THE IMPACT OF ENVIRONMENTAL ISSUES ON MATERIALS AND PROCESSES

Thomas E. Graedel and Leslie A. Guth

Thomas E. Graedel *and* ***Leslie A. Guth*** *are associated with AT&T Bell Laboratories. Mr. Graedel is a distinguished member of technical staff in AT&T's Materials Processing Research Laboratory, Murray Hill, New Jersey, where he is responsible for research and consulting in atmosphere-surface interactions and the atmospheric corrosion of materials. He joined AT&T in 1969 with a B.S. in chemical engineering from Washington State University, Pullman; an M.A. in physics from Kent State University, Kent, Ohio; and a Ph.D. in astronomy from the University of Michigan, Ann Arbor. Ms. Guth is a distinguished member of technical staff in the Environmental Materials and Processes department of the company's Engineering Research Center, Princeton, New Jersey, where she is responsible for evaluating and* (continued on page 140)

Environmental change is now widely recognized, and its effects on the quality of life and the sustainability of the properties of the planet as we know them are of broad concern. Less widely appreciated are the future effects of environmental change on corporations that manufacture and sell products in the global market. Clearly, the major markets for advanced technology are also those with the worst environmental conditions. Not only can environmental considerations affect the selection of materials, manufacturing processes, and the useful life of products, but manufacturing processes themselves also can have far-reaching effects on the environment. Air quality levels, their variability and long-term change, and the industrial impacts of environmental legislation, can become major problems to corporations that ignore them. Conversely, they can provide opportunities for corporations that plan for them. A technique for doing so—cradle-to-grave design and manufacturing—is presented and discussed.

Introduction

Though most manufacturing processes and products work satisfactorily most of the time, difficult environmental conditions can expose weaknesses in otherwise reliable equipment or processes. Telecommunications equipment has always been subject to the same environmental factors and problems as other types of equipment. Potential concerns may include low manufacturing yields, corrosion, excess wear, or mechanical or electrical interference in the normal operation of components. Whether the degradation processes occur during manufacturing or use, they are often severe and generally unexpected.

Materials stability concerns have historically spurred control of the manufacturing and operations areas in telecommunications facili-

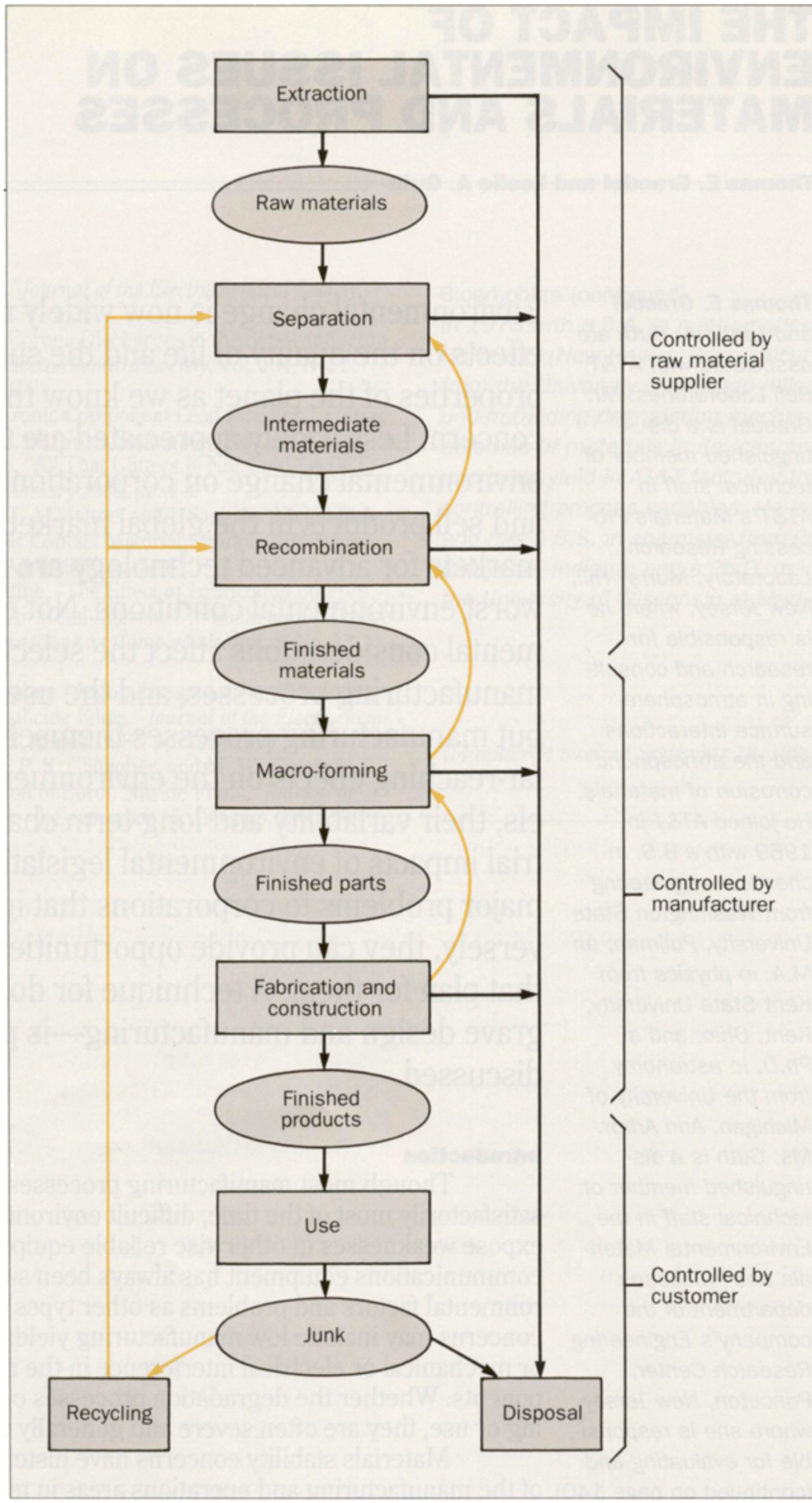


Figure 1. An overview of industrial metabolism. Arrows show direction of materials flow. Where dual flows are possible, the solid line shows the current dominant flow for most manufacturing processes; the dashed line shows the flow preferred by cradle-to-grave design and manufacturing. (Adapted from Reference 5)

Panel 1. Terms and Acronyms in This Paper

CFC	chlorofluorocarbon
CF_3Cl	CFC11
CF_2Cl_2	CFC12
CGDM	cradle-to-grave design and manufacturing
CH_4	methane
CO_2	carbon dioxide
ICOLP	Industry Cooperative for Ozone Layer Protection
N_2O	nitrous oxide
O_3	ozone
SO_2	sulfur dioxide
UST	underground storage tank

ties. Compounding these traditional concerns are the current efforts of corporations to manufacture and market their products internationally, in countries where the environment is often more humid and more polluted than in the United States and Canada. In such locations, equipment buildings may not be designed with air filtration or air conditioning. Therefore, manufacturing techniques or equipment that have been evaluated in North America may need to be substantially modified in locations such as Indonesia, China, or Saudi Arabia. In addition, because environmental conditions may occur on short time scales with respect to the projected lifetimes of manufacturing facilities or products, product or process designers may need to plan for a range of external conditions, not just the conditions at the time of construction or manufacture.

Moreover, product manufacturing processes and materials can themselves dramatically alter the global environment. Among the potential concerns are those of stratospheric ozone depletion, photochemical smog, waste disposal, and global warming. AT&T is committed to eliminating, or at least minimizing, those manufacturing materials and processes that have a deleterious effect on the environment.

Cradle-to-Grave Design and Manufacture

Environmentally-conscious manufacturing is not a subject with a long history, yet the approaches to it are starting to be defined and explicated. The unifying concept might be termed *cradle-to-grave design and manufacturing* (CGDM). To accomplish CGDM, one must assess the "industrial metabolism" of each product of interest.

Recall that the biological concept of metabolism is the complex of physical and chemical processes that sustain life; and that efficient metabolic processes maximize use of resources and minimize production of disposable byproducts. Similarly, the ideal industrial ecosystem is one where energy and materials consumption is controlled, waste generation is minimized, and at least some fraction of the effluents of one process serve as raw materials for another. As Frosch and Gallopoulos[3] have pointed out, "an ideal industrial ecosystem may never be attained in practice, but both manufacturers and consumers must change their habits to approach it more closely if the industrialized world is to maintain its standard of living—and the developing nations are to raise theirs to a similar level—without adversely affecting the environment."

Figure 1 presents a schematic picture of the industrial ecosystem, showing the entire cycle from raw material extraction to eventual disposal. Mass flow is from top to bottom on the figure, but many paths exist to permit recycling within the system. In the Figure 1, note that:

- *Separation* includes such processes as smelting and refining
- *Recombination* includes alloying and synthesis
- *Macro-forming* refers to processes such as machining of engineering components or chip manufacturing of electronic components
- *Fabrication and construction* embodies assembling finished products from components.

