

# EDUCATION FOR A NEW ENVIRONMENT: BIOMEDICAL ENGINEERING\*

RICHARD C. SEAGRAVE

*Iowa State University*

*Ames, Iowa*

## INTRODUCTION

During the last third of the twentieth century, engineers will become increasingly involved in two relatively new phenomena of enormous social, scientific, and economic consequence. **The first of these phenomena, increasingly evident in recent years, is the emergence of the interdisciplinary approach—the exploitation of historically separated talents to solve new problems.** Whereas the major scientific and engineering advances of this and the previous century have been wrought by intradisciplinarians such as Planck, Einstein, Gibbs, Westinghouse, and von Karman, the increasing complexity and communication capability inherent in the modern world is thrusting together scientists, engineers, and many other practitioners of widely varying professional and disciplinary training, making in many cases strange bedfellows by necessity, and reuniting in some cases disciplines separated since the 19th century. The emergence of entirely new areas of activity are becoming almost an annual phenomenon, and while perhaps the lifetimes and eventual relevance of many of these new activities may still be in doubt, it is becoming more obvious that the engineer and scientist of tomorrow will to an increasing degree be an interdisciplinarian in his professional activities. While the need for rigorously trained specialists in very narrow disciplines will undoubtedly continue, the important scientific discoveries and engineering developments of social significance in the next 30 years will most probably be affected by teams of interdisciplinarians rather than by teams within existing disciplines or by individuals.

**The second, and probably the more significant phenomena, is the invasion by the engineer, with his tools and talents, of hostile and unexplored environments.** During this century, we have for the most part carried out our activities at a

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Richard C. Seagrave received his BS in ChE from the University of Rhode Island in 1957, and his PhD from Iowa State University in 1961. After four years on the faculty of the ChE Laboratory at Cal Tech, he joined the faculty at Iowa State as an associate professor with a joint appointment in Chemical Engineering and Biomedical Engineering. His research interests have been in the areas of transport phenomena in flow systems, and in the simulation of chemical reactor systems. He is currently directing research in these areas, and participating in the research and teaching activities of the Biomedical Engineering program at Iowa State.

macroscopic level on the surface of the earth, concerning ourselves with ideal gases and Newtonian fluids, dealing with the corrosive effects of our relatively friendly atmosphere, and to a large degree extrapolating and interpolating the efforts of our ingenious professional predecessors. Certainly the engineer has made enormous contributions to the welfare of his fellow man, although as we look into the atmospheres near our large cities, to our stockpiles of incredible weaponry, and to our highway systems, we occasionally notice some interesting and somewhat worrisome side effects of our rampant and fulminating technology. Here at the two-thirds point in this century, we now find ourselves, as a consequence of these advances in science and technology, stimulated by a myriad of political, social, and economic factors, on the thresholds of entirely new environments, for which we possess the tools and capabilities of entrance. The foremost examples are those of the reaches of interplanetary space and the unexplored and unexploited depths of the oceans. *But perhaps the most interesting of these new environments, the most hostile, the most complicated, the most studied and the least understood, and the one most urgently calling for engineering attention, is the environment found within the human body.* The popular press, as well as the

technical press, bears daily witness to the impact that cooperative efforts between engineers and physicians will have on our lives in the future.

**The problems faced on entering this new environment are formidable indeed, and they require the fervent cooperative efforts of the life scientist, the physical scientist, and the engineer, not to mention the lawyer and the theologian.**

### **Biomedical Engineering**

*It has often been observed that prior to the middle of the 19th century there was little to distinguish the methodology of the physical scientist and that of the life scientist. The landmark efforts of the French physician Poiseuille concerning the flow of blood in capillaries, resulting in a basic engineering equation, is a good example of the quantitative approach employed by life scientists at that time. When the hyper-complexity of living systems became increasingly apparent due to the development of better observational tools, the life scientist by necessity chose to resort to a more qualitative or descriptive approach, while the physical scientists continued along more quantitative or analytical paths, concerning themselves with simpler systems. In recent years, we have witnessed the slow but steady re-convergence of the methodologies, and once again life scientists are employing quantitative techniques based on a growing understanding of the physical and chemical processes which take place in living systems. The physical scientist, in turn, is extending his quantitative and analytical methods to the study of more complicated systems.*

