physical models for complex systems. The field abounds in unexpected phenomena. There is considerable strength in India in this field, and pioneering science is possible with investment mainly in people and some computing power!

There is no major effort in most of these areas, though in many cases their value is realized. Lack of long-term commitment, lack of faith in ourselves and interagency confusions, are some contributory factors. It is no secret that we are falling behind, or have not started in many of these fields; nor are we running a different race. Unless action is taken early, making full use of the scientific infrastructure that has been built up over the last four decades and augmenting it pragmatically, we will become mere spectators in science and clients in technology.

Conclusion

I believe that there is every kind of interesting physics in our future, because of the continuing strength of the Indian tradition in this field and in spite of our slow responses. Some suggestions on how to make it happen are given above.

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Engineering science in India: Some issues and challenges

R. A. Mashelkar

INDIA is a nation in transition today. The new Industrial Policy announced in July 1991 has opened up the Indian industry to foreign investment and technology collaboration. With a move towards the market-driven economy and integration with the global economy, it has become imperative that the Indian processes and products become competitive in the international context, both in terms of quality and cost. In product and process development the future emphasis will have to be on competitive export. The path from 'discovery to delivery' or 'concept to commercialization' will, therefore, have to be traversed with a sense of urgency and daring. The innovativeness of our R&D will play a crucial role in India gaining a technological supremacy in at least some select areas. This implies a major responsibility on the engineers of tomorrow. Not only will we need hard core practising engineers but we will also need new generation engineering scientists, who would interface effectively with science on one hand and technology on the other.

What is the status of engineering science in India today? It is sad to see that barring a few isolated islands of excellence, our performance in engineering science has not been up to the mark. What is the reason for this sad state of affairs? Unfortunately, the interface between science and engineering research as well as that between engineering research and engineering industry has been rather poor. Among Indian engineers, there is an erroneous impression that engineering research consists only of design, development and aspects relating to production. The fact that a close symbiotic relationship exists between science and technology and therefore, new concepts and new knowledge make a direct impact on engineering has been, by and large, missed. It is obvious that in order to produce world-class technologies not only do we require high class science, but also the level of originality and innovation in engineering needs to be comparable to that in the frontline scientific research, on which the original inventions are based. Our engineering graduates, by and large, have not been attracted towards engineering science. The reason is that there has been no demand on engineering scientists in Indian industry.

It is well known that the R&D capabilities in the Indian industry generally are poor and manufacturing in Indian industry, based on its own R&D, has been rather limited. The major emphasis so far has been on reverse engineering and import substitution. Therefore, well trained engineering scientists armed with modern tools and analytical skills, who can establish an intelligent relationship between the advanced level of research on one hand and the traditional industry on the other, have not been in demand. This state of affairs cannot simply continue any more. The new context of international competitiveness itself will put serious demands on everyone. One therefore hopes that engineering science will flourish in years to come.

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With the above backdrop, we will first review briefly the present status in engineering and engineering science. We will then peep into the future and suggest some key research endeavours that we need to focus on and also the new strategies that we need to adopt. We will briefly review the present funding situation for support for research in engineering science, which is rather dismal, and suggest new initiatives that we need to take in enhancing this funding; with a proviso, of course, that it be linked to assured performance and delivery!

The present Indian scenario

The engineering profession in India has certainly made a contribution to the manufacturing in major industries like textile, sugar, cement, paper, iron and steel, petrochemicals, fertilizers, drugs, etc. The steel produced in India has provided the basis for the manufacture of a range of engineering goods from fasteners to giant machinery. The textile industry now covers not only the traditional sector of cotton and jute but also different types of synthetic fibres. The machine tool industry has made good progress. The engineering industry today can supply requirements of power-generating equipments, equipment for railways, road transport and communications. Sugar machinery, cement machinery, power boilers, material handling equipments and a large number of consumable durables are today made so that there is a self-sufficiency in many of these items in the country.

As regards construction activity about half of the five year plan outlay goes into this activity. Apart from housing, there is a significant construction activity in areas like agriculture, irrigation, communications, power, transport and industry. India has built some of the largest dams and hydroelectric projects. India has the second largest area in the world provided with irrigation water. Indian experience and capability in building large earthen and masonry dams are commendable. In the power sector, India has built large hydroelectric stations involving major dams and power houses, with many power stations having capacity in excess of 500 MW. Headway in even super thermal power stations has been made.

