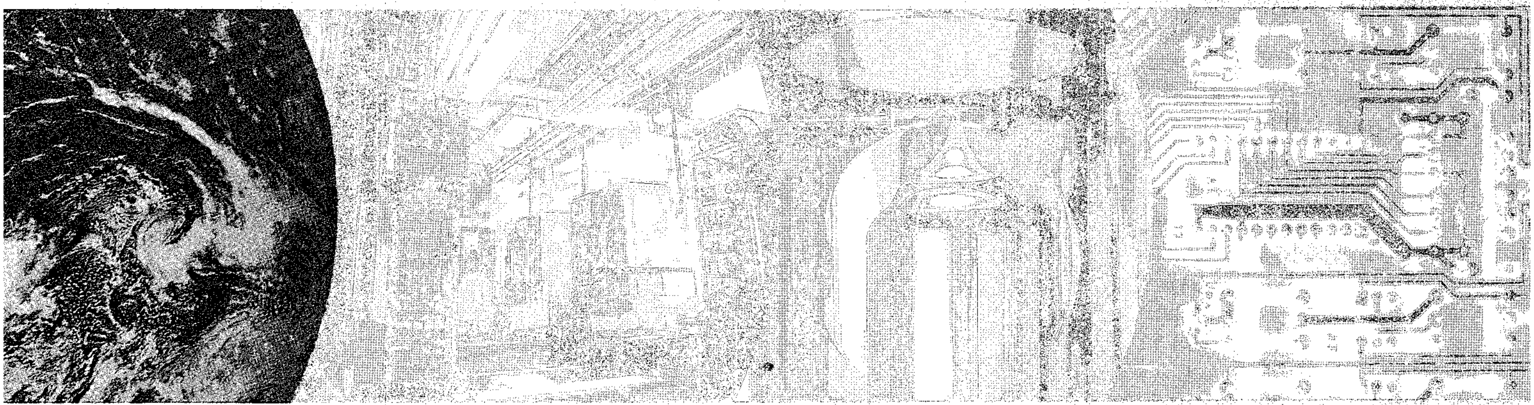

BACKS TO THE FUTURE:

U.S. GOVERNMENT POLICY TOWARD ENVIRONMENTALLY CRITICAL TECHNOLOGY

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WORLD RESOURCES INSTITUTE

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B.R.
R.S.

FOREWORD

Without a dramatic technological transformation throughout the economy, economic and population growth will create increasingly severe environmental pressures. New technologies are needed that markedly increase the efficiency with which energy and raw materials are used, and that eliminate virtually all of the pollution from agricultural and industrial processes.

Many industrial countries are now devoting larger R&D resources to the search for such technologies, not only to solve environmental problems at home but also to strengthen the competitive position of their industries internationally. In the United States, however, where national security has dominated the technological agenda for half a century, public priorities have been slower to shift. We are still spending 60 percent of federal R&D dollars on defense-related research. Despite the U.S. head start in environmental protection, Germany, Japan, and other OECD countries have acquired an edge in many environmental technologies—air pollution equipment, for example. In these countries, industry and government often cooperate in developing advanced technologies, including those with potentially momentous environmental advantages.

Fortunately, some American leaders in and out of government are awakening to these technological and economic challenges. Moves are afoot in the U.S. Congress to create national institutions to support environmental R&D and to stimulate technological advances. If properly designed and implemented, such institutions could give the United States a major environmental and economic boost.

WRI welcomes these signs of new thinking among our country's leaders. To contribute to these new policy ideas, we offer *Backs to the Future: U.S. Government Policy Toward Environmentally Critical Technology,* the first American attempt to identify advanced technologies critical to environmental sustainability. In this report, George R. Heaton, a WRI consultant, Robert Repetto, a vice president at WRI and its chief economist, and Rodney Sobin, formerly a WRI research assistant, present findings that can help shape a public consensus on how our nation should revamp technology policies to protect the environment and regain our competitive edge.

From a wide-ranging literature review and interviews with experts, the authors have constructed an exemplary list of environmentally critical technologies across the spectrum of economic sectors. In energy, for instance, they assert that the ripest areas for research are batteries, superconductors, fuel cells, and the storage of heat and hydrogen fuel. Technological breakthroughs in energy production and storage would spin off into many other sectors. Transportation and buildings, for example, each now accounts for about one third of our carbon dioxide emissions. The sooner we can develop renewable energy systems to power tomorrow's "green" cars and "smart" roads and buildings, the sooner we can bring emissions under control.

Heaton, Repetto, and Sobin argue that public support for technology R&D is especially needed at the "precompetitive" stage that yields ideas and generic techniques, not products or processes immediately useful in the marketplace or on the shop floor. To ensure our nation's ability to compete with industrial rivals, they call for U.S. policies that provide funding, information, facilities, and other incentives that would encourage public-private partnerships among universities, industry, and the national laboratories. Revamping environmental research funding criteria and mobilizing the national laboratories are also among the seven steps the authors say the U.S. government should take to pursue the most-needed technologies effectively.

The policy recommendations spelled out in *Backs to the Future* extend and complement those of such studies as *Transforming Technology: An Agenda for Environmentally Sustainable Growth in the Twenty-first Century,* and *Promoting Environmentally Sound Economic Progress: What the North Can Do.* In these and related reports, WRI has sought to identify and promote the means needed to achieve large-scale technological transformation to meet the environmental and economic needs of the 21st century.

James Gustave Speth
President
World Resources Institute

I. INTRODUCTION

A. National Technology Policy

The world over, governments support and encourage technological change by funding research, by awarding patents, and by other means. Throughout most of the post-World War II period, the United States has led the world in supporting science and technology. Until recently, the American ratio of R&D spending to GNP was higher than that in other OECD countries, and a higher proportion of the national R&D total (typically, more than 50 percent) has been publicly funded. [NSF, 1991] Since the publication of the Vannevar Bush report in 1945, a strong conceptual paradigm has dominated government policy [Bush, 1945], anchored in three principal tenets: 1) that advances in science eventually spawn new technology; 2) that science is a "public good" dependent on broad public support; and 3) that technology development, a commercial phenomenon, is the function of the private sector.

In fact, other considerations have always modified the theoretical consistency of this policy. The lion's share of the federal R&D budget has routinely been devoted to defense, space, energy, and such other "missions" as medicine—most of which are closer to technology than to science. [NSF, 1989] Although explicit U.S. government support for industrial technology has been vastly smaller than similar public support in other advanced countries, government programs have nevertheless successfully advanced selected fields—for example, agriculture, aviation, and computers. [Finneran, 1986; Flamm, 1988.] Except perhaps in the case of agriculture, the rationale has been that these areas are vital to national well-being and that government participation in research is essential.

Perhaps the most significant recent development in U.S. policy is a strong new focus on industrial technology, which emerged by the late 1980s from concerns over the deterioration of the United States' relative economic position. In 1988, Congress articulated this focus clearly by committing itself to support "areas of technological development. . . essential for long-term security and economic prosperity." [The Omnibus Trade and Competitiveness Act of 1988] This legislation thus validated the concept that technology, like science, could be seen as a public good. Subsequently, new institutions, such as the Advanced Technology Program in the Department of Commerce, have been created to support civilian technology development. [Heaton, 1989] In 1990, the Bush Administration's Technology Policy statement also contained the idea that public support should be directed to "generic" technologies in a "precompetitive" stage of development. [OSTP, 1991]

By early 1991, the concept of "critical" technologies had assumed the central place in technology policy discussions. Variously defined, critical technologies were seen as those that "enable" a wide range of related technical and economic developments, confer a strategic economic lead, augment national security, or dominate the technological future. Lists of critical technologies were issued by the White House Office of Science and Technology Policy, the Commerce Department, the Defense Department, and the private Council on Competitiveness. (These lists, along with others from Europe and Japan, are compared in Table I.)

Although some criticize such lists as arbitrary, even faddish, [Schrage, 1991] others see them as a useful delineation of a core of technologies critical to the nation's future. [Council on Competitiveness, 1991] A conciliatory view is contained in the recent Carnegie Commission report [1991], which relates such lists to the need for broad-based national support for developing critical technological capabilities. Most recently, the Competitiveness Policy Council [1992] has endorsed public support for critical technologies as a core element of a national competitiveness strategy and has made assessments or projected "visions" of the directions in which U.S. industries should move.

In the overall context of technology policy, any such lists of critical technologies are likely to prove less important than the policy movement that produced them. That movement has been reinforced in the early 1990s by the slackening of the Cold War

Table I. International Comparison of Critical Technology

U.S. White House Office of Science and Technology Policy

MATERIALS
- Materials synthesis and processing
- Electronic and photonic materials
- Ceramics
- Composites
- High-performance metals and alloys

MANUFACTURING
- Flexible computer integrated manufacturing
- Intelligent processing equipment
- Micro- and nanofabrication
- Systems management technologies

BIOTECHNOLOGY AND LIFE SCIENCES
- Applied molecular biology
- Medical technology

AERONAUTICS AND SURFACE TRANSPORTATION
- Aeronautics
- Surface transportation

ENERGY AND ENVIRONMENT
- Energy technologies
- Pollution minimization, remediation, and waste management

INFORMATION AND COMMUNICATIONS
- Software
- Microelectronics and optoelectronics
- High-performance computing and networking
- High-definition imaging and displaying
- Sensors and signal processing
- Data storage and peripherals
- Computer simulation and modeling

Council on Competitiveness

MATERIALS AND ASSOCIATED PROCESSING TECHNOLOGIES
- Advanced structural materials
  —Metal Matrix Composites
  —Polymers
  —Polymers Matrix Composites
- Electronic and photonic materials
  —Magnetic Materials
  —Optical Materials
  —Photoresists
  —Superconductors
- Biotechnologies
  —Bioactive/biocompatible materials
  —Drug discovery techniques
  —Genetic engineering
- Materials processing
  —Catalysts
  —Chemical synthesis
  —Net shape forming
  —Process Controls
- Environmental technologies
  —Emissions reduction
  —Recycling/waste processing