Once the industrial ecosystem for a specific product has been diagrammed, CGDM can be begun with this definition in mind: *CGDM is the process of designing and manufacturing the highest quality products at the*

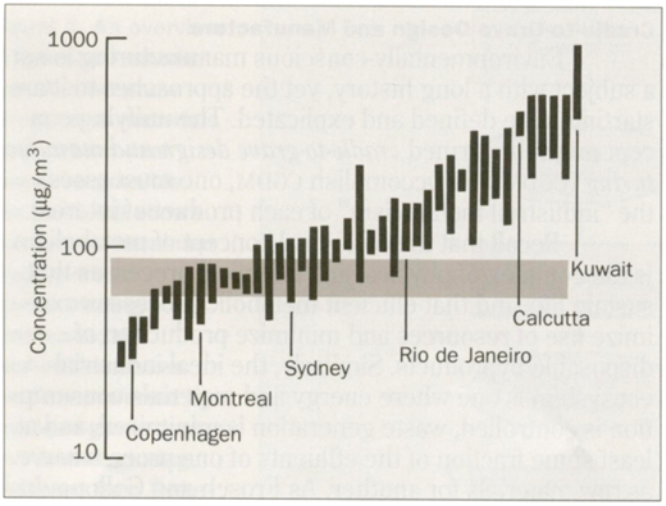


Figure 2. Range of annual averages of particulate matter concentrations for cities throughout the world, 1980-1984. Several cities are identified. The gray shading shows the concentration range recommended by the United Nations Environment Program as a reasonable target for preserving human health; it appears suitable as well as a reasonable target for preserving telecommunications equipment. (Adapted from Reference 1)

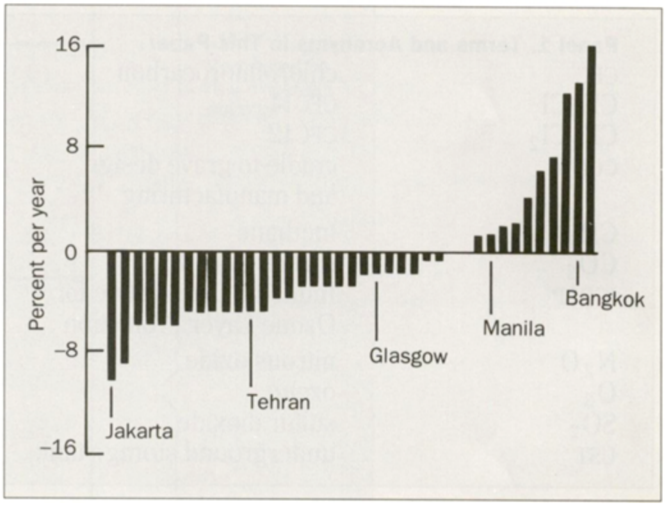


Figure 3. Trends in annual average suspended particulate matter concentrations in cities. Each bar represents a city, several of which are identified. (Adapted from Reference 1)

lowest cost, while simultaneously minimizing undesirable byproducts and optimizing recycling and reuse. Among the basic questions involved in the process are:

- *Materials Selection.* What are the short- or long-term supply limitations for materials included in the original product design? Are the materials environmentally robust to work well under difficult conditions? What changes in product or process design will avoid relying on rare or toxic materials, or improve the product's recyclability?
- *Recycling During Manufacture.* Are waste products from each manufacturing step maximally recycled? How are the non-recyclable waste products from each step treated? Can they be retained for controlled disposal rather than released to the environment? In either case, are the waste products known to be harmful to the environment, or might they be recognized as such in the future? What changes in product or process design might minimize problems connected with disposal or dispersal?
- *Energy Efficiency.* Is energy use minimized at each manufacturing step, and do options exist for how the needed energy might be provided? What changes in product or process design can be made to reduce the energy consumption of the manufacturing process?
- *Recycling After Use.* Will material changes during use affect product performance and recycling potential (e.g., will corrosion of otherwise recyclable metals make recycling difficult)? What changes in product design will minimize difficulties related to use rather than manufacture? What changes in design can make recovery of materials from obsolete products easier and more efficient?

