Bhabha and electronics

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This article surveys the impact of Homi Bhabha's visionary initiatives in the area of electronics in India. We begin by surveying the early years at the Tata Institute of Fundamental Research, Mumbai and the Atomic Energy Establishment at Trombay that nucleated these activities and gave shape to Bhabha's conviction on the importance of electronics for the growth of science and technology and nuclear energy in the country. We trace the evolution of indigenous technology in the areas of nuclear electronics, instrumentation and control systems for nuclear power plants, and assess their impact. This is followed by a review of the role of the Electronics Corporation of India Ltd in the growth of indigenous electronics in the country. We conclude with an appraisal of the current state of electronics in India.

Keywords: AEET, electronics, nuclear power plants, PHWR, radiation detectors.

Beginnings

WHILE addressing the inaugural session of the Nuclear Electronics Conference on 22 November 1965, Homi J. Bhabha[1] articulated the motivations for launching a development programme on electronics in the Department of Atomic Energy (DAE).

> 'It is now well recognised that without a full-fledged programme for design and development of nuclear electronic equipment, no country can embark on any meaningful atomic energy program. Thus, in any developing country, which does not already have an organised electronics industry, a self-reliant atomic energy programme will necessitate not only the indigenous development of nuclear electronic instruments but also organised work on other aspects of electronics such as computers, process instruments and control systems.'

He was speaking at the Conference after two decades of spectacular progress in electronics in DAE. It had all begun when in the late 1940s Bhabha invited a young Stanford-returned A. S. Rao to help him with cosmic-ray experiments at the Tata Institute of Fundamental Research (TIFR), Mumbai. Presciently recognizing the vital role of electronics in growing science in India, Bhabha formed the Electronics Division and appointed Rao to lead it. A fledgling nuclear programme spawned a vibrant community of researchers in electronics in TIFR and the Atomic Energy Establishment at Trombay (AEET) (Figure 1).

The commissioning of the Apsara reactor in 1956 with completely home-grown instrumentation and control was a testament to the strength of India's domestic research and development (R&D) programme in electronics. Consisting of relay-based protection-cum-operational interlocks and control rod drives, Apsara marked the first milestone in the journey of nuclear control and instrumentation (C&I) systems in India.

In 1958, the production unit of electronics was shifted from TIFR to Trombay. Rao was made in charge of the Health Physics and Electronics Divisions of AEET. The Electronics Division produced many models of instruments and systems. In the following years, the development, installation and commissioning of control systems for Zerlina and radiation monitoring systems for the Plutonium Plant were also achieved through these Divisions at AEET.

By the mid-1960s, nuclear instruments such as radiation survey meters, scalers, power supplies, a variety of nuclear front-end amplifiers, single and multi-channel analysers, and nuclear spectrometer systems were designed and produced in large quantities in AEET. While the total value of production exceeded 50 lakh rupees, the import component was less than 15% (ref. 1).

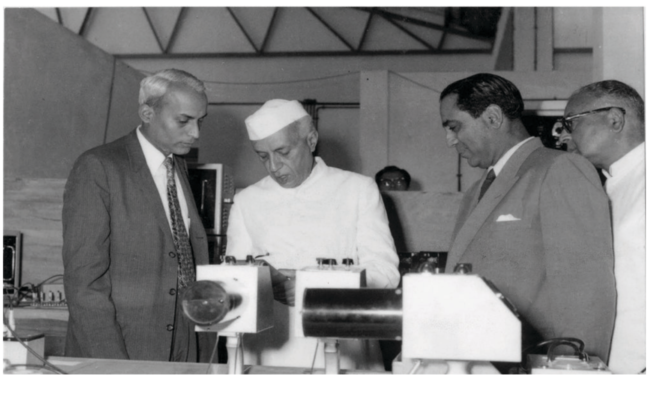

Figure 1. A. S. Rao, Jawaharlal Nehru and Homi Bhabha at TIFR (1962).

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The work on semiconductors and components was intensified in the 1960s to minimize import dependency. The list of achievements runs long – silicon crystals, compound semiconductors, ceramics, transistors, diodes, carbon and metal film resistors, tantalum capacitors, high-precision stable resistors, Zener diodes, silicon rectifiers, low-frequency germanium (Ge) transistors, Ge power transistors, thermoelectric coolers, metal-film resistors, multi-turn potentiometers and components for servo instruments. This in turn led to the development of modules and instruments using these components.

A variety of outstanding products such as bismuth–telluride technology for thermo-electricity, variable time (VT) fuzes for defence, analog and digital computers, and aviation black boxes were made at TIFR and AEET during this golden period.

Yet, industrial activity in electronics in India was not vibrant. The Chinese war of 1962 was a wake-up call for the government – electronics was not just for entertainment; it was vital for defence, nuclear programmes and the economy as a whole. A National Committee on Electronics was formed in 1963, with Bhabha as its Chairman. Vikram Sarabhai, S. Bhagavantham and Rao were among the members of the committee which had to prepare a blueprint for the development of electronics in India for the next decade. Rao recounts those days[2]:

> 'The committee prepared a comprehensive report covering all major areas of electronics including computers, communications, components and consumer electronics. A 10-year growth profile, investment and manpower needs, product and application priorities and guidelines for organising the industry in a systematic manner were evolved. The object was clearly on achieving self-reliance in electronics so as to put India on par with the developed countries, modernize Indian industry through new technology and open up vast employment opportunities for Indian scientists and engineers. While surveying the potential and recommending policies for the development of electronics in the country, the committee did not, however completely rule out foreign collaboration in selective areas; self-sufficiency was not lost sight of in the enthusiasm for promoting self-reliance. But advocacy of self-reliance with selective imports itself was too radical at the time to many individuals and institutions who were used to spending enormous foreign exchange on collaborations, imports and later, under the guise of obsolescence, on more collaborations and more imports.'

