

balloons! That is equivalent to nearly 200 balloons for every human on the planet. These balloons, moreover, would not be permanent. If carefully designed, they might, on average, last 1 year in the upper atmosphere. In other words, 1 trillion balloons must be launched every year. If everyone alive launched one balloon each morning (like taking a vitamin pill), the reflective shield could be maintained.

The problems with such a plan are overwhelming to say the least. What would the sky look like with a trillion balloons floating around? Occasionally the balloons would cluster together over a region, accidentally creating a solar eclipse. The surfaces of the balloons would strongly affect gases, like ozone, in the stratosphere. It is likely that there would be major chemical perturbations. Spent balloons falling from the sky at a rate of several billion per day would foul the countryside, waterways, and the oceans. If longer-lived miniblimps could be designed—to last 10 years, say—they would tend to collect at high latitudes, forming massive superballoon clusters that would black out these regions all year around. Putting motors on the balloons to push them around would create other problems.

OK, instead of balloons, a cheaper and faster scheme has been proposed: the “boogie board” solution. Styrofoam is a white, reflective material that floats on water. The oceans have a naturally low albedo, less than 0.1. By floating styrofoam on the oceans, the planetary albedo could be increased to 0.5 or more. It is logical to ask how much of the ocean must be covered by styrofoam to achieve climate protection. The required reflective area is similar to, but larger than, the area that must be shaded by balloons—equivalent to a small percentage of the cross-sectional area of the Earth. The oceans cover only about two-thirds of the surface area of the planet, and clouds normally blanket half of the ocean area at any time. Accordingly, the fractional area of the oceans that must be covered by styrofoam would need to be about three times as large, or close to 10 percent.<sup>10</sup>

10. Clouds having a relatively high albedo always cover about 50 percent of the Earth. Styrofoam lying under these clouds would not be effective in increasing the albedo. Accordingly, twice the ocean area must be covered. An additional increase by a factor of 1.5 would be needed because the oceans account for only two-thirds of the Earth's surface (1.5 is the inverse of 2/3). A simple multiplication of the two factors shows that about 10 percent of the ocean surface would need to be paved with styrofoam.

Think of the oceans awash in styrofoam. Life in the seas would be devastated. Alternatively, styrofoam continents (something like two Antarcticas) could be constructed and moored in the major oceans. The continents could serve a number of useful purposes, such as providing space for resorts along a vast coastline. Guests could be entertained by fireworks shot by naval guns to fill the stratosphere with dust. One vision of the engineered world of the future is depicted in Figure 14.10.

### 14.3.3 FIXING THE OZONE SHIELD

The role of chlorofluorocarbons (CFCs) in reducing stratospheric ozone was outlined earlier (Section 14.2.3). CFCs already contaminate the environment, and the CFCs already released will linger well into the twenty-first century. The Antarctic ozone “hole” and serious worldwide ozone depletion are among the identified consequences. Although the Montreal Protocol (Section 13.8.1) has been adopted, which proposes to eliminate CFC production before the turn of the century, it will be decades beyond that time before the ozone layer recovers significantly. What if we cannot wait that long? Suppose that ozone becomes even more depleted, as now appears to be happening in the Northern Hemisphere? What technological alternatives should society have at its disposal to preserve the ozone layer? Are there any corrective schemes that make sense? If one were found, would industry then argue that CFCs could be safely manufactured again?

Ideas for saving global ozone have surfaced as the ozone crisis has deepened. Next we look at a few of these schemes.

#### *Lasers Against CFCs*

The problem with CFCs is their long lifetime in the lower atmosphere. There are no known significant sinks for CFCs in the troposphere. Photodecomposition in the stratosphere determines the loss of chlorofluorocarbons. All the CFCs that are released must eventually be processed and destroyed in the stratosphere, which suggests a rather obvious solution: Introduce a new sink for CFCs in the lower atmosphere. This simple idea has led to a number of proposals.

One of the most thoughtful ideas is to use laser beams to break down CFC molecules. The action

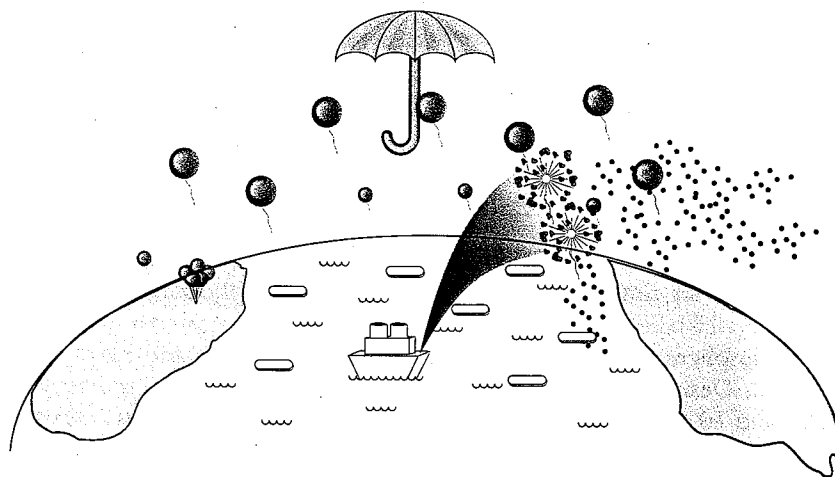


Figure 14.10 The world as it might look with active global environmental engineering to control the climate. The temperature correction schemes include lofting artillery shells filled with dust into the stratosphere from naval vessels, releasing a trillion large balloons into the upper atmosphere, and floating styrofoam on the world's oceans. All these schemes would seek to enhance the planetary albedo, thereby reducing the solar forcing of the climate. An alternative concept, whimsically illustrated in the form of a large umbrella, would place large sunshades in space to decrease the sun's illumination. The engineering scale and cost of these proposals would be astronomical.

would be much like that occurring in the stratosphere, where energetic ultraviolet solar radiation does the job. Unfortunately, ultraviolet radiation does not travel very far in the lower atmosphere, limiting the lasers' effective range. Moreover, radiation that is capable of destroying CFCs would also attack a wide range of substances. Heavy artificial doses of UV in the troposphere could create all sorts of strange chemical side effects, including a choking global smog. What is needed is a magic bullet that destroys only a particular CFC molecule and nothing else. That bullet would be a photon of radiation specially tuned to each CFC. Such a selective bullet does not exist, however.

A clever scientist has come up with an answer: Use more than one bullet, or photon, in rapid sequence. The photons would excite a CFC molecule by a series of steps to an energetic state that readily dissociated. Think about climbing a ladder to reach the top of a building from the ground. If the ladder had only one rung at the top, you might have difficulty getting there in one step. It would be much easier to move up the ladder in small steps, rung by rung. You might also envision spacing the rungs in a particