Baldev Raj (1947–2018)

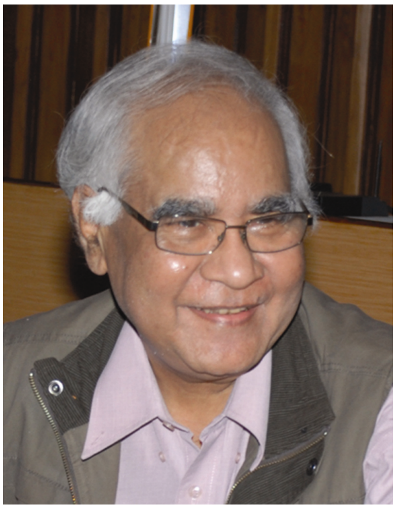
Baldev Raj (BR), a distinguished scientist and technologist of India passed away on 6 January 2018 at Pune while he was on official duty.

BR was born on 9 April 1947 in Jammu. He lost his father at a very early age. In 1969, he graduated with a gold medal in the engineering discipline (metallurgy) from Ravishankar University, Raipur. In 1970, he joined the 14th batch of Bhabha Atomic Research Centre (BARC) Training School in Trombay. After successful completion of training, he joined BARC as a Scientific Officer. BR obtained his Ph D from the Indian Institute of Science (IISc), Bangalore in 1990 in the Faculty of Engineering, in a multidisciplinary area encompassing collaboration between the Department of Metallurgy and Aerospace Engineering.

BR was deputed to RISO National Laboratory, Denmark during 1973–74 and on his return assumed duties in Radio Metallurgy Laboratory (RML) at the Reactor Research Centre, Kalpakkam (renamed as Indira Gandhi Centre for Atomic Research (IGCAR) in 1985). He had a long and distinguished scientific carrier at IGCAR and also served as its Director during 2004–2011. Subsequent to his retirement from IGCAR, BR was with the P.S.G. Institutions, Coimbatore during 2011–2014. He then took over as the Director of the National Institute of Advanced Studies (NIAS), Bengaluru and continued until his sudden demise.

While at IGCAR, BR galvanized a whole community of staff, scientists and engineers for the development and advancement of the fast breeder reactor (FBR) technology in India. He provided the umbrella under which scientific work in many areas including non-destructive evaluation (NDE), nuclear materials development, physical and mechanical metallurgy, welding science and technology, corrosion science and engineering, separation science and technology, liquid sodium science and technology, mechanics, safety research, electronics and instrumentation, materials science, nanoscience and technology, robotics and automation flourished at IGCAR. Work in the area of NDE was initiated and nurtured by BR, whose personal example of dedication to work and emphasis on meaningful research has been an inspiration to many scientists and engineers in DAE as well as other strategic sectors, including DRDO and ISRO.

BR was associated with the construction and commissioning of the hot cells in RML for carrying out post-irradiation examination (PIE) of the irradiated fuel sub-assemblies from the Fast Breeder Test Reactor (FBR). He visualized a four-pronged strategy which envisioned: (a) establishing the conventional non-destructive testing methods, such as radiography and ultrasonics which serve as the workhorse for the manufacture of



reactor components; (b) identifying and establishing advanced NDE methods such as multi-frequency eddy current testing and acoustic emission (AE) which would serve as valuable tools for in-service inspection of reactor components; (c) developing insights into the fundamental physics of NDE and interactions of probing medium with materials for research and enhanced technological applications, and (d) development of sensors, instrumentation, signal processing and imaging approaches. BR's visionary approach transformed RML into a Centre of Excellence in NDE, the first of its kind in India. PIE of the highly irradiated mixed carbide fuel sub-assemblies has provided a valuable feedback for assessing performance and residual life of fuels and structural materials used in a reactor. The NDE techniques of dimensional measurements, X-ray and neutron radiography, eddy current testing, metallography, fission gas extraction and analysis, high-temperature tensile tests, micro hardness, small specimen testing, etc. were employed in hot-cell facilities of highly irradiated, plutonium-rich fuels, wherein BR played a key role in mastering this complex technology. This resulted in stage-wise assessment and performance of fuels, up to a burn up of 165 GWD/T.