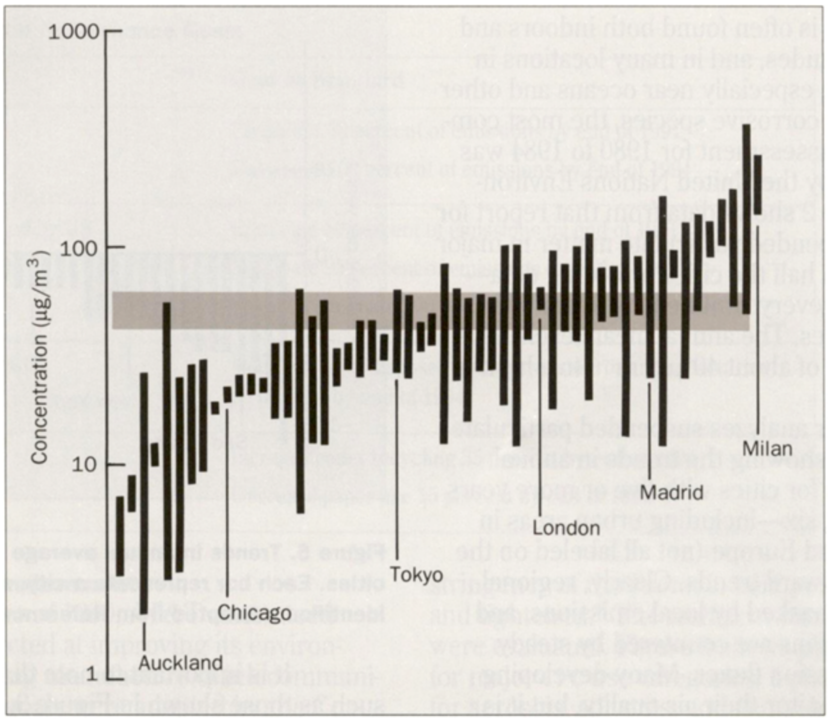


Figure 4. The range of annual averages of SO_2 concentrations for cities throughout the world for the period 1980-1984. Several major cities are identified. The gray shading shows the concentration range recommended by the United Nations Environment Program as a reasonable target for preserving human health; it appears suitable as well as a reasonable target for preserving telecommunications equipment. (Adapted from Reference 1)

It is of interest that three different parties—the raw material supplier, manufacturer, and consumer—play roles in the CGDM process (see Figure 1). The practice now is for the three parties to interact with the ecosystem independently. Viewed narrowly, corporate CGDM might include only those activities listed within the current control of the manufacturer. The broader CGDM concept, however, would include the raw material supplier and consumer as well. One can envision a process where corporations create partnerships that optimize the use, recycling, and reclamation aspects of the entire product process, much as the "just-in-time" process currently uses such partnerships to minimize inventory and improve efficiency.

Several benefits can be anticipated from well-performed CGDM:

- Assembly line shutdowns because of materials supply problems will be avoided.
- Process changes resulting from new environmental regulations will be reduced.
- Loss of market share to competitors whose designs show more environmental sensitivity will be minimized.
- *Planning* rather than *responding* will be promoted.
- A more assured entry into diverse global markets will be assured.
- CGDM will demonstrate good corporate citizenship.

Assessing Corrosive Environments

Corrosive environments differ greatly in severity throughout the world. For significant corrosion to occur, the ambient relative humidity must be higher than about 50 percent, and corrosive gases or particles must be present. High humidity is often found both indoors and out in most tropical latitudes, and in many locations in the temperate latitudes, especially near oceans and other large water bodies. For corrosive species, the most comprehensive worldwide assessment for 1980 to 1984 was recently published for by the United Nations Environment Program.[1] Figure 2 shows data from that report for annual averages of suspended particulate matter in major urban areas. More than half the cities providing data—cities located on nearly every continent—exceed the recommended guidelines. The annual mean levels have a large range, from a low of about 40 $\mu g\ m^{-3}$ to a high of about 800 $\mu g\ m^{-3}$.

Figure 3 further analyzes suspended particulate matter air quality data, showing the trends in annual average concentrations for cities with five or more years of data. Of the 37 cities, six—including urban areas in South America, Asia, and Europe (not all labeled on the figure)—have major upward trends. Clearly, regional trends are sometimes masked by local emissions, and efforts to control emissions are countered by steady increases in global emission fluxes. Many developing countries do not yet monitor their air quality, but it is likely that most of them now have increasing levels of emissions and pollution.

Figure 4 shows data for sulfur dioxide (SO_2) in a display similar to that of Figure 2. In more than 25 percent of the cities, the annual average SO_2 concentrations exceed that believed to have a high potential for severe corrosion. The highest SO_2 average concentration in the 54 cities surveyed is nearly 100 times that of the lowest. The half-dozen cities with the highest annual averages include locations in Europe, Asia, and South America.

Trends in the ambient annual average levels of SO_2 are shown in Figure 5. Of 33 cities, 27 have downward or stationary trends, reflecting strong efforts to reduce emissions of sulfur gases. However, six cities have upward trends, including locations in Asia, Australasia, and Europe.

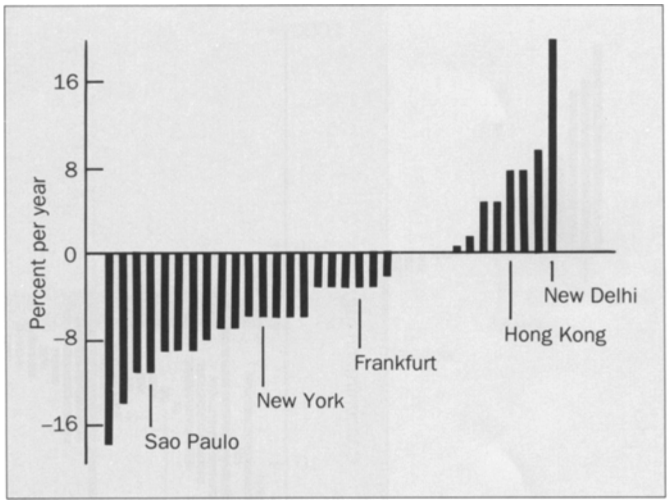


Figure 5. Trends in annual average SO_2 concentrations in cities. Each bar represents a city, several of which are identified. (Adapted from Reference 1)

It is important to note that long-term averages, such as those shown in Figure 3, include a few periods when concentrations of corrosive species are extremely high. During severe smog episodes, concentrations of air pollutants can be significantly above the high impact criteria of Figures 2 and 3. The extent to which these periods of extreme concentrations control the overall degradation of exposed material—contrasted with the much longer periods at much lower concentrations—has not yet been determined.

