the emitted neutrons, shielding and radiation protection requirements at VECC. This experience helped in the commissioning of the 2.5 GeV Indus synchrotron source at RRCAT in 2005. Radiation environment assessment was challenging due to the complex nature of secondary radiations from GeV range pulsed radiation. Radiation dosimetry posed many hurdles in accurately measuring the absorbed dose for the intense, highly focused beam in the experimental station. Sarkar[38] carried out many experimental investigations, and developed detector systems and deduced response correction factors for conventional dosimeters. Now, the accelerator radiation safety programme in DAE has matured enough to take up new challenges for futuristic requirements.

Radiation protection programme for non-DAE institutions in India

The radiation protection programme for industrial and medical uses of radiation in India has its origin in the nuclear emulsion activities of TIFR for cosmic-ray research. The radiation monitoring programme was initiated at TIFR in 1952 for a small group of radiographers working with X-rays in hospitals using Kodak photographic film as a film badge system designed by Raja Ramanna's group[9]. This service was later extended to other cancer hospitals like the Adayar Cancer Institute, Madras, on receipt of a request from eminent British radiation physicist W. V. Mayneord to A. S. Rao during a conference in London, UK. A proposal was put forth to Bhabha for setting up a countrywide radiation protection programme and envisaging a broad scope of radiation protection in the public domain. Bhabha readily agreed and accordingly asked Rao to set up a Radiological Measurements Laboratory (RML) at Trombay. RML was set up in 1956 to provide radiological protection services to institutions outside DAE and thereby ensure radiation protection on a countrywide basis[39]. The monitoring programme for radiographers was even appreciated by the then Prime Minister of India Jawaharlal Nehru, who stated in the Lok Sabha (Parliament) on 10 April 1958 that 'Health Physics Section, AEET has organized Film Badge Service for radiation workers not only in Trombay but elsewhere in India'.

In the meantime, the use of X-ray machines, sealed and open radioactive sources was rapidly increasing in medicine, industry, agriculture and research in the country, which had a considerable bearing on radiation safety-related issues[39]. In 1959, Rao asked P. N. Krishnamoorthy to take over RML and thus the latter led the diffusion of the radiological protection programme in India. RML was later renamed as the Radiological Measurement Section (RMS). The dosimetry group in RMS started the film badge service for nearly 2000 persons in about 200 institutions from all over the country during 1959–60 (ref. 39). It further initiated radiological protection surveys in X-ray and teletherapy installations, radioisotope laboratories and industrial institutions across India. As part of the countrywide radiation safety programme, in 1959 RMS conducted various short-term (four to six weeks duration) training courses on the safety aspects in the medical uses of radiation on collaboration with the World Health Organization (WHO), Geneva, Switzerland[40]. These courses were attended by doctors and medical physicists from all parts of India. In the following years, more such courses covering radiation applications in other fields became a matter of practice. To make its activities more broad-based, RMS also started personnel neutron monitoring services, radiation dose records maintenance, radiological protection surveys of institutions using neutron sources, industrial and medical advisory services, and R&D on radiation measuring instruments[41].

In another major initiative, in 1962, Krishnamoorthy started a 'one-year post-graduate course on radiological physics' on the lines of the Training School in the erstwhile AEET, in collaboration with WHO. The first batch of ten candidates completed its training in March 1963 (ref. 42). This course got recognition from the University of Bombay as a ‘Diploma in Radiological Physics’ (Dip R.P.), and it helped in establishing medical physics as an essential and well-respected profession in the country. The hospitals handling radiation sources for radiation therapy started appointing Dip R.P. students as qualified Radiological Safety Officers (RSO) cum Medical Physicists.

In 1963, Bhabha reconstituted the Radiological Measurements Section as a separate Directorate of Radiation Protection entrusted with the work as a result of the enactment of the Atomic Energy Act, 1962 with Krishnamoorthy as the Deputy Director[43]. Both HPD and DRP were part of the group under A. S. Rao. With his administrative acumen and organizational skill, Krishnamoorthy established DRP and equipped it for covering safety in the applications of radiation sources in non-DAE institutions, and provided advisory services to radiation facilities in the industrial and medical sector. After the promulgation of Radiation Protection Rules (RPR), 1971, the Director of DRP was also notified as the competent authority for enforcement of RPR 1971. In 1972, DRP was renamed as Division of Radiological Protection and in 1973, both HPD and DRP were brought under the Chemical Group of BARC headed by Ganguly.

Industrial hygiene and safety at BARC

Since the early days of AEET, Bhabha identified industrial hygiene activities along with radiation safety in the Health Physics Division. He envisaged that while radiation hazards were unique to the atomic energy programme, the need for invoking industrial safety from conventional accidents was also equally important as casualties due to them are more of a concern. Bhabha nominated a two-member team led by K. S. Somayaji and A. Ramamurthy for one-year training in industrial hygiene under the Point Four Programme of the US International Cooperation Administration. The Accident Prevention Programme of the Department was officially initiated on 1 August 1962, and is still in vogue. It put into place the important check measures in the form of a mandatory requirement for a direct supervisor at a work-related injury, to file a formal intimation report (injury-on-duty form) with the Industrial Hygiene and Safety (IHS) Unit. This Unit in turn would conduct an unbiased inquiry into the identification of root causes and suggest remedial actions to prevent recurrences. Reports highlighting the critical analyses of accidents, observations made and subsequent remedial actions recommended were released periodically for general alertness and education. The illustration of typical incidents was entitled, ‘This need not have happened’. A comprehensive industrial hygiene programme for evaluating chemical agents present in the work environment is in vogue and continuous surveillance concerning ventilation, breathing air quality checks and advisory services on control measures are in place.

Radiation emergency – preparedness and response

In the initial days, the Medical and Industrial Advisory Sections in DRP were providing response services on radiation emergency to teletherapy centres and industrial radiography centres in the country. Consequent to the Chernobyl nuclear accident and other radiological incidences around the world and considering the regional security environment, DAE took measures to strengthen and enhance nuclear security and safety aspects, and a Site Emergency Control Centre (SECC) was established at Trombay in 1988. Subsequently, other DAE units across India also started implementing radiation emergency preparedness to mitigate any consequences due to potential radiation emergency situations.

Radiation Emergency Response Centres (DAE-RERCs) were established under the aegis of HS&EG of BARC with coordination of response with all departmental facilities and other ministries. These centres were mandated to be provided by the Crisis Management Group of DAE, which was established in 1987. Presently, the ESLs of all seven nuclear power plant sites, HPU of all DAE facilities (including aided institutions of DAE) spread across India have a network of 25 DAE-RERCs. Over the years, many state-of-the-art systems have also been developed for radiation emergency response. The guideline documents on emergency preparedness and response (EPR) developed for the Indian context is according to the international guideline documents (IAEA-GSR-Part 7) and is also in sync with the response measures for nuclear and radiological emergency drafted in the National Disaster Management Plan, 2019 (NDMP 2019).

Evolution of a sound regulatory framework

The main legal framework for nuclear power and applications of radiation in India is provided by the Atomic Energy Act, 1962, and the Rules and Notifications issued under it. However, the Atomic Energy Act, 1948, which was the first legislation to regulate atomic energy in the country, did not have any explicit provision for the regulation of safety. During 1960–61, preparatory work regarding amendment of the Atomic Energy Act was completed, and work connected with the formulation of rules and regulations, to be issued under the amended Act, for the procurement, use, transport and disposal of radiation sources in a safe manner was underway.

In 1962, Bhabha set up a formal reactor safety committee with Ganguly as one of the members. The committee had three working groups, one each for Apsara, ZERLINA and CIRUS. Any proposal would first go to the respective working group and then the groups would send their report to the main committee. This paved the way for a multi-tier safety review, which became the hallmark of regulatory oversight subsequently. When Apsara and CIRUS reactors in Trombay started producing significant quantities of radioisotopes, there was a phenomenal growth in the application of isotopes in medicine, industry and research. Soon it became apparent that the use of radiation sources in the public domain warranted greater attention than the DAE facilities which were all under the surveillance of HPD, BARC. Though the Atomic Energy Act was promulgated in 1962, RPR, 1971, the first subordinate legislation was issued only in 1971 as it took time to develop adequate infrastructure. DRP, headed by Krishnamoorthy, was responsible for radiation surveillance in hospitals, industries and research institutions, authorization to procure sources, approval of site plan, provision of personnel monitoring services, preparation of safety standards, organization of radiation safety training programmes and also drafting of RPR, 1971. Krishnamoorthy was a part of the IAEA team drafting the regulations for the transport of radioactive sources.

When BWRs at Tarapur were ready for commissioning in 1969, there was no formal regulatory system, to approve the first approach to criticality. Sarabhai, the successor to Bhabha, set up an independent committee under the chairmanship of Ganguly to review the commissioning activities at every step and advise him on the authorization of the next step. In due course, the need for an independent group for safety evaluation was felt and resulted in the conversion of the Safety Committee of the TAPS reactor into the DAE Safety Review Committee (DAE-SRC) for all the DAE reactors and nuclear facilities. DAE-SRC was reconstituted in 1981 and temporarily given responsibilities to carry out regulatory and safety functions under the Atomic Energy Act, 1962.