Meanwhile, the engineer, born of the needs of society to translate the results of the physical sciences into practical terms, has also been historically separated from the life scientist and his counterpart "engineer", the physician. As the sophistication of both of these professions has increased, as major developments in techniques of instrumentation and fabrication of materials have been made, and as the needs of an educated and complex society have mushroomed, communication between the disciplines has increased, and cooperative interdisciplinary programs have appeared worldwide, to the point where new educational and research programs bearing names such as "Biomedical Engineering" are currently being developed on many campuses across the country and indeed around the world.

*I submit that no discipline or profession is better equipped to promote this reunion and this entry into a new environment for engineering, and to indeed benefit from it, than is chemical engineering. The chemical engineer was the first truly interdisciplinary engineer. He combines an engineering mentality and training with the pure sciences of chemistry and physics, and out of necessity has had to be conversant with the other "lesser species" of engineer as well as with the physical scientist. Many of us now believe that the chemical engineer can, and in fact must, become equally involved in the life sciences and their engineering application, and in fact is splendidly prepared to do so. It comes as no surprise to a chemical engineer, for instance, that examples of almost every classical unit operation can be found within the confines of the human body. The applications of chemical engineering thermodynamics and transport phenomena in the study of physiology and in the design and operation of artificial organs are legion. The concept of the body as a mobile, reproducible aggregation of isothermal chemical plants has a validity far beyond that of a tongue-in-cheek lecture device.*

I hasten to point out that while the chemical engineering principles required for the design and operation of artificial organs encompasses almost the entire breadth of our training, the converse is of course not nearly true. That is, the breadth of our training naturally falls far short of the skills and background that are required for the design of such devices. We must not only rely heavily on communication with our colleagues who are experts in the environment, but we must also be prepared to speak an entirely new language. We must be prepared to hold our patience when encountering the maddening maze of descriptive jargon which we would instinctively replace with equations and graphs. And finally, we must also be prepared to play "second fiddle" in many respects to those who must bear the public responsibility for our joint efforts. But above all, we must be expert chemical engineers. We must be strong enough in our parent discipline, interdisciplinary as it is, to become an expert member of a team possessing a myriad of skills, and to be able to make unique and sound engineering contributions. This is perhaps the most important part of this discussion. It is vitally important for us to realize that chemical engineering can be broad enough in its content to accomplish this.

There are few things more personally distressing to me than hearing that a graduate chemical engineer has decided to go to medical school. Although a chemical engineering background is excellent preparation for a professional medical education, it appears to me that the real contributions in this new arena of interdisciplinary activity will be made by experts who can communicate, and who can understand the environment, rather than by people with piecemeal or hodgepodge training who are likely to be masters of no trade. The standard medical school program represents an extraordinarily inefficient and time consuming way for a graduate engineer, with six or eight years already invested in his professional education, to learn to communicate and to understand the environment. However, there is another factor at work here. *There unfortunately exists in many of us a professional "second class citizenship" mentality which makes many feel that somehow an engineer is professionally inferior to a physician.* This is undoubtedly stimulated somewhat by the enormous difference in mean income, and by consequences arising from the fact that a physician's effectiveness is often critically dependent on his public image. Any fair comparison of a graduate program in engineering and the program of studies leading to an MD degree should quickly modify this image problem. While the MD usually interacts directly with his "customer" and hence bears a special kind of responsibility the engineer while usually operating behind the scenes, bears a different kind of responsibility and by no means has to be considered as a "second class citizen" on the team.

#### **Education for Biomedical Activities**

At this juncture we should consider some facets of the education and training which would be desirable for a chemical engineer who wants to participate in biomedical activities during his professional life. While we cannot anticipate all of the developments and discoveries of the next thirty years, there does appear a fair number of guideposts in the form of current research problems to indicate the direction in which we need to move.

