Chapter 8

Environmental Applications

"If it wasn't for the high cost of the alternative, this (bioremediation) wouldn't be worth considering at all.'

Perry L. McCarty
Stanford University, 1987

CONTENTS

Boxes

Figure

Tables

Chapter 8

Environmental Applications

INTRODUCTION

Micro-organisms have several potential uses in the environment, for purposes as diverse as agriculture, pollution control, mining, and oil recovery. With the arrival of biotechnology, the potential of improving micro-organisms for selected uses has received increased attention and speculation. However, research and product development in the environmental sectors are minuscule compared to more commercially lucrative sectors influenced by biotechnology, and international activity to date is limited. This chapter summarizes some potential environmental uses of biotechnology and uses a case study approach to analyze bioremediation efforts to commercialize biotechnology for hazardous waste management.

ENVIRONMENTAL USES OF BIOTECHNOLOGY

Biotechnology has several potential applications, including pollution control, agriculture, mining, and microbial enhanced oil recovery (MEOR). For all four areas, commercial hurdles exist: technical, research funding and priorities, scale-up, regulatory approvals, and economics.

Pollution Control

Biotechnology has several applications for pollution control, including solid and liquid waste treatment, hazardous waste management, slime control (e.g., manufacture of paper), and grease decomposition (e.g., meats and certain foods, and waste water collection) (13).

Current commercial applications of biotechnology rely on conventional techniques of genetic manipulation and microbiology; the use of recombinant DNA (rDNA) to develop microbes with special capabilities for waste degradation has been limited. As of 1988, 65 companies were involved in some aspect of biotechnology for waste management (15). None is currently using or even testing genetically engineered micro-organisms in the environment, although research is going on in the lab (see table 8-1).

Table 8-l-Challenges for Pollution Control and Toxic Waste Treatment

- The isolation and characterization of enzymes to degrade low molecular weight organic compounds.
- Better characterization of metallothioneins (proteins that have a high affinity for heavy metals) from various species.
- The identification of polysaccharides to serve as bioflocculants (materials that thicken sludges for separation treatment).
- The development of enzymes for sludge dewatering.
- The development of microbial strains or enzymes that degrade toxic compounds.
- The development of improved polysaccharide hydrolyses to degrade slimes.
- To decrease regulatory uncertainty.

SOURCE: Office of Technology Assessment, 1991.

The *Exxon Valdez oil* spill in Prince William Sound in 1989 focused public attention on the use of bioremediation for oil-spill cleanups. Of the various environmental applications possible through biotechnology, oil-spill cleanup and hazardous waste treatment constitute the only major commercial activities to date.

Agriculture

Potential environmental applications of genetically engineered organisms in agriculture are varied (see table 8-2). Genes have been introduced into

Photo credit: Environmental Protection Agency

Prince William Sound, Alaska site of the extensive bioremediation experiments carried out by the Environmental Protection Agency, Exxon, and the State of Alaska.

Table 8-2—Some Potential Environmental Applications of Genetically Engineered Organisms in Agriculture

Micro-organisms

Bacteria as pesticides:
- "Ice-minus" bacteria to reduce frost damage to agricultural crops.
- Bacteria carrying *Bacillus thuringiensis* toxin to reduce loss of crops to dozens of insects.
- Mycorrhizal fungi to increase plant growth rates by improving efficiency of root uptake of nutrients.
- Nitrogen-fixing bacteria to increase nitrogen available to plants and decrease the need for fertilizers.

Viruses as pesticides:
- Insect viruses with narrowed host specificity or increased virulence for use against specific agricultural insect pests, including cabbage looper, pine beauty moth, cutworms, and other pests.

Vaccines against animal diseases:
- Swine pseudorabies
- Swine rotavirus
- Vesicular stomatitis (cattle)
- Foot and mouth disease (cattle)
- Bovine rotavirus
- Rabies
- Sheep foot rot
- Infectious bronchitis virus (chickens)
- Avian erythroblastosis
- Sindbis virus (sheep, cattle, chickens)

Plants

Herbicide resistance or tolerance to:
- Glyphostae
- Atrazine
- Imidazolinone
- Bromoxynil
- Phosphinotricin

Disease resistance to:
- Crown gall disease (tobacco)
- Tobacco mosaic virus

Pest resistance:
- BT-toxin protected crops, including tobacco (principally as research tool) and tomato.
- Seeds with enhanced antifeedant content to reduce losses to insects while in storage.

Enhanced tolerance to environmental factors, including:
- Salt
- Drought
- Temperature
- Heavy metals

Enhanced marine algae:
- Algae enhanced to increase production of such compounds as B-carotene and agar or to enhance ability to sequester heavy metals (e.g., gold and cobalt) from seawater.

Forestry;
- Trees engineered to be resistant to disease or herbicides, to grow faster, or to be more tolerant to environmental stresses.

Animals

Livestock and poultry:
- Livestock species engineered to enhance weight gain or growth rates, reproductive performance, disease resistance, or coat characteristics.
- Livestock animals engineered to function as producers for pharmaceutical drugs.

Fish:
- Triploid salmon produced by heat shock for use as game fish in lakes and streams.
- Fish with enhanced growth rates, cold tolerance, or disease resistance for use in aquiculture.
- Triploid grass carp for use as aquatic weed control agents.

SOURCE: Office of Technology Assessment, 1991.

several plant species to confer resistance or tolerance to certain herbicides. Plants have also been better engineered to resist disease and to confer pest resistance. Most deoxyribonucleic acid (DNA) work on animals focuses on altering livestock, poultry, or fish to improve reproductive performance, weight gain, or disease resistance. Many promising environmental applications of engineered micro-organisms are also being developed.

