Chapter 14

Personnel Availability and Training

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Introduction

Adequately trained scientific and technical personnel are vital to industrial competitiveness in biotechnology. Countries lacking highly skilled personnel cannot have companies that compete internationally in highly technical operations such as the design and manufacture of a computer-controlled bioreactor, the discovery of a new biochemical pathway for the production of a specialty chemical, or the development of a microorganism that produces a desired protein.

An important factor in the success of companies attempting to commercialize biotechnology is the degree of sophistication of their research and development (R&D) personnel with respect to state-of-the-art developments in the field. Despite the fact that there is no "typical" firm or organizational structure among the firms using biotechnology, most corporate activity in new biotechnology at present is dedicated to R&D.* Thus, for example, a July 1982 report on a survey of California firms using new biotechnology estimated that 63 percent of the employees in these companies were professional and technical personnel involved in R&D (11).** The other employees were clerical workers (17 percent), managers (15 percent), and floor-level production and maintenance workers (5 percent).

An indication that the commercial development of biotechnology is highly dependent on skilled personnel is the fact that companies are offering special inducements to highly qualified personnel. Many companies have given their scientists and engineers considerable freedom with respect to the pace and direction of their work. U.S. firms using biotechnology stress the independence and flexibility of the work environment in order to attract qualified personnel from academic environments (11). In Japan, companies that persuade Japanese doing academic research abroad to return promise them a flexible research environment (35).

As background for the analysis that follows, the first section of this chapter discusses the quantity and types of scientific and technical personnel needed for the commercial development of biotechnology. The second section compares and contrasts the availability of especially important categories of personnel in the United States and four other countries commercializing biotechnology—Japan, the Federal Republic of Germany, United Kingdom, and France—while the third section compares the training systems in biotechnology-related areas in these countries. Also presented is the information that is available on Switzerland. In the concluding section, congressional issues and policy options with respect to the training and retraining of U.S. personnel in biotechnology are outlined. Because the amount of government funding of specific research areas can attract or discourage students from entering those areas, the reader may wish to review *Chapter 13: Government Funding of Basic and Applied Research*.

*See *Chapter 4: Firms Commercializing Biotechnology* for a description of the firms involved in the development of biotechnology in the United States and other countries.

**This survey identified 50 companies and interviewed a simple random sample of 10 firms (20 percent). All were new biotechnology firms, as defined in *Chapter 4: Firms Commercializing Biotechnology*. The survey's definition of biotechnology was "the use of living organisms or their components in industrial processes."

Size and future growth of the biotechnology labor force

It is very difficult to estimate the size of the biotechnology labor force, Theoretically, the number of personnel in supply and technological support firms, which is approximately four to five times that of firms commercializing biotechnology (11), should be included in the estimate. This chapter, however, focuses exclusively on the personnel requirements for professional and technical personnel of firms commercializing biotechnology. It does not consider the requirements of supply and technological support firms, the vast majority of which market products not only to companies commercializing biotechnology but to other companies as well.

A July 1982 report estimated total U.S. private sector employment in "synthetic genetics" to be 3,278, * including about 2,000 "professional and technical" employees (1 1). The same report estimated that U.S. private sector employment in "synthetic genetics" had grown at a rate of 54 percent annually since 1976 and projected that total employment would reach about 40,000 in 1992.

OTA estimates that about 5,000 employees are employed by companies in the United States in biotechnology R&D. In April 1983, OTA and the National Academy of Sciences (NAS)* * conducted a survey to determine the personnel needs in biotechnology of companies in the United States. The questionnaire, reproduced in ***Appendix E: OTA/NAS Survey of Personnel Needs of Firms in the United States,*** was sent to **286** companies. of the 133 that responded, 18 indicated that they were not engaged in biotechnology activities, and 20 others were determined not to be engaged in biotechnology activities from their answers to the questionnaire. To estimate the total number of firms engaged in biotechnology in the United States, OTA determined which of the 153 nonresponding companies were engaged in biotechnology by telephoning the companies, examining annual reports, reading newspaper reports, etc. OTA's estimate of the total number of companies engaged in biotechnology activities in the United States is 219. *

As of April 1983, the 95 companies that responded to the OTA/NAS survey employed 2,591 individuals in industrial biotechnology R&I). These 95 firms represent 43 percent of the 219 firms in the United States estimated to be engaged in biotechnology activity. Extrapolation of this number suggests that the number of individuals employed in biotechnology R&D in all 219 companies using biotechnology could be about 5,000.

The 95 firms that responded to the survey indicated plans to hire an additional 1,167 technically trained employees over the next 18 months.** No company indicated plans to reduce the number of technically trained employees in the next 18 months, so this figure represents an annual employment growth rate approaching 30 percent (not including any new companies formed in the next 18 months). A 30-percent annual growth rate in the number of R&D personnel probably will not be sustained over any length of time, so it is unlikely that the commercialization of biotechnology will lead directly to large increases in employment in the R&D sector. The need for marketing and sales personnel and the potential for spinoff industries are difficult to assess at this time. However, these sectors could be high-growth sectors for biotechnology.

"This number was arrived at by taking estimates of total worldwide shipment of biotechnology products estimated for the target year from OTA's 1981 report *Impacts of Applied Genetics: ,} Micro-Organisms, Plants, and Animals* (40). This estimate was converted to employment of production workers by using case study data from the same OTA report, Next, this estimate was converted into total employment, including nonproduct ion workers, by utilizing data for established industries Finally, total worldwide employment was subdivided and a weighted allocation made to the United States

**NAS Committee on National Needs for Biomedical and Behavioral Research Personnel; Robert Barker, Cornell University, Chair of Panel on Basic Biomedical Personnel

*For a list of companies engaged in biotechnology in the United States, see *Appendix D: Index of Firms Commercializing Biotechnology in the United States*

**For a tabulation of the numbers and types of employees these companies indicated they planned to hire, see question 4 in *Appendix E OTA/NAS Survey of Personnel Needs of Firms in the United States*

One reason that commercialization of biotechnology will not directly contribute to a rapidly expanding U.S. work force is that bioprocess technology is not labor intensive (11).* It is estimated that personnel requirements for bioprocessing, even after firms enter mass production, will be only 10 to 15 percent of the total biotechnology work force. Furthermore, with more sophisticated, computer-controlled continuous bioprocesses, the labor intensity of bioprocesses could decrease (11).

*Feldman cites a 1980 report by the National Institute for Occupational Safety and Health (NIOSH) in which NIOSH reported on a Schering-Plough (US) process for producing human leukocyte interferon. Only six people were assigned to production, and probably all six were not needed to monitor the bioprocess (11).

The demands for biotechnology R&D personnel are estimated to be fairly small in foreign country calculations as well. Britain's Royal Society has estimated that about 100 graduate biotechnologists per year will be needed over the next 10 years to commercialize biotechnology in the United Kingdom; about four times that number of technicians and technical support staff will be needed (45). The French Biotechnology Commission has forecast a need for about 1,830 researchers and engineers in biotechnology in France over the next 5 years (44).

Availability of biotechnology personnel

Categories of technical expertise

The industrial development of biotechnology will require several specific categories of technical personnel, many of which are listed in *Appendix E: OTA/NAS Survey of Personnel Needs of Firms in the United States.* Especially important categories include specialists in genetic manipulation such as molecular biologists and immunologists, specialists in scale-up and downstream processing such as bioprocess engineers, biochemists, and microbiologists. Generalizations with regard to the relative importance of these various categories of technical specialization in the development of biotechnology can be drawn from the responses of the 95 companies that responded to the OTA/NAS survey.

SPECIALISTS IN GENETIC MANIPULATION: MOLECULAR BIOLOGISTS AND IMMUNOLOGISTS

The development of hybridoma and recombinant DNA (rDNA) technologies brought molecular biology into the marketplace. A sufficient supply of molecular biologists and immunologists who are specialists in genetic manipulation has been critical to the development of corporate biotechnology R&D in the United States. As shown in table 62, about one-third of the technical personnel employed by the 95 companies responding to the OTA/NAS survey are specialists in rDNA/molecular genetics or hybridoma/monoclonal antibody (MAb) technology (there are twice as many specialists in rDNA as in hybridoma technology). These specialists in genetic manipulation are expected to become increasingly important in the next 18 months, constituting 37 percent of new hirees.

Most molecular biologists trained in the United States at present are specialists in animal molecular biology. The development of agricultural applications of biotechnology will require specialists in plant molecular biology with knowledge of both plant physiology and molecular genetics. According to the OTA/NAS survey, specialists in plant molecular biology currently constitute only 3 percent of the U.S. biotechnology R&D labor force and will constitute 5 percent of all new hirees in biotechnology in the next 18 months.

SPECIALISTS IN SCALE-UP AND DOWNSTREAM PROCESSING: BIOPROCESS ENGINEERS, BIOCHEMISTS, AND MICROBIOLOGISTS

Specialists in scaling-up the production of genetically manipulated micro-organisms (and higher organism cells) and in separation and purification

Table 62.—Major Categories of Biotechnology R&D Personnel in Firms in the United States (OTA/NAS Survey)

Area of technical expertise	Present employees: Number	Present employees: Percent of total[a]	Employees to be hired in the next 18 months: Number	Employees to be hired in the next 18 months: Percent of total[a]
Areas related to genetic manipulation:				
rDNA/molecular genetics	586	23%	302	25%
Hybridoma/monoclinal antibodies	247	10	146	12
Plant molecular biology	76	3	63	5
Areas related to scale. up/downstream processing:				
Microbiology[b]	**334**	**13**	160	13
Biochemistry[c]	**326**	**13**	125	10
Bioprocess engineering	**186**	**7**	100	8
Areas related to ***all*** aspects *of* biotechnology:				
Enzymology/immobilized systems	**219**	9	59	5
Cell culture	**187**	7	66	5

[a]The total number of industrial personnel (currently engaged in R&D in new biotechnology) identified in the OTA/NAS survey was 2,591, The total number Of personnel to be hired in the next 18 months, according to the survey responses, was 1,167 (see app. E)
[b]Microbiology, as used in this table, combines the OTA/NAS survey responses to industrial microbiology and general microbiology (categories g and s of the survey questionnaire reproduced in app E)
[c]Biochemistry as used in this table combines the OTA/NAS survey responses to analytical biochemistry and general biochemistry (categories j and k of survey questionnaire reproduced in app E)

SOURCE Office of Technology Assessment

of products will become increasingly important as companies developing commercial applications of biotechnology move into production. Although few companies have reached the scale-up stage for new biotechnology products to date, * a substantial amount of R&D in companies developing commercial applications of biotechnology is related to scale-up,

As shown in table 62, about one-third of the biotechnology R&D technical personnel at the 95 companies responding to the OTA / NAS survey are specialists in areas related primarily to scale-up and downstream processing: bioprocess engineering, biochemistry, and microbiology. Bioprocess engineers are needed to design, construct, and maintain scale-up equipment and bioprocesses. Biochemists (apart from enzymologists, discussed below) are involved in the recovery, purification, and quality control of protein products. Microbiologists are needed for the isolation, screening, and selection of micro-organisms having particular catalytic properties. Such specialists are also needed to determine the optimal growth and production conditions for micro-organisms in order to facilitate the design of environments that maximize the micro-organisms' productivity, In the context of the commercialization of biotechnology, bioprocess engineering, biochemistry, and microbiology are generally considered to be more applied science disciplines than are molecular biology and immunology.

As shown in table 62, the OTA / NAS survey of firms in the United States found that bioprocess engineers constitute approximately 7 percent of the current biotechnology R&D work force and will constitute 8 percent of all new hirees over the next 18 months. Specialists in microbiology constitute 13 percent of current employees and 13 percent of the employees to be hired in the next 18 months. Biochemists constitute 13 percent of current employees and will constitute 10 percent of new hirees in the next 18 months.

SPECIALISTS IN ALL ASPECTS OF BIOTECHNOLOGY: ENZYMOLOGISTS AND CELL CULTURE SPECIALISTS

Enzymologists and cell culture specialists are important for many aspects of biotechnology. Advances in the understanding of enzyme structure and function are important in developing the potential of biocatalyst for product formation. Cell culture is used at early R&D stages, but it is becoming increasingly important for the large-scale growth of higher organism cells, especially hybridomas. As shown in table 62, according to the OTA / NAS survey, enzymologists constitute 9 percent of current biotechnology employment in R&D; cell culture specialists constitute 7 percent

*In 1982, about 2 percent of all biotechnology workers in California were production workers (11).

of current biotechnology employment. Both categories of specialists constitute a smaller fraction of future biotechnology hirees (5 percent each) than they do of current employees.

Availability of biotechnology personnel in the United States

Of the countries studied, the United States has the largest number of specialists in genetic manipulation. The large supply of well-trained molecular biologists and immunologists in the United States is one reason for the rush of small company startups and the initial American lead in biotechnology. A primary reason for the large number of basic life science specialists in the United States is that for the past three decades, there has been substantial support from the U.S. Government, primarily from the National Institutes of Health (NIH), of basic research in the life sciences (26). In 1978, for instance, while the governments of most other developed countries were putting 2 to 4 percent of their R&D expenditures into health-related basic research, the United States was putting 11 percent of a much larger R&D base into health research (26). U.S. Government funds have strengthened the foundation of basic life science research, produced trained graduates, and generated an infrastructure for U.S. industrial growth in molecular biology (12). The dominance of the United States in the life sciences is supported by scientific and technical article publishing data. In 1979, U.S. authors published 40 percent of the world's articles in biology and 43 percent of the world's articles in biomedicine (26).

The results of the OTA/NAS survey of U.S. industrial biotechnology personnel needs reflect, with few exceptions, the United States' abundance of personnel trained in basic biological science. Relatively few of the 95 companies responding to the survey indicated that they were experiencing shortages of biochemists, pharmacologists, and toxicologists, who will be needed for the purification, recovery, and testing of biotechnology products. Furthermore, relatively few companies cited shortages of personnel in the areas of hybridoma and cell fusion technology.*

*For a tabulation of responses, see question 1 in *Appendix E: OTA/NAS Survey of Personnel Needs of Firms in the United States.*

Despite the abundance of personnel in the basic biological sciences in the United States, participants at two recent National Science Foundation (NSF) workshops* expressed concern that the United States currently may not have enough well-trained bioprocess engineers necessary for design and monitoring of biological scale-up processes (27). A shortage of highly trained bioprocess engineers in the United States, workshop participants suggested, could be a bottleneck to the rapid commercialization of biotechnology in the United States. The NSF workshop participants also pointed to an insufficient supply of industrial microbiologists. Between 1979 and 1981, the number of industrial microbiology positions listed in the United States nearly doubled, while the number of doctorates in "microbiology and bacteriology" has remained constant for the past 15 years (4). As shown in table 63, the results of the OTA/NAS survey also suggest that the United States may be experiencing shortages of bioprocess engineers: 11 of the 26 U.S. companies planning to hire Ph. D. bioprocess engineers in the next 18 months are experiencing shortages. The OTA/NAS survey results with respect to shortages of microbiologists are more equivocal.**

Shortages in bioprocess engineers, and possibly, industrial microbiologists, may be due in part to the fact that in the past three decades, there has been relatively less Federal support for applied microbiology, applied biochemistry, and bioprocess engineering research than for basic research in molecular biology, biochemistry, and immunology. Thus, university research activities have been guided by Federal funding toward basic biological research and away from these applied disciplines. The shortages may also reflect the fact that U.S. industrial support for university R&D in applied biology and bioprocess engineering has declined in the past three decades (12). After World War

*"Prospects for Biotechnology," University of Virginia, Apr. 5-6, 1982; "Developing the Biotechnology Component of Engineering," North Carolina Biotechnology Center, Apr. 24-25, 1983.

