HOMI JEHANGIR BHABHA*

1909-1966

Elected F.N.I. 1941

BHABHA's death in an air crash on Mont Blanc on 24 January 1966, while he was on his way to Vienna for a meeting of the Scientific Advisory Committee of the International Atomic Energy Agency, lost to the world an outstanding scientist who was an imaginative administrator with a rich and many-sided personality and a great capacity for friendship. His scientific status in India was pre-eminent and for a decade or more before his death, his proposals on science and technology in India, especially for a large programme on the peaceful uses of atomic energy, were backed by the Government of India with unhesitating confidence. Scientists in India have felt a sense of loss so deep that nothing like it could happen again in a generation. The sense of loss was made even deeper by grief at the death thirteen days earlier, on 11 January 1966, of Prime Minister Lal Bahadur Shastri at Tashkent, only a few hours after signing the historic Tashkent Declaration, bringing peace to the Indo-Pakistan sub-continent.

Many tributes from many countries have already been paid to Bhabha. They have come from people all over the world who were his friends and had worked with him in one or more of his wide fields of interests. He was a truly international figure of science and was known to everybody at the many international conferences which, somehow or other, he managed to attend without in any way neglecting his other multifarious duties and activities.

During the 56 years of his life he grew to know and understand many countries. The account of Bhabha's life reads like that of a great international statesman. The United Kingdom, the United States of America, the Soviet Union, Denmark, Holland, Switzerland, France, Canada, Australia, Italy and many others had welcomed him to work with their own scientists on some common task at some period of his life, and in all of them he has many friends who will remember him with deep affection.

India has commemorated one of her most distinguished men in a postage stamp. The 15 paise stamp, first issued on 4 August 1966 measures 2 cm x 4 cm. On the right-hand side is an excellent head and shoulders of Bhabha in profile, facing, on the left-hand side, a view of the Trombay Establishment with the reactor dome of the C.I.R. reactor prominent. The lettering under the profile is 'Homi Bhabha 1909-1966' and on the left is 'Atomic Energy

*Reproduced from the *Biographical Memoirs of Fellows of the Royal Society*, Volume 13, 1967.

Homi J Bhabha

& Research'. We can find no evidence that a scientific Fellow has ever before been commemorated by a postage stamp.

At the time of his death, Bhabha was Director and Professor of Theoretical Physics of the Tata Institute of Fundamental Research, Secretary to the Government of India in the Department of Atomic Energy and as such also *ex officio* Chairman of the Indian Atomic Energy Commission, and Director of the Atomic Energy Establishment at Trombay.

Bhabha's Early Life

An admirable account of Bhabha's early life is to be found in a memorial lecture given by Sir John Cockcroft at the Royal Institution in January 1967; and we have drawn freely on this account and also from another memorial lecture by Professor M. G. K. Menon given on the same occasion.

Homi Jehangir Bhabha, was born on 30 October 1909, at Bombay, son of Jehangir H. Bhabha, M.A. (Oxon), Barrister-at-Law, and Meherbai Framji Panday, grand-daughter of Sir Dinshaw Petit, First Baronet, widely respected in Bombay for his philanthropic endowments. Bhabha's family had a long tradition of learning and service in the field of education, and his paternal grandfather, Dr Hormusji Bhabha, C.I.E., was universally respected as the Inspector-General of Education in the State of Mysore.

Homi was educated at the Cathedral and John Connon Schools, the Elphinstone College and the Institute of Science in Bombay, up to the age of seventeen. As a boy, he had access to his grandfather's large library which had been supplemented by his father's fine collection of books on painting and art in general, collected during his student years at Oxford and London.

Thanks to his father's and his aunt's collections of recorded music, Homi Bhabha, by the age of 17, was already familiar with the recorded symphonies, concertos, quartets and sonatas of Beethoven and Mozart, and of the recorded operas of Wagner and Verdi. Listening to music for Homi and his younger brother and boyhood friends was a serious matter. Lights were dimmed and listeners even sat in hushed absorption during the frequent changes of gramophone disks in the days before the long-playing records.

As a result of the marriage of his paternal aunt, Meherbai, to Sir Dorab Tata, Homi Bhabha as a boy, until the time he passed his senior Cambridge Leaving Examination with Honours, used to go across the road every day for lunch to the ancestral home of the founder of the House of Tata, J. N. Tata. He would often hear discussions between older members of the family relating to projects for the industrial development of India, ranging from iron and steel and hydro-electrical power generation to the manufacture of heavy chemicals.

Bhabha's family on both sides was strongly nationalist and as a young boy, Homi would listen to the conversation of Mahatma Gandhi when he visited his maternal aunt at the time of the launching of India's first civil disobedience movement. Friendly ties also existed between the Nehru family and the families of Tata and Bhabha.

Bhabha joined Caius College, Cambridge, in 1927 and was a Scholar of the College, 1929-1930. The intention of his father and of his uncle, Sir Dorab Tata, was that he should obtain an engineering degree with a view to joining the Tata Iron and Steel Company at Jamshedpur. During the course of his engineering studies, Bhabha wanted to change to mathematics, but his father urged that he should complete the engineering course and promised that if he got a first he would finance further studies in mathematics. Bhabha duly obtained his first class in the mechanical sciences tripos in June 1930 and thereafter went on to work as a research student in theoretical physics. It would seem that he had decided to embark on a career in theoretical physics, leading him away from industry into a more restricted academic sphere. The next fifteen years fostered this belief, but later events brought him almost back to the original intentions of his family.

Bhabha the Man

In addition to great gifts in science, technology, scientific policy-making and administration, with which this Memoir must primarily be concerned, Bhabha also possessed sensitive and trained artistic gifts of the highest order, especially in painting, pencil portraits, and music.

To understand his life and achievements, it is necessary to remember the many influences which shaped him into the man he was. He grew up in a cultured and wealthy environment where education, art, science, technology, and heavy industry were intermingled. Then he spent thirteen of the most impressionable years of his youth in the West, from the age of 17 to 29, during which period his exceptional scientific ability enabled him to work or associate with some of the greatest physicists of the time, and win a place among them.

When the Second World War started in 1939, Bhabha happened to be on holiday in India. Thereafter he lived in India. As the international stresses gradually diminished in the decade following the War, Bhabha came to play an ever-increasing role in international scientific affairs. M. G. K. Menon considers that the five years Bhabha spent at the Indian Institute of Science in Bangalore was 'the period when he found his mission in life; when he became aware of the role he would play in the development of India.'

