

R. Krishnan (1935–2021)

Rangachari Krishnan (RK), born on 26 December 1935, passed away in Bengaluru on 16 April 2021, battling for life against his steadily failing health. He is survived by his wife, daughter and a son.

RK had an outstanding record throughout his academic career. He obtained his B.Sc. (Honours) in 1956 and M.Sc. in 1957 from Madras University and Ph.D. in 1967 from Bombay University. After obtaining M.Sc., he joined as a trainee in 1957 in the Atomic Energy Establishment, Trombay (AETT) and was inducted as a Scientific Officer in 1958. He served at Bhabha Atomic Research Centre (Department of Atomic Energy) between 1958 and 1985 and held the position of Head, Metallurgy Division in 1982. Later, he joined as Director, Naval Chemical and Metallurgical Laboratory, Bombay in the Defence Research and Development Organisation (DRDO) in 1985 and continued up to 1988. He served as the Chief Controller (R&D), Delhi (DRDO) from 1988 to 1990. He was Director of Gas Turbine Research Establishment (GTRE), DRDO, Bangalore from 1990 till his superannuation from Government Service in 1995. He served as Chief Executive of Shiva Analyticals, Hoskote, Bangalore from 1996 to 1999. He was associated with Centre for Science, Technology and Policy (CSTEP) as its Chief Advisor from 2008 to 2011.

Because of his specialization in X-rays and crystallography during M.Sc. degree, he was asked to undergo training in chemistry in X-ray crystallography which was being carried out in the Chemistry Division of AETT. He approached Raja Ramanna, who was in-charge of training school then, and explained his predicament and reservation in continuing the training in chemistry discipline, because of his chosen interest in physics from his school-days. Ramanna obliged and changed him to the physics stream. After successful completion of training in physics in the first batch, he was initially posted in Nuclear Physics Division as a Scientific Officer, and he was subsequently asked to shift to Metallurgy Division led by Brahm Prakash. The construction of research reactor CIRUS was then in progress at Trombay complex with Canadian design, and Homi Bhabha wanted AETT to fabricate half the (Half-of-Full Core) requisite quantity of metallic uranium fuel elements indigenously. One of the critical factors to be in-

vestigated in metallic uranium fuel was the texture or the crystallographic orientation. Since RK was the only person from the training school who had the requisite background to conduct research in this area, he was finally posted to Metallurgy Division. This research activity became a stepping stone for his transformation from a Physicist to a Metallurgist. RK often used to express that choosing metallurgy as his research field was the most significant and fortunate decision he took in his career.



Based on detailed studies, RK showed that quenching of uranium fuel rods from high temperature beta-phase leads to a random texture. Subsequent to this investigation, when the source of natural uranium for fuel making was changed, the fuel rods started shrinking instead of anticipated marginal growth. RK predicted that the introduction of cold work by drawing operation after beta quenching can alleviate this problem. In fact, the uranium fuel rods that underwent such a treatment behaved better with no shrinkage/growth. He advanced valuable suggestions to overcome the bulging of the uranium metallic fuel occurring due to irradiation. V. S. Arunachalam, from the second batch of AETT training school became his valued colleague and important research contributions were made jointly by them. Their research work on X-ray line broadening on cold-worked uranium was accepted for publication in *Acta Metallurgica* (1962, 10, 81). This turned out to be the first paper in this prestigious journal from an Indian research group. Detailed studies pertaining to the deformation of uranium metallic fuel under irradiation led to effective correction in the fabrication processes.

All these fundamental research works were found useful in establishing that the life of the metallic uranium fuel rods made indigenously was twice that of a Canadian Fuel Element in the CIRUS reactor. He also found solution for the variation in sintering behaviour exhibited by UO₂ powders derived from different sources and used as a fuel in nuclear power reactors. He conducted extensive X-ray line broadening studies, estimated the particle size and the degree of crystallinity in the powders and related them to sintering behaviour. Powders which were fine in the range 20–40 nm sintered to a higher density at lower temperatures. He was the first to show the existence of stacking faults in uranium.

