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FIRST SYED HUSAIN ZAHEER MEDAL LECTURE—1980*

MATERIALS SCIENCE AND ENGINEERING—AN OVERVIEW

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Modern civilisation is closely linked with development of materials. The last fifty years have seen more new materials development than the previous history of mankind. The requirements of aero-space, nuclear power and armament industries for specialised materials to withstand high fluctuations of stresses, temperatures and pressures and the need to miniaturise control and similar equipment has seen a revolution in the development of materials using metals, polymers and ceramics or combinations of such materials.

Metallurgists have played and continue to play a pioneering role in studies and application of knowledge relating to the composition, structure and problems of materials to their properties and uses. Because of increasing diversity of materials and their applications, it is necessary that today's engineers in all disciplines understand fully the relation of properties to structure and composition.

The proper study of materials requires a multi-disciplinary approach and a fundamental knowledge of many basic and applied disciplines is necessary not only for evaluation of structure-property relationships but also for selection of materials.

The author briefly describes the relationships between Materials Science and Engineering and problems connected with selection of engineering materials. He also gives highlights of some of the work done in India on materials science and technology in various research and educational centres.

Since minerals form the basic of all important engineering materials, the author examines India's minerals position giving estimates of Indian requirements and reserves of minerals. Since there are deficits in the reserves of certain minerals he advocates an integrated and rational policy of exploitation, conservation, exports, imports, etc. He proposses holding a Second Minerals Policy Conference (the first having been held in 1947) to clearly enunciate India's minerals policy for the coming decades and recommends establishment of Central Coordinating Agency to guide to those engaged in minerals exploitation so that the agreed upon policies are properly implemented.

In conclusion, he touches upon some of the important future goals for materials development and emphasises reducing input of material by input of strength, reduction of input of energy per unit of material manufactured and thirdly recycling and recovery of waste materials.

Keywords : Multidiscipline; Inter-Institutional; Austenitic Transformation; Minerals Policy

IT is a great privilege to be the first recipient of Syed Husain Zaheer Medal. Dr Zaheer was a Chemist and Chemical Technologist educated at Lucknow, Oxford and Heidelberg. His pioneering research work on coal carbonisation and hydrogenation as well as on industrial fine chemicals, oils and fats is well known and brought him many distinctions and awards from several countries. He organised the Centre for Scientific and Industrial Research in Hyderabad and was also responsible for establishing the Department of Chemical Technology in Osmania University. As a teacher and director of research, he brought a great sense of urgency,

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dedication and overall vision to a large group of associated younger scientists. As Director-General of the Council of Scientific and Industrial Research, he was responsible for extending the work of the Council to establish Indian Toxicology Research Centre, Lucknow; National Institute of Oceanography, Goa; Central Scientific Instruments Organisation, Chandigarh; Structural Engineering Research Centre, Roorkee; Central Mechanical Engineering Research Institure, Durgapur; Indian Institute of Petroleum, Dehra Dun etc.

He dedicated his life to science and technology and it is but fitting that the Indian National Science Academy has endowed a medal in his name.

Dr Zaheer's work both as a research worker and as an organiser of scientific activities embraced many types of Materials. The subject of my lecture viz, 'Materials Science and Engineering—an Overview' is, I think, topical and I shall examine many aspects of this subject in some detail.

INTRODUCTION

The history of mankind is the history of development of materials by man both for constructive and destructive purposes. This long and simultaneous evolution of man and materials has brought us the materials revolution of modern times with its electronics technology and space exploration on the one hand to the nuclear weapons on the other, which have the potential for destruction of all that is valued by mankind. The last fifty years have seen changes in materials innovation and utilisation which stands quite apart from the slow evolution from Stone to Bronze to Iron ages. The advances in Materials Science and Technology have revolutionised engineering concepts and the whole field is characterised by a new language of science and engineering through both fundamental and applied research.

Not only is there a qualitative change in usage of materials but also the quanti-

TABLE I

World consumption of various materials during 1977

Materials		Million Tonnes	
Timber	..	1500	
Concrete	..	800	
Steel	..	668	(712 in 1978 and 745 in 1979).
Polymers	..	32	
Aluminium	..	14	(15 in 1978)
Copper	..	10	(10 in 1978)
Zinc	..	6	(6 in 1978)
Lead	..	5	(5 in 1978)
Nickel	..	0.6	(0.7 in 1978)
Tin	..	0.23	(0.23 in 1978)
Magnesium	..	0.3	
Silver	..	0.02	
Gold	..	0.002	

ties used are increasing phenomenally year after year. Table I shows world consumption of various materials during 1977.

As can be seen, timber, concrete and steel are the materials used in the largest quantities throughout the world. They are followed by polymers and then by the various nonferrous metals such as aluminium, copper, zinc, lead, nickel etc. and their alloys. Energy whether it be in the form of fossil fuels, or nuclear energy is, of course, the most essential item which makes possible the manufacture of metallic, polymer and other materials.

All materials are derived from the earth as the prime source and excepting for agricultural products which can be grown, all other materials get depleted as they are removed from the earth's crust and used. Excepting those of the materials which are recycled, there will come a time when the easily available materials in the earth's crust will be very difficult to win and convert into useful materials. Even recycling does not mean that all the materials are recovered or recoverable.

One facet of materials problem is the fact that the world's mineral resources are finite. Whereas some of the commonly used resources are fairly widespread and plentiful, the rest are unevently distributed and are quite often located in inaccessible or 'politically sensitive' places.

Timber is the material which is used universally and in the largest tonnage. Timber can, of course, be grown continuously by proper care of forests. However, all other materials have to be converted from mineral resources including hydrocarbon resources and it is here that materials science has to come to the rescue of engineers. By judicious selection, engineers can build structures, machinery and equipment which can use the minimum amount of material.

It was only during and after the Second World War that it was realised that materials and their development required an interdisciplinary approach of physical sciences and technology. Materials science can therefore generally be defined as an interdisciplinary study of materials required for practical use.

Materials have been classified as metallics, ceramics, polymerics and composites. While metallics have been associated with high electrical conductivity, ceramics and polymers are generally considered electrical insulators. However, materials are now being developed called organic conductors which have electrical conductivity almost equivalent to that of metals.

Polymers are generally non-crystalline while metals are distinguished by their crystal structure. Today, new techniques have been invented to cool molten metal at very rapid rates—rates exceeding a million degrees per second. With such rapid solidification, a new class of materials has been produced called metallic glasses. Such metallic glasses have properties which are better in many respects than the normal metals and their alloys.