Among the many tributes paid to Bhabha, two have been chosen for quotation here. The first, by Mrs. Indira Gandhi, Prime Minister of India, testifies to the high esteem felt for Bhabha by the Government and people of India. The second, by Lord Redcliffe-Maud, gives an impression of Bhabha the man.

Mrs. Indira Gandhi said: 'To lose Dr. Homi Bhabha at this crucial moment in the development of our atomic energy programme is a terrible blow for our nation. He had his most creative years ahead of him. When we take up the unfinished work he has left behind, we will realize in how many fields he served us. For me, it is a personal loss. I shall miss his wide-ranging mind and many talents, his determination to strengthen our country's science and enthusiastic interest in life's many facets. We mourn a great son of India'.

Lord Redcliffe-Maud wrote:

'Affectionate and sensitive, elegant and humorous, dynamic—and now dead, Homi was one of the very few people I have ever known (Maynard Keynes was another) who enhance life whatever the context of their living. In Homi's case this was because he was fantastically talented but so fastidious about standards that he was never a dilettante. Whatever he set himself to do, he did as a professional—but one who worked for love. He was restlessly creative, enhancing life because he loved all forms of it. So he became a living proof that scientific excellence can go with excellence in art, and racial differences need be no bar to friendship. When Indian Art was last exhibited in London, the one picture chosen for reproduction on the poster outside Burlington House was one of Homi's. He was as fond of music as he was of pictures, contriving to fly in from India as the first Edinburgh Festival began and, when the question of a late Beethoven quartet was raised in conversation, knowing the opus number. At one Unesco Conference after another he stood out, even among the other distinguished members of the Indian delegation, as a world citizen qualified in all three subjects—education, science and culture—as hardly another member of the Conference was. He was in fact an obvious choice for the headship of the Organization if he had felt inclined that way. Those qualified must judge how grievous is his death for India and for science and for civilization. His friends know that for them it is irreparable loss.'

Science Reporter, a journal of the Council of Scientific and Industrial Research, New Delhi, Volume 3, page 476, 1966, contains an interesting article by R. von Leyden entitled 'Dr. Homi Bhabha and the world of art'. von Leyden recalls spending an evening with Bhabha at a time when Bhabha was visualizing how he wanted the Trombay Establishment to be. There was an enormous drawing-board with huge printed plans of the trees and gardens of Trombay. By the side of the drawing-board were fine illustrated books of the gardens of Versailles, of the English gardens of the eighteenth century, and of Italian, Japanese and Persian gardens. 'We talked about the apotheosis of water, which is the central theme of the Persian and the Indian Moghul Garden. His detailed knowledge was tremendous.' 'We talked of Hauz Khas and the Lodi Tombs and the magnificent facade of Shershah's mosque at Purana Quila (Bhabha did fine water-colours of the Moghul Garden and the gate of Purana Quila).'

von Leyden considers that the Tata Institute of Fundamental Research is the supreme monument to Bhabha's artistic vision. Bhabha collected for the Institute one of the finest and most representative collections of contemporary Indian art. The paintings and the sculptures bought by him not only adorn the gardens, the vestibule and the corridors but also the individual study chambers and the seminar rooms.

Bhabha's Work in Theoretical Physics

Bhabha's first years of research work coincided with a remarkable period in the Cavendish Laboratory. In 1932 Chadwick demonstrated the existence of the neutron; Cockcroft and Walton produced the transmutation of light elements by high-speed protons; and Blackett and Occhialini demonstrated by cloud-chamber photographs the production of electron pairs and showers by gamma radiation. During two years of work at the Cavendish he held Salomons studentship in engineering during 1931-1932; and was awarded the Rouse Ball travelling studentship in mathematics in 1932-1933. He travelled in Europe and worked with Pauli in Zurich, Fermi in Rome and Kramers in Utrecht. Bhabha's first scientific paper in 1933 considered the part played by electron showers in the absorption of gamma radiation and was influential in winning for him the Isaac Newton Studentship in 1934. He held this studentship for three years, working mainly at Cambridge, but also for a short time with Bohr in Copenhagen. He took his Ph.D. at Cambridge in 1935. In 1937 he was awarded a Senior Studentship of the 1851 Exhibition, and continued work at Cambridge until the Second World War began in 1939.

The discovery of the positron in 1932, and the explanation of its properties by Dirac's theory of the electron, opened up a wide field for theoretical physicists. Almost simultaneously, the experimental studies of cosmic rays had extended the range of the energy of elementary particles by a large factor. Bhabha threw himself with enthusiasm and great success into this field of high energy physics: most of the 50 scientific papers published by him during the 22 years of active researches—the last was in 1954—were concerned with high energy physics.

In particular Bhabha took a prominent part in the early history of the development of quantum electrodynamics, a subject which in those days was practically synonymous with theoretical high-energy physics. The very small band of research workers then in the field—among whom Bhabha soon became a leading member—faced the same twofold division of their research as that which exists today. They could either strive to advance basic theory, which then as now was very far from logical and mathematical completeness, or they could attempt to relate observed phenomena to predictions of the theory such as it was. Success in the latter direction was of course the main justification for faith in the correctness of the theory and among such successes, those achieved by Bhabha were most important. Thus he was the first person to calculate the cross section for electron-positron scattering which is known as Bhabha scattering. Of very great importance for the development of the experimental study of cosmic rays was a paper written in 1937, in collaboration with W. Heitler, on the theory of cosmic ray showers by the cascade production of gamma rays and positive and negative electron pairs. They showed that the photon-electron cascade provided an explanation both of the shower transition curve observed in the laboratory and of the altitude dependence of the electron-photon component in the atmosphere. In addition, they concluded that the very penetrating particles observed at ground-level and underground could not be electrons. These particles were later shown to be μ-mesons.

From 1935 onwards, as a result of the work of H. Yukawa and others, the emphasis in relativistic quantum theory ceased to be almost exclusively on the study of electrons and photons. Meson theory began and the problem of explaining nuclear forces and the properties of protons and neutrons attracted the interest of many workers. Bhabha was one of the first to be drawn into this field. Almost simultaneously with Yukawa, Sakata and Taketani in Japan, and with Fröhlich, Heitler and Kemmer working independently in Britain, Bhabha put forward what became known as 'vector meson theory', a variant of the theory of nuclear forces which was closely patterned on the electrodynamics with which Bhabha's earlier researches had been concerned. Bhabha was the first to point out that the measured lifetime of a meson in flight is affected by the time dilatation predicted by Einstein's Special Theory of Relativity, and we know today that this measurement is the most direct demonstration of that phenomenon.