India produces many electronics requirements such as radios, television sets, broadcasting equipment, telecommunication, switching and transmission equipment, radars, earth stations, nuclear reactor control power electronics, etc.

The performance in the chemical, petrochemical and fertiliser sectors has been rather impressive. Good expertise in manufacturing, detailed engineering, fabrication and commissioning exists today.

The achievements in the area of space, defence and atomic energy have been laudable. For instance, in the area of nuclear energy, achievements include exploration and mining for atomic minerals, preparation of high purity nuclear materials such as uranium, thorium, plutonium, etc., production of fuel elements for reactors, production of heavy water, health and safety instrumentation, etc. The space programme has blossomed with successes in launching of satellites with increasing sophistication and complexity, all designed and fabricated in India. The INSAT series of satellites has provided vital services in television, radio, telecommunications and remote sensing. Similarly in the area of defence, many achievements relating to field guns, combat vehicles, defence materials, electronic warfare, radars, missiles, etc. can be cited. What is remarkable is that technologies were not available from abroad for love or for money—and India had to follow the route of establishing these technologies entirely on her own.

Some disturbing facts

The foregoing list of achievements, if read wrongly, can give us a false sense of security that we are doing well. We must realize that industrial production and technological capability are not synonymous with each other. Operating 'screwdriver technologies', as we have done in many cases, do not take a nation very far. Bulk of the industrial production in the civilian sector has been on the basis of imported know-how, which has come in the form of packaged, hard-wired and unabsorbable black boxes. The large base of our industry owes its size to our large markets and it can take little credit for opening up new markets through new products. In the absence of competition, there has been no driving force that has stirred our industry to innovate. There are glaring examples of where we have missed the bus, in spite of obvious advantages that we enjoyed. For instance, we are amongst the largest producers of bicycles, fans and sewing machines in the world and yet we have seen no improvements in any of these. We are the largest producers of sugar in the world, but our technology has remained old and outdated. Our iron ore is one of the best but our steel is one of the most expensive in the world. In power-generating equipment, we have a large share of the world market today. We should have been among the world leaders as technology suppliers, but still we are nowhere. We have lost a potential world leadership in railways, road building, construction, fertilizer production and so on.

Reasons for this sad state of affairs are obvious. High level inputs from science and engineering science have not gone in either absorbing or improving the technology or in creating new technologies. We have some isolated islands of excellence in engineering science but many of them have not integrated with the larger process of industrial manufacture. Bulk of the engineering science work has been driven by the desire of mere exploration, so that the results of research could find a place in engineering science journals. These explorations should have been linked to exploitation, which will eventually create the wealth for the nation. The fact that exploration without exploitation is sterile is a message that has not dawned on our engineering scientific community. We urgently need to change this situation.

Engineering science research: Need for a new approach

On the backdrop of what we have presented so far, how should we plan the future efforts in engineering science? The research in engineering science will be obviously dictated by the demands put by our societal and industrial requirements and also aspirations and plans in the strategic areas that are crucial to the country. We will have to realize that acquisition of technology is going to be increasingly difficult in years to come. Clear indicators during the past one or two years are there for all of us to see. The advent of special 301, harsh duties on drugs and pharmaceuticals, prolonged difficulties on acquiring the Cray Supercomputer, the implications of Dunkel draft, sanctions on ISRO as regards its cryogenic engines deal, etc. are clear indicators of the shape of things to come. Furthermore, the attempts to use semimilitary considerations to deny even the transfer of civilian technology from north to south are becoming obvious in recent months! The Missile Technology Control Regime, London Nuclear Suppliers group, Coordinating Committee for Multilateral Export Controls are here to stay and we should be able to read these messages clearly. There will be no easy purchase of high technology in the offing and what will be given to us will be just left overs. Therefore there is no substitute to making massive investments in S&T in the country through a grand plan. Promotion of research in engineering science will have to be a part of such a grand plan.