ENGINEERING AND PRODUCTION TECHNOLOGIES
- Design and Engineering Tools
  —Computer-aided engineering
  —Human factors engineering
  —Measurement techniques
  —Systems engineering
- Commercialization and production systems
  —Computer-integrated manufacturing
- Process Equipment
  —Advanced welding
  —Joining and fastening technologies

ELECTRONIC COMPONENTS
- Microelectronics
  —Logic chips
  —Microprocessors
  —Submicron technology
- Electronic controls
  —Sensors
- Information storage
  —Magnetic information storage

INFORMATION TECHNOLOGIES
- Software
  —Applications software
  —Artificial intelligence
  —Computer modeling and simulation
  —Expert systems
  —High-level software languages
  —Software engineering
- Computers
  —Hardware integration
  —Neural networks
  —Operating systems
  —Processor architecture
- Human interface & visualization technologies
  —Animation and full motion video
  —Graphics hardware and software
  —Handwriting and speech recognition
  —Natural language
  —Optical character recognition
- Database systems
  —Data representation
  —Retrieval and update
  —Semantic modeling and interpretation

- Networks and communications
  - —Broadband switching
  - —Digital infrastructure
  - —Fiber optic systems
  - —Multiplexing
- Portable Telecommunications Equipment & Systems
  - —Digital signal processing
  - —Spectrum technologies
  - —Transmitters and receivers
- Powertrain and Propulsion Technologies
  - —Alternative fuel engines
  - —Electric motors and drives
  - —Electrical storage technologies
  - —Low emission engines
- Propulsion
  - —Airbreathing propulsion
  - —Rocket propulsion

Japanese Ministry of International Trade and Industry

NEW MATERIALS
- High-temperature superconducting materials
- Nonlinear optoelectronic materials
- Ferromagnetic materials
- Molecular functioning materials
- Advanced composite materials
- Alloys/metallic compounds
- Fine ceramics
- Carbon materials
- Amorphous materials
- Highly pure polymer materials
- Silicon chemical materials
- Microelectronic materials

ELECTRONICS
- Superconducting devices
- Quantized elements
- Power electronic elements
- Optical elements
- Large area circuit elements

BIOTECHNOLOGY
- Animal and plant cell engineering
- High performance enzymes and biomaterials
- Genetic engineering
- Bio-databanks
- Screening and isolation of genes from all sources
- Bioreactor technology

NEW MATERIAL/ELECTRONICS-RELATED TECHNOLOGIES
- Atomic level precision manipulation technology
- Metallic and inorganic material process technology
- Precision molecular alignment technology
- Evaluation, analysis, and measuring technology
- Design and simulation technology
- Photoreactive process technology
- Processing technology for extreme environments

BIOELECTRONICS
- Protein alignment technology
- Biomembrane technology
- Analysis of bio-related materials

BIOMATERIALS
- Bio-mimicking materials
- Biocompatibility materials
- Biochemical technology
- Bioprocessing

COMPUTER SOFTWARE AND SYSTEMS ENGINEERING
- Self-organized data processing systems
- Self-organized neural networks
- Ultraparallel processing architecture
- Integrated mechanical control software
- Software development technology
- Disaster prevention technology
- Environmental control technology
- Human-related technology
- Resource and energy technology
- Robotic technology

TABLE I Continued

European Community

INFORMATION TECHNOLOGY AND TELECOMMUNICATION
- Electronic components
- Software and information processing
- Peripherals
- Fundamental research
- Prenormative research (standards, systems-integration-related)
- Broadband infrastructure
- Broadband equipment
- Broadband services

INDUSTRIAL MATERIALS AND TECHNOLOGIES
- Quality and Reliability Technology
- Techniques for shaping, joining and assembly; for surface treatment
- Catalysts and membranes
- Powder technology
- Other high-value materials (composites)
- Superconducting materials

AERONAUTICS
- Aerodynamics and flight mechanics
- Materials
- Acoustics
- Computation
- Airborne systems and equipment
- Propulsion integration
- Design and manufacturing technologies

LIFE SCIENCES
- Basic plant biology
- Molecular investigation of genomes of complex organisms
- Neuroscience
- Biotechnology based agro-industrial research and technology development

ENERGY
- Controlled nuclear fusion
- Non-nuclear energy
- Energy efficient technologies
- Energy from fossil fuels
- Energy modelling and environment

Sources: Council on Competitiveness. 1991. *Gaining New Ground: Technology Priorities for America's Future*; and White House Office of Science and Technology Policy. 1991. *Report of the National Critical Technologies Panel.*

and the disintegration of the Soviet Union. These momentous changes have fundamentally altered the sense of national priorities, downplaying military

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Lists of critical technologies are likely to prove less important than the policy movement that produced them.

"

threats and bringing to the fore economic and environmental threats to U.S. national security. In fact, these two goals—an improved environment and international competitiveness—are intimately related, and the same technological advances speak to both. Among U.S. industries, the most forward-looking firms are capitalizing on this connection, realizing that the technological advances necessary to ensure environmentally benign products and processes correlate with high quality, production efficiency, and market acceptance. [Smart, 1992] Within the international milieu, some countries, most noticeably Japan, consider environmental technology important to their future economic and societal well being. Many Americans in and out of government see the need for a parallel shift in priorities, mission, and funding in U.S. technology policy.

B. Critical Technologies and the Environment

The lists of national critical technologies in the United States and other countries were developed primarily out of concern about national security and international economic competitiveness. Environmental technology did not figure prominently in the initial European and Japanese lists.[1] In the United States, the OSTP list combined an extremely large, diverse group of technical fields under the general heading of "Energy and Environmental Technology," while recognizing that other technologies also have environmental implications.

If environmental technology is segregated and regarded narrowly as remediation and pollution treatment equipment, environmental concerns will inevitably be neglected in the promotion of critical technologies, and the potential of many emerging technologies for environmental improvement will be overlooked.

If environmental technology is segregated and regarded narrowly as remediation and pollution treatment equipment, environmental concerns will inevitably be neglected in the promotion of critical technologies, and the potential of many emerging technologies for environmental improvement will be overlooked. If this connection remains unrecognized, public policies to support critical technologies are unlikely to channel them in environmentally beneficial directions. Environmental concerns will continue to be compartmentalized in regulatory agencies and seen as distinct from, if not impediments to, the realization of national security and competitiveness.

Some private sector analyses of critical technologies have been more attuned to environmental issues. The Carnegie Commission report, for example, mentioned environmental concerns as a critical dimension in technology development, but did not pursue the idea further. The private Council on Competitiveness' report identified environmental technologies and services as areas of increasing importance in which the United States appears to have an international competitive advantage. This finding is particularly important because it reflects industrialists' opinions.

Within the federal government, technology policy continues, for the most part, to neglect environmental issues. If and when environmental concerns surface, they tend to be relegated to a separable category. [Ross and Socolow, 1991] This gap between technology policy and environmental issues is particularly striking because many private firms recognize the environment as a strategic business challenge and opportunity and assign new priority to environmental research. *[See Chapter IV]*

C. Environmentally Critical Technologies: This Report

"Can technologies critical to the achievement of environmental sustainability be identified?" Although this question—which is at the heart of this report—seems to be distinct from the dominant concerns of recent technology policy with national security and economic competitiveness, it is actually closely tied. As intense Cold War military competition recedes and global environmental risks multiply, the recognition grows that environmental sustainability—that is, the long-term balance between the use of nature's capital and economic growth—is essential to national security and economic well-being. [Mathews, 1989] A far-reaching transformation of technology is required if environmental sustainability is to be achieved. [Heaton, Repetto, Sobin, 1991] Consequently, environmentally critical technologies are increasingly important to both national security and economic progress.

This report finds that there are indeed environmentally critical technologies and that public policies can be crafted to support them. The following chapter outlines criteria for defining environmentally critical technologies. In Chapter III, these criteria are applied: a list of environmentally critical technologies is derived from literature reviews and interviews with technical experts. Chapter IV assesses private sector views and public programs in the United States and abroad, and Chapter V offers the authors' conclusions and policy recommendations.

II. CRITERIA FOR IDENTIFYING ENVIRONMENTALLY CRITICAL TECHNOLOGY

Environmentally critical technologies are those that can reduce environmental risk substantially through significant technical advance. Because society as a whole will benefit from environmentally critical technologies, they represent appropriate targets for public investment. Technological developments can be considered environmentally critical if:

- their use brings about large, cost-effective reduction in environmental risk;
- they embody a significant technical advance;
- they are generically applicable at the precompetitive stage; and
- their adoption involves favorable ratio of social to private returns.

As for technology's potential to make possible major reductions in environmental risk, the first criterion, environmental risk, must be interpreted broadly to encompass diverse threats in incommensurable categories: human health, public welfare, and ecology. Technological developments that can avert serious risks to which large populations in the United States and elsewhere are likely to be exposed, or that can markedly reduce the costs of coping with such risks, rank high under this criterion.

A substantial literature has developed over the last several years identifying the most serious environmental risks and overall priorities for environmental improvement. This literature addresses highly complex and inherently judgmental issues. Our approach is not to add to this literature, but to draw on the best available work in applying our own risk-reduction criterion. The study we have found most useful is *Reducing Risk: Setting Priorities and Strategies for Environmental Protection* published in September 1990 by the EPA Science Advisory Board. This analysis grouped risks into two basic categories: risks to natural ecology and human welfare, and risks to human health. In the former category, high-risk, medium-risk, and low-risk problems were identified; in the latter, the data permitted only a listing of several major types of human health risks. (This risk priority schema is presented in capsule form in Table II.)

