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BIOPROCESSING APPLICATIONS IN THE MANAGEMENT OF NUCLEAR AND CHEMICAL WASTES

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INTRODUCTION

The projected requirements for waste management and environmental restoration activities within the United States will probably cost tens of billions of dollars annually during the next two decades.[1-2] Expenditures of this magnitude clearly have the potential to affect the international competitiveness of many U.S. industries and the continued operation of many federal facilities. In fact, the U.S. Department of Energy (DOE), the U.S. Department of Defense (DOD), and other federal agencies already face profound challenges in finding strategies that manage budgets and priorities while bringing their sites and facilities into compliance with current statutes and regulations and with agency policies and orders. While it is often agreed that current technology can be used to address most waste management and environmental restoration needs, it is also argued by many that the costs of implementing current technology will be too high unless the standards and schedules for compliance are relaxed. Since this is socially unacceptable, efforts to improve the efficiency of existing technologies and to develop new technologies should be pursued. A sizable research, development, and demonstration effort can be easily justified if the potential for reducing costs can be shown. Bioprocessing systems for the treatment of nuclear and chemically hazardous wastes offer such promise.

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BACKGROUND

Hazardous Waste Laws

Many federal and state statutes establish the basic compliance requirements for waste management activities. The Toxic Substances Control Act (TSCA), the Resource Conservation and Recovery Act (RCRA), and the Comprehensive Environmental Response, Compensation and Liability ACT (CERCLA), otherwise known as Superfund, and their various amendments have the most far-reaching impacts. The management of mixed wastes (i.e., waste co-contaminated with hazardous chemicals and radioactive materials) is especially complicated for facilities such as those managed by the DOE because the Environmental Protection Agency (EPA) and state governments have jurisdiction over hazardous materials while the Nuclear Regulatory Commission (NRC) and the DOE are responsible for radioactive materials. Final strategies for the management of mixed wastes will depend on the results of ongoing negotiations among DOE, EPA, and state governments. However, it is reasonable to assume that the management of both radioactive and chemically hazardous wastes will eventually be integrated under a RCRA-like philosophy that requires cradle-to-grave responsibility for hazardous materials. Under this philosophy, radioactivity would be added to the criteria currently used to identify hazardous materials.

TSCA will have an impact on bioprocessing applications through regulatory authority over the development and use of intergeneric microorganisms, especially their release to the environment. RCRA and the Hazardous and Solid Waste Amendments of 1984 require EPA to prohibit the land disposal of many untreated wastes and to set standards for the treatment, storage, and disposal of hazardous wastes. CERCLA requires EPA to establish a program for environmental restoration of contaminated sites. While CERCLA does not regulate treatment, it requires EPA to develop and promote innovative technologies for application at Superfund sites. The 1987 Superfund Amendment and Reauthorization Act (SARA) required EPA to establish various research, development, and demonstration programs. The best known of these is the Superfund Innovative Technology Evaluation (SITE) Program. The goal of the SITE Program is to have ten annual field demonstrations of innovative technologies through 1991.

A potential incompatibility seems to exist between the goals of the RCRA and CERCLA programs. RCRA regulates rather than promotes technologies and does not pursue innovation. In fact, RCRA sets standards based on Best Demonstrated Available Treatment Technology (BDAT). In many cases, standards are based on optimal incinerator performance. RCRA currently has not recognized biodegradation as BDAT. The need for Superfund demonstrations to comply with RCRA inevitably limits the application of biodegradation systems.[3]

Magnitude of Compliance Costs

The generation of hazardous waste within the United States exceeds 300 million tons annually under current RCRA criteria. More than 90% of this waste is generated by the manufacturing industry, and 70% of the manufacturing total is derived from the chemical sector.[4] The Congressional Budget Office has estimated that the 1984 amendments to RCRA could result in annual expenditures of $11 billion by private industry by 1990.[5] Environmental restoration activities on current or abandoned industrial sites contaminated with hazardous chemicals may cost $100 billion and require 50 years to complete with current technology. By 1990, Superfund (CERCLA) and other waste-related regulations could cost U.S. industry $20 billion annually.[5] Costs for bringing federal facilities into compliance have not been established, but they will undoubtedly be significant (i.e., billions of dollars) and will represent a significant drain on federal agency budgets.