BR conducted a systematic scientific analysis of AE generated during movement of dislocations and established that the predominant frequency of AE signals is inversely proportional to the duration of the dynamic event. This led to quantitative estimation of the mobile dislocation density associated with the deformation process and a methodology to find the waiting time of the dislocations at obstacles during tensile deformation. BR discovered acoustic amplification from potentially subcritical sources, which enabled elucidation of new information regarding dislocation movements in austenitic stainless steel (SS). Barriers to movement of dislocations in Nimonic PE16 superalloy have been characterized by AE time-domain signatures. Identification of predominant strengthening mechanisms in gamma-prime size range of 10–50 nm had remained an unresolved issue even after extensive electron microscopic studies. The AE-based studies conducted by BR resolved this issue. Additionally, when more than one strengthening mechanism is operative, the superimposed AE signatures were resolved to determine the operative mechanisms and their relative dominance. BR was successful in characterizing the break-away and spalling nature of oxidation in a variety of materials and demonstrating the ageing-induced alpha-prime martensite formation during continuous cooling of the metastable 304 SS through shear process by developing advanced AE signal analysis approaches.

Another important contribution of BR was in establishing the magnetic Barkhausen emission (MBE) as a tool for characterizing the microstructure and mechanical behaviour of materials. The stages of fatigue deformation and damage in 9Cr–1Mo steel such as cyclic hardening, softening, saturation, cusp formation which is an indication of crack initiation, creep deformation and fracture, development of substructure, precipitation of various phases and their growth in various stainless steels, ferritic–martensitic steels and superalloys have been correlated using MBE signals. He made innovations in experimental methodology by utilizing the complementary nature of hysteresis (bulk) and MBE (surface) characteristics to separate the individual effects of residual stresses and dislocation density on MBE. These studies have been found indispensable in structural integrity assessment and life assessment of the power plant components. An invited paper on 'Assessment of microstructures and mechanical behaviour of materials through non-destructive characterization' in *International Materials Reviews* (2004) is testimony for his contributions in the NDE field.

BR championed the cause of NDE science and technology with ingenuinity, vitality and cohesiveness. He played a pivotal role during design and commissioning of KAMINI – the U-233 fuelled reactor at IGCAR with experimental facilities for neutron radiography and activation analysis. His expertise in NDE was effectively utilized in strategic sectors for solving challenging problems. The significant contributions made by him include structural integrity assessments of some of the most difficult engineering components such as end shields and coolant channels of pressurized heavy-water reactors, Inconel alloy tubes of heavy-water plants, concrete ring beam of Kaiga-I PHWR, heat exchangers and pressure vessels of nuclear, petrochemical and fertilizer plants, detection and evaluation of fatigue cracks in maraging steel weldments of rocket motor casings in satellite launch vehicles, in-service inspection – NDE of the first PSLV and GSLV, development of NDT methodologies for life assessment of tail rotor blades of Mi-8, Mi-17 defence helicopters and MIG 21–23 defence aircraft and landing gears of MIG-21 aircraft. The challenge in all these assignments was the variety of materials involved and detection of defects with high sensitivity. Solving these demanded a good understanding of the metallurgy, modelling for understanding and optimizing the inspection techniques, and procedures and development of appropriate sensors and hardware.

BR had the ability to plan and execute large-scale science and technology projects comprising multiple tasks and stakeholders, and navigated through the complex ecosystems that cut across various Government agencies, research laboratories, production units and academia. During his long tenure at IGCAR, BR gave thrust to science and knowledge-based materials development that included control of composition, microstructure and grain boundary engineering. He steered his group towards the indigenous development of modified austenitic stainless steels and dispersion strengthened ferritic–martensitic steel for FBR fuel-clad tubes, and corrosion-resistant Ti-5Ta-1.8 Nb alloy for nuclear fuel reprocessing applications. The indigenous development of void swelling-resistant 9Cr-ODS steel FBR clad-tubes was successfully carried out in the country in collaboration with Nuclear Fuel Complex (NFC) and International Research Center for Powder Metallurgy and New Materials (ARCI), Hyderabad. These tubes not only possessed high yield and ultimate tensile strength (due to fine dispersion of 5–20 nm yttrium oxide complexes), but also significant irradiation resistance. The material upon qualification showed considerable microstructural stability and demonstrated the long-term creep rupture strength necessary for minimizing nuclear fuel cycle costs.

