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Biotechnology

Abstract

Biotechnology is a discipline that integrates biology, chemistry, physiology, information technology, engineering, and nanotechnology with the potential to revolutionize every aspect of modern life. This critical sector of United States industry is developing products that will improve health care, agriculture, industrial processes, and environmental remediation and provides the foundation of national biological defense. Millions of people worldwide benefit from revolutionary vaccines, antibiotics, drug therapies, and new medical devices. Agricultural advances include crops engineered to be pest resistant, to survive extreme climates, and to produce additional nutrients or therapeutics. Biotechnology, from vaccines to sensors to biometrics, is a cornerstone of homeland defense. However, many ethical issues abound, from stem cell research limitations to acceptance of foodstuffs from genetically modified crops to policies for vaccination against bioterrorism. Because of long product research, development, and testing times, many promising ideas run out of cash. In the wake of a financial downturn, venture capitalists are cautious, and many small companies simply expire. Inefficiencies plague huge investments made by the U.S. government. Despite economic challenges, the biotechnology industry is poised to be a major factor in the growth of pharmaceutical and agriculture sectors of the U.S. economy. As we enter the "Era of the Biomolecule," the United States must implement policies and allocate resources to maintain its lead in biotechnology for national security and economic power.

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ORGANIZATIONS VISITED OR BRIEFING ICAF:

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Affymetrix, Bedford MA

Agricultural Research Center, Beltsville, MD

Armed Forces Institute of Pathology, Rockville, MD

Biotechnology Industry Organization, Washington, DC

BC International, Dedham, MA

Charles River Lab, Wilmington, MA

Genzyme, Boston, MA

GTC Biotherapuetics, Boston, MA

Hemodyne, Inc., Richmond, VA

Human Genome Sciences, Inc., Rockville, MD

MedImmune, Inc., Gaithersburg, MD

National Institute of Allergy and Infectious Diseases, Bethesda, MD

National Science Foundation, Washington, DC

Office of Net Assessment, Office of the Secretary of Defense, Washington, DC

Photonics Center, Boston University, Boston, MA

Talent Capitol, Boston, MA

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Whitehead Labs, Massachusetts Institute of Technology, Boston, MA

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Introduction

Biotechnology has tremendous potential to positively impact the quality of life in the United States and abroad. Challenged by lackluster capital markets, efforts of the plethora of small firms attempting to get products to market are remarkable for their tenacity. The last year in biotechnology has produced a variety of new products. Significant events in the industry over the past year include: a large increase bioterror defense spending for homeland security; the continuing fiscal challenges of biotech companies with rising research costs and scarce venture capital; and the resurgence of ethical questions over cloning (2002 saw the first purported cloning of a human). The acceptance of genetically modified agricultural products remains an ethical and political chasm between the United States and much of Europe. Ineffectively addressing some ethical issues, such as stem-cell research and genetically modified organisms, threatens the United States' lead in biotechnology. The strong potential of biotechnology to fundamentally change health care and agriculture, and to grow and profit, depends on the fulfillment of its scientific promise. Government must continue its strong support of research and development and implement policies that will foster the United States' continued lead in biotechnology.

Industry Defined

Biotechnology has exploded in the last twenty-five years. A core biotechnology is difficult to define. Yet, when every frontier of science is pushed to new limits, biotechnology benefits. Material sciences bring new capabilities to bone and tissue repair; molecular genetics provides products as varied as pharmaceuticals and motor fuels. Biotechnology is not as much a specific industry as a means to solve macro problems with micro sciences. The Biotechnology Industry Organization (BIO) represents a wide range of interests…and has members in agriculture, medicine, and animal science. Clearly the United States Office of Technology Assessment definition is most catholic in application and meaning: biotechnology is "any technique that uses a living organism, or parts of organisms, to make or modify products, to improve plants or animals, or to develop microorganisms for specific uses."[1,2]

Biotechnology: Key Technologies

Biotechnology encompasses a collection of technologies using cells and biomolecules as well as information technology. Key among these technologies are:[3]

Cloning Technology: A clone is an exact copy of an entity, produced by asexual means. In the biotechnology industry, cloning can be achieved at the level of molecules, cells, or complete organisms. Cloning technology allows us to generate an entire population of genetically identical molecules, cells, plants, or animals. In molecular cloning, a clone refers to a gene or DNA fragment and to the collection of cells or organisms, such as bacteria, containing the cloned piece of DNA. Cellular cloning produces *cell lines* of identical cells. Plant cloning using rhizomes or root propagation has long been considered a *natural* and uncontroversial means of plant generation. In its earliest forms, animal cloning has been an extension of selective breeding but with far greater capabilities. The term "cloning" today is widely used in public fora to refer to the specific technology of using adult cells' nuclei in enucleated eggs to produce

offspring identical to an existing adult. This is the technology that spawned Dolly the Sheep and that raises questions about possible cloning of living human beings.

Monoclonal Antibodies: One type of cell in the immune system produces proteins called antibodies. Antibodies exhibit specificity that makes them powerful tools for locating substances that occur in minuscule amounts. A monoclonal antibody is a type of antibody produced from a single cell. All antibodies produced by a given cell are identical and bind to the same specific target in the same way. Monoclonal antibody technology uses the specificity of antibodies in a variety of ways, including treatment of various diseases and detection of the presence of drugs, bacteria, viruses, abnormal cells, food contaminants, and environmental pollutants.

Genetic Engineering: In genetic engineering, genes whose functions are known are moved from one organism to another using recombinant DNA technology without restriction to exact species. This introduces new genetic instructions to the recipient cells to produce needed chemicals, to carry out useful processes, or to give the organism some new and desired characteristics. Currently, genetic modifications are used to produce high-yield, pest-resistant varieties of crops, and safer medicines.

Protein Engineering: Genetic modifications are used to improve existing proteins, usually enzymes, to provide targeted proteins to individuals who lack them because of genetic defects, and to create proteins not found in nature. These new and improved proteins can encourage the development of ecologically sustainable industrial processes because they are renewable and biodegradable resources. A complementary technology is the design of small molecules to bind to specific proteins to inhibit their biological activity – a process of rational drug design.

Gene Sequencing: Robotics and information technology have revolutionized gene sequencing, allowing high throughput and high quality assurance. Key technologies integral to gene sequencing include genetic engineering, polymerase chain reaction (PCR) amplification, and electrophoresis. Highly related is the field of DNA identification using PCR or GeneChip® technologies to uniquely recognize specific DNA rather than sequencing the entire DNA.

Bioremediation: Bioremediation is the treatment of soil or water to enhance the microbial degradation of contaminants. Composting is a traditional type of bioremediation where organic agents are added to promote biodegradation and reduce contaminants. It is one of the oldest examples of environmental biotechnology. Modern environmental biotechnology makes use of microorganisms and enzymes, often specifically genetically engineered, to clean up oil spills and toxic waste sites, and to purify sewage.