The second criterion, whether a technology represents a significant technical advance, excludes currently available technologies or those close to commercialization. The focus here on technologies of the future does not imply that wider application of today's clean technologies cannot yield major environmental improvements; obviously, it can. Nevertheless, there are good reasons to limit the analysis to possible innovations over the medium-term future. The incentives and policies that encourage technological innovation do not necessarily encourage technological diffusion and vice versa. Moreover, while analysts and policy-makers are already concerned about implementing today's technical options, they are insufficiently concerned about creating new options.

A significant technical advance might well materialize in an entirely new approach to a problem, such as pest-resistant plants that obviate the need for chemical pesticides. Alternatively, the cost-effectiveness of an existing technological approach might improve dramatically—as, for instance, it has in the case of photovoltaic energy conversion.

Whether a technological advance has generic applicability at the precompetitive stage, the third criterion, begins to define environmentally critical technologies in policy terms, by helping to identify circumstances that justify public support for private sector technology development. To the extent that environmentally critical innovations have broad generic applicability at the precompetitive stage of development, a public interest arises because private investors may not be able to capture the full R&D benefits.

A generic technology is one likely to have wide importance across a class of problems or industrial contexts. Its realization may underlie or make possible the solution to a sequence of technical problems. For example, overcoming the technical problems associated with high-temperature superconductivity could pave the way for profound changes in electrical power and transportation systems.

Because new generic technologies typically involve ideas not yet practiced, their development is usually removed, in terms of time and resource commitments, from the normal competitive marketplace.

Table 1. Environmental Risk Priorities

Risks to Natural Ecology and Human Welfare

Relatively High-Risk
- Habitat Alteration and Destruction
- Species Extinction and Loss of Biological Diversity
- Stratospheric Ozone Depletion
- Global Climate Change

Relatively Medium-Risk
- Herbicides/Pesticides
- Toxics, Nutrients, BOD and Turbidity in Surface Waters
- Acid Deposition
- Airborne Toxics

Relatively Low-Risk
- Oil Spills
- Groundwater Pollution
- Radionuclides
- Acid Runoff
- Thermal Pollution

Risks to Human Health
- Ambient Air Pollutants
- Worker Exposure to Chemicals in Industry and Agriculture
- Pollution Indoors
- Pollutants in Drinking Water

Source: U.S. Environmental Protection Agency. 1990. *Reducing Risk: Setting Priorities and Strategies for Environmental Protection.*

For example, although chemical sensor and fiber optics technologies are widely envisioned as effective, low-cost environmental monitoring technologies in the future, much more technical work is required before individual firms can market them. The ideas underlying such precompetitive technologies may be poorly defined and require additional basic research before becoming useful in practice. Particularly at this precompetitive stage—as contrasted with later commercial application—public support is appropriate. In several respects, these generic precompetitive technologies resemble scientific advances. Often, they consist of techniques and knowledge—not specific products, processes, or systems. As such, they may not be legally appropriable as intellectual property. In some instances, the broad applicability of such technologies may persuade normally rivalrous firms to cooperate in developing them. For these reasons, development of generic technologies at the precompetitive stage, like science, merits public support.

The last criterion that defines environmentally critical technology, a high ratio of social to private returns, corresponds to a large difference between economic and financial benefits. Often, research shows, important technological innovations yield greater social and economic benefits than their developers can capture—a disparity routinely advanced as the principal argument for public investments in science and new technology. In addition, market or institutional barriers in some instances make it difficult or impossible for private actors to recoup R&D investments in new technology.

Developers of environmentally superior technologies depend on incentives created and driven by environmental regulations. Such incentives are uncertain, sporadic, and, often, weak.

Environmental technologies offer a classic example of this problem, since environmental damages typically take the form of unpriced external costs. Typically, those who would benefit from a reduction in environmental damage or risk are not able to express their willingness to pay through the marketplace. Developers of environmentally superior technologies thus depend on incentives created and driven by environmental regulations. Such incentives are uncertain, sporadic, and, often, weak. [TIE, 1990] Moreover, the sectors with the most serious pollution problems—energy, agriculture and transportation, for example—are so highly distorted by environmentally insensitive public policies that the economic incentives facing the developers of new technology are skewed. Obviously, an important public policy goal is to reduce these market incentive failures, many of which are long-standing. Nonetheless, even if private actors find it uneconomical to invest in environmentally critical technology under current conditions, the large rewards that accrue to the public at large justify public support.

III. A LIST OF ENVIRONMENTALLY CRITICAL TECHNOLOGIES

A. How the Technologies Were Identified

The illustrative list of environmentally critical technologies, presented below, was derived through interviews and a wide-ranging literature review. Existing literature on technology and the environment, critical technologies, and current technological development does not define or identify environmentally critical technology. But, the literature does provide useful background on worldwide trends in technology development and indicates which technologies can be considered strategic on grounds of economic competitiveness and national security. In addition, technical experts in industry, universities, research institutes and government were interviewed. Mostly Americans, those technical experts and research managers are all deeply involved in technology development and able to envision its future direction, at least within their own fields. These informal interviews focused on two main issues: what technologies are environmentally critical, using the criteria discussed above; and how environmental factors are affecting technology development and strategic choices in the interviewees' institutions now, as compared to a few years ago.

B. The Environmentally Critical Technologies

The list of technologies that appears below was developed by applying the four criteria for defining environmentally critical technology to technological developments on the horizon. The list is exemplary rather than exhaustive. It indicates that a broad range of technologies can be considered environmentally critical, not that those on the list are necessarily the only or most critical ones. Some of the technologies are environmentally important applications of broader technological building-blocks, while others are closer to the building blocks themselves.

A schematic analysis relating the criteria to the list is presented in Table III. Although each technology or technical area on the list satisfied the four criteria, some criteria assumed greater importance than others in some cases. (In the Table, pluses denote whether a criterion was of primary or secondary importance with respect to any given technology.)

1. Energy Capture

Energy extraction, processing and use—the source of both localized pollution and the major contributor to global climatic change—represent what is arguably the single gravest environmental challenge of the coming decades. World-wide economic reliance on the conversion of fossil fuel sources is at the root of the problem. Fossil fuel use accounts for two thirds of human contributions of carbon dioxide and significant amounts of methane, nitrous oxide, and tropospheric ozone in the atmosphere. [WRI 1990] In addition, oxides of nitrogen and sulfur from fossil fuel burning are progenitors of acid rain; and toxic air emissions, oil spills, and mining-related pollution and land degradation—environmental insults of wide scope and diversity—all trace back to fossil fuel use.

Among the list of environmentally critical technologies, those for producing and using non-fossil fuel energy sources offer the largest potential to reduce environmental risk. Many such technologies, now in early stages of development, would yield large social returns from technical advances. The following are among the most important examples.

a. Photovoltaics

Because photovoltaics rely on the virtually limitless and non-polluting solar resource, they offer enormous potential for environmental risk reduction. Photovoltaic technology has progressed markedly in recent years, resulting in a cost decrease from $15 per kWh in 1973, to about $.30 today. Costs may decline further to an estimated $.15 by the mid-1990s. [Hubbard 1989] Nonetheless, significant technical advances will still be necessary to make photovoltaics competitive with conventional fuel sources. These include new cell designs, such as multi-junction cells that absorb greater portions of the solar spectrum, and new semiconductor materials

Table III. Environmentally Critical Technologies

Technology	Risk Reduction	Technical Advance	Generic Precompetitive	Social/Private Return Ratio
Energy Capture	+ +	+		+
Energy Storage	+	+	+	+
Energy End-Use	+ +			+ +
Agricultural Biotechnology	+	+ +		
Alternative & Precision Agriculture			+ +	+
Manufacturing Modeling, Monitoring, & Control	+	+	+ +	
Catalysis		+	+ +	
Separations	+	+	+ +	
Precision Fabrication			+ +	
Materials	+		+ +	
Information			+ +	+
Contraception	+ +	+		+ +

\+ secondary importance
\+ + primary importance

for improved efficiency and lower cost. Besides these generic developments, manufacturing process improvements—such as microfabrication and large-scale applications of thin-films—are needed to make PV cells competitive in mass markets.

Although a nascent photovoltaics industry now sells some products that are competitive in remote locations (such as mountaintop weather stations), in off-grid applications, and in watches and calculators, the industry as a whole remains at a precompetitive stage of development, limited by the technical and economic factors mentioned above. The need for research thus characterizes the entire industry, and possibly other electronics and optoelectronics. The U.S. position in the development of photovoltaic technologies and manufacturing capabilities has slipped significantly in the past decade, relative to that of Japan.

b. Geothermal

Although naturally occurring hot water and steam formations now provide modest quantities of electricity (e.g., 7 percent of the total in California), hot dry rock, magma, and geopressurized formations represent huge energy sources that have been virtually untapped by today's technology. World resources of hot dry rock alone are estimated at 100 million quads (quadrillion BTUs), which is twenty times all fossil fuel resources. [Brown, *et al.*, 1991; INEL *et al.*, 1990]. Because this resource is widely distributed and potentially non-polluting, its potential risk reduction benefits are very high.

Current geothermal technology (e.g., site assessment and drilling) derives largely from technologies used by the oil and gas industry. A great deal of independent development is possible in this area—for example, fracturing of hot dry rock formations and deep drilling. Some underlying developments, such as high-temperature wear-resistant materials, could be widely applied in other industrial contexts. Since the industry is virtually undeveloped, these technologies remain far from the competitive stage.

c. Solar Thermal Electricity

The environmental benefits of solar thermal electricity are potentially enormous. Like photovoltaics, solar thermal captures a non-polluting energy source; however, solar thermal probably has narrower applications than photovoltaic technology. Solar thermal or hybrid gas-solar thermal plants have been able to provide electricity at about $.08 per kWh in 1989 at an 80-MW unit. Further improvements rest on various potential avenues of technical advance. In particular, improvements in Stirling engines could make diffusion of solar thermal technology possible for small-scale operations, while improvements in heat-transfer fluids would have generic applicability for energy storage in buildings and industry.

d. Nuclear Fission

Nuclear fission technology could potentially supply energy with few or no emissions. At the same time, the technology is highly controversial, plagued by problems of reactor safety, waste disposal, weapons proliferation, economic cost, and technical reliability. Current development of new reactor designs—modular high-temperature gas-cooled reactors (MHTGR), process inherent ultimately safe reactors (PIUS), various liquid metal cooled reactors, and advanced pressurized water reactors—could lead to so-called passively safe systems and more economical fabrication and installation. All require considerably more research and demonstration. For waste handling and disposal too, technically and publicly acceptable options have yet to be demonstrated. Although the technologies involved are potentially commercial, the long history of public investment in the nuclear industry, the scale of R&D required, the pervasiveness of current problems, and the possibility of solution all suggest the strategic value of publicly supported R&D on nuclear fission.