Interdisciplinary approach on materials has made possible technologies that will expand the use of naturally occurring clays, sands, stones, rocks, low grade ores, agricultural wastes and forest products. Energy shortages will be one of the major constraints in expanding the production of metals in future. It will, therefore, be necessary to develop processes and materials which will require the least energy per unit of the material produced. Engineers, therefore, have to be conscious of tech-

nology changes and technology forecasting in development of newer materials and how they can be used in modern engineering.

The need is for high strength material in smaller sections, which can withstand the demands made on it not only of high stresses in tension and compression but of high fluctuations in temperatures. Large number of investigations are now being conducted in various parts of the world including India to develop newer alloys and materials which can be suitable for use in all types of engineering applications including electronics, spacecrafts, aircrafts, power plants, machine tools etc. In fact, without the newer alloys and materials it would be imposible to imagine the advancement that has taken place in all engineering disciplines. The science of materials, their engineering design and production engineering at both the chemical and mechanical stages are all inter-related. We, therefore, require a new type of scientific engineer to establish liaison between scientific advances and engineers' needs to bring balance between the various disciplines. This is now becoming increasingly apparent. In Western countries, a great deal of progress has been made in the concept and education for developing such specialised engineers. In India also education in Materials Science has been introduced in Engineering Colleges and Institutes of Technology but being a multi-discipline it requires immense amount of pioneering work through inter-institutional collaboration.

There has been good progress made in India in Materials Technology because of research and development work conducted in areas of nuclear energy, space, defence, electronics etc. The work done, for instance, at the Bhabha Atomic Research Centre, Vikram Sarabhai Space Centre, Defence Metallurgical Research Laboratory, the various laboratories under the Council of Scientific and Industrial Research, as well as at Universities and IITs on materials, is of national importance and has helped put India on the map of nuclear and space age.

These new technologies have been developed because the material users need certain properties to be met by the materials. In India and elsewhere, the material users themselves have entered into the field of materials development. The advancement in the knowledge and understanding of solid state physics and chemistry have evolved many unifying concepts and provide guidance in problems of materials development. This enables technologists to design materials properties to exacting specifications. Although this has been most spectacularly proved in the case of electronic materials, we have a long way to go before we design materials to withstand new uses and environmental conditions without trial and error. What is being evolved is science based or science intensive technology without which our atomic energy and space programmes would not make any headway.

I shall discuss later in this paper many aspects of materials science and particularly its relationship to engineering, problems of materials selection, some highlights of mateials research and important Indian Mineral resources and their intelligent and proper use.

Materials Science, A Multidiscipline

Before we examine the various aspects of Materials Science & Engineering, we

should define the terms concisely and carefully. The best definitions are those given by COSMAT :*

(1) "MATERIALS are substances having properties which make them useful in machines, structures, devices and products."

(2) "MATERIALS SCIENCE AND ENGINEERING (MSE) is concerned with the generation and application of knowledge relating to the composition, structure and problems of materials to their properties and uses."

The above definitions are very relevant and significant. First of all, the definition clearly implies that all MATTER is not included in the definition of MATERIAL. The scope is, therefore, limited and we are concerned with materials that are to become part of a 'device or structure or product made by man.' The science part in MSE relates to the study, analysis and understanding of the nature and properties of the materials. The engineering aspect takes this basic knowledge and develops, prepares or applies the materials so developed for specific uses or needs. It is, therefore, obvious that MSE embraces many disciplines or specialities and a multidisciplinary approach has to be adopted to cover the various facets of MSE.

MSE therefore deals with industrial materials used for machines, devices and structures. The principal disciplines involved are solid state physics and chemistry, organic chemistry, polymer physics and chemistry, metallurgy and ceramics and portions of most engineering disciplines. The fields in these disciplines which embrace MSE are synthetic, structural, dynamic and theoretical chemistry and chemical, mechanical, electrical, electronic, civil, environment, aeronautical, nuclear and bio-medical engineering among others. Because of increasing diversity of materials and their applications and their complex performance requirements, it is necessary that today's engineers understand fully the relation of properties to structure and composition. Selection of materials for particular applications can no longer be left entirely to designers but specialists with the background of materials science are constantly required for material selection.

Role of Metallurgists

Metals and alloys are a a class of materials which have been used in engineering structures over centuries. A great impetus to the use of metals and to the industrial revolution was achieved due to increased understanding of processes for manufacture of steel, copper, zinc, aluminium and other metals and alloys. The fundamental studies on metal single crystals brought important phenomena like plastic deformation, annealing, hardening, grain growth, age hardening etc. to a level of understanding which made possible the advent of modern technology. In fact, the studies of phase transformations in metals and alloys in the solid state was undertaken by metallurgists well before the classical physicists paid much attention to it.

The pioneering work of Austen, Hadfield, Sauveur, Rosenthal, Sorby, Hume-Rothery etc. developed the techniques and science of physical metallurgy which was of course aided by the discovery of X-Ray diffraction, electron microscopy, the scanning electron miscroscope etc. In the early days, many of the alloys and their

*Coined name given to comprehensive study of the field of materials science and engineering conducted by US National Academy of Sciences in 1970.

properties were developed by trial and error methods. Scientific bases and understanding were not always achieved before many of the alloys were put in service. Some of the discoveries such as age hardening, corrosion resistance etc. were due to accidental observations and not as a result of systematic search for such alloys. Be it as it may, the understanding of materials in terms of structure-property relationship was pioneered by metallurgists who were in the forefront of utilising advances in physics and chemistry to applications in metallurgy not only to produce purer metals and complex alloys but also provide properties in such metals and alloys, which could be used by engineers, for building structures requiring high strength-weight ratios at reasonable cost. Metallurgists not only made better metals and alloys available but have been instrumental in the development of the art and science of shaping the metallic materials into useful and complicated shapes by either casting (sand, gravity, pressure), hot and cold working (rolling, extrusion etc.), electro-forming, by compaction of powder or by joining (fusion welding, soldering, deformation welding etc.). Over 50 to 60 per cent of investment in industrial plants throughout the world is either for recovery of metals or for shaping them for manufacture of structures or machines.

The metallurgical profession was, therefore, the first to feel the need for a multi-disciplinary approach to materials and materials engineering. The properties of most available materials were found to be inadequate for the high performance and items required to withstand severe pressure, temperature, radiation and stress environment. Studies on metals were extended to ceramics, polymers, composite materials etc. and techniques similar to those applied in physical metallurgy were used viz., structure-property relationship to see to what extent these materials could be useful to meet the demands made by designers who needed very exacting properties in materials required for aerospace and nuclear applications.