If we look at the current research areas at the interface between engineering and medicine, the single and most immediate deficiency that we seem to face is the need for new materials suitable for use in this new environment. For exam-

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ple, about 5000 people per year in the United States need to have part of their face removed, either as the result of injury or disease. At the present time no completely suitable material for facial prostheses exists which meets the structural, mechanical, biological, and cosmetic requirements of this application. The search for biologically suitable materials for many similar applications has proceeded along very empirical lines. Most probably, this search process has been duplicated for many other engineering and processing problems. One gets the feeling that somewhere a tremendous amount of technological information about materials must be accumulating. The person that many feel should be aware of and familiar with this technological information, and who should be able to produce or predict these results, is the chemical engineer. We somehow need to increase the emphasis in our curricula on problems of materials — possibly as a start at the graduate level — and to develop some understanding and appreciation in our students of problems in this vitally important area.

**We easily could, and certainly should, spice our regular undergraduate and graduate coursework with selected examples and problems of a biomedical nature. For example, let the thermo student compute how long it takes to freeze to death, or explain why fever must accompany chills. Let the unit operations student compute how much area is needed in the blood oxygenator or in an artificial kidney. Our sophomores could perform their material balance calculations on the lung and the kidney.** We need to convince our students (it won't be difficult) that the application of chemical engineering principles in the body are often quite interesting and easily understandable. The necessary qualitative and descriptive material, once the physical and chemical principles are understood, can be picked up quite easily. I hasten to point out that at this level only enough understanding of the living system to remove fear and stimulate interest is required, and the student should be made to realize the degree of the oversimplification with which he is presented. There is certainly good precedent for this pedagogical trick in chemical engineering education.

In the study of simulation and process con-

trol, there are many good examples and applications in the body which chemical engineering students would find challenging and interesting. The student can undoubtedly feel more personally involved in a problem of respiratory feedback control than in a constructed problem involving some hypothetical process.

*In the study of typical chemical processes or of the process industries, we might include selected topics such as the artificial kidney to illustrate the application of chemical separation techniques in a fascinating context. I know of at least one chemical engineering department which devoted an entire one term course in the sophomore year to this topic as a means of introducing chemical engineering.*

What I am saying is that to a large degree our present curricula, inoculated with a medium of selected examples, represents an excellent technical preparation for further interdisciplinary study. One of the fringe benefits of such a strategy might be an improvement in the public image of our curricula. **Chemical engineers, like all engineers, suffer somewhat these days from a public relations problem.** This is continually manifested by the problem of stagnating engineering enrollments, and by the fact that recognition of or acknowledgement for engineering accomplishment is rare in the public press. If we could demonstrate that our professional curricula contains considerations of these apparently more relevant aspects, perhaps our role would become more fully realized and even appreciated. Of course, we should continually stress the relevance of the things we study to all aspects of modern technology, as well as to the area of biomedicine.

#### Some R and D Problems

Perhaps some examples of current research and development problems in which chemical engineers are participating could serve to illustrate this point. These examples have been selected with no particular criteria except as interesting examples involving among other things direct application of principles presented in undergraduate chemical engineering curricula.

*The problem of carefully heating a premature infant that has underdeveloped thermal auto-regulation is a complicated heat transfer and control problem involving all three classical modes of heat transfer as well as elements of some rather sophisticated control system. Cur-*

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rent research on this problem involves measurement of the newborn's skin temperature in the period shortly following delivery. A simple energy balance computation will show that a nude, wet newborn will lose 2 degrees of body temperature per minute unless preventive measures are taken to drastically reduce thermal losses.

Another interesting heat transfer problem involves the apparent use by the body of a countercurrent heat exchanger using facial venous blood to control the temperature of arterial blood leading to the brain, and hence the operating temperature of the brain. **The brain produces 15% of the body's total heat yet while it is encased in a thick skull covered with hair, it apparently operates nearly isothermally under wide environmental conditions.** Current research involves temperature and flow rate measurements around the heat exchanger in the nose and facial regions of dogs and horses to determine the actual operating characteristics of the heat exchange system.

