MATERIALS MATTER

TOWARD A SUSTAINABLE MATERIALS POLICY

KENNETH GEISER

FOREWORD BY BARRY COMMONER

Materials Matter

Urban and Industrial Environments

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Materials Matter
Toward a Sustainable Materials Policy

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In memory of my parents, Kenneth R. and Kathryn R. Geiser

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Foreword

After several decades of debate among proponents of environmental improvement, there is convincing evidence that the dominant cause of environmental degradation—and hence the proper locus of remedial action—is the design of the major technologies of production. Thus, the modern automobile, which is a useful social and economic good, became a major source of photochemical smog when its engine was redesigned for high compression. In turn, this required the introduction of a new material—tetraethyl lead—as a fuel additive, which sharply increased human exposure to this toxic element. Once more redesigned, but this time to be driven by electric motors and powered by batteries recharged from solar sources, automobiles could again become less polluting.

It follows that if we are to pursue the goal of environmentally sustainable production, then the component factors of production—labor, energy, and materials—should conform to this mandate. The requirements, if far from being met, are well known: labor's working environment and the general environment should be free of anthropogenic toxic substances and conserving of natural resources; and energy sources should be renewable, that is, solar. However, as *Materials Matter* shows, the suitability of different materials to systems of sustainable production has been less explored. Indeed, past experience suggests that there has been little effort to deliberately design materials to suit *any* system of production, let alone one dedicated to environmental quality. Instead, new materials are often created not to specifically meet a stated need, but in the hope that the need will be found or created.

The most demonstrative examples of this designless approach can be found in the petrochemical industry, which produces a multiplicity of materials from a single basic source, such as crude oil or natural gas. For example, the manufacture of ethylene, which is heavily used to produce a large-scale plastic end product, polyethylene, yields propylene as a byproduct. Since the manufacturing process is continuous, the propylene must be disposed of. However, the cost of manufacturing ethylene can be reduced by half if propylene is instead used as a raw material for the production of acrylonitrile. In turn, acrylonitrile can be polymerized into acrylic fiber, which is tough enough for use in outdoor carpets. This chain of chemical events is, of course, driven by economics: the profit margin of polyethylene in the massive and highly competitive market for household plastic film ultimately depends, to a degree, on the sale of acrylic outdoor carpet. On its face, such an item would be expected to represent a relatively small market. However, that problem was overcome when someone realized that green acrylic carpet could substitute for grass on such admirably large areas as baseball diamonds and football fields.

Now let us consider the suitability of the material that has emerged from this petrochemical odyssey, acrylic carpet, as an input to an environmentally sustainable production system, let us say, a baseball diamond. Let us suppose that in the course of planning a new major league baseball stadium, a meeting is held to consider the choice between alternative materials to cover the playing field: grass and acrylic carpet. And since the team owners, we shall assume, have decided to join the ranks of “green” corporations, the discussion includes the environmental suitability of the field covering. With the help of consultants, grass and acrylic fiber are compared with respect to durability, energy required in manufacturing, waste disposal problems, and initial and annual costs. Finally, the players’ representative on the planning team brings up an issue that turns out to be definitive: on synthetic carpet, players experience uncomfortably hot feet, sprained big toes, and abrasions when sliding to make a difficult catch. Grass wins, as it has, in fact, in most of the new stadiums built in recent years.

Acrylic carpet—and plastics generally—exemplify a policy made explicit in a history (self-published) of the Hooker Chemical Company, a pioneer petrochemical company now extinct:

> Rather than manufacturing known products by a known method for a known market … the research department is free to develop any product that looks promising. If there is not a market for it, the sales department group seeks to create one.

It is this policy that has driven the petrochemical industry's remarkable growth since the 1940s. The industry has grown by invading *existing* markets—for soap, natural fabrics, paper, glass, and grass—and replacing them with detergents, synthetic fabrics, plastics, and acrylic carpet. And, as we now know, this economically driven process has invaded the ecosystem as well, so that detergents pollute surface waters; plastic film, intended to wrap food, turns trash-burning incinerators into dioxin sources; and a polyurethane mattress, when it smolders, suffocates the sleeper.

Modern environmentally destructive systems of production have arisen not from a failure of design, but from a principle of design that, since it is based only on technical feasibility and economic desirability, excludes from consideration the systems' impact on the global ecosystem on which productive enterprises—not to speak of their customers—depend. As we strive toward sustainable systems of production, it will be essential to incorporate in them materials, working conditions, and forms of energy that are—by design—intended to support the quality of the environment and the welfare of the people who live in it.

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Preface

The origins of this book, though I certainly did not know it at the time, go back 15 years ago to the dusty streets of Bhopal, India. It was 1985 and I had been invited to speak at a conference on chemical plant safety. The conference had been organized in memorial to the terrible night that methyl isocyanate gas had been released from the Union Carbide pesticide production plant in Bhopal, resulting in the deaths of thousands of sleeping neighbors of the plant. Upon the invitation of the conference hosts, I and two other participants agreed to spend a couple of afternoons in the streets of the neighborhoods nearest the plant, where we could listen to the accounts related by the victims of the accident. We sat behind small card tables, often in silence, as family after family came forward to tell us of the horror of that night and about the losses they could count in terms of friends and family members who were killed, neighbors who were disabled, personal health problems, and nightmares that would not end. It was a profound and moving experience. There was little that I or the others could offer except a willingness to sit and listen. When I asked these distraught and grieving people what they wanted me to do, they repeatedly pleaded that I go back to the United States and make certain such an accident could never happen again. Sitting there in the heat and grief, I made a silent promise that I would commit what energies I had in my life to trying to fill that request.