Departments of metallurgy in many countries took the lead in starting courses and conducting research in materials science or materials engineering. They applied, as stated earlier, the methods and techniques of physical metallurgy to other materials and found that the properties not only of metals but ceramics, plastics and elastomers, glasses and semi-conductors could be explained and controlled, on the basis of their atomic or molecular structure and configuration. Thus the techniques of solid state physics was found to be applicable to all materials, to provide a common basis for the understanding and control of materials. This unified approach to the study of solid materials came to be known as materials science. Even in India many metallurgical departments have extended their courses and research to include materials science, and some of the work they are doing will be reviewed later in this paper.

One of the important contributions of the metallurgist is towards the problems of analysis of failure of materials. Using sophisticated scientific techniques, it is possible to pinpoint how exactly a metallic material behaved in service and whether the failure was due to fatigue, brittle fracture, casting or machining defects or various other causes. Metallurgists are also playing a very important role in helping engineers in standardisation of materials specifications and promotion and use of substitute materials.

Metallurgists have a reputation for supply of materials which have properties in excess of the maximum specified for a particular application. They also strive to overcome and avoid failure which can arise in service from arduous operating conditions. It is not surprising, therefore, that the role of the metallurgist has been defined as developing and selling properties.

There are many linking points between metals, polymers and ceramics. The classical division of materials into crystalline and amorphous is no longer valid. The concept of ideal crystal structure is useful but it is not realised that an enormous amount of work has been done by metallurgists on the role of defect structures or mixed phases in improving physical properties. The study of defects in crystal lattices has been highly developed for metals. These defects have been studied in great detail by the electron microscope in the last few years confirming the work previously done from indirect observation like X-Rays, etch pits, resistivity etc. Defects such as (1) point defects e.g., vacancies, interstitials, (2) lined defects e.g. dislocation, (3) surface defects e.g. grain or sub-grain boundaries etc. are related to strength and ductility and to structural changes such as precipitation and transformation.

The techniques developed for study of defect structures in metals were used by ceramicists to great advantage. By developing suitable techniques for etch pitting and for preparing films of their materials, a whole new field of ceramics was opened up to them with a ready-made background of theory developed for metals. This does not mean that the role of defects and other structural features in determining physical properties will necessarily be common to different classes of materials but it is always useful to try and extend established concepts to other materials.

Materials Selections

Engineering design in the ultimate analysis boils down to choosing materials which will meet the specifications required to perform the functions for which a structure or system is designed. This is a complex matter involving many factors some of which may be difficult to assess or may act in opposition to each other. Technical parameters and fabrication methods and costs play an important part but one cannot ignore environmental problems, legal requirements and aesthestic values in any design. Decisions regarding the selection of materials and processes by which the material is manufactured are of the greatest importance to the engineering industry and to the country's economy as a whole. There is a definite inter-relationship between materials properties, manufacturing processes and engineering design. The selection procedure may be time-consuming but is essential and requires the efforts of many people such as designers, production engineers, quality control experts, purchasing managers and, of course, materials engineers. Material selection problems arise on innumerable occasions. Creation of a new product or device which has to perform a new function for which there is no previous history or materials used is, of course, the most difficult. Examples are not difficult to find. Deep sea oil drilling rigs or deep sea mining rigs are complicated structures and function under many exacting environmental conditions. Selection of materials for such rigs is naturally a very complex procedure as failure would entail lives as well as hazards

due to oil spills etc. Similarly, metals and materials required for atomic energy and space programmes have to be developed, tested and studied intensively before their application can be recommended.

Modification of an established product to meet new demands or operating under changed conditions pose material selection problems of a different kind and would also lead to development of new materials. For example, need for harder and more refractory materials lead to the development of cermets (combinations of ceramic materials and metals). The heat shield of the reentry vehicle of a space ship is a classic example of new material development. Similarly, when competition from high strength—low density aluminium alloys became very severe, the steel industry developed high strength low alloy structural steels to enable designers to use lighter sections of steel at lower costs without sacrificing safely.

Value engineering and cost reduction exercises as well as ease of fabrication where complicated parts are involved, is another area where material selection plays an important part. Examples are plastics which have replaced metal parts in transport equipment or replacement of wear resistant rubber for alloy steels in lining materials in equipment for handling minerals.

Another example relates to the use of PVC in implant surgery. It was found that as a result of the materials used in curing and plasticising, certain types of PVC were found to contain carcinogenic impurity. It is essential in such cases to use only tested and recommended materials.

Compounds can be made from totally different manufacturing routes starting for example with conventional steel making on one hand and with the use of powdered iron and alloying elements on the other. One route uses traditional metallurgical practices while powder metallurgy techniques will have more chemical engineering inputs. The chemistry of the steels will also have to be different even though the end use may be similar. This is because the process of sintering in powder metallurgy techniques is better controlled and managed with some alloying elements like nickel, while in the case of conventional steels alloying element may not be necessary. Chemical composition is found to be as much related to methods of manufacture as to end use. Shape and dimensional tolerances play a hey role in deciding how and what material a component should be made of. Conventional mechanical property data do not provide an adequate description or guidance for service conditions.

One must realise that properties and designs cannot usefully be discussed in isolation from each other. The use of combination of different materials often leads to design solutions which are more satisfactory than would have been achieved by exclusive reliance on one material. Traditionally, mechanical and structural engineers are not concerned with properties of 'materials' but with the performance in service of components, assemblies and structures. Materials scientist however, is the central figure in the field of structure, properties and applications of materials. He is capable of specialising in a number of different fields because of his general background which fosters close association with other specialist.

During the next two decades, we in India will have to catch up with the science intensive technologies in all spheres of our industrial activities. The concept of compartmentalisation of engineering studies and research into Mechanical, Electrical,

Chemical or Metallurgical engineering will have to give way to the multidisciplinary concept of Materials Engineering and systems approach. Those concerned with education and research in engineering disciplines must, therefore, realise this and shape future programmes accordingly.

Materials Science Research in India

As mentioned earlier, Indian metallurgists and scientists have been engaged in a good deal of research and development work on materials. The work done at Bhabha Atomic Research Centre (BARC) and their allied laboratories like Reactor Research Centre, Kalpakkam, as well as at Defence Metallurgical Research Laboratory (DMRL) is mostly need-oriented although they also do original and fundamental work on many related phenomena and problems. Following the pattern of USA, some of the Indian Institutes of Technology as well as Universities have started departments of Materials Science both for teaching special courses in materials and for research. Materials research is also being done in almost all National Laboratories and I shall only touch the highlights of some of the work done in these places in India.