Increased mass transfer efficiency of devices such as the artificial kidney and the membrane blood oxygenator continues to be a subject of much attention among biomedical engineers. More recently, efforts are being extended to the development of miniature oxygenators suitable for pediatric use in the treatment of cardiac and respiratory disorders in newborns. The delicate physical and chemical nature of the working fluid and the difficult fluid mechanics problem of forming stable thin flowing films continues to impede development in this area.

The transient relationships between pressure, volume, flow, and compliance in the extracorporeal space during heart-lung bypass procedures is an interesting problem involving elements of fluid mechanics and process control. **The changes which occur in the vascular system during surgery have a complicated and profound effect on the distribution of blood inside and outside of the subject, and on the "holdup" in the bypass system.** Current research on this problem is directed to determine the effects of various drugs used during surgery on the operation of the bypass system to optimize the blood distribution in the system.

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The problem of optimally managing subjects during post-operative recovery can be aided by knowledge of the material and energy balance relationships in effect. Work is being done to develop instrumentation and computational procedures to aid in gathering this type of data.

A classical problem involving many elements of chemical engineering is the simulation of the behavior of the human respiratory system during obstructive lung disorders or circulatory abnormalities. The system of equations required to describe this situation represents a challenging problem which when solved can hopefully be used to provide insight for the clinician as well as the physiologist. Current research in this area is directed to developing models which can account for the variations in the mass transfer capability at the blood-gas interface as well as mis-matching of the streams due to flow anomalies.

#### Educational Trends

One of the trends that seems to be evident is that following the experiences of our colleagues in electrical engineering, our activities are going to become increasingly more microscopic. That is, we will spend a higher and higher percentage of our time dealing with systems and with problems which are related to smaller and smaller spaces, and as a consequence, we must continue to insure that our students are exposed to the physical and chemical principles which can be used to describe these systems.

The most important of our educational tasks, however, in my opinion, is one that we often overlook. It is especially critical with regard to this new environment which we have been discussing. We need to instill and to develop in our students and in our graduates some feelings about the social responsibilities of an engineer. As indicated earlier, we need only look around us to realize how delinquent we as a group have been in providing the social leadership necessary for the balanced good of society. **The concept of an engineer as a technical member of a team who produces a service for a fee without regard for its social or moral consequences is outmoded.** Engineers must provide leadership in this area, and the field of interaction between engineering

and medicine is presently crying out for such leadership. Few professional people who have the influence required to control the course of things are presently concerned with the overall impact on our society that unbridled advances in areas such as artificial organ technology will have. We can see around us — too late in many cases — the undesirable side effects which could have been avoided by a combination of engineering and social concern. The overdevelopment of the American automobile is perhaps the clearest (or most obvious to our senses) on a smoggy day. Somehow we need to educate the chemical engineers of tomorrow in an atmosphere that promotes the consideration of responsibility to society before the fact, instead of after.

#### Conclusions

In summary, the following points have been offered.

- Advances in science and technology along with an increased awareness among scientists and engineers of their mutual needs and similarities have stimulated the phenomena of the interdisciplinary team.

- Engineers are concerning themselves with new and unexplored environments, a notable example being living systems, particularly the human body.

- It is important to realize that a chemical engineering background is well suited for many current problems in biomedicine.

- Chemical engineers working in this area must maintain their identity, and in fact must be unusually well grounded in chemical engineering principles to make maximum contribution. It is probably inefficient to undertake a formal educational professional program in the life sciences.

- The problem of finding suitable materials for biomedical applications is presently critical, and represents a logical stamping ground for chemical engineers.

- Examples of current research problems in medical areas involving chemical engineering demonstrate interesting applications of principles presented in undergraduate chemical engineering curricula.

- Chemical engineering education can exploit these new phenomena by making curricula more attractive and more relevant. By spicing fundamental courses with problems and examples taken from physiology and medicine the student can become more conscious of the breadth of chemical engineering.

- It appears that our activities will become increasingly more microscopic, and we need to insure that our future students can continue to handle these new and smaller systems.

- We somehow need to give our students more appreciation of the social responsibilities of an engineer, so that they can provide leadership in many of the complex situations of the future, which will continue to evolve from these interfacial activities, and expanding technology, and the exploration and exploitation of new environments.