Bioinformatic Technologies: Bioinformatics is the fusion of information technology and biotechnology. Typifying the ability of biotechnology to leverage off advances in disparate fields, bioinformatics is conceptualizing biology in terms of molecules and applying informatics techniques to understand and organize the molecular information on a large scale. In short, bioinformatics is a management information system for molecular biology.

Biosensors: Biosensor technology couples biological reactions with microelectronics. A biosensor is composed of a biological component, such as a cell or antibody, linked to a tiny

transducer. Biosensors are detecting devices that rely on the specificity of cells and molecules to identify and measure substances at extremely low concentrations. When the substance of interest collides with the biological component, the transducer produces a digital electronic signal proportional to the concentration of the substance. Biosensors can be used to measure many blood components, the safety of food, and the level of environmental pollutants.

Biometrics: Biometrics use digital techniques to attempt to measure, quantify, and positively identify an individual. It is the technique of verifying a person's identity from a physical characteristic or personal trait. Physiological biometric identifiers include fingerprints, hand geometry, eye patterns, and facial features. Behavioral identifiers include voice acoustic pattern and handwriting signature. Biometrics may also measure human performance.

Fermentation Technology: The early history of biotechnology lies in this area and is important today. The baking industry still uses yeast as a leavening agent. Yeast also produces alcohol during the production of wine and beer. Other fermentation technologies that are currently emerging from biotechnology laboratories provide an alternative to fossil fuels using one of three dominant technologies: alcohol as a gasoline substitute and additive, biodiesel fuel, and biomass fuel pellets.

Current Condition

The following charts provide a background view of the financial and structural summary of the biotechnology industry from 1992 through 2001. The biotechnology industry doubled in size between 1993 and 1999.[4] After receiving a steady flow of investment capital throughout the second half of the 1990's, the industry absorbed a $37.2 billion[5] infusion in 2000, which exceeded the previous five years combined. This growth is evident since "in the 1990's, 100 to 150 companies received biotech mutual fund financing, with the overall amount invested in that decade totaling about $1 billion. In the current decade, about 250 companies are getting funded annually, and the annual investment total is close to $3 billion per year."[6]

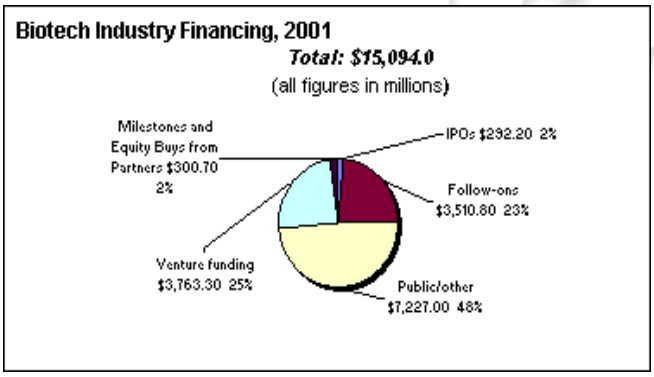

Figure 1: Biotech Industry Financing
Source: BioWorld Financial Watch
Public/other is defined as financing of public companies, including loans, bridge financings, exercises of warrants, etc.

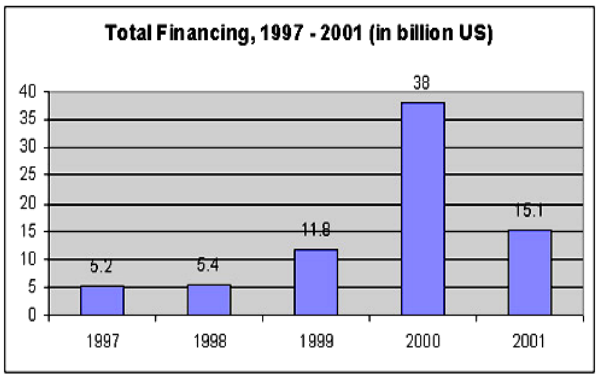

Figure 2: Venture Capital Invested in Biotech
Source: BioWorld Financial Watch

Industry Statistics: 1992–2001*

Year	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992
Sales*	20.7	19.3	16.1	14.5	13	10.8	9.3	7.7	7.0	5.9
Revenues*	28.5	26.7	22.3	20.2	17.4	14.6	12.7	11.2	10	8.1
R&D Expense*	15.7	14.2	10.7	10.6	9.0	7.9	7.7	7.0	5.7	4.9
No. of Public Companies	342	339	300	316	317	294	260	265	235	225
No. of Companies	1,457	1,379	1,273	1,311	1,274	1,287	1,308	1,311	1,272	1,231
Employees	191,000	174,000	162,000	155,000	141,000	118,000	108,000	103,000	97,000	79,000

*Amounts are U.S. dollars in billions.
Source: Ernst & Young LLP, annual biotechnology industry reports, 1993–2002.
Financial data based primarily on fiscal-year financial statements of publicly traded companies.

Because of the availability of funding in the late 90's a number of biotechnology startup companies entered the industry that were at least 7-10 years away from bringing a product to market. This has resulted in institutional investors and venture capitalists becoming more selective in which companies they funded. In 2000, "total capital raised by the industry in the United States hit $37.2 billion… but then fell to $15.1 billion in 2001."[7] The fact that the overall economy has been sluggish over the past two years has also affected the biotechnology industry. In 2001, 63 public companies went bankrupt or were delisted; another 123 now have less than two years' worth of operating cash on hand. As shown in Figure 3 below, 2002 was one of the most difficult years in the history of the biotechnology industry, measured by the decrease in market capitalization. The NASDAQ Biotech Index fell 45 percent. While biotech stocks may be partially rebounding, many companies have delayed initial public offerings and have restructured their R&D to conserve cash. In the short-term, it appears that venture capitalists and public investors will remain wary and will focus primarily on "companies with tangible products, not promising genome technology."[8] Firms without products close to entering the market place will have a difficult time obtaining financing.