**Results concerning personnel shortages from the OTA/NAS survey are equivocal because the responses of the firms that indicated that they were not experiencing personnel shortages could indicate merely that the firms have not begun a search for personnel or instead indicate that they are not having any difficulty finding trained personnel. Furthermore, the 95 firms that responded to the survey represent less than half of the total number of companies commercializing biotechnology in the United States and may not be representative of the level of scale-up taking place as a whole.

Table 63.—Shortages in Major Categories of Ph. D. Biotechnology R&D Personnel in Firms in the United States (OTAINAS Survey)

Area of technical expertise (Ph. D.)	Number of firms: Experiencing shortages and plan to hire in the next 18 months	Experiencing shortages and do not plan to hire in the next 18 months	Not experiencing shortages but plan to hire in the next 18 months
Bioprocess engineering , ., . . .	11	1	15
Recombinant DNA	10	1	29
Gene synthesis	7	3	7
Plant molecular biology.	4	4	15
Industrial microbiology	3	4	**14**

SOURCE Office of Technology Assessment

II, U.S. chemical companies switched from biomass to petroleum feedstocks and consequently decreased their demand for bioprocess engineering and applied biology programs. Conditions in Japan, the Federal Republic of Germany, and the United Kingdom have differed markedly from those in the United States; in these countries, both public and industrial support have helped maintain a strong academic base for the microbial and bioprocess industries over the past several years (12).

The late David Perlmann wrote in 1973 (8):

> The interest in the U.S. has shifted in the past 20 Years toward molecular biology. Few students are being trained for the fermentation industries. In the long run, this has worked to the disadvantage of the industries. Unless present trends in the U.S. are reversed, we can expect that in the future it will be desirable to send our students to Japan to learn the techniques that will assure the continuation of the fermentation industries in the United States.

This situation does not appear to have changed much in the last 10 years.

The OTA/NAS survey also showed that 10 of 39 companies planning to hire Ph. D. specialists in rDNA in the next 18 months are experiencing shortages. Much of the R&D activity now in the commercialization of biotechnology is in this area, and, thus, the demand for these specialists is high. However, as companies move toward production, the demand for scale-up and downstream processing specialists will increase, while the demand for the more basic scientists will not. Thus, the current shortages of bioprocess engineers and industrial microbiologists are considered to be more serious.

The shortages in biotechnology personnel in the United States may be partially counteracted by a flow of skilled foreign personnel into the United States. * A representative of one U.S. company stated that of the company's R&D staff of 130, 13 were foreign nationals (9 Ph. D.s). The foreign nationals were from Taiwan, India, Canada, and Hong Kong, and had expertise in nucleotide chemistry, applied microbiology, and bioprocess engineering. U.S. companies using biotechnology might be hiring an even greater percentage of foreign technical personnel if cumbersome and strict immigration regulations did not exist.

Availability of biotechnology personnel in other countries

The number of scientists and engineers engaged in R&D activities in the United States, Japan, the Federal Republic of Germany, the United Kingdom, and France is shown in table 64. As can be seen from that table, in 1977, the United States had more R&D scientists and engineers than any of its principal competitors in biotechnology. Japan had the second largest number, with half that of the United States. The size of a country's R&D labor force is one measure of a nation's R&D capacity. It is only an approximate measure, however, because it does not take into account such factors as the level of sophistication or specialization, utilization, or productivity of a country's R&D personnel. Furthermore, these data cannot

*Reliance on foreign R&D personnel has been common in other U.S. high-technology industries. Many semiconductor and computer companies hire foreigners in order to compensate for shortages of U.S. electrical engineers. At [rite] (U.S.), for instance, 50 percent of the engineers holding M.S. degrees and 64 percent of the engineers with Ph. D.s are foreign (15).

Table 64.-Number of Scientists and Engineers Engaged in R&D by Country, 1977

Country	Number of scientists and engineers	Scientists and engineers as percentage of work force
United States	573,900	0.580/o
Japan	272,000	0.50
Federal Republic of Germany	111,000	0.44
United Kingdom.	80,700[a]	0.31
France	68,000	0.30

[a]1975

SOURCE National Science Foundation, Scierrce Indicators, 1990, Report of the National Science Board, Washington, DC , 1961

be dissected into the percentage of biological personnel.

There are few statistics documenting numbers of specific types of biotechnology personnel in countries other than the United States. For that reason, shortages and surpluses in foreign countries are difficult to identify. Nevertheless, distinct patterns with respect to the availability of biotechnology personnel in foreign countries can be discerned through an examination of available government policy documents and other supporting evidence.

JAPAN

Several experts noted that in the early 1980's, Japan experienced a shortage of experts in genetic manipulation. This shortage was undoubtedly due to the inadequacy of the basic biological sciences in the universities. * Japanese universities have received limited Government support for basic research, so most Japanese universities have not developed extensive research programs in the basic biological sciences. Japan's public universities have been a relatively minor source of highly trained personnel in rDNA and hybridoma techniques (35). Thus, Japanese companies have had to look to other sources of trained basic biological scientists. Some companies have started in-house training programs. Japanese companies have also hired Japanese researchers from abroad, sent employees to be trained abroad and at Japanese universities, and recruited midcareer researchers from other Japanese companies (35). The last option is particular unique for Japan, a country noted for a lack of personnel mobility. The extensive effort exhibited by Japanese companies seems to have overcome the personnel shortages documented a few years ago.

The supply of bioprocess engineers and industrial microbiologists is larger in Japan than in any of the competitor countries. Japanese Government officials monitoring biotechnology have indicated that the supply of personnel to handle the challenges of scale-up in Japan is not an area of concern (19)35). In fact, a major proportion of biotechnologists in Japan have their background in microbial physiology, an area of neglect in every country examined here except Japan (29).

The specialties of bioprocess engineering and industrial microbiology are strong in Japanese universities in part because the specialty chemical and other industries using traditional bioprocesses in Japan have kept the demand for graduates in these specialties high. After World War II, when chemical companies throughout the world largely switched to processes using petroleum feedstocks, Japanese chemical companies retained some processes using biomass feedstocks and came to dominate the international amino acid market. Furthermore, applied biology departments at Japanese universities have kept in close contact with industry representatives. Each year, 75 students in applied biochemistry graduate from Tokyo University alone; half go on to graduate studies, and half of these go beyond their M.S. degrees. Most are employed by Japan's leading bioprocess companies (35).

FEDERAL REPUBLIC OF GERMANY

The Federal Republic of Germany has sufficient personnel to compete with the United States and

“There is little communication between the basic and applied science departments in Japanese universities Only t he applied science departments have traditionally' maintained close relationships with industry, For a more extensive description of the Japanese university system and its relationship with industry, see *Chapter 17: University/Industry* ***Relationships*** other countries in biotechnology. It is possible that there are some shortages of molecular biologists with expertise in rDNA and hybridoma research. However, according to Norman Binder, the cabinet head of the German Ministry of Science and Technology (BMFT, Bundesministerium für Forschung und Technologie), the training of people in rDNA and hybridoma technology is now a high priority in West Germany (21).

The Federal Republic of Germany's supply of personnel in specialties related to scale-up and bioprocessing appears to be adequate. Like Japan, the Federal Republic of Germany maintained a steady supply of both industrial and government funding for applied microbiology and bioprocess engineering after World War II. According to BMFT, however, the number of both bioprocess engineers and industrial microbiologists in Japan surpasses the number in West Germany (21).