Surely DAE's successes formed the basis for the committee's exuberant optimism. For almost a decade now, AEET and TIFR were developing world-class electronic components and instruments. India's expanding portfolio of nuclear plants – Apsara, Uranium Metal Plant, Nuclear Fuel Facility, Zerlina, Plutonium Plant, CIRUS, Tarapur Atomic Power Station (TAPS) – was being equipped with home-grown electronics and instruments. The product portfolio was bursting at the seams, spilling into medical, industrial and other applications.

The Bhabha committee's report, submitted to the Government in 1966 by Sarabhai after Bhabha's untimely death, resulted in the formation of the Electronics Commission and Department of Electronics tasked with the promotion of the electronics industry in India. The most visible form of these policy initiatives was import restrictions and steep tariff barriers for imports. These measures protected the fledgling electronics industry from unequal competition.

Meanwhile, microelectronics was growing at breakneck speed obsoleting itself every few years. Computers grew faster and smaller as predicted by Moore's law, entered homes, offices and factories, embedding themselves in most man-made items. India had missed this bus. By the 1980s the Indian electronics industry was in death throes, left far behind and dependent. The inevitable liberalization of imports that followed rung the death knell of what was left of the hardware industry. That was not much of a worry for most sectors of the economy which merrily imported whatever was needed. The easy availability of computers even led to the growth of the software industry in India and spurred growth in other sectors. However, matters stood differently in DAE. After the events at Pokhran in 1974, DAE came increasingly under sanctions. Over the years, technology denial regimes became pernicious and all-encompassing. DAE needed to continue to be self-reliant. Embargos stimulated developments in nuclear electronics, C&I and computers ensuring that DAE programmes became largely invulnerable to sanctions.

In the following sections, we review these five decades of advances in electronics in DAE, focusing on nuclear electronics, controls and instrumentation.

Radiation detectors and nuclear instruments

Dhruva

The nuclear instrumentation for Apsara as well as Zerlina and Purnima that followed it, was somewhat simpler (Figure 2).

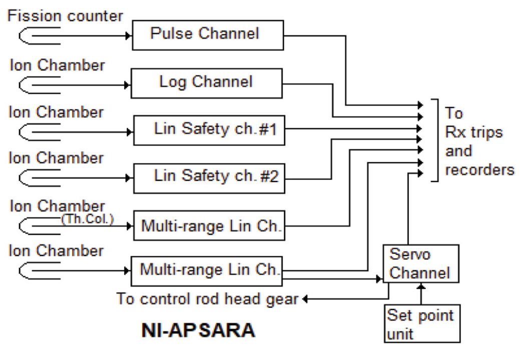

Figure 2. Nuclear instrumentation scheme for Apsara (1956).

Following the successful commissioning of CIRUS, AEET – renamed Bhabha Atomic Research Centre (BARC) – embarked on the construction of the fifth reactor, R5, in its Trombay campus. The 100 MWth Dhruva as it was named later, marked an important milestone in the development of nuclear electronics in India. In CIRUS most of the instruments had come from Canada and the involvement of Indian engineers was limited to installation and commissioning. Hence, Dhruva was the first large reactor where indigenous instruments would be deployed in scale (Figure 3).

There were significant challenges to be overcome. The ion chambers with integrated Kapton cable and ceramic insulated connectors that were developed for core neutron detection had to be deployed in a lead basket for eliminating gamma signals. The fission counter was located outside the basket and was designed to work in pulse, Campbell, and DC modes covering a measurement range of over ten decades with adequate overlap between the different ranges[3].

The upgradation of nuclear instrumentation of Apsara and CIRUS was also taken up in the late 1970s for improving the performance and to address obsolescence. Components such as vacuum tubes, magnetic amplifiers and sensitrol meter relays were replaced by screened solid-state devices. The modular concept was introduced for all the research reactors, including Purnima for ease of maintenance. The principle of channel independence was applied uniformly to conform with evolving regulatory norms. This minimized common cause effects and improved availability by facilitating online isolation for testing[4].

These years also witnessed the development of a host of radiological protection and health physics instruments such as area monitors for neutrons and gamma, tritium in air, air-particulates, portal monitor, contamination monitors of alpha, beta, gamma and neutron dose monitors, besides thermoluminescent dosimeters (TLD) (Figure 4).

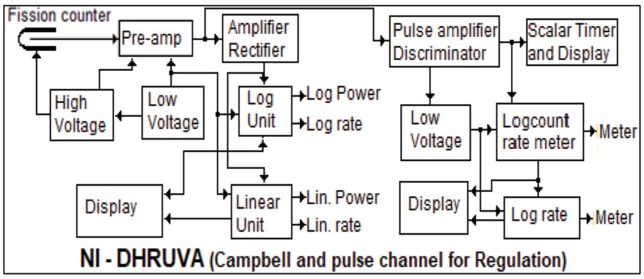

Figure 3. Nuclear instrumentation scheme for Dhruva (1985).

Figure 4. Radiological instruments.

PHWR

With the experience of Dhruva behind them, the Electronics Division (ED) of BARC went on to develops neutron detectors – pulse as well as DC – for the fleet of pressurized heavy water reactors (PHWRs), starting with Narora. These boron-based detectors measure the core neutron flux in over 14 decades covering reactor start-up to normal operation. These would be vital for the protection and control of the reactor. The safety and availability of the reactor depended on them. These were seismically qualified and standardized in all PHWRs. Subsequently, self-powered neutron detectors (SPNDs) and low-sensitivity fission counters too got added to the portfolio and 540 MWe reactors employed SPNDs in large numbers (~200)[5]. Electronics Corporation of India (ECIL) was the natural custodian of this technology. Currently, all the neutron detectors and instrumentation required for the family of Indian PHWRs – 220, 540 and 700 MWe – are standardized and manufactured by ECIL.

Over the years the radiation instrumentation systems have got upgraded to networked architecture with centralized redundant monitoring and data collection. The flux mapping system for Tarapur Atomic Power Station (TAPS) units 3 and 4 set a new benchmark in this regard (Figure 5).