The discovery of new particles and the development of meson theory suggested a new direction to which speculative theoretical investigations might turn—the question of the existence and properties of 'elementary' particles not yet discovered. During the war years Bhabha's research interest veered in this direction and he contributed notably to the theory of particles of high spin. In this phase of his work he displayed knowledge of and skill in methods of modern algebra to a degree quite unusual among theoretical physicists of the time. He also proved in this work that he could see further ahead than most of his contemporaries; as resonances in high energy collisions, particles of higher spin are today part of the observed external world.

Indian Institute of Science, Bangalore—The Tata Institute of Fundamental Research, Bombay

Bhabha in 1940 accepted the post of Reader at the Institute of Science, Bangalore, in charge of a special cosmic ray research unit set up for him with money given by the Sir Dorab Tata Trust. He became Professor in 1942. At Bangalore he was indeed in a class of his own. The papers which he published were more mathematical than his earlier work and dealt with the classical theory of point particles moving in a general field. The theory was constructed with great generality and mathematical exactness within the framework of the special theory of relativity. While this work at Bangalore was less recognized internationally, it appeared to give him greater intellectual pleasure than the earlier and more celebrated work done whilst in Europe.

During the five years when he worked at the Bangalore Institute, the deep feeling of identity which he established between himself and his country gradually began to form. He was conscious of the great cultural heritage and tradition of India; and he began to be conscious of the possibility of economic prosperity and social change based on science and technology, as demonstrated in the West. This broad vision caused him to write a letter to Sir Sorab Saklavata, Chairman of the Sir Dorab Tata Trust, in which the following passages occur:

> 'There is at the moment in India no big school of research in the fundamental problems of physics, both theoretical and experimental. There are, however, scattered all over India competent workers who are not doing as good work as they would do if brought together in one place under proper direction. It is absolutely in the interest of India to have a vigorous school of research in fundamental physics, for such a school forms the spearhead of research not only in less advanced branches of physics but also in problems of immediate practical application in industry. If much of the *applied* research done in India today is disappointing or of very inferior quality it is entirely due to the absence of a sufficient number of outstanding *pure* research workers who would set the standard of good research and act on the directing boards in an advisory capacity. ... Moreover, when nuclear energy has been successfully applied for power production in say a couple of decades from now, India will not have to look abroad for its experts but will find them ready at hand. I do not think that anyone acquainted with scientific developments in other countries would deny the need in India for such a school as I propose.
>
> 'The subjects on which research and advanced teaching would be done would be theoretical physics, especially on fundamental problems and with special reference to cosmic rays and nuclear physics, and experimental research on cosmic rays. It is neither possible nor desirable to separate nuclear physics from cosmic rays since the two are closely connected theoretically.'

In this letter, which was written from Bangalore one year before the military aspects of atomic energy were revealed to a shocked world, lay the seeds of both the Tata Institute of Fundamental Research and the Indian Atomic Energy Department.

The next year, 1945, the Tata Institute of Fundamental Research was inaugurated in a house in Bombay, but moved into the old buildings of the Royal Bombay Yacht Club in 1948.

The foundation stone of the present building of the Tata Institute, as it is usually called, was laid in 1954 and the laboratory was opened in 1962, on both occasions by Mr. Nehru. Architecturally, and by its site close to the Arabian Sea, the Institute must be one of the most beautiful in the world. Every part of it bears Bhabha's stamp, the structure, furniture, decoration and pictures.

Though Bhabha wrote no more purely scientific papers after 1954, due to his increasing commitment to administration, he initiated and closely followed the researches being carried out in the Institute.

He brought Professor Bernard Peters from the U.S.A. to the Institute and the latter trained a fine group of workers in cosmic ray research, using photographic emulsions, and later in geophysics. The group pioneered the use of stripped emulsions, and among other results first identified the K minus strange particle. Menon, trained with Powell in Bristol, joined this group. Recently, pioneering works on the very penetrating particles observed deep underground has been carried out at the Kolar Gold Fields in Southern India at a depth of over 8000 feet. Important results have been obtained relating to muons and neutrinos.

Another very strong group was built up in pure mathematics under Professor K. Chandrasekharan. A geophysics group under Professor D. Lal has done excellent work on cosmo-geo-astrophysics using the many radio-elements present in the natural environment, particularly in the atmosphere and in the oceans.

In the 21 years since the Institute was inaugurated in Bombay to Bhabha's death in 1966, the Tata Institute has grown to be one of the finest research institutes of the world.

Professor M. G. K. Menon, previously Deputy Director, has succeeded Bhabha as the Director of the Tata Institute.

Bhabha's Work as a Government Adviser on Science and Technology

Bhabha was a keen member of the Scientific Advisory Committee to the Indian Cabinet and its Chairman from July, 1964, until his death. He was largely responsible for the introduction of the Indian space programme through the setting up in 1962 of the Indian National Committee for Space Research under the chairmanship of Dr. Sarabhai. The establishment of the Thumba Equatorial Rocket Launching Station near Trivandrum followed and was accorded recognition by the United Nations in December 1965, as the first International Sounding Rocket Launching Facility. Plans for an Indian Space Science and Technology Centre were then put in hand. Bhabha was also Chairman of the Government Electronics Committee, in whose work he took a strong personal interest.

In all these varied fields Bhabha stressed his conviction that research scientists must make the maximum contribution to technology and to industrial development and that the wealth and prosperity of a nation must depend on the effective use of human and material resources through industrialization. This belief is enshrined in the Scientific Policy Resolution adopted by the Government of India in 1958, largely at Bhabha's instigation.

Bhabha's Work on Nuclear Power in India

The great expansion planned after the Second World War in the Indian economy demanded a steady increase in electricity generating capacity. Piecemeal solutions envisaging new conventional units of a relatively small size were possible, but in view of India's apparently limited resources of fossil fuels on a long-term projection and their geographical distribution, such answers could only touch the fringe of the problem. Bhabha believed that the only way of ensuring that difficulties over power supplies never became a drag on industrial development was through the introduction of nuclear power in a phased programme which could ultimately be based on fuel fabricated from India's natural resources of uranium or thorium.