2. Energy Storage and Application

Many of the technical options for environmentally benign energy conversion have only limited applicability until energy storage and application are improved. The following technologies represent particularly critical directions for research in this field. The inclusion of these technologies on the list is justified by a relatively even weighting of all four criteria.

a. Batteries

Improved batteries make possible the use of a wide variety of environmentally superior technologies, such as emission-less vehicles and applications of solar and wind power. Key to the development of improved batteries will be design advances that lead to a reduction in toxic heavy metal components and to the efficient recovery and reuse of these components. Wide-ranging technical options are currently being investigated, including improvements in conventional lead-acid and nickel-cadmium electrochemistries and the development of batteries using aluminum-air, lithium-aluminum-iron sulfide, sodium-sulfur, sodium-iron-sulfide, and substances. Higher energy density, higher power density, longer life, lower cost, and faster charging are some of the clear technical goals. The improved products and services new battery technology could allow make the potential returns on its development very high. Although considerable research is now under way, the basic challenge is to achieve generic advances in electrochemistry.

b. Superconductors

High-temperature superconductors would make it possible to store electricity directly without converting it to chemical, thermal, or mechanical forms. If affordable superconducting coils could store electrical current with virtually no resistance loss, the applications would be virtually limitless. Consequently, this technology is already the focus of worldwide R&D efforts to overcome the fundamental technical challenges impeding commercial use.

Superconductors might provide direct environmental benefits by improving energy transmission, and indirect benefits by making such intermittent energy sources as solar and wind energy technologies more competitive. On the other hand, the development of the technology may also pose environmental risks if such toxic elements as thallium are used inappropriately. Superconductors are a prime example of a potentially revolutionary generic technology that must be developed and applied in an environmentally beneficial manner.

c. Hydrogen Storage

Problems with hydrogen storage now limit the feasibility of hydrogen-powered vehicles, which offer potentially high environmental benefits. Hydrogen is a clean-burning fuel that yields water when burned. It can also be used in fuel cells. Although electrolytic and transmission technologies do not appear to present major problems, improvements in metal or organic hydride storage are necessary before hydrogen-powered vehicles become viable. Since fundamental advances in materials science and chemistry may be critical to the solution of these problems, hydrogen storage illustrates how important generic technical advances can be as a foundation to solve particular environmental problems.

d. Heat Storage

Improved heat-storage devices and materials could raise the energy efficiency of buildings, solar thermal electric systems, and other storage applications. Environmental benefits would result from both decreased energy demand and the availability of new power systems. Although water-based systems have recently become better established, advanced heat-storage materials, such as phase-change salts, are far from commercialization. The technical problems involved require both highly generic materials research and the development of specific devices.

e. Fuel Cells

Fuel cells, extremely quiet and non-polluting, can produce electricity at efficiencies greater than that in fuel combustion, and could be used in vehicles, houses, and industries with considerable environmental benefits. Currently, some applications are commercially viable, but further development and extension beyond limited niches depends on advances in electrochemistry, materials and membrane technology. Phosphoric acid, molten carbonate, solid oxide, and proton-exchange membrane cells are among the major types of systems under investigation. None will be viable until costs fall and reliability and performance improve. Both the possibly wide diffusion of fuel-cell technology and the generic nature of the technological advances on which it will rest suggest that fuel cells represent a strategic opportunity for the future.

3. Special Energy End-Uses

The end-uses of energy—in industry, agriculture, transportation, and buildings—vary significantly in terms of the efficiency improvements that can be made and the incentives and opportunities energy users have to modify them. Technological improvements in transportation and buildings, discussed below, offer the greatest strategic opportunities. Because improved technologies would be applied broadly, they could reduce environmental risk substantially. Although the returns to private developers and users may be relatively modest, in the aggregate, the high social returns justify including these technologies on the list.

a. Transportation

The adverse environmental consequences of transportation are well-recognized: transportation emissions constituted 32 percent of U.S. carbon dioxide in 1987, of which three quarters arose from road transport [OTA 1991]; and in 1990 transportation was the source of 38 percent of nitrogen oxides, 31 percent of lead, 23 percent of particulates, and one third of volatile organic compounds. [EPA 1990] Three basic technological strategies could lessen or eliminate these environmental costs: cleaner vehicles, more efficient vehicle use, and decreased travel demand. Although radically new technologies that could make a major contribution—for example, electric or hydrogen vehicles—are currently impeded by energy-storage problems, advanced engine designs (e.g., low heat rejection engines), ceramic engines, improved electronic controls, and continuously variable transmissions, among others, would be comparatively easy to integrate into the current vehicular fleet. Technology could contribute much to improvements in surface travel efficiency through, for example, "smart highway" systems. The underlying technological advances need to revamp infrastructure systems such as these are particularly appropriate for public support.

b. Buildings

Because space heating and cooling, lighting, water heating, and appliances account for about 36 percent of U.S. carbon dioxide emissions, making buildings more energy efficient would reduce environmental risk substantially. Many technological improvements now available—for example, more efficient lighting and appliances—are not being diffused as rapidly as would be desirable. Even where current heating and cooling plants, such as furnaces, operate near their theoretical maximum efficiency, substitute or combination technologies, such as heat pumps, could, in theory, improve efficiency as much as several-fold. Alternative refrigeration cycles and refrigerants, improved controls, capacity modulating systems and thermally activated heat pumps can all offer substantial efficiency gains. [ORNL, 1989]

Advanced materials have a myriad of potential applications as high-performance insulation in building shells and other uses. Evacuated powder panels and phase-change salts for thermal storage provide two of many examples. In addition, the combination of new materials and information systems could lead to "active" and "smart" building or component systems that monitor and adjust to external conditions. Last, long-term research may fundamentally alter the concept of building shells and components: the next generation could incorporate heat, humidity, and light control. [Pellish, 1991] These are environmentally important applications of more general building-block technologies.

4. Agricultural Biotechnology

Agriculture is already responsible for widespread and severely negative environmental repercussions: chemical pollution from pesticides and fertilizers, deforestation, soil erosion, and damage to plant and animal life. By the middle of the next century, when a doubling of population will have dramatically raised demand for agricultural production, an ecological crisis may be at hand, unless radically altered, environmentally sustainable technologies are in use by then. Biotechnology appears to hold the potential to bring about a second, environmentally friendly "green revolution" if the diverse technical options are adequately and wisely developed. Included in virtually all lists of critical technologies, biotechnology is critical from an environmental viewpoint as well, not only because it can reduce environmental risk, but also because it can be applied generically to a wide range of problems.

Biotechnology is an exceptionally broad technical field. It includes recombinant DNA techniques, protein engineering, monoclonal antibody production, and bioprocessing. [OSTP, 1991] Much of biotechnology research has been supported with generous public funding. In 1990, for example, some $3.5 billion in federal funds were directed at biotechnology research, compared with some $2 billion of private monies. [President's Council on Competitiveness, 1991] More recently, large infusions of private capital, domestic and foreign, have moved toward the industry. [Hamilton *et al.*, 1992]

Most funding for biotechnology research, both public and private, has been directed to medical applications. For several reasons, agricultural applications, particularly those with the largest environmental payoff, have been relatively underemphasized. First, a number of solutions to the technological obstacles to be overcome are highly generic and thus unlikely to attract sufficient private investment—a classic example of "underinvestment" from a societal viewpoint. Examples include routine and efficient gene delivery to and regeneration of the tissues of such important agricultural crops as wheat, and understanding of plant physiology at the molecular level. In addition, much of agricultural biotechnology is still highly experimental and precommercial. [OTA, 1991] Thus, the potential reductions in environmental risk that seem possible depend highly on technical advance.

Biotechnology's agricultural applications include gene-transfer techniques, genetic engineering of plants, and new approaches to animal breeding and bioprocessing. Many important environmental advances are under way: the development of microbial inocula that diminish the need for chemical fertilization and pest control, advances in biological pesticides, and the modification of such genetic characteristics as nitrogen fixation and photosynthetic efficiency. Some fruits of this research are already at hand or are on the horizon. Bt (bacillus thuringiensis), a "biorational" pesticide that quickly breaks down into harmless components, is well-known; insect-herbicide resistant corn is expected to be approved by 1994 and may mature into a $1 billion market. [Hamilton *et al.*, 1992]

Biotechnology in general is vitally important to the solution of non-agricultural environmental hazards. The bioremediation of hazardous wastes, now in limited use, can provide a cost-effective and environmentally superior option. Biosensors, combining information and biotechnology, may become an important element of pollution monitoring.

Biotechnology stands as a classic example of the close link between scientific research and technological innovation. The federal government has therefore long posited its heavy support for the field on the need for underlying generic research that private firms cannot appropriate. These same considerations apply with equal or greater force to biotechnology's potential agricultural and environmental benefits.