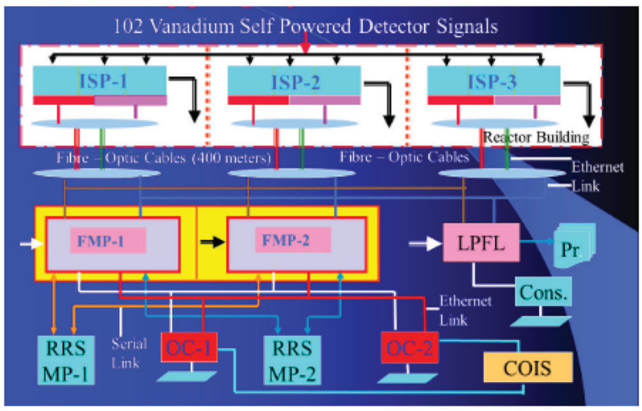

Figure 5. Distributed FMS architecture.

PFBR

Upcoming prototype fast breeder reactor (PFBR) marks a major recent milestone in the development of reactor instrumentation for the measurement of neutron flux (Figure 6). The compact size of the core, high temperature and high gamma background were daunting challenges to begin with. These were eventually overcome – high-temperature fission chambers (HTFCs) having 0.2 cps/nv with low collection time were developed and qualified for continuous operation near 600°C with five decades of measurement range and accuracy of 1% in the presence of about 10^5 R/h gamma field. Besides HTFC, multi-section fission detectors and high-temperature (250°C) boron detectors were also produced to cater to power range, fuel loading and for start-up after prolonged shutdown (Figure 7).

HTFC necessitated ab initio development of special technologies and processes, such as uranium coating for high-temperature application, brazing of ceramic seals to mineral-insulated (MI) cables and qualification of components for high-temperature operation in high radiation fields. In-house developed hybrid pre-amps and constant fraction discriminator (CFD) application-specific integrated circuits (ASICs) were deployed for better gamma discrimination and improved signal-to-noise performance. This generation of instruments also incorporated features of built-in tests and online fault detection.

Microelectronics and mega science

By the early 1990s, it was becoming evident that microelectronics would turn out to be the 'Achilles' heel' of the indigenous programme. As a mitigation measure, a fabless very large scale integration (VLSI) design facility named the Centre of Micro-electronics (CMEMS) was established for the design, development, modelling, testing and packaging of ASICs, hybrid micro circuits (HMCs), sensors and detectors. The Centre is equipped with facilities for carrying out integrated circuits (ICs) design, technology CAD, embedded design, semiconductor device characterization, spice modelling, packaging and wafer-level IC testing. The Centre has many successes to its credit, such as a variety of front-end signal processing ASICs, HMCs, data conversion and processing ASICs. These employ process technologies ranging from 1.2 to 0.35 μm on standard CMOS (complementary metal-oxide semiconductor) as well as SiGe BiCMOS. Successful development of RAD HARD pilot chips has established a vital capability required in reactors and high-energy physics experiments. It is a matter of pride that as international embargo regimes attempted to scuttle our programmes, these Indian ASICs were deployed in International Mega Science projects such as the Large Hadron Collider (LHC) of the European Centre for Nuclear Research (CERN), Geneva. ASICs from CMEMs will also populate the detectors of the proposed Indian Neutrino Observatory (INO).

Enthused by these successes, work on large-area, position-sensitive silicon sensors and photodetectors was initiated in right earnest. International experimental facilities for physics research such as CMS and ALICE at CERN, PHEONIX at Brookhaven National Laboratory, USA, and GASPARD in GANIL, France, provided a platform to showcase these cutting-edge capabilities (Figure 8).

The development of these detectors used the facility available at Bharat Electronics, Bengaluru, initially. Subsequently, a comprehensive detector development facility was funded by DAE at the Semiconductor Laboratories (SCL), Chandigarh for handling thin, high-quality, large-sized Si wafers. This facility has developed a variety of detectors such as silicon photomultiplier (SiPM), large-area

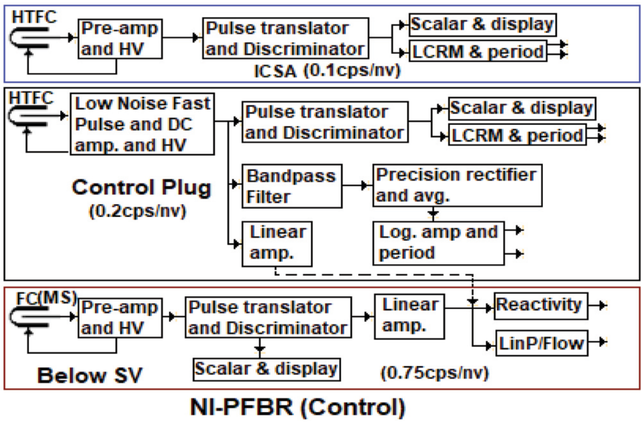

Figure 6. Nuclear instrumentation for PFBR.

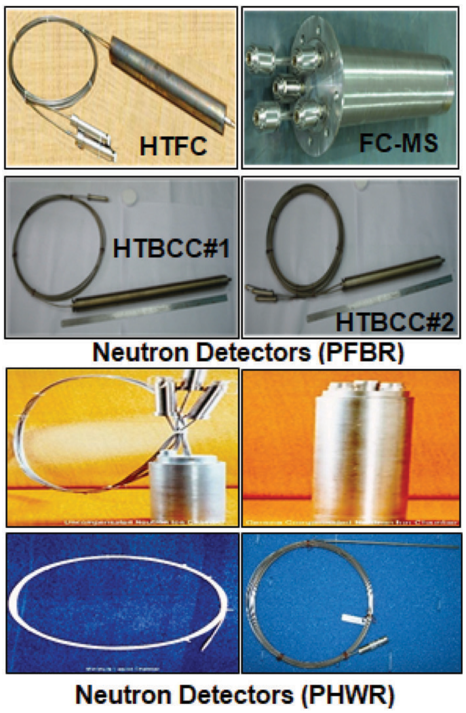

Figure 7. Types of neutron detectors.