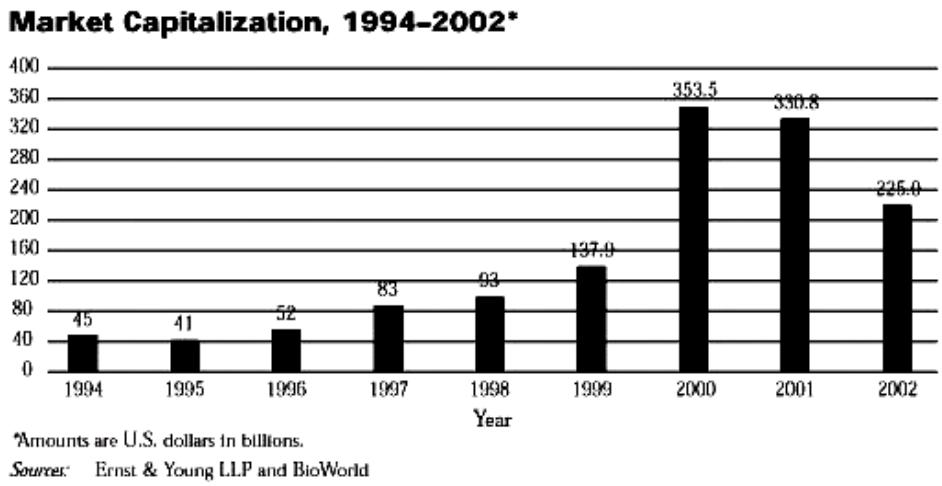

Figure 3: Biotech Market Capitalization

The federal government, especially in a weak economy, is another funding source for many biotechnology firms. Grants and business loans are available to companies that can work their way through the bureaucratic process. The National Institute of Health (NIH) is one of the largest distributors of these funds, typically budgeting in excess of $400 million annually to support biotechnology. Small Business Innovation Research (SBIR) grants and Small Business Technology Transfers (STTR) are the primary financial tools that the government can use to provide funding to biotech firms. "Last year, the NIH awarded 1,375 SBIR and STTR grants."[9] Normally these grants go to firms with less than 40 employees, which are typical of the companies that have the most difficulty obtaining institutional and venture capital. Basic research is crucial to advancements in biotechnology, and the university-industry model in the U.S. is the envy of the worldwide scientific community. Federal funding primarily supports the academic community, and, in turn, universities and public research institutes are the leaders in crucial biotechnology research. As an added incentive to the academic community, the Bayh-Dole Act (1980) provides "monetary incentives for universities and their professors to market products that were developed with federal grants."[10]

Biomedicine

"More than 2,000,000 people worldwide have been helped by the 90+ biotechnology drug products and vaccines approved by the U.S. Food and Drug Administration"[11] There are four primary areas in health care in which biotechnology is currently being used: medicines, vaccines, diagnostics, and gene therapy. In using the body's own complex mechanisms to fight disease, biotechnology has dramatically changed the nature and approach to health care. New medicines and therapies employ proteins, enzymes, antibodies, and other substances naturally produced in the body and apply these mechanisms in novel or more effective ways. Biotech innovatively expands on the use of other living organisms including plant and animal cells, viruses, and yeasts to assist in the production of medicines for human use.

Biotech products are used across the spectrum of health care in prevention, diagnosis, treatment, and post-treatment follow-up. These products affect every aspect of life from medical diagnostic tests through home pregnancy kits and include: monoclonal antibody technology; mammalian cell culture; biosensor technology; gene modification technology; and antisense

technology that uses small nucleic acids to block the genes responsible for making specific proteins.[12]

The impact of biotechnology and its application in health care and medicine is intuitively obvious. Over 600 biotechnology drug products and vaccines are currently in human clinical trials and hundreds more in early development in the U.S.[13] Biomedicine is one of the most research-intensive industrial sectors in the world, with the U.S. industry alone spending more than $12.3B on research and development in 2001.[14] Within biotech health care, about ten large companies control the largest segments of the industry. However, smaller companies that fit into the approximate 85% of companies that have fewer than a thousand employees conduct much of the R&D that leads to products submitted for trials. This industry has been marketing biotech medicines and treatments from as early as the mid-80's, but the flood gates to exponentially increased discovery were opened with the recently completed human genome project. It is a speculative yet highly regulated industry, with the U.S. Food and Drug Administration having the predominant regulatory role.

Research and development priorities within biotech result from two differing yet supportive business approaches. First and foremost are projects that look for potential treatments for specific diseases or categories of diseases. An ongoing initiative of this type is the Congressionally mandated research to develop a treatment for specific cancers including breast, ovarian, prostate and certain types of leukemia. Government funding, that is administered to participating companies and educational and research institutions, supports this research. The second approach is the discovery of a new technology or capability that is then examined for applicability in developing a particular medicine or treatment. Recently this has resulted in some companies using a computer assisted screening approach for identifying potential applications for new technologies as opposed to the traditional scientific method. The preference of the methods may be academic, but it portrays the driving force of profitability and the resultant need for rapid research and development.

Biotech companies with a good idea and a product to enter into the approval process currently have an extremely difficult time raising start-up funding. Venture capitalists are leery of biotech because of the long-lead development times. The returns venture capital investors demand are not normally available nor reasonably to be expected in the biotech health care field. This said, 2001 was still the second-best financing year in biotech history with total financing of $16,212M, although this does represent a significant decrease from more than twice this amount the preceding year.[15] Collaboration between biotech companies, both within this country and globally, has added significantly to the potential of the industry in the last few years. This joint effort takes many forms, from supportive R&D to linear flow arrangements where smaller companies develop products that will be manufactured and marketed by the pharmaceutical giants. This arrangement makes efficient use of fiscal resources.

There is, under consideration, an exception to the lengthy biopharmaceutical approval process. Under the Hatch-Waxman Act, a generic drug manufacturer can submit an abbreviated new drug application showing that its version of a drug is equivalent to the approved drug without showing safety and efficacy. This process is the primary reason generic drug manufacturers are able to obtain quick approval of their generic versions of approved drugs.

Although there are problems in transferring approval criteria to biological material, steps are being taken on Capitol Hill to adjust the regulatory structure to provide for expedited approval of generic biologic drugs.[16]

The impact of biotech medicine on national defense is direct, extremely significant, and inseparable. Biotech products and technologies have reduced morbidity and mortality caused by disease and illness. Research initiatives funded through the Department of Defense benefit all U.S. citizens and indeed the entire world community.

Bioagriculture

Since its introduction in 1995, the planting of transgenic food crops has increased from less than one million acres to over 130 million acres worldwide. The United States represents approximately 68% of the total, followed by Argentina with 22%, Canada with 6% and China with 3%.[17] The predominant crops are herbicide/insecticide resistant soybeans, cotton, corn and canola. The value of the global market for transgenic seed is estimated to exceed $3 billion annually.[18]

The rapid adoption rate of this technology is due largely to a lower overall cost of production. While the transgenic seed is usually more expensive than non-transgenic, the higher seed cost is more than offset by decreased herbicide and insecticide costs, increased yield, and the use of less labor-intensive conservation tillage practices. The use of fewer chemicals and conservation tillage practices also have associated environmental and health benefits.

The most common transgenic traits now in use are glyphosphate[19] resistance and Bt insecticide. Glyphosphate is a broad spectrum, post emergent herbicide. Its popularity is due to low cost, effectiveness against a broad spectrum of weeds and ease of application. It has the added benefit of being environmentally friendly due to its rapid breakdown to harmless by-products. The Bt trait allows producers to avoid applying costly, non-specific, insecticide. With the Bt trait integrated into the plant, only insects that are actually attacking the plant are affected. In addition to the cost savings, there are significant environmental benefits to avoiding broadcast application of highly toxic, long-lived organo-phosphate based chemicals.