Changes in population and technology may require large increases in energy generation, and appear likely to be accompanied by steadily worsening air quality, as suggested by Figures 2 to 5. The problem is clear: the major markets for advanced technology are also those with the worst environmental conditions, and many areas can be expected to degrade still further for decades to come.

Table I. AT&T Environmental Performance Goals

Type	Goal or Standard
Chlorofluorocarbons	Phase out 50 percent of emissions by end of 1991 Phase out 100 percent of emissions by end of 1994
Toxic Air Emissions (defined by US Code SARA 113; chiefly volatile hydrocarbon emissions)	Eliminate 50 percent of emissions by end of 1991 Eliminate 95 percent of emissions by end of 1995 Strive to eliminate 100 percent of emissions by end of 2000
Manufacturing waste	Decrease total disposed process waste from manufacturing 25 percent by end of 1994
Paper	Increase paper recycling 35 percent by end of 1994 Decrease paper use 15 percent by end of 1994

Manufacturing and the Environment

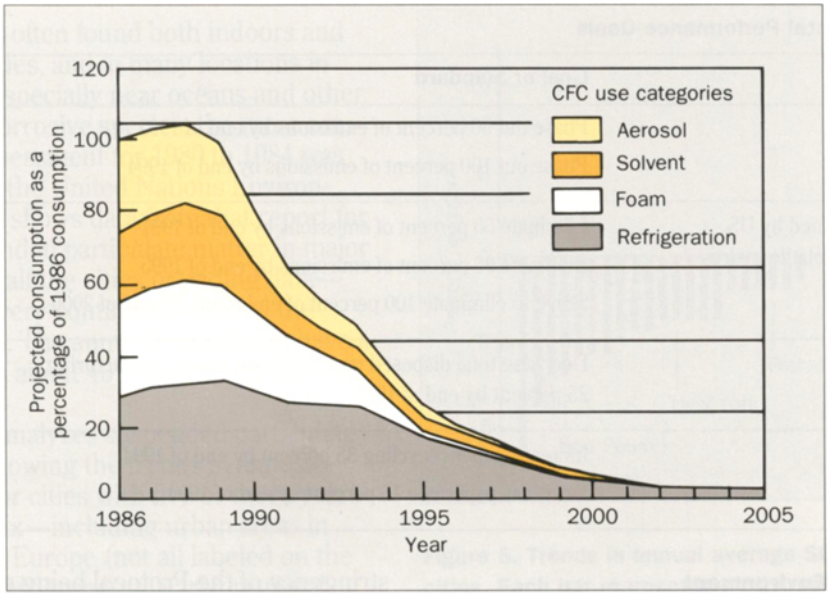
In the first quarter of 1990, AT&T announced company-wide goals directed at improving its environmental performance during manufacture of telecommunications products. These goals were adopted by the Corporate Environmental and Safety Council, consisting of representatives from every major business unit and division. They are shown in Table I.

Stratospheric Ozone Depletion. Chlorofluorocarbons (CFCs), widely used in the electronics industry for cleaning and defluxing components before and during manufacture, have been implicated in ozone reduction chemistry in the stratosphere. The international agreement known as the "Montreal Protocol on Substances that Deplete the Ozone Layer" was signed in September 1987, and to date has been ratified by 59 nations. It called for a 50 percent reduction from 1986 rates of CFC consumption by July 1, 1998. In addition, the Protocol included regularly scheduled technology reassessments. The first reassessment, completed during 1989-1990, resulted in the scope, timetable, and stringency of the Protocol being expanded, accelerated, and tightened.[8] The technical feasibility of such actions were evaluated. Figure 6 shows phasedown projections for major CFC use categories: a phase-out of CFC usage for aerosols, solvents, and foams by the year 2000, and a restriction for refrigerants. The revised Protocol now calls for a complete CFC phase-out by 2000.

In addition to the CFCs, methyl chloroform and carbon tetrachloride are contributing to the depletion of stratospheric ozone. Although phase-outs for these substances were not originally included in the Montreal Protocol, its 1990 amendments now include them. Figure 7 shows the effect on the concentration of stratospheric chlorine of phasing out or freezing the production of various CFC substances.

AT&T has been a leader in efforts to develop and test alternative processes and chemicals for manufacturing operations currently involving CFCs. Process changes, the development of a terpene-based cleaner designated EC-7, and attention to losses during manufacturing, have made it possible for AT&T to publicly state its intention to

Figure 6. Technically feasible phasedown projections for major CFC use categories. (Adapted from Reference 8)



eliminate CFC emissions from its manufacturing operations by the end of 1994. The AT&T reduction schedule is compared with other relevant schedules in Figure 8.