Like the United Kingdom (see below), the Federal Republic of Germany is concerned about a brain drain of biotechnology R&D personnel to other countries. According to the Max Planck Society's senate and the present Minister of Research and Technology, shortages of suitably qualified workers in West Germany are partially due to a brain drain to the United States (9,37). The brain drain of scientists from West Germany, however, appears to be less serious than that from the United Kingdom.

UNITED KINGDOM

Like the United States, the United Kingdom boasts both qualified personnel and excellent training and education programs for personnel in the basic life sciences. In the 1950's and 1960's, there was considerable expansion of basic life science research in British universities. By 1972-73, health-related R&D, supported mostly by the Medical Research Council (MRC), had risen to 5 percent of the British Government's R&D budget, nearly twice the percentage of Japan, the Federal Republic of Germany, or France (26).* MRC's past investment in biology is now paying off. Molecular biologists and immunologists supported by MRC are internationally prominent in the development of rDNA and hybridoma technologies. Nevertheless, there may be shortages of molecular biologists if the industrial development of biotechnology expands rapidly (2).

Like Japan and the Federal Republic of Germany, the United Kingdom has a good academic base for training bioprocess engineers. Nevertheless, the United Kingdom appears to be experiencing a shortage of bioprocess engineers (2). A brain drain from the United Kingdom is viewed as partially responsible for this shortage. Many British biotechnologists are leaving for the United States, Switzerland, and other countries of the European Economic Community, because sufficient posts do not exist in the United Kingdom at present and salaries in the United Kingdom are not competitive with those in other countries (45). When the Swiss company Biogen S.A.* advertised for 30 molecular biologists, half of the 600 applications they received were well-qualified British (45).

Analysts estimate that a total of between 100 and 1,500 experts in some aspect of biotechnology have left the United Kingdom over the past several years (30). Governmental institutions are taking active measures to counteract the brain drain. The Research Councils, the United Kingdom's public research institutes, have adopted an active policy of encouraging scientists from the United Kingdom who have spent time in industry abroad to return home. The Science and Engineering Research Council (SERC) maintains a list of British biotechnologists outside the United Kingdom and may be taking measures to encourage them to return (30), and MRC has announced publicly that it will provide laboratory space and allow reentry into the career structure without penalty for scientists who return to the United Kingdom (45).

SWITZERLAND

The access to distinctive universities and the high standard of living in Switzerland attract highly qualified personnel from around the world to participate in Swiss biotechnology. Although the availability of personnel may not be impor-

*Since 1973, Government expenditures in the United Kingdom for health-related research have dropped and are now equivalent to those of the other foreign countries studied here (26).

* Biogen S.A. is one of the tour principal operating subsidiaries of Biogen N.V., which is registered in the Netherlands Antilles. Biogen N.V. is about 80-percent U.S.-owned.

tant for the large pharmaceutical companies which conduct a large proportion of their R&D in other countries, it is crucial to the Swiss advancement of biotechnology in other sectors. The attraction of talent from other industrialized countries may help the competitive efforts of Swiss companies in biotechnology in the future.

FRANCE

France has a serious shortage of qualified personnel that could well undermine the country's basic and applied science base and prevent France and its industries from competing successfully in the world biotechnology marketplace. Specialists in the fields of general and industrial microbiology, rDNA and hybridoma technologies, enzymology, plant and animal cell culture, and bioprocess engineering are few (3). Although some French research centers boast internationally recognized teams, such as the enzymology and bioprocess technology teams at the technical University of Compiegne or the immunology groups at the Institut Pasteur (44), these are isolated clusters of expertise. Thus, France will have difficulty matching the total output of the large and balanced national research bases of other competitor countries.

The scarcity of personnel in France cuts across several sectors of R&D in these technologies and applies equally to different categories of personnel, from scientists and bioprocess engineers with advanced degrees to skilled laboratory and production technicians. In order to correct this situation, the French Government has given special attention to the education and training of qualified personnel. The research law passed in July of 1982 called for the active involvement in the educational process of public sector researchers outside universities (46). And the Programme Mobilisateur presents educational guidelines for all stages of schooling from secondary to postdoctoral levels, placing special emphasis on an interdisciplinary approach within the universities (24). The education of a specialist in rDNA technology, nonetheless, takes many years, as does the implementation of such training programs. As a short-term solution to its present lack of personnel, therefore, France imports foreign experts (24).

Personnel training

The availability of the scientific and technical personnel necessary for the commercialization of biotechnology is highly dependent on a country's educational infrastructure. The discussion here compares various aspects of training, all of which are important to the development of biotechnology: 1) secondary school education, 2) biotechnology-related undergraduate and graduate education, 3) transnational training opportunities, and 4) mid-career retraining opportunities.*

Secondary school education in the United States and other countries

Secondary school education in science and mathematics in the United States trails that in Japan and many European countries. High school students in Japan are required to complete 2 years of mathematics and 2 years of science before graduating (42). Secondary school students in many European countries, even students specializing in classics or languages, similarly get far more extensive training in mathematics and science than do students in the United States (6).

Several recent studies have identified a decline in the quality of science and mathematics education in U.S. secondary schools, attributing it to a lack of good teachers, instrumentation, Federal support, and local community support in the form of bonds and taxes (6,10,16,31,47). Furthermore, many leading scientists, engineers, and politicians in the United States fear that the decline is leading the United States to become a nation of technological illiterates and is compromising the U.S.

*For general information" on science and engineering education and personnel interna tionally, see (39) position in international competition in high-technology areas (1,38,49).

Undergraduate and graduate education in the United States and other countries

There is near unanimous agreement that the development of biotechnology will require personnel capable of operating in an interdisciplinary environment with various levels of expertise in both biology and engineering (29). Because of traditional barriers between basic biological science and engineering departments in most higher educational institutions, the challenge of providing interdisciplinary undergraduate and graduate education for personnel in biotechnology is a challenge common to all industrialized countries.

UNITED STATES

The United States has an adequate supply of personnel in nearly all the fields of basic biological sciences relevant to biotechnology, with the possible exception of plant molecular biology. For the training of plant molecular biologists, new and modified curriculum offerings may be needed. Most classical plant breeders in the United States are trained at agricultural research stations and land-grant colleges; thus, their training does not traditionally include molecular biology. Because the new genetic technologies grew out of biomedical research at universities and NIH, few traditional plant breeders have the training that would allow them to do experiments using rDNA technology. Nevertheless, interest in plant molecular biology is increasing dramatically. Botanists are learning the new techniques, and biomedically trained researchers are applying their expertise to plants. Because of the separation of agricultural researchers and plant molecular biologists in the United States, however, there are problems of communication between these groups which may slow research advances (34).

There is a growing concern that a shortage of plant molecular biology professors in the United States could result from a drain of Ph. D. plant molecular biologists from U.S. universities to industry (25). As numerous companies have started efforts in plant molecular biology and existing companies have expanded into plant molecular biology, industry has been competitively recruiting university researchers. As shown in table 65, according to the OTA/NAS survey, all of the companies wanting to employ Ph.D. plant molecular biologists intend to hire from academia, and half intend to hire from industry as well.

Bioprocess engineering education in the United States, now almost exclusively provided in university chemical engineering departments at the graduate level, * is closely tied to training opportunities in chemical engineering (12). Between 1970 and 1980, the number of Ph. D.s graduating in chemical engineering declined by nearly 25 percent, and the bioprocess subset of the chemical

*At the undergraduate level, there are only two accredited bioengineering (distinct from biomedical engineering) programs in the United States, one at the University of Illinois at Chicago and one at Texas A&M.

Table 65.—Sources of New Ph. D. Biotechnology R&D Personnel In Selected Categories in Firms in the United States
(OTAINAS Sumey)

Area of technical expertise (Ph. D.)	Companies planning to hire from industry		Companies planning to hire from academia		Companies planning to retrain current staff	
	Number	Percent of total[a]	Number	Percent of total[a]	Number	Percent of total[a]
Recombinant DNA	15	380/o	35	84 "/0	3	7"/0
Gene synthesis	9	64	13	93	3	21
Industrial microbiology	11	67	13	81	2	13
Bioprocess engineering	19	86	11	50	2	9
Plant molecular biology	9	50	18	100	3	17

[a]Refers to percent of companies that both indicated plans to hire in the specialty area *and* revealed the sources from which they would hire new Personnel, Many companies indicated more than one hiring source for each specialty area.

SOURCE: Office of Technology Assessment.

engineer category probably declined proportionally. At most, only about 10 percent of the recent M.S.s and Ph. D.s in chemical engineering are ready to enter the bioprocess industry without additional formal training (13).

The decline in the number of Ph. D.s graduating in chemical engineering in the United States in part reflects declining graduate student enrollment. Because industry salaries are quite high for bachelor's degree engineers, fewer and fewer people have gone to graduate school. Another reason for the decline is a shortage of engineering professors. Most American universities do not pay salaries commensurate with industry. Currently, there are 1,600 faculty vacancies at U.S. engineering schools in all disciplines (43). Participants at a 1982 workshop on biotechnology sponsored by the University of Virginia and NSF agreed that the shortage of faculty in engineering is a more pressing problem for the long-term educational stability of the United States than the declining engineering graduate student enrollment (28).

According to the OTA/NAS survey of firms using biotechnology in the United States, Ph. D. bioprocess engineers are in high demand by industry (see table 63). If incentives for Ph. D. bioprocess engineers to remain in the academic field are not improved, the loss of these Ph. D.s to the private sector may reach the point that the American Society for Engineering Education refers to as "industry eating their seed corn" (32). If the United States is to produce high-quality Ph. D. engineers, salary money and research funding for engineering faculty, as well as a restructuring of bioprocess engineering education emphasizing interdisciplinary training may be necessary.

JAPAN

In Japan, training in basic biology research is relatively weak. The director of the new Bioindustry Office of Japan's Ministry of International Trade and Industry (MITI) has listed as one of his primary concerns the state of basic biology research in Japan. However increased Japanese Government funding for such research is not apparent. The University of Tsukuba, the heart of a new $5 billion "science city" 37 miles north of Tokyo, has the largest budget of Japan's 95 national universities, but has no plans to expand its graduate enrollment in biology (22).

The distinction between basic and applied science departments at Japanese universities is great. At Tokyo University, for example, basic and applied science departments are located on separate campuses and have little interaction. Furthermore, professors in pure science areas such as biology are proud of their independence from industry (35). There is little direct correlation in Japan between university basic sciences curricula and corporate personnel needs. Special interdisciplinary biotechnology programs combining basic and applied sciences have not been instituted at Japanese universities.*

Because of Japan's need to generate and transfer basic science to industry more rapidly, the Japanese Government is attempting to end the isolation of Japan's basic research. Japan's Science and Technology Agency (STA) funds "Leading Technology" (Senatsu Gijutsu) projects, that allocate research responsibilities between university and corporate laboratories, but this funding has not yet been applied to the biotechnology field. STA is also funding a new program called the New Technology Development Fund (Shingijutsu Kaihatso Jigyodan) that was established to help companies commercialize university-generated research. The Government has also proposed building two new biotechnology centers open to private sector corporations through universities. Each researcher will conduct research in his or her own laboratory, but exchange of information between the corporate and academic researchers will take place on a regular basis (35).

National laboratories supported by the Agency for Industrial Science and Technology of MITI encourage the flow of personnel into interdisciplinary generic applied research. The national laboratories provide a place for university professors, Government researchers, and corporate researchers to work together. These laboratories have been especially important in the development of agricultural sciences and applied microbiology, because there are few private institutes

*See *Chapter 17: University/Industry Relationships* carrying on significant research in these areas (35).

FEDERAL REPUBLIC OF GERMANY

In the Federal Republic of Germany, three types of nonindustry laboratories conduct basic research in biotechnology: 1) laboratories belonging to universities, 2) laboratories dependent on BMFT for operating expenses and on the German Research Society (DFG, Deutsche Forschungsgemeinschaft) for project support,* and 3) laboratories in institutes supported by the Max Planck Society (Max-Planck Gesellschaft zür Forderung der Wissenschaften), which in turn receives support from BMFT.

Although laboratories supported by BMFT and DFG, such as the Cancer Research Center at Heidelberg, carry out important biotechnology-related work, institutes funded by the Max Planck Society are responsible for the bulk of basic research advances in biotechnology. The Max Planck Institute for Plant Breeding Research in Cologne, which recently received an unrestricted grant from Bayer, boasts some of the best plant genetics teams in the world. BMFT would like to see closer cooperation between the Max Planck institutes and industry (21).

The center for generic applied research in biotechnology in the Federal Republic of Germany is the Society for Biotechnological Research (GBF, Gesellschaft für Biotechnologische Forschung). GBF is a Government-supported private institution that was founded to conduct generic bioprocessing research to meet the needs of industries (23). In 1972, 89 percent of its $13 million (DM31.6 million) came from BMFT (14).

Among the factors cited to explain Germany's slow entry into biotechnology is an educational system that prevents the kind of interdisciplinary cooperation that is viewed by most experts as essential to the development of this field (21). Because of the traditional separation of technical faculties from arts and science faculties in West Germany, bioprocess technicians, usually located in technical schools, rarely come into contact with colleagues holding university appointments in biochemistry or microbiology (21). In August 1981, BMFT policy called for greater interdisciplinary cooperation among biologists, chemists, medical experts, and engineers (21).

*See *Chapter 13: Government Funding of Basic and Applied Research*.

UNITED KINGDOM

The United Kingdom's system of funding research in biology and the medical sciences at universities has produced highly trained personnel in rDNA and hybridoma technology for industry. Furthermore, the country's Plant Breeding Institute is considered a model for interdisciplinary research on plants. Unlike the United States, therefore, the United Kingdom is probably not suffering interdisciplinary training problems in plant molecular biology.

Many British universities have programs in bioprocess engineering. Bioprocess engineering has been taught at the postgraduate level at University College in London and Birmingham to biologists and biochemists for nearly 20 years. Furthermore, at least 10 to 15 university centers are now involved in postgraduate biotechnology education, and these centers are receiving extra money from the University Grants Committee. One of these, the Centre for Biochemical Engineering and Biotechnology, was set up by three universities both to acquire new laboratory space and to launch new courses. Imperial College in London set up the Centre of Biotechnology with four new faculty positions. This center will work with other departments of the college involved in biotechnology to launch a biotechnology masters course. Funding for bioprocess graduate research and training in Britain's universities is also being provided by SERC. SERC has plans to fund four new specialized biotechnology courses in universities, which will all contain elements of bioprocess engineering. SERC will fund a maximum of 60 places for graduate students, and industry is encouraged by the Government to finance more places (45).

British universities have 30 to 40 teaching staff who teach biotechnology (including bioprocess engineering) on a full-time basis and a much greater number of teaching staff who devote varying proportions of their time to teaching biotechnology. According to bioprocess expert Malcolm Lilly, the United Kingdom has more teaching biotechnologists than the United States and is also ahead of other European countries. Thus, there appears to be no current shortage of biotechnology faculty at British universities. Nevertheless, Government officials are worried that a lack of bioprocess engineering faculty may be a problem for the United Kingdom in the future because of the fairly small numbers of chemical engineers getting higher degrees in bioprocess engineering in recent years (45). To counter any shortage in teaching capabilities, the United Kingdom plans to involve industrialists in teaching bioprocess engineering courses at the universities.