Science and Technology of Nuclear Materials

A successful nuclear power programme requires a wide variety of special materials for various specific functions. BARC's metallurgy and scientific group has done very commendable work in the development and production of not only nuclear materials such as Uranium, Thorium, Plutonium, Zirconium, Niobium and Beryllium but also Tantalum, Titanium, Rare Earths, Ceramic materials and corrosion resistant alloys. Although technologies for these materials have been developed by advanced industrial countries, it was not always possible to acquire such technology. Work had, therefore, to be started from fundamental principles and a great deal of sophistication had to be achieved in manufacturing processes, equipment and instrumentation.

Our progress in the nuclear power programme has been slow partly bceause we do not have in India a strong base of conventional technology and existing manufacturers could not be relied on to produce the required materials for the nuclear programme. The Atomic Energy Programme, therefore, had to be based on carrying out fundamental investigations, pilot plant studies and later, production based on such studies. The work embraces many important facets such as preparation of Boron Carbide and Boral Sheets for the R5 reactor under construction at Trombay and for the Tarapore Atomic Power Station. Another important achievement is preparation of Copper-Beryllium alloy and vacuum hot pressed Beryllium Metal to meet the requirements of electronics, space and atomic energy programmes.

The atomic and space age has brought in extensive use the most modern technologies such as Plasma Technology, Fluidisation Technology, Superconducting Materials Technology, Diffusion Bonding Technology and many others. At BARC, these technologies are studied and applied to extraction of zircon, sulphatation roasting of nickel sulphide, preparation of high field super conducting magnets, extractive metallurgy of Niobium, eutectic diffusion bonding of zircon alloy sheets

etc. Freeze drying techniques are also used for the production of ultra-fine metal and metal oxide powders. Besides this, work has been carried out on rare earth cobalt alloys which have high coercivity and high curie temperature as well as on rare earth silicon alloys which are used for grain refinement and improved workability by control on sulphur content of steels.

Any nuclear materials programme has to carry out studies on effect of neutron irradiation on the properties of these materials. The most common phenomena are that of radiation hardening and blister formation on the surface of the material due to ion implantation. These phenomena have been studied extensively particularly at the Reactor Research Centre at Kalpakkam. Our future nuclear power programme calls for designing, building and operating Fast Breeder Reactors (FBR) which are sodium cooled. In a fast breeder, materials encounter unusually severe service conditions in the hostile environments of high flux of fast neutrons, liquid sodium, high temperatures and large temperature gradients which impose special demands and stringent requirements of properties on the materials used. Two major material problems which arise in the core due to fast neutron flux are void swelling and irradiation embrittlement.

Void swelling is a consequence of the displacement damage caused by fast neutrons which produce a vacancy for each atom knocked into an interstitial position. At the high temperatures existing in FBRs, a supersaturation of vacancies precipitate as void results, since the interstitials are preferentially annihilated at sinks like dislocations. Austenitic stainless steels are being used extensively as structural materials in FBRs because of their superior mechanical properties at elevated temperatures. In a type 316 stainless steel (12 per cent Ni, 16 per cent Cr, 2 per cent Mo) in the solution annealed condition at 140 displacements per atom, at 625 °C, the swelling can be as large as 62 per cent. Irradiation embrittlement in fuel cladding and core components of FBRs is essentially intergranular embrittlement resulting from the formation of helium bubbles at the grain boundaries.

Enhancement of creep rate by irradiation, corrosion problems due to use of sodium, fuel swelling, fission gas release, fission product attack on cladding and innumerable other problems are encountered and have to be solved which all bear on materials. I do not presume to know much about generation of nuclear power but when I hear criticism of how our nuclear power programme is behind schedule, my sympathies are all with the materials scientists and engineers who are struggling with a plethora of new and unfamiliar materials problems.

Defence Metallurgical Research

Till the turn of the century, the best metallurgists were found either in ordnance factories or in mints. In fact, in mediaeval ages and even after the industrial revolution, ordnance factories and mints were places where more investigation and experiments were carried out on metallic materials than anywhere else. The position in a way is not different today. A great deal of research and investigation is centred around supplying all types of materials to the armed forces for their needs of transport and weapons. Although investigations on defence materials and systems are carried out at various centres, the Defence Metallurgical Research Laboratory

(DMRL) at Hyderabad is a good example of how we solve the complex replacement parts problems for the defence equipment we import from various countries and how without an adequately trained and dedicated group of material scientists our defence preparedness would be inadequate.

Much of the work done at DMRL is, of course, classified and not available for public information. However, there is enough published material available to show that the group at DMRL has the capability to think and help in the investigation and technology of manufacture of sophisticated items needed in modern equipment for armed forces. A classic example is the MIG aircraft break pads which wear out very fast and need constant replacement. These pads are made of a complex metallo-ceramic composition and had to be made available to the Air Force urgently. With the help of electron probe microanalysis and other sophisticated analytical research tools, the composition of imported pads was determined, and experiments conducted to manufacture and test these friction pads, first on laboratory scale and subsequently on production bases in a factory operated by Hindustan Aeronautics Ltd.

Unfortunately, we do not have only any sizeable automobile, aircraft or aerospace industry and, therefore, everything including radiographically sound aluminium and magnesium castings have to be developed at DMRL. They have also developed and made the so-called "shatter alloy" components used on Vijyanta tanks. Their most outstanding achievement is however in the field of high temperature alloys which have to be resistant to creep, oxidation and corrosion at elevated temperatures. Such alloys mostly nickel based are required for gas turbines and aero engines. Apart from developing such alloys including their fabrication technology, DMRL is developing directionally solidified air-cooled turbine blades. The operating temperature of a gas turbine has to be increased in order to achieve higher efficiency. Near the melting temperature of an alloy, it looses its creep strength completely but if the interior of the turbine blades can be air-cooled, the creep strength could be retained. DMRL is developing specially thin investment cast blades which can be air-cooled. Another technique is to use directionally solidified turbine blades where the grain boundaries, which are the main source of high temperature weakness, are made sterile by making them columner or even by eliminating them altogether. The latest development is however to use turbine blades of ceramic materials and DMRL is working on synthesis and shape forming of silicon carbide and silicon nitride which could be used for such applications.

Like BARC, a great deal of work is being done by DMRL on titanium, Beryllium, rare earths etc. Ferro-cerium, cerium and misch metal produced by DMRL are being used as alloying additions to some heats of high strength steels made at Durgapur Alloy Steel Plant. Other interesting achievements are the laboratory scale production of Samarium by lanthano-thermic process, and production of nickel-lanthanum (Ni_5 La) sponge which has a high capacity to absorb hydrogen.

