ANNALS OF CHEMISTRY

IN THE FACE OF DOUBT

FOR a time in the nineteen-seventies, no environmental problem caused a greater stir in the United States than the revelation that chlorofluorocarbon gases were thought to be rising into the stratosphere and depleting the ozone layer. Ozone is a gas formed by the action of sunlight on oxygen, and it can be found everywhere in the atmosphere from ground level to the top of the stratosphere, some thirty miles above the surface of the earth. The threat posed by chlorofluorocarbons to the ozone layer, which shields the earth from harmful solar radiation, had been proposed as a theory by Professor F. Sherwood Rowland and Dr. Mario J. Molina, both of the Department of Chemistry of the University of California at Irvine, in the summer of 1974; the announcement received extensive coverage in the press and on television, and captured the imagination of the nation's consumers, who, through the use of aerosol sprays containing chlorofluorocarbon gases as a propellant, were directly contributing to the threat. Troubled by the notion that the touch of their fingertips on the valves of aerosol cans containing hair spray, shaving cream, deodorants, insecticides, and the like might spell disaster for mankind, they proceeded to reduce their purchase of these products, and fired off more letters to Congress on the issue than they had on any other since the Vietnam War. When the existence of the hazard was substantiated by a government-sponsored study published in September of 1976, officials of the Environmental Protection Agency, the Food and Drug Administration, and the Consumer Product Safety Commission decided to restrict the nonessential uses of chlorofluorocarbons. In the autumn of 1978, the E.P.A. and the F.D.A. imposed a ban on the manufacture and use of the compounds as propellants in aerosol sprays. At that point, public concern about the problem virtually disappeared, for most Americans were persuaded that whatever calamity might have been in store for the ozone layer had been averted.

During the nearly eight years since then, the government has spent several hundred million dollars on research relating to the depletion of stratospheric ozone by chlorofluorocarbons, and estimates of this depletion have gone up and down in roller-coaster fashion as a succession of committees convened by the National Academy of Sciences and the National Aeronautics and Space Administration have assessed and reassessed the problem. Generally speaking, the conclusions of the members of these committees—atmospheric scientists of renown from all over the world—have reflected uncertainties: on the one hand, there has been general agreement that chlorofluorocarbons would gradually deplete ozone in the upper stratosphere, twenty to thirty miles above the earth; on the other hand, no consensus has been reached on just how rapidly or severely this might occur. In May of 1985, however, scientists of the British Antarctic Survey, which is based in Cambridge, England, published an article in the international scientific journal *Nature* reporting large and unexpected losses of ozone in the stratosphere above the Survey's station on the Antarctic coast at Halley Bay. As might be expected, these losses have proved highly disturbing to the world's scientific community.

The total amount of ozone in the atmosphere can be estimated by measuring the intensity of selected wavelengths of solar ultraviolet radiation arriving at the earth's surface. The distribution of ozone at various altitudes of the stratosphere, where about ninety per cent of all ozone occurs, can be determined by measuring the intensity of ultraviolet radiation as the sun's angle changes through the day. The validity of this technique has been confirmed by direct chemical measurements made from high-altitude balloons. Since 1957, the scientists of the British Antarctic Survey had been estimating the amount of ozone in the atmosphere above Halley Bay between October and March—months during which there is sunlight in Antarctica—and since 1977, it turned out, they had been observing a steady decline in ozone but had not notified the scientific community of the finding, because they mistrusted their measurements. However, when they began to observe similar losses of ozone at a second measuring station—at the Argentine Islands, about a thousand miles to the northwest—they were persuaded to trust the Halley Bay data, which showed that the kind of ultraviolet radiation known to be harmful to human skin had increased tenfold and that the ozone layer above Antarctica had decreased by almost forty per cent. In August of 1985, their observations of Antarctic ozone depletion were confirmed by a reassessment of data collected by NASA's Nimbus 7 satellite. Since 1978, Nimbus 7 had been taking measurements of ozone from a vantage point six hundred miles above the earth, but its low readings of ozone levels above Antarctica had been automatically discarded by the project's computer. NASA's atmospheric scientists, daunted by the prospect of having to pore over two hundred and fifty thousand separate ozone measurements taken by Nimbus 7 each day, had chosen to program their computers not to record exceptionally low ozone levels, because such levels had never been observed and might be expected to have resulted from faulty measurements. Suffice it to say that when Nimbus 7 confirmed the British observations of ozone depletion above Antarctica it became clear that—far from having been averted—the calamity that Rowland and Molina had predicted for the ozone layer back in 1974 might have come sooner than anyone expected.

DR. ROWLAND had become interested in chlorofluorocarbons in the winter of 1972, when he learned that one of them—trichlorofluoro-

methane—had been found throughout the troposphere, which is the six-to-ten-mile-high portion of the atmosphere that lies between the surface of the earth and the stratosphere. Both trichlorofluoromethane and dichlorodifluoromethane—a companion gas that was also found to be ubiquitous in the troposphere—had been synthesized in 1928 by chemists in the General Motors research laboratories who were trying to find a nontoxic, nonflammable refrigerant. Dichlorodifluoromethane has been used ever since as a coolant in refrigerators and automobile air-conditioners, and, starting in the early nineteen-fifties, it was mixed with trichlorofluoromethane as an aerosol propellant. Trichlorofluoromethane is also used extensively as a foaming agent in the manufacture of polyurethane. At the time when Rowland became interested in the chlorofluorocarbons, their pervasiveness in the troposphere was regarded as harmless; the two gases had been used industrially for more than forty years, and were known to be chemically inert. Rowland, however, wondered where the gases were going and what would become of them, and in the autumn of 1973 he and Dr. Molina, a photochemist from Mexico City, who was a member of his research group, decided to investigate the matter.

Chlorofluorocarbons, like all molecular gases, are decomposed by short-wavelength ultraviolet light from the sun—a process known as photolysis. Such decomposition can occur only in the stratosphere—from twelve to twenty-three miles above the surface of the earth. Below that, almost all short-wavelength ultraviolet light is absorbed by the ozone layer before it can interact with chlorofluorocarbons. Rowland and Molina decided after careful study that chlorofluorocarbons, because of their relative insolubility in water, could not be removed from the atmosphere by rainfall or by dissolution in the oceans, and, because of their chemical inertness, could not be broken down rapidly by any other known mechanisms in the troposphere. They concluded that the several million tons of chlorofluorocarbons estimated to be floating about in the troposphere—an amount about equal to the total amount ever manufactured—would eventually rise into the stratosphere, where they would be photolyzed by ultraviolet light, releasing atoms of chlorine in the process. Rowland and Molina now determined that each atom of chlorine released in the stratosphere would almost instantly seek out and react with a molecule of ozone—an extremely unstable substance—and that this would initiate an extensive and complex catalytic chain reaction in which, over a period of a year or so, tens of thousands of molecules of ozone would be converted into molecular oxygen and thus eliminated from the stratosphere. They calculated that if chlorofluorocarbons continued to be manufactured and used at the 1972 worldwide rate of almost a million tons a year the amount of chlorine released annually from their decomposition in the stratosphere would within a century or so be sufficient to roughly double the annual rate of removal of ozone known to occur naturally, chiefly through a reaction initiated by nitrogen oxides converted in the stratosphere from nitrous oxide released as a result of bacterial action in the soil. If the rate of ozone destruction doubled, there would be a tremendous increase in the kind of solar radiation known to be most detrimental to plant and animal cells, with consequences that could conceivably disrupt, and perhaps destroy, the biological systems of the earth. Moreover, the two scientists realized that even if the use of chlorofluorocarbons were to cease at once—an unlikely event, since their production had been doubling every seven years since the early nineteen-fifties—destruction of part of the ozone layer was foreordained, because the chlorofluorocarbons already in the troposphere were rising into the stratosphere, and so constituted a planetary time bomb.

In June of 1974, Rowland and Molina described their findings in *Nature*, and in September they presented their data at a meeting of the American Chemical Society, in Atlantic City. By that time, they had calculated that if chlorofluorocarbon production continued at the present rate, between seven and thirteen per cent of the ozone layer would be destroyed in about a hundred years. Their calculation was based on a principle known as steady state. This condition would arise in a hundred years or so, and the rate of destruction of chlorofluorocarbons by ultraviolet radiation would then be equal to the rate of their influx into the atmosphere. During this century, however, the rate at which chlorofluorocarbons are being destroyed by ultraviolet light has lagged well behind their influx, and as a result the amount of the compounds in the atmosphere has steadily increased.

Rowland and Molina told the Chemical Society meeting that the increase of ultraviolet light resulting from ozone depletion would cause a significant rise in the worldwide incidence of skin cancer and might also cause crop damage. They went on to warn that ozone depletion might even shift stratospheric temperatures sufficiently to create changes in the world's weather patterns. They predicted that if nothing was done in the next decade to prevent further release of chlorofluorocarbons the vast reservoir of the gases that would have built up in the meantime would provide enough chlorine atoms to insure continuing destruction of the ozone layer for much of the twenty-first century. They urged that the use of the compounds as aerosol propellants be banned.

The Atlantic City meeting triggered its own chain reaction. Environmentalists called for an immediate halt to the purchase of aerosol sprays containing chlorofluorocarbon propellants, which by then accounted for the largest and best-known commercial use of the two gases, and the threat to the ozone layer was soon making headlines from one end of the country to the other. That autumn, the National Academy of Sciences announced that it would conduct a full-scale investigation of the hazard, and in December the Subcommittee on Public Health and Environment of the House Committee on Interstate and Foreign Commerce held two days of hearings to consider legislation that would regulate—or possibly ban—the manufacture of the gases.

Meanwhile, the chlorofluorocarbon industry had responded to the situation by pointing out that ozone depletion by chlorofluorocarbons was a hypothesis based upon computer models of the stratosphere—that no real proof existed that the two gases could rise into the stratosphere, let alone that they could lead to the destruction of ozone. E. I. du Pont de Nemours & Company, the chief manufacturer of chlorofluorocarbons, announced soon after the Atlantic City meeting that the industry would finance studies of the problem, which would be undertaken by scientists at several universities and would take three years to complete. Pending the first results of the industry-sponsored research, du Pont maintained, there was no reliable evidence that chlorofluorocarbons posed

a hazard to ozone—or, for that matter, that the chain reaction worked out by Rowland and Molina could occur at all. A du Pont official testifying before the Subcommittee on Public Health and Environment declared that until there was actual proof to support the ozone-depletion theory government regulation of chlorofluorocarbons was unwarranted. He added, however, that if credible evidence should be developed to show that the compounds posed a threat to human health du Pont would cease to produce them.

Perhaps mindful of the adverse effects of regulatory legislation in a time of recession, Congress took no action on either of two bills that had been drawn up to deal with the problem. In January of 1975, the President's Council on Environmental Quality and the Federal Council for Science and Technology created a task force to conduct an intensive study of the situation. The panel included representatives of seven Cabinet departments and five government agencies. In June, its members issued a report stating that release of chlorofluorocarbons into the atmosphere was a legitimate cause for concern. Unless new scientific evidence was found to remove this concern, the task force felt, it would probably be necessary to restrict the uses of the two chemicals, and they proposed that if their assessment was confirmed by the National Academy of Sciences federal regulatory agencies should put such restrictions into effect by 1978. (In March, the Academy had appointed a Panel on Atmospheric Chemistry to look into the chlorofluorocarbon problem for its Climatic Impact Committee. This committee had originally been established to assist the Department of Transportation's Climatic Impact Assessment Program, set up in 1971 to investigate the threat posed to the ozone layer by nitrogen oxides and other emissions from the exhausts of supersonic transports.) The task force called for international coöperation on the problem, noting that foreign countries accounted for about half the world's chlorofluorocarbon production and use, and that the effects of the compounds upon stratospheric ozone transcended national boundaries.

As might be expected, the chlorofluorocarbon and aerosol-spray industries bitterly opposed the findings of the report, which, by recommending that regulation be considered, undermined their contention that chlorofluorocarbons should be regarded as innocent until they were proved guilty. In fact, industry representatives went to the White House and tried, unsuccessfully, to have the report suppressed, on the ground that it was premature. Du Pont issued a statement pointing out that the task force was proposing restrictions "before the scientific evidence is available to make an informed judgment as to whether such restrictions are necessary," and that this was "tantamount to prejudging the results of research, which, if it is to be thorough, will take at least three years to complete." Be that as it may, no sooner had the report been released than the governor of Oregon, Bob Straub, signed a bill banning the sale of spray cans containing chlorofluorocarbons by March of 1977; and in the summer of 1975 the New York legislature passed a measure requiring such products to carry a label stating that they contain chlorofluorocarbons, which may harm the environment. In other states, however, industry lobbyists helped prevent the passage of similar restrictions by arguing that legislative action should await the report being prepared by the National Academy of Sciences, which was due in the spring of 1976. And du Pont continued to urge delay by taking out double-page advertisements in newspapers and magazines across the country which informed readers that "to act without the facts—whether it be to alarm consumers, or to enact restrictive legislation—is irresponsible." Such appeals appeared to fall upon sympathetic ears in Congress, where, in spite of the fact that additional hearings had produced detailed evidence to corroborate the theory of ozone depletion, a consensus had developed that the decision to regulate could be put off until the Academy completed its study. Meanwhile, the nation's consumers had begun voluntarily reducing their purchase of aerosol sprays, and a number of cosmetic manufacturers had abandoned chlorofluorocarbon propellants in favor of alternative methods of delivery, such as pump sprays.

In the winter of 1975-76, a draft of the forthcoming Academy report was circulated for review; it contained the estimate that continued release of chlorofluorocarbons at the 1973 level would result in the destruction of about fourteen per cent of the ozone layer by the time a steady state was reached. This estimate was slightly above the upper limit of the depletion range that had been predicted by Rowland and Molina. At the same time, however, an element of uncertainty was introduced into the ozone-depletion hypothesis by none other than Rowland and Molina themselves. They had conducted some experiments showing that the chain reaction between chlorine and ozone, which would be initiated by the decomposition of chlorofluorocarbons in the stratosphere, would itself interact with the chain reaction taking place between ozone and naturally occurring nitrogen oxides. The result would be the formation of chlorine nitrate—a compound that would temporarily disrupt the working of both chains, and prevent either one from depleting ozone as rapidly as each had been predicted to do alone. When the two men announced their findings, in February, scientists who were engaged in modelling stratospheric chemistry were thrown into confusion, for the new data indicated at first that previous estimates of ozone depletion might have to be drastically lowered.

This unexpected development was also dismaying to the members of the National Academy of Sciences group. Apprehensive lest the stratosphere hold other surprises in store, and concerned about their public credibility, they postponed their report for several months while the modellers wrestled with the problem. In the end, the modellers determined that the inclusion of chlorine nitrate in the stratospheric scenario would indeed reduce the long-term depletion of ozone by chlorofluorocarbons—to about seven per cent, the lower end of the range that had been predicted by Rowland and Molina. Meanwhile, industry public-relations groups had capitalized on the situation by holding press conferences designed to sow doubt about the validity of the ozone-depletion theory. Stories appeared in a number of prominent newspapers suggesting that Rowland and Molina had been proved wrong, that the chlorofluorocarbon threat had been exaggerated, and that the ozone layer was safe after all.

BECAUSE the chlorine-nitrate episode served to underscore the uncertainties in stratospheric chemistry, the National Academy of Sciences' long-awaited report—it was finally issued in September of 1976—was, many observers felt, considerably more cautious in tone than it might other-

wise have been. The report consisted of two separate documents—a highly detailed study of the scientific findings, by the Panel on Atmospheric Chemistry, and an over-all assessment of the problem, by the Committee on Impacts of Stratospheric Change (which had replaced the Climatic Impact Committee). The committee's report incorporated the panel's findings in less technical form, and it attracted widespread attention in the press, because it addressed itself to the sensitive political issue of regulation. However, it received mixed reviews, because its conclusions and recommendations were riddled with caveats and qualifications.

The authors of the report upheld the ozone-depletion hypothesis that had been worked out by Rowland and Molina and confirmed the lower range of their depletion estimate, concluding that continued release of chlorofluorocarbons at the 1973 rate could eventually cause a reduction of up to fifty per cent of the ozone in the upper stratosphere and approximately seven per cent of the total atmospheric ozone. At the same time, they left considerable room for doubt by placing the seven-per-cent figure in a range of uncertainty of between two and twenty per cent. They did agree that such depletion would greatly increase the amount of ultraviolet radiation able to reach the surface of the earth and could thus lead to a larger incidence of skin cancer and to harmful effects on plants and animals. Moreover, the report not only concurred with Rowland and Molina's warning that chlorofluorocarbons might cause climatic changes by altering temperatures in the stratosphere but also pointed out that by absorbing infrared radiation from the ground the compounds would add to the "greenhouse effect" already being created by the increasing amount of carbon dioxide that was finding its way into the atmosphere through the burning of fossil fuels. At the time, increased levels of these gases were expected to cause a rise in global temperatures, which threatened to eventually cause a melting of polar ice and a significant rise in sea level.

When it came to recommending how to deal with the chlorofluorocarbon problem, however, the committee members were prone to temporize. Having stated that selective regulation of the compounds "is almost certain to be necessary at some time and to some degree of completeness," they added that "neither the needed timing nor the needed severity can be reasonably specified today." By way of justifying this, they concluded that the costs of postponing the decision to regulate would not amount to "more than a fraction of a per cent change in ozone depletion for a couple of years' delay." They then expressed confidence that new measurement programs would reduce the uncertainties about how much of the ozone layer would eventually be destroyed. And on that hopeful note they proceeded to recommend against the imposition of immediate restrictions.

The language of the National Academy of Sciences report left room for widely differing interpretations of just what the Academy was recommending. On the day after the report's release, the *Times* ran a story under the headline "SCIENTISTS BACK NEW AEROSOL CURBS TO PROTECT OZONE IN ATMOSPHERE," while the Washington *Post* headed its account "AEROSOL BAN OPPOSED BY SCIENCE UNIT." In other quarters, the document was assessed in similarly conflicting fashion. Environmentalists pointed out that it provided confirmation of Rowland and Molina's theory of ozone depletion by chlorofluorocarbons, while industry public-relations people trumpeted the fact that the Academy had not found sufficient evidence to warrant regulation. Du Pont, for its part, issued another position paper, declaring that the Committee on Impacts of Stratospheric Change had reached "what was obviously a difficult, but, we believe, correct decision."

Two days later, a powerful rebuke to the Academy's equivocal assessment of the problem was delivered by Russell W. Peterson, the chairman of the President's Council on Environmental Quality, who spoke at the International Conference on Problems Related to the Stratosphere, at Utah State University. Peterson, a former governor of Delaware, had worked as a chemist for du Pont for twenty-six years, and he now declared that "the problem of determining prudent public policy in the face of scientific doubt recurs again and again as some chemicals developed for specific purposes prove to have—or threaten to have—unanticipated side effects." He asserted that "we cannot afford to give chemicals the same constitutional rights that we enjoy under the law," and that "chemicals are not innocent until proven guilty," and he concluded by calling upon the federal regulatory agencies to begin developing rules to restrict the discharge of chlorofluorocarbons into the atmosphere. Peterson's call for action was echoed by officials of the Environmental Protection Agency and the Consumer Product Safety Commission, who also spoke at the conference. It was given further impetus by the revelation that recent balloon measurements in the stratosphere had detected the presence of chlorine oxide—a compound formed by the reaction of chlorine and ozone, and a necessary participant in the catalytic chain reaction predicted by Rowland and Molina. Before the end of the year, the E.P.A. and the F.D.A. announced that they were initiating rules to phase out the use of chlorofluorocarbons as aerosol propellants.

IN the spring of 1977, the regulatory agencies came up with a joint timetable, known as Phase One, which called for banning the bulk manufacture of chlorofluorocarbon propellants as of October 15, 1978; for banning the manufacture of aerosol products containing chlorofluorocarbon propellants as of December 15, 1978; and for prohibiting interstate shipment of the existing stocks of these products as of April 15, 1979. However, in spite of widespread public belief that further ozone depletion would be averted by such action, the fact was that the proposed restrictions could at best provide only a partial solution to the problem. For one thing, nearly half the chlorofluorocarbons produced in the United States were being used in the manufacture of products like polyurethane foam and as a coolant in refrigerators and in automobile air-conditioners. For another, since the United States produced only half the world's total output of the compounds, a ban on chlorofluorocarbon propellants in this country would reduce the worldwide problem by only a quarter.

To deal with the domestic aspect of the situation, the E.P.A. announced that in the summer of 1978 it would propose a Phase Two timetable, for reductions in the non-aerosol uses of chlorofluorocarbons. This plan was shelved by the agency when it appeared that suitable substitutes for chlorofluorocarbon coolants in refrigerators and air-conditioners would be expensive and hard to come by. It was also decided that further regulatory action in the United States should be deferred until other nations could be persuaded to reduce their use of the compounds as propellants in aerosol sprays. However, in spite of strong appeals for international coöperation

made by the State Department and the E.P.A. during the next few years, the major chlorofluorocarbon-producing nations of Europe, as well as Japan and the Soviet Union, refused to take regulatory action. Indeed, between 1976 and 1979 only Sweden, Canada, and Norway joined the United States in enacting measures to reduce chlorofluorocarbon emissions. /Elsewhere, and especially in England and France, scientists and government officials expressed considerable skepticism about the extent of the hazard; they conceded that Rowland and Molina's ozone-depletion hypothesis might be correct, but they advocated a wait-and-see approach, claiming that there were too many uncertainties in atmospheric chemistry to warrant regulation of an important industry.

The validity of the wait-and-see approach received something of a jolt in the summer of 1977, when scientists at the National Oceanic and Atmospheric Administration, in Boulder, Colorado, undertook to remeasure the rate of one of the reactions between nitrogen oxides and hydrogen oxides, and found it to be about forty times as fast as had been indicated by previous laboratory measurements. Hydrogen oxides are formed in the stratosphere from hydrogen atoms released through various chemical reactions involving water vapor and methane, and, like nitrogen oxides and chlorine, they initiate a chain reaction that contributes to the natural removal of ozone. The discovery of the increased reaction rate with nitrogen oxides meant that earlier estimates of nitrogen oxide's ability to deplete ozone would have to be drastically scaled down; nitrogen-oxide emissions from S.S.T.s, which since the early nineteen-seventies had been under indictment as a killer of ozone, could henceforth be expected to play a far less important role in the scenarios of ozone destruction which were being compiled by atmospheric scientists. Another corollary of the new measurement was that chlorine nitrate—the compound whose unexpected appearance on the stratospheric stage in 1976 had resulted in cutting previous estimates of ozone depletion in half—was now thought to be not nearly as effective in retarding ozone depletion as had previously been believed. When scientists included the revised reaction-rate data in their computer models of the stratosphere, their predictions for ozone destruction by chlorofluorocarbons went back up. In 1979, the National Academy of Sciences issued a second report on the hazard, which estimated that if the compounds continued to be emitted at the 1977 rate eventual depletion of the ozone layer would total sixteen and a half per cent, with a three-out-of-four chance that the depletion would fall somewhere between nine and twenty-four per cent.

In spite of the fact that the predicted severity of the ozone problem had more than doubled within a span of three years, the Academy's new report received relatively little attention in the press, and the public remained largely unaware that the Academy's experts had described the hazard in considerably more forthright and foreboding terms than had been the case in 1976. Among other things, they warned that increased ultraviolet radiation, in addition to producing thousands of additional cases of skin cancer, could have intolerable consequences for the world's food supply by reducing crop yields, killing the larvae of several important seafood species (including shrimp and crab), and destroying microorganisms at the base of the marine food chain. They supported worldwide elimination of the use of chlorofluorocarbon aerosol propellants. They also pointed out that other uses of the compounds throughout the world were increasing at such a rate that even if a ban on chlorofluorocarbon propellants were put into effect immediately, emissions from other uses would equal the current levels within seven to ten years, and they urged that a coördinated international policy be developed for dealing with the problem. They stated that the wait-and-see approach was "clearly not a prudent strategy," concluding that if the decision to control chlorofluorocarbon emissions was postponed until a crucial depletion of the ozone layer was observed the slow but inexorable movement of the gases into the stratosphere would double that depletion within twenty years and cause prolonged exposure to dangerous levels of ultraviolet radiation for decades to come.

In keeping with past policy, the chlorofluorocarbon industry wasted no time in criticizing the National Academy of Sciences' latest assessment of the problem. On the day the report appeared, du Pont issued a statement declaring—once again—that predictions of ozone depletion by chlorofluorocarbons were based not on actual measurements but on theoretical calculations. "No ozone depletion has ever been detected, despite the most sophisticated analysis," du Pont pointed out, adding that "all ozone-depletion figures to date are computer projections based on a series of uncertain assumptions." According to du Pont, scientific studies being conducted by government and industry would require from two to four more years to obtain the evidence needed to answer such questions as whether chlorofluorocarbons could break down chemically in the troposphere and whether destruction of the ozone layer was actually taking place.

Some observers felt that du Pont, which had asked for several additional years of research on two previous occasions, was stalling. However, the company's latest position was supported in part by a study that members of the Stratospheric Research Advisory Committee had conducted for the United Kingdom's Department of the Environment during 1978 and 1979. Although the British investigators agreed with the National Academy of Sciences that the amount of ozone in the stratosphere could eventually fall by as much as sixteen per cent if the release of chlorofluorocarbons continued at the current rate, they concluded that the validity of the ozone-depletion hypothesis remained in doubt, because of the many uncertainties still prevailing in the knowledge of stratospheric chemistry and in modelling technology. They called for voluntary steps to reduce chlorofluorocarbon emissions, but they declared that for the time being strict regulation of the chemicals was unwarranted. Not surprisingly, chlorofluorocarbon manufacturers on both sides of the Atlantic lined up solidly behind this approach to the problem, and du Pont issued yet another statement, this one calling for a "resolution of the scientific differences between the National Academy of Sciences and the British Department of the Environment."