Another category of transgenic food crops improves nutritional content, flavor, and shelf life. These consumer-focused products are just now reaching the market place. The best example of a product in this category is "Golden Rice." This transgenic rice has been genetically modified to produce vitamin A and iron. It is estimated that over 200 million people worldwide suffer maladies from vitamin A and iron deficiency.[20] Since rice is a dietary staple in many under-nourished parts of the world, Golden Rice has the potential to improve the health and well-being of a significant number of people. Other products in the pipeline that will benefit consumers include flavor and nutrient enhanced tomatoes and vitamin E enhanced fruits and vegetables.

The next "Big Thing" in agronomic biotechnology is the use of transgenic plants to produce pharmaceutical products such as biomolecular drugs, antibodies, and vaccines. The primary reason for turning to transgenic crops is the potential for significantly lower production costs. Production costs for corn-based systems are estimated to be between $10 and $100 per gram for proteins that currently cost as much as $1000 per gram.[21]

Several examples of how the economics of this technology could benefit consumers are illustrated by the following. It currently costs $400,000 per year to treat a patient for Fabry's disease. With a plant-produced treatment, the cost is estimated to drop to $40,000. Similarly, it is claimed that the leaves from 26 transgenic tobacco plants could make enough glucocerebrosidase, currently one of the most expensive drugs in the world, to treat a patient with Gaucher's disease for an entire year.[22] Industry projections estimate the market for PMPs and industrial chemicals could reach $200 billion by 2010.[23]

Changes to the Biotech Industry in 2002-2003

The breadth and depth of the biotechnology industry provides significant dynamic examples of financial, political, technical, and ethical issues across all domains within this field. The central theme of biotechnology developments over the last year is the complexities of realizing the great promise in biotechnology. The final refinements of the sequence of the human genome marked the 50th anniversary of Francis Crick and James Watson's discovery of the structure of DNA. The speed of DNA sequencing offered rapid information to attack emerging diseases. The controversy of human cloning research raged during a year that saw Dolly the Sheep die while a cult claimed to have cloned a human. Much money was infused into biodefense and biomedicine, but systemic challenges reduced the effectiveness of resource allocation.

The final refined sequencing of the human genome by an international consortium led by the Whitehead Institute and the Sanger Institute provides insight into how fast biotechnology has increased its capabilities. Acquired Immune Deficiency Syndrome (AIDS) was identified in 1981. It took until 1985 to complete the sequencing of the full genome of HIV-1.[24] Automated DNA sequencers only started coming into use around 1989.[25] After Severe Acute Respiratory Syndrome (SARS) emerged from Southeast Asia in November 2002, the virus was isolated and its sequence completed by April 2003. The powerful combination of advanced information technology and signal processing has emerged as a critical element of biotechnology: bio-informatics. The returns on this merging of technologies are just now beginning to be realized.

Dolly the sheep was successfully cloned in 1996 outside of Edinburgh, Scotland at the Roslin Institute.[26] Although Dolly lived almost seven years, and gave birth to four healthy lambs, she developed arthritis at a very early age. Her death on February 14, 2003, due to a lung disorder, was not attributable to her genesis as a cloned animal yet the postmortem analysis did not answer questions regarding the "DNA age" that Dolly may have been at birth.[27] Clearly, we have proven the ability to clone a large complex animal, but the difficulty associated with such an effort is best characterized by the multiple attempts it took to successfully clone Dolly from adult sheep cells. To illustrate the continuum of stability in the cloning field, there was a reported cloning of a human by a fringe group known as "Raelians," who claimed they had cloned a human baby that was born on December 27, 2002.[28] This remains unsubstantiated by independent analysis. The purported birth of baby "Eve" received significant media coverage, but was not regarded as a scientific, moral, or ethical achievement.

The ability to conduct research and development, and to commercialize products and services to detect, diagnose, protect, and treat people against maladies that impact humans is more than a function of technology or finances. The major pharmaceutical developments over the last year have occurred in the policy arena. The planning for massive use of the smallpox vaccine in response to a bioterrorist event in the United States has lost momentum. Although field trials have been conducted, to evaluate the mechanics of mass inoculation, the discussion regarding who should be vaccinated, and when, remains problematic. The threat of smallpox has been characterized, following the rapid defeat of Iraq, as not meriting even a limited inoculation program for first responders. The few deaths associated with the initial vaccine program received enough negative publicity that planning for a larger program was put on hold.[29] Still, manpower and communications shortfalls in the Public Health Departments nationally would make rapid response to any bioterrorist use of pathogens problematic.[30]

The economic slump in the United States economy created an environment that confounded some elements of the biotechnology sector. With venture capital markets providing less capital than in the booming 1990s, new companies are reliant of a variety of schemes to sustain their nascent product lines or ideas. Both the United States and the United Kingdom have programs in place at the federal level to support these companies. The ability of scientists to obtain initial funding remains adequate. There is a shortfall in the resources required to get products to Stage III Clinical trials. All too often companies are recipients of research grants that only support basic product research and then promising potential products are lost to the public as resources are not available to support the next level of development. Meanwhile, some entrepreneurs move from company to company, generating government grant money in excess of their companies' potential to bring biotechnology to market. The government (in the U.S., trusts in the UK) provides resources without a sufficient roadmap to keep the successful initiatives on track. Relying on markets to see the merit in any individual product or initiative is sometimes chancy; important potential products have dropped out of development.

The future integration of biotechnology for solving medical, agricultural, material, and energy problems remains problematic. Some key developments may be left behind by relying on the market to select goods that reach the consumer. The ability of government to successfully intercede in markets, or to accept a monopsony relationship with industry by product (the case of orphan drugs) creates microeconomic inefficiencies in the market place. Yet, the current method of selecting winners and losers in biotechnology may be as much a political as technical issue. Pending the revamping of the governmental resource allocation process and the creation of federally mandated Science Boards for follow-on capital support, the problems of technical closure will remain.

Challenges

FDA Approval Process for Medicines

The costs associated with regulatory requirements are significant for all biopharmaceuticals. The Food and Drug Agency (FDA) is the agency responsible for regulating and licensing all drugs and devices used in the U.S. for medical purposes. The interaction between the FDA and the pharmaceutical industry over the last few decades has resulted in a safe, well-defined, but expensive and lengthy process for development and testing of new products.

Biotech research and development is exorbitantly expensive. The FDA approval process for new drugs drives this in large part. Related closely is the cost of obtaining a patent for biotech medical products. Tying the former and the latter together is the length of the potential period of profitability, defined as the time during which the company may sell its product under the patent protection.

The U.S. process for drug approval is perhaps the most rigorous in the world. On average, it takes 12-15 years for a drug in the U.S. to go from the laboratory to U.S. patients. Only five in five thousand compounds that enter preclinical testing make it to human testing, and only one of those five is approved for sale.[31] The oft-cited figure to bring a biotech drug to the market is $500M.[32] The U.S. patent process that guarantees protection for a period of 20 years after a patent is applied for compounds this. In the instance of drug patents in particular, this is an extremely important consideration as the patent may be filed prior to FDA testing, meaning the entire period of testing is subtracted in effect from the patent-protected marketing window. To ameliorate this concern, companies may file for a five-year patent extension based on the time required for clinical trials.