Back at my university, I continued my teaching and research on environmental policy. As that work matured, I was often struck by the way in which my students and colleagues seemed inclined to focus on environmental protection, rather than on the technologies of production that seemed to me to be so much at odds with natural systems. As I came to learn more about the toxicity and hazards of industrial materials, a question kept creeping into my mind that I often asked other faculty and business acquaintances—why were so many industrial materials toxic and hazardous? Sure, pesticides were toxic for a reason, but why were cleaning solvents, pigments, flame retardents, and plasticizers toxic? Was toxicity a result of the function that an industrial material was designed for, or was toxicity some kind of inadvertent property that had simply not been "designed out" when the material was first developed?

As it turned out, I would have lots of time to contemplate this question. Beginning in 1986, I and several environmental leaders in Massachusetts began a campaign to enact a state law that would directly address toxic chemicals. Concerned about the plight of local community residents (such as those in East Woburn) who feared that their drinking water had been contaminated by mismanaged toxic and hazardous wastes, we were convinced that proposed waste incinerators were not an acceptable solution to the increasing volumes of hazardous wastes. Seeking a better solution, we crafted a legislative bill that would encourage the state's manufacturing firms to reduce the volume and toxicity of their hazardous waste streams by reducing the use of toxic chemicals in their production processes. Following the passage of the law, I was invited by colleagues at the University of Lowell (later renamed the University of Massachusetts Lowell) to take over as the director of the university's new Toxics Use Reduction Institute, one of the three state agencies charged with implementing the law. The Massachusetts Toxics Use Reduction Program proved to be a remarkable experiment for testing our hypothesis that the use of many toxic chemicals could be reduced or eliminated by focusing the attention of industry managers directly on those chemicals in the design of their products and production processes. The results have been quite impressive. By 1998, the use of some 190 toxic chemicals in Massachusetts industry had been reduced by 33 percent and the generation of toxic chemical by-products had been cut nearly in half. Indeed, an independent evaluation of the experience revealed that after accounting for all expenses, Massachusetts manufacturers had actually saved money by reducing the use of toxic chemicals.

Still, the question about toxicity persisted. If we could dramatically reduce the use of toxic chemicals and save industry money in one state, then why were these chemicals used at all, and why had they not been eliminated earlier? Why had chemists and materials scientists produced so many toxic and hazardous chemicals, and why had those in manufacturing so willingly bought and used them, even though the chemicals were known to be dangerous? Why had the materials production industries produced such highly effective materials and so defiantly downplayed their hazards? And what about the environmental and public health activists? Had they settled too early, accepting pollution abatement and exposure control technologies rather than agitating for inherently safer and cleaner materials and processes? Was it even technically and economically possible to produce a safer menu of industrial materials? Finally, thinking beyond the immediate problems, was it possible for us to offer our children an array of highly functional chemicals that would be cleaner, safer, and less energy intensive than those that we had been offered by our parents? For several years I wrestled with these questions and engaged my colleagues in endless discussions about them. Finally, fed up with just talking about all this, I found the motivation that drove me to conceptualize, research, and eventually write this book.

I am quite grateful that Robert Gottlieb of Occidental College encouraged me to stop procrastinating and get down to the task of writing, and am even more thankful that MIT Press was interested in publishing the book. I am particularly appreciative that my colleagues at the university, in the Toxics Use Reduction Program, and at the Toxics Use Reduction Institute provided me with a year-long sabbatical during which I conducted most of the research. Over nearly 18 months of writing, a variety of people read drafts, offered advice, and assisted with references. For all of their help and support, I would like to thank Frank Ackerman, Paul Anastas, Nicholas Ashford, Scott Bernstein, David Berry, Halena Brown, Barry Commoner, Pat Costner, Greg DeLaurier, Louise Dunlap, Michael Ellenbecker, Dan Fiorino, Nadia Haiama, Elizabeth Harriman, Don Huisingh, Fran Irwin, David Kriebel, Sheldon Krimsky, Carl Lawton, Charles Levenstein, Gracia Matos, David Morris, John O'Connor, Kirsten Oldenberg, Joanie Parker, Amy Pearlmutter, Margaret Quinn, Mark Rossi, Lyle Schwartz, Neil Seldman, Ted Smith, Randall Swartz, Beverly Thorpe, Joel Tickner, Sukant Tripathy, Hans van Weenen, David Wegman, Bill Walsh, Iddo Wernick, and Rand Wilson.

By focusing directly on industrial materials, it has become clear that we are not facing an environmental crisis so much as an industrial and technological crisis. We have created an innovative and vibrant industrial economy that produces products galore, but it is little accountable for the environmental or health consequences of these commodities. It is a kind of two-dimensional system (cost and performance) when what is needed for a truly sustainable society is a more multidimensional system that is much more socially responsive. The development and management of industrial materials is critical to our ability to survive and prosper. However, we should not accept a materials system that creates tragedies like Bhopal, Love Canal, or Woburn. We must find a better way to ensure that the economy of the future is more respectful of nature and more accountable to all of us who wish to share in its material benefits.