The regulatory framework for safety in the nuclear power programme in India had evolved organically in conjunction with the development of the programme itself[44], with the involvement of the scientists and engineers. In the initial years, safety regulation of the facilities, mainly the research reactors, was essentially based on the principle of self-regulation, wherein the responsibility for safety was placed on the facilities themselves. While this had worked well, the need for a separate mechanism for overseeing how the facilities were fulfiling their responsibility for safety in their activities was realized, which led to the evolution of a safety review committee structure. Subsequently, as the nuclear power programme was expanding, a strong need was felt for having a separate body for discharging the regulatory roles and responsibilities.

Towards this end, in November 1983, AERB was constituted under the provisions of the Atomic Energy Act, 1962 with A. K. De as Chairman and V. N. Meckoni (Chairman, DAE-SRC) as one of its members and Krishnamoorthy as its first Member-Secretary. Many members of DAE-SRC and DRP later became key members of AERB. This enabled practical experience in the safety of nuclear power stations and radiation applications to be inducted into the regulatory activities. After the successful initial transition, it was felt necessary to strengthen AERB and entrust it with all the regulatory work, so that it acquires greater credibility and is enabled to function with the requisite authority. In 1987–88, DAE-SRC was merged with AERB and progressively, the regulatory activities of DRP were taken over by AERB.

AERB is responsible to the Atomic Energy Commission (AEC), which is a high-level body dealing with policy matters concerning atomic energy in India. Towards this, AERB submits its annual reports and budget proposals to AEC. The Department of Atomic Energy provides the necessary administrative support required for the functioning of AERB, including interfacing with the Government. This existing arrangement provides AERB with access to resources necessary for office functioning without compromising its effective independence. It also enables AERB to get qualified, trained and competent personnel at different levels with the required experience.

The methodologies and processes evolved in the initial days such as the plant management being primarily responsible for safety, participation of the plant representatives in the safety review process, learning from operating experience, etc. have been inherited in the present system and continue to be part of the regulatory system. Over the years, AERB has established a regulatory framework which involves stipulating the regulatory requirements for safety, issuance of regulatory consents and licenses, verification of compliance through safety reviews and inspection during various stages in the lifetime of the plant, right from siting, design, construction, commissioning, operation to decommissioning. AERB also regulates those aspects of nuclear security which have a bearing on nuclear safety.

The insights on safety issues gained by various units of DAE further helped AERB in its initiative to establish safety codes, standards and guides, which serve as the basis of its regulatory activities. Thus, the Indian regulatory system has realized concurrent development of technology and regulation, with the strong backing of a long-term R&D programme. These are in line with the requirements specified in the IAEA safety standards for best practices and are periodically updated based on experience, feedback and new technological advancements.

The AERB issues regulatory consent for any particular stage in the lifetime of a nuclear/radiological facility based on the culmination of safety reviews and ascertaining compliances with the specified regulatory requirements. Its compliance is verified by conducting periodic regulatory inspections during various stages of the project. The safety reviews are conducted by multitier safety committees of AERB consisting of experts from various units of DAE and other scientific/academic institutes. These comprehensive safety reviews follow a graded approach with the associated safety significance.

Under AERB requirements, state-of-the-art safety features are provided in NPPs based on principles of defence-in-depth (defences in the form of features and equipment at several levels), redundancy (more numbers than required) and diversity (back-up systems operating on different principles). These design safety features are evaluated to ensure an adequate margin of safety so that NPPs can be operated without undue risks to the plant personnel, members of the public and environment, both during normal and accidental scenarios. Regulatory reviews of engineering aspects of nuclear security within the main plant boundary of NPPs are also performed based on the nuclear security requirements.

The success and effectiveness of the Indian regulatory process can be judged from the history and statistics of the safe operation of nuclear facilities in India. So far, there has not been any event in any of the nuclear power plants of India which has resulted in an adverse radiological impact on the environment. AERB has specified the radiation dose limits for the workers and members of the public along with various other regulatory constraints and limits on environmental discharges. The monitoring of doses to the workers, public and environment assures that safety practices are well implemented. To sum up, as a functionally independent regulatory organization, AERB had an organic growth in tune with the expanding nuclear industry[39].