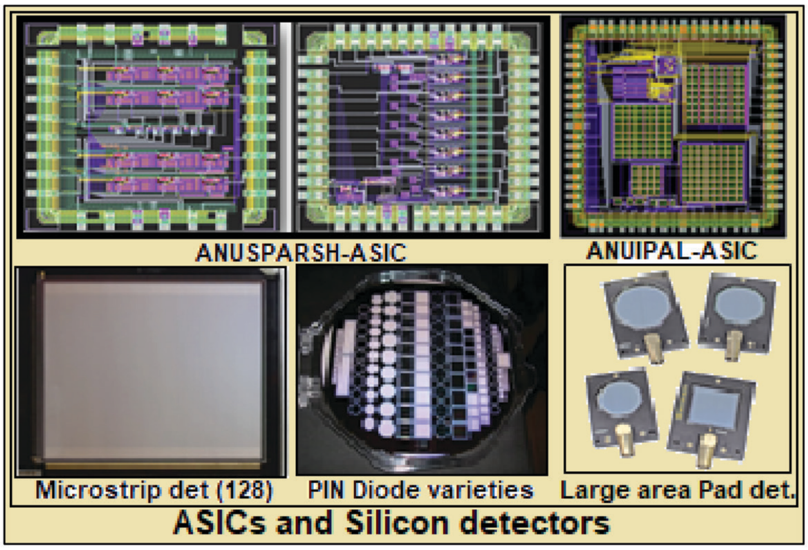

Figure 8. ASICs and silicon detectors.

Figure 9. Silicon detectors are used in a variety of applications such as X-ray baggage inspection, cargo scanner, radiation detectors in vehicle and limb monitors.

pad detector (300 to 600 mm^2) used for Pu activity monitoring in the air in reprocessing plants, photodetectors for X-ray baggage inspection systems and cargo scanners. PIN diodes developed here are used in a variety of applications of radiation measurements (Figure 9).

Control and instrumentation

As already noted, the commissioning of Apsara in 1956 marked the beginning of reactor C&I activity in DAE. This was followed by the commissioning and operation of

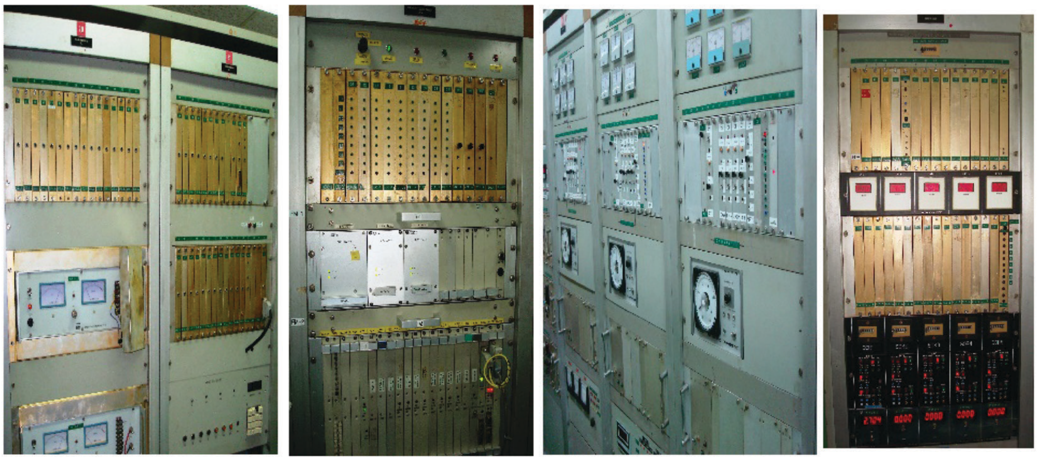

Figure 10. Computer-based I&C systems of Dhruva (1985).

the CIRUS reactor in the 1960s, which provided valuable experience to the C&I community.

The TAPS units 1 and 2 were the first power reactors to be built on Indian soil. These boiling water reactors (BWRs) with 160 MWe capacity were supplied by General Electric, USA. The commissioning of this reactor provided the much needed hands-on experience to the nascent C&I groups in AEET. While most of the C&I equipment came from abroad, operator control consoles were developed and fabricated by AEET. This was a modest, yet significant beginning. These twin units attained criticality in October 1969.

Parallelly, DAE had launched the PHWR power reactor programme and as the first step, two 220 MWe reactors were constructed at Rajasthan by the Atomic Energy Canada (AECL). This gave Indian engineers exposure to PHWR C&I. RAPS-1 went critical in 1973.

During the 1970s, the need was felt for a research reactor with higher neutron flux to meet the growing requirements of high specific-activity radioisotopes as well as research in basic science and engineering. Groundbreaking of 100 MWth research reactor R5 (Dhruva) was performed on 7 May 1974 at Trombay. The entire C&I for Dhruva was developed indigenously, thus ushering a new era in reactor C&I in India. For the first time, microprocessor-based control systems were introduced in a reactor in the country. These included all the C&I systems, viz. reactor regulating system (Figure 10), alarm annunciation system, start-up logic system, emergency cooling system, and failed fuel detection system. All the hardware and software were bespoke and developed by BARC. Features like finite impulse testing (FIT) were incorporated to aid in online diagnostics. Cathode ray tube (CRT) monitors made an entry into the control room. The trip systems and control-rod drive mechanisms continued to be hardwired and analog. Dhruva attained criticality on 8 August 1985.

The opportunity to field fully indigenous C&I in a power reactor arrived with the Madras Atomic Power Project (MAPP). This laid the foundations of home-grown C&I for PHWRs – hardwired control consoles, analog-based nuclear instrumentation and reactor regulating systems, relay-based process logic and reactor trip logic. MAPS-1 attained criticality on 2 July 1983.