Materials Matter

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Material Incompatibilities

Materials flow through a system, which is made up of materials, energy, and the natural environment and is governed by man-made institutions such as production, consumption, technology, transportation, and government. What is significant about the interaction between the parts is that they compose a material system; they function like a system and have to be treated by policy-makers as a system.

—National Commission on Materials Policy, 1973

From an environmental perspective, materials do matter. Some materials are exceedingly hazardous to make and use and, once discarded, pollute and contaminate the environment, while other materials are made safely and degrade naturally once disposed. Consider the silk "drop line" that is produced by a common spider. The substance is made from pure protein and water in a gland below the spider's abdomen. It is strong, elastic, resilient, and easily decomposed when discarded. Compared ounce for ounce with steel, the silk drop line is five times stronger, and compared with our strongest plastics, it is able to absorb several times the impact force without breaking. However, unlike steel or plastic, the spider manufactures the drop line at ambient temperatures, under normal pressure, without the use of toxic chemicals, and with no hazardous wastes left over. The feat is enough to incur the envy of any materials scientist.[1]

Every day we use scores of products made from a broad array of materials. Many are naturally occurring substances, mined from the earth or harvested from the land, while others are synthetic materials manufactured in complex chemical cracking and conversion processes. The seemingly endless supply of products that we purchase are assembled from a wide range of these substances. Refrigerators today may contain more than seventy different materials and automobiles are assembled from hundreds of unique substances. Every year the world's industrial enterprises pump out a torrent of products that enrich our lives, support our health, ease our work, and entertain and amuse us. Yet many of the materials in the same products that so satisfy us also create risks to our health and the environment. As we mine, synthesize, process, distribute, use, and, finally dispose of these materials, we generate worrisome threats to the sustainability of the ecological systems upon which we depend.

We do not need these threats. We could enjoy a rich and rewarding supply of products with substantially less impact on the environment and on our health. The enormous wastefulness of advanced consumer economies could be redirected to using and recycling materials more efficiently. By reusing materials in continuous, closed loops, we could significantly reduce the environmental burden of consumer wastes. By paying closer attention to the efficiencies of material use, we could extend the use of materials and better manage their flow though our economies. Of even more significance, we could redesign the physical and chemical properties of our materials and reengineer their uses to create safer and less problematic substances that could be used in more sensitively managed operations.

The premise of this book is quite simple. If we paid closer attention to the materials that we produce, we could pay less attention to the impacts of those materials once they are released to the environment and people are exposed to them. Instead of investing in complex technologies for managing toxic pollutants and hazardous wastes and negotiating complicated institutional systems for permitting environmental releases and enforcing standards of human exposure, we could try to produce safer materials and use them more carefully. While there are probably several criteria that could be used to define "safer materials used more carefully," this book will focus on two rather broad and encompassing factors: toxicity and dissipation. By designing less toxic materials and using them in processes that are less likely to dissipate them into the environment, we could go a long way to creating sustainable materials systems.

In doing this we could learn from the way in which nature produces and uses materials. By more consciously modeling our materials and their uses on processes of nature, we would be more likely to fit our materials needs into the ecological systems by which the planet operates. This trend is already under way. There are government and industrial programs organized to promote more efficient and less wasteful production and consumption processes. Product and materials recycling programs thrive in some countries and some industries. There are research scientists studying how nature makes and uses materials, and there are technologies that perform useful functions with little pollution, material consumption, or energy requirements. These modest experiments point the way to a more sustainable economy, one that more lightly touches the earth's systems. But we need more. To move toward sustainable materials systems, we will need a much more extensive commitment. We will need greater attention—public, private, and governmental attention—to the materials that we use today and those we could be using in a safer future.

1.1 Materials and the Environment

The U.S. economy consumes a vast amount of materials. This includes metals, various nonfuel minerals, wood- and plant-based materials, and a host of synthetic chemicals. A century ago, 161 million metric tons of materials flowed through the national economy; by 1995 the figure was well over 2.8 billion metric tons. This translates into nearly 10 metric tons of raw materials moved per person per year. Over the course of the twentieth century, the rate of materials consumption has steadily increased, with consumption of more than half of the materials occurring during the last 25 years of the century. This includes a 29-fold increase in the consumption of nonfuel minerals, a 14-fold increase in use of metals, and an 82-fold increase in the use of fossil fuel-based synthetic chemicals.[2]

During the past century, we also witnessed a remarkable change in the composition of the materials we use. Traditional materials such as wood, natural fibers, and agricultural materials have been replaced by new, syn-

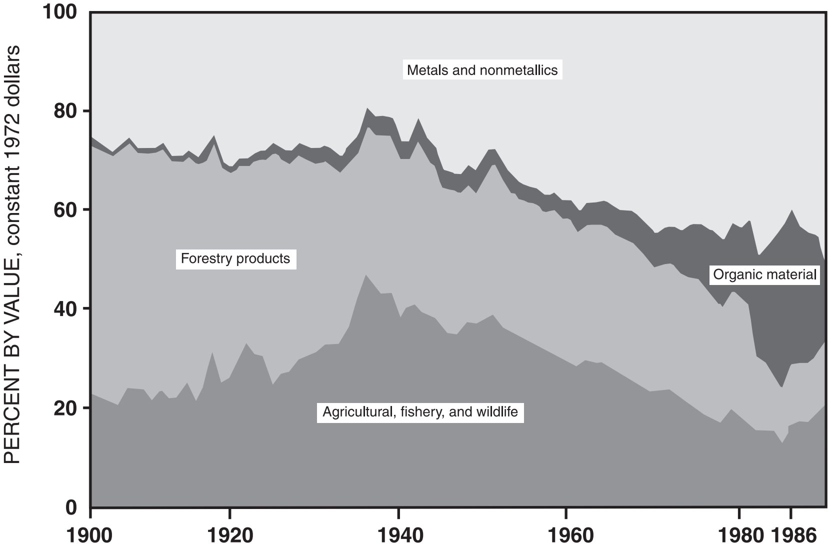

Figure 1.1
U.S. consumption of materials since 1900. Source: U.S. Bureau of Mines, *The New Material Society: Material Shifts in the New Society*, Vol. 3, U.S. Department of the Interior, Washington, D.C., 1991.