WHATEVER scientific differences remained to be resolved to the satisfaction of du Pont, it had become clear in other quarters that only strenuous international efforts

would be able to protect stratospheric ozone against further depletion by chlorofluorocarbon emissions. In March of 1980, the Council of the European Economic Community, whose then nine-nation membership accounted for about a third of the world's consumption and production of the chemicals, asked each of its members not to increase production capacity of the compounds, and to achieve a thirty-per-cent reduction in the use of chlorofluorocarbons as aerosol propellants by the end of 1981. In April, representatives of Canada, Denmark, the Federal Republic of Germany, the Netherlands, Norway, Sweden, and the Commission of the European Communities agreed at a conference in Oslo that a wait-and-see policy toward the hazard was unacceptable, and called upon all major chlorofluorocarbon-producing nations to reduce emissions from both aerosol and non-aerosol uses of the compounds. Representatives of the United States Environmental Protection Agency, who also attended the Oslo meeting, described the hazard as "one of the leading environmental issues of the decade," and—hoping to ameliorate the problem as well as to encourage further action on the part of the Europeans—made a proposal to freeze the annual production of chlorofluorocarbons in the United States at the 1979 level, of five hundred and fifty-one million pounds. Later in the month, the governing council of the United Nations Environment Programme recommended that its member governments reduce chlorofluorocarbon uses and not increase production capacity of the chemicals. In September, Japan announced that it intended to take similar action.

Here in the United States, where the lost market in aerosol propellants had been largely made up by increased use of chlorofluorocarbons in refrigeration, liquid fast-freezing, automobile air-conditioning, industrial solvents, and the manufacture of plastic foams, industry officials were up in arms about the E.P.A.'s plan to curtail chlorofluorocarbon production. A lobbying group called the Alliance for Responsible CFC Policy, made up of producers and industrial users of chlorofluorocarbons, was formed during the summer of 1980 to head off any further attempts to regulate the chemicals. It was able to make use of such sensitive election-year issues as the faltering economy and the country's changing mood with regard to environmental causes, and its purpose was, according to one of its spokesmen, "to convince the government—Congress, the White House, and anyone else—that E.P.A.'s proposal to restrict CFCs is ill-advised."

In spite of the new lobby, the E.P.A., during the first week of October, went ahead and published advance notice in the *Federal Register* of its latest proposals to control chlorofluorocarbon emissions. By this time, the agency had come up with two possible solutions to the problem. The first, known as the mandatory-controls approach, would place an indirect ceiling on chlorofluorocarbon uses through restrictions on production or through standards based upon technology. Under this system, the E.P.A. could ban certain industrial uses of the chemicals and could require their recovery and recycling in the manufacture of plastic-foam products. It could also require the substitution of less hazardous compounds as refrigerants in certain types of refrigeration equipment. The second solution, which the agency described as "a more efficient method of reducing the environmental and human health risk," was known as the economics-incentive approach. Under this plan, a ceiling on total chlorofluorocarbon production would be established through a system of permits, which could be either directly allocated to makers and users of the compounds or auctioned off to those who were willing to pay the highest price.

As might be expected, industry reaction to the proposed rulemaking was highly unfavorable. A du Pont spokesman declared that the ozone problem could not be solved by unilateral action on the part of the United States. He added that "the E.P.A. should attempt to gain international scientific consensus on whether there is a potential problem and, if so, how the world community should address it." An E.P.A. official replied that from five to ten years might pass before sufficient data could be acquired to conclusively prove the theory of ozone depletion by chlorofluorocarbons, and pointed out that all the chlorofluorocarbons produced in that period would make their way into the stratosphere. "If we wait until 1990 to make the decision, it could be too late," he said.

Thanks to a combination of public apathy and an intensive campaign waged by the Alliance for Responsible CFC Policy, only four out of more than two thousand written comments that were sent to the E.P.A. over the next three months supported its latest proposals for limiting chlorofluorocarbon emissions. Combined with the newly elected Reagan Administration's vociferous bias against environmental regulation, this response was more than enough to cause the agency to back away from its announced intention of issuing new rules in the spring of 1981. The E.P.A. was further encouraged to relax its rulemaking timetable when improved measurements of several chemical-reaction rates caused atmospheric scientists to lower their predictions of the extent of ozone depletion. They now estimated long-term depletion to be in the range of five to nine per cent.

During the summer of 1981, it became apparent that a wholesale reevaluation of the E.P.A.'s position on chlorofluorocarbons was under way. In July, an official of the agency told members of the House Subcommittee on Anti-Trust and Restraint of Trade Activities, who were meeting to consider the effect of additional chlorofluorocarbon restrictions on small businesses, that no decision to regulate was in the offing and that the E.P.A. was "extremely sensitive to the needs of small businesses." Another indication that the E.P.A. was changing its policy had come when Anne Gorsuch, the new agency administrator, testified at her Senate confirmation hearings, in May, that she understood that the theory of stratospheric ozone depletion was "highly controversial," and that there was a "need for additional scientific data before the international community would be willing to accept it as a basis for additional government action." Attempts to legislate a new outlook for the E.P.A. were made in September, when draft bills introduced into the House and Senate to amend

the Clean Air Act proposed to shift the focus of the agency's activity from regulation to research, and to restrain it from imposing additional restrictions on the production and use of chlorofluorocarbons until there was "clear scientific evidence" to show that they were a threat to human health and the environment. By calling upon the E.P.A. to measure actual depletion of the ozone layer before taking further action, the bills were, of course, extending the presumption of innocence to chlorofluorocarbons. Meanwhile, data collected by NASA's Nimbus 4 and Nimbus 7 satellites indicated that ozone at the twenty-five-mile altitude of the stratosphere, where the maximum destructive effect of chlorofluorocarbons was expected to occur, had been depleted by several per cent between 1970 and 1979.

Here on earth, where the so-called "ozone debate" was entering its eighth year, spokesmen for the chlorofluorocarbon industry were assuring everyone that careful monitoring of ozone levels around the world could provide an early-warning system for ozone depletion. Considerable publicity was also given to a scheme whereby instruments designed not only to measure ozone but also to detect chemical reactions that might be depleting it would be carried to an altitude of twenty-five miles by a balloon four hundred and fifty feet in diameter and then lowered and raised through the stratosphere on a twelve-mile-long synthetic line that —as it happened—had been developed and manufactured by du Pont. Billed as the world's biggest yo-yo, the new device was supposed to undergo testing before the end of 1981. However, difficulties encountered in design and construction soon put this plan way behind schedule. The first test flight of the balloon did not take place until 1982; the first measurements were not taken until 1984, and then the instruments simply confirmed that chlorine oxide was present in the upper stratosphere in quantities sufficient to deplete ozone; and subsequent difficulties with faulty balloons have postponed further flights.

The amendments to the Clean Air Act were bitterly debated in Congress during the autumn of 1981, and the industry continued its campaign against further regulation of chlorofluorocarbons. In October, the Chemical Manufacturers Association released its analysis of figures gathered from measuring stations operated by governments around the world; this analysis indicated that ozone levels in the earth's atmosphere had actually *increased* during the nineteen-seventies. Toward the end of the year, the association reported that since 1974 there had been a twenty-per-cent decrease in the production and release of chlorofluorocarbons throughout the world. By the spring of 1982, however, both sets of data furnished by the industry were called into question by observations from other sources. In the first week of April, researchers from the National Oceanic and Atmospheric Administration described the results of a study showing that the total amount of atmospheric ozone over North America had decreased by about one per cent between 1961 and 1980. At the same time, Professor Rowland and some of his colleagues announced the findings of a study showing that chlorofluorocarbon concentrations in the atmosphere had almost tripled within the last ten years, and that total release of dichlorodifluoromethane from 1976 through 1979 was almost thirty-five per cent greater than the estimate given out by the Chemical Manufacturers Association.