5. Improved Agricultural Techniques

Standard agricultural practice in the United States has until recently tended toward large-scale monoculture and reliance on chemical fertilizers and pesticides as productivity enhancers. Two disparate developments in agricultural technique, "alternative" agriculture and "precision" agriculture, hold out the prospect that technical knowledge can transform these standard practices. Precision agriculture makes extensive use of monitoring and information technologies to target inputs of fertilizer, pesticide, or water to best advantage. Ideally, all elements of precision farming could be linked in an intelligent system that monitored and managed agricultural operations to respond to weather, soil, and even market conditions. Alternative agriculture denotes a combination of techniques and technologies for taking best advantage of natural cycles, ranging from crop rotation to integrated pest management.

Results from many fields of research could speed the development of precision farming and alternative agriculture. For example, electronic, chemical, and biological sensors could all lead to better monitoring of soils, animal nutrition, and pest-infestation levels. Agricultural machines and techniques need to be improved in tandem with increased farm-information resources. Many different directions of inquiry could improve alternative agriculture, including the identification and propagation of natural pathogens to pests, research on repellants and such attractants as pheromones, and pest-resistant plants.

Precision and alternative agricultural techniques both face impediments to further development. Many alternative agricultural techniques are hard for private firms to appropriate. Many of the benefits of using these techniques will be largely environmental, and farmers will find them profitable only if market failures are overcome. Therefore, relatively little private research has been directed at developing these potentialities. Precision agriculture, though more easily appropriable, depends on a synthesis of developments in the information sciences and other fields outside of agriculture. Another obstacle is that agricultural policies and research priorities until now have also favored conventional chemical-intensive monocultural farming techniques.

6. Manufacturing Monitoring, Modeling, and Control

Manufacturing operations are extremely heterogeneous, and they create even more diverse environmental problems: damage to land and ecosystems from plant siting, internal occupational safety and health problems, the release of by-products into the environment, energy use, and resource waste. Manufacturing practice in the United States and elsewhere is amid a technological and managerial revolution in which advances in materials science and engineering, electronics, information, and the chemical and biological sciences are combining with radically altered management practices, notably, "lean production." [Womack *et al.*, 1990] These changes may, if appropriately nurtured, help craft new industrial processes that are substantially cleaner and more efficient than those now in use.

Sensors, process models, and controlled actuators (pumps, valves, robots, numerically controlled machine tools, etc.) are key components of newly emerging "intelligent manufacturing systems." Such systems can optimize process inputs and flow to improve productivity and decrease waste. Computer-automated control of distillation columns and paper mills, for example, lowers energy requirements by 15 and 20 percent, respectively, and improves the quality or quantity of production. [Ross and Steinmeyer, 1990] The wide-ranging applications of such systems are essential for monitoring environmental changes and impacts. As one example, precise information and monitoring could facilitate market-based approaches to pollution control that are more efficient than regulation—among them, pollution taxes and tradable emissions allotments.

While manufacturing modeling, monitoring, and control systems are obviously already in place in both primitive and fairly advanced forms, many generic technological advances can be envisioned. Chemometrics—techniques for analyzing signals from complex chemical mixtures—improved sensors, supramolecular assembly, and self-calibrating machines all offer fertile areas for research. In fact, considerable academic and industrial research on manufacturing is under way. It provides an opportunity, by no means fully realized, to integrate environmental factors into the development of emerging technologies and practices.

7. Catalysis

Catalysts, which trigger chemical reactions, are used throughout the chemical, materials processing, and food-production industries. The field of catalysis is currently achieving significant advances, with contributions from new developments in chemistry, materials science, and biotechnology. In industrial processes and effluent treatment, catalysts can reduce environmental risks by preventing pollution. In process control, for example, catalysts can improve product yield, permit the use of more benign feedstocks, or remove undesirable by-products. Several research areas appear vital for continued advances in catalysis: better understanding of chemical reaction mechanisms and material surface phenomena, the improved understanding of protein structure and function needed before enzymes can be engineered, and the fabrication of highly ordered supramolecular structures, which may suggest new catalysts. Since all of these fields are at the basic end of the research spectrum, they are both far from competitive forces and widely applicable to many industrial and environmental problems.

8. Separations

Separation operations—e.g., distillation, drying, cleaning, degreasing, and evaporation—are among the most environmentally troublesome activities in industry, and also among the most environmentally useful. They account for 20 percent of industrial and 5 percent of total U.S. energy demand (ORNL 1989), and many use hazardous substances ranging from toxic solvents to ozone-depleting CFCs. By the same token, separation technologies also have wide environmental uses in, for example, waste treatment, particulate removal, or sewage filtering. Improved separation techniques would reduce energy use and environmental insults in such industries as food processing, chemical manufacturing, energy production, pulp and paper, metals, electronics, machining, and waste and water treatment.

Separation operations present one of the clearest opportunities for preventing pollution by using appropriate technology instead of resorting to remediation after-the-fact. A number of separation technologies are emerging as critical. Better membrane systems, for example, could eventually replace conventional distillation and evaporation processes. Super-critical fluid extraction may obviate the use of organic solvents in many industrial processes and could also help in cleaning up contaminated soil and water. Affinity separation, based on specific binding of particular molecules to a target molecule, could conceivably be used in large-scale efforts to purify dilute products and, in other settings, could be used to remove dilute pollutants.

Better fundamental and practical understanding of the engineering of separations technologies, as used in various separations operations, would contribute substantially to subsequent improvement of environmental and economic importance. Because theoretical development of this nature is inherently non-appropriable, and new techniques could be so widely applied, the societal returns to developments in this area promise to be very high.

9. Precision Fabrication

The ability to manipulate matter precisely, thanks mainly to computer controls and miniaturization, would allow a great reduction in industrial use of natural resources and industrial emissions. Although precision fabrication of electronic and optical materials is widely recognized as a critical technological capability (COC, 1991; OSTP, 1991), its environmental benefits remain largely unsung. A wide diversity of techniques fall under the rubric of precision fabrication. Nanolithography—x-ray, electron beam, and ion-beam techniques for etching features on chips—can, with increasing precision, improve chip capacity and quality dramatically. Thin films or precision coating techniques, including chemical and physical vapor deposition and laser and ion-beam implantation, can decrease the cost of photovoltaic cells, improve the performance of electronic components, increase wear and corrosion resistance, and make "smart" building components more widely available.

Precision fabrication, like many emerging technologies, draws from various technical fields, including manufacturing, materials, and chemical sciences. While many of its techniques are still precommercial, eventually their use will be almost ubiquitous.

10. Materials Design and Processing

The current "revolution" in materials design and processing involves not only the development of new and superior metals, polymers, ceramics, and composites, but also radically new ways of producing them. (OSTP, 1991) The trajectory of development is wide-ranging, merging materials sciences with chemistry and precision manufacturing with biotechnology. Given these trends, materials synthesis and processing, along with the development of electronic and photonic materials, ceramics, composites and high-performance metals, and alloys, should all be considered critical technologies for the United States. (OSTP, 1991)

The materials revolution has myriad implications for the environment. New methods of materials processing, such as direct steelmaking, electrochemical processing of metals and chlorine, and microbial mineral processing could dramatically diminish pollution and energy requirements. While increased design capabilities make it possible to work around many of the environmental hazards associated with products in the past, new materials may also present new hazards. The applicability of materials technology is so broad and materials R&D so vibrant at present that many environmentally beneficial technologies could appear on the scene soon if the criteria for public funding and private development adequately reflect environmental needs.

11. Information, Communications, and Computing

Development of information technologies has probably been more rapid and dramatic than progress in any other field within the last half century. This dynamism may continue into the foreseeable future. Information technologies are often seen as the new bedrock on which modern societies depend. From an environmental point of view, the benefits associated with increased applications of information technology are manifold, though often very indirect. At the most general level, dematerialization—the tendency among highly developed societies to use fewer material inputs for a given level of output [Herman *et al.*, 1989]—is a matter of substituting information for natural resources. Far more particularly, improving environmental quality depends increasingly on developing and deploying information technologies, such as computerized effluent monitoring and process control. It is beyond the scope of the analysis here to catalogue the vast range of information technology applications, but they are crucial nonetheless. For instance, understanding and managing complex global environmental problems, such as climate change, require that vast quantities of observational information be recorded, stored, analyzed, shared, manipulated, and displayed in ways convenient to scientists, policy-makers, and the public. These requirements cannot be met without significant advances in information technologies.

Information technology is included here because its use tends to make economies less resource-intensive and because potential applications of information technology to environmental problems are generic, essential, and widespread. Development of many of these applications would pick up speed if public policy provided for their support and encouraged their diffusion.

12. Contraception

Population growth, because of the increasing demands it places on finite world resources, is a major source of environmental problems. Although population has stabilized or even declined in many of the developed economies, world population is expected to double by the middle of the next century. Most of this growth will occur in the developing world.

While fertility decline depends at least as much on complex social, cultural, economic, and political factors as on technology, a number of important emerging technological avenues could radically expand contraceptive alternatives to meet unmet needs. These developments could help the huge number of adults who want to limit or time their reproduction but, for one reason or another, do not practice contraception, thus reducing the number of unwanted pregnancies. The scope of potential developments is very large, ranging from less invasive and reversible surgical techniques to vaccines and implants. Developments within each of these categories can apply to both males and females. Research and development of contraceptive technologies in the United States has slackened dramatically—in the private sector because of liability risks and in the public sector because of political currents. The inverse relationship between population growth and environmental sustainability makes pursuit of these and other inadequately researched technical alternatives an environmentally critical opportunity. [Mastroioanni *et al.*, 1990]

C. Comparison to Other Lists of Critical Technologies

No other U.S. researchers have, so far as we know, identified a set of technologies critical to achieving environmental sustainability. A list of opportunities in environmental technology developed by the Centre for the Exploitation of Science and

Technology (CEST) in the United Kingdom [Good, 1991] is the most similar compilation, but it focused primarily on technical solutions to current problems. This report, in contrast, looks to the future, examining the potential of emerging technologies.