Instead of simply examining the cleaning operation in circuit pack assembly during manufacturing, AT&T has successfully evaluated the total soldering process. By doing so, several alternatives have been developed to replace CFC and other halogenated solvent-based cleaning processes. These include using water-soluble flux with aqueous-based cleaning, low-solids flux that eliminates the need for cleaning, and rosin flux residue removal with EC-7.

AT&T has also shown its interest in searching for CFC alternatives by working with others in the industry. The corporation has played a significant role in an industry program to test CFC alternatives by comparing their cleaning efficiency with a CFC-based benchmark. Moreover, AT&T is a founding member of the Industry Cooperative for Ozone Layer Protection (ICOLP), an organization whose primary role is to coordinate exchanges and compilations of non-proprietary information on CFC alternatives, particularly for small manufacturers and developing countries.

Photochemical Smog. Photochemical smog (i.e., unhealthy and visibly contaminated air resulting from chemical reactions with sunlight) was first reported in Los Angeles in the early 1950's, and is now widespread. It has three ingredients: oxides of nitrogen from high temperature combustion (especially from motor vehicles), volatile hydrocarbons from many sources, and sunlight. It is most often characterized by concentrations of ground-level ozone. Reducing ozone concentrations and the other products to healthy levels generally involves reducing emissions of both nitrogen and hydrocarbon oxides. In practice, because it is usually easier to control hydrocarbon emissions, they have been and will continue to be under severe scrutiny.

AT&T has set stringent goals for reducing its toxic air emissions (including many volatile hydrocarbons), and for monitoring emission levels in its facilities. Important initiatives include replacing wet chemical etching with dry chemical processing, including photoresist