Planned introductions of genetically engineered organisms into the environment, often called ***deliberate release,*** was the focus of an earlier Office of Technology Assessment (OTA) report (14). Commercialization in agriculture is discussed elsewhere in this report (see ch. 6).

Mining

Natural micro-organisms have been used for mineral leaching and metal concentration processes. No Federal funding directly supports microbiological mining, however, and commercial activity is sparse (see table 8-3).

Limited international research in the field of biohydrometallurgy is proceeding. Canada, South Africa, the United Kingdom (U.K.), and the United States have ongoing programs in biohydrometallurgy. The Canadian Center for Mineral and Energy Technology is the leading governmental research agency in this area. One area of focus for the Canadians is uranium bioleaching; one mine is now bioleaching 90,000 pounds of uranium per month. The biological mitigation of acid mine drainage is another Canadian project (7). Research is slow, however, because of economic aspects in the mineral market. As long as metals are plentiful and easily mined, no economic advantage is realized by microbiological mining.

Microbial Enhanced Oil Recovery

It has been estimated that more than 300 billion barrels of U.S. oil cannot be recovered by conventional technology but may be accessible through enhanced oil production. This volume is 2.5 times as large as the amount of oil produced by the United States since 1983. The actual enhanced oil recovery production has been low, no greater than 5 percent of total U.S. production, even though a variety of Department of Energy (DOE) incentives have been available. Other countries, such as Canada, have projected that by the year 2010, one-third of its oil recovery will utilize enhanced techniques. In recent years, advanced oil-drilling techniques have enhanced overall yield, and it is expected that these techniques, not micro-organisms, may satisfy oil companies' needs for greater yield in the short term.

Table 8-3-Challenges for Microbiological Mining

- The development of micro-organisms that could leach valuable metals, such as thorium, silver, mercury, gold, platinum, and cadmium.
- A better understanding of the interactions between the micro-organisms and the mineral substances.
- The development of DNA transfer technologies for use at low pH.

SOURCE: Office of Technology Assessment, 1991.

Although most of the major oil companies have in-house staff investigating and perfecting MEOR, the methodology's low cost may appeal more to small-field operators, who have already pumped and sold the easy-to-get component of their field (8). MEOR is not predictable; just like the use of micro-organisms for hazardous waste remediation, the use of micro-organisms for oil recovery is site-specific. Individual oil deposits have unique characteristics that affect the ability of micro-organisms to mobilize and displace oil. An understanding of the microbial ecology of petroleum reservoirs is a prerequisite to the development of any MEOR process, whether microbial or not, since an inappropriate design may accelerate the detrimental activities of micro-organisms (e.g., corrosion, reservoir souring, and microbial degradation of crude oil) (l). Basic environmental biotechnology research underway for contaminated soil and groundwater will provide much needed information to those working on MEOR (see table 8-4).

CASE STUDY: BIOREMEDIATION

Cost estimates for the cleanup of contaminated soils and groundwater and the routine disposal of industrial and municipal wastes, range up to $23 billion for the United States and $60 billion for Western European countries (3,6). The price tag for construction and maintenance of treatment systems used for continually produced waste is unknown. In the search for a cleaner environment, claims have been made that biotechnology holds great promise for hazardous waste reduction and cleanup as well as permanent restoration of air, water, and soil.

Table 8-4-Challenges for Microbial Enhanced Oil Recovery

- Better biochemical and physiological understanding of micro-organisms already present in oil reservoirs.
- Development of micro-organisms that degrade *only* the less useful components of oil.
- Screening of micro-organisms for production of surfactants and viscosity enhancers and decreases.

SOURCE: Office of Technology Assessment, 1991.

Bioremediation is a term that refers to efforts to use biotechnology to cleanup waste. These efforts involve the engineering of systems that use biological processes to degrade, detoxify, or accumulate contaminants. These systems can use naturally occurring or laboratory-altered microbes or both. Current applications rely on conventional techniques of genetic manipulation and microbiology; the use of rDNA to develop microbes with specific capabilities for waste degradation has been limited (see figure 8-l).

Bioremediation can be used at a variety of sites and in a variety of applications, including waste-stream cleanup, wood treatment-site cleanup, degradation of polychlorinated biphenyls (PCBs), groundwater treatment, and cleanup of chemical manufacturing wastes. The rationale for using micro-organisms to degrade pollutants comes from experience with nature. Micro-organisms have a variety of capabilities that can be exploited for waste management and disposal. Many organic compounds of biological origin are readily degraded. Industrial chemicals similar in structure to natural compounds are also frequently biodegraded (15).

The recent use of naturally occurring microbes in oil-spill cleanup--off the coasts of Alaska and Texas--has focused public attention on commercial uses of bioremediation. This attention is enhanced by frequent claims that biotechnology can be used to mitigate environmental pollution (see box 8-A).

This section describes the U.S. and international biotreatment industries, the advantages and barriers facing the commercialization of bioremediation, and the prospects for using genetically engineered organisms for hazardous waste cleanup.

The U.S. Biotreatment Industry

The frost U.S. company to produce microbes for waste treatment opened in the early 1950s. Over the next 20 years, the U.S. biotreatment market expanded to a handful of companies specializing in the production of microbial "cocktails" for municipal sewage treatment plants and odor control. In 1970, the establishment of the Environmental Protection Agency (EPA) and the creation of Federal and State environmental statutes governing the treatment of wastes guaranteed a market for the environmental services industry, to which bioremediation firms belong. Today, the U.S. biotreatment industry includes 134 firms and has evolved into four segments: bioremediation services, multidisciplinary environmental services, products, and waste generators.