The list set forth here complements other studies in both environmental and technology policy. For example, several assessments of national environmental priorities, most notably the EPA report on risk priorities [EPA, 1990], have attempted to determine the country's most pressing environmental problems, largely without reference to the availability of technical solutions. Other studies evaluate alternative technical solutions to particular environmental problems [Nadis and MacKenzie, 1992 (forthcoming); Kosloff and Dower, 1992 (forthcoming)]. None, however, broadly surveys overall technological development and relates it to emerging critical environmental challenges.

Several lists have recently been compiled of technologies critical for economic growth, competitiveness, or national security, but none emphasizes environmental problems. Environmental and energy technology emerges as a critical area on one list (OSTP), however, and in another (COC), environmental technology is cited as an opportunity for the United States to increase its competitiveness.

Although derived from different criteria, the technologies this report identifies as environmentally critical overlap somewhat with those on other lists of critical technologies. This congruence shows that many of the technological areas identified as critical on other criteria are important from an environmental perspective as well. However, within these broad technological areas, certain lines of development are particularly relevant to environmental concerns.

IV. PRIVATE AND PUBLIC SUPPORT FOR CRITICAL ENVIRONMENTAL TECHNOLOGIES

A. Technology Development and Environmental Concerns in the Private Sector

The interviews conducted for this study focused on two main concerns: identifying environmentally critical technologies, and changes in the private sector R&D process brought about by environmental concerns. Technical experts and R&D managers in universities, industry, and government were asked to give their first-hand impressions of how environmental imperatives—regulation, market forces, or public opinion—has affected technology development in their institutions by influencing R&D priorities, new business opportunities or strategies, and organizational structures. From these interviews emerged a surprisingly strong consensus about the relationship between environmental issues and technological change. *(See Table IV.)*

The strongest finding is the increasing importance of environmental factors in technology development, a change recognized by virtually all interviewed, whether or not their institutions were directly engaged in environmental R&D activities. Perhaps the most persuasive illustration of this change came from a number of industrial research organizations in the United States and abroad recently established to address the critical technological issues facing industry in the future. These groups indicated that R&D on environmental technology is frequently requested by industry and may comprise as much as half of their institution's research budget.

The R&D devoted to solving immediate environmental problems has increased vastly in both private firms and universities and has become more formal. The keenly felt need to see that new technologies do not create new environmental problems has led many institutions, especially leading technology-based companies, to conduct environmental reviews routinely at all stages of the R&D process. Many new research centers, departments, and divisions have been established to explore particular environmental technical issues. Environmental R&D budgets appear to be surviving or growing even while funding for R&D in general is shrinking. One interviewee even reported that environmental imperatives furnished the strongest argument for protecting the overall corporate R&D budget from threatened reductions.

"*Contradicting the conventional wisdom that environmental factors constrain technology development, those interviewed for this study frequently characterized environmental problems as new strategic business opportunities.*"

Contradicting the conventional wisdom that environmental factors constrain technology development, those interviewed frequently characterized environmental problems as new strategic business opportunities. Those who saw these opportunities were not, for the most part, from the traditional pollution-control industries, but rather, from companies that foresaw new applications of their products, services and information systems in a more environmentally conscious future. Often, such companies have taken steps to determine how their expertise can be marketed to solve others' environmental problems.

Despite this increased emphasis on solving environmental problems, many of those interviewed expressed frustration at the lack of a long-term perspective in the United States on broad technical solutions to environmental problems. Even though work on technologies to solve immediate environmental problems has increased, research and development on longer-term technological solutions to impending environmental problems was seen as inadequate.

It was not surprising, therefore, that the concept of environmentally critical technology as a critical R&D priority for the United States met with widespread assent. Appreciation of the need for public support for such research and development was

Table IV. Changes in Private R&D Process

Findings based on interviews with technical experts in universities, industry, and government during summer 1991.

- Wide-spread recognition of environmental criteria as critical to new technology development;
- Significant increases in percentage of R&D portfolio devoted to environmental problems;
- Environmental reviews routine throughout technology-development process, particularly in leading technology-based companies;
- Environmental technology increasingly seen as a strategic business opportunity, particularly outside the realm of traditional pollution control;
- Widely perceived need for national long-term technology strategy for the environment; and
- Frequent duplication of environmentally-oriented R&D among companies in some industries underscores the need for industrial R&D cooperation.

similarly strong. At the same time, the distinction between generic, precompetitive technologies of critical environmental importance and particular market-driven applications (discussed in the previous chapter) was the basis for deciding whether public R&D support is justified.

One key deficiency in private sector R&D on environmental issues is that it appears to be duplicative. The speed with which environmental issues have come to the fore and the immediate need for technical solutions have driven many companies to undertake almost identical research simultaneously on almost identical problems. Where the technologies sought would not afford their developers a major competitive opportunity, cooperative R&D could be a highly cost-effective strategy for eliminating such duplication. There are already several examples of such cooperation, but public policies that provide funding, information, facilities, regulatory relief, or other incentives for getting universities, industry, and public labs to form partnerships, could encourage much more cooperation.

B. Treatment of Environmental Needs in U.S. Technology Policy

The national policies and institutions in the United States that support technology have accorded little prominence to environmental issues. Although environmental science programs have benefitted from increased visibility and a great deal of relevant R&D is being conducted in research institutes, universities, and firms, explicit support for environmental technology has not surfaced as a clear policy objective. In this regard, the United States stands in stark contrast to other highly industrialized countries.

More specifically, many of the technological areas identified in the preceding chapter as critical to environmental sustainability have received scant support from the federal government. Renewable energy and its supporting systems have received only 5 percent of the Department of Energy's R&D funding over the past fifteen years, far less than nuclear and fossil fuel energy. Moreover, R&D funding for renewable energy declined in real terms by more than 90 percent from its peak in 1979 to a trough in 1990, before a modest revival began in the 1990s.[2] Advances in renewable energy technologies could be accelerated with more adequate R&D support.[3]

Precision and alternative agriculture have likewise received only a tiny share of the agricultural research budget in recent years. Only 2 percent of public agriculture research budgets have been spent on alternative, low-input, or alternative agriculture.[4] This lack of support has been particularly hindering to progress in this field, since many of the techniques of precision and low-input agriculture are not appropriable through patents or copyrights. Accordingly, private agricultural research has been overwhelmingly devoted to the development of new chemical, mechanical, and seed inputs.

As for contraceptive development, the U.S. private sector has largely withdrawn because of the risks of product liability lawsuits and the delays and risks of regulatory approval. Only one of the many large pharmaceutical companies previously involved in contraceptive research is still active. At the same time, federal funding for contraceptive development remained virtually constant throughout most of the 1980s at levels between ten and fifteen million dollars per year (1973 dollars). According to a recent National Research Council review, "research in reproductive biology and contraceptive technology is underfunded. Development of new contraceptive methods is expensive, and additional resources could speed the process of innovation. Federal funding in these areas should keep pace with the rising costs of research and development."[5]

In part, the reason technology policy has not addressed environmental issues springs from unique features of the American government. Technology policy in the United States is highly decentralized and diverse. This country has, for example, no national department of research and technology, which is the norm abroad, nor any national university system. Second, the U.S. government has historically withheld support for industrial technology in general, concentrating instead on science and mission areas: defense, space, health, agriculture, and energy. In most other industrial countries, public R&D budgets have provided heavy support for civilian technologies. These distinctive features of the U.S. system, whatever their advantages, make it difficult to direct public R&D support to environmentally critical technologies. Given the close connection between environmental and other industrial technology, other countries have found it comparatively easier to redirect or expand public policies and institutions to support environmentally critical technologies.

During the 1980s and 1990s, two other shifts within U.S. policy affected support for environmental science and technology both positively and negatively. Particularly in the early 1980s during the Reagan Administration, the composition of R&D budgets shifted away from applied topics toward basic research. By decade's end, however, concern about U.S international competitiveness had led to several new initiatives directly focused on technology of generic economic importance.

As Table V indicates, overall federal R&D funding increased significantly during the late 1980s. Life sciences R&D grew somewhat more slowly than the general trend, but environmental sciences grew much more quickly, due mostly to the increases in basic research. EPA's R&D budgets show a similar pattern: overall growth was faster then the norm, fueled by large increases in basic research; indeed EPA's applied R&D fell. The overall tendency has

Table V. Trends in U.S. Government R&D Expenditures

(In Billions of Dollars)

	FY88	FY89	FY90	FY91	% Increase or (Decrease) over Period
TOTAL	56.6	61.3	65.5	68.8	21.5
Life Sciences	7.7	8.3	8.7	9.4	18.0
Environmental Sciences	1.3	1.7	2.1	2.3	76.9
Environmental Protection Agency (EPA)	0.347	0.387	0.420	0.442	27.3
Basic Research					
Total	9.5	10.5	11.2	12.2	28.4
Life Sciences	4.5	4.8	5.2	5.5	22.2
Environmental Sciences	0.87	0.99	1.0	1.3	49.5
EPA	0.027	0.044	0.076	0.097	185
Applied Research					
Total	9.2	9.9	9.9	10.1	9.7
Life Sciences	3.2	3.5	3.5	3.8	18.7
Environmental Sciences	0.73	0.78	0.91	1.01	38.3
EPA	0.240	0.259	0.262	0.222	(11.0)

Source: National Science Foundation. 1991. *Federal Funds for Research and Development: Fiscal Years 1989, 1990, 1991.* NSF 90-327.

thus been to increase the salience of environmental sciences without similarly increasing support for environmental technology.