FRANCE

In France, those pursuing higher education in scientific and engineering education go either to universities, to the more prestigious grandes écoles, or to Government-funded laboratories. French universities do not have graduate interdisciplinary courses in microbiology, rDNA technology, enzyme engineering, or bioprocessing techniques (33), and their creation will be difficult because of the lack of funds and a shortage of faculty. Four grandes écoles have interdisciplinary courses in biotechnology, but they produce only about 40 graduates a year total. However, other grandes écoles are now introducing courses in biotechnology (44). The Institut Pasteur, which is 49-percent Government-owned, regularly accepts doctorate students in biotechnology fields.

Other important loci of graduate training for biotechnology personnel in France, apart from the grandes écoles, are public research centers (grandes organismes), a very important part of the French research establishment. The grandes organismes have approximately 600 technical workers in biotechnology-related fields (nearly one-half of all of France's personnel in biotechnology), but they will probably find it difficult to create interdisciplinary training programs. At the largest and most significant organisme, the National Center for Scientific Research (CNRS, Centre National de la Recherche Scientifique), for example, there are communication problems between the scientific and engineering departments (44).

Transnational training in the United States and other countries

A trend evident in many scientific and technical fields, including biotechnology, is the training of increasing numbers of foreign students in the United States. In **1982,** foreign students constituted 2.6 percent of the total U.S. university enrollment, and 23 percent of the foreign students enrolled at U.S. universities were studying engineering. In 1981, for the first time, more foreigners than Americans received doctoral degrees in engineering in U.S. graduate programs (15). The proportion of foreign students in American postdoctoral engineering programs was more than 60 percent. Furthermore, foreign students constituted a third of all postdoctoral students in American science and engineering programs (26). These numbers illustrate the esteem with which U.S. science and engineering education is held throughout the world (43).

In the areas of molecular biology and immunology, foreign nationals are actively seeking training at U.S. institutions. Hoechst's (F. R. G.) 10-year, $70 million contract with Massachusetts General Hospital, for example, was, in part, established to train Hoechst's personnel at Harvard Medical School (21). *

NIH has several programs that sponsor research by foreign nationals in NIH laboratories. Under the "visiting program, " NIH sponsors and pays visiting scientists studying at NIH labs. In 1983, 810 foreign nationals were enrolled in this program. Of these visiting scientists, 158 were from Japan, 97 from India, 62 from Italy, 27 from France, and 6 from the United Kingdom. Under the '(guest researchers program, " foreign nationals are sponsored by their native country. In 1983, 32 Japanese were enrolled, 23 Italians, 21 French, 10 Indians, and 4 British (36).

Japanese personnel trained in the United States are now being actively recruited by Japanese

* This arrangement is discussed in ***Appendix H: Selected Aspects of 1',S. University Industry Relationships.***

firms. In a 1982 Keidanren survey* of 60 Japanese companies using biotechnology, 35 percent of the companies were active in recruiting researchers already studying or working abroad (35). When the Japanese company Suntory hired new employees for about one-third of the 126 research positions in its Biomedical Research Institute established in 1979, for example, many of the new employees were Japanese who had been working abroad (35).

The larger more established Japanese companies sponsor translational training of their employees. Sixty-two percent of Japanese companies responding to the 1982 Keidanren survey indicated that some scientific and engineering personnel would be sent abroad for training in specialized technologies (35).

Foreign nationals are being trained not only at university and government centers in the United States, but at U.S. companies looking for supplemental sources of revenue. Five corporate researchers from Japan recently attended a 3-month course at Genex in rDNA technology offered at $120,000 per person. According to the Japanese companies, they learned "highly specific knowledge . . . and key points for developing specific products by using the rDNA technology " (18).

Amid all the evidence that foreign countries are making use of U.S. training facilities, data show that U.S. doctoral graduates are going abroad for postdoctoral study less frequently. During the decade of the 1970's, postdoctoral training abroad decreased by nearly 50 percent (26), In biotechnology especially, postgraduate training abroad appears to be an area poorly funded by the United States. Professor Arnold Demain, for example, has indicated that 8 of the 11 students currently enrolled in his graduate program in industrial microbiology at Massachusetts Institute of Technology (MIT) are foreigners, all sponsored either by their government or company. Money to send Americans overseas to do postdoctoral work in industrial microbiology, however, is not available (7).

Midcareer retraining in the United States and other countries

To address the challenges of biotechnology, industrial scientists and engineers can probably be retrained. Retraining in the United States is often viewed as the responsibility of the individual scientist or engineer and not that of the employer, with some exceptions (see below). A problem is that it is very difficult for a scientist or engineer in midcareer to take a year off to go back to school.

Reflecting concern over this situation, four senior professors at MIT recently published a report advocating "lifelong cooperative education" (48). The report's major recommendation was that engineering schools and neighboring industries collaborate in making off-campus graduate programs available to working engineers. Although the report was addressed specifically to the electrical engineering department of MIT, it could also be addressed to a larger community, and many of its recommendations may apply to biotechnology. For example, MIT Professor Daniel Wang recently stated that chemical engineers who "don't know the faintest thing about how proteins are isolated)" if taught some basic protein chemistry, could develop new techniques for large-scale purification (17). Historically, chemical engineers in the United States have been retrained by pharmaceutical companies to be bioprocess engineers (7).

As shown in table 65, a relatively small percentage of the 95 companies responding to the OTA/NAS survey intend to retrain their workers to fill vacancies in areas of biotechnology personnel shortages. For most categories of Ph. D. personnel, hiring from academia is considered the optimal choice. In the case of Ph. D.s in bioprocess engineering, however, 86 percent of the companies planning to hire Ph. D. bioprocess engineers intend to hire them away from other companies, 50 percent plan to hire from academia; only 9 percent of the companies plan to retrain. * one

" Keidanren, the Japan Federation of Economic Organizations, is a national organization composed of about 700 of' the largest Japanese companies. It enjoys the regular and active participation of the top business leaders working closely with a large professional staff to forge agreements on behalf of business as a whole. It often surveys its members on issues of economic importance.

*These percentages exceed 100, because some companies indicated more than one hiring sourer.

reason for the very small amount of retraining in biotechnology may be the small size of many of the U.S. companies using biotechnology. The small companies that account for much of the biotechnology research activity in the United States probably do not have the resources to retrain personnel in-house.

Some foreign countries are pursuing the retraining of personnel more actively than the United States. The retraining of workers in Japan, more than in any other industrialized country, is viewed as the responsibility of the corporation. The Japanese permanent employment programs, prevalent in a majority of companies in the Japanese biotechnology-related industries, make it economically feasible for a firm's employees to be optimally trained at company expense (35). Japanese employees' salaries are in part based on the number of years they have been employed by the firm, so employees have strong incentives not to leave the firm for which they are working. Because employees in Japan are more likely to stay with their firms than employees in the United States, a far larger proportion of total training is sponsored by the Japanese private sector than in the United States (35).

The provision of corporate funding for worker retraining in biotechnology is common in Japan. According to the 1982 Keidanren survey, 53 companies indicated that they planned to use in-house training to meet, at least partially, their personnel needs (35). Some Japanese corporations, by commissioning research on a particular topic, are able to send their researchers to train at a university laboratory with a professor and his or her staff. At national universities, each professor is limited to approximately six or seven corporate trainees a year, but at private universities, there is no such restriction. As discussed above, training of Japanese workers at institutions in other countries is also common.