thetic materials such as metal alloys, composites, and plastics. Figure 1.1 shows that almost half of the materials consumed in 1900 were based on renewable resources such as wood and plant- and animal-based materials, while by 1990, the consumption of these resources had declined to less than 8 percent. Since World War II, the use of nonrenewable resources such as petroleum-based materials has grown substantially.

Historically, the United States has been a major consumer of the world's resources. With about 5 percent of the global population (270 million people) and 7 percent of the its land area, the United States consumes nearly one-third of the world's nonenergy materials. This is changing. Growth of the world's population and the increasing social and economic development of the rest of the planet's people is slowly eroding this dominance. Today, consumption of materials in the rest of the world is growing at nearly twice the rate as that in the United States.[3]

There are well over 700,000 chemical substances identified in the scientific literature, although fewer than 70,000 are used in industrial production. Of these, the U.S. Environmental Protection Agency (EPA) estimates that 15,000 nonpolymeric chemicals are produced or imported into the United States in amounts of more than 10,000 pounds per year and just over 2800 chemicals are produced or imported in excess of 1 million pounds per year. Each year the materials industries add another 1000 new chemicals to this long list.[4]

The production, use, and disposal of these materials generates substantial costs to the environment. These costs show up in the damage caused during the extraction of materials, in the pollution generated and energy consumed in producing and using materials, and in the disposal of waste materials. The amount of polluting materials emitted into the air is estimated to have doubled and in some cases tripled over the past century, peaking around the 1970s. For instance, sulfur dioxide emissions increased from about 10 million tons in 1900 to about 30 million tons in 1970. Likewise, emissions of volatile organic compounds (VOCs) rose from 7 million tons to over 25 million tons during the 1960s. Both have decreased since the 1970s, unlike nitrogen oxide emissions, which rose to a peak in 1970 and have not decreased since.[5]

In 1997, more than 21,000 industrial facilities in the United States reported releasing 2.58 billion pounds of toxic chemical wastes to the air, water, land, and disposal facilities. Over half of these releases occurred as air emissions, while another 218 million pounds of chemicals were discharged into the nation's rivers, lakes, and bays.[6] These are the figures reported by some of the nation's largest chemical processing firms to the EPA for its Toxics Release Inventory (TRI), but these reports include only a portion of all of chemicals released by literally thousands of other facilities that are not covered by this inventory. Add to these numbers the huge amounts of less toxic wastes generated by commercial businesses and domestic activities, and the impact on the environment is staggering.

The nation produces just over 209 million tons of municipal solid wastes a year, or about 4.3 pounds of waste per person per day. Of this volume, over 16 percent is burned in incinerators and 57 percent is buried in landfills, with the remaining 27 percent is recycled or composted. The country's industries generate some 40.7 million tons of hazardous wastes a year. This works out to about 300 pounds for every man, woman, and child per year. Of this hazardous waste, nearly 76 percent is disposed of on land, while 10 percent is recovered and 9 percent is incinerated. It is expected that over the next decade the total waste stream in the United States will increase by over 20 percent.[7]

Once municipal and industrial wastes are released to the environment, they can cause significant hazards. The landfilling of wastes produces volatile emissions to the air and potent liquid leachates that seep into unprotected groundwater. The incineration of municipal wastes converts solid and liquid materials into hazardous air emissions and toxic ash. Even more potential damage is caused by the extraction and processing of raw materials in the nation's hundreds of mines, smelters, refineries, pulp mills, and chemical synthesis plants. The four primary materials processing industries—metals, chemicals, paper, and plastics—generate 71 percent of the country's toxic air releases, and these airborne industrial discharges can be carried by global air currents to the far reaches of the planet and far up into the atmosphere. In addition, these same four industries create the largest industrial energy demand, which further adds to the planet's pollution. Mining and smelting are estimated to consume between 5 and 10 percent of the world's generated energy supply.[8]

1.2 Problem Materials

Many of the materials we use today have been produced and disposed of for decades with little evidence of concern. Yet, some materials have proven to be quite harmful either because of direct human exposure or, more indirectly, because of their effects on ecosystems. With mounting evidence of significant impacts, various national governments have moved to sharply regulate and even ban the production and use of the most hazardous of these substances. The United Nations International Registry of Potentially Toxic Chemicals lists some 600 substances that have been banned or severely restricted by at least some governments.[9] Pesticides such as DDT, mirex, chlordane, and heptachlor have been banned or heavily controlled in many industrialized countries. Even quite common industrial chemicals such as carbon tetrachloride, chlorofluorocarbons, trichloroethane, and asbestos have been phased out or restricted to only the most limited uses. Efforts to regulate or phase out the use of these chemicals have often been quite complex, costly, and contentious. As an illustration of these struggles, we can consider here three brief case studies on tetraethyl lead, polychlorinated biphenyls, and chlorofluorocarbons.