What should be our priorities in S&T in the coming decade? A considerable thought has been given in the past to this issue. For instance, the erstwhile Science Advisory Council to the Prime Minister (SAC-PM) has outlined[1] the detailed approaches we need to take in frontier areas of research and development (such as advanced materials, photonics, lasers, parallel computing, instrumentation, robotics and automation, etc.) as well as socio-economic areas of relevance (such as management of renewable resources, health care, food needs, building materials, fertilizer use, etc). These S&T perspectives clearly define the goals for research in engineering science also. Furthermore the famous 'Baroda Seminars' conducted by DST have helped define the future perspectives for research in engineering science. Such and other similar documents are the ones, on which we can certainly begin to build. It is important to reemphasize that there are many problems peculiar to India, where we will have to obviously focus. We will illustrate a few of these in the following.

Some thrust areas in engineering science

The global competitiveness is going to place enormous demands on us. Take manufacturing as an example. If our products have to be competitive in the world market, then we will have to develop manufacturing skills by using the latest tools of engineering science. Different disciplines will have to contribute to this endeavour.

In the area of mechanical engineering, aspects of low energy consumption, high efficiency and reliability, performance improvement and development of expertise in frontier areas like advanced mechanical design, automation and robotics, etc., will need urgent attention. Areas like precision engineering will have to be given top priority, since efficiency, reliability and quality will be increasingly important in the changing context. For international competitiveness of our products, new materials, new design concepts and totally new manufacturing methods will have to be continuously sought.

We will have to concentrate on a few sectors that are crucial to India and make a major headway. For instance, in spite of having one of the largest railway networks, we have lagged behind in terms of a strong capability in engineering science in this area. Thus rail–wheel interaction, inertial profile, lateral dynamics, bridge-vehicle dynamics, etc. are areas that will need attention. However, such knowledge will have to be exploited for improved designs otherwise it will have no relevance. In a similar way, we will have to ask searching questions about our capabilities, where we have large scale manufacturing. For instance, in spite of being the world's second largest producers of two wheelers, do we have the capability to design fuel-efficient vehicles, which are completely indigenous? We are one of the largest producers of refrigerators. However, when the new chloroflurocarbon (CFC) substitutes become mandatory, will we have the capability to design a new compressor or a completely new refrigerator? Our future efforts in mechanical engineering science will have to be dictated by such concerns.

As regards materials, mining and mineral engineering, an excellent perspective of the integrated efforts we need to take up has been given by Rama Rao[2] and it is also given in the reports prepared by SAC-PM (ref. 1). Concerted efforts towards the manufacturing and processing of engineering ceramics, speciality polymers, advanced composites, rare earths, light metals and their alloys, special steels and their products and fabrication processes will have to be launched.

Take some key issues for consideration. New mineral beneficiation techniques for conservation of resources and energy will have to be taken up on a priority basis. Improvement of processing techniques for high ash content Indian coal, treatment and utilization of coal ash and red mud are some of the other examples. India is the third largest producer of rare earths, which are being used for making super performance materials. We export rare earths rather cheaply. We need to export products based on value addition to rare earths. High level engineering science (e.g. innovative separation technology) will be needed here. Development of technologies for highly priced rare earths and their oxides and development of rare earth-based catalysts will have to assume priority.

Ceramics will have an enormous potential for application in automotives, aerospace, pollution control, etc. In these applications, the superior properties of ceramics at high temperature, their superior wear and corrosion resistance as well as oxygen sensitivity, etc. can be effectively exploited. Development of engineering ceramics, development of production of fine products starting materials, development of refractory materials and their products will require high level efforts in ceramic science and engineering.

Polymers are emerging as exciting materials with a range of applications. Although production facilities for commodity polymers have been set up, we have yet to make a breakthrough in engineering plastics. Aspects related to engineering science of manufacture and processing of polymers are poorly understood in India. Strong polymer science and engineering efforts focusing on polymer reaction engineering, non-Newtonian fluid mechanics, rheology, etc. need to be taken up at all polymer engineering centres. Application of polymer engineering science to a variety of areas can have a major impact on the country's economy. Food preservation through superior barrier packages, development of speciality synthetic fibres to suit the Indian needs, membrane separators for ammonia recovery in our massive fertilizer industry, are some obvious examples.