Bioremediation Services

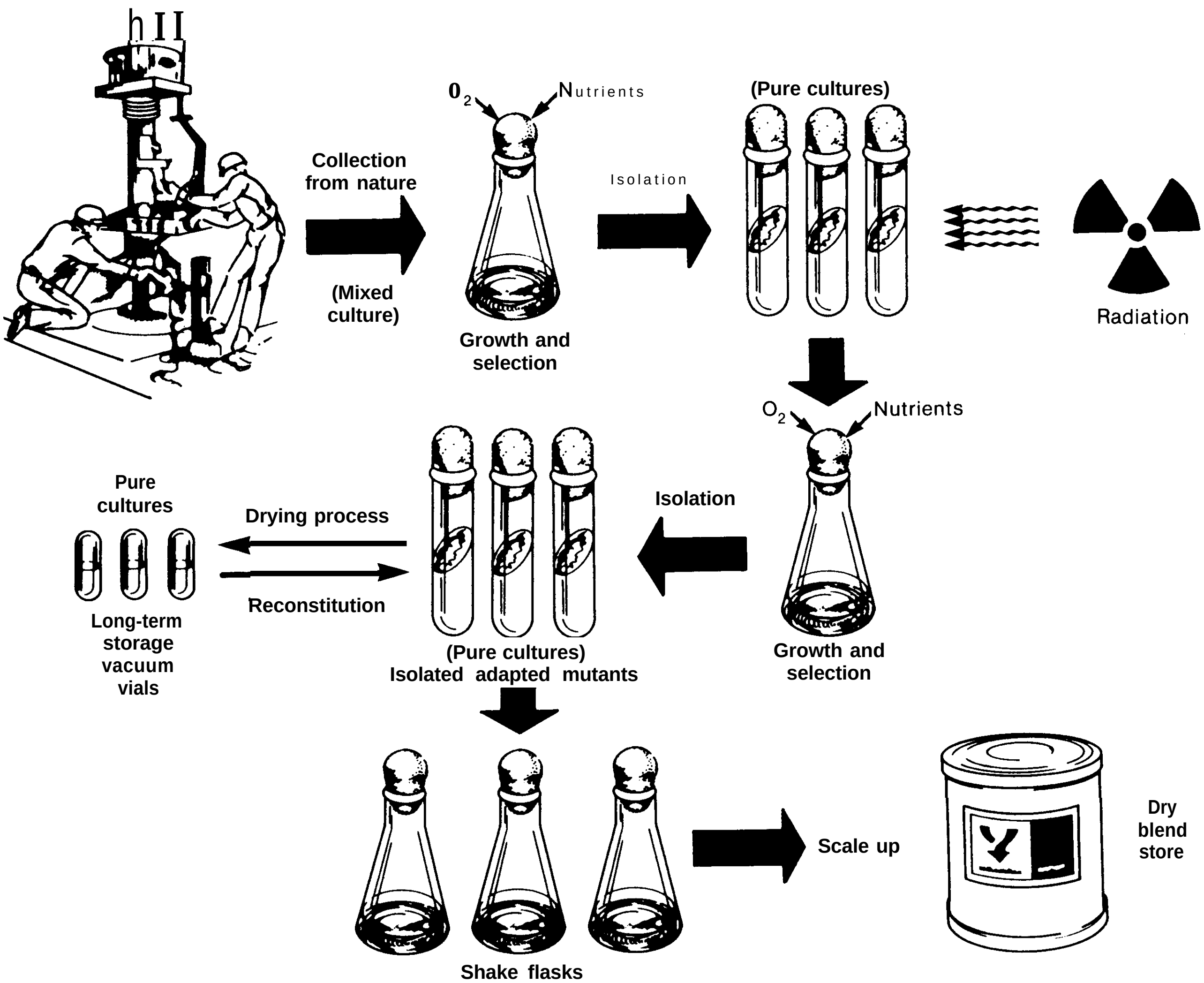
Firms specializing in biotreatment services make up the majority of the U.S. market in this area. These firms are small and are generally founded by a scientist or engineer convinced that biology-based waste management can be commercially viable. Some firms began in university laboratories, while others spun-off from larger companies. Most of these specialized companies have relied on laboratory analytical services or equipment sales to maintain income as they develop their bioremediation services component. Only a few have had venture capital support. These small companies serve as a pool of expertise for larger, full-service engineering and consulting firms. Contract and subcontracting activities between companies are common.

Diagnosis and treatment services are provided by bioremediation firms. Diagnosis of a waste problem can include analyzing the site or waste treatment facility for indigenous microbial activity, adequate nutrients, suitable moisture, and appropriate oxygen. Treatment may involve enhancement of indigenous micro-organisms by nutrient addition, batching preconditioned organisms found at the site, or using selected off-the-shelf microbes.

Multidisciplinary Environmental Services

In 1988, few multidisciplinary environmental companies offered bioremediation expertise. Bioremediation was typically used by firms competing in the wastewater treatment sector but not by firms focusing on hazardous waste markets. Growing optimism that bioremediation can be used to tackle hazardous waste problems has led to increased involvement by multidisciplinary firms incorporating bioremediation expertise. Growth in this sector has generally occurred in one of three ways:

Figure 8-l—Laboratory Selection and Enhancement of Micro-organisms



Micro-organisms indigenous to various environmental sites can be isolated and screened for degradative capabilities. This figure shows how naturally occurring organisms can be selected in the laboratory and, if desired, subjected to mutagenizing agents such as radiation. This imprecise method can sometimes produce new strains of organisms with enhanced capabilities.
SOURCE: Polybac Corp.

1. consolidation of large environmental firms with smaller biotreatment firms (e.g., the-merger of Theme Environmental with Biota);
2. creation of biotreatment groups in larger environmental service firms; or
3. hiring of a limited number of bioremediation professionals to recommend appropriate projects and to handle subcontracts with bioremediation specialty firms.

Products

Approximately one dozen companies manufacture organisms that are sold as biological treatment products. Most of these products consist of preselected mixtures of naturally occurring micro-

Box 8-A—The Exxon Valdez Bioremediation Project

On March 23,1989, ***the Exxon Valdez*** tanker, freshly loaded with 1.2 million barrels of crude oil, left Alaska's south coast headed for California Twenty-five miles out, the ship ran into a reef at. Bligh Island in Prince William Sound. The accident resulted in the largest oil spill in U.S. history and the first major spill to foul the waters off Alaska's coast. Patches of oil and water-in-oil emulsion spread over 3,000 square miles and onto unestimated 1,000 miles of shoreline.

Environmental factors have been substantial obstacles in the Alaska cleanup. Alaskan waters are extremely cold and there had been little experience with oil spills in subarctic conditions. Only a half-dozen or so tanker spills had been studied, and most occurred in temperate waters, The surface water temperature in Prince William Sound is approximately 3 degree Celsius in mid-April. At that temperature, degradation by micro-organisms, which ultimately removes much spilled oil, takes twice as long as it does at 10 degree Celsius.

The ***Valdez*** spill prompted a monumental cleanup effort and launched significant scientific research efforts. In addition the traditional methods (i.e., containment, skimming, and **burning)** of oil cleanup, the EPA Office of Research and Development initiated a bioremediation study to determine the feasibility of using nutrients to enhance micro-organisms' degradation of oil on the shorelines of Prince William Sound A major portion of this venture was funded by the Exxon Corp. In 1989, Exxon contributed approximately $3 million, and EPA contributed approximately $1.6 million.

The major portion of the Alaskan oil spill bioremediation project involved a field test to determine if adding fertilizer to contaminated beaches would effectively stimulate native bacteria to breakdown the oil. The EPA selected two sites—Passage Cove and Snug Harbor-based on type of shoreline, area, size, and uniformity of oil conlamination. It was determined that two types of fertilizer would be needed to release nitrogen and phosphorous nutrients over an extended period of time. One type was a solid, slow-releasing briquette fertilizer that released nutrients slowly from point sources distributed over the beach through tidal action. The second type, a liquid oleophilic fertilizer, dissolved into the oil covering rock and gravel surfaces.

Before the fertilizer was applied, each beach was hosed down to disperse the oil across the beach. Researchers packed the fertilizer briquettes into biodegradable sacks and tied the sacks to pipes anchored in the test site beach, Over the course of a month, wave and tidal action flushed the slowly dissolving fertilizer back-and-forth across the shoreline.

Both EPA and Exxon officials acknowledged that the use of fertilizers could pose a risk to some sea life. To determine the potential toxicity of the fertilizers to native organisms, a wide range of species were tested. The results demonstrated that certain components of the oleophilic fertilizer were mildly toxic when first applied to the most sensitive marine species. Tidal action, however, quickly diluted these toxic components to nontoxic levels.

Approximately two weeks after the fertilizer was applied to the test plots in Snug Harbor, scientists observed reductions in the amount of oil on rock surfaces. All other plots, however, appeared as oiled as they had been at the beginning of the field study. Toward the end of the summer season, the entire test area became steadily cleaner. In contrast, an untreated area of Snug Harbor remained considerably contaminated.

By the end of September 1989, Exxon and EPA had treated 70 million miles of shoreline in the largest bioremediation project ever conducted. The initial findings from the study indicate that using nutrients to enhance microbial degradation are effective and environmentally safe.

SOURCE: Office *of* Technology Assessment, 1991.

organisms advertised as additives to improve performance. Product uses include: decreasing pipes, degrading food processing facility wastes, odor control, and remediating oil spills.

Microbial cocktails, the commercial name for combinations of microbes packaged for sale for specific uses, are available from companies in the United States, Japan, and Europe. Because information about sales of such products is proprietary, no reliable data exist regarding the volume of sales of these products.

Waste Generators

Significant fourth players are generators of hazardous wastes. In addition to employing biological treatment staffs, some chemical and energy companies are supporting in-house research to perfect biodegradation of their specific production facilities' wastes. Such research may result in biology-based treatment methods and products that can be marketed directly or licensed to bioremediation vendors.

International Biotreatment Industry

Despite the limited size of the bioremediation industry in the United States, U.S. commercial activity far exceeds that of other nations. Four factors account for the United States' lead in this area:

1. The size and scope of U.S. environmental law exceeds that of other nations.
2. The majority of research has been conducted in the United States.
3. The size of the biotreatment industrial sector in the United States, albeit small, exceeds that of other nations.
4. Public acceptance of bioremediation in the United States has been spurred by recent, well-publicized uses of bioremediation for oil spill cleanup.

Research and Industrial Development

The existence of environmental laws and regulations are prerequisites to the formation of a waste treatment market. Although several nations have enacted environmental regulatory programs, enforcement of regulations and funding of hazardous waste infrastructures are often not sufficient. A barrier to the international use of bioremediation is the view, held by many, that pollution control costs industry money and makes industry, in its own view, less competitive in world markets. To some, investment in and operation of effluent treatment facilities is money down the drain (5).

Several Organization of Economic Co-operation and Development (OECD) countries have been pursuing biotechnology research and development (R&D) in improved waste treatment, notably The Netherlands, France, Japan, and Germany (see box 8-B). Still, research efforts are generally minimal in many countries, and the diffusion of research results into commercial applications is negligible when compared to other sectors affected by biotechnology. This is due to lax regulations that encourage the payment of fines by industry for waste emission rather than the use of systems to reduce or cleanup pollution (1 1). In the United States, by comparison, several Federal agencies support biological research related to waste management. In 1987, eight Federal agencies spent $11 million on such research (15).

In order to provide equal access to waste treatment for all industrial sectors, The Netherlands, Belgium, Denmark, and Germany have centralized waste treatment facilities. Those handling recurrent, solid hazardous waste do not appear to utilize biological treatment at this time; however, these countries have well-maintained wastewater treatment systems that rely on micro-organisms. The primary bioremediation focus in these countries is the use of biostimulation to encourage indigenous organisms to degrade wastes in contaminated soils and groundwater. In contrast to publicly run treatment and disposal facilities found in northern Europe, Italy prefers private-sector waste management and cleanup services. The Italian tourist industry has created a market for environmental restoration. Work is underway at a popular beach to biologically disperse algae. France has diversified privately run waste management and remediation services, and French firms dominate the private-sector market.

Although stronger enforcement could generate more demand for waste treatment, public expecta-

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Box 84?—international R&D, Improved Waste Treatment Processes

The Netherlands. Companies, such as Gist-Briocades use and are attempting to market advanced anaerobic waste water cleanup processes. The Dutch Government supports research in soil biodegradation and the development of systems to convert farm waste in small fermenters into marketable fertilizers for export to developing countries.

United Kingdom. Research and Development efforts are being undertaken by several small companies and regional water authorities. The use of waste treatment processes by industry is minimal, due to a less stringent regulatory climate and weak incentives for efficient industrial cleanup.

Japan. A 5-year, V5 billion project on waste water treatment through biotechnological processes was launched in the 1980s by the Ministry of Construction.

Germany. The Ministry for Research and Technology plans to introduce a program supporting risk assessment research.

SOURCE: organization for Economic Co-operation and Development, *Biotechnology and the Changing Role of Government, 1988.*

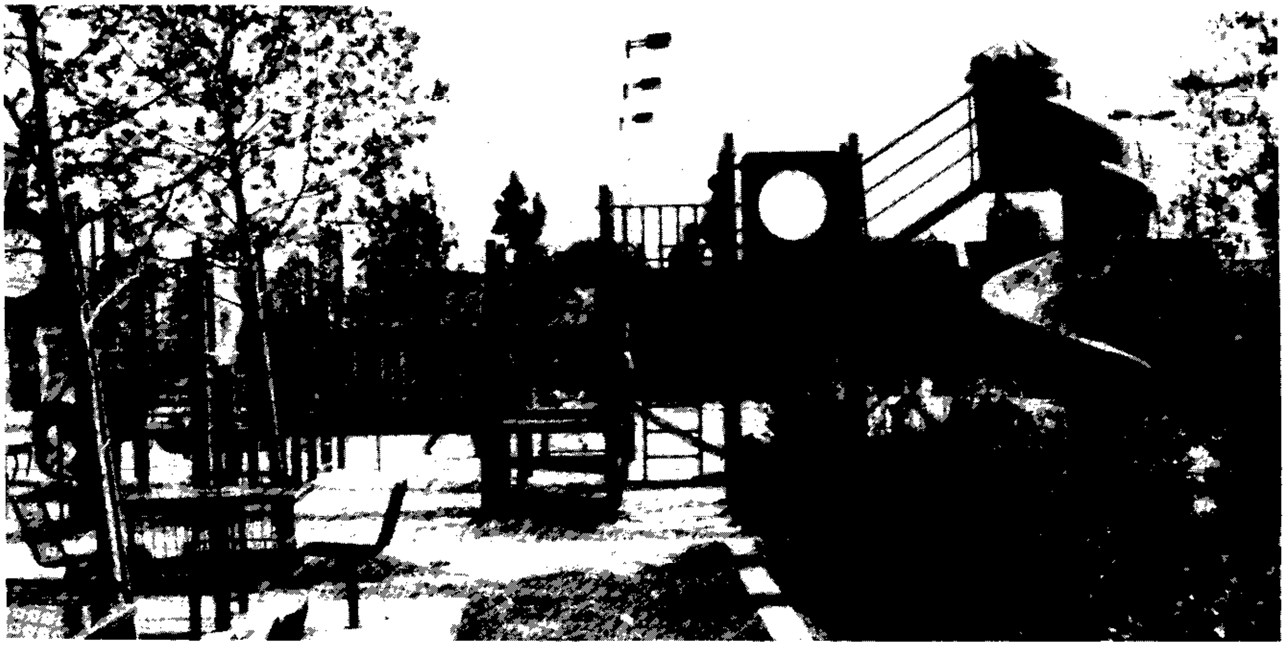

Photo credit: Kevin O'Connor

This park in Torrance, California, was once the site of an oil refinery. After several years of bioremediation, a community center, several ballfields, and a playground were constructed.

tions in both Pacific Rim countries and the European Community (EC) are forcing some governments to inventory contamination problems, actively participate in cleaning up existing pollution, and monitor-the effectiveness of waste treatment for newly created wastes.

The United States, in contrast, has an elaborate environmental protection program already in place. Unlike many other countries, the enforcement of that program is generating a market for environmental cleanup. Cleanup goals and the size of the problem-the universe of waste management facilities, leaking underground storage tanks, and abandoned sites with contaminated soils and groundwater--are better defined for the United States than for other countries surveyed.

Advantages of Bioremediation

Depending on the situation and type of site, bioremediation offers several advantages over more conventional waste treatment technologies, such as incineration or chemical fixation, these include:

- Minimal disruption. Bioremediation generally involves only minimal, if any, physical disruption of a site. This can be very important on beaches where other available cleanup technologies (e.g., high- and low-pressure spraying, steam cleaning, manual scrubbing, and raking of congealed oil) may cause additional damage to beach-dwelling biota (2).
- Permanency. Micro-organisms can convert a selected number of wastes into carbon dioxide, water, and cell mass. For these completely biodegradable wastes, no toxic residues remain to manage. For other wastes that are not completely mineralized by biological actions, biodegradation can transform hazardous chemicals into stable, more benign, and less-toxic compounds.
- Lower costs. The capital costs of biology-based systems are relatively low, compared to other treatment technologies. The microbes used are generally inexpensive, and once applied, they self-replicate. In some cases, in situ bioremediation may be utilized without excavation or demolition of buildings. For these reasons, the costs of bioremediation should be lower than those systems with more expensive input requirements.
- Public acceptability. Bioremediation offers the public a treatment process that relies on natural degradation, transformingg hazardous wastes into familiar compounds, such as carbon

dioxide and water. The biotreatment system design, itself, is nonthreatening. For example, some bioremediation systems may only require the removal of contaminated soils and groundwater to a tank, which looks like the usual sewage treatment plant, or a vat as used to make beer or wine. In situ bioremediation does not even require moving toxic wastes or siting a treatment unit. Such in-place treatment minimizes the public and environmental risks created by the handling of waste.

Barriers to Commercialization

Despite the advantages of bioremediation—research, technical, and regulatory barriers hinder the use of biotechnology for hazardous waste cleanup.

Research Barriers

Much needs to be learned regarding the scientific underpinnings of bioremediation. Waste takes on many forms, occurs in many sites, and is subject to varying environmental conditions. To date, promising targets for use of bioremediation include oil spills, point sources of industrial effluents with high concentrations of specific chemicals, spills of particular chemicals in contained areas, and dump sites being prepared for encapsulation or excavation (9,10).

To assess the feasibility of biotreatment, several areas of science and engineering must be understood.

- Microbial physiology, biochemistry, and genetics, to understand the metabolic processes leading to detoxification and the genetics controlling the enzyme functions involved.
- Microbial ecology, to appreciate the structure and fiction of indigenous or inoculated microbial communities and the microenvironment in which treatment must be effective.
- Field-site engineering, to implement the desired biodegradation scheme, to maintain optimal growth conditions, and to combine physical and chemical methods (10).

The application of biotechnology to waste disposal is still largely experimental, and investment is small compared with efforts in pharmaceuticals and agriculture. Two significant perceptual problems have been voiced repeatedly to OTA: 1) because pharmaceuticals and agriculture are seen as being areas of greater promise (e.g., ability to produce high-value-added products), those areas attract more dollars and more highly trained personnel than programs involved in research targeted toward the cleanup of waste; and 2) fears of regulatory barriers, especially for the development of genetically engineered organisms for use in the environment, discourage researchers from investigating genetic engineering as a way to discover potentially beneficial organisms.

The EPA is the lead agency in conducting R&D in waste disposal. However, EPA's current investment in R&D for biotechnology--$8.3 million in fiscal year 1990-is small compared to other Federal agencies. Additionally, there has existed a widespread feeling that EPA is biased against biological approaches to waste disposal and is unwilling to support approaches involving biotechnology (15). Some researchers, however, say this bias is changing, pointing to EPA involvement in the ***Valdez oil*** spill cleanup and strong statements by EPA officials touting the use of bioremediation.

Another significant research problem is the paucity of published scientific literature on the results of bioremediation. Much of the activity in this area is conducted by private businesses engaged in contractor-client relationships. As such, the results of many small-scale uses of bioremediation constitute privately held business information or trade secrets and, thus, remain hidden from competitors and researchers alike. As one company executive noted, some clients want to have hazardous waste removed from their property, but they do not want their neighbors to know about the scope of the problem or the nature of treatment undertaken (4).

Technical Barriers

Several technical problems hinder the broader application of biology to waste treatment and cleanup:

- Although bioremediation works faster than natural biodegradation, it is generally slower to implement than "burn or bury" technologies that are the most likely alternatives to biotreatment.
- Bioremediation must be specifically tailored to each polluted site. Each waste site presents unique facts, requiring individualized attention. Not enough is known about bioremedia-

Box 8-C—Federal Statutes Relevant to Bioremediation

Several Federal environmental laws are relevant to biology-based waste treatment, including:

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The 1986 amendments to CERCLA (Public Law 99-499) state" [t]he President shall select a remedial action that is protective of human health and the environment, that is cost effective, and that utilizes permanent solutions and alternative treatment technologies. . . to the maximum extent practicable.'