Tetraethyl Lead

Tetraethyl lead (TEL) was first introduced commercially during the 1920s as an additive to gasoline to improve performance and reduce the audible "knock" during combustion. The chemical was the product of a research consortium set up between the General Motors Corporation, Du Pont Chemical, and Standard Oil of New Jersey. For General Motors, the additive opened a new era in automobile comfort and convenience, and for Du Pont and Standard Oil, the chemical represented a windfall because of its potentially large market.[10]

The toxicity of TEL was well recognized at the time of its first commercialization. German chemists had warned Thomas Midgley, the chief research chemist at the consortium laboratory, about lead poisoning hazards in the manufacture of TEL. Even with this warning, the executives at General Motors and Du Pont decided to proceed, assuming that they could control the hazards in production and that the dilute nature of the additive in the finished gasoline product would not create a significant environmental hazard. During the first 2 years of production, several workplace fatalities associated with exposure were reported, but they attracted little public attention. Then rather suddenly, in October of 1924, five workers died and many others became ill at Standard Oil's Elizabeth, New Jersey, production facility and media coverage of the conditions at the plant first brought the hazards of TEL to public attention.

The reaction was intense, with New York City, Philadelphia, and several states initiating actions to ban the sale of leaded gasoline. Although the U.S. Bureau of Mines issued a report downplaying the occupational and environmental hazards of TEL in 1925, the Surgeon General of the U.S. Public Health Service (USPHS) called for a temporary ban and organized a conference on the hazards of leaded gasoline. While the noted public health advocate, Alice Hamilton, and others argued at the conference that leaded gasoline was both an environmental and an occupational hazard, the conference focused solely on the occupational issues and concluded that a ban on leaded gasoline was not warranted if "its distribution and use are controlled by proper regulation."[11]

Between 1926 and 1977 production of TEL by Du Pont and that by a new joint venture with General Motors and Du Pont, the Ethyl Corporation, rose from 1000 tons a year to over 233,000 tons a year. Although the corporations continued to defend TEL, medical research began to show that many Americans had elevated levels of lead in their blood and that the lead came from gasoline. Still, the decision to phase out TEL was not based on environmental contamination, but rather on the decision by General Motors to comply with the 1970 federal Clean Air Act by installing catalytic converters to control vehicular emissions. The converters selected by General Motors were easily compromised by the lead in gasoline and therefore General Motors finally concluded that leaded gasoline would need to be phased out. Du Pont and the Ethyl Corporation were reluctantly convinced during the early 1980s to abandon their resistance to regulations on TEL and by 1984 the use of leaded gasoline in the United States was discontinued.

Polychlorinated Biphenyls

Polychlorinated biphenyls (PCBs) are a group of aromatic hydrocarbons that have been used as dielectric fluids in electrical transmission equipment, transformers, and capacitors; as oil stabilizers in some heat exchangers and hydraulic systems; and as plasticizers. These chlorinated compounds have been highly valued because they are chemically inert (resistant to oxidation, acids and bases, and other chemical agents), heat resistant, nonflammable, and electrically nonconductive. PCBs were first produced commercially by Monsanto Chemical in 1929 under the trade name, Aroclor, with little suspicion of their potential hazards. While PCBs were also produced in Germany, France, and Japan, Monsanto remained the only U.S. manufacturer of PCBs until 1977, when the company closed down its primary production facilities. Between 1929 and 1977, approximately 1.4 to 1.7 billion pounds of PCBs were produced in the United States.[12]

Monsanto closed out its PCB production because of increasing evidence of health effects in wildlife and mounting government pressure to legally prohibit production. The first scientific evidence of PCBs entering the environment came from two Swedish studies in the mid-1960s.[13] The studies that followed demonstrated that PCBs were released to the environment when electrical equipment or hydraulic systems leaked or were incinerated or improperly discarded. PCBs are highly persistent and resist natural degradation; once released into the environment, they tend to accumulate in the fatty tissue of living organisms.

PCBs were first found in the United States in 1969 in oysters harvested from Florida's Escambia Bay. The following year 146,000 chickens had to be destroyed in New York because they were contaminated with high levels of PCBs. PCBs were soon identified in both wildlife and humans. Ospreys living along the Massachusetts and Connecticut coasts were found to have high PCB concentrations in their body tissue. In 1968 a major human exposure occurred in Kyushu, Japan, where 1300 people became ill from consuming rice oil accidentally contaminated with PCBs. Symptoms that included eye disturbances, skin lesions, and adverse neurological effects were blamed on the accident. Soon studies of nursing mothers in the United States found significant concentrations of PCBs in their breast milk, and several leading public health professionals began to advocate phasing out the use of PCBs. Although Monsanto withdrew PCBs as a plasticizer in 1970, company scientists debated the health studies and argued that the chemicals were effectively safe if used properly in contained systems.[14]

By the 1970s, professional associations and government agencies began to respond. Although acute occupational hazards of PCBs had first been observed in the 1950s, the American Conference of Government Industrial Hygienists now moved to set voluntary threshold limit values for Aroclor. In 1971 the U.S. Food and Drug Administration (FDA) set a residue level for PCBs in food at 5 parts per million. With increasing evidence of both human and environmental risks, a ban on the production of PCBs was inserted into the Toxics Substances Control bill being considered by the U.S. Congress in 1976. Recognizing the inevitability of this legal prohibition, in 1976 Monsanto announced its decision to cease production.