Bhabha's case, however convincing in the technical sense, was not easily accepted because it demanded immediate large-scale investment, including the provision of foreign exchange, against distant returns which could not easily be reduced to facts and figures. He was not the man to be daunted by opposition or worried by criticism. He stressed again and again in New Delhi that even if nuclear power could not then compete on economic grounds with new conventional power stations, it was the only prospect of a solution to one component of the vast complex of problems involved in making improvements in the standard of living in India. That he finally persuaded his Government to put in hand a nuclear programme for which direct responsibility was accepted by the Prime Minister was a triumph for his energy, his clear-sightedness, his versatility and his tenacity.

While he was fighting his case with ministers, with economists and with industrialists, he was also laying the foundation of the research and development work which he knew must be started as the basis for any nuclear power effort. In 1945, since there was no Indian establishment devoted to nuclear studies, a programme of basic research in his field was undertaken at the Tata Institute.

Bhabha's advocacy led to the Indian Atomic Energy Act 1948. This Act gave to the Central Government wide powers, including powers to survey the country for atomic minerals: to work and develop such minerals on an industrial scale: to do research in the scientific and technical problems connected with the release of atomic energy for peaceful purposes: to train and develop the necessary scientific and technical personnel for this work; and to foster fundamental research in nuclear sciences in its own laboratories and in the universities and research laboratories in India. The Act also stated: 'The Central Government may by order direct that any power conferred on it by this Act shall be executed or discharged by such officer or officers in such circumstances and under such conditions as may be specified in the order'.

A Commission was created in the Department of Scientific Research, and later in the Ministry of Natural Resources and Scientific Research, to carry out the responsibilities of the Central Government, given by the 1948 Act. Bhabha was appointed Chairman of the Commission on 10 August 1948.

Much of the early work for the Commission was done in the Tata Institute, but on 3 January 1954, the Commission decided to build an atomic energy establishment at Trombay. Later, in 1954, the activities of the Commission had shown such promise that the Indian Government decided to make certain administrative changes which would expedite progress. Using the authority of the 1948 Act, a separate Ministry, the Department of Atomic Energy, was created in August 1954, and was charged solely with the development of atomic energy for peaceful purposes. The Department was in the direct charge of the Prime Minister and Bhabha was appointed Secretary to the Government of India in the Department. The headquarters of the Ministry were located in Bombay in order to have close contacts with the main centre of its scientific activities, the Trombay Establishment.

Annexure number 127 to the Lok Sabha Debates, Appendix V of the Fourth Session 1958, was a Resolution by H. J. Bhabha, Secretary to the Government of India, defining the Constitution of the Indian Atomic Energy Commission and vesting in the Atomic Energy Commission full executive and financial powers of the Government of India.

The preamble stated that 'research and development in the peaceful uses of atomic energy have made important and rapid strides and a greatly expanded programme is envisaged for the future, in the course of which India should be able to produce all the basic materials required for the utilization of atomic energy, and build a series of atomic power stations, which will contribute increasingly to the production of electric power in the country. These developments call for an organization with full authority to plan and implement the various measures on sound technical and economic principles. . . .

The Resolution then stated:

'(*a*) The Commission shall consist of full-time and part-time members and the total number of members shall not be less than three and not more than seven.

(*b*) The Secretary to the Government of India in the Department of Atomic Energy shall be the *ex-officio* Chairman of the Commission.

(*c*) Another full-time member of the Commission shall be the Member for Finance and Administration, who shall also be the *ex-officio* Secretary to the Government of India in the Department of Atomic Energy in financial matters.

(*d*) The Director of the Atomic Energy Establishment, Trombay, shall be the third *ex-officio* full-time member in charge of research and development,' The Atomic Energy Commission shall be responsible for

'(*a*) formulating the policy of the Department of Atomic Energy for the consideration and approval of the Prime Minister;

(*b*) preparing the budget of the Department of Atomic Energy for each financial year and getting it approved by Government; and

(*c*) the implementation of Government's policy in all matters concerning atomic energy.'

The rapid development of atomic energy in India began to make the 1948 Act inadequate. Accordingly, new legislation was introduced in the Atomic Energy Act, 1952. The 1948 Act was repealed but the new Act was substantially the same except that the extra powers and responsibilities given to the Central Government took account of changing circumstances including the power to make rules under the Act. Thus in addition to matters specified in the 1948 Act, the 1962 Act empowered the Central Government: to manufacture, buy or otherwise provide for control over radiation hazards and public safety; and, notwithstanding anything contained in the Electricity (Supply) Act of 1948, to develop a sound and adequate policy in regard to atomic power, and to co-ordinate such policy with the Central Electricity Authority and the State Electricity Boards: to operate atomic power stations in the manner determined by it in consultation with the Boards or Corporations concerned, with whom it shall enter into agreement regarding the supply of the electricity so produced, including tariffs and transmission rights across State boundaries.

The Central Government, as before, used the Department of Atomic Energy as its instrument. The responsibilities of the Department were extended but the Department continued to operate under the direction of the Atomic Energy Commission, with Bhabha as the Secretary to the Government of India in the Department, and *ex-officio* Chairman of the Atomic Energy Commission.

The Atomic Energy Establishment, Trombay
(*the Bhabha Atomic Research Centre*)

The staff and facilities of the Indian Atomic Energy Commission steadily increased year by year, and the budget for atomic research in 1965/66 was about £5·5M. The main centre of atomic research and development was the Atomic Energy Establishment at Trombay. At a ceremony attended by many well-known international figures in atomic energy, on 12 January 1967, the Prime Minister of India, Mrs. Indira Gandhi, renamed the Trombay Establishment as the Bhabha Atomic Research Centre. The Centre at present employs over 8000 persons, including 1800 graduate scientists and engineers.

During the growing days of this Centre, Bhabha sent for training to this country and to the United States many young physicists, metallurgists and chemists as a nucleus for Trombay. He also invited overseas scientists and technologists to work at Trombay, in particular to advise him and his staff on the organization and programme which would best fit the Centre to provide the support necessary for India's nuclear power industry. He stressed that while India needed to draw on the expertise already built up in other countries her objective must be to exploit her own resources of scientists and technologists and of raw materials; and to manufacture and obtain all plant and equipment possible from her own resources. While contracts for India's first nuclear power stations had therefore to be placed with overseas countries, even for these the maximum amount of work was carried out in India. This policy could not always be directly justified economically, but Bhabha's goal of a nuclear power station constructed without outside help could thereby be achieved at the earliest possible time.