Powder metallurgy techniques today are used to a great extent for manufacture of superalloy and composite material parts. DMRL has developed expertise not only in production of powders of different compositions but also in compaction of powders by hot and cold isostatic pressing. Powder metallurgy is preferred to make

'near net' shapes in complex refractory alloys without need for any final machining. It is also less expensive in capital investment and can conserve a great deal of energy. Very often as in the case of fabrication of nuclear fuel elements this is the only technique available to the metallurgist and has a great future in Indian industry.

Materials Research at National Laboratories

The large number of National Laboratories under the Council of Scientific and Industrial Research carry out many programmes of materials and process research in areas of their speciality. The National Metallurgical Laboratory (NML) has of late concentrated their attention on more industrially oriented investigations and research rather than on theoretical investigations. Their work on mineral beneficiation is well known and extensive investigations have been carried out on beneficiating various minerals in their pilot plant. Their major achievement is in the area of high temperature material development through their Central Creep Testing Laboratory where they evaluate various steels for applications such as steam turbine bolts, super heater tubes, residual creep life of materials etc.

NML has also developed high permeability nickel — iron alloys and heat resistant cast alloys. They have patented and successfully tested a new composition of aluminium-magnesium alloy conductor which can find application as a good substitute for copper in electrical applications. They have also successfully tested a composite material consisting of thin layers of high speed steel bonded surface to surface with a thick layer of mild steel for use as shear blades.

The National Physical Laboratory (NPL) has been involved in carbon materials technology for a long time and have successfully developed processes for manufacture of carbons for various uses including electrodes, brushes, arc carbons etc. Their important current programme is directed towards the development of carbon fibre reinforced plastics. Carbon fibres in continuous stretches have been developed using textile grade processors as well as petroleum pitches.

Development and production of electronic materials has been going on at NPL for a long time and they have a well-equipped pilot plant and supporting facilities where ferrites, magnetic tapes, semi-conductors, piezoelectric materials and devices have been developed.

Work done at several other laboratories on ceramics, plastics etc. is extensive but I have confined myself to work on metallic materials only.

Materials Research at Institutes of Technology

Materials research at IITs has centred mostly around the activities of the Departments of Metallurgy or Materials Science at these Institutes. Emphasis is put at all the IITs both on theoretical and practical aspects of materials. Work is carried out on technical innovations and important aspects of metals and alloys, ceramics, glasses, composites and semi-conductor materials and interdisciplinary approach involving other disciplines and departments is being promoted. A very large number of research programmes are in hand and it is my intention here to bring out a few examples of the outstanding work being done with which I am acquainted.

The Department of Metallurgical Engineering at Banaras is working both at newer materials and processes as well as on utilisation of low grade ores and wastes.

They have made good progress in the study of amorphous alloys more commonly known as metallic glasses. Metals and alloys are normally crystalline but solidification under drastic cooling rates of 10^6 degrees per second or higher, metallic alloys solidify as noncrystalline or amorphous alloys. A group of metallurgists at Banaras is engaged in both devising ways and means of achieving such drastic cooling rates and studying the properties and characteristics of such alloys including their atomic arrangement, mechanical properties, environmental stability etc. Alloys of Pb-Sb, Al-Pd, Al-Ge, Al-Ni, etc. ate being studied. This programme promises to be of immense interest both theoretically and practically for the future, because metallic glasses are characterised by extremely high combination of strength and toughness. For instance, Fe_{80} B_{20} alloy has an yield strength of 370 kg/mm^2, an extensional modulus of 16.9 $\times$ 10^3 kg/mm^2 with a vickers hardness of 1100 kg/mm^2. Similarly, corrosion resistance of chromium containing amorphous alloys are far superior to many types of stainless steels particularly in their stress corrosion cracking properties. The rapid solidification process has made it possible to produce ductile materials from alloys that are extremely brittle when fabricated by conventional methods. Other rapidly solidified materials have demonstrated improved chemical homogeneity and crystal structures. Realisation of the potential applications in commercial devices has led to a great deal of research in this field and India is contributing its share to this research.

Two other areas of work done by the Banaras group are worth mentioning. They are (1) production of high density hollow iron ore pellets which are stronger and have better reducibility than ordinary pellets ; and (2) Hydrogen Reduction of Metal Sulphides. Although hydrogen reduction of sulphides is thermodynamically inefficient, its advantage lies in the fact that several metal sulphide-hydrogen reactions can be carried out at relatively low temperatures. This research has great significance for the future as it can save energy as well as reduce environmental pollution.

On the practical side, metallurgy department of IIT, Madras has been successful in developing a new and inexpensive method for producing aluminium-nickel and aluminium-nickel-cobalt magnets which does away with use of virgin metals and melting in high frequency furnaces. By mixing together calculated amounts of oxides of iron, nickel, cobalt and any other required elements with aluminium powder and igniting the mixture, a molten Alni or Alnico alloys of the desired composition is obtained directly. Since oxides are less expensive than virgin metals and the reduction reactions are exothermic, developing enough heat to yield a molten alloy with enough super heat, uniformity of composition and good castability are ensured. Similar technique has been developed for manufacture of aluminium phosphorous master alloys to replace copper-phosphorous master alloys for modification of hypereutectic aluminium-silicon alloys. Use of Aluminium-Phosphorous master alloys is a distinct advantage in the aluminium foundry. They have also developed a new method of electro-co-deposition called Sediment Codeposition (SCD) for producing thin layers of composites on metallic surfaces. The main features of the SCD method are in regard to the disposition of the electrodes, particularly the cathode, and the regulation of the active and

quiescent cycles. Hard and wear resistant composites of copper and nickel with silicon carbide, and low friction composites of copper and nickel with graphite, sulphides of molybdenum etc. have been obtained on steel and other components. The composites obtained by SCD method are far superior to those obtained by conventional electro-deposition techniques, in regard to extent of uniformity of incorporation, absence of porosity, hardness and wear resistance.