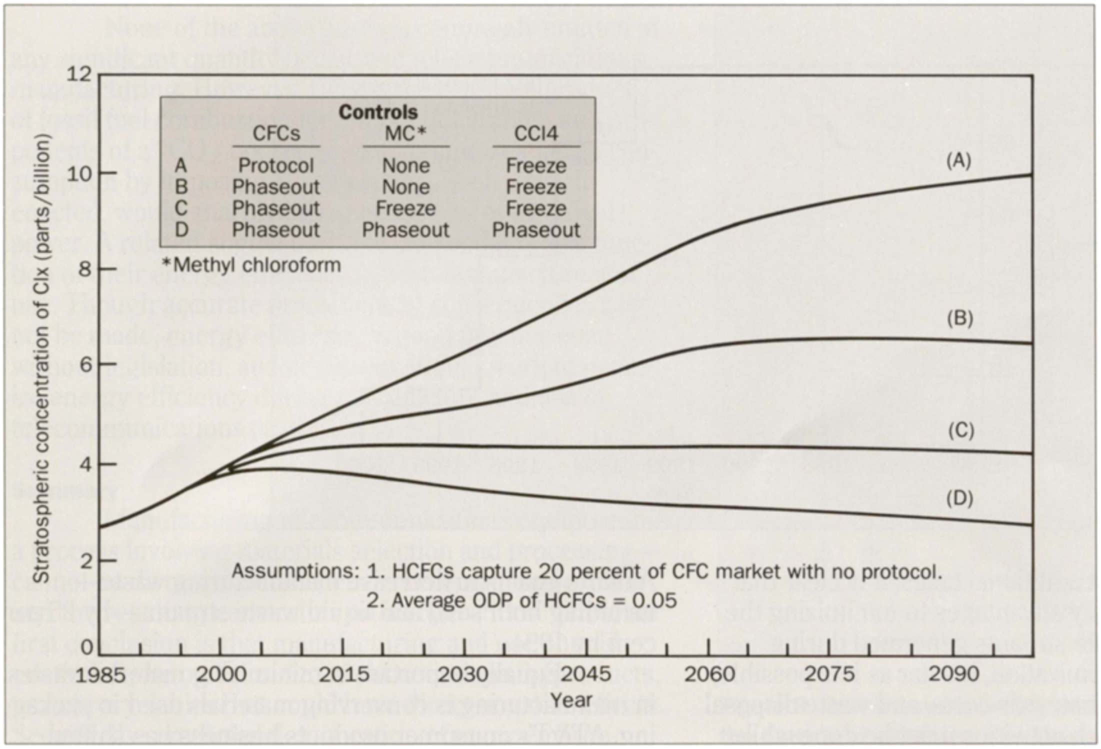


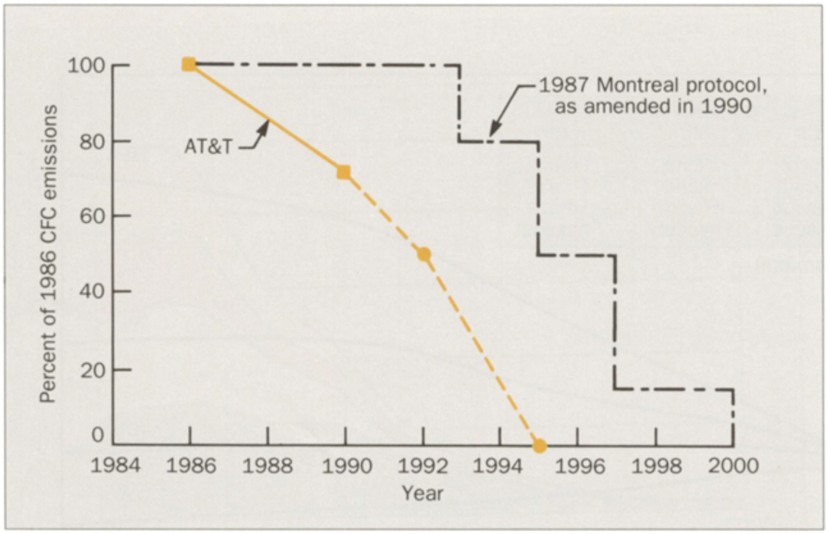
Figure 7. Projections for the chlorine concentration in the stratosphere as a function of four different phase-out and freeze scenarios for CFCs, methyl chloroform (MC), and carbon tetrachloride (CCl_4). (Adapted from Reference 8)

strip, planarization, and pattern transfer; and vacuum-handling of semiconductors to minimize the need for additional cleaning processes. Although AT&T's volatile hydrocarbon emissions alone are seldom large enough to have a significant deleterious effect on local air quality, reducing them is an important component of AT&T's corporate goal of minimizing its impact on the local and global environments.

Waste Disposal. In many areas of the world it is becoming harder to dispose of processing waste, manufacturing byproducts, and obsolete equipment. Landfill sites are becoming unavailable, transporting waste across state and national boundaries is increasingly prohibited, and costs are rising rapidly. Landfills and underground storage tanks (USTs) are coming under closer Federal scrutiny than before. Responsibility and accountability by the originating company continues even after the material is barreled, trucked off, and disposed of. The waste problem has led some lawmakers to suggest a "virgin materials tax" that imposes a monetary penalty for using new materials if recycled materials could be used instead. Such an approach would affect current design techniques that do not consider recyclability as a component of the design process.

Legislation is also being discussed to more severely limit the composition of liquid effluents and scrutinize heavy metal discharges and organic contaminants. Process water from manufacturing facilities can contain organic wastes as well as metals such as copper and lead, and will need increasingly detailed monitoring.

Figure 8. Time scales for the reduction of CFC use in manufacturing. The top line is the scale promulgated by the US EPA, following the Montreal Protocol, as amended. The dotted line shows AT&T's commitment to cease its use of CFCs by the end of 1994. The solid line shows AT&T's progress toward its corporate goal.



With or without additional taxes, it is clear that there are major monetary advantages to minimizing the volume and type of waste streams generated during manufacture. Such minimization, insofar as it is possible, will lower inventories, materials costs, and waste disposal expenses. However, such activities must be done while preserving and enhancing quality.

Reducing the waste flow from AT&T manufacturing processes begins with such items as eliminating obvious leaks and inefficient use of chemicals, and reducing excessive packaging of incoming components. New trace metal recovery techniques have allowed spent plating and etching solutions to be reused rather than consigned for disposal. Plastics and metal scrap recovered from obsolete telecommunications equipment by the Nassau Recycle Corporation, a former AT&T subsidiary, has also historically been highly significant.

Most waste stream reduction requires complete process redesign above and beyond optimizing existing processes. This task is complicated by ever-increasing targets of throughput and reliability, and environmental constraints on many possible options. Nevertheless, AT&T's goal is to decrease manufacturing waste—including both solid and liquid waste streams—by 25 percent by 1994.

Equally important in minimizing material wastes in manufacturing is conserving materials used in packaging. AT&T's consumer products business has shifted from foam packaging to smaller and lighter corrugated cardboard. This change reduces the amount of packaging used, as well as shipping and storage costs. Also, the all-cardboard package is more easily recycled than foam packaging.

Global Warming. Global warming, also known as the Greenhouse Effect, has become *the* environmental topic of the 1990s, and legislation to minimize global warming effects probably will result. Greenhouse gases are characterized by low reactivity and efficient absorption of infrared radiation. The gases of principal concern are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), CFC11 (CF_3Cl), and CFC12 (CF_2Cl_2). Figure 9 shows a theoretical assessment of their individual contributions to global warming, projected for the year 2030.

None of the above gases is commonly emitted in any significant quantity because of telecommunications manufacturing. However, CO_2 is the principal product of fossil fuel combustion for energy generation, and proponents of a "CO_2 tax" propose to minimize energy consumption by imposing a cost penalty. Such a tax, if enacted, would sharply increase the cost of electrical power. A related suggestion is to tax products as a function of their energy efficiency in both manufacture and use. Though accurate predictions of consequences cannot be made, energy efficiency is good practice even without legislation, and designers should work to optimize energy efficiency during manufacture and use of telecommunications products.