For these reasons, biotech health care companies must quickly evaluate the sales potential of new products. Many medicines or technologies with direct applicability to health care and treatment of disease may never make it out of the laboratory because there will not be enough of a market to make a business case for producing them. In some instances, the U.S. government, through selective R&D and contracted production, will fund the cost for specific medicines that companies independently cannot produce profitably because of exorbitant unit costs or very limited demand for the drugs.

Genetically Modified Organisms

Despite the obvious benefits, transgenic food products have their critics. Concerns regarding food safety, accelerated pesticide resistance and the introduction of "unnatural" genes into the environment are often expressed as drawbacks to transgenic agricultural plants. While these concerns appear legitimate, they are largely discredited by seven years of widespread use and extensive scientific analysis by the United States Department of Agriculture, The Food and Drug Administration and the Environmental Protection Agency.

Perhaps the most significant issue facing transgenic agriculture is the moratorium imposed by the European Union (EU) on the importation of genetically modified products into the EU marketplace. Proponents of transgenic crops contend the ban is not scientifically supportable and is being used as a protectionist trade tactic. The U.S. has recently been joined by nine other countries in filing suit with the World Trade Organization on the grounds the ban is not scientifically based.

Ethical Concerns in the Biotech Industry

Stem Cell Research and Cloning: In the fall of 1998, "President Clinton charged the National Bioethics Advisory Commission with the task of conducting a thorough review of the issues associated with human stem cell research, balancing all ethical and medical considerations."[33] The Commission made recommendations that effectively made federal funding on stem cell research contingent on the material's sources. This effectively eliminated some institutions, and government funded labs from continuing research due to those sources. The Commission is not

the only entity to question the practices of this research. Several organizations, institutes, and religious organizations debate the ethical implications of stem cell research and have supported legislation that has effectively inhibited scientists looking for cures to cancers, and other diseases. An example of this is the prohibition on the use of appropriated funds in support of embryonic research. In particular, it was aimed at the National Institute of Health, and the Department of Health and Human Services.

In June of 2001 the Biotechnology Industry Organization (BIO) took issue with Senator Sam Brownback who had offered an anti-cloning patent amendment.[34] One of their concerns was that Congress was using a back-door maneuver to prohibit stem cell research by making it unprofitable for investment. BIO stated that, "This amendment could stop stem cell research. The amendment would appear to ban issuing patents for the process of deriving stem cells. The NIH has concluded that embryonic stem cells have the potential to form any cell in the body and therefore could hold the key to treatments and cures for many diseases."[35]

Biomedicine is an area that increasingly squares ethical beliefs against scientific possibilities.[36] These conflicts will continue to demand attention, as scientific advances will time and again challenge ethical views. In many cases, stem cell research being a specific example, there is a risk of the technology moving overseas to less restrictive research environments. This portends a loss of the technological edge, and concurrently poses the threat of scientific research of potentially profound consequence in a less regulated venue than we in the U.S. may prefer.

Some have asked, "What is the role of religious faith in all this? It may seem immaterial, or even counterproductive, to bring questions of faith and religious belief to the table when the legislative, economic, and social ramifications of new biological and medical technologies clamor for our attention. Religion and science are pitted against each other in romantic images of the lone scientist defending scientific truths and the spirit of inquiry against the onslaughts of reactionary organized religion--John Scopes standing up for evolutionary theory. One must proclaim faith in either God or scientific method, it seems, never allegiance to both."[37] The author suggests that ethical and religious positions must be brought into a dialogue with scientists to know "how to handle the knowledge and technology garnered by scientific research."[38]

Ethical Testing: Testing vaccines and treatments on humans for effectiveness against biological pathogens is governed by ethical concerns because human testing would require deliberately exposing subjects to biowarfare agents. Testing on humans is rarely permitted, with the possible exception of those rare cases when developmental drugs or vaccines are available in the event exposure to pathogens has occurred. Development of genetically engineered animals that incorporate human characteristics provides animal models of human exposure to pathogens for use in testing. The FDA has recently indicated that they may approve testing methods that substitute animal models for testing human drugs for use against biological weapons.

Advanced computer modeling techniques are beginning to allow analysis of molecular dynamics of infectious processes and cell membrane permeability to pathogens. Discovering the biologic mechanisms of infection or cellular process disruption of pathogens using advanced

computing techniques would lead to approaches to interfere with infectious processes. It will also possible to run large numbers of virtual experiments using computer models that simulate interactions of known genetic structures with experimental proteins.

Biotechnology Industry Workforce

Workforce Demand: The biotechnology workforce has experienced substantial growth over the last 10 years as evidenced in the table below. In fact, the biotechnology industry workforce has more than doubled during the last decade from approximately 80,000 employees in 1992 to the current estimate of 200,000 employees.[39]

The growth and subsequent demand in the workforce is likely to continue in the future, especially when the expanding numbers of products transitioning from research and development to production are considered. Moreover, the increase will require a workforce with a broader set of skills, particularly in the manufacturing and business fields. The biotechnology workforce is conservatively estimated to grow to 500,000 by 2012.[40] And, interestingly, biotechnology's growth has weathered the recent economic downturn with only a slight contraction—stock prices notwithstanding. While many high technology companies have been letting people go, many biotechnology companies have active hiring programs and opportunities.[41]

Biotechnology Industry Employment	
Year	**Employment (in '000s)**
1992	79
1993	97
1994	103
1995	108
1996	118
1997	141
1998	155
1999	162
2000	174
2001	191

Satisfying the biotechnology workforce demand presents challenges for the United States. The skill set needed does not necessarily compare with the workforce skills in other industries. Hence, there cannot be an easy migration from other industries into the biotechnology workforce. Virtually all members of the current biotechnology workforce have education and training beyond secondary school. The workforce education levels are as follows: PhD – 19%, MS – 17%, BS – 50%, and employer trained – 14%.[42] Inherent in the requirement for an educated workforce is a need for education in highly scientific fields. A recent study by the Rochester Institute of Technology found that the primary disciplines viewed as important by prospective biotechnology employers are microbiology, biochemistry, and molecular biology.[43] In addition, follow-up training in laboratory management and information management are necessary to complete workforce development. Even with a shift from research and development activities to larger production activities, the requirement for a highly trained workforce will remain. As the biotechnology industry shifts from "R" to "D," increasing requirements for employees possessing skills in regulatory matters, quality issues, technology management, and interdisciplinary aspects of product development and manufacturing are anticipated.[44]

Workforce Education: Noting the skills and education requirements for the biotechnology workforce discussed previously, the adequacy of the U.S.'s education system to supply a workforce becomes another challenge for the industry. The issue fits nicely—or unfortunately, as the case may be—into the national desire to place more emphasis on science and engineering

education. Much of the U.S.'s biotechnology success is derived from the investment in venture capital funds, government-sponsored research, and biotechnology investment.[45] A portion of the success can also be attributed to the human capital products of U.S. colleges and universities. However, the higher education system may find it difficult to keep up with the predicted growth in the biotechnology workforce.