Transformation of Austenite

Among metals, iron and steel are used to the largest extent and the study of phase transformation in iron-carbon alloys has, therefore, fascinated all physical metallurgists throughout the world — India being no exception. All IITs as well as the National Metallurgical Laboratory have programmes of study of transformation of Austenite and my own research at M.I.T., in the early forties was also on this subject. Since then, many scientists have further studied the kinetics of martensitic transformation and strengthening of steel by different heat treatments, as well as through the processes of precipitation and recrystallisation in micro-alloyed steels. The Applied Mechanics Department of IIT, Delhi and the Metallurgy Department of IIT, Madras have been working on both these aspects but recently by sophisticated computer analysis IIT, Delhi have studied nucleation kinetics of martensite. The results reported for the first time by them at the International Conference on Martensitic Transformation at MIT in June 1979, are very promising. They have shown that small quantities of carbon in iron-nickel alloys have a remarkable influence on the thickness of martensitic plates. It was known earlier that martensite transformation is inhibited by small quantities of carbon, the Ms temperature changing by 10 °C for every 0.01 per cent C. The work done at IIT, Delhi shows that the inhibiting effect arises from the thinness of the plates. Thinner plates mean more plates have to form before the steel is fully transformed to martensite. The associated decrease in the grain size of martensite is a potential factor in increasing the toughness of steels. This opens up a new field of investigation for not only the strengthening mechanism but may also lead to the development of higher strength alloys.

The influence of hydrogen on the stabilisation of austenite has been the subject of extensive study and many interesting observations have been made, many for the first time by the IIT, Madras group that hydrogen is quite effective, if introduced in a specially devised manner, in stabilising austenite.

The role of carbon and nitrogen in the stabilisation of austenite is well known and has been explained by the concepts advanced by Cohen and his co-workers at M.I.T. in the immediate post-war years. The stabilisation is attributed to the deactivation of the strain embryos constituting the reactive centres in austenite, by the migration towards and capture by them of the interstitial solute atoms of carbon and nitrogen the driving force for such migration being provided mainly by concentration gradients. Although one should reasonably expect, on the above basis, that hydrogen would also effectively stabilise austenite, virtually all attempts to detect stabilisation experimentally yielded generally negative results. The primary reason for this situation was apparently that the methods used for the introduction

of hydrogen into the steel were not effective or appropriate enough to reveal the stabilisation.

By introducing hydrogen electrolytically, from aqueous acidified baths, into steels while still in their austenitic condition, substantial stabilisation of the austenite was observed. X-ray, hardness, metallography and magnetic testing methods were employed to determine the extent of stabilisation, siung in some cases, final reference temperatures as low as 4.2 °K. The stabilisation in some of the steels studied, was as high as 13.5 per cent, resulting in a decrease of hardness of about 80 V.P.N. From these experiments, it also became clear that high residual amounts of hydrogen were not necessary to stabilise the austenite, the critical criterion being rather the mode and stage of introduction of hydrogen into austenite.

Whether the atomic state of hydrogen or the enormously high pressure at which it is generated during electrolysis is the predominant, if not the sole factor has been examined, by equilibriating austenite with hydrogen at low pressure, but with the hydrogen dissociated by constinuously having an electrical spark in it. Considerably higher amounts of hydrogen enter into the austenite when it is in its atomic state, although at low pressure and stabilises the austenite appreciably.

Austenite appears to be wholly stabilised by cathodic hydrogen, right down to temperatures at which such impregnation is continued, even though these are considerably below the Ms temperature of the steel. The transformation of martensite is seen to commence only after the impregnation is stopped and to proceed almost apace with the effusion of hydrogen. These observations are easily understood on the basis of the le Chatelier principle and Cohen's own observations on the suppression of the austenite-martensite transformation by pressure.

These investigations have been described in detail in several papers published in India and abroad Presently, the study of the effects of hydrogen on the transformation of austenite to pearlite and other two-phase intermediate structures has been taken up. Various treatments, like ultrasonic bombardment, which activate austenite, are also being studied for their effectiveness. This work also opens up new fields of research on heat treatment of steels and will have far-reaching consequences on understanding and developing new high strength steels.

As can be seen, materials science research in India is being pursued in many directions. We have the talent to extend this research and investigation in many fields both theoretical and practical. The examples I have given are just a glimpse of what is happening in materials research. It appears to me however that because of many centres and many agencies carrying out such research there is not enough co-ordination in the areas of research and investigations to be undertaken as major projects. Duplication in areas such as work on magnetic materials, powder manufacture and powder metallurgy, rare earth metals and alloys, cermets etc. needs to be avoided. On materials science education also, there needs to be more interdisciplinary, inter-departmental and inter-institutional co-ordination. My suggestion is that since a great deal of finance and expert manpower is engaged in materials education and research this area should receive special attention of the various funding authorities and a co-operative and co-ordinated plan should be formulated. The science-oriented 6th plan should emphasise materials science as a major platform

for the country. All Engineering Colleges and Universities do not need a separate materials science department. The few we have should be made into national centres. What is important however is that all technical education establishments should have adequate courses in materials sciences irrespective of the areas of speciality offered. These courses need careful planning of both theoretical lectures and laboratory courses and should be taught by persons with proper background in materials sciences. In fact, we need national recognition of this important subject by endowing chairs of Materials Science in a few IIT's.

A matter of concern is the preference among Indian research workers to have their research papers published in foreign Technical Journals. While this gives some personal satisfaction and recognition of the work done, I strongly recommend that because most of this research is funded through public money, such papers should be preferably published in India. There are many publications of international reputation in India e.g., the "*Transactions of the Indian Institute of Metals*" which should be the medium through which Indian materials research papers should be publicised.

India's Mineral Wealth

Since minerals are the major sources of materials we use, I want at this stage to briefly examine India's mineral position. Tables II to VI give figures of Indian production,

Table II

Indian production of important minerals, ores & metals

	('000 tonnes)		
	1977	1978	1979
Iron ore	43,673	38,445	37,015
Manganese ore	1,824	1,609	1,686
Chromite	360	266	308
Limestone	29,951	30,709	37,284
Finished steel	7,000	6,563	5,285
Steel ingots	8,575	9,917	8,360
Pig iron	9,797	9,432	8,715
Ferro manganese	206	220	180
Ferro chrome	20	21	22
Petroleum	10,152	11,251	12,796
Coal	100,297	101,549	103,455
Lignite	3,632	3,613	3,247
Copper ore	2,589	2,133	2,173
Lead concentrate	16	17	21
Zinc concentrate	45	66	71
Aluminium	184	205	211
Copper	23.5	19.5	21.3
Zinc	36	59	63
Lead	7.6	10	9.6

TABLE III

Indian imports of major metals, petroleum & coal

	1977	1978	('000 tonnes) 1979
Iron & Steel	593	820	* 1,700
Aluminium	4.8	24.4	41.5
Copper	47.1	81.7	44.2
Lead	46.67	28.40	29.6
Znic	63.97	58.92	51.2
Tin	5.5	6.4	2.8
Nickel	7.3	8.2	4.1
Antimony	0.526	0.744	0.308
Copper concentrate**	NA	NA	NA
Zinc concentrate	19.1	18.2	12.8
Petroleum	14,548	14,892	16,200
Coking Coal		1,200	800

* during fiscal year 1978–79.
**23,534 tonnes in 1975–76
13,231 tonnes in 1976–77.