In order to increase the economic competitiveness of FBRs, the design life of future reactors has to be increased to at least 60 years from the present 40 years. BR's foresight enabled comprehensive development and characterization of the low carbon and nitrogen alloyed 316 stainless steel and fabrication technologies for various structural components. He initiated the indigenous development of reduced activation ferritic–martensitic steel for the Indian test blanket module of the international thermonuclear experimental reactor. In close collaboration with Mishra Dhatu Nigam Limited (MIDHANI), India-specific RAFM steel was developed with stringent chemical composition requirements with respect to radiologically undesirable elements by proper selection of raw materials and employing a combination of vacuum induction melting and vacuum arc refining techniques. The required elevated temperature creep strength and very low ductile-to-brittle transition temperature were achieved through optimization of W and Ta contents, thermomechanical processing and heat treatments.

BR was a strong advocate of the concept of closed fuel cycle with FBRs. He was the chairman of a long term R&D committee on fuel cycle which was instrumental in identifying, promoting and nurturing several R&D programmes related to fuel cycle at BARC as well as IGCAR. He co-authored a book titled *Sodium Fast Reactors with Closed Fuel Cycle*, which is considered to be a valuable resource material for students, researchers and industry professional.

The spin-off applications of NDE were realized for societal applications, especially in the area of healthcare, and characterization and conservation of heritage structures. The Department of Science and Technology, New Delhi entrusted BR with the responsibility of scientific characterization of ancient South Indian Panchaloha idols and the Delhi Iron Pillar based on NDE methodologies. He has written a monograph *Where Gods Come Alive* on South Indian bronzes and published a comprehensive article on 'History of metallurgy in India'.

The foresight and imagination of BR in planning and organization, and his dedicated efforts in the successive stages of the nuclear programme development over the decades, have paid rich dividends in the form of a strong and comprehensive base that we now have in NDE, materials development, welding science and technology and FBR technologies in India. Based on his immense all-round contributions in science and engineering, he was awarded *Padma Shri* in 2007. He was a fellow of the four Academies of Science, and Engineering in India, German Academy of Sciences, Third World Academy of Sciences, International Medical Sciences, ASM International and The Indian Institute of Metals.

The 2004 tsunami had caused massive destruction in the DAE township at Kalpakkam. BR worked relentlessly to evolve a strategy with innovative ideas and coordinated the reconstruction plan of the township.

While at Coimbatore, BR took the initiative to establish a Sustainability Centre for Micro, Small and Medium Enterprises in PSG Institutes. At NIAS, he was engaged in nuturing leaders with immense conviction and confidence in harnessing a synergy of the capabilities in disciplines like social sciences, humanities, culture and heritage, science and technology, policies, etc. He was an acknowledged manager par excellence with the ability to initiate and execute projects of national importance by bringing together experts in various disciplines and motivating them to perform as a team to achieve success.

BR's work on science policy and science diplomacy was acclaimed and harnessed by the country at the apex level. He chaired the National Materials Policy for Strategic and Critical Materials Committee of the Ministry of Defence, GoI; National Expert Committee on Rare Earths for Policy and Plans, NITI Aayog; Explosive Detectors and Systems Research and Developments, Office of the Principal Scientific Advisor; Clean Coal Technologies Committee of DST and the Indian National Academy of Engineering; Steel Research & Technology Mission of India; Ministry of Steel, GoI, etc. He was a member of the Committee for forming S&T Vision for India, NITI Aayog. The formulated roadmap of the Committee for indigenous competence and delivery provides a framework of R&D to realize the objective of addressing national priorities. He co-chaired in preparing the national vision paper on S&T and action plans for 3 years, 7 years and 15 years for the Committee. The team formulated a paradigm shift in strategies for a robust and implementable S&T framework in the country for realizing priorities for society and security.

As his colleagues at IGCAR, we observed that BR worked round the clock on the challenges in science and technology in the country. He had a deep understanding of his colleagues, gauged their knowledge and aspirations, understood their commitments, sentiments and sensitivities, and chose the right person for executing a task. His leadership skills were expressed through character, commitment, competence of professional skill, ability to conceptualize problems, plan strategies and tactics, and execute the action plans. He had a deep knowledge of human psychology, and always kept the morale of his colleagues high and motivated them. He was always keen to foster talent and develop new scientific leaders for the future. In his passing away, India has lost one of her worthy sons, who was a visionary leader in science and technology and more importantly, a human being par excellence.

Baldev Raj is survived by his wife (Aruna Kumari) and two sons (Hemant and Kunal).

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