It is particularly challenging to find qualified specialists in bioinformatics. The wealth of biotechnology-related data continues to expand, along with the need to analyze and understand it, and specialists in bioinformatics are now in great demand.[46] A recent national survey has shown that less than 250 people are being trained in bioinformatics.[47] Difficulty in finding qualified individuals at the intersection of two sciences should not be surprising given the difficulty in satisfying demand in single science areas.

Role of Foreign Workers: Under U.S. immigration law, workers with unique skill sets who are not available in the existing labor pool acquire (through a company-sponsored application process) permission to stay in the U.S. for up to six years, after which they can apply for permanent status.[48] These workers are designated as H-1B visa holders. Law caps the number of H-1B visa holders. Estimates of the biotechnology industry indicate that between 6% and 10% of the workforce are H-1B visa holders. This percentage increases if the biotechnology-related portion of information technology is included. It is important to note that 80% of biotechnology H-1Bs are products of U.S. colleges and universities, and 85% of those eventually acquire permanent residency.[49]

There are two issues surrounding the role of foreign workers in the biotechnology industry. The first concern is the ability to keep these workers in the U.S. biotechnology workforce. The second issue is the concern with foreign access to critical technologies. The latter issue is one of particular importance because of the potential harmfulness of biotechnology products and, more seriously, the possible desire to use this technology to build weapons.

While the evidence cited previously indicates a large proportion of the H-1B visa holders remain in the U.S., that phenomenon may not hold in the future. As biotechnology industries develop and mature outside of the U.S., more foreign nationals may be compelled to return to their countries of origin or recruited to other countries. This could conceivably reduce the U.S.'s competitiveness in the global biotechnology industry. Subsequently, the loss of this portion of the workforce would mean not only the loss of talent, but also perhaps the loss of intellectual property. The biotechnology industry is information-based and information is very portable.

The second issue associated with foreign nationals in the biotechnology industry is the potential for the technologies and skills to be used for harmful purposes. Biotechnology products have the potential to be made into devastating weapons. The threats include biological warfare agents that are harmful to people as well as other agents directed against the nation's agricultural system. Considering the list of countries that have H-1B visa holders, one cannot overlook the fact that several of the countries may feel compelled to develop weapons programs for their own national security. Some foreign nationals who to return to these countries may be compelled to use their skills for weapons development. This should no doubt be a concern, not only for the biotechnology industry, but also for the U.S. Government and policy makers.

Defending Against Biological Terrorism

Bioshield: The President proposed a plan to protect the nation against biowarfare attacks in his 2003 State of the Union address. Project BioShield proposes funding of about $6B over the next 10 years to buy and stockpile vaccines and drugs for protection against smallpox, botulinum and anthrax. Project BioShield also promotes research on countermeasures against other potential biowarfare agents. The project will also speed development of recent scientific discoveries in prevention and treatment concepts and give the FDA authority to allow use of new treatments quickly in a crisis. Biotechnology firms like Human Genome Sciences, developers of the monoclonal antibody 'Abthrax' to treat anthrax infections, anticipate that Project BioShield will provide both grant assistance for clinical trials and a market for licensed product.[50]

Detection: Development of detectors for biological weapons should remain a priority. Bioweapons are often invisible, odorless, and tasteless. In addition, BW is suitable for covert delivery and useful to terrorists.[51] Early detection and identification of biowarfare agents provides warning time to implement protective measures and plan post-exposure treatment and decontamination. Detection of biological threats could also be an important market for biotech companies. A characteristic of biological weapons that makes them attractive is stealthy use. The effects of biological weapons may not be apparent for days after the deployment of the agent, and identifying the specific agent and treatment can take even longer. In the case of infectious viruses, this delay can allow an infection to spread unchecked. The Centers for Disease Control (CDC) are addressing solutions to the detection problem by training primary care practitioners in recognizing symptoms and reporting patterns of illness, but even faster detection and verification testing is needed.[52]

Viability of Biodefense Industry: Traditional business tradeoffs also come into play when companies consider manufacturing biological products. Biopharmaceuticals require huge capital investments for production facilities, so there is a minimum production size required to cover production costs. The annual military needs for special biowarfare vaccines are small compared to products for commercial markets, and unless the price of the defense vaccine is high, there is no incentive for companies to dedicate development or manufacturing resources to it.

Market forces determine whether a biodefense product such as a vaccine is developed commercially. Pharmaceutical companies are the only source of both the expertise and huge sums of money required to bring drugs to market so they often form partnerships with biotech research companies to obtain access to new products. Some pharmaceutical companies with research interests in both biopharmaceuticals (large molecule) and drugs (small molecule) may decide that the additional costs and risks associated with some biopharmaceuticals will not return as much on investment as drug production, leading to some biopharmaceutical products being abandoned. Even if promising biopharmaceutical innovations are marketed to other companies, the project might not find a sponsor.

Liability concerns effect decisions to produce vaccines and treatments. When many people receive treatment, the medical outcome for every individual may not be optimal. Some of these unfortunate recipients will seek damages in court from manufacturers. Emotion, rather than

science, can influence juries in medical claims cases, and exposure to huge judgments can have a chilling effect on the entire vaccine industry. Lawsuits reached such a level in the 1980s that they threatened to force manufacturers out of the vaccine business. Congress passed the National Vaccine Injury Compensation Act in 1986 giving limited relief to manufacturers by capping liability for damages caused by manufacturing error. Though the industry did gain some relief from this act, liability remains a concern.

Future Trends in the Biotech Industry

Biotechnology's future will be our future. It will affect our daily lives, from its ubiquitous presence in the production of common items and materials to the creation of fantastic health benefits. It will add to our nation's defensive capabilities in critical ways. It will provide significant economic challenges and benefits. It will significantly change the quality of life for vast numbers of people. It will not satisfy our quest for understanding nature nor our desire to control it, but it will take us further down those paths. It will bring continued ethical debates.

Paths of science are not always linear. Science's history is replete with serendipitous accidents, revolutionary ideas, and unexpected discoveries. These discontinuities of discovery and development reinforce the unpredictability of biotechnology's future. However, in modern bioscience, some fundamental questions could provide foundations for future biotechnology just as important as today's central dogma. "How do cells differentiate?" "What is the molecular basis for aging and dying through apoptosis?"[53] "How does the mind function on a molecular level?"

There are practical reasons to explore these questions and develop applications. The motivations are varied – continuance of life on earth, extension of human life, improvement of health, enrichment of the quality of life, security, food, profit, lust, power, narcissism, self-appointed apotheosis, and destruction. These motivations will influence resource allocation and regulation, whether for a profitable biotechnology industry or for national defense.