The introduction of computers in PHWR C&I was calibrated and cautious. First in the line were systems not important to safety. The difficulty of quantifying the reliability of software and the impossibility of exhaustive testing delayed their application in the safety island. In light of the experience in Dhruva where microprocessor-based C&I systems were providing satisfactory performance, it was decided to introduce computer-based systems for class IC and IB functions at the Narora Atomic Power Station (NAPS). Hence, NAPS ushered in microprocessor-based reactor regulating system, channel temperature monitoring system, fuel handling control system, and process control systems. However, the trip logic system remained relay-based. NAPS-1 was connected to the grid in January 1991. The Nuclear Power Corporation (NPCIL), BARC, and ECIL worked together in an exemplary collaborative spirit to develop and deliver these systems.

The benefits of the computerization of C&I were becoming apparent. Based on the design and operational experience, a microprocessor-based programmable digital comparator system (PDCS) was introduced for the primary shutdown system of Kakrapar units 1 and 2 units for the first time. It replaced a whole lot of conventional hardwired indicating alarm meters. However, being a class-IA equipment, regulatory approval and certification proved to be a daunting task involving rigorous verification and validation protocols. This was a period of learning for everyone – the licensee, developers and the regulator. The team effort not only helped to build indigenous technology, but also regulatory standards, verification & validation (V&V) tools and industrial practices.

Parallelly, the Atomic Energy Regulatory Board (AERB) developed a series of safety standards and guides for the classification, development and certification of C&I systems

Figure 11. Computer-based fault-tolerant control systems for PHWRs.

of PHWR. Design principles and techniques such as fail safety, fault tolerance, single failure criteria, redundancy, defence-in-depth, design diversity and common mode failure criteria were brought to bear to maximize safety and availability. KAPS-1 was connected to the grid in May 1993.

With the government approving a fleet of 220 MWe-type PHWRs in the 1990s, the time was ripe for standardizing computer hardware for C&I. NPCIL, BARC and ECIL collaborated closely to develop a library of 8086 based single-board computer (SBC) and input–output (IO) cards with associated standardized cabinets, card-cages and wiring schemes.

Using these boards, a standard fault-tolerant architecture was evolved to cater to the safety and reliability targets of IB systems. Systems such as the reactor regulating system (DPHS-RRS) which regulates the reactor power, and process control systems (DPHS-PCS) which regulate the primary and secondary systems of the power plant were all built around this dual processor hot standby (DPHS) architecture (Figure 11). Other computer-based systems like computerized operator information system (COIS), radiation data acquisition system (RADAS), fuel handling control system (FHCS) and electrical data acquisition system (EDAS) were also developed for supporting and supervisory control and monitoring functions[6]. Relay-based systems were retained for the actuation systems of primary and secondary shutdown systems.

This phase in the evolution of C&I also witnessed the introduction of local area networks (LANs). Till then, system interconnectivity was limited to low-speed point-to-point serial channels. LANs permitted geographical distribution of equipment, sharing of IO, reduced cabling, sharing of information across plant systems and software configurability. The first systems to employ networked architecture were the programmable logic controllers (PLCs) of ECIL. The company had a product line of stand-alone PLCs and sought BARC's support in developing a real-time network backbone. BARC teamed with ECIL to develop IEEE 802.4 compliant token-bus LANs. These had won the 'determinism' argument over Ethernet, which was perceived as unsuitable for real-time systems due to its collisions and statistical nature of response delays. The PLC systems for Kaiga and RAPS were configured as distributed systems with a group of nine PLCs interconnected by dual redundant token-bus LANs. Following this, other systems such as RRS and PCS too were architectured as multi-nodal networked systems over token-bus LANs.

Migration from a centralized to a distributed scheme was not without hiccups. Interconnectivity introduced new interdependencies making verification difficult and fault propagation likely. It took some time for these systems to stabilize in the plant environment. However, just within a decade, Ethernet had become all-pervasive, driven by the explosion of the PC market and the internet. With the increasing speed, availability of switches and routers which facilitated reliable network topologies, the old concern about collisions became irrelevant. Token bus died a natural death, forcing a phased replacement by Ethernet.

Concurrent to the standardization of C&I hardware, steps were taken to standardize software development processes. A systematic lifecycle approach was prescribed for the development of software, following IEC standards and AERB guidelines such as D-25 (ref. 7). Software reliability was taken up as an important area of research for the development of high-integrity software. The activities in this area encompass the application of advanced V&V techniques such as static analysis, assertion-based verification of safety-critical software, development of V&V tools based on formal techniques, application of formal techniques of verification, standards, and guidelines for the development of safety-critical software.

The 540 MWe reactors at Tarapur marked a mature stage in the computerization of PHWR C&I. One of the important new developments was the liquid zone control system (LZCS) for fine control of reactor power and power distribution. Valuable lessons were learnt during the root cause analysis and mitigation of the problem of bulk-power

Figure 12. Full scope engineering simulators.

Figure 13. Evolution of control rooms: RAPS-1, Dhruva, RAPS-5 and TAPS-4.

oscillations. TAPS-3 was connected to the grid in August 2006 and TAPS-4 in September 2005.

The current fleet of 700 MWe PHWRs is being equipped with a new generation C&I developed indigenously by NPCIL incorporating contemporary technology and regulatory standards. The development of indigenous simulators too was critical to the success of the Indian nuclear programme and it went hand in hand with the evolution of Nuclear Power Plants (NPPs). Designing a simulator requires an in-depth understanding of neutronic and process dynamics, human–machine interactions, failure modes and accidental conditions. Training simulators are mandated today for licensing NPP operators. It is to the credit of our human resource development programme that all NPP operators are trained in indigenously developed simulators – be it the generation of PHWRs or upcoming PFBRs.