Japan's ability to overcome weaknesses in its labor force rapidly, due largely to corporate financing of worker retraining, is truly extraordinary. In 1981, for example, no more than 10 private Japanese firms had more than 10 researchers working on rDNA projects. A year later, the Keidanren survey in March 1982 revealed that 52 out of the 60 leading Japanese firms surveyed had 10 or more research workers in the area (35). It is partly because of the large-scale retraining of industrial personnel that Japan has been able to overcome a weak biological science base to remain a leading international competitor in the commercial development of biotechnology.

The European leader in the industrial retraining of its biotechnology work force is the Federal Republic of Germany. The German chemical industry association, DECHEMA, has an expert group on biotechnology, a standing body to bring academics and industrial scientists into regular contact. It organizes continuing education courses in various aspects of biotechnology (e.g., the use of immobilized enzymes, measurement needs, and control of bioreactors) (21).

The British and French Governments are adopting active policies to encourage retraining. In the United Kingdom, some Research Councils are offering short courses for midcareer scientists. Currently, MRC establishments are providing training in cell fusion and rDNA technology to the employees of Celltech and some larger companies, including Glaxo, ICI, and Seralab (45). In France, the Institut Pasteur runs postgraduate courses in biotechnology, long courses in both microbiology and immunology, and short specialized training courses (44).

Findings

The OTA/NAS survey of 95 companies using biotechnology in the United States suggests that approximately 5,000 workers are now doing biotechnology R&D in the 219 companies using biotechnology in the United States. Though the number is expected to increase about 30 percent over the next year, it is unlikely that a 30-percent annual growth rate can be maintained over the next decade. The commercialization of biotechnology is unlikely to contribute directly to large increases

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in employment. Bioprocess technology, an essential part of industrial biotechnology activities, is not labor intensive.

About one-third of the technical personnel currently employed in 95 surveyed companies using biotechnology are specialists in basic science areas related to genetic manipulation: rDNA / molecular genetics and hybridoma / MAb technology. Specialists in these categories will continue to be important to biotechnology R&D, and more hirees are expected. Another third of the technical personnel currently employed by the US. companies using biotechnology are specialists in areas of applied science related to scale-up and downstream processing: microbiology, biochemistry, and bioprocess engineering. Of these categories, only hirees in bioprocess engineering will increase over the next 18 months. About one.fifth of the biotechnology work force are specialists in areas important to all aspects of biotechnology: enzymology and cell culture. The balance of people are specialists in such fields as pharmacology and toxicology.

The United States currently has a competitive edge in the supply of scientific personnel able to meet corporate needs for R&D in rDNA and hybridoma technology. This edge is primarily due to generous Federal support for university life science research since World War II. Nevertheless, the supply of Ph. D. specialists in plant molecular biology and in applied disciplines such as bioprocess engineering and industrial microbiology may be inadequate for U.S. corporate needs. It may be difficult to alleviate rapidly the shortage of engineers because of the shortage of Ph. D. engineers serving as university faculty and the lack of governmental training programs. To an extent, foreign technical personnel are alleviating some of the industrial shortages.

With the exception of France, the other competitor countries have adequate supplies of basic biological scientists. French companies are importing foreign specialists. German and Japanese companies, where slight shortages do exist, are making efforts to train some of their personnel abroad and to retrain workers. Some Japanese companies are making successful efforts to repatriate Japanese workers trained overseas.

Japan, the Federal Republic of Germany, and the United Kingdom, unlike the United States, maintained a steady supply of both industrial and government funding for applied microbiology and bioprocess engineering after World War II. Japan's supply of scale-up personnel appears to be sufficient. However, the United Kingdom and West Germany are suffering from a brain drain to foreign countries (in particular to the United States), and shortages of scale-up personnel may occur.

The United States has very few undergraduate or graduate interdisciplinary programs in biotechnology. Consequently, in the agricultural fields, for example, there are communication barriers between classical plant breeders and plant molecular biologists. Bioprocess engineering education in the United States is provided almost exclusively at the graduate level and is closely tied to training opportunities in chemical engineering with few interactions occurring between biologists and engineers. Funds for Ph. D. and postgraduate education in bioprocess engineering in the United States have been inadequate for the training of sufficient numbers of specialists for industry and academia. Furthermore, the high industrial demand for Ph. D. bioprocess engineers is likely to create a shortage of university faculty in the field,

Universities in the United Kingdom, in contrast to their counterparts in the United States, have long had interdisciplinary programs in biotechnology, and the British Government is encouraging the formation of overarching biotechnology programs in those universities where they do not already exist. Though France, the Federal Republic of Germany, and Japan have systematic barriers to interdisciplinary programs, their governments are utilizing national research institutes to facilitate interdisciplinary research in biotechnology.

The funding by foreign governments and companies for the training of domestic workers overseas is far more extensive than that of organizations within the United States. In fact, in biotechnology-related areas, the U.S. Government appears to fund more the training of overseas nationals in the United States than the training of U.S. nationals abroad.

Switzerland, which has not been extensively discussed in this chapter, appears to have no trouble meeting the personnel needs in either its universities or companies developing biotechnology. Particularly in relation to the size of the country, Swiss academic institutions show unusual strength in both basic and applied research relevant to biotechnology. Swiss companies seeking to develop and expand their expertise in these technologies may choose to work with the qualified Swiss researchers in the university or may recruit foreign scientists, with apparently little difficulty, to work in Slvitzerland (20).

Retraining of corporate workers in biotechnology is being pursued more actively in foreign countries than in the United States. Japanese companies, in particular, make a regular practice of sending their workers to be retrained at Japanese and foreign universities and research institutions. Only a very small percentage of companies using biotechnology in the United States intend to retrain their workers in areas of personnel scarcity.

Issues and options

ISSUE 1: HOW **could training for biotechnology at the graduate–and postdoctoral levels be improved?**

The United States appears to be suffering shortages of Ph. D. plant molecular biologists, applied microbiologists, and bioprocess engineers in its biotechnology-related industries. Although improved science education at the secondary school and undergraduate level could enhance the development of biotechnology in the future, the graduate level seems to be the best place to address the shortages of certain types of personnel.

For the past several years, U.S. Government funding for research in the areas of plant molecular biology, applied microbiology, and bioprocess engineering has been far less than funding for research in animal and bacterial molecular biology and immunology. Increasing Federal funding for research grants in plant molecular biology, applied microbiology, and bioprocess engineering, by encouraging more investigators to enter these fields, could help alleviate shortages of personnel. Since fields of faculty endeavor are at least partially determined by the availability of research grants, increased funding for research might encourage training and indirectly prevent future shortages of faculty. Options for directing research funds toward areas of personnel shortages are discussed in ***Chapter*** 13: ***Government Funding of Basic and Applied Research.***

Another area where more Federal research funding could potentially reduce personnel shortages is that of interdisciplinary research. The interdisciplinary nature of biotechnology requires research collaboration among people with backgrounds in biology, engineering, and chemistry. Options that Congress could take to encourage interdisciplinary research are discussed below.

0PTION 1: Authorize increased funding for LISDA, NIH, and NSF graduate and postdoctoral training grants in plant molecular biology, applied microbiology, and bioprocess engineering.

The lack of training grants is probably the single most outstanding reason for U.S. shortages in selected areas of biotechnology personnel. There are no NIH or NSF training grants for industrial microbiology or process engineering. The U.S. Department of Agriculture (USDA) this past year gave only five training fellowships in plant science. NSF until recently had no training grants at all in plant science, although in May of 1983, NSF's Biological and Behavioral Directorate approved 24 postdoctoral fellowships for study in plant cell biology.

In fields such as molecular biology, competitive training grants have been one of the most effective uses of Government funds for graduate and postdoctoral education. Training grants encourage university departments to carry on a cohesive training program and allow money from faculty research grants to be used for research instead of salaries. The institution of adequate training grants in the areas of plant molecular biology, applied microbiology, and bioprocess engineering would be a long-term strategy to counter personnel shortages in these areas. Such grants could be administered by NIH (for applied microbiology and plant biology), USDA (for plant biology), and NSF (for all three).