RK was deputed to CEN de Saclay in France for a one year training which enabled him to get insights into the formation of stacking faults in alpha-uranium. RK utilized the opportunity as well, to work with Andre Guinier (Laboratoire de Physique de Solid at Orsay) for six months, on X-ray small angle scattering of irradiated quartz. RK was the first to show an epoch-making result that under neutron irradiation, amorphous regions develop as small pockets, while the crystalline structure was retained. RK submitted Ph.D. thesis to Bombay University on X-ray line-broadening studies which revealed that cold-working of an alloy whose composition is very near the FCC/HCP phase boundary, would easily get transformed from one structure to another.

In addition to his individual academic excellence, RK displayed very high quality technical leadership. As head of structural metallurgy group in BARC, RK established a world class research laboratory for characterization of microstructure at various levels, and steered the activities from forefront by initiating and nurturing a very comprehensive programme in the field of phase transformations and structure–property correlations. The dedication and commitment of RK towards performing hard work and emphasis on meaningful fundamental research employing optical, scanning and transmission electron microscopy was an inspiration to a competent group of several young metallurgists from the structural metallurgy group. He mentored P. Mukhopadhyay and Srikumar Banerjee and several others, and the research in physical metallurgy flourished as evidenced by several original contributions

and joint publications. RK used to feel proud that Srikumar Banerjee, later became Director, BARC and subsequently Chairman of the Atomic Energy Commission and Secretary DAE.

RK played a pivotal role in understanding the physical metallurgy of several zirconium-base alloys which are the most important cladding materials for power reactor fuel, and also for the construction of in-reactor components like pressure tubes. He showed that martensitic transformation in Zr–Nb, Zr–Ti and Zr–O was characterized by an inhomogeneous shear which changes from slip to twin as the alloy is enriched in Nb and Ti, with accompanying morphological change from lath to twin. Factors contributing to the strength of martensite were evaluated by choosing the Zr–Ti system where the solid solution strengthening factor could be isolated from the structural strengthening. RK showed that the twin boundaries act as effective barriers for the motion of dislocations whereas the substructures contribute to the athermal component of the flow stress. His studies on Zr–Ti system revealed the relative effectiveness of lath and twin boundaries to martensite strengthening. Thus, RK created a base of expertise for zirconium alloys which can be readily tapped when necessary. In fact, the basic research carried out by RK and his colleagues on Zr-alloys enabled solving the production problems faced by the Nuclear Fuel Complex when they did not obtain the strengths expected from zircaloy tubes. These studies acted as a boon in establishing later the flow sheet for the production of Zr–Nb tubes at NFC by Metallurgy Group scientists of BARC.

RK made excellent research contributions towards understanding the phase transformations and strengthening mechanisms in alloys of titanium which have applications in heat exchangers and other special components for reactor systems. The precipitation of the alpha-phase from the supersaturated beta phase was examined in detail in relation to crystallography, morphology and kinetics in the binary (Ti–Cr, Ti–Mo) alloys, whereas stress-induced transformation characteristics were established in the commercial alloys (Ti–6Al–4V, Ti–8Al–1Mo–1V). The abnormal behaviour of the martensite in Ti–6Al–4V is shown to be the result of co-operative movement of the twin boundaries in martensite. In the Ti–8Al–1Mo–1V alloy the strength abnormality was attributed to the presence of the metastable

beta-phase which undergoes martensitic transformation during mechanical deformation.

RK also conducted research on stainless steels of importance to the nuclear programme. He found that the deformation of FCC 316 SS at cryogenic temperature creates deformation bands of overlapping stacking faults and sheets of HCP phase. The BCC phase was shown to nucleate preferentially at the intersection of the two sets of bands. Ageing experiments on a PH 13–8Mo revealed that the BCC lath martensite has a fine distribution of spherical particles of NiAl. The strengthening was attributed to these fine coherent NiAl particles and to the reverted austenite which was also appearing as fine particles.