As it turned out, word of these developments was overshadowed by press coverage of yet a third National Academy of Sciences report, which had been issued on the last day of March. The latest study contained little that was new in the realm of stratospheric chemistry—its prediction that eventual depletion of the ozone layer would fall within the range of between five and nine per cent was based upon calculations that had been made a year before and published by the World Meteorological Organization and NASA—but it presented an unusually grim analysis of the human-health hazards that would result from such a depletion, warning that the accompanying increase in ultraviolet light would cause much more skin cancer than had previously been suspected, and would also cause painful irritation of the eyes and have adverse effects upon the body's immune system. Yet in spite of these ominous conclusions the new Academy report was greeted from one end of the country to the other by newspaper headlines declaring that the threat to the ozone layer was not as serious as had been thought —a comfortable assessment that depended upon comparison of the latest Academy estimate of ozone depletion with the one that had appeared three years earlier, in its 1979 report, which had predicted that the long-term loss could be as high as sixteen and a half per cent. It was less comforting to compare the most recent forecast with the seven-to-thirteen-per-cent depletion range that Rowland and Molina had predicted when they first brought their worrisome findings to public attention, back in 1974. Indeed, when this comparison was made it was clear that their original estimate of ozone depletion had held up remarkably well over the years—especially in light of the many uncertainties that had characterized the course of atmospheric chemistry. It was equally clear that during this whole period precious little had been done to resolve the problem the two scientists had described, and that its outcome, like the chlorofluorocarbons, remained in the air.

AT this point, with no apparent end to the controversy in sight, I decided to fly out to California and pay a call upon Professor Rowland, whom I had first met in 1974, in order to get his reaction to the situation. Originally a specialist in the chemistry of radioactive isotopes, he is a large, patient man in his late fifties, who regards his career as having been relatively uneventful until he became involved with chlorofluorocarbons, and who recalls ironically that his only previous brush with controversy occurred when, in 1971, following the discovery that swordfish and tuna contained high levels of mercury, he and some colleagues drew the ire of environmentalists by demonstrating that these levels were in fact no higher than those found in specimens of swordfish and tuna that had been preserved in alcohol for decades. Since 1974, however, he had been very much in the thick of the dispute surrounding the ozone-depletion hypothesis that he and Molina had worked out, and had spent much of his time and energy describing the scientific background of the ozone problem at congressional hearings, before state legislative committees, for various federal and state regulatory agencies, to university audiences, and at international meetings around the world. He had also been elected to the National Academy of Sciences and the American Academy of Letters and Sciences, and had received the American Physical Society's Leo Szilard Award for Physics in the Public Interest.

At the time of my visit—in April of 1982—I found him in the cluttered office he occupies on the top floor of the Physical Sciences Building, a fortresslike structure on the sprawling fifteen-hundred-acre campus of the University of California at Irvine. When I asked him how he felt about the current state of the long-drawn-out debate that he and Molina had initiated, he smiled grimly and handed me a newspaper clipping containing the announcement that the Pennwalt Corporation was investing ten million dollars to modernize and expand its chlorofluorocarbon plant at Calvert City, Kentucky. "As you can see, industry has become so confident that there will be no further regulation of chlorofluorocarbons that it is increasing its capacity to manufacture them," he said. "I feel as if we had circled the board and returned to Square One. Meanwhile, of course, I'm concerned that time is running out for the ozone layer."

The inability to resolve the chlorofluorocarbon problem, Rowland said, reflected a failure on the part of society to come to grips with an issue whose consequences were less than certain, and this failure had, in his opinion, been brought about by indecisiveness on the part of the scientific community, timidity on the part of the regulatory agencies, ignorance on the part of the public, inconsistency on the part of the press, indifference on the part of other nations, and obstruction and obfuscation on the part of industry. "The authors of the first National Academy of Sciences report established a debilitating precedent at a crucial time in the whole affair when they advocated a delay in regulation for a year or two and tried to justify it on the ground that the resulting accumulation of chlorofluorocarbons in the atmosphere would produce only a minor additional loss of ozone," he said. "In so doing, they gave the impression that we could continue to put off finding a solution to the problem indefinitely, and that is exactly what industry has been urging ever since. As for the regulatory agencies, their subsequent decision to impose a ban solely on the use of chlorofluorocarbons as aerosol propellants fragmented the problem, and inadvertently created the idea in the mind of the public that it had been solved when in fact it had been only partly alleviated. The news media played a role in the rise of this misconception. Of course, the press was instrumental in bringing the chlorofluorocarbon problem to public attention, but once the partial ban was announced most newspaper accounts conveyed the false impression that the matter had been taken care of. Then, as the novelty of the story wore off, the press lost interest and failed to describe the growing complexity of the issue as it unfolded over the next few years. The result is that relatively few people appear to understand the magnitude of what is happening. For example, it is not well known that chlorofluorocarbon molecules, no matter where they are released, disperse very quickly throughout the atmosphere, and that an emission in Europe, say, will sweep across Asia and the Pacific and reach the California coast in about a month. Few of our fellow-citizens seem to realize that the damage now being inflicted upon the ozone layer above the United States—or, for that matter, above any other nation—is cumulative damage caused by chlorofluorocarbons that have been released throughout the world. People are unaware of the importance of obtaining international agreements to deal with the threat. English and French atmospheric scientists have always been skeptical of our concern for the ozone layer. At first, many of them chose to think that it was a ploy directed against their joint Concorde project, and later they carried their skepticism into the discussions of international control of chlorofluorocarbon emissions. Moreover, along with other major European chlorofluorocarbon-producing nations, the English and the French have resented our suggesting that they cut down on their use of chlorofluorocarbons in aerosol sprays while we continue to use huge quantities of chlorofluorocarbons to air-condition our automobiles and make plastic-foam products, such as packages for fast foods. Here again, you see, the partial ban has come back to haunt us."

When I asked Rowland why he thought his fellow-scientists had for the most part failed to take a strong stand on the chlorofluorocarbon issue, he replied that scientists generally avoid speaking out on any subject with which they are not wholly conversant, and rarely become involved in controversial matters unless they are appointed to a study group by some such organization as the National Academy of Sciences. "Chemists, in particular, have tended to feel stigmatized by all the adverse publicity that has surrounded their profession in recent years," he said. "Their reaction to environmental problems caused by chemicals—whether it's the pollution of Love Canal, the contamination of ground water, or the destruction of the ozone layer—is frequently a defensive withdrawal from public involvement. Many of them are convinced that such problems are either nonexistent or grossly exaggerated. For those of us who are concerned with the stratosphere, the problems are somewhat different. We are fascinated by the incredible complexity of the chemical reactions that occur up there, and we take great delight in trying to understand them in every last detail. We find it profoundly exhilarating, for example, to attempt a prediction and then obtain confirmation of it by making an actual measurement—or, conversely, to come up with a new and unexpected measurement that sends us back to revise our mathematical models. The trouble is, we have become so absorbed in the minutiae of our work that we tend to spend our time filling in elaborate details and sometimes fail to see things in sufficiently large perspective. Over the past eight years, I have probably been to more than a hundred scientific meetings about the ozone problem—meetings that were attended by at least half of the thousand or so atmospheric scientists who are conversant with this problem—and I have never failed to wonder at how completely the sheer technical aspects of stratospheric science dominate such gatherings, and how little discussion, either formal or informal, is given to the implications of ozone depletion upon plants, crops, fish, weather, or, for that matter, human health.

"Another problem, in my view, is the fact that the chlorofluorocarbon panel of the Chemical Manufacturers Association has become an important source of financing for atmospheric research, with the result that a substantial number of our finest atmospheric scientists are being supported in their work by companies engaged in the manufacture of chlorofluorocarbons. It may prove easier for those scientists to suggest new studies of the ozone layer and different techniques for measuring chemical reactions in the stratosphere than to call for regulatory action against chlorofluorocarbons. In any case, we find ourselves, one way or another, in the midst of a large-scale experiment to change the chemical construction of the stratosphere, even though we have no clear idea of what the biological or meteorological consequences may be."

Researchers in the Department of Transportation's Climatic Impact Assessment Program, Rowland told me, decided in the early nineteen-seventies that the maximum tolerable amount of long-term worldwide ozone depletion would be any detectable change. "At that time, assuming some improvement in measuring capabilities, this was estimated to be one-half of one per cent," he said. "Later, the members of the National Academy of Sciences' Committee on Impacts of Stratospheric Change suggested that an eventual two-per-cent reduction of ozone might be acceptable. Today, it is the assessment of the chlorofluorocarbon industry that we can afford to wait until we have measured an actual loss of one and a half per cent. The fact is, of course, that none of these estimates of what degree of depletion would be tolerable have been based upon science. All of them represent guesswork, crossed fingers, and wishful thinking. No one has the slightest way of knowing, for example, what amount of ozone depletion is required to produce an important shift in the climate of the earth. We do know, however, that if *another* eight years go by without our taking adequate steps to reduce chlorofluorocarbon emissions approximately four million tons of chlorine will have been added to the twelve million tons that are now estimated to be floating about in the atmosphere. We also know that if we continue on our present course enough chlorine will eventually make its way into the stratosphere to create a dangerous situation. What we don't know is how far in the future the point of danger lies—or, for that matter, whether it has already been passed. At this point, it seems obvious that we have only two alternatives. We can continue the large-scale experiment on the stratosphere which is now in progress, in order to determine what its consequences may be. Or we can discontinue the experiment, for the simple reason that its consequences may prove to be disastrous for mankind. One thing we cannot do is undo what we have done. Even if a total, worldwide ban on chlorofluorocarbons were put into effect today, the level of ozone destruction in the upper stratosphere would continue to increase until the end of this century and would persist with gradually decreasing severity throughout the next. All things considered, it seems sensible to discontinue the experiment as rapidly as possible. As a first step, I would make the same recommendation that was made by the authors of the National Academy of Sciences' report of 1979. I would urge that the use of chlorofluorocarbons as aerosol propellants be banned on a worldwide basis without further delay. I would also urge that all nations proceed to reduce sharply their use of these chemicals in other nonessential applications."