The work of the Centre can be classified in five main groups—physics, electronics, engineering, metallurgy and biology. There is also a medical division and a Directorate of Radiation Protection.

The first reactor to be built was of the swimming pool type of 1 MW, called APSARA. This reactor became critical on 4 August 1956, just one year after its construction was started. It was entirely designed, engineered and built by Indian scientists and engineers, with enriched fuel elements supplied by the United Kingdom Atomic Energy Authority.

While the first reactor was being built, consideration was given to the selection of a reactor of higher power and higher flux, for engineering experiments, materials testing and radioactive isotope production. Canada offered assistance for the design and construction of a reactor similar to an NRX at Chalk River. Half of the cost of the reactor would be India's liability and the other half would be met by Canada under the Colombo Plan. The offer was accepted, and the Canadian-Indian Reactor (C.I.R., 40 MW (H)) duly became critical in July 1960.

Bhabha's plan of working towards complete self-sufficiency in a national nuclear power programme required a considerable effort on the procurement and processing of ores, uranium metal fabrication, fuel element development and manufacture of irradiated fuel elements.

A Government-owned company, Indian Rare Earths Limited, began processing the monazite sands of the Kerala beach in 1952, and separated rare earths, thorium and phosphates. A plant was built in the Trombay Centre to process the crude thorium hydroxide, and uranium fluoride was obtained as a by-product. In addition, a small uranium metal processing plant was built at Trombay with an initial throughput of 30 tonnes of metal per annum. However, technical improvements later enabled the throughput to be greatly increased. Another plant, the Fuel Element Fabrication Plant, was added initially to produce half the charge for C.I.R., but the capacity of this plant has also been substantially improved.

The most sophisticated of these fuel plants at the Trombay Centre is the Plutonium Plant which separates the plutonium from the fission products and other materials in irradiated fuel.

Other Atomic Energy Plants in India

In addition to the plants at Trombay, or mentioned above in connexion with the Centre at Trombay, several more atomic energy plants were constructed, or were started, while Bhabha was Secretary to the Government of India in the Department of Atomic Energy.

Work has begun on the designing of the Hyderabad Complex, containing a number of nuclear fuel plants to meet the special requirements for the CANDU type of power reactor. Most of the uranium would come from the mine discovered at Jaduguda near the large industrial city of Jamshedpur. A uranium mill was also built at the mine to process the ore won from Jaduguda to produce uranium concentrate. Another plant to be built in the Hyderabad Complex was the electronics factory which would produce a variety of equipment and components to meet not only the needs of the nuclear power programme but also some of the electronic needs of industry, research institutions and hospitals. One of Bhabha's most significant contribution was the laying down of the blue-print for a ten-year development of the electronics industry which he did as the Chairman of the Electronics Committee.

The decision in India to choose the heavy water moderated, natural uranium oxide reactor system, based on CANDU, at least for the first few stations of the Indian nuclear power programme, required, on Bhabha's thesis of self-sufficiency, an Indian source of heavy water. Bhabha stated that while 'in a line which is on the frontiers of knowledge, it is clearly impossible to give an assurance that heavy water will be required permanently, there was every indication that its uses in atomic energy are not likely to diminish'. Accordingly, the Indian Government authorized the construction of heavy water plant at Nangal as part of a fertilizer project of the Fertilizer Corporation of India Ltd. The plant was constructed with the active cooperation of the Trombay Establishment and production began on 2 August 1962. The plant has a design capacity of 14 metric tonnes of heavy water per annum. Subsequent events in India have been consistent with Bhabha's views, and it became clear that India would have to build another heavy water plant with a capacity of about 200 tonnes per annum.

The water moderate reactor systems require an advanced zirconium technology, and Bhabha started research and development work on zirconium at the Trombay Establishment, with a view to building a zirconium fabrication plant in due course.

The Indian Nuclear Power Programme

The situation in the Indian nuclear power programme at the time of Bhabha's death was as follows. The C.I.R. reactor at Trombay had been operating at full power for about two and a half years. The Tarapur B.W.R. nuclear power station of 380 MW(E) had been ordered from the International General Electric Company of U.S.A. with American financial aid to cover imported equipment, and will be in full power operation towards the end of 1968. The bilateral agreement relating to this station provides for the safeguard procedures specified in the Agreement being implemented by the International Atomic Energy Agency one year after it becomes fully operational. The Rajasthan nuclear power station of two reactors, each 200 MW(E) of the CANDU type, was to be built by the Atomic Energy Commission, with Canadian collaboration, and the design and some of the equipment will be supplied by Canada. The first unit is expected to go into operation by the end of 1969, and the second by 1971. This station is subject to bilateral Canadian/Indian safeguards, though a possible role for the Agency was foreseen.

Early planning had also started on the Madras nuclear power station. This station would also contain two units, each reactor producing 200 MW(E). The design and construction of this power station was to be entrusted to the Bhabha Atomic Research Centre, although the design would be substantially the same as that for the Rajasthan station.

Bhabha was predicting a considerable growth in the nuclear generation of electricity in India over two decades, rising from 1200 MW(E) by 1971 to 18 to 20 000 MW(E) by 1986. The growth rate in these numbers was probably greater than he expected to be achieved, but he was no doubt seeking to keep up the pressure in India for a large installation programme in which he had implicit faith.

Research Centres sponsored by the Department

A number of research institutes working in one or more fields closely connected with atomic energy are sponsored by the Department of Atomic Energy, and look to the Department for most of their funds. Bhabha, as Secretary in the Department of Atomic Energy, had an influential voice in these Research institutes. The institutes are: the Tata Institute of Fundamental Research, the Tata Memorial Hospital, the Indian Cancer Research Centre, the Saha Institute of Nuclear Physics and the Physical Research Laboratory at Ahmedabad.

Bhabha's Work in International Science and Technology

Most of Bhabha's work in international science and technology stemmed from his atomic energy activities in India. However, his appointment as President of the International Union of Pure and Applied Physics 1960-63 was a recognition of his eminence in mechanics and theoretical physics. He presided with great distinction at the Warsaw General Assembly in 1963. At the time of his death he was its Past President.

Bhabha's name was of course well known in scientific circles from the time he began publishing his scientific works in his middle twenties but the event which brought Bhabha into the newspapers of the world was the first United Nations Conference on the Peaceful Uses of Atomic Energy, held in Geneva in 1955. He immediately became known as an articulate scientist who could speak for science in language which everybody understood.