TABLE IV

Indian exports of major minerals and metals

		1977	1978
		N(1)	N(2)
Iron & steel	—	1860	943
Aluminium	—	16	10
Iron ore	—	23191	19778
Manganese ore	—	554	577
Chromite	—	167	59
Ferro manganese	—	19.3	76
Ferro chrome	—	8.3	9.0
Ferro-silicon	—	6.4	NA
Asbestos	—	0.37	0.194
Barytes	—	177.18	201.04
Bauxite	—	47.66	1.90
Keolin (China Clay)	—	6.2	4.0
Dolomite	—	7.4	5.8
Gypsum & Plaster	—	12.5	4.5
Kyanite	—	8.8	3.5
Magnesite	—	13.07	6.8
Mica (manufactured & unmanufactured)		23.21	23.58
Steatite	—	18.0	12.45
Sulphur	—	0.75	0.99

N(1) Fiscal year 77–78; N(2) Fiscal year 78–79

TABLE V

Estimates of indian minerals & ore reserves

Mineral	Reserves				Total
	Unit	Measured	Indicated	Inferred	
Iron Ore					
(a) Hematite Ore	Million tonnes	3,140	3,912	3,486	10,538
(b) Magnetite Ore	„ „	717	2,499	1,023	4,239
Manganese (Recoverable)	„ „	11.871	17.882	49.757	79.510
Limestone					
(a) S M S grd.	„ „	142.62	333.75	369.02	845.39
(b) B F grd.	„ „	1,370.80	1,181.53	2,066.418	4,618.748
(c) Cement grd.	„ „	3,212.627	1,546.656	30,244.819	35,004.102
Dolomite	„ „	704.93	412.36	2,954.57	4,071.86
Gypsum	„ „	0.73	17.91	1,185.92	1,204.56
Magnesite	„ „		332	7,452	7,784
(a) Insitu	„ „	0.54	216	271.10	487.64
(b) Recoverable	„ „	10.94	13.30	37.58	61.82
Coal (Gondwana)	„ „	—	—	—	85,444 (all categories)
Coal (Tertiary)	„ „	—	—	—	849 (all categories)
Chinaclay	„ „	66.75	395.73	247.80	710.28
Copper Ore	„ „	122.25	121.67	169.43	413.35
Lead-Zinc Ore	„ „	33.105	82.526	166.990	282.621
Nickel Ore	„ „		55.31	82.64	137.95
Bauxite	„ „	117.91	213.30	1,965.71	2,296.92
Chromite	'000 tonnes	6,379	5,575	5,319	17,273
Sillimanite	'000 „	1,199	155	8,210	9,564
Graphite	'000 „		332	7,452	7,784
Asbestos	Tonnes	8,671	53 279	708,098	770,048
Baryte	Tonnes	108,321	78,704	69,877,071	70,064,096
Kyanite	Tonnes	101,985	225,148	3,077,346	3,404,479

imports and exports of various important minerals and metals for the last 2–3 years. Demand projections as well as figures available for reserves of minerals are also given. The overall position is that while we have sufficient quantities of iron ore, our reserves of metallurgical coal are not sufficient to last for more than a few years. We have already started importing low ash coking coal. Proved reserves of manganese and bauxite are also not very large although indications are that, with more development work additional reserves of bauxite will be proved. The position as regards copper, lead and zinc is also not very happy and we have to continue to import either the respective metals or their concentrates. We are completely dependent on imports for tin, nickel and antimony, three very important industrial metals. Although the various agencies entrusted with prospecting, exploration and deve-

TABLE VI

Estimates of Indian requirements of major minerals and metals

Mineral	Unit	1982–83	1984–85	1987–88
Limestone	Million tonnes	60.98	68.22	78.97
Gypsum	„ „	2.53	2.73	3.04
Dolomite	„ „	3.356	3.473	3.518
Coal	„ „	150.5	—	214.3
Manganese Ore	'000 tonnes	1384	—	1674
Fireclay	„ „	793	894	1040
Aluminium	„ „	365	445	595
Copper	„ „	108.8	122.2	145.5
Zinc	„ „	123.8	133.8	150.5
Lead	„ „	50.8	55.0	61.9
Nickel	„ „	12.48	—	—
Asbestos	Tonnes	81720	88590	98880
Kayanite	„	31000	26900	36600
Sillimanite	„	15600	17100	19500
Magnetite	„	404000	595000	649000
Graphite (Crucible Grades)	„	2900	3750	4150
Barytes	„	50342	53930	58682
Bantonite	„	202500	—	288000

lopment are reporting new discoveries and proving additional reserves, it can be generally stated that we are not self-sufficient in many important minerals for the manufacture of metals and alloys. We also need a well thought-out and comprehensive minerals policy to enable us to pursue a more systematic approach towards exploitation, conservation, export and domestic utilisation of various minerals.

MINERAL'S POLICY CONFERENCE

The goal and objective of our mineral's policy should take into account social needs, effect on environment, benefits derived from export, conservation, multiple resource development etc. Very often our mining methods are very wasteful and we have paid scant attention to pre-planning of land use, recovery and recycling of waste materials and proper use of technology adequate for development and elimination of environmental hazards.

In my Wadia Memorial Lecture to the Indian Institute of Metals in 1978, I have discussed in detail the mineral policy we should follow. However, two major points need to be emphasised. The first Minerals Policy Conference was held in 1947, which took certain important decisions regarding exploration, mining concessions, centre-state relationships etc., in the exploitation of minerals in the light of the then prevailing conditions. We also appointed a large number of autonomous or departmental agencies to carry out various functions of our minerals management.

Although a great deal of activity goes on in the mineral front there has not been any comprehensive public debate on mineral policies since 1947. I, therefore, strongly recommend convening a Second Minerals Policy Conference which should be attended by mineral economists, geologists, metallurgists, major users of minerals, exporters and owners of mineral concessions etc. Detailed papers on various policy objectives on exploration, conservation, environmental protection, multiple resource development, exploration of sea bed resources, strategies to be adopted, methods of implementation etc. should be prepared and presented at such a Conference. These papers should be fully debated and a comprehensive policy document prepared for implementation.