Toxic Substances Control Act (TSCA). The TSCA was enacted by Congress in 1976 (Public Law 94-469). In contrast to other environmental statutes specifically regulating the quality of air, water, or other natural resources, TSCA gave EPA broad authority to regulate "chemical substances and mixtures." Under TSCA, the manufacturer of a new chemical must submit a premanufacture notice to EPA that describes test data referring to identity, use, amount, disposal, and so forth. EPA then has 90 days to consider the notice and decide whether to approve production. Under the Coordinated Framework for Regulation of Biotechnology, EPA notified the public that biotechnology processes and products not covered or regulated by other Federal agencies would be included under the jurisdiction of TSCA.

Clean Water Act (CWA). CWA'S pretreatment program's July 24, 1990, final rule states". . . the Industrial User shall certify that it has a program in place to reduce the volume and toxicity of hazardous wastes generated to the degree it has determined to be economically practical."

Resource Conservation and Recovery Act (RCRA). The Hazardous and Solid Waste Amendments to RCRA, enacted by Congress in 1984 (Public Law 98-616), emphasize permanent treatment technologies. Congress declared "it to be the national policy of the United States that, wherever feasible, the generation of hazardous waste is to be reduced or eliminated as expeditiously as possible. Waste that is nevertheless generated should be treated, stored or disposed of so as to minimize the present and future threat to human health and the environment."

Superfund Amendments and Reauthorization Act (SARA). SARA directs that "[remedial actions in which treatment which permanently and significantly reduces the volume, toxicity, pollutants, and contaminants is a principal element, are to be preferred over remedial actions not involving such treatment. "

SOURCE: Office of Technology Assessment, 1991.

tion to be able to predict results in specific situations with a high degree of accuracy.

- Successful mineralization of pollutants has been limited to relatively easy-to-degrade compounds (12).
- There are no official scientific measures for evaluating the success or failure of bioremediation. The only well-known successful use of bioremediation has been for the cleanup of oil spills.

Regulatory Barriers

Regulations both drive and constrain the use of bioremediation. Regulation creates the bioremediation market by dictating what must be cleaned up, how clean it must be, and which cleanup methods may be used. A number of Federal statutes and relevant regulations control waste disposal activities (see box 8-C). The passage of Federal statutes has increased pressure on waste generators to reduce waste and to find permanent solutions to waste that is generated. Although these laws can apply to all permanent waste treatment methodologies, biology-based approaches offer destruction of selected hazardous wastes without toxic residues—a result certainly in accordance with the intent of these laws.

However, several regulatory barriers hinder the commercialization of bioremediation:

- Cleanup standards. How clean is clean? The achievable endpoint for biodegradation may be limited for specific pollutants. Biology-based remediations maybe able to reach health-based standards but not lower residue levels resulting from thermal treatment technologies, such as incineration.
- Standards are still under development. Treatability studies used by regulatory agencies to determine the efficacy of a waste treatment regime have not been standardized for biological treatment.
- Little biotreatment permit experience. The permitting of biotreatment activities today relies on individuals' best professional judgment. Based on the small number of permits issued to date, experience in the approval of

Photo credit: Kevin O'Connor

Through bioremediation, former industrial sites such as this may be used for other purposes.

treatment protocols using naturally occurring and recombinant micro-organisms is limited.

- Land disposal regulations limit reactor design. Recent land disposal regulations promulgated by EPA's Office of Solid Waste prohibit the recirculation of contaminated groundwater through an in situ bioreactor arrangement, a common design for bioremediation of contaminated soils and groundwater.

Economic Barriers

Unlike the pharmaceutical industry, bioremediation does not result in the production of high-value-added products. Thus, venture capital has been slow to invest in the technology, and commercial activity in research and product development has lagged far behind other industrial sectors.

The majority of the bioremediation firms are small and lack sufficient capital to finance sophisticated research and product development programs. In addition, bioremediation lacks a strong, publicly funded research base. Federal research dollars have been scarce to support discovery or improvements of biology-based waste treatment.

Because basic research is limited and most products and processes are developed by small entrepreneurs or companies, bioremediation relies on trade secrets, not patents, for intellectual property protection. Biological treatment currently relies on naturally occurring organisms that cannot be patented and can be reproduced by one's competitors. This lack of intellectual property protection subjects the industry to constant competitor stress. Further, many clients of bioremediation companies do not want public attention focused on hazardous waste cleanups. This results in proprietary business relationships that do not foster the sharing of scientific and business practices.

Experienced personnel are in short supply. University programs are now being establishing for bioremediation specialists, but continuing education programs are not common. Marketing of products and services has, historically, been done by individual companies. Few firms exist that act as brokers for the technology. Such an arrangement is personnel-intensive.

The key marketing promise of the biotreatment industry is less cost through remediation. No academic or regulatory agency has published a study analyzing the costs of biological treatment compared with other technologies, such as incineration. The only information currently available is found in individual companies' marketing materials.

Prospects for Genetically Engineered Microbes

Some basic research is underway on the use of genetically engineered microbes for waste cleanup. The first out-of-laboratory applications of genetically engineered microbes for waste cleanup will be done in bioreactors, because conditions for microbial survival and monitoring are easier to control in a closed system then in an open field. Today's bioremediation sector continues to rely on naturally occurring micro-organisms. Due to scientific, economic, regulatory, and public perception reasons, the imminent use of bioengineered micro-organisms for environmental cleanup is not likely to happen in the near future. More needs to be learned about naturally occurring microbes-much less those that are genetically engineered. The lack of a strong research infrastructure, the predominance of small companies, the lack of data sharing, and the existence of regulatory hurdles all serve as dominant barriers to commercial use of genetically engineered organisms.