The 1955 Geneva Conference

By unanimous vote, the General Assembly of the United Nations decided in December 1954 that an international technical conference should be held under the auspices of the United Nations to explore means of developing the peaceful uses of atomic energy through international co-operation.

The General Assembly also decided that all States Members of the United Nations or of the specialized agencies should be invited to participate in the conference. It left the precise date and venue to be decided by the United Nations Secretary General (Dag Hammarskjold) and an Advisory Committee composed of representatives of Brazil, Canada, France, India, the Union of Soviet Socialist Republics, the United Kingdom and the United States. These Member States were represented in the Advisory Committee by Dr. J. Costa Ribeiro, Dr W. B. Lewis, Dr Bertrand Goldschmidt, Dr Homi J. Bhabha, Academician D. V. Skobeltzin, Sir John Cockcroft, Dr I. I. Rabi.

The Advisory Committee met the Secretary General and agreed that the Conference should be held in Geneva from 8 to 20 August 1955 and that invitations should be sent to the sixty United Nations Member States and to twenty-four countries not in the United Nations but which were members of the specialized agencies.

The invitations to Governments were sent by the Secretary General on 1 February 1955. In his letter, the Secretary General informed the Governments that he had appointed Dr Homi J. Bhabha, Chairman of the Atomic Energy Commission of India, as President of the Conference and Professor Walter G. Whitman of the Massachusetts Institute of Technology to be Conference Secretary General.

Bhabha's presidential address to the Conference was a brilliant essay about energy and population, and described in simple direct style the changes in living conditions of man during the last 2000 years, made possible by technology. The address is as vivid and true today as when it was written. Only on one point was the perspective wrong, and Bhabha used only five lines of his address to make the point. However, most of the 905 representatives of the press, radio and other public information media chose to make this their lead story. Bhabha said: 'I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens, the energy problems of the world will truly have been solved for ever for the fuel will be as plentiful as the heavy hydrogen in the oceans'.

The press story was centred on 'taming the H-bomb'. Bhabha's statement can be interpreted in more than one way, but he probably meant that some primitive type of controlled fusion reactor, liberating calories of energy per second, would be operating somewhere in the world before 1972. The press thought he meant much more.

At the time of writing this Memoir it is still possible that the prediction will prove correct, but the prospects by the date given are not good.

Bhabha also presented to the Conference, Section 2.2, a paper on the role of nuclear power in India and its immediate possibilities. His broad conclusions were that in India there was clearly a long-range necessity for atomic power as the main source of electricity and that already nuclear power at places in India remote from coal would be economic.

In another outstanding address to the Conference in his concluding speech, Bhabha gave a clear summary of the world need for more energy and correctly expressed the confidence of the Conference that nuclear energy would make a vital contribution. Two of his remarks are worth quoting to illustrate the scientist who was aware of political events and saw clearly that this Conference was much more than a meeting of technologists discussing their particular expertise.

> 'A remarkable feature which the Conference brought to light was the parallel work which has been done in secrecy till now in several countries. No less than five countries have developed the same techniques, ... with remarkable agreement among their results.'
>
> 'This scientific Conference, which will inevitably have far-reaching political consequences, differs in one important respect from all political conferences. Knowledge, once given, cannot be taken back, and in organizing this Conference, the nations of the world have taken an irreversible step forward, a step from which there is no retreat.'

The first United Nations Conference on the Peaceful Uses of Atomic Energy was certainly a conference of outstanding technical importance, and was possibly the most informative scientific conference ever held. All of the countries with civil nuclear programmes freely presented their results, and a vast amount of high quality data was published. The importance of the Conference was enhanced by the fact that it was a political event of great significance. The international tension of the Cold War had gradually been relieved and scientists from the Soviet bloc and the West were being encouraged by their Governments to collaborate on a great technical peaceful enterprise under the auspices of the United Nations. Looking back with hindsight, the general consensus of opinion about the economics of nuclear power misjudged the time-scale of the growth of cheap nuclear power by some five to ten years.

The International Atomic Energy Agency

The International Atomic Energy Agency, a specialized branch of the United Nations, was created in 1955, and its headquarters was placed at Vienna. Bhabha certainly had some part in the choice of Vienna. He wanted to combine his scientific duties with the opportunity of hearing fine music. The Secretary General of the I.A.E.A. decided that he needed a scientific advisory committee, and his proposal was accepted that the committee should have, on a personal basis, the same seven scientists who represented their countries on the United Nations Secretary General's Scientific Advisory Committee. Bhabha, therefore, became a member of the I.A.E.A. Scientific Advisory Committee, and remained a member until his death.

Bhabha made powerful contributions to the work of the I.A.E.A., both as a member of the Scientific Advisory Committee and as the Indian spokesman at the General Assembly of the Agency. He was the man primarily responsible for providing the Indian specialists implementing their country's contribution to the work of panels, symposia and other Agency activities. He was a fervent believer in untrammelled scientific cooperation and the declared opponent of any proposals for international control over information exchanges or on the operations of reactors or on reactor fuels. While this frequently brought him into conflict with the atomic energy leaders of other nations who supported some form of voluntary regulation, his criticisms made them keenly aware that every step they took must be clearly justifiable as contributing to a coherent and workable scheme of control which would be acceptable not only to those countries with a major nuclear effort, but also to those which had not yet embarked on atomic energy programmes.

Once again, to show something of the quality of the man and the affection in which he was held, 'Bhabha's little joke' might be recorded. When the Scientific Advisory Committee was meeting on United Nations business, Bhabha was meticulously punctual, but when the same seven scientists in a personal capacity were meeting on I.A.E.A. business, Bhabha was not always so punctual at early morning meetings. Gradually, the Secretariat diplomatically stated in the notice of the meeting a time earlier than the actual time planned for the meeting. Bhabha would appear punctually late, with all the others joking about his late arrival, and the meeting would start. None of the other members ever attempted to be later than Bhabha; that was his little joke, enjoyed by everybody.

The Second and Third General Conferences

The second United Nations Conference on the Peaceful Uses of Atomic Energy was held at Geneva in September 1958 and was even larger than the first. An enormous amount of new technological data was presented and the Conference was widely considered to have been a great success. However, the second Conference did not have the dramatic character of the first Conference, where technologists from the Soviet bloc and from the West first revealed to each other and to the world what they had been doing. There was also a realization at the second Conference that nuclear power from fission energy was not proving as cheap as the first Conference had predicted. The second Conference gave great prominence to controlled fusion, and although the predictions were hopeful, a note of caution, well justified by later work, was creeping into the predictions. Bhabha took the chair of Session 4: the possibility of controlled fusion. Bhabha and W. B. Lewis also presented a paper on 'The Canada-India reactor: an exercise in international collaboration'.