Conclusion

Safety has been accorded top priority since the inception of the Indian nuclear energy programme. The country has established a glorious record for over six decades of safe operations of its nuclear and radiological facilities without any incidences having a major impact. The health physics activities have grown over the years with the multi-dimensional expansion of the Indian nuclear energy programme. These activities were restructured and regrouped to strengthen the R&D and for management of the radiation protection programme. The health physics programme has achieved the goal of protection of workers, the public and the environment from the operation of nuclear and radiation facilities in the country. The national regulator AERB inherited the core values and good practices of its founder members and established a multi-tier system of safety review and assessment based on sound scientific principles. It is now regarded as a competent and mature regulator by the utilities and peer regulators across the world.

1. Hacker, B. C., In *Radiation Damage: Early Assessments: The Dragon's Tail. Radiation Safety in the Manhattan Project, 1942–1946*, University of California Press, Berkeley, CA, USA, 1987.
2. AEET, Radioactive materials and radiation sources. Atomic Energy Establishment, Trombay Office order, DAE/I/16/B(ii)/4813, 27 February 1960.
3. AEET, *Manual for Radiation Protection in AEET*, Health Physics Division, Atomic Energy Establishment Trombay, 1965, p. 223.
4. Iyer, M. R., Anil Kumar Ganguly (1918–1988) – the evolution of health physics science in India. Compendium of Memoirs. *Radiat. Prot. Environ.*, Spec. Issue, Wolters Kluwer – Medknow, January–March 2018.
5. Iyer, M. R., *The Saga of Atomic Energy in India. Why is Nuclear Power Still Subcritical*, Authorspress, New Delhi, 2020, ISBN 978-93-86722.
6. Soman, S. D., Safety perspective – then and now. *Bull. Radiat. Prot.*, July–December 1996, **19**(3&4).
7. Subbaratnam, T. and Soman, S. D., Derivation of working limits for controlled discharge of radioactive wastes from nuclear installation. In IAEA Seminar, Vienna, Austria, IAEA-SM-184/5, 1974.
8. ICRP, Statement from the 1985 Paris Meeting of ICRP, ICRP/85/G.03, International Commission on Radiological Protection, 1985.
9. Sundararajan, A. R., Parthasarathy, K. S. and Sinha, S. (eds), Atomic Energy Regulatory Board 25 Years of Safety Regulation, Atomic Energy Regulator Board, India, November 2008.
10. Gopal Ayengar, A. R. *et al.*, Evaluation of long-term effects of high background radiation on selected population groups on the Kerala coast. In Proceedings of IV International Conference on Peaceful Uses of Atomic Energy, United Nations, New York, USA, 1972, pp. 31–51.
11. Nambi, K. S. V., Bapat, V. N., David, M., Sundaram, V. K., Sunta, C. M. and Soman, S. D., Natural background radiation and population dose distribution in India. Health Physics Division, Bhabha Atomic Research Centre, Mumbai, 1986.
12. Vohra, K. G. *et al.*, A personnel dosimeter TLD badge based on $CaSO_4$: Dy Teflon TLD discs. *Health Phys.*, 1980, **38**, 193–197.
13. Pradhan, A. S. *et al.*, Parameters of large scale production of personnel monitoring TLD cards based on $CaSO_4$: Dy. *Radiat. Prot. Dosim.*, 1999, **85**, 67–70.
14. Kannan, S., Ratna, P. and Kulkarni, M. S., A fully automated TLD badge reader. *Radiat. Prot. Environ.*, 2003, **26**, 254–255.
15. Kher, R. K., Procedures for maintenance of dose records in the national occupational dose registry. In Proceedings Theme Meeting on Radiation Protection Activities, BARC, Mumbai, 18–20 August 2004.
16. Kulkarni, M. S. *et al.*, *BARC Newsletter – Founders Day Special Issue*, 2015, pp. 265–276.
17. Soman, S. D., Bioassay procedures in Trombay establishment. AEET/HP/BA/1, 1959.
18. Soman, S. D. and Kamath, P. R., Bioassay procedures in Trombay establishment. AEET/HP/1, 1961.
19. Kamath, P. R. *et al.*, Recent radiochemical procedures for bioassay studies at Trombay. Assessment of radioactivity in man. In Proceedings of a Symposium, IAEA, Heidelberg, 1–16 May 1964, vol. 1, SM/52-67, pp. 195–215.
20. Venkataraman, K., Raghunath, V., Santhanam and Somasundaram, S., Physiological norms in Indian adults. Statistical analyses of data on organ weight. *Health Phys*., 1966, **12**(4), 572–574.
21. IAEA, Compilation of anatomical, physiological and metabolic characteristics for a Reference Asian Man, Volume 1: data summary and conclusions. Results of a co-ordinated research programme, 1988–1993. IAEA-TECDOC-1005, 1998, p. 124.
22. IAEA, Compilation of anatomical, physiological and metabolic characteristics for a Reference Asian Man: volume 2: Country reports. IAEA-TECDOC-1005, 1998, p. 184.
23. IAEA, Reference Asian Man: Ingestion and organ content of trace elements of importance in radiological protection. IAEA-TECDOC-1592, 2008.
24. Chhabra, A. S., An improved whole-body counting geometry with a single NaI(Tl) detector (8×4). *Radiology*, 1964, **82**(5), doi:org/10.1148/82.5.816.
25. Sharma, R. C., Krishnamachari, G., Haridasan, T. K. and Somasundaram, S., A large-area phoswich detector for measurement of low levels of low-energy photon emitters. *Nucl. Instrum. Methods*, 1975, **130**(1), 305–311.
26. Krishnamachari, G. *et al.*, Design of a compact aerial gamma spectrometry system (AGSS). *Bull. Radiat. Prot. Environ.*, 1998, **21**, 21–27.
27. Raja, V. *et al.*, Continuous tritium in air monitor with multi-line area sampling. In Proceedings of the DAE–BRNS National Symposium