Composites are fast replacing metals and alloys in automobiles, aircrafts and several engineering applications, since they offer high strength to weight ratio and excellent corrosion resistance. Concerted efforts on upgrading our base on manufacturing science of carbon and aramid fibres, silicon carbide fibres, ceramics and metal matric composites will have to be launched.

Newer techniques in materials processing will assume importance. Plasma, electron beams, laser and ion beams are emerging as new tools in metal extraction, joining of materials, surface alloying and surface modification of materials for wear and corrosion resistance. Similarly attention will have to be given to in-depth engineering analysis of fabrication processes, mathematical modelling and non-destructive evaluation.

Chemical industry contributes today to 40% of the nation's GDP. It is slated to have a growth in excess of about 10% in the coming decades. A strong basis in chemical engineering science is thus crucial. New perspectives for research in chemical engineering science in India have been already provided[3–5]. A major research effort is required in separation science and engineering, interfacial science and engineering, biochemical engineering linked specially to modern biotechnology, processing of advanced materials, effluent treatment technology and so on.

Many of the separations now in use are energy-intensive and there is a need for developing new separation techniques such as adsorptive separations, membrane separations, etc. Development of selective membranes for gas separation such as in oxygen enrichment of air, separation of hydrogen from synthesis gas, etc. can have a major impact on the Indian industry. Combination of reaction and simultaneous separation of products (combo systems) need to be looked at with urgency, since it can give our industry a competitive edge.

Interfacial science and engineering will be of great importance in coming years, both in chemical reactions and in processing. Investigations on microemulsions, colloid systems, etc. are of great importance. Key areas like secondary oil recovery, done either through the use of polymer flooding or through biosurfactants, will depend crucially on our strengths in interfacial science and engineering.

A chemical engineer will have a crucial role to play in effluent treatment. With newer and more and more stringent regulations on environmental protection world-wide, the chemical engineers will be involved in handling chemicals from 'the cradle to the grave'. Development of more cost-effective effluent treatment methods, recovery of valuable products from waste streams, etc. will continue to be major challenges facing the chemical engineering scientists in the coming decade.

In the area of civil engineering, shipping and transport there is a great deal of scope for engineering science of a high order. The spatial problems in India of availability of water, storage and conveyance systems are ones, where major efforts need to be put in. India has a large coastal line. Coastal engineering will have to be strengthened to control the siltation caused by long-shore sediment transport, determined by the wave characteristics and near-shore topography. Studies on coastal processes and sediment transport including mixing and ground improvement techniques under water offer interesting challenges. As India continues to explore and exploit ocean's resources, which include oil, gas, minerals and ocean energy, we will have to develop strong engineering science basis. Numerical models for forecasting the environmental parameters like waves, study of the interaction between large floating platforms and long rigid suspended pipes interconnections, etc, will become important.

Geotechnological engineering is in a stage of infancy today. The use of geosynthetics in civil engineering practice, integrated monitoring of structures, development of appropriate technology packages including design guidelines for ground improvement, will assume importance.

Knowledge-based expert systems to tackle complex problems in civil engineering will be particularly needed. These could specifically pertain to irrigation and water management, environmental pollution, dispersion in river streams, etc. To meet all these challenges, civil engineering science, which is not well developed in India, will have to be upgraded urgently.

One could go on and list out similar priorities in electricity and power, electronics, computer engineering, aeronautical engineering and so on. The intention here is not to be exhaustive. However, it is indicative of how solutions to some of the typical Indian problems could be obtained through tools based on engineering science.

New strategies in engineering science

With some major challenges that the engineering science community will be facing in the years to come, we will have to make some strategic and cultural changes in the way we do things. We will highlight some of the more important ones here.

Engineering scientists will have to realize that environment is going to be a serious concern in the decades ahead. Therefore, the orientation will have to be towards processes and products oriented towards zero pollution. Eventually there will have to be the concept of total quality management, which will not only encompass the quality of products but also the processes and systems used for manufacturing of products. Our antiquated ways of doing things will have to change. We continue to use cyanides in electroplating without concern for occupational health hazards and effluents. We continue to pollute the air with carbon monoxide and carbon dioxide in metallurgical industries. We continue to use CFCs in electronic industries. The new manufacturing processes will have to take the issues concerning the environment seriously, and this poses an interesting challenge for engineering scientists.

The role of individual disciplines in engineering will have to be carefully identified and then orchestrated with other disciplines. For instance, environmental engineering today is identified mostly with civil engineering. Chemical engineers will have to come in aggressively in environmental technology.

One of the primary foci of the emerging engineering science will have to be on conservation of energy and materials resources. Getting 'more from less' will become increasingly important in the coming decades. Using sophisticated tools such as modelling, simulation and optimization in all disciplines will be imperative. Teams of engineering scientists will have to work together to solve the problems. (Something that the Indians are not good at!) Take, for instance, the problem with two-wheelers. It is known that the fuel efficiency in existing two stroke engines is rather poor and close to 15% hydrocarbons are thrown out in the exhaust. One estimate actually shows that by the year 2000, about 1 million tonnes of fuel will be released in air in India through this mode alone! New engine designs using improved understanding of combustion chemistry, fluid dynamics, etc. will have to be seriously considered by mechanical engineers. At the same time, chemical engineers, material scientists and catalyst experts will have to take up the task of development of catalytic converters to suit Indian conditions with truly innovative designs. Such converters do not exist today in the world, since the western world does not need them. Similar examples can be given in many other key industries, such as textile, cement, fertilizers, etc., where different disciplines of scientists and engineers will have to work together for achieving results.

Product design and product development is an area that is sadly neglected in India. The engineering scientists of the future will have to focus on these. The product design of the future will not only have to use scientific ideas, and innovative engineering science, but also market considerations. Thus close understanding of the technological implications of innovative product designs, especially in view of the reduced life cycles of products and also the dynamics of national and international markets, will be crucial. This calls for evolution of a new breed of engineering scientists!

Our engineers have a role in not only manufacturing but also in consultancy. Today many consultancy organizations are manned by engineers, but they perform mundane jobs using mundane knowledge bases. There are hardly any engineering-science based consultancy services in the country. We will have to develop strong capabilities in this area.

Today not only is it important to have interdisciplinary interactions with other scientific disciplines such as physics, chemistry, biology, etc. but interactions between different engineering disciplines also become crucial. Thus the problem of particle capture studied by chemical engineers as an exercise in particle fluid mechanics has far-reaching implications in setting up microelectronics laboratories of Class 1000! The understanding of dynamics of nonlinear systems, control, chaos, etc. reached by electrical engineers is far ahead of that of chemical engineers—and yet the chemical engineers keep on rediscovering what the electrical engineers have found two or three decades ago! Similarly the level of sophistication of modelling on aeration through in-depth convective diffusion models reached by chemical engineers is far superior to that evident in the civil engineering science literature. A closer awareness between developments in each others' field is thus very crucial.

We have suffered from isolation in the past in a broader sense. We have not learned lessons from non-civilian sectors that can be used in civilian sectors and vice versa. For instance, we have used high technology in space, defence and atomic energy. Especially important is the fact that systems engineering has been used effectively to accomplish tasks. However, neither this sophistication in high technology nor in the systems engineering approach has been used in the civilian sectors to create products based on new innovations. The spin-offs from product research in space, atomic energy and defence have been known to give rise to new industrial endeavours all around the world but this has hardly happened in India. Part of the reason, of course, is the fact that if a technology developed in a protected sector has to be truly successful in the open civilian sector, then it must stand on its own merit w.r.t. the production costs etc. Technological innovativeness, judged in an everchanging global market situation, is a different game altogether. Therefore, the industry, which takes up such technological spin offs has the task of continuous upgrading—something that our industry has failed to do so far. Again, we need to change this situation.

As a further extension to this thought of removing the isolation, it is also important to utilize the high level of expertise in engineering that exists in the non-civilian sectors for tasks in civilian sectors. I personally realized these strengths, when I recently headed the inquiry committee to investigate the accident in the giant Maharashtra Gas Cracker Complex. The inputs provided in mechanical, chemical and materials engineering by laboratories under Atomic Energy Commission were world class. It seems that we do have the capability, the challenge is in putting it together to accomplish a mission or a task.