DURING the next two years, the debate over the ozone layer continued to be carried on largely out of public sight and mind, and without much urgency, as laboratory experiments to remeasure and refine the rate of various chemical reactions taking place in the stratosphere further reduced the estimate of long-term ozone depletion by chlorofluorocarbons. As a result of some of these experiments, stratospheric ozone losses from nitrogen oxides emitted by high-flying S.S.T.s were once again estimated to be significant. At the same time, actual measurements at ground level showed that there was a slow but steady increase in the concentration of other atmospheric gases—nitrous oxide, for one, and methane, which is produced primarily by bacterial action in rice fields, in swamps, and in the digestive tracts of cattle and other domestic animals. Since it had been known for two decades that concentrations of carbon dioxide in the atmosphere were also increasing, this meant that predictions of changes in the chemical composition of the atmosphere were going to continue to require the assessment and analysis of a mixture of gases. A fourth National Academy of Sciences report, issued in February of 1984, depicted the stratospheric scenario in terms of a whole new set of chemical uncertainties.

To begin with, the authors of the latest report reduced their estimates of eventual ozone depletion from chlorofluorocarbons from the five-to-nine-per-cent range to a two-to-four-per-cent range. Their new prediction was again based on the assumption that the yearly emission of chlorofluorocarbons would remain unchanged over the next century; it was also based on an estimated increase of ozone in the lower atmosphere—an estimate based on revised chemical-reaction rates—which was expected to partly offset a heavy loss of ozone in the high stratosphere resulting from the invasion of chlorofluorocarbons. However, when they took into account the combined effect of carbon dioxide, methane, nitrous oxide, and the nitrogen oxides emitted by subsonic aircraft, the authors of the Academy's 1984 report were able to predict that the total ozone level in the atmosphere might actually *rise* by one per cent over the next few decades. They arrived at this happy possibility by calculating that the increasing level of carbon dioxide and its consequent absorption of infrared radiation would eventually lower stratospheric temperatures, thus slowing down chemical reactions that remove ozone; that methane reacting with chlorine atoms in the stratosphere would prevent the chlorine from reacting with and depleting ozone; that the decomposition of nitrous oxide in the stratosphere would increase concentrations of nitrogen oxides, which would react with chlorine compounds to form chlorine nitrate, the gas that disrupts the ozone-depleting chain reactions of both chlorine and nitrogen; and that the nitrogen oxides emitted by subsonic aircraft in the lower stratosphere would be photolyzed by sunlight to form ozone.

In the end, the Academy's report contained good news and bad news. The good news was that the growing concentrations of so-called trace gases might ameliorate the problem of ozone destruction by chlorofluorocarbons. The bad news was that some of these gases could enhance the dreaded greenhouse effect; chlorofluorocarbons, for example, are known to be at least ten thousand times as efficient as carbon dioxide in preventing the escape of infrared radiation. In view of the immense difficulty of quantifying the separate and combined effects of carbon dioxide, methane, nitrous oxide, and nitrogen oxides, it was not surprising that the authors of the latest report should attempt to outline the uncertainties inherent in their findings. They pointed out that if chlorofluorocarbon emissions were to increase at a rate of three per cent per year, and if measures were taken to reduce carbon-dioxide and nitrogen-oxide emissions from airplanes, the total ozone level in the atmosphere could decrease by as much as ten per cent by the year 2040. Still, they took comfort in the fact that between 1970 and 1980 detailed statistical analysis had found

"no discernible trend" in the total amount of ozone in the atmosphere.

As might be expected, the press response to the report tended to emphasize its decreased estimate of ozone depletion and to ignore its prediction of dire consequences if chlorofluorocarbon emissions were to rise. The reaction of the chlorofluorocarbon industry was also unsurprising. "It shows we don't have an imminent crisis on our hands," Donald R. Strobach, the manager of environmental programs at du Pont's Freon Products Division, said of the report. "What we have is time to research in a rational way." But even as he and the authors of the report were assuring the nation and the world that no drastic changes in the level of ozone were expected in the next few decades, meteorologists who were engaged in measuring ozone with ultraviolet spectrometers at stations in the Northern Hemisphere were finding that ozone concentrations in the atmosphere had in fact fallen sharply since late 1982. Scientists at the Swiss government's ozone-monitoring facility at Arosa, Switzerland, reported that the 1983 ozone average in the atmosphere above their measuring stations was fully eight per cent below the annual average for the previous half century and was the lowest yearly value they had ever recorded; meteorologists at the West German government's weather station at Hohenpeissenberg, in the Bavarian Alps, recorded an ozone reduction of seven per cent in 1983—the lowest in the station's twenty years of operation; and researchers in Toronto found that the five stations of the Canadian government's ozone-monitoring network had measured an average ozone reduction over Canada of three per cent. As a result of these and other measurements from around the world, scientists at the National Oceanic and Atmospheric Administration calculated that during the first half of 1983 there had been a drop of between five and seven per cent in ozone concentrations over the entire Northern Hemisphere.

This staggering loss of ozone was not publicly reported in the United States until the autumn of 1984, and when I first heard about it—at the end of June, ten years almost to the day after the publication of Rowland and Molina's original hypothesis of ozone depletion by chlorofluorocarbons—I decided to pay another call upon Rowland, to find out if he had any light to shed upon the situation. Since my visit two years earlier, he had won the American Chemical Society's Award for Creative Advances in Environmental Science and Technology; he had been a co-winner of the Tyler Award in Ecology and Energy, with Molina and Harold S. Johnston, of the University of California at Berkeley, whose work on nitrogen oxides in the stratosphere had stimulated the debate over the environmental effects of S.S.T.s. Rowland had also served for two years on the Acid Rain Peer Review Panel of the Executive Office of the White House. "Most of the ozone loss in 1983 occurred in the lower stratosphere—between twelve and twenty miles in altitude," he told me. "What is surprising is that not only were most of the predicted effects of chlorofluorocarbons expected to take place in the high stratosphere—about twenty-five miles above the earth—but no strong effects of any chemicals were predicted in the lower stratosphere. No one yet knows why ozone levels dropped so sharply in the lower stratosphere in 1983, but it could have been related to the presence of particles of sulfuric acid and other gaseous debris that were thrown into the atmosphere by the eruption of the Mexican volcano El Chichon in April of 1982. My colleagues and I are currently investigating the possibility that there might be some reaction between chlorine nitrate and other molecules, such as water, on the surfaces of the volcanic debris, but the precise chemical connection between them remains a mystery that will probably not be solved for some time. Whatever the outcome, the loss of ozone in 1983 serves not only to emphasize our lack of understanding of chemistry in the lower stratosphere but to call into question our ability to make accurate predictions about what is happening there. Remember that the atmospheric models cited in the most recent National Academy report suggested that an *increase* in ozone should be expected in that very region. Remember also that while the predictions for the lower stratosphere have fluctuated widely over the past decade, all the calculations have shown that continued use of chlorofluorocarbons will eventually cause losses of ozone as high as fifty per cent in the upper stratosphere. Thus, it stands to reason that the high stratosphere is an ideal place to seek evidence of ozone depletion by chlorofluorocarbons. As it happens, statisticians from the University of Wisconsin and the University of Chicago reported a few weeks ago that analysis of data provided by thirteen stations in the Northern Hemisphere and Australia, all of which used ultraviolet spectrometers to measure ozone in the atmosphere, showed what they called 'statistically significant negative ozone trends' in the upper stratosphere. These data confirmed previous measurements, by NASA satellites, of ozone loss in the upper stratosphere, which had been occurring since 1970. Back in 1974, an official of the du Pont Company told a congressional subcommittee that if credible evidence should be developed to show that chlorofluorocarbons posed a hazard to human health du Pont would stop manufacturing them. These days, the chlorofluorocarbon industry appears to have decided that it does not intend to consider any evidence credible as long as there is the slightest doubt about the validity of any part of the ozone-depletion hypothesis. Thus, credible evidence becomes impossible to achieve—simply because there will always be some degree of uncertainty in measuring atmospheric changes and there will always be discrepancies in the mathematical models that simulate chemical reactions in the stratosphere. For this reason, one can expect industry to keep on asking for more time, to conduct other investigations. The tactic is known as studying the problem to death, and—considering what is at stake—it is a blatantly cynical one. We have been studying the chlorofluorocarbon problem for more than ten years now, and during each of these years at least a million tons of chlorofluorocarbons, worth more than a billion dollars, have been sold throughout the world. That's the bottom line as far as the chemical companies are concerned. The bottom line for the rest of us is that during each of these ten years a million tons of chlorofluorocarbons, containing at least five hundred thousand tons of chlorine, have been added to the atmosphere, and that sooner or later all this chlorine will be unleashed in the stratosphere to attack the ozone layer."