In addition to training simulators, hardware-in-the-loop simulators were also developed to qualify and validate the control equipment hardware and software in an integrated environment before their commissioning at the site. This is particularly important with today's multi-layered distributed architectures. These engineering simulators implement mathematical models of all major processes and reactor systems, sensors and actuators. These simulators generate steady-state and dynamic responses similar to the plant in normal and abnormal conditions. Performance and responses of the developed systems can be certified by simulation of large set test cases during validation of C&I systems (Figure 12).

The control room of today's PHWRs reflects years of evolution assimilating decades of operating experience. It is compact, ergonomically designed and replaces an array of meters and lamps with a few large LCD monitors (Figure 13).

A regime of qualification for NPP C&I got evolved over a period, encompassing seismic, electromagnetic compatibility

Figure 14. Nucon 1000 programmable logic controller from ECIL.

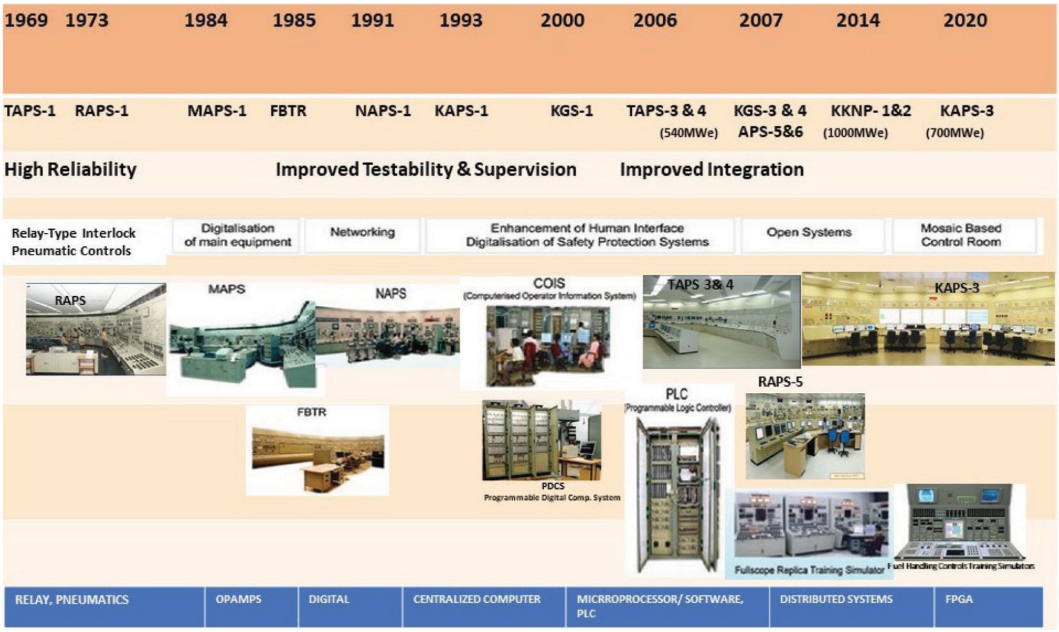

Figure 15. Evolution of nuclear power plant C&I in India.

(EMC), climatic and environmental standards. ECIL equipped itself with practices and facilities that would produce nuclear-grade equipment. Control and shut-off rods and their drive mechanisms (CRDM) are the vital components in a nuclear reactor. They are the actuators using which the C&I system regulates power and shuts down the reactor safely. From Apsara to the current generation of PHWRs, all our reactors are equipped with indigenous CRDMs. Indigenous capabilities also extend to specialized tools developed to aid in maintenance. BARC channel inspection system (BARCIS) is developed for in-service inspection of coolant channels of PHWRs. BARCIS is being used for the detection of flaws such as through-wall crack, nodular corrosion, inspection of rolled joints, etc.

This chronicle would not be complete without noting that in parallel to NPPs, indigenous C&I systems were evolving for the front-end and back-end facilities of the nuclear fuel cycle. These include heavy water plants, nuclear fuel fabrication plants, separation units, reprocessing plants and waste management facilities. Most of these C&I systems are now configured around commercial PLCs. In a major initiative, BARC and ECIL have joined hands to develop a new generation of safe and secure PLC for our reprocessing plants and other strategic applications (Figure 14).

Today indigenous C&I manages all Indian PHWRs. Multiple 220 MWe stations at Kaiga, Narora and Rajasthan have broken world records of working continuously for 760-plus days, creditable in no small measure to the quality of C&I systems that control them. During these five decades, systems have been successfully upgraded and refurbished to take care of ageing, obsolescence and new regulatory requirements, negotiating three generations of technology change, from vacuum tube/relay/analog systems to today's computerized, software-driven distributed control systems. Figure 15 depicts this evolution pictorially.

Electronics in other sectors

In the true spirit of being a national powerhouse of technology, BARC has been proactive in applying its know-how in diverse applications. A few of these are highlighted below.

The development of VT fuze was initiated in BARC in 1968. This technology formed the basis of a successful product line at ECIL. The development of servo systems for telescopes, antennas and airborne radars also has its origins traceable to the early days of DAE. High voltage supplies and pulse power systems find many applications in the strategic arena. The core competency developed in designing such systems for PHWRs forms the foundation on which such systems for compact LWRs are built.

Bhabha's cosmic-ray experiments had triggered the systematic R&D programme in electronics in DAE. With this pedigree, it is apt that indigenous electronics continues to have a major presence in national and international discovery science projects such as the Giant Meter-wave Radio Telescope (GMRT) of TIFR, 32 Meter Deep Space Network Antenna of ISRO, Multiple Atmospheric Cerenkov Emission (MACE) Telescope of BARC, LHC at CERN, International Thermo-nuclear Experimental Reactor (ITER) in France, Facility for Antiproton Ion Research (FAIR) in Germany and high-intensity accelerators of Fermilab, USA. These projects push the frontiers of technology catalysing innovations, inspiring teamwork and creating a skill pool.