Chlorofluorocarbons

In 1987 the Montreal Protocol to the International Convention for the Protection of the Ozone Layer set out a plan for the phaseout of the production and use of chlorofluorocarbons (CFCs). CFCs are a family of chlorinated fluorine compounds that are generally nontoxic, nonflammable, and chemically inert. CFCs were first developed by Du Pont's Thomas Midgley during the early 1930s and marketed as a refrigerant called Freon. In the United States, Du Pont Chemical became the major supplier, marketing CFCs as substitutes for industrial solvents suspected as carcinogens and as safe substitutes for the flammable gases used as refrigerants. Because CFCs appeared nonhazardous and chemically stable when they were first introduced, there was little concern about their environmental effects.[15]

Initial concern over CFCs did not originate from direct evidence of harm, but rather from a hypothesis put forward by two research scientists, Mario Molina and Sherwood Rowland. In an influential article in the magazine *Nature*, Molina and Rowland hypothesized that once released to the atmosphere, CFCs could float to the upper stratosphere and react with the sensitive ozone layer that protected the planet from ultraviolet radiation.[16] At the time there was no evidence of ozone damage, in part because there was no continuous monitoring of the ozone layer, so many were skeptical of the ozone threat, particularly those who manufactured CFCs.

Still, the Molina and Rowland hypothesis raised the first public concern over CFCs. The initial focus was on CFCs used as aerosol propellants. First Oregon and then the EPA banned the sale and use of CFCs as propellants. Internationally only Sweden, Norway, and Canada followed the United States in this ban. Most countries waited for further studies. In 1977 and again in 1980 the U.S. National Academy of Sciences prepared reports assessing the potential for CFC destruction of the ozone layer. Then in May of 1985 the British Antarctic Survey published a report providing the first clear evidence of a weakening trend from 1979 to 1985 in the ozone layer over Antarctica. Subsequent studies validated this evidence and identified a similar weakening in ozone concentrations over the Arctic as well.

The large CFC manufacturers remained skeptical of the link between CFCs and ozone layer loss, but increasingly government and the scientific communities came to a consensus that "man-made chemicals are responsible for much of the ozone loss."[17] With broad government and scientific support, the Montreal Protocol was signed in 1987, and after the announcement that Du Pont could produce a functional substitute, the protocol was activated in 1989 with the ratification by eleven nations that represented two-thirds of global CFC use. A timetable was worked out at a London meeting in 1990 that set a schedule for the phaseout of all CFC production and use in the industrialized nations by the year 2000.

1.3 Toward a Safer Materials Management System

These three brief cases have several common features. Each demonstrates how innovative research and corporate entrepreneurship led to the development and commercialization of a highly effective industrial material. In each case a darker side of the material came to be recognized and a protracted struggle led to the eventual phaseout of the material's use. Each case reveals the same underlying conflict in social values: product functionality and economic performance conflict with human safety and environmental protection. Such conflicts are common in the history of industrial materials. Performance and cost drive a search for increasingly sophisticated materials, but health and safety and concern for the environment raise cautions and restrain the enthusiasm with which materials are adopted.

The cases are also different. PCBs and TEL were of concern because of their toxicity. Toxicity is a property of a material that is determined by its chemical structure. Many chemicals are quite toxic and many others are less so. When living organisms are exposed to a toxic material in volumes or under conditions that are likely to inflict harm, the substance is said to be hazardous. Thus toxicity is determined by the chemical composition of a substance, while the hazardousness of a chemical is determined by the manner in which the substance is used. Hazardous human exposures to toxic materials can occur in occupational settings where workers produce, use, or dispose of toxic substances and in domestic settings where consumers use products containing toxic chemicals. Both people and other living organisms can be exposed to hazards when toxic wastes are released to the environment, when accidents occur, or when products containing toxic chemicals are discarded. Tetraethyl lead was identified first as an occupational health hazard, and from its earliest production there was evidence of mortalities associated with workplace exposures. Only later was it recognized that the burning of leaded gasoline was likely to distribute small amounts of lead throughout the environment from automobile exhaust. This is more like the problem of CFCs.

CFCs were never identified as hazardous to human health. Indeed, they were marketed as a nontoxic substitute for the ammonia used in refrigeration and the chlorinated solvents used throughout many workplaces. It was not human toxicity that drew Molina and Rowland to hypothesize about environmental damage, it was atmospheric dissipation. The volatile nature of CFCs meant that during manufacture and use a certain amount of CFCs would be dissipated into the atmosphere and slowly float up to the ozone layer, where it could stimulate chemical changes. The world's most concerted effort to phase out a dangerous industrial material was focused, not on a material toxic to humans, but on one that could threaten the sensitively balanced chemistry of the planet.

Dissipation is a term drawn from physics to describe the conversion of concentrated amounts of high-quality materials into widely dispersed substances that are of lower quality because they are so difficult to recapture and reuse. Dissipation of this sort is not readily recognized as hazardous, but when chemicals—even quite benign chemicals—overload sensitive parts of the environment, ecological systems can be compromised and the effects can be life threatening. When extensive dissipation is combined with high levels of toxicity, as occurs in the application of pesticides to agricultural fields or the runoff of hydrocarbons from roadways and parking lots, the combination of factors increases the significance of environmental harm.