<u>The Potential of Bioprocessing Applications</u>

Several prestigious studies have identified significant opportunities for reductions in waste management costs through the development of bioprocessing options. The area of hazardous waste management has recently been reviewed by a committee of the National Research Council as part of a study of research needs and opportunities in chemical engineering.[6] In this review and others,[7] the development of biodegradation processes for the detoxification of currently generated chemically hazardous waste was cited as a promising area for research and development based on engineering considerations. The National Science Foundation has also sponsored a recent workshop on biotechnology for the management of hazardous waste.[7] This workshop documented the need for and potential of interdisciplinary bioprocessing R&D intended to produce new technologies for waste management. Needed interfaces among the fields of microbial biochemistry, genetics, ecology, environmental microbiology, and chemical and environmental bioprocess engineering were reviewed, and a comprehensive R&D agenda encompassing bioreactor systems development was proposed.

Our understanding of biodegradation processes at the molecular level has been rapidly expanding over the past decade. For example, the use of genetically engineered microorganisms as well as the use of indigenous organisms isolated from various environments can offer dramatic increases in the specificity and efficiency of mineralization of many organic compounds. Coupled with the possibility of pursuing low-temperature, low-pressure processes, these advances suggest the potential for cost-effective technologies. The potential for exploitation of such microorganisms within engineered bioreactor systems has been widely recognized,[7-8] but the development of bioprocesses for waste management is still limited by several factors. These include the limited characterization of microorganisms for specific applications and a paucity of data and experience supporting process design, scale-up, and operation. Since waste management practitioners have high legal and financial liabilities, the acceptability and eventual deployment of newly developed technologies may depend on successful field demonstrations that define costs and eliminate performance uncertainties.

The problems of hazardous waste management that may be addressed by biotechnology are generally of two types - either the treatment of currently generated wastes or the remediation of toxic waste sites. In situ bioremediation technologies are not considered bioprocessing applications for the purposes of this discussion. The use of bioprocessing applications in the treatment of currently generated wastes may be accomplished through destruction or detoxification processes (e.g., by biodegradation) or through segregation of hazardous materials from the bulk of the waste (i.e., by biosorption processes). In the special case of mixed waste, which is prevalent on DOE sites, detoxification may refer to the removal of chemically hazardous characteristics from a given waste to yield a low-level radioactive product suitable for subsequent disposal under agency orders.

Bioprocessing applications can also be a part of site remediation programs if contaminated waters are pumped to the surface for treatment (e.g., by either biodegradation or biosorption processes), or if soils are excavated and treated (e.g., in slurry bioreactors where biodegradation processes are involved).

Biodegradation and biosorption processes are readily functional in dilute aqueous solutions and, therefore, are of great interest since a large fraction of the hazardous waste generated in industry and from site remediation programs is in that form. The development of bioreactors exploiting biodegradation and biosorption processes must obviously accommodate some or all of the following fundamental phenomena:

* removal of wastes from the aqueous system by biomass;
* action of extracellular enzymes on wastes outside of microorganisms;
* transfer of degraded or transformed chemical species through the cell wall;
* action of intracellular enzymes on wastes (products) inside of microorganisms;
* conversion of products into cellular components, use of products for energy, or storage of products for potential future use; and
* elimination of metabolic wastes or unnecessary products from cells.

If these phenomena are indeed to be accommodated during the treatment of dilute wastes, highly efficient pollutant/biomass contacting systems must be devised. Methods for developing and maintaining high concentrations of active microorganisms and for monitoring their viability and activity must be demonstrated.

The ability to maintain a small ecosystem within the bioreactor may be required where mixed substrates, biotransformations involving intermediates, and changing influent conditions are present. Mass transfer rates and biotransformation kinetics, as well as the variables that control them, must be carefully studied for particular applications if efficient design and operation of bioreactors for waste management are to be achieved. Understanding and controlling complex bioprocessing applications will require advances in methodologies for monitoring biotransformations.

Other obvious considerations for bioreactor development include the need for separation of biomass from treated waste streams and the management of excess biomass or any gaseous wastes released from the system as potential wastes. This will be especially relevant in cases where removal without destruction has occurred, as in the cases of inorganic, nonbiodegradable, and radioactive pollutants.

If bioprocessing applications are developed for the detoxification of soils, the biomass/pollutant contacting problem is considerably different from that in the general case discussed above. Contact between microorganisms and a pollutant initially sequestered within a porous, surface-active medium (i.e., soil) is required. Expertise in hydrology, geochemistry, and interfacial/surface sciences should be part of all integrated approaches to this problem.

It is worth noting that the development of bioprocessing applications may address certain TSCA and RCRA concerns. With respect to TSCA, environmental releases of engineered microorganisms can be avoided if treatments are conducted in closed systems rather than in the environment. With respect to RCRA, the placement of hazardous wastes in or on the ground can be avoided.[11] Bioprocessing in closed systems may provide efficient and acceptable near-term treatment while generating the data and experience needed to use selected biodegradation processes in eventual in situ applications.

RESEARCH, DEVELOPMENT AND DEMONSTRATION OPPORTUNITIES

There are several general characteristics that should apply to RD&D programs in this area. First, a view toward timely transfer of new biotechnology to the private sector should be maintained. Under the schedule pressures driven by hazardous waste laws, solutions to waste management problems are being selected as early as possible. If savings from innovative approaches are to be realized, the development and deployment of new technologies must begin as soon as possible. Collaborative research among universities, national laboratories, and the private sector should be encouraged. Second, technologies should be demonstrated on a scale adequate to answer questions about design and scale-up issues and about economic viability. Economic questions should be answered within a total systems context that addresses cradle-to-grave responsibilities. Comparisons to conventional physical and chemical systems, with an emphasis on incineration, should be developed to facilitate the technology selection and approval processes. Finally, the development of mobile pilot units for field work should be sought. Field studies on real wastes often identify different problems and produce different results than do laboratory studies. Lacking relevant data and operational histories, both the waste management industry and government agencies have been reluctant to recommend innovative treatment technologies. Concern for liabilities for damages resulting from failures of technologies is widely expressed.[8]

The opportunities for RD&D activities dealing with bioprocessing applications for waste management are innumerable. However, any work in the following areas which has the above characteristics and is successfully completed would have important national significance.

Groundwater Treatment

Most aqueous waste treatment operations (approximately 70%) on Superfund sites deal with contaminated groundwaters and leachates. Organic chemicals are the major problem. Solvents are the predominant contaminant, with trichloroethylene being of major concern.[8-9] The presence of heavy metals has also been widely noted. The development of bioprocessing approaches should include consideration of both biodegradation and biosorption operations and their integration into total treatment systems.

Contaminated Soil Treatment

Most solid waste treatment operations on Superfund sites deal with contaminated soils (approximately 54%) and sludges from pits and lagoons (approximately 18%). Contaminants include organics, solvents, heavy metals, other inorganics, and pesticides.[10] The development of slurry bioreactors should be pursued with an emphasis on treatment of contaminant/soil/water systems that are not amenable to in situ bioremediation. Both PCBs and PAHs are organics of major concern.

Treatment of Aqueous Wastes Containing High Concentrations of Heavy Metals and Nitrate Compounds

Processes in the nuclear fuel cycle produce liquid low-level radioactive waste (LLLW) streams containing high concentrations of nitrates.[11] Management of these streams is complicated by the presence of nitrates which may be leached from the solidified LLLW that is being prepared for disposal. Biodenitrification of LLLW streams that are characteristic effluents of the nuclear fuel cycle of national defense activities should be pursued.

Volume Reduction of Solid Low-Level Radioactive Wastes

Various DOE facilities, and probably numerous other concerns, produce large volumes of solid low-level radioactive wastes.[11] The disposal of this material is problematic and expensive, and any means of efficiently reducing its volume would be important. Even if waste segregation methods are employed to remove wastes suitable for disposal in sanitary landfills, a significant fraction of the residual waste will be cellulosic material amenable to anaerobic digestion. The feasibility of using this process within integrated waste treatment systems should be analyzed, and needed RD&D activities should be pursued. Obviously, the gas, liquid, and solid discharges would require special attention to determine the ultimate fate of radioactive materials.

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BIOPROCESSING APPLICATIONS FOR HAZARDOUS WASTE MANAGEMENT

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HAZARDOUS WASTE LAWS

- CERCLA/SARA (SUPERFUND)
  - MANDATES DEVELOPMENT AND PROMOTION OF INNOVATIVE SITE REMEDIATION TECHNOLOGIES
  - MANDATES ENVIRONMENTAL RESTORATIONS
- RCRA/HSWA
  - SETS STANDARDS FOR TREATMENT, STORAGE AND DISPOSAL
  - DOES NOT ACCEPT BIODEGRADATION AS BEST DEMONSTRATED AVAILABLE TECHNOLOGY
  - PROHIBITS LAND DISPOSAL OF UNTREATED HAZARDOUS WASTES
- TSCA
  - CONTROLS SOME R & D ON ENGINEERED MICROORGANISMS
  - LIMITS RELEASE OF MICROORGANISMS TO THE ENVIRONMENT