Summary

Manufacturing telecommunications equipment—a process involving materials selection and processing—cannot be divorced from its environmental implications and the resulting constraints on its operations. Thus, our first conclusion is that manufacturing and use should continually be optimized to avoid emissions, byproducts, or nonrecyclables that could have direct negative effects. Second, the predicted deterioration of many environments throughout the world in the decades ahead will demand more environmental ruggedness in manufacturing processes and final products. Third, manufacturing and use should be designed to minimize the effects of external factors that might restrict raw materials or energy. Finally, good corporate citizenship is now an essential component of international business, and many cooperative efforts have been advocated.[7] Edgar Woolard, chairman of E. I. DuPont, has stated: "Our continued existence as a leading manufacturer requires that we excel in environmental performance and that we enjoy the nonobjection—indeed even the support—of the people and governments in the societies where we operate around the world."[5]

Environmental leadership is a corporate goal of AT&T. It is a salutary benefit that pursuing such a goal is good corporate citizenship. Just as important, however, are the benefits that will accrue to the corporation as such issues become more integral parts of product design, manufacturing, sales, and service. In many ways—including the "bottom line"—environmental leadership is good business.

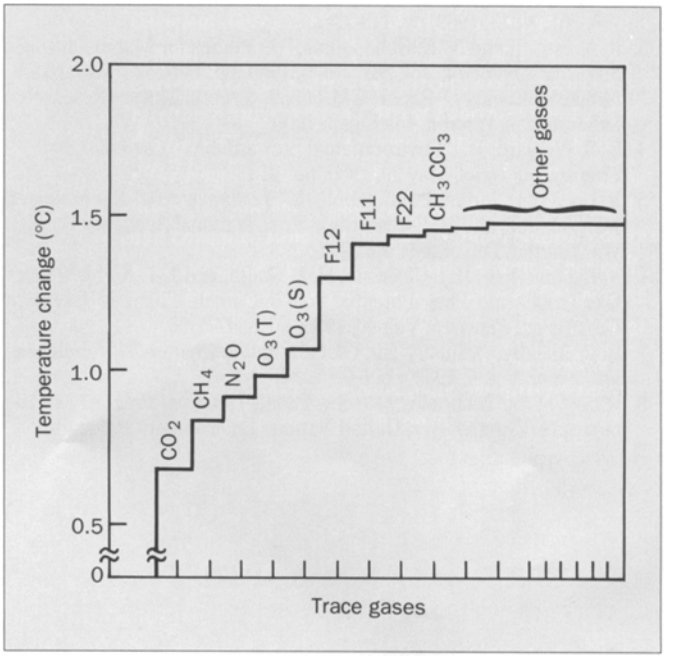


Figure 9. Greenhouse warming potential of trace gases in the Earth's atmosphere. The graph shows a theoretical calculation of global surface warming in the year 2030, compared with the present surface temperature. Of the predicted change of 1.5° C, that portion attributed to each individual "greenhouse gas" is shown. (Adapted from Reference 6)

139

References

1. Global Environment Monitoring System, *Assessment of Urban Air Quality*, United Nations Environment Program, Geneva, Switzerland, 1988.
2. N. Keyfitz, "The Growing Human Population," *Scientific American*,

Vol. 261, No. 3, 1989, pp. 119-126.
3. R. A. Frosch and N. E. Gallopoulos, "Strategies for Manufacturing," *Scientific American*, Vol. 261, No. 3, 1989, pp. 144-152; "Toward an Industrial Ecology," Report GMR-6959, General Motors Research Laboratories, Warren, Michigan, 1990.
4. E. S. Woolard, Jr., "Environmental Stewardship," *Chemical and Engineering News*, May 29, 1989, pp. 12-15.
5. R. U. Ayres, "Industrial Metabolism," *Technology and Environment*, J. H. Ausubel and H. E. Sladovich, Eds., National Academy Press, Washington, D.C., 1989, pp. 23-49.
6. V. Ramanathan, R. J. Cicerone, H. B. Singh, and J. T. Kiehl, "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research*, Vol. 90, 1985, pp. 5547-5566.
7. B. R. Allenby, "Industry and Global Climate Change," *Environmental Forum*, Vol. 6, 1989, pp. 6-9.
8. Report of the Technology Review Panel, *Technical Progress on Protecting the Ozone Layer*, United Nations Environment Program, June 30, 1989. K. C. Zachariah and M. T. Vu, *World Population Projections, 1987-88 Edition*, The Johns Hopkins University Press, Baltimore, Maryland, 1988.

Biographies (continued)

implementing low solids "no clean" soldering fluxes. She joined AT&T in 1984 with a B.A. in physics from the University of North Carolina, Chapel Hill, and a Ph.D. in materials science from the University of Pennsylvania, Philadelphia.

(Manuscript received September 17, 1990)