As Head of a much larger Metallurgy Division, RK led multifaceted activities including extractive metallurgy, ceramics, powder metallurgy, mechanical metallurgy, corrosion, melting, casting, etc. With enormous contributions in several fields and technical expertise, he proved himself as a total metallurgist.

V. S. Arunachalam, former colleague of RK in BARC, who assumed offices of Scientific Advisor to Raksha Mantri and Secretary, DRDO later, was looking for a Director for the Naval Chemical and Metallurgical Laboratory (NCML) located at the Naval Dockyard of Bombay. After obtaining the necessary approvals, Arunachalam appointed him as Director of NCML, on deputation to DRDO, in February 1985. Although NCML was equipped with excellent facilities, RK noticed that there was not much basic research in progress. He introduced a research culture by making several of his senior colleagues register for M.Tech. and Ph.D. programmes, and encouraged them to publish their findings in reputed journals. He initiated some new programmes on naval bronzes, brasses and molybdenum-bearing steels. In a short period of three years, RK changed the complexion of NCML. As the Chairman of the Materials Advisory Committee for the ‘Advanced Technology Vessels’ programme, RK was responsible for the Indian Navy rejecting the age old AK 25 steel, as the hull material, which the Russians initially proposed for the Indian nuclear submarine. The credit goes to RK for induction of AB grade steels with a good combination of mechanical properties, weldability and corrosion resistance. Subsequently, the Defence Metallurgical Research Laboratory in Hyderabad indigenized these grades of steels.

In March 1988, RK assumed office of Chief Controller R&D at DRDO Headquarters in Delhi. In this capacity, he assisted more than half the technical laboratories in DRDO. He also served as in-charge of the Human Resources Development. As an active researcher and scientist, he was not happy with the pure administrative job and sought a transfer to a laboratory. He was posted as Director of GTRE with effect from 1 January 1990.

By the time RK joined GTRE, it had built the after burner for the Orpheus 703 engine, but that was not accepted because it was overweight. It had also built two technology demonstrator engines designated as GTX-37-14U and GTX-37-14UB, the former being a straight jet while the latter was a by-pass version. This had given confidence to GTRE to bid for building the gas turbine engine (Kaveri) for the Light Combat Aircraft (LCA). The design of the Kaveri engine was based on a mixture of eastern and western philosophies. Obviously, several problems did surface. RK took over the reins of GTRE at this critical juncture. He had detailed discussions with experienced design engineers and the number of stages in the high pressure compressor was increased from 5 to 6. He emphasized that the engine design dimensions specified shall account for thermal as well as centrifugal expansion to arrive at the dimensions for manufacturing. RK assisted in developing a step wise annealing schedule to reduce the dimensional distortion resulting from residual stresses associated with welding/machining. GTRE had five engine test beds and it used to test the prototype engine only once in a day. He convinced the scientists/engineers and increased the frequency of testing, culminating into the test run of the first prototype of Kaveri in 1994. RK showed exceptional ability to plan and execute several other key projects consisting of multiple tasks and stakeholders, and navigated through the complex ecosystems that cut across various Government agencies, research laboratories, production units and academia.

RK realized that some of the problems that GTRE faced were due to lack of adequate research experience on the subsystems of the engine and initiated a few basic research programmes to surmount them. RK built an efficient team of Metallurgical Engineers and Material Science Experts and mandated them to support the Engine Development Programme. Initial effort put in by GTRE scientists was also given a huge momentum and accelerated to integrate

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with several expert teams of Public/Private Sector Units and Laboratories from DRDO, DAE, CSIR and ISRO Units. RK led various activities from the front and plugged several technology gaps that existed in the development of Gas Turbine Engines. He was associated with the development of whole gamut of Gas Turbine Materials in different forms such as forgings, castings, bar and sheet materials, heat treatment processes, coatings, etc. Most of the super alloys required for the manufacture of various discs and blades were initially imported, but later made by Mishra Dhatu Nigam Limited (Midhani), which were certified by CEMILAC, the agency for certification of materials for airworthiness. In view of the necessity to generate adequate mechanical properties data of the materials in use, RK established the Aeronautical Materials Testing Laboratory near Midhani in Hyderabad. In fact, one of the authors of this article (K. Bhanu Sankara Rao) was fortunate to be associated with this project and provided the specifications for tension, fatigue and creep-fatigue interaction test facilities, and in their procurement and installation.