In studying the hazards of industrial materials, it is important to consider both the potential toxicity of the substances and the potential for dissipation during their production, use, and disposal. We have long recognized the threats posed by toxic chemicals. There is a substantial literature in the fields of public and occupational health that analyses the complex interaction of chemical structure, human exposure, and biological response. The specialties of epidemiology, toxicology, and pharmacology today provide the core scientific underpinnings of this literature, but the much earlier writings of Alice Hamilton, Ellen Swallow, John

Andrews, Harriet Hardy, and many others identified the basic principles of material toxicity decades ago.[18]

Awareness of material dissipation is a more recent phenomenon. Although concern over the loss of the nation's high-quality natural resources appears in a broad body of literature from the turn of the century on, it is only in the past 30 years that much study has been carried out on the effects of wasted materials widely dispersed into the environment. Much of the analysis in this area has been conducted by chemical, civil, and environmental engineers. During the past decade a new specialty called "industrial ecology" has developed that is focused on tracking materials flows, reducing materials wastes, and creating opportunities for more intensive use of materials during their life cycle.[19]

The cases of tetraethyl lead, polychlorinated biphenyls, and chlorofluorocarbons reveal the process by which industrial materials are adopted and the long and protracted process by which their hazards are recognized and addressed. A more comprehensive review of the history of industrial materials reveals many other similar struggles, although the way in which each conflict arises and is addressed is determined by the characteristics of the specific material and its uses. Nevertheless, the processes are always lengthy, costly, and often contentious, and they are likely to be continuously repeated in the future unless we change the strategies we use to manage industrial materials.

In the United States and most other industrialized countries, these conflicts are institutionalized in the structural relationship between private and public organizations. We rely on private corporations to invent, distribute, and market the materials used to manufacture products. Government agencies are empowered to regulate environmental and human exposures to those materials. These agencies base their regulatory policies on scientific studies of the health and ecological effects of each substance. With nearly 70,000 substances used in industry, this would be an enormous task even if we had enough scientific studies to rely on, but we do not. Most of today's industrial materials are used with an incomplete understanding of their health and environmental effects. Of the chemicals produced and imported into the country in quantities of over 1 million pounds a year, a recent EPA study found that only 7 percent had a complete set of the basic health and environmental screening tests, while 43 percent lacked even one of the most basic studies.[20] This only accounts for the largest-volume chemicals used in the country; we have far less data on the thousands of other substances manufactured and used in much smaller quantities. However, the dilemma is not simply caused by an absence of evidence. Even if we had the data, the task of writing regulations for thousands of chemicals and monitoring and enforcing those regulations would be well beyond the means of any government. Instead, we rely on a lot of good will among chemical users, a lot of concern over liability for chemical damage, a lot of professional denial, and a lot of just plain ignorance.

Fifty years ago, when there were far fewer firms producing far fewer products and using chemicals that had been around for some time, this dilemma may have been less worrisome. However, the scale of production today, the rapidity of industrial development around the world, and the kind of environmental concerns that are arising—climate change, endocrine disruption, biodiversity loss—suggest that the conventional approach to the management of industrial materials is inadequate. The current strategy alone is too uncertain, too burdensome, and too costly to guarantee the level of safety we should desire.

The problems of the current system of materials management are clear: It focuses on one substance at a time; it is dependent on a vast amount of scientific study; it requires a large investment of public and private resources; and it addresses the issue of a material's safety long after most materials have been on the market. This approach focuses too much on identifying and ensuring a nonhazardous level of exposure and not enough on developing a safer system of materials. From this perspective, it appears that a more efficient and effective approach would be to focus on the materials and not on the exposure. Manufacturing less-toxic materials and using them in less-dissipative processes would ensure more safety. Safer materials that are used more intensively and in more contained processes would provide for a more sustainable future.

This is a very exciting time in the development of industrial materials. Our scientific and technical knowledge means that chemicals that were once available only through serendipitous discovery can now be easily designed for quite tailored and imaginative uses. These new materials could be as safe and ecologically sound as they are effective and inexpensive. They could be managed in ways that reduce the wastefulness and dissipation that currently prevails, without compromising the material quality of our daily lives.

1.4 The Objectives of This Book

It is this prospect of a more sustainable materials system that underlies the purpose of this book. In pursuing this goal, the text draws on a large literature on resource management, environmental pollution, and hazardous chemicals, although it differs from much of that work by placing the central focus on industrial materials rather than on the environmental effects of materials or on the economics of resources and wastes. This is a focus that has been less developed until relatively recently.[21] Specifically, the book has three objectives: first, to examine the history of industrial materials in order to identify how today's materials were developed and what efforts were made to respond to their environmental and human health impacts; second, to examine potential future routes for materials development that might be more conducive to health and environmental protection; and, third, to consider what private and public policies could most effectively guide such developments. The book looks to both history and the future in its search for a means of ensuring safer and more effective materials for future generations.

The term *materials* is used quite broadly and extensively in this text. The conventional concept encompasses all those substances, chemicals, and compounds that make up the earth. This book focuses on those materials that are produced and used in human societies. Often the term *materials* is used in this particularly anthropogenic sense (i.e., related to humans), as in "our materials." In particular, the book focuses on industrial materials, which means those materials that are commonly used by industries to make the goods and services that support consumer economies. Materials such as food and drugs and energy materials used as fuels are not covered. Forest and wood products are also excluded, but primarily to reduce the scope of the research. Industrial materials may be products, process chemicals, or wastes. No distinction is made between those materials that end up in consumer products and those that are used to make products but do not show up within the finished products. Thus, industrial materials include raw materials, feedstocks, process chemicals, intermediates, recycled materials, materials as industrial pollutants, materials in production wastes, materials in products, and materials in discarded products.