Another way to evaluate U.S. technology policy's responsiveness to environmental issues is to consider the thrust of recent institutional change. Such change was most marked during the late 1980s, when a number of new public and publicly supported institutions made technology their principal focus. Some of these new institutions concern themselves with environmental technology; others do not. A survey of these recently established or proposed programs *(See Table VI)* leads to the following conclusions:

- Given the close connection between environmental issues and industrial technology development, technical institutions have a potentially large role to play in solving environmental problems—the National Institute of Science and Technology may illustrate this potential most clearly;
- A number of new programs focus on environmental technology almost entirely; these include National Environmental Technology Applications Center, the National Defense Center, and some Environmental Research Centers;
- Industry demand has caused some institutions to turn more toward environmental issues than originally anticipated; the National Center for Manufacturing Sciences best illustrates this trend;
- The major new initiatives to support industrial R&D—Intelligent Manufacturing Systems and Advanced Technology Program, most notably—have failed to include environmental issues or to emphasize the applicability of new technologies to environmental improvement; and
- Newly proposed environmental research initiatives have not emphasized environmental technology. This is illustrated by the National Institute for Environmental Research, which appears to be focusing on science.

Table VI. U.S. Technology Programs and the Environment

Illustrative Examples

Program	Focus	Assessment
NIST (National Institute for Standards and Technology, DOC)	Reformulated National Bureau of Standards; wide-ranging support for industrial technology.	Large potential to address environmental issues.
ATP (Advanced Technology Program, DOC)	Recently instituted R&D funding for emerging technology.	Environmental benefit could be added as funding criterion.
Cooperative Research Centers—e.g., ERCs (Engineering Research Centers)	NSF funded network of cross-disciplinary centers at universities, linking academe, industry.	Some centers focus on problems.
NETAC (National Environmental Technology Applications Corporation, Pittsburgh)	Technology transfer center, combining EPA and private support.	Possible prototype for expansion.
National Defense Center for Environmental Excellence, Johnstown, PA.	DOD/University cooperation.	Indicates new DOD interest.
NCMS (National Center for Manufacturing Sciences, Michigan)	Private organization with initial public support, addresses manufacturing technology questions for industry.	Environmental technology issues substantial part of activities.
NIER (National Institute for Environmental Research—proposed)	Feasibility under study by NRC.	Original proposal emphasized science more than technology.
IMS (Intelligent Manufacturing Systems)	Major U.S.-Japan-Europe cooperative R&D, in feasibility study.	Environmental issues may appear, although not originally included.

C. Support for Environmental Technology in Other Countries

Since environmental problems and the technological resources needed to address them are very similar throughout highly developed countries, it is worthwhile to compare programs, policies, and institutions that other countries have developed with those in the United States. Table VII presents some illustrative results from such a comparative survey. (Although many more programs could have been included in the chart, the ones chosen are broadly representative.)

The programs that promote environmental technology in other countries must be viewed in the context of these nations' overall technology policies. In each of the five countries surveyed, the development of technologies to solve pressing national economic problems is a matter of longstanding public policy. Government and industry usually see themselves as partners in efforts to improve national economic competitive position. Typically, policies identify broad technical areas within which government R&D funding supports the development of specific industrial technology. This approach has made it easy to develop environmental technology programs.

Table VII. National Institutions Supporting Environmentally Critical Technologies

Illustrative Examples

Country	Institution	Focus	Budget
JAPAN	RITE (Research Institute of Innovative Technology for the Earth	Founded 1990. MITI-sponsored research institute; greenhouse warming main initial target.	> $1 billion cooperative national, local, private funding.
	NEDO (New Energy & Industrial Technology Development Organization)	MITI-origin; Environmental technology one of four areas of R&D support.	$1.8 billion (1990)
GERMANY	BMFT (Ministry for Research & Technology)	4 programs; Environmental technology; R&D funding & demonstration.	$470 million (5% R&D budget)
	STATES	Similar to national.	23% national R&D total.
THE NETHERLANDS	TNO (longstanding technical research, technology transfer organization)	Contract research and technical assistance to industry	Environmental technology approximately 10% portfolio.
ITALY	TIF (Technological Innovation Fund)	Established 1990. Research and precommercial development loans. Environment priority sector. Projects in all other areas require assessment of potential environmental benefit.	Before 1990 5% environmental; will now increase.
CANADA	Technology for Environmental Solutions (combines Science & Environment Ministries)	Established 1991. Three components: demonstration, technology transfer, and information network.	$100 million

Indeed, the assumption is widespread outside the United States that environmental technologies will become increasingly important in international economic competition.

All five countries that appear on the chart, plus others—France, the United Kingdom, and Norway—have developed public programs that specifically target the development of environmentally critical technologies. In Germany and elsewhere, these have simply been folded into existing technology programs; in other countries, such as Japan, new institutions have been created. Many programs, particularly those emphasizing remediation technology, started decades ago. Others, particularly those focused on pollution prevention, have arisen within the last few years.

Clearly, Japan is pursuing the development of environmental technology most vigorously, followed by Europe and then the United States. This ranking is based on the number of programs, their funding, and the activism of the government role. The precise environmental concerns and, accordingly, the target technologies vary from country to country. Italy, for example, appears to be emphasizing water pollution; Japan, greenhouse warming.

The most common support mechanism for environmentally critical technologies is government funding of private R&D through loans or grants. The size of such programs varies greatly. Japan's are the largest. In Germany, the Netherlands, and Italy, devoting around 10 percent of public R&D spending toward environmental technology is not unusual. The creation of a special research institute in Japan, RITE (Research Institute of Innovative Technology for the Earth), represents an unusual strategy. Italy's Technological Innovation Fund is also unique in combining funding for environmental technology with a requirement that all projects supported by public R&D funds take into account the kinds of environmental benefits they might create.

The specific technologies these programs support range widely and vary from country to country. Table VIII presents some illustrative examples. Although these examples in no way suggest that the United States should adopt the same priorities, they reinforce the point that most other countries have committed substantial resources to developing environmental technologies valuable to industry for both social and economic reasons.

Table VIII. Environmentally Critical Technologies Abroad*

Japan

- Advanced Chemical Processing Technology
- High Performance Bioreactor for Production of Biochemicals
- Development of Biodegradable Plastics
- Environmentally Friendly Technology for the Production of Hydrogen
- CO_2 Fixation And Utilization
- Advanced CFC Substitutes
- Reusable Metallic Materials

Netherlands

- Environmental Biotechnology
- Recycling and Process—Integrated Techniques
- Manure Processing
- Soil Cleaning

Germany

- Waste Management
- Low-emissions Processes and Products
- Water Analysis
- Radiation Protection
- Sewage Sludge

* Excludes energy-related projects.

Sources: NEDO (Japan), August 1991; RITE (Japan), 1991; TNO Survey of Activities 1987; OECD, CSTP Project on Responsiveness of Science and Technology Institutions to Environmental Change, 3 June 1991.

V. CONCLUSIONS AND POLICY OPTIONS

A. Needed: An Environmental Technology Policy

The creation of an environmentally sustainable economy is among the most pressing challenges facing U.S. public policy. This is true not only domestically, where major changes will be necessary to forestall environmental deterioration, but also in foreign policy, where global environmental issues affect international relations, trade, and competitiveness. New technology is central to these concerns: it offers at once the most effective solutions to environmental problems and the only viable long-term basis for continued economic growth and competitiveness.

Despite these new concerns, U.S. science and technology policies still appear rooted in an obsolete paradigm. As recently as 1991, the vast bulk of federal R&D funding was devoted to fields with little relevance to environmental quality: five areas—defense (60 percent), health (13 percent), space (11 percent), science (4 percent), and energy (4 percent)—accounted for 92 percent of the national total. [NSF, 1991]. In 1991, a list of critical technologies, drawn up to set national technological priorities for the future, slighted environmental concerns.

The intention here is not to suggest that environmental issues have not been accorded high national prominence in the U.S.; that public policies—principally regulatory—have not attacked them vigorously; or that the scientific community has not committed significant resources to their understanding. The heart of the argument, instead, is that the need for new technology to solve environmental problems has been inadequately recognized and that the government's role in encouraging such technologies is underdeveloped.

The public sector's underallocation of attention and resources to environmental technology contrasts with what is occurring in the U.S. private sector. Among industrial firms and universities, environmental R&D is increasing markedly, and environmental factors have become a routine, but critical, element in technology development. Strategic business opportunities based on environmental needs and capabilities are widely perceived among the private sector's technical community.

Nonetheless, many in the business community believe that their technological progress is being impeded by a lack of direction in public policy. The long-voiced complaint—that regulatory policy inhibits innovative solutions—is still heard. More frequently, however, businesspeople express two different sources of frustration. First, the lack of a long-term technology development vision in environmental policy casts uncertainty over their investment strategy. Especially when the needed changes are pervasive—modifications to manufacturing in materials processing, for example—industry action depends on clear and consistent long-term public policy. Second, nearer-term efforts to overcome environmental problems are hampered by the virtual absence of support for generic technical areas—such as those incorporated in the list above—that underlie a wide range of solutions.

The need for technological solutions to the environmental issues critical to U.S. well-being and security, as well as strong demand from the private sector, argue convincingly that a coherent set of policies, institutions, and programs to support environmentally critical technologies should be a major element of both technology and environmental policy in the United States. In broad outline, these policies should further the development and implementation of environmentally critical technologies, such as those listed above. The breadth of the items on that list suggests that an environmental technology policy must also employ a portfolio approach, thus promoting a wide range of relevant new developments. The close connection of these environmentally critical technologies to industrial technology in general suggests a common underlying technical base and complementarity between environmental and economic objectives.

Strong public support in other advanced countries for environmentally critical technology underscores how important it is to environmental progress and economic competitiveness in the United States.

It also suggests how our country could structure similar programs. In Japan, Germany, and France, among other countries, environmental technology has already gained widespread acceptance as a subset of the industrial technology so critical to national well-being. Initiatives in other countries combine a desire to solve environmental problems with the goal of strengthening national competitiveness by mastering environmentally sound technology.