When I asked Rowland if he thought there was much chance of preventing this, he shook his head and said he did not. "As a professional scientist, I hate to have to admit that," he said. "After all, what's the use of having developed a science well

enough to make predictions, if in the end all we're willing to do is stand around and wait for them to come true? But, from what I've seen over the past ten years, nothing will be done about this problem until there is further evidence that a significant loss of ozone has occurred. Unfortunately, this means that if there is a disaster in the making in the stratosphere we are probably not going to avoid it."

A POWERFUL indication that the disaster Rowland had been predicting for a decade might be at hand arose just a few months after our talk. In October of 1984, the atmospheric scientists of the British Antarctic Survey who had been disregarding their ozone measurements taken at Halley Bay—which had recorded a steady loss of stratospheric ozone above Antarctica since 1977, with especially large temporary decreases every October during that seven-year period—had begun to observe similar losses at their measuring station in the Argentine Islands. Late in December, the British scientists submitted to *Nature* their paper describing the large losses of ozone above Antarctica—losses they characterized as "a dramatic change." But when their paper was published, in May of 1985, there was almost no reaction either in the press or within industry or government circles. Among the members of the world's atmospheric-science community, there was an initial call for more information and for corroboration. This was quick in coming, for by August the atmospheric scientists who were assessing data collected by NASA's Nimbus 7 satellite had belatedly reprogrammed their computers to stop rejecting indications of severe ozone loss just because such low levels had never been seen before. As a result, they were able not only to confirm the disturbing observations of their British colleagues but to provide a detailed map of an enormous hole that had appeared in October of 1983 in the ozone layer above the Antarctic continent. The loss of ozone above Antarctica that month had approached forty per cent, and by October of 1985 was nearly sixty per cent. Moreover, a new analysis of data that had been collected by the satellite between 1978 and 1984 showed that there had been a significant decline of ozone over that period in all latitudes of the globe.

The autumn of 1985 saw a frantic scramble among atmospheric scientists to account for this latest phenomenon. None of the existing atmospheric models upon which they had depended for estimating ozone depletion were predicting large-percentage losses of ozone until the middle of the twenty-first century. Some of the scientists now assumed that their models had omitted certain critical chemical reactions—for example, the possible interaction of chlorine nitrate with water or hydrogen chloride on the surfaces of stratospheric particles, such as the ice crystals that are formed during the cold polar night. Other scientists tried to explain the hole in the Antarctic ozone layer as the result of a special meteorological condition, in which ozone-depleted air from the upper stratosphere might somehow subside upon the Antarctic continent during the months of darkness, or in which ozone-poor air from the lower atmosphere might somehow be drawn up into the stratosphere. Most of them tended to agree, however, that the large ozone losses above the Antarctic were associated with the rapid increases in chlorofluorocarbon concentrations in the atmosphere over the previous decade. The trouble was that, as usual, none of the explanations of ozone depletion could be proved by actual measurement of chemical processes in the Antarctic atmosphere. This, as usual, allowed the chlorofluorocarbon industry to suggest that any connection between chlorofluorocarbons and ozone depletion in the Antarctic rested on theory. Indeed, Dr. Robert Orfeo, a scientist with the Allied Corporation—the nation's second-largest producer of chlorofluorocarbons—declared on a Cable News Network television program that any such linkage amounted to "sheer speculation."

Dr. Rowland, for his part, reacted to the news by pointing out in interviews that the chlorofluorocarbon industry's often repeated assurances that there would be ample early warning of any serious ozone depletion had turned out to be worthless. He also pointed out that for nearly twelve years the prevailing assumption of industry, government, and many members of the scientific community had been that his and Molina's original hypothesis of ozone depletion by chlorofluorocarbons would prove to have been overestimated, and that the appearance of a vast hole in the Antarctic ozone layer tended to show just the opposite. And he concluded that the margin of safety for the world's ozone layer was so thin that no nation should any longer permit the release of chlorofluorocarbons in any form. In short, he now advocated a worldwide ban on virtually all uses of the compounds.

During the winter, I telephoned Rowland and asked him to explain how and why the unexpected loss of ozone was taking place in the stratosphere above Antarctica, and why the depletion was so pronounced in October. To begin with, he told me that atmospheric scientists were not certain about the precise chemistry that occurs in the Antarctic stratosphere and that very few balloon measurements of it had been made. "What is known is that Antarctic meteorology between May and November—roughly the time of Antarctic winter and early spring—is dominated by a rotating air mass called the polar vortex," he said. "This air mass is still dominant in September at the start of the Antarctic spring, which means that any decomposition product such as chlorine nitrate has for the most part remained sequestered in total darkness for many months and has been essentially unaffected by solar radiation. My colleagues and I believe that during this time there is a strong possibility that the chlorine nitrate interacts with molecules of water or hydrogen chloride on the surfaces of stratospheric ice particles, thus forming even more reactive chlorine compounds. When these compounds are struck in September by the first sunlight of the Antarctic spring, they decompose immediately and commence the chlorine chain reaction that results in very rapid destruction of ozone. The depletion is all the greater because as a result of the sun's low angle on the horizon the ultraviolet component of Antarctic sunlight is filtered out, which means that almost no ozone is being formed by the natural reaction of short-wavelength ultraviolet radiation on molecular oxygen. The problem is further exacerbated by the fact that ozone-bearing air masses from other latitudes do not migrate to the Antarctic until November, when the sun rises high enough above the horizon to heat the Antarctic air, causing the polar vortex to break up and the hole in the ozone layer to be filled once again with ozone-rich air from elsewhere. The trouble is that in spite of this annual replenishment there is about six to ten per cent less ozone over Antarctica during the summer and fall these days than there was twenty years ago. In their 1985 article in *Nature*, the scientists of the British Antarctic Survey

took pains to point out the striking correlation between this decline of ozone above Antarctica and the rapid increase of chlorofluorocarbon concentrations in the Antarctic atmosphere. Indeed, when one remembers that the British scientists did not measure any significant ozone depletion in the Antarctic between 1957 and 1977, what could be a more likely cause of the sudden appearance of an enormous hole in the Antarctic ozone layer than the explosive growth of chlorofluorocarbons in the world's atmosphere during the past fifteen years?"

NEWS of the catastrophic loss of Antarctic ozone notwithstanding, the Environmental Protection Agency had little to say about stratospheric problems during 1985. Many observers believe that the agency was still bound by the anti-regulatory fetters that had been imposed upon it during the early years of the first Reagan Administration. (Some idea of the mind-set of high E.P.A. officials during that era can be had from a recent book entitled "Are You Tough Enough?," by Anne Gorsuch Burford, who in the course of describing her two-year stint as the agency's administrator dismisses the ozone-depletion problem as a scare issue, calling upon her readers to "remember a few years back when the big news was fluorocarbons that supposedly threatened the ozone layer?") An indication that the E.P.A. might be reëvaluating the chlorofluorocarbon threat came in November, however, when officials of the agency and the Natural Resources Defense Council—an organization that has won a number of landmark court cases involving environmental problems—announced that they had reached an out-of-court settlement of a lawsuit brought against the E.P.A. by the Council in 1984. The lawsuit had called upon the E.P.A. to carry out its 1980 promise of Phase Two regulation of the uses of chlorofluorocarbons other than as aerosol propellants, and, as part of the settlement, E.P.A. officials had agreed to make a decision on the matter by November of 1987.