PROJECTED COSTS OF COMPLIANCE BY PRIVATE SECTOR

- RCRA

  $10 BILLION ANNUALLY

- CERCLA

  $20 BILLION ANNUALLY

INTERNATIONAL COMPETITIVENESS OF SOME INDUSTRIES WILL BE THREATENED

FEDERAL FACILITY COMPLIANCE ISSUES

- HUGE LEGACY OF ENVIRONMENTAL RESTORATION NEEDS

- LARGE CAPITAL EXPENDITURES NEEDED FOR NEW WASTE MANAGEMENT SYSTEMS

- AVAILABLE BUDGETS ARE INCONSISTENT WITH SCHEDULE REQUIREMENTS

<u>THE CONTINUED OPERATION OF</u>

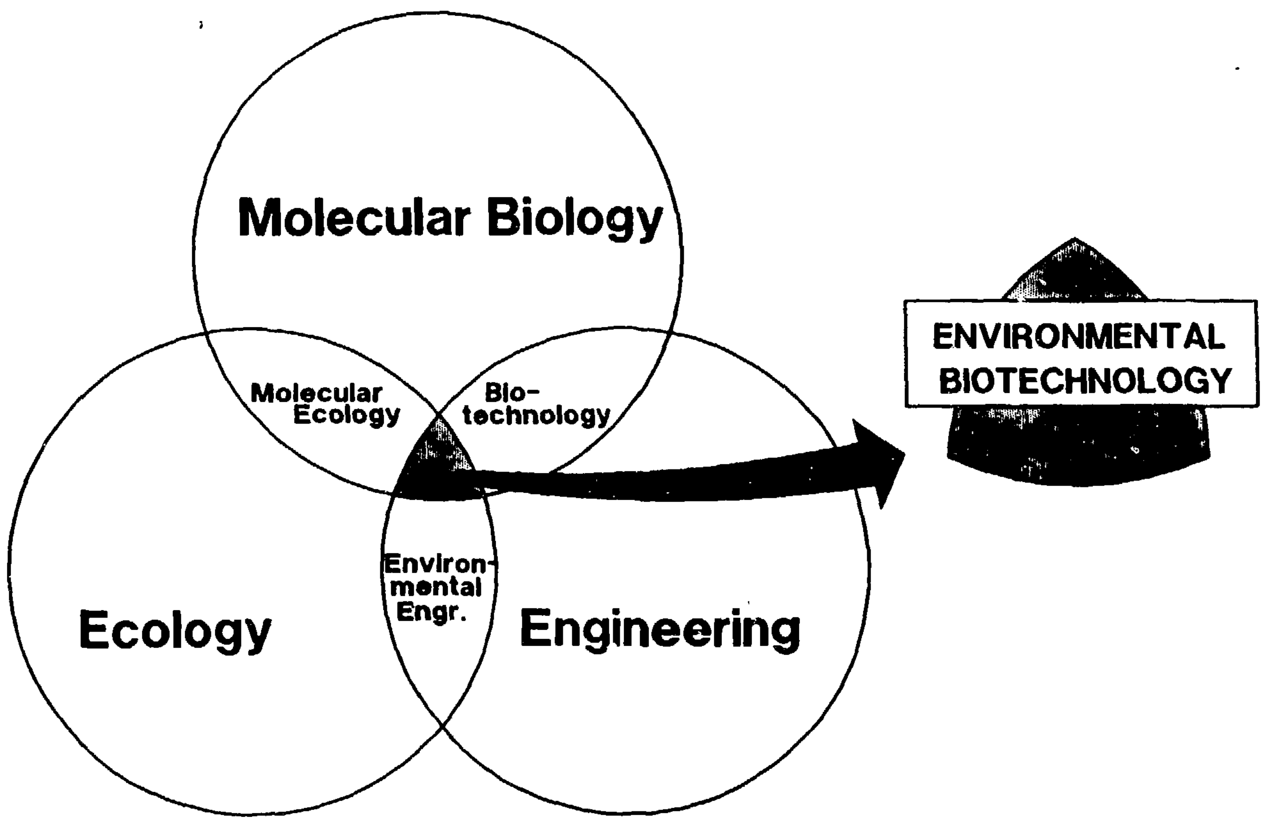
<u>MANY FACILITIES IS IN JEOPARDY</u>

THE POTENTIAL OF BIOPROCESSING APPLICATIONS

- NSF WORKSHOP ON ENVIRONMENTAL BIOTECHNOLOGY (1987)
  - CITED PROGRESS IN SCIENTIFIC RESEARCH
  - OUTLINED THE FIELD OF ENVIRONMENTAL BIOTECHNOLOGY AND ITS POTENTIAL
  - CALLED FOR MULTIDISCIPLINARY RD & D INCLUDING ENGINEERING SCALE WORK

- NATIONAL RESEARCH COUNCIL COMMITTEE REPORT ON FRONTIERS IN CHEMICAL ENGINEERING (1988)
  - CITED PROGRESS IN SCIENTIFIC RESEARCH
  - CALLED FOR INCREASED ENGINEERING RESEARCH