On the cyber security front, indigenous developments in the area of trusted platforms, crypto products, network security, etc. have proliferated beyond the nuclear energy sector. BARC pioneered the development and deployment of access control and physical protection technologies in India. This knowledge helped the department of Atomic Energy (ECIL) to implement an effective security system for the Parliament House Complex in the aftermath of the 2001 terrorists attack.

During the 1970s and 1980s, BARC along with ECIL did pioneering work in developing thyristor converters for railway locomotives and choppers for Mumbai suburban trains. The instrumented pipeline inspection gauges developed by BARC are widely used by the Indian Oil Corporation for inspecting their oil pipelines.

From tele-ECG to deep-brain stimulators, BARC laboratories continue to develop medical electronic devices and transfer technology to industry.

Laboratory to the field: ECIL

ECIL under A. S. Rao played a pioneering role in the growth of indigenous electronics in India. It is instructive to hear the story of ECIL's beginnings in his words[2]:

> '...By the late 60s, the Atomic Energy Establishment at Trombay had a fairly large electronic group consisting of a nuclear instruments section and a components section.... All these sections together with the production division not only met the requirements of AEET but also of other industries and research organisations in the country. Nearly 1600 scientists, engineers and technicians were working in the electronic group by this time.
>
> The requirement of electronic items increased both in variety and volume as the years rolled by and the shifting of operations to some other places had to be considered seriously. A committee constituted with senior members of BARC for site selection recommended Hyderabad as an ideal location with a good climate, availability of trained manpower, and the existence of a large number of educational and research establishments. The Government of Andhra Pradesh readily came forward to give 1000 acres of land in a convenient location for the proposed new unit along with the Nuclear Fuel Complex.'

There was no ambiguity in Bhabha's mind that the new organization should be a corporation run on commercial lines and not yet another division of BARC funded by the exchequer. Here we see his conviction that public-funded R&D should prove itself by adding to wealth generation and stand on its own against the competition. Rao continues[2]:

> 'My initial attitude to the new unit was that it should be a division of AEET and not an autonomous corporation since it was an off-shoot of the developments at AEET. Bhabha had a different view. He had the confidence that the electronics know-how generated in BARC would measure up to the work done anywhere else in the world and had settled on the idea of an autonomous electronics factory to be run on commercial lines based on BARC know-how.'

After Bhabha's untimely death in 1966, Sarabhai carried 'mission ECIL' to its logical conclusion. Sarabhai combined the flair for research with the instincts of a businessman. While advocating the importance of translating R&D into saleable products, brought by independent users, he also recognized the need for a scientific approach to the management of such an organization.

When ECIL was set up as a public sector company under DAE on 11 April 1967, the initial manpower of about 400 dedicated people drawn from the Electronics Group of AEET formed the nuclei around which ECIL grew. This transfer of people enabled continuity of R&D work carried out at AEET (BARC).

The first product Divisions were the Nuclear and Allied Instruments Division (NAID), the Resistors and Capacitors Division (RCD), the Semiconductors Division (SMD), the Power Reactor Instruments Division (PRID) and the Microwave Division (MWD). Antennas and Computer groups moved in a few years later. Between 1967 and 1977, ECIL achieved an annual growth rate of nearly 80%, attaining

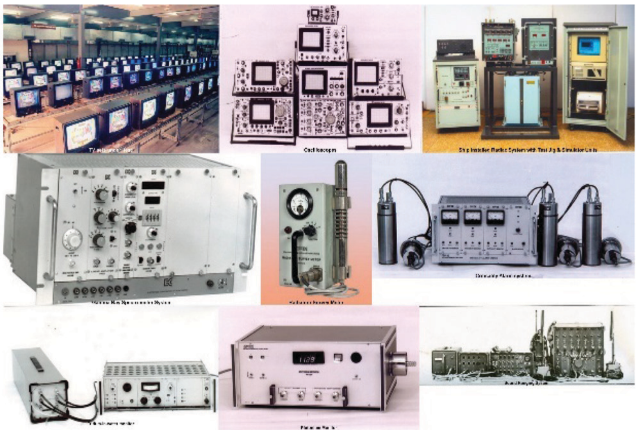

Figure 16. Products of ECIL through the 1970s.

Figure 17. ECIL's legacy computer product range.

breakeven operations within three years and earning a maiden profit of Rs 1.4 million during 1970–71, the fourth year of operation[2].

The pioneering efforts of ECIL resulted in several products that positioned the company as a torchbearer of the electronics and IT revolution in India. EC-TV and EC computers were the flagship products of this period. This phase was characterized by an explosion of indigenous products, infectious enthusiasm, a young workforce and growth in manpower. A poor, young nation was mastering another advanced technology and proving the sceptics wrong (Figures 16 and 17).

ECIL thrived during this period of import restrictions and protected market, which was dictated by the nation's dire position on the foreign exchange front. The good days did not last long, however. The emphasis on self-reliance and doing everything in-house, right from components to complex computer-based control systems underplayed the need to be competitive in the market. The large product range of ECIL was unwieldy and unviable. The liberalization of imports during the 1980s further exposed the Company's weaknesses. It had to vacate components, TV and computer markets, and recalibrate its 'self-reliance' posture to survive. The fact that ECIL has lived to tell the tale is a testimony to its innate resilience and core strength.

In five decades, ECIL has grown into a modest INR 1500 crore company, profitable during most of its life. It is slimmer and younger with 1500+ employees. It has gained new ground in other strategic sectors of the Indian economy such as defence electronics, aerospace and security electronics (Figure 18).

Table 1 groups ECIL's technology footprints into two categories – the ones which lasted and those which did not. In the following paragraphs, we attempt to provide a rationale.