The short-term objectives and achievements of RK comprised integration of Midhani and production units of Hindustan Aeronautics Limited (HAL) to set up National production facilities for directionally-solidified turbine blades and vanes, development of forgings of several titanium-alloy discs, blades, many nickel-based super-alloy discs, and more importantly the commissioning of fully certified Aeronautical Material Testing Laboratory (AMTL) dedicated to the Country's Engine Development Programme.

He was the force behind the kick-start and launch of the National Rapid Prototyping Centre for all DRDO Labs in the country which made a major stride in the 90s: this has now grown up into a successful venture in additive manufacturing and handling many critical metallic parts of gas-turbine engines. A futuristic initiative of RK, this kept DRDO at the forefront to leverage the advantages of this marvel of additive manufacturing for aerospace applications in the country.

He was a staunch believer in cross-fertilization and flow of experience across several departments and laboratories in

both government establishments and private industries to nurture many interdisciplinary and multi-disciplinary programmes. This outlook enabled him to support many life-extension programmes of several aircraft and aero-engine systems of the Indian Air Force. He also shouldered the responsibility of monitoring the progress of Projects like PTAE-7 engine for Lakshya Aircraft and gave active and personal support to many classified Naval Projects such as Nuclear Powered submarines.

RK knew and used his administrative powers and exercised them without too much of noise and friction. What was a chaotic trade union atmosphere in GTRE before his arrival settled down to normalcy within a short period. In fact, GTRE employees found in RK an affable, calm, firm and focused personality, radiating authority and a confident technology-laboratory captain, blended with R&D administrative acumen, which he acquired during his days in DAE and a stint at the DRDO headquarters. 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 was a shrewd and skilled negotiator with reference to financial issues of technological programmes and was highly successful in bringing down the cost of propulsion systems for the Air India fleet, many manufacturing machinery, material processing and testing equipment. One of the authors of this article, K. Ramachandra as a senior scientist of GTRE, witnessed all his activities from very close quarters.

RK took keen interest and created some excellent reports that include (i) Successes and failures of metallurgical R&D in India for INAE (with K. K. Sinha and V. Ramaswamy), (ii) Rare earths and energy critical elements for the Ministry of Mines, Government of India and (iii) Concentrated Solar Power for the Ministry of New and Renewable Energy. The last two reports emanated while he was the advisor for Centre for Science, Technology and Policy founded by V. S. Arunachalam.

A highly accomplished researcher with strong academic connectivity, he was linked with many universities and was active on the Editorial Boards of many

prestigious international scientific and engineering journals. He guided several scientists from BARC and IGCAR to obtain their Masters and Ph.D. degrees from Bombay University. He served as an Editor of the *Transactions of the Indian Institute of Metals (IIM)* with great enthusiasm and diligence. For his outstanding contributions in the area of physical metallurgy of nuclear materials, RK was bestowed with the National Metallurgist Award from the Ministry of Steel, Government of India in 1977, and Lifetime Achievement Award in 2014. He received Binani Gold Medal of IIM in 1969 and INSA Brahm Prakash Medal in 2000. RK served as the President of IIM during 1993–94. He was a Fellow of all the four Academies of Science and Engineering in India, Fellow of Institute of Metallurgists (UK), Fellow of Aeronautical Society of India, Fellow of Astronautical Society of India and Honorary member of IIM.

RK believed that for a successful career, one needs to be lucky to have good and understanding bosses, and he never failed to express his gratitude to M. K. Asundi, Brahm Prakash, C. V. Sundaram, P. K. Iyengar and K. Balaramamoorthy in DAE and V. S. Arunachalam in DRDO in this regard.

In his passing away, India lost one of her worthy sons, who contributed significantly to science and technology in nuclear and defence fields. It is rare to find a professional who displayed technical excellence, ethics, empathy, and a human being par excellence.

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