The third United Nations Conference on the Peaceful Uses of Atomic Energy, held at Geneva in September 1964, again showed Bhabha as one of the leading figures in nuclear power.

He presented a paper 'World energy requirements and the economics of nuclear power with special reference to underdeveloped countries', in which he estimated that by the year 2000 nuclear power throughout the world will have a generating capacity of two million megawatts. To put this astonishing prediction in perspective, it might be stated that the net output of electricity from all types of stations in the United Kingdom in 1966 was about 44000 MW. In presenting his paper, Bhabha made a remark which registered with many from underdeveloped countries who heard him speak and which was widely quoted. In speaking for the underdeveloped countries he said, 'No power is as expensive as no power'. This aphorism illuminates the driving force of the last twenty years of Bhabha's life.

Honours and Awards

Bhabha was elected a Fellow of the Royal Society of London in 1941. He was awarded the Adams prize in 1942 for a thesis on 'The theory of the elementary particles and their interaction'. In 1948 he was awarded the Hopkins prize of the Cambridge Philosophical Society. He was also given the Melchett Award of the Fuel Institute in London. His services to India were recognized in 1954 by the award of the Padma Bhushan. In 1957, he was elected an honorary fellow of Gonville and Caius College and also elected to honorary fellowship of the Royal Society of Edinburgh. In 1959 he was elected to honorary fellowship of the American Academy of Arts and Sciences. In 1963 he was elected a foreign associate of the National Academy of Science of the United States. He was awarded honorary doctoral degree in science at Patna (1944), Lucknow (1949), Banaras (1950), Agra (1952), Perth (1954), Allahabad (1958), Cambridge (1959), London (1960), Padova (1961).

I have been greatly assisted by many colleagues in preparing this Memoir, including those mentioned in the text and also Miss B. D. MacLean, Professor P. M. S. Blackett, Sir James Chadwick, Professors N. Kemmer, P. T. Matthews and Abdus Salam, Dr. V. A. Sarabhai and Mr. H. N. Sethna.

PENNEY

BIBLIOGRAPHY

1933. Zur Absorption der Hohenstrahlung. *Z. Phys.*, **86**, 120.
1934. Passage of very fast protons through matter (letter), *Nature, Lond.*, **134**, 934.

1934. (With H. R. Hulme) Annihilation of fast positrons by electrons in the K-shell. *Proc. R. Soc.*, A, **146**, 723.
1935. On the calculation of pair creation by fast charged particles and the effect of screening. *Proc. Camb. phil. Soc.*, **31**, 394.
1935. Creation of electron-pairs by fast charged particles. *Proc. R. Soc.*, A, **152**, 559.
1935. Electron-positron scattering. *Proc. R. Soc.*, A, **154**, 195.
1936. (With W. Heitler) Passage of fast electrons through matter (letter). *Nature, Lond.*, **138**, 401.
1936. Wave equation in conformal space. *Proc. Camb. phil. Soc.*, **32**, 622.
1937. (With W. Heitler.) Passage of fast electrons and the theory of cosmic showers. *Proc. R. Soc.*, A, **159**, 432.
1937. Negative protons in cosmic radiations (letter). *Nature, Lond.*, **139**, 415.
1937. Experimental test of the proton-neutron exchange interaction (letter). *Nature, Lond.*, **139**, 1021, 1103.
1938. Penetrating component of cosmic radiation. *Proc. R. Soc.*, A, **164**, 257.
1938. Theory of heavy electrons and nuclear forces. *Proc. R. Soc.*, A, **166**, 501.
1938. Production of electron showers by cosmic rays. *Nature, Lond.*, **141**, 90.
1938. Nuclear forces, heavy electrons and the β-decay (letter). *Nature, Lond.*, **141**, 117.
1939. Cosmic radiation. *J. Univ. Bombay*, **8** (Pt. 3), 3.
1939. Fundamental length introduced by the theory of the mesotron (meson) (letter). *Nature, Lond.*, **143**, 276.
1939. (With H. Carmichael & C. N. Chou) Production of bursts and the spin of the meson. *Proc. Indian Acad. Sci.*, A, **10**, 221.
1939. Classical theory of electrons. *Proc. Indian Acad. Sci.*, A,**10** 324.
1939. Classical theory of mesons, *Proc. R. Soc.*, A, **172**, 384.
1940. Classical theory of spinning particles. *Proc. Indian Acad. Sci.*, A, **11**, 247, 467.
1940. Classical theory of point dipoles (letter). *Nature, Lond.*, **145**, 819.
1940. Elementary heavy particles with any integral charge. *Proc. Indian Acad. Sci.*, A, **11**, 347, 468.
1941. (With H. C. Corben) General classical theory of spinning particles in a Maxwell field. *Proc. R. Soc.*, A, **178**, 273.
1941. General classical theory of spinning particles in a meson field. *Proc. R. Soc.*, A, **178**, 314.
1941. (With B. S. M. Rao) Scattering of charged mesons. *Proc. Indian Acad. Sci.*, A, **13**, 9.
1941. Note on the correspondence between the classical and quantum theories of neutral mesons. *Proc. Indian Acad. Sci.*, A, **13**, 249.
1941. Protons of double charge and the scattering of mesons (letter). *Phys. Rev.*, **59**, 100.
1942. (With D. Basu) Theory of particles of spin half and the Compton effect. *Proc. Indian Acad. Sci.*, A, **15**, 105, 461.
1942. Radiation reaction in relation to scattering phenomena. *Proc. natn. Acad. Sci.*, A, **12**, 33.
1942. (With S. K. Chakrabarty) Calculations on the cascade theory with collision loss. *Proc. Indian Acad. Sci.*, A, **15**, 464.
1943. (With S. K. Chakrabarty) Cascade theory with collision loss. *Proc. R. Soc.*, A, **181**, 267.
1943. Recent advances in the theory of fundamental particles. Presidential address, Section of Physics, *Proc.* 30th *Indian Science Congress*, 33-49.
1944. Note on the separation of the electronic and nonelectronic components of cosmic radiation. *Proc. Indian Acad. Sci.*, A, **19**, 23.
1944. Allocation of scientific research to the Universities. *Proc. natn. Inst. Sci. India*, **10**, 29.
1944. (With Harish-Chandra) On the theory of point particles. *Proc. R. Soc.*, A, **183**, 134.
1944-45. Theory of the elementary particles. *Rep., Prog. Phys.*, **10**, 253.
1945. Relativistic wave equations for the elementary particles. *Rev. Mod. Phys.*, **17**, 200.
1945. Relativistic wave equations for the proton. *Proc. Indian Acad. Sci.*, A, **21**, 241.
1945. (With S. V. C. Aiya, H. E. Hoteko & R. C. Saxena) Meson intensity in the sub-stratosphere. *Phys. Rev.*, **68**, 147.
1945. Relativistic equations for particles of arbitrary spin. *Curr. Sci.*, **14**, 89.
1945. (With S. V. C. Aiya, H. E. Hoteko & R. C. Saxena) Latitude effect for mesons. *Curr. Sci.*, **14**, 98.
1946. (With S. V. C. Aiya, H. E. Hoteko & R. C. Saxena) Meson intensity in the sub-stratosphere II. *Proc. natn. Inst. Sci. India*, **12**, 219.
1946. (With Harish-Chandra) On the fields and equations of motion of point-particles. *Proc. R. Soc.*, A, **185**, 250.
1946. On the equations of motion of point particles. *Proc. R. Soc.*, A, **185**, 269.
1946. On the expansibility of solutions in powers of the interaction constants. *Phys. Rev.*, **70**, 759.
1947. Relativistic wave equations for the elementary particles. *Rep. Int. Conf. 'fundam. Part low Temp.* (1946). *Phys. Soc. Camb.*, **1**, 22.
1948. (With R. R. Daniel) Meson scattering with nuclear excitation (letter). *Nature, Lond.*, **161**, 883.
1948. (With S. K. Chakrabarty.) Further calculations on the cascade theory. *Phys. Rev.*, **74**, 1352.