OPTION 2: Continue to support special incentives to encourage young engineers to stay in academia.

The shortage of engineering faculty at U.S. universities could seriously hamper efforts to increase the number of qualified engineers, including bioprocess engineers, in the United States. The recently instituted Presidential Young Investigator Awards to be administered by NSF is an example of the sort of special incentives program that Congress could continue to support to counteract the shortage of engineering faculty. Two hundred of these awards, 100 of which are to go to engineers, are to be awarded each year for 5 years to scientists and engineers in academia who have fewer than 7 years postdoctoral experience. Each award could total up to $100,000 per year for 5 years. The first $25,000 per year is to come from NSF. Industry funding for the engineers, of up to $37,500 per year, is matched by NSF, giving the total amount of $100,000.

OPTION 3: Specific that a certain percentage of NSF graduate and postdoctoral grants be used for training in other countries and authorize NIH and other relevant agencies to initiate researcher exchanges with other industrialized countries.

Increasingly fewer U.S. Ph. D.s are doing postdoctoral work abroad, while the number of foreign Ph. D.s doing postdoctoral work in the United States is increasing. The U.S. Government supports the training of its nationals overseas far less than its industrialized competitors.

Foreign countries have many significant and growing research programs in biotechnology that U.S. researchers could fruitfully be visiting-e. g., Japan's Fermentation Research Institute and University of Tokyo; the Society for Biotechnological Research (GBF) in Braunschweig, Federal Republic of Germany; and the John Innes Institute and Plant Breeding Institute in the United Kingdom. Few Americans are studying at those institutions. Though NSF's Science and Engineering Directorates can give grants to students studying overseas, such grants are not generally given because they are usually more costly than regular grants.

NSF's Science, Technology, and International Affairs Directorate has an International Cooperation and Scientific Activities program that provides special funds for researchers to study abroad—funds that can supplement the grants of other programs within NSF. One advantage of authorizing more money for this program is that this program has had experience negotiating standards of bilateral student exchange with foreign governments, having negotiated a successful bilateral agreement with France. In most foreign countries, American students cannot study at the best institutions (usually national) without the proper contacts and encouragement of the domestic government.

Congress could also specify that the NSF international grants that are given have a clearer training component. Currently, even the international fellowship grants are evaluated on the basis of their proposed research, rather than the quality of training for the US, nationals. It should be noted, however, that setting aside a part of NSF international grants for graduate and postdoctoral training would probably reduce the current percentage of international grants given to junior professors.

NIH's unilateral programs to support the study and research of foreign postdoctoral personnel in the United States could also be expanded to support the study of American nationals overseas. Since the United States is not the sole source of advanced R&D capability, Congress could authorize NIH to formulate programs that result in reciprocal exchanges and postdoctoral research opportunities for American scientists and engineers in areas of foreign expertise.

ISSUE 2: How could Congress improve interactions between classical plant biologists and plant molecular biologists?

Many people would argue that the agricultural research system in the United States does not need to be improved because the United States has the most productive agricultural system in the world. Nevertheless, there are specific areas where some advances in plant science, aided by new biotechnology, may be crucial to feeding the world's population in the coming years. These advances can be made only with the interaction of classical plant breeders and plant molecular biologists. Yet, because of the historical separation of agricultural researchers and plant molecular biologists in the United States, these groups do not have established communication networks. Most of the classical plant breeders are trained at agricultural research stations and land grant colleges, whereas most of the plant molecular biologists were originally trained in biochemistry, bacterial genetics, and animal biology (funded extensively by NIH) and are now working at the universities where much of the molecular biology is done. The lack of interaction between these two disciplines puts the United States at a disadvantage in modern agricultural research. *

The agricultural surpluses that the United States has today could vanish in a single year and probably are temporary. Greater productivity will be necessary as we move into the 21st century. The United States is also depleting its water resources and its topsoil. Advances in biotechnology can contribute to the solution of these problems with the development of plants that need less water, have greater nutritive value, and are more resistant to the high saline content of irrigation water. The costs of production can be lowered if plants are pest-resistant, and fewer fertilizers will be needed if plants can fix their own nitrogen. These advances cannot be made without greater interaction between classical plant breeders and plant molecular biologists. The Federal Government is spending about $20 billion on an acreage diversion program. This money subsidizes the market price, but does not address the central agricultural production issue, the farmer's low profit margin. Diverting a portion of this money to research on plant genetics could go a long way toward reducing agricultural production costs.

OPTION 1: Legislate the creation of one or more plant research institutes.

A plant research institute was established under the Department of Energy's (DOE's) management and with cooperation from the State of Michigan in 1965. DOE's contribution to this effort was $1.65 million in fiscal year 1983 and will be $1.7 million in fiscal year 1984. This is a beginning toward solving some of the problems of communication among biologists of different disciplines, but it is only one effort.

The creation of several more plant research institutes could facilitate interdisciplinary research between classical plant biologists and plant molecular biologists, although there could be some problems. First, a large amount of money would be required. Second, scientists to work in the institute would have to be drawn from other institutions, thereby possibly causing a shortage of teaching faculty. Faculty shortages could be partially alleviated if the institute were located near a major research university or land grant college. Third, it is not obvious what agency would administer the institute. DOE is one choice because it already has experience with one institute. USDA is another choice, but recent studies (see preceding footnote) have suggested that the research stations it already administers have not kept up-to-date with the latest molecular techniques being applied to plants. NIH, which is well versed in molecular biology, is not an ideal agency to administer an essentially agricultural program, NSF might be a candidate to administer a new plant research institute because of its interdisciplinary staff,

OPTION 2: Establish grants for cooperative research between classical and molecular plant biologists from different institutions.

* The administration of basic research in agriculture has recently been reviewed by several agencies (5,34,41). Changes in the administration of USDA research will be extremely important to the direction of development of biotechnology in agriculture. A proposal within USDA to significantly increase the competitive grants in plant biology has recently been published (25). However, an assessment of the USDA technical and administrative infrastructure is beyond the scope of this report.

An increase in funding alone would facilitate interaction between classical and molecular plant biologists. Because of its interdisciplinary focus, NSF might be the agency to administer these grants.

Careful specification of requests for proposals and monitoring of the grants by technically qualified staff would be needed to ensure that the research that is funded is truly cooperative. Otherwise, some researchers experiencing difficulties in obtaining research funding might be tempted to cooperate in proposal writing in order to obtain a grant and then carry out independent research.

ISSUE 3: How could the retraining of industrial personnel in biotechnology be improved?

The OTA/NAS survey of companies using biotechnology in the United States shows that there is little retraining of personnel in this field. This situation is probably due, in part, to the fact that many of the US. companies using biotechnology are small and have neither the resources nor incentives to retrain personnel. These small companies depend on their ability to attract already highly qualified personnel. However, the pharmaceutical industry has shown that chemical engineers can be retrained in bioprocess engineering.

Continuing education sponsored by large U.S. companies, in general, takes place through short courses or joint research performed at universities. University/industry training and research agreements in biotechnology are being developed without the assistance of the Federal Government. But the Government could further encourage retraining in biotechnology by increasing funding for NSF's Industry/University Cooperative Centers Program, which provides seed money for a university to set up a research center with industrial partners. This option is discussed in Chapter 13: ***Government Funding of Basic and Applied Research.***

Whether human resources in the United States are used and retrained adequately is a larger, national question that addresses the transition of the U.S. labor force from declining to growing industrial sectors. Suggestions to encourage more retraining have included revision of the tax code to encourage business loans to employees for retraining and an extension of unemployment insurance to include payment for retraining. The comparative evaluation of measures such as these that include other disciplines is beyond the scope of this study.

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