A further indication that the E.P.A. was rethinking its position came early last January, when the agency published in the *Federal Register* an announcement of what it called a Stratospheric Ozone Protection Plan. The announcement stated that by enhancing the E.P.A.'s research and analysis of stratospheric-ozone problems the program would provide "necessary technical information for use in future Agency decisions on whether or not to regulate chlorofluorocarbons (CFCs) or other chemicals that may affect the ozone layer." After reviewing the possible environmental and health effects of exposure to increased ultraviolet radiation resulting from the depletion of ozone by chlorofluorocarbons, the E.P.A. declared that the production and use of the chemicals might also "contribute to the predicted global warming from the 'greenhouse effect.'" The agency went on to say that a major review of atmospheric-science issues related to ozone modification had been sponsored by NASA, the World Meteorological Organization, the United Nations Environment Programme, and other national and international organizations, and that a report of this review would soon be published. It then described international negotiations concerning the protection of the ozone layer which had been conducted in Vienna under the auspices of UNEP, and had resulted, in March of 1985, in the adoption of the Vienna Convention for the Protection of the Ozone Layer. After acknowledging that the Vienna conference had "failed to agree on any appropriate global control measures," the E.P.A. said that in lieu of such measures a resolution had been passed "calling for an economic workshop to analyze relevant aspects of control options and for continued negotiations culminating in a second Diplomatic Conference planned for April 1987."

As for the E.P.A.'s own efforts at researching and analyzing the threat to the ozone layer, the agency declared that its new program would stress evaluation of future rates of growth in chlorofluorocarbon emissions, modelling of changes to the ozone layer resulting from changes in the chemical composition of the earth's atmosphere, assessment of the performance of atmospheric models in light of atmospheric-monitoring data, and continued study of environmental and health effects from exposure to increased ultraviolet radiation or to changes in climate resulting from ozone modification. As its first order of business, the E.P.A. announced that it would convene a domestic workshop in March of 1986 to analyze the future demand for chlorofluorocarbons and other atmospheric pollutants, as well as the costs and feasibility of emission-reduction technologies, and that UNEP would sponsor an international workshop in May to deal with the same issues. The agency reported that the United States and UNEP were jointly sponsoring an international conference on the environmental and health consequences of ozone depletion and climate change, to be held in mid-June in Washington; that it was planning to convene a workshop to evaluate global and domestic control strategies in July; and that UNEP would follow up with an international workshop on the same issue in September. In conclusion, the E.P.A. pointed out that once it had reviewed the results of all this evaluation and analysis it would publish a notice in the *Federal Register* no later than November, 1987, in which it would either promulgate new regulations or announce another decision to take no immediate action. Nowhere did the agency acknowledge that it had agreed to do so as a result of its out-of-court settlement with the Natural Resources Defense Council, nor did it make any mention of the hole that had appeared in the ozone layer above Antarctica.

In spite of the generally sanguine tone of the E.P.A.'s January announcement in the *Federal Register*, it soon became apparent that the chlorofluorocarbon threat to the ozone layer had finally begun to worry high officials of the agency. The hundred and fifty or so participants at its March workshop on the future demand for chlorofluorocarbons and the feasibility of controlling them were greeted by none other than Lee M. Thomas, the agency's new administrator. After assuring his listeners—they included a bevy of economists, E.P.A. officials, and chlorofluorocarbon-industry representatives, and a handful of atmospheric scientists—that the E.P.A.'s new Stratospheric Ozone Protection Plan should be viewed as a commitment to deciding whether there was a need for regulatory action rather than as a presupposition that additional controls were in fact needed, Thomas warned that a substantial change in global climate caused by ozone-modifying gases could "alter the current ecological balance of our planet." He said that after reviewing a recent NASA report on stratospheric protection he had been struck

by the uncertainties in accurately predicting future atmospheric changes, and he cited as a prime example the discovery of the forty-per-cent depletion of ozone during the spring season in Antarctica over the previous decade, stressing the disturbing fact that this phenomenal change had not been predicted by any of the atmospheric models currently in use. He then described what amounted to a brand-new, if somewhat after-the-fact, E.P.A. attitude toward the chlorofluorocarbon problem: "In the face of all this scientific uncertainty, one might ask why has E.P.A. embarked on programs to assess the risks and to decide whether additional CFC regulations are necessary? Why not simply adopt a 'wait-and-see' attitude and hold off a decision until depletion is actually confirmed? Let me address this question squarely. E.P.A. does not accept, as a precondition for decision, empirical verification that ozone depletion is occurring. Several aspects of the situation suggest we may need to act in the near term to avoid letting today's 'risk' become tomorrow's 'crisis.'" In conclusion, Thomas said that the protection of stratospheric ozone was a vital issue, which his agency was "determined to deal with," and that its implications for human health and the environment were "as potentially vast as any I have to deal with as administrator of E.P.A." He then read a sentence from the NASA report which echoed the warning that Dr. Rowland had been issuing for more than a decade: "Given what we know about the ozone and trace-gas-chemistry climate problems, we should recognize that we are conducting one giant experiment on a global scale by increasing the concentration of trace gases in the atmosphere without knowing the environmental consequences."

As might be expected, Thomas's opening remarks to the E.P.A. workshop sent a chill along the spine of the chlorofluorocarbon industry and its lobbying group, the Alliance for Responsible CFC Policy. Industry anguish was readily apparent at a luncheon on the following day, when the workshop participants were addressed by Richard Barnett, the chairman of the Alliance. Barnett told his audience that the E.P.A.'s emphasis on further research and international coöperation should be perceived as "good news," but that the "seemingly good news may be an illusion," because the title of the agency's new program, Stratospheric Ozone Protection Plan, was apparently being used in some quarters as a synonym or code word for further chlorofluorocarbon regulation. "To say the least, we are troubled by the current strategy of the E.P.A. to hold a series of international and domestic conferences intended to build a consensus around the nature and severity of the [chlorofluorocarbon] problem and the major options for remedy," Barnett declared. "We should remain focussed on the stratospheric-ozone-protection problem." After complaining that chlorofluorocarbons were being singled out unfairly for scrutiny, he cited the NASA report, which stated that the chemical effects of trace gases such as carbon dioxide, carbon monoxide, nitrous oxide, methane, and chlorofluorocarbons on atmospheric ozone were "strongly coupled and should not be considered in isolation." He dismissed the suggestion that the depletion of ozone over Antarctica indicated that the "theorized depletion" of ozone by chlorofluorocarbons might already be taking place, declaring that atmospheric-model calculations "continue to suggest that no significant change in total ozone will occur through the next several decades," and that "although the observed reductions in the ozone over the Antarctic region are real, the ozone levels return to near normal soon after the October springtime begins, and no plausible mechanism has been proposed to explain this phenomenon." The many uncertainties regarding the effects of man's activity upon ozone could be resolved only through vigorous research programs, Barnett said, and science could not today provide definite conclusions to justify a specific regulatory policy. He warned that the economy of the nation would be severely penalized if chlorofluorocarbons could not be used in foam insulation, air-conditioning, and refrigeration, and that there could be "substantial risks to worker safety by converting to substances that may be of greater toxicity or possess less desirable properties."

Barnett's arguments were supported by Igor Sobolev, a scientist with Kaiser Aluminum—a major producer of chlorofluorocarbons—who suggested that up to ten years of further research would be needed to clear up the uncertainties in stratospheric chemistry; and by a number of papers submitted by various scientists whose work was being financed by the Alliance for Responsible CFC Policy, including one that listed the fast-freezing of French-style green beans as one of the important contributions of chlorofluorocarbons to the current quality of life. Less helpful—indeed, downright disconcerting to some of the atmospheric scientists who attended the meeting—was an admission by Donald Strobach, of du Pont, that the company had given up looking for chlorofluorocarbon alternatives some five years earlier. Moreover, it would soon come to light that du Pont was in the process of expanding its chlorofluorocarbon production in Japan, and was introducing it into China.

WHEN I telephoned Rowland, who had been at the meeting, to get his reaction to what had been said there, he sounded—as well he might—like a man who had heard it all before. "A lot of discussion was devoted to estimating chlorofluorocarbon production over the next ninety years," he said wearily. "There happens, however, to be the enormous reality of a vast hole that is opening up in the Antarctic ozone layer each October—an event that went totally unpredicted by the atmospheric models we have been depending on. Even though this hole is replenished in November, the fact that total Antarctic ozone levels are down some ten per cent from twenty years ago can scarcely be described as near-normal, and is certainly no excuse for inaction. I believe that the hole we are seeing in the Antarctic ozone layer is going to continue to grow deeper and deeper with each succeeding October, and that serious ozone losses are likely to occur in the stratosphere at *all* latitudes of the world during the twenty-first century. It is pointless to waste time estimating what the production of chlorofluorocarbons will be in the year 2050, because the environmental consequences of their use will have long since overtaken us. In short, the atmospheric experiment whose end cannot be predicted is well under way and the hole in the ozone layer above Antarctica is, unfortunately, just the beginning."

—PAUL BRODEUR