Proteomics: As genetics has formed much of the basis for current biotechnology, proteomics will form the basis for the next generation. This study of the structure and function of proteins has its origins decades ago. While genes store the information for life, proteins are the products of those genes – the products that make life occur. From enzymes that catalyze the biochemical reactions of metabolism to structural proteins essential to cell organization to antibodies, signaling peptides, and hormones, proteins put the information of life to work. The protein's sequence of amino acids, coded for by the gene, is responsible for the protein's structure and function.

Current biotechnology that exploits molecular genetics uses techniques to change where genes are expressed – human genes put into bacteria to produce human proteins for injection into patients or human genes put directly into gene-deficient patients through the process of gene therapy. Here, biopharmaceuticals are based on existing genes coding for existing proteins.

Some firms have made slight genetic changes or combined genes to make modified proteins. The goal is to produce a protein that has slightly different characteristics, perhaps a longer

duration in the body[54] or an increased efficacy through enhanced binding. This remains much a trial-and-error process. Changing the amino acid sequence even slightly may change the protein's structure and affect its functionality. Biological activity may be lost or an agonist could become an antagonist.

The ability to quickly determine or accurately predict protein structure and function from a gene code will set the stage for designing proteins as biopharmaceuticals *ab initio*. Today, many pharmaceutical corporations employ three-dimensional computer modeling to design small molecule drugs when protein receptor sites are well characterized. Such rational drug design is limited by an incomplete knowledge of those sites and by the complexities of human metabolism. Just because a drug may be designed to affect a certain receptor does not guarantee that the drug will be effectively delivered to the site, that the drug will not have deleterious side effects in its interactions with other biomolecules, or that the drug will not be metabolized into harmful products. Due to the specificity and efficiency of protein interactions, along with known degradation pathways, rational biopharmaceutical design holds potential for creating medicines with unprecedented efficacy and safety. Information technology holds the promise of creating such products with unprecedented speed.

Deciphering Metabolism: Complex biological problems rarely have simple solutions. Human metabolism abounds with complex biochemical pathways replete with positive and negative feedback mechanisms, inhibitors and activators, and signaling and transport mechanisms. Enzymes often require small molecules or metal ions as cofactors. Once again, advances in techniques and computing power, along with the persistent build-up of knowledge, promise a future of understanding disease mechanisms with unprecedented resolution to molecular level. Researchers will build models of disease action from genetic code to molecular cellular biology to whole organs.[55] This knowledge will enable the rational design of both small molecule pharmaceuticals and biopharmaceuticals. Based on one's genes, treatment may start before symptoms manifest themselves.

A step beyond the *in vitro*, *in vivo*, or even *in situ* production of medicinal proteins is the exploitation of the mechanisms of cell growth and differentiation. Being able to transform a patient's adult stem cells into organs for transplantation back into that person would prevent rejection and relieve a critical shortage of organ donors.[56] One step further would be the creation of a single treatment, perhaps a gene therapy cocktail or even something quite different, which would promote healthy tissue regeneration *in situ*.[57] Given the favorable acceptance of organ transplants, such treatments likely would not raise much controversy. On the other hand, similar treatments aimed at overcoming the mechanisms of aging will be both hailed as miraculous and subjected to discerning ethical debates.

Beyond Biopharmaceuticals: Clearly, there will be huge profit motives to produce performance-enhancing biochemicals. This will bring additional controversy in sports and raise other ethical questions. On an economic side, one can question whether profit motives will divert valuable resources in research and development away from less-prevalent orphan diseases and toward performance enhancers. These performance enhancers will be available to those who can pay. This will further stratify segments of our society as well as our nation from other,

poorer countries. If the biotech industry produces true memory enhancers, what will this do for stratifying educational opportunities and career fields in advanced countries?

Biotechnology holds promise in producing unique materials, enhanced agricultural products, and biochemical-based machines. Biotechnology has demonstrated promise in the production of unique materials, such as spider web protein expressed in goat milk for high-tensile-strength fibers for military applications such as ballistic-resilient cloth.[58] Genetically modified foods, while currently experiencing a certain level of controversy, hold great potential for more nutritious, hardier crops. Science also could enhance non-food agricultural products used as materials. A logical further step would be the use of microorganisms, enzymes, or discrete biochemical processes for the production of materials, especially with intricate, nanoscopic architectures that produce enhanced properties. Biotechnology and nanotechnology may find areas of convergence in miniature environmental sensors,[59] while areas such as vivisystems, hybrid biosystems, and biomimetics mesh biology and machinery.[60] Biochemicals hold potential as unique nano-machines, such as a DNA motor.[61] Biotechnology holds the potential for creating efficient organisms or biochemical-based machines to harvest energy from sunlight or organic material, converting it directly into electricity. Biotechnology and information technology may find convergence in DNA computing.[62, 63] Could further convergence bring an understanding of how human memory is molecularly organized or how animals inherit instincts? What would be the ethical debates and political implications of "learning" through the uptake of selected biochemical libraries?

Ethical controversies will abound whenever biotechnology creates a nexus with procreation / creation of life, destruction of life, the basic nature of man, immorality, or "playing God." Thus, issues such as human cloning, creation of embryos solely for harvesting stem cells, or growing fetuses for harvesting nascent organs will evoke strongly emotional ethical controversy. Creating transgenic humans or children with certain traits (gender, hair color, eye color, predisposition toward athleticism, freedom from genetic diseases, absence of predispositions toward obesity, alcoholism, or violence) will produce complex issues requiring greater public education and intellectual debate.

National Strategy for Biotechnology

Biotechnology is emerging as a significant factor in America's growth, prosperity, and defense, building on the information technology wave that began to crest ten years ago. Biotechnology has crept into our national strategy by design and default. The most affluent generation in U.S. history has been demanding a better quality of life and improved health care. Science has been aided by improvements in information technology that facilitated collaboration, experimentation, and modeling. Biotechnology has been a critical enabler in increased productivity in our agricultural sector. Since September 11th, we have seen clearly the security of our nation requires we invest in preparedness and an ability to respond to biological warfare and bioterrorism. Government and private investment will remain necessary for the biotechnology industry to grow and compete internationally. As a sign of its commitment to the industry, three of the four policy initiatives in the Administration's FY 2003 budget center directly or indirectly on biotechnology: support to first responders, defending against bioterrorism, and using 21st century technology for homeland security.

We believe biotechnology can be a powerful engine for economic growth. The life sciences sector as a whole provides fertile ground for continued research and development that will expand our technological base, create jobs, and develop several economic sectors. While numerous states are offering tax incentives and other financial inducements to attract biotech firms, the biggest economic benefit will come to the regional centers where the industry already is located. Several states such as California, Massachusetts, and Maryland have developed biotechnology strategies of their own to encourage university research and commercial opportunities as well as partnerships among government, business, and higher education. The biotechnology industry itself actively pursues collegial efforts to promote the emerging technology. The Biotechnology Industry Organization (BIO) seeks to encourage economic opportunities and supportive government policies for the industry.