The potential savings from the use of biology-based treatments, compared to conventional incineration, and the interest of generators to limit their long-term liability for wastes are positive reasons for the development and use of genetically engineered microbes. In the United States and the European Community, government, private, and academic institutions are increasingly confident that environmental biotechnology offers a more ecologically sound approach to waste remediation. This may play the most important role in moving genetically engineered microbes into the field.

The majority of current bioremediation firms are small and lack sufficient capital to finance sophisticated research and product development programs. This is a problem when using naturally occurring organisms, but a crisis for the development of bioengineered products and related services. Until barriers to development are reduced, widespread commercial use of genetically engineered organisms for environmental waste reduction is unlikely.

SUMMARY

Biotechnology has several potential environmental applications, these include: pollution control, agriculture, mining, and microbial enhanced oil recovery. Bioremediation--efforts to use biotechnology for waste cleanup-has received public attention recently because of the use of naturally occurring micro-organisms in oil-spill cleanups. Bioremediation can be used at a variety of sites and in a variety of applications, among these are waste-stream cleanup, wood treatment-site cleanup, PCB degradation, groundwater treatment, and chemical cleanup of manufacturing wastes. The rationale for using micro-organisms to degrade pollutants stems from experience with nature. Micro-organisms have a variety of capabilities that can be exploited for waste management and disposal.

The use of bioremediation in the United States is increasing. Today, the U.S. biotreatment industry includes more than 130 firms and has evolved into four segments: bioremediation services, multidisciplinary environmental services, products, and waste generators. The commercial bioremediation sector in the United States, though small, far exceeds activity in other nations. Four factors account for the United States' lead: the size and scope of U.S. environmental law, more advanced research, the number of companies, and public acceptance, spurred by recent uses of bioremediation for oil-spill cleanup.

Although bioremediation offers several advantages over conventional waste treatment technologies, several factors hinder widespread use of biotechnology for waste cleanup. Relatively little is known about the scientific effects of micro-organisms in various ecosystems. Research data are not disseminated as well as with research affecting other industrial sectors. This is caused by limited Federal funding of basic research and the proprietary nature of the business relationships under which bioremediation is usually used. Regulations provide a market for bioremediation by dictating what must be cleaned up, how clean it must be, and which cleanup methods may be used; but regulations also hinder commercial development due to their sheer volume and the lack of standards for biological waste treatment.

Bioremediation, unlike the pharmaceutical and agricultural industries, does not result in the production of high-value-added products. Thus, venture capital has been slow to invest in the technology, and little incentive exists for product development. The majority of bioremediation firms are small and lack sufficient capital to finance sophisticated research and product development programs. Bioremediation primarily depends on trade secrets, not patents, for intellectual property protection.

Although some research is being conducted on the use of genetically engineered organisms for use in bioremediation, today's bioremediation sector relies on naturally occurring micro-organisms. Scientific, economic, regulatory, and public perception limitations that were viewed as barriers to the development of bioremediation a decade ago still exist. Thus, the commercial use of bioengineered micro-organisms for environmental cleanup is not likely in the near future

CHAPTER 8 REFERENCES

1. **Ehrlich,** H.L., and **Brierly,** C. (eds.), ***Environmental Biotechnology: Microbial Mineral Recovery (New*** **York,** NY: McGraw Hill, 1990).
2. Foster, M. S., et al., "To Clean or Not To Clean: The Rationale, Methods, and Consequences of Removing Oil From Temperate Shores," ***The Northwest Environmental Journal,*** vol. 6, 1990, pp. 105-120.
3. Granger, T., EBASCO Environmental, personal communication, August 1990.
4. **Grubbs,** J., president, **Solmar** Corp., personal communication, October 1990.
5. Harrier, G., "The Impact of Government **Legislation** on Industrial Effluent Treatment,' ***Conservation and Recycling,*** vol 8, Nos. **1/2,** 1985, p. 27.

6. Henley, M., "Europe Poses Multi-billion Environmental Market," ***WasteTech News,*** vol. ***2, No. 24,*** Aug. 13, 1990.
7. McCready, D., director, Canadian Center for Mineral Energy Technology, personal communication, September 1990.
8. McInerney, M. J., University of Oklahoma, personal communication, September 1990.
9. Omenn, G.S. (cd.), ***Environmental Biotechnology: Reducing Risks from Environmental Chemicals Through Biotechnology (New*** York, NY: Plenum Press, 1988).
10. Omenn, G. S., professor and dean, School of Public Health & Community Medicine, University of Washington, "Environmental Biotechnology: Biotechnology Solutions for Hazardous chemical Wastes and Oil Spill Clean-up," presentation at Biotechnology Forum on Oil Spills in Marine Environments, Cincinnati, OH, September 1990.
11. Organization for Economic Co-operation and Development, ***Biotechnology and the Changing Role of Government (Paris,*** France: OECD Publications Office, 1988).
12. Rochkind, M.L., et al., ***Microbial Decomposition of Chlorinated Aromatic Compounds, EPA-600*** (Washington, DC: EPA Publications Office, February 1986) p. 90.
13. U.S. Congress, Office of Technology Assessment, ***Commercial Biotechnology: An International Analysis*** (Elmsford, NY: Pergamon Press, Inc., January 1984).
14. U.S. Congress, Office of Technology Assessment, New ***Developments in Biotechnology: Field-Testing Engineered Organisms: Genetic and Ecological Issues,*** OTA-BA-350 (Springfield, VA: National Technical Information Service, May 1988).
15. U.S. Congress, Office of Technology Assessment, New ***Developments in Biotechnology: U.S. Investment—Special Report OTA-BA-360*** (Spring field, VA: National Technical Information Service, July 1988).