Funding engineering science research

Over the years engineering science research has received a moderate support in India. Thus, the Ministry of Human Resource and Development (MHRD) had identified thrust areas in emerging technologies and tried to help in the creation of infrastructure in some areas. Rs 108 crores were allocated by MHRD during 1985–90 to support higher technical education in 52 different areas. A greater degree of scrutiny and prioritization will, of course, help enormously, when such funding is given. Similarly support given by UGC through the COSIST programmes has also been helpful. CSIR itself supports engineering science research through its own laboratories and also through the extramural support it provides.

As far as identification and promotion of engineering science activity is concerned, the Department of Science and Technology (DST) has played a major role through its Science and Engineering Research Council (SERC). The identification of thrust areas in engineering science done periodically since 1975 has set the trends on R&D funding in this area. The famous 'Baroda Seminars' have helped in identifying different thrust areas. Support in diverse areas of engineering science such as chemical engineering, electricity and power, electronics and communications, energy, materials, mining and mineral engineering, etc. has been given. DST has not only supported engineering science activities, but has also, over the years, brought in industry, the universities and IITs together towards a common goal. If one looks at the discipline-wise breakup of SERC funding for chemical sciences, life sciences, physical sciences and engineering sciences, then the percentage of funds for engineering science has fluctuated from 16% (during 1975–80), 8% (during 1980–85) to 24% (during 1985–90). This support has to be seen in a context. Thus during 1985–90, the total outlay on S&T was about Rs 5000 crores. SERC had about 1.4% share of it and a small but reasonable fraction (in real terms about Rs 12 crores) was given to engineering sciences. SERC thus has had a small share in supporting engineering science but it is fair to say that it has indeed played a very crucial catalytic role.

Our strategy on funding engineering science research in the future will have to change. The government will have to increase its funding levels several folds since engineering research is expensive. However, the industry participation will have to be vigorous too. Therefore even when the government is funding research the 'end-to-end projects' will have to be given preference. Furthermore in many frontline areas, it is the government that is initiating action (the fibres and composites programme of DST, which is a good success story is a typical example). However, in many areas industry also will have to initiate research and the government will have to provide complimentary funding.

There has to be a clear understanding about the role of the government and the role of the industry in supporting engineering science. It is obvious that national test facilities such as steam test facility, machinery noise test facility, water tunnel, wind tunnel, bearing test facility, etc. would not be set up by industry and the government will have to inject funds in such activities. However, the commitment of the industry to use all such massive infrastructure set up by the government will have to be ensured on a formal cost sharing basis.

Although the role of the government in supporting R&D is undisputed, it must be realized that it is the industry that must make major and aggressive investments in R&D as we draw close to the year 2000. Referring specifically to support for engineering science research, one would have hoped that the Indian engineering industry would strongly support this. The real picture of such support from the leaders in Indian engineering industry makes dismal reading. The recent annual report (1991–92) of DSIR shows the following figures (turnover/R&D expenses) for the year 1991–92. TELCO (3100 crores/13.5 crores), TISCO (2900 crores/6.00 crores), L&T (1780 crores/5.9 crores), Escorts (1223 crores/2.7 crores), Mahindra and Mahindra (1166 crores/2.8 crores), etc. are the companies that lead the engineering industry in terms of production, but their R&D investments range from a meagre 0.2% to 0.4% of their sales turnover. In areas where we have world leadership in manufacturing, our R&D inputs are miniscule. For instance, we referred to the fact that we are one of the largest manufacturers of bicycles and sewing machines in the world. It is amazing to see that the total expenses on the bicycles and sewing machines R&D centre were about 84 lakhs in 1991–92! Without a greater commitment to R&D by the engineering industry, we have no hope of surviving in an internationally competitive environment.

Although the economy has opened up, it will be several years before the real results of this opening up will be visible. Our industry, so much used to a noncompetitive environment, cannot be suddenly expected to make massive investments in R&D. The government will thus continue to play a crucial role in supporting and promoting R&D in the coming decade. The government must, therefore, increase its contribution significantly in the 'interim' period. The total R&D expenditure should progressively rise to about 2% of GNP by the year 2000 and at least 25% of it must go in the support of engineering science research. Out of this, at least 50% to 60% must be contributed by the Indian industry.

If the level of commitment in R&D is stepped up progressively, if our societal and industrial aspirations are clearly understood, if we are able to prioritise and perform to time targets, then we see no reason why India cannot be at the top of the ladder among industrialized nations.

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