ORNL DWG 88-1024



POTENTIAL CHARACTERISTICS
OF NEW MICROORGANISMS

- TOLERANCE OF SEVERE AND VARIANT ENVIRONMENTAL CONDITIONS
- HIGHER RATES OF DEGRADATION
- BIODEGRADATION OF RECALCITRANT COMPOUNDS
- ABILITY TO DEGRADE MORE THAN ONE COMPOUND
- INCREASED BIOSORPTION CHARACTERISTICS

GENERAL R & D NEEDS IN BIOPROCESSING APPLICATIONS FOR WASTE MANAGEMENT

- DESIGN DATA (MASS TRANSFER RATES; REACTION KINETICS; ALLOWABLE OPERATING CONDITIONS) FOR KEY WASTE MANAGEMENT APPLICATIONS

- EFFICIENT POLLUTANT / BIOMASS CONTACTING SYSTEMS

- HIGH DENSITY (I.E. HIGH ACTIVE SURFACE AREA) BIOMASS SYSTEMS

- LOW HYDRAULIC RETENTION TIMES; HIGH SOLIDS RETENTION TIMES; BIOMASS MANAGEMENT

- BIOREACTOR MONITORING AND CONTROL SYSTEMS ADEQUATE TO MAINTAIN MICROBIAL CONSORTIA INVOLVED IN MULTIPLE BIOTRANSFORMATIONS

RD & D OPPORTUNITIES

GROUND WATER TREATMENT

- THE MAJOR AQUEOUS TREATMENT NEED ON SUPERFUND SITES

- ORGANIC CHEMICALS (TCE) ARE THE PREDOMINANT PROBLEM

- HEAVY METALS ARE OFTEN NOTED

GOAL: DEVELOP AND DEMONSTRATE INTEGRATED TREATMENT SYSTEMS USING BIODEGRADATION AND BIOSORPTION STEPS

RD & D OPPORTUNITIES

CONTAMINATED SOIL TREATMENT

- THE MAJOR SOLID WASTE TREATMENT NEED ON SUPERFUND SITES

- CONTAMINANTS INCLUDE ORGANICS (PCB'S, PAH'S), SOLVENTS, HEAVY METALS, OTHER INORGANICS, AND PESTICIDES

GOAL: DEVELOP AND DEMONSTRATE SLURRY BIOREACTORS FOR DIFFICULT APPLICATIONS

RD & D OPPORTUNITIES

TREATMENT OF AQUEOUS WASTES CONTAINING HIGH CONCENTRATIONS OF HEAVY METALS AND NITRATE COMPOUNDS

- LIQUID LOW-LEVEL WASTES FROM THE NUCLEAR FUEL CYCLE AND NATIONAL DEFENSE ACTIVITIES

- ENVIRONMENTAL RELEASE OF NITRATES IS HIGHLY REGULATED

- NITRATES MAY LEACH FROM SOLIDIFIED WASTE FORMS AND THUS LIMIT OR COMPLICATE DISPOSAL OPTIONS

GOAL: DEVELOP AND DEMONSTRATE BIODENITRIFICATION SYSTEMS FOR RELEVANT EFFLUENTS

RD & D OPPORTUNITIES

ANAEROBIC DIGESTION OF CELLULOSIC WASTES

- CERTAIN FEDERAL FACILITIES PRODUCE LARGE VOLUMES OF DRY, SOLID LOW-LEVEL RADIOACTIVE WASTES

- A SIGNIFICANT FRACTION OF THESE WASTES ARE LIGHTLY CONTAMINATED CELLULOSICS

- WASTE DISPOSAL CONCERNS COULD BE DECREASED IF COST EFFECTIVE VOLUME REDUCTION COULD BE OBTAINED

GOAL: DEVELOP AND DEMONSTRATE ANAEROBIC DIGESTION PROCESSES OF LIGHTLY CONTAMINATED CELLULOSIC WASTES (PERHAPS ANIMAL WASTES ALSO)

GENERAL GOALS OF BIOPROCESSING RD & D ACTIVITIES IN HAZARDOUS WASTE MANAGEMENT

- TECHNOLOGY TRANSFER
  - COLLABORATIVE RESEARCH
  - TIMELY DEMONSTRATIONS

- ENGINEERING SCALE ACTIVITIES
  - DESIGN INFORMATION
  - ECONOMIC EVALUATIONS

- DEVELOPMENT OF MOBILE PILOT UNITS
  - TREATMENT OF REAL WASTES
  - MAXIMUM DATA FOR CAPITAL INVESTMENTS
  - SUPPORT FOR FUTURE PERMITS