on Nuclear Instrumentation, Electronics and Instrumentation Group, BARC, Mumbai, 2013.
28. Garg, S. *et al*., The central monitoring station of Indian Environmental Radiation Monitoring Network (IERMON): the architecture and functions. In *BARC Newsletter, Founder's Day Special Issue*, October 2011, pp. 419–422.
29. Raghavayya, M., A study of the distribution of radioactivity in uranium mines. M.Sc. thesis, University of Bombay, Mumbai, 1976.
30. Khan, A. H. and Raghavayya, M., Radon emanation studies in Jaduguda uranium mine. In Proceedings of Third International Congress of the International Radiation Protection Association, Washington, USA, 9 September 1973, pp. 939–944.
31. Srivastava, G. K., Raghavayya, M., Khan, A. H. and Kotrappa, P., A low-level radon detection system. *Health Phys.*, 1984, **46**, 225–228.
32. Srivastava, G. K., Raghavayya, M., Kotrappa, P. and Somasundaram, S., Radium-226 body burden in U miners by measurement of Rn in exhaled breath. *Health Phys*., 1986, **50**, 217–221.
33. AEET, Plutonium plant hazard evaluation report. AEET/HER-3, 1965.
34. Krishnamony, S. and Kotrappa, P., *Manual for Radiation Protection in Plutonium Plant*, AEET/HP/S.M/14, 1965.
35. HPD, Monitoring and control of low level liquid effluent discharges from the Trombay plutonium plant, 1965–1972, RHCS/HPD, 1972.
36. Sreedevi, B. and Rao, B. S., Assay of stable chromosomal aberrations by fluorescence *in situ* hybridization application in biodosimetry. *Radiat. Prot. Environ*., 2001, **24**, 42–47.
37. Misra, S. C., Standards of ionising radiation in India. In Proceedings of the Conference-cum-Workshop on Radiation Standards and Measurements, BARC, Mumbai, 4–6 January 1993.
38. Sarkar, P. K., Radiological safety in positive ion accelerator. *Radiat. Prot. Environ*., 2000, **23**, 255–260.
39. Susheel Kumar, Harikumar, S., Varghese, C. S. and Shukla, D. K., Regulatory aspects of nuclear power program in India. *Prog. Nucl. Energy*, 2017, **101**, 146–159.
40. DAE Annual Report 1959–60, Department of Atomic Energy, Government of India (GoI).
41. DAE Annual Report 1960–61, Department of Atomic Energy, GoI.
42. DAE Annual Reports 1959–64, Department of Atomic Energy, GoI.
43. DAE Annual Report 1963–64, Department of Atomic Energy, GoI.
44. Pathak, B. C., Kaushik, C. P., Vyas, K. N. and Grover, R. B., The status of nuclear power development in India. *Curr. Sci*., 2022, **123**(3), 281–293.

ACKNOWLEDGEMENTS. We thank M. R. Iyer (Ex-Head, RSSD, BARC, Mumbai) and many former colleagues from the Health Safety and Environment Group, BARC, for their valuable suggestions during the course of this work. We also thank our colleagues in AERB and HS&EG, BARC, for useful discussions and suggestions.

doi: 10.18520/cs/v123/i3/343-352