Current and future applications of biotechnology will provide better health care and food production, lessening the effects of poverty and improving the quality of life. Our higher education situation has profited as it attracts the most gifted students, both from the U.S. and abroad. We still need to do more to bring U.S. students into the sciences at the undergraduate and graduate levels, but the influx of different perspectives and the personal drive of many immigrants add to our national strength.

There are actions the federal government can take to help create and sustain an environment that encourages the development of new technologies, intellectual property, and innovative products to improve health care and the quality of life. First is the continued encouragement of applicable R&D through grants and cooperative programs of directed and fortuitous research. In addition to direct financial incentives, our government should examine potential regulation of export laws and patent protection through international regulating bodies. Proprietary rights need to be respected in kind by other nations, yet there are countries today that replicate medicines without any regard for patents.

The FDA's long and thorough approval process has survived the test of time and effectiveness. Many biotech drugs are geared toward treatment of late stages of disease, specifically toward advanced cancers or patients who have exhausted previous drug regimens. In these instances, the FDA, in concert with the patients, drug companies and physicians, should consider the applied use of these treatments as a possible avenue of last resort with the concurrent benefit of gaining clinical trial data. The FDA should expand clinical trials to include the widest possible applicable population consistent with at least a preliminary approval of the drug as an experimental regimen.

To ensure biotechnology follows the path most beneficial to society, we should demand government regulatory oversight and coordination of directed research and development of significant advances in this field. This is particularly pertinent in areas in which companies do not have sufficient economic incentive to pursue narrowly defined goals, for instance undertaking lengthy programs such as the Congressionally mandated work on finding cures for cancer.

Biodefense: The U.S. appears to continue leading the world in the development and production of vaccines and drugs with potential for use against biological weapons. The new Bioshield initiative sets priorities and will provide funds for development and stockpiling of vaccines and drugs for the prevention and treatment of bioweapon exposure. Recent advances in the biotechnology industry may provide a number of new tools to deal with biological threats. The successful acquisition of many of the most useful advances may be determined by the social and business contracts we make with this industry. Only a small number of companies in a specialized segment of the pharmaceutical industry make biological products. Biological manufacturing processes have more inherent variability and risk than the chemical processes of drug manufacture. Without a very good expectation of profit, companies are not likely to pursue research or production.

The DoD can sponsor the development and manufacture of vaccines and drugs directly. The U.S. Army has traditionally managed government efforts to research vaccines and stockpile treatments for biological weapons. Several vaccines are in advanced development.[64] The Government can provide contracts and financial support to a company with a licensed product. The DoD also has unique authority to indemnify contractors against risk. This ability can be a powerful incentive to companies who may be very risk-averse to potential liability claims for new vaccines. Government departments can relax licensing requirements and procure huge amounts of vaccines at one time to make development and production more attractive to industry. One recent government proposal for a new recombinant anthrax vaccine would award a development and production contract for up to 25 million doses of vaccine based on a recombinant form of the anthrax Protective Antigen (rPA). The vaccine would have to be developed and produced under Current Good Manufacturing Practices, however licensing would not be required. Should the stockpiled vaccine be required for use, it could be administered under the regulation for Investigational New Drugs (IND) by the President's authority[65]

Advances in biotechnology will offer new methods of countering biological threats. Commercially produced biological treatments and vaccines will continue to be the preferred weapon in the military and public health arsenals. A coordinated effort involving the military, public health agencies, regulators, and private enterprise is producing new approaches for preventing infection and treating exposure to pathogens, but the cost of developing and licensing the new treatments will be high. The relatively small vaccine needs of the government may not make economic sense to commercial vaccine producers. We should attempt to make development and manufacture of defense vaccines more attractive by: supporting cooperative research, allowing regulatory flexibility to reduce testing time, indemnifying manufacturers of military and public health vaccines, making commitments for mass purchases, and exploring the construction of government-owned manufacturing facilities.

Long-term implications for national defense are manifold. People have assembled virulent viruses *in vitro* using inert biochemicals, starting from gene sequences, simply to show it was possible.[66] Speedily deciphering disease mechanisms and creating countermeasures will be critical to the nation's defense against bioterrorism. This area must be a priority for resources and teaming between public and private sectors.[67] Eventually, the fidelity of computer modeling may preclude the need for a conventional FDA clinical trial regime, especially in an emergency, while providing great confidence in the safety and efficacy of the countermeasure. There will be

many cutting-edge applications for materials created by biotechnology, with research funded by government long before such materials show promise for commercial development. Performance-enhancing biopharmaceuticals that society deems ethically acceptable may boost soldiers' endurance, strength, mental ability, or sensory capabilities (such as infrared vision).

Conclusion

Biotechnology is arguably the next revolution in the application of science. The industry is fueled by the expanding knowledge base in microbiology and biochemistry, and it is employing information technology to the greatest possible advantage. Judging from the products in the pipeline and those predicted, the potential benefits to society are extensive. The industry promises to improve the quality of health, agricultural production, and the environment. There are, however, bumps in the road to biotechnology's success and commercial viability. The inevitable failures in applied research, the instability caused by investor impatience, and perhaps most important, the ethical debate associated with genetic engineering are chief among the forces that affect this industry. Moreover, no discussion of an industry or technology is complete without a treatment of its impact on national security.

Biotechnology is a unique industry, but it is an industry nonetheless—subject to regulatory constraints, workforce issues, and economic cycles. Biotechnology's dawn is no different from the first years of the automobile or information technology industries. The industry will no doubt stabilize and standardize; there will be winners and losers; and ultimately, the industry will become an ingredient in the economic component of national security. Investor cynicism is presently a key issue affecting the industry. With decade-long lead times from basic research to marketing of commercial products, continued infusion of cash to sustain research and development is paramount. Protection of intellectual property is another critical challenge for the biotechnology industry as well as concerns over foreign nationals in the workforce. Additionally, the need for a highly skilled and educated workforce highlights the problems in attracting students to the science and engineering disciplines.

Part of the uniqueness of biotechnology is attributable to the ethical debate it cultivates. The debate is reminiscent of the effects that Copernicus and Darwin had on science and society. Those debates were overcome once the observations became obvious. The debate over biotechnology is much more complex. Humankind is now about to deconstruct, reconstruct, and manipulate the basic building blocks of life. It generates not only religious issues, but issues of unintended consequences. Biotechnology as a tool in war is also a concern, leading to the necessity of an investment in biodefense.

Despite the challenges and issues, one is assured that biotechnology will have a significant impact on world politics, economies, and militaries. Globalization and the eventual spread of science means the United States will not have a monopoly on biotechnology. Policymakers must flesh out the debate while not impeding the advancement of science. Continued federal investment and private sector stimulus in biotechnology is warranted because the need for economic power dictates it, and the need for military power demands it.

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