1949. On the postulational basis of the theory of elementary particles. *Rev. mod. Phys.*, **21**, 451.
1949. Recent scientific developments in India. *Proc. 2nd math. Cong. Vancouver*, p. 42.
1949. Theory of elementary particles fields. Lectures delivered at 2nd Summer Seminar held at University of British Columbia, August, Canadian Mathematical Congress.
1950. On the new theory of nuclear forces. *Phys. Rev.*, **77**, 665.
1950. On the stochastic theory of continuous parametric systems and its application to electron cascades. *Proc. R. Soc.*, A, **202**, 301.
1950. (With H. J. TAYLOR, R. R. DANIEL, J. R. HEERAMANECK, M. S. SWAMI & G. S. SHRIKANTIA). Stars and single tracks in nuclear plates. *Proc. Indian Acad. Sci.*, A, **31,** 130.
1950. (With A. RAMAKRISHNAN). Mean square deviation of the number of electrons and quanta in the cascade theory. *Proc. Indian Acad. Sci.*, A, **32,** 141.
1950. Note on the complete stochastic treatment of electron cascades. *Proc. Indian Acad. Sci.*, A, **32,** 154.
1951. Present concept of the physical world. Presidential address, *Prcc. 38th Indian Sci. Congress*, 12.
1951. Some new results on relativistic wave equations. *Rep. Int. Conf. elema. Particles*', 1950 (*T.I.F.R. Bombay*), 81.
1951. On a class of relativistic wave-equations of spin 3/2. *Proc. Indian Ac. Sci.*, A, **34,** 335.
1952. An equation for a particle with two mass states and positive charge density. *Phil. Mag.* (Ser. 7), **43**, 33.
1953. Production of mesons and the localization of field energy. *Proc. R. Soc.*, A, **219**, 293.
1954. High-altitude measurements of intensity of cosmic radiation. *Proc. Int. Conf. 'Theoretical Physics,' Tokyo* (1953), 95. Science Council, Japan.
1954. Investigation of heavy mesons of a solid emulsion block. *Proc. Int. Conf. 'Theor. Physics', Tokyo* (1953), 98. Science Council, Japan.
1954. Summary of the Bagneres de Bigorre Conference report. *Proc. Int. Conf. 'Theor. Physics', Tokyo* (1953), 131. Science Council, Japan.
1954. On multiple meson production. *Proc. Int. Conf. 'Theor. Physics, Tokyo (1953)*, 143. Science Council, Japan.
1956. Role of atomic power in India and its immediate possibilities. *Proc. Int. Conf. peaceful Uses atom Energy, Geneva*, 1955 (New York, United Nations), **1**, 103.
1956. Presidential address. *Proc. Int. Conf. peaceful Uses atom. Energy, Geneva*, 1955 (New York, United Nations), **16**, 31.
1956. Closing Presidential address. *Proc. Int. Conf. peaceful Uses atom. Energy, Geneva*, 1955 (New York, United Nations), **16**, 52.
1957. On the economics of atomic power development in India and the Indian Atomic Energy Programme. Evening discourse at the Dublin meeting of the British Association for the Advancement of Science.
1958. (With N. B. PRASAD). Study of the contribution of atomic energy to a power programme in India. *Proc. Conf. peaceful Uses atom. Energy, Geneva*, 1958 (Geneva, United Nations), **1**, 89.
1958. (With W. B. LEWIS.) Canada-India reactor: an exercise in international co-operation. *Proc. Conf. peaceful Uses atom. Energy, Geneva*, 1958 (Geneva, United Nations), **1**, 355.
1958. Need for atomic energy in the under-developed countries. Evening lecture at the International Conference on the Peaceful uses of Atomic Energy, Geneva.
1959. (With M. DAYAL). Role of atomic energy in Indian development. Annual Number 'Capital'.
1961. Atomic energy in the Indian economy. Address to the American Nuclear Society, Chicago.
1962. (With M. DAYAL). Some economic aspects of nuclear power in India. *Sixth World Power Conf. Melbourne*.
1963. India's development strategy. *Internat. Sci. Tech.*, 93.
1963. (With M. DAYAL) Economics of atomic energy in the underdeveloped countries. *United Nations Conf. on Science and Technology, Geneva*.
1964. (With M. DAYAL) World energy requirements and the economics of nuclear power with special reference to underdeveloped countries. *Third Internat. Conf. peaceful Uses atom. Energy, Geneva*.
1965. Atomic energy and industrial development. Address to Japan Atomic Industrial Forum.
1966. Science and the problems of development. Lecture delivered at ICSU Conference Bombay, January.