While the virtue of a comprehensive environmental technology policy is clear, the ways to create and implement a policy of such broad scope need to be worked out. Congressional articulation of a new environmental mission for technical agencies and translation of this mandate into new funding patterns represent only the first steps. Within the Executive Branch, environmental concerns need to be elevated much higher in R&D priorities, perhaps by giving them a cross-cutting focus in the White House Office of Science and Technology Policy. Within federal technical agencies, environmental issues need to become a more explicit programmatic focus, and more environmental applications of technologies should be underwritten with public monies.

B. Policy Options

Developing a coherent environmental technology policy will require changing U.S. legislation significantly, modifying public technical institutions, establishing new relationships between the public and private sectors, and reorienting R&D funding. The seven policy options outlined below address each of these needs. Although all of the options could be undertaken separately, they are not mutually exclusive. Indeed, enacting all seven proposals would move environmental technology policy forward on many fronts.

1. A Federal Institute for Environmental Technology

The most straightforward approach to support the development of new technology is public funding of relevant R&D in private firms or public laboratories. Consistent with the criteria set forth in Chapter 2, public funding could be focused on R&D projects at a precommercial stage of development that have generic applicability and a potentially high social and environmental payoff.

Creating a new institution to support or carry out R&D on environmentally critical technologies has the virtue of clarity of purpose. It is consistent with other U.S. programs directed toward areas of strategic national importance—Defense Advanced Research Projects Agency, Sematech, and the Advanced Technology Program are examples. These programs, at their best, are focused on R&D that the private sector does not support, but that are potentially profitable or broadly beneficial to the public. The most difficult judgment to make about this approach is whether devoting a new institution solely to environmental technology makes sense, given the intimate connection of environmental goals to most emerging technologies. On a more practical level, however, the creation of any new public program poses budgetary, jurisdictional, and institutional difficulties. For this reason, a better tactic might be to reconstitute an existing national lab, perhaps one previously oriented toward military R&D, giving it a new environmental mission.

> ***"Creating a new institution to support or carry out R&D on environmentally critical technologies has the virtue of clarity of purpose."***

The foremost example of an R&D institution for environmental technology is RITE in Japan. Although funded by the Ministry of International Trade and Industry (MITI), RITE is a reasonably autonomous institution, with a specific environmental mandate. With its current focus heavily on alternatives to carbon fuels, RITE bespeaks the Japanese government's long-held belief that private firms benefit from assistance in endeavors of long-term strategic importance and that a future economic payoff will materialize from providing it. Even so, RITE is an internationally open institution, and it has already funded several non-Japanese research projects.

2. Environmental Funding Criteria

The U.S. government, like governments worldwide, funds a large portion of the nation's R&D.

Currently, R&D projects on defense, space, health, transport, industrial development, and the like receive half of all public funds for research in the United States. Although few of the public R&D programs are directed principally at environmental concerns, almost all are potentially relevant to the development of environmental technology.

Environmental concerns could be built into ongoing government programs that support R&D, particularly those targeted at industrial technology, through new funding criteria. Some European nations take this approach, notably the Italian Technological Innovation Fund (TIF), which since 1990 has had a discrete environmental program and has also developed criteria to ensure that all funded projects take into account environmental objectives.

A major virtue of this policy approach is its administrative ease: ongoing R&D program managers simply apply new environmental criteria in their funding decisions. In addition, this approach is conceptually appealing because it augments the inherent connection between environmental and other industrial R&D objectives. The major drawback is that environmental objectives may be accorded only marginal importance in ongoing programs. Environmental objectives and criteria in existing research programs could be reinforced if the White House Office of Science and Technology Policy assigned a cross-cutting budgetary priority to environmental technology programs throughout the Federal R&D establishment. Cross-cutting program coordination efforts such as this have already been launched for manufacturing, biotechnology, and global change. The Federal Coordinating Committee for Science and Technology (FCCSET) could be a useful mechanism for realizing this goal.

Within budgetary categories specifically devoted to environmental issues—EPA's R&D budget for example—a change of focus should also be considered. Although the recent increased emphasis on basic research and science is undoubtedly valuable, the importance of applied research for technology development needs to be emphasized more than in the past, and applied research budgets increased, as an element of environmental technology policy.

3. New Missions for National Laboratories

A third policy option would mobilize the substantial resources of federal laboratories—estimated to comprise about one sixth of the nation's technical personnel—to develop environmentally critical technology. This approach could be analogous to that written into the Federal Technology Transfer Act of 1986, which created a new mission for all federal research institutions: to transfer technology to the private sector. More specifically, all labs should establish a technology transfer office and commit staff to the effort. Legal restrictions on public-private relationships have been eased, allowing for cooperative technology development between lab personnel and private firms, and cooperation is encouraged by an incentive structure—lab personnel whose inventions are commercially successful receive monetary rewards.

The new institutional arrangements effected by the Technology Transfer Act establish the preconditions needed to mandate federal laboratories to encourage the development of environmentally critical technologies. To a limited extent, this process has begun already. Programs and people in national labs, such as Oak Ridge, Sandia, NIST, and others, have helped industry solve environmental problems. In addition, the diffusion of lab technology to the private sector is a major element of the Bush Administration's February, 1992 "Technology Initiative." But while making an explicit environmental technology component to the federal labs' technology transfer programs mandatory would help focus resources and attention on this area of need, the initiative must also be viewed with realistic expectations. Inertia has plagued federal technology-transfer efforts to date, so considerable skill and development will be needed to make government technology appropriate for private use.

4. New Patterns of R&D Cooperation

Cooperative R&D is increasingly recognized as a useful strategy for augmenting individual firms' R&D effectiveness. Inter-firm cooperation, long frustrated by antitrust concerns, was encouraged by the National Cooperative Research Act of 1984. Cooperation between federal labs and private firms was aided by legal changes during the 1980s pertaining to intellectual property rights and joint public-private endeavors. State government programs have also encouraged cooperation among universities, industrial firms, and public institutions.

Cooperative R&D is nevertheless still underutilized as a means of attacking environmental problems. The needs to be served stem from deficiencies in the private sector: environmental R&D is often focused on the short term, is inefficiently organized, and rarely addresses problems of generic applicability. Among small and medium-sized firms, R&D resources are often minimal. Cooperative R&D represents a particularly attractive way to overcome these impediments.

An important aspect of the public role is to provide a forum for cooperation. Public-private partnerships have been developed in many states but could benefit from federal technical support. In particular, the network of cooperative manufacturing technology centers, funded through state and federal efforts, could be encouraged to include more environmental issues in their portfolios. The National Center for Manufacturing Sciences in Michigan has done so already.

A second important public role is the creation of intermediary institutions that facilitate technology transfer between the private and public sector or among private firms. The National Environmental Technology Applications Center (NETAC) in Pittsburgh stands as one valuable example that could be greatly expanded and replicated. NETAC illustrates how industry, universities, and the public sector can cooperate effectively.

Last, R&D consortia devoted exclusively to environmental technology development deserve consideration. Given that initiatives such as Sematech in the semiconductor industry have received large-scale industrial and public support, similar undertakings to solve large-scale environmental questions, such as CO_2 emissions, may well merit parallel resource commitments.

5. International Collaboration

Although it is well-accepted that environmental pollution, a global phenomenon, demands international solutions, attempts to develop the technologies that can bring about solutions on a worldwide scale have received less attention. In contrast, international collaboration in other areas of science and technology seems to represent the wave of the future. Several enormous projects—IMS (Intelligent Manufacturing Systems) and the Human Genome Project, for example—will be funded and executed cooperatively among many countries. Japan in particular has committed much of its future technology budget to international projects.

Considerably more effort could be profitably devoted to international collaboration in environmental technology development. Either new institutions could be dedicated to this purpose or emerging programs, like IMS, whose potential applications to environmental problems have not been realized, could be reoriented.

6. Regulatory Reform

Public regulation, the mainstay of environmental policy in the United States, has been a major force creating demand for environmental technology. At the same time, U.S. regulatory regimes have often been technologically conservative, relying heavily on today's best available technology. It is now imperative that regulatory policies and practices be reoriented to become as supportive as possible of technological innovation. Indeed, EPA's NACEPT advisory council, among other groups, has already examined in detail ways of accomplishing this. Implementing NACEPT's recommendations would be an important step forward.

Over the longer term, the regulatory system must be redesigned to encourage emerging technological innovation. In addition, regulatory and economic incentives need to be linked much more closely to public support for R&D to foster new technologies able to meet the public's demand for better environmental quality.

7. Reorient Ongoing Programs

Immediate changes in various ongoing governmental activities could help promote the development of environmentally critical technologies in the United States. Although many new federal programs to support industrial technology have been mounted in recent years, most ignore environmental needs. Of the first eleven R&D programs funded under the Advanced Technology Program's auspices, for instance, none emphasized environmental issues even though such a connection could plausibly be made in many cases. Environmental applications of these R&D projects could easily be made a priority in subsequent grants by inserting environmental considerations into the grant-application process.

Similarly, federal support for biotechnology research, carried out through a number of agencies, could be redirected to encourage the application of biotechnology to the solution of environmental problems in agriculture, waste disposal, and other areas. Perhaps most important, currently emerging technology-development programs need to emphasize environmentally critical technology. One example is the proposed National Institute for Environmental Research (NIER), an R&D funding institution, currently under study at the National Research Council. In NIER's design, the public interest in generic technologies should be considered just as important as that in environmental science. Another institution now emerging is the Critical Technologies Institute, mandated by legislation to analyze and develop strategies for enhancing critical technologies. Environmental needs deserve to be a priority item on this Institute's agenda and environmental analytical capability an important component of its expertise.

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NOTES

1. Note that the European and Japanese lists predate those in the United States and that, more recently, environmental technology has become a priority. See discussion of these countries in Chapter IV.

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The World Resources Institute (WRI) is a policy research center created in late 1982 to help governments, international organizations, and private business address a fundamental question: How can societies meet basic human needs and nurture economic growth without undermining the natural resources and environmental integrity on which life, economic vitality, and international security depend?

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