ECIL's impressive portfolio of components (passive and active components, power transistors, synchro, etc.), instruments (covering scientific, analytical, nuclear, biomedical, photonics and industrial applications) and computers had to be closed by the 1980s. The company was not alone in this. Most of the electronics hardware industry in India also wound-up business, swept away by the forces

Figure 18. ECIL's current portfolio covers discovery science, nuclear and defence sectors.

Table 1. ECIL's products – past and present

Past products	Components, semiconductors, computers, consumer electronics (television), instruments, telecom
Present products	NPP C&I, antennas, nuclear instruments and radiation detectors, power electronics, defence electronics, EVM, security electronics

of globalization. All the policy support provided by the government through the Electronics Commission and Department of Electronics had not prepared the Indian industry to be globally competitive. The protection only delayed the demise. In hindsight, it appears that incentivizing exports rather than import substitution might have helped India preserve the great gains made in the early decades and align with global trends. Dependency on imported components, semiconductors and instruments is perceived today as a major weakness from economic as well as strategic angles.

However, ECIL endured in certain other business segments such as nuclear instruments and antennas, though their beginnings too could be traced to those heady days of the 1950s. It can justly lay claim to its share of kudos for the depth and breadth of indigenous capability in India's nuclear programme. The Company has left its footprints in all the NPPs and all the fuel-cycle facilities, acting as a bulwark against sanctions, mitigating obsolescence and providing cradle to grave service. Even though much of manufacturing is now outsourced, ECILs capabilities in product engineering, quality control and qualification continue to make it important to the nuclear energy sector.

Yet, there are gaps in ECIL's capabilities as a 'build-to-specs' nuclear C&I company. With the preponderance of software in contemporary C&I, this gap has further widened. The company had to pay a heavy price when the NPP C&I business too was opened to the competition where the customer did not find much to differentiate ECIL from other electronics system manufacturers. If anything, this setback further validated Bhabha's maxims on effective technology transfer – the need to absorb and assimilate technology through people. ECIL's delinking from the BARC Training School too was a contributory factor.

ECIL's journey on the trail of defence electronics too is revealing in many ways. The company set up a manufacturing facility for electronic fuzes in 1971 with technology developed by BARC. Based on this technology, various types of electronic fuzes were produced and supplied to defence forces. However, with technology evolving, competition soaring and threats to business mounting, it took the foreign tie-up route to upgrade technology and enhance production capacity. This enabled the company to set up a state-of-the-art, high-quality, large-scale production facility for universal electronic fuzes, operating in various modes such as proximity, time delay and point detonation, for 105, 130 and 155 mm artillery guns. This indigenous production capability stood the nation in good stead during the Kargil war, while adding substantially to the company's top line. Yet, it did not help the bottom line. Bhabha's cautionary tales of perennial dependence if we follow the easy route of importing technologies continue to ring true.

Defence electronics forms a lion's share of ECIL's technology landscape, manpower and earnings today. This diversification was expected, given the company's birthing credo. In the beginning, it was by way of applying nuclear electronics for military applications. The communication and microwave groups that moved from TIFR and AEET seeded military communications radios and microwave equipment initially and then evolved to develop COMINT, electronic warfare and C4I domains in the new millennium. Today, ECIL is a well-regarded entity in this space integrating solutions with a pragmatic mix of in-house, domestic and imported technology. However, there is much scope to reduce dependence on imported subsystems and enhance value addition.

The story of power electronics in ECIL is more convoluted. In the 1970s the company invested heavily in R&D for railway locomotive technologies, but had to taper down the activity when users abandoned indigenous development and opted for the import route. Power electronics activity was revived again when opportunities arose in international discovery science projects – LHC at CERN, FAIR in Germany, ITER in France and Fermilab in USA.

ECIL has earned itself a name in security electronics, once again leveraging its umbilical connections with BARC. The portfolio covers X-ray baggage systems, radiological detectors, video surveillance systems, personnel access control, vehicle access control gadgets, perimeter protection devices, etc. However, ECIL is more of a system integrator, designing solutions around third-party gadgets, IT hardware and software. This is not an ideal situation, either for business or for self-reliance.

If TVs and computers were ECIL's flagship products once, it is electronic voting machines (EVMs) today. EVMs stand as a shining example of an India-specific technology, designed and developed in and for the country – the product founders would be proud of the same.

An appraisal

Why did certain indigenous technologies prosper while the others withered? Is it that indigenous technology thrived only when the market was reserved or when imported technology was denied to us, as is often suggested?

For Bhabha and Sarabhai, hard-headed economic considerations drove the policy of self-reliance in electronics in no less measure than strategic independence. It required courage of conviction to start an industry purely based on indigenous development. This policy has stood the nation in good stead when it was confronted with embargos.

Until the 1980s, professional electronics led the pace of technology in microelectronics, computers and communications. It was a high-performance, high-cost, low-volume market. Consumer electronics was considered a low-tech follower. The tables have turned since. This shift had a profound impact on the reliability and cost of electronics, compelling the strategic electronics sector to adapt commercial technologies and standards.

Consumer electronics also accelerated the globalization of manufacturing and design, creating in the process complex supply chains and intellectual property (IP) rights regimes. Manufacturing has become passé – it is IP ownership that counts. A product today may incorporate many third-party IPs. This has created complex interdependencies, with no single nation in control of all technologies.

Electronics systems have become all-pervasive and critical to national strategic infrastructures being susceptible to supply uncertainties, obsolescence and cyber-attacks. In such a scenario, complete technology independence may not be a practical solution. Instead, building interdependencies that leverage our strengths to advance our strategic as well as commercial interests may be the right strategy.

At around US$ 50 billion, electronics is a major item of import by India, second only to oil. Imports constitute a large percentage of the domestic electronics market, which is also growing. There are good signs too – buoyed by recent policy initiatives, the domestic manufacturing sector is once again showing signs of growth, easing the import burden and creating mass employment. This would be the moment to reinvigorate the innovation ecosystem, create Indian IP and world-class technologies. DAE's experience of the past decades has many lessons to offer in this regard.

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