Central Co-ordinating Agency

My second recommendation is to appoint a Central Co-ordinating Agency which would be the clearing house for implementation of the mineral policies adopted at the conference. This Co-ordinating Agency should guide all ministerial departments and corporate bodies engaged in mineral and metal exploration and exploitation so that the overall objectives of the mineral policy are achieved. This agency should be headed by a well-known mineral economist supported by geologists, mining engineers and other personnel who have had experience in the minerals field. What is needed, is a clear enunciation of broad policies and implementation of such policies to enable the country to derive maximum benefits from its mineral resources.

There are at least 15 important industrial minerals, of which more than 75 per cent are located in five or fewer countries. These minerals include iron, aluminium, titanium, chromium, cobalt, manganese, molybdenum, nickel, tantalum, tungsten, vanadium, mercury, silver, platinum and asbestos. Table VII gives the nine most critical industrial raw materials giving the share held by five countries as of 1974. India does not figure in this list as possessing large deposits of such critical or strategic industrial raw materials. To that extent India will have to be dependent in future on minerals from other countries. The aims and objectives of our mineral policy should be to make ourselves less vulnerable on other countries for our critical materials and also be able to derive maximum benefit from minerals we export.

The demand for physical resources increases with the growth in population and also for higher standard of living. Simultaneously, the exploration for and exploitation of mineral resources becomes progressively difficult and costly. Much could be done to alleviate future problems of scarcity in materials by more rational use and by conservation measures, by reduction of material waste in the production chain, better design ensuring longer product life and increased recycle and reuse of materials from scrap products. A great deal of research and investigation work is carried out on mineral beneficiation and processes for winning metals from low grade ores. Prices of metals have risen considerably and what at one time was an unprofitable mineral to smelt has now become a profitable proposition. Apart from that, it is imperative that we produce some metals like nickel and tin for stratgic reasons even though the projects may be uneconomic.

TABLE VII

The nine most critical industrial raw materials

Metal	Share held by five countries 1974(%)	Indicated ore reserves (percentage share 1974)
Titanium	98.2	Brazil (65.9) India (21.7) Australia (5.4)
Chromium	98.2	South Africa (73.9) Rhodesia (19.7) USSR (2.9)
Cobalt	91.1	Zaire (27.7) New Caledonia (27.1) Zambia (14.2) Cuba (13.8) USSR (8.3)
Niobium	96.4	Brazil (75.8) Canada (7.6) USSR (6.3) Zaire (3.8)
Manganese	97.7	South Africa (45.0) USSR (37.5) Australia (8.0)
Tantalum	84.8	Zaire (55.0) Nigeria (11.0) USSR (6.7) Thailand (6.7)
Tungsten	87.1	China (53.6) Canada (12.1) USSR (8.9) North Korea (6.4)
Vanadium	97.3	USSR (74.7) South Africa (18.7)
Platinum	100	South Africa (71.3) USSR (26.7) Canada (1.8)

MATERIALS FOR FUTURE DEVELOPMENT

I pointed out earlier that the important materials which are consumed in large quantities are wood, concrete, metals and polymers. In 1930, polymers did not figure in consumption pattern while consumption of metals like aluminium was at a very low level. In future, many materials and alloys will be developed for new applications or to replace some currently used materials. What is most significant both for India and other countries is to improve quality per tonne of production of any material as well as reduce its cost per unit. The objectives to achieve will therefore be qualitative and not quantitative. The criteria of per capita production or consumption will have to give way to quality and cost and it is in this direction

that materials science and engineering has to make its greatest contribution and impact.

If we look at total global availability, we see no shortage of ores of aluminium, magnesium, manganese, iron and titanium. There is, however, shortage of ores of copper, chromium, nickel, tin, silver, molybdenum, cobalt and tungsten. These are some of the strategic materials and will remain in short supply and to that extent limit availability. The second important limitation is energy. Energy inputs in winning metals increase with use of leaner ores. First, energy is required for mining, drilling and transport purposes. Energy is then required for crushing, concentration and preparation of the ore for smelting. The reduction of the ores and chemical reactions require more energy while energy is also needed for subsequent shaping of the various smelted metals and alloys into usable shapes and articles. For instance, on the average with today's equipment and processes we require 9, 20, 30, 48 and 120 kWh to produce one kilogram of steel, copper, nickel, aluminium and titanium respectively. Almost all industries are engaged in seeing that energy use is reduced but there is a limit to this exercise unless major investments are made.

What are, therefore, the possible solutions to our materials and energy problems? Some answers are obvious. Firstly, we should reduce input of material by input of strength. Secondly, we must reduce input of energy per unit of material and thirdly, recycle material and recover material from scrap and waste. We shall also have to replace batch processes by continuous processes and to recycle and recover heat from the metallurgical and other processes we use today.

Other answers include replacement or substitution of strategic and short supply materials with others and newer materials and composites. We have also not paid much attention to the metal silicon or materials derived from the most abundant mineral silica. The problem of course is to get rid of the oxygen from silica. Use of silicon hydride or silicon carbide in ceramic and high temperature material should be studied and increased. Not enough attention has been paid to wood in our economy as a construction material. Wood impregnation with high polymer can impart high strength to wood. Similarly, natural fibres can make high strength materials through impregnation. Jute and coir are fibres which need a good look and intensive research as they are indigenous.

The materials revolution will touch all nations and all individuals. The recently published report of the Interfutures Group, a Sub-committee of the Organisation of Economic Cooperation and Development, predicts not only that interdependence of developing and developed countries will increase but that there will be major upheavals in the geographical redeployment of manufacturing facilities between the developing and developed countries. The iron and steel, chemical, automotive and ship-building industries will see a gradual transfer of production facilities to currently less developed countries, partly because of resource availability; (minerals, petroleum, scientific and skilled manpower etc.) and partly because of environmental considerations. They, however, do not predict any slow-down of growth in any country due to lack of energy or technological reasons. They predict a tremendous growth in electronic industry in developed countries. The growth of microprocessor technology will continue unabated with continued research in newer materials and appli-

cations. For instance, development of cryogenically controlled micro-processors will render 'chips' obsolete. The second major thrust will be in the direction of exploration of minerals including energy resources for the sea bed. For instance, the exploration for hydrocarbons along continental shelves will grow and depth of exploration and offshore mining of mineral resources will increase. The third major change predicted is the increase in the use of nuclear fusion technology and solar energy. All these developments underline the major need for materials of enormously different variety, complexity and properties which will be needed for such applications. India has to take its rightful and leading place in these new materials development.

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