A large number of materials exhibit toxic properties and there are many different forms of toxicity (carcinogens, teratogens, neurotoxins, ecological toxins, etc.). The poisonous effects of these substances is typically determined by the nature of the exposure, or the dose. Still, not all substances are equally toxic, and the potency of toxic materials varies a great deal. Here the term *toxic material* is used to refer to substances with relatively high degrees of potency in at least some form of toxicity.

In seeking a more sustainable system of materials, the analysis attempts to link the development and use of materials with the international search for more sustainable forms of development.[22] Sustainable development involves economic activities that meet current social needs without threatening the capacity of future generations to meet their own needs. By trying to link these two subjects, the book builds an argument that the materials systems of the past were not sustainable and that the vision of sustainability is a useful metaphor for redirecting our patterns of materials development and use in the future. In doing so, the text recognizes that the materials of the future must continue to meet the conventional criteria of high performance and low cost, but adds to these objectives a commitment to human safety and environmental protection. Specifically, the argument tries to address the dual problems of toxicity and dissipation with two strategies: detoxification and dematerialization.

The term *detoxification* arises out of toxicology. Here the term describes the reduction of the toxic characteristics of materials used in products and processes. This could be accomplished by reducing the volume of toxic materials used in a process or product, or by substituting more benign substances for toxic chemicals, or by changing the toxicity of materials through chemical changes that reduce or eliminate their toxic properties. *Dematerialization* is a term that arises out of the recent work in industrial ecology. It means increasing the intensity of service derived from each unit of material used. This could involve recycling and reusing materials, designing products that use fewer materials, or substituting nonmaterial services for material-intensive products. Moving toward a more sustainable system of materials will require various economic and corporate strategies, but in terms of the materials themselves, these two strategies—detoxification and dematerialization—offer avenues for achieving a safer and more environmentally protective future.[23]

This book attempts to build a foundation for those who are promoting a more sustainable materials future. The subject is very broad, and there was no expectation that the text could cover all of the relevant factors or details. In order to properly focus the book, certain somewhat arbitrary boundaries have been set on the subject, and these need to be acknowledged before proceeding because they are true limits of the book. First, the book focuses centrally on industrial materials and then primarily on metals and chemicals. A more expanded coverage would include nonmetallic minerals, wood, fuels, and perhaps materials used in agriculture, because these materials also contribute to the great material wealth of our national economy and to environmental damage. While it would be useful to consider these other materials, this would have greatly expanded the text.

Second, the subject describes only the experience in the United States. This is a particularly difficult limit because for many years Europe led in materials development and today materials supplies and problems are certainly global in nature. Nevertheless, materials policies are still largely national in scope, and there is at least some justification in focusing on the United States because this country remains one of the most dominant players in shaping materials policies throughout the international economy. Finally, the book focuses specifically on the environmental and public health issues of the development and use of materials. Remaining true to the broadest goals of a sustainable society would require consideration of other factors, such as social equity and justice. Again, while it is regrettable, these aspects have been given little space here.

The book is divided into four parts. The first presents a history of industrial materials and the efforts made by government and private officials to respond to concerns raised over environmental and public health issues. This history provides a perspective on how industrial materials developed and a background for considering how people tried to identify and respond both to the dissipation of these materials and to their toxicity. The second part provides an overview of the primary federal policies developed to address industrial materials and then reviews the performance of those policies as to their effectiveness. This leads to a proposal for an alternative approach that integrates detoxification and dematerialization as policy strategies. The third part considers several avenues of materials development and use, including the familiar ones of recycling and reuse and use of renewable materials, as well as the possibilities of advanced and engineered materials and biobased materials. It assesses the likelihood that these approaches will lead to more sustainable results. The final section sketches out in more detail a set of policy strategies that would lead toward less toxicity in the menu of industrial materials and less dissipation in how they are used.

The story begins in the middle of the nineteenth century. An understanding of the origins of industrial materials and what was known and done offers a beginning for considering how to better direct the materials systems of the future. The period that lasted from the 1860s to the 1980s was an exciting time for industrial materials. During this period, thousands of materials and production processes were invented and patented. Many technologies for extraction and synthesis of materials were invented and refined, and most of the major production operations of manufacturing were established and optimized. The majority of commercial products that we enjoy today were invented and commercialized, and the technologies of waste treatment and pollution control were developed and adopted.

The history of industrial materials continues with a more focused consideration of the way in which the awareness of the environmental and public health aspects of these materials emerged and tended to shape their use. The second part of the book turns more centrally to the evolution of federal policies directed at industrial materials and assesses the effectiveness of these policies. With this background, it is then possible in the final two parts to consider the possibilities of a new and different approach to the development and use of industrial materials in this new century.

Bibliography

The text relies on a broad array of secondary materials from a variety of different fields. Therefore a bibliography must mix together many quite diverse citations. In order to facilitate a review of the references, they are presented in two sections. The first covers the materials used in preparing the more historical chapters, specifically chapters 2, 4, 5, and 6. The second covers the more contemporary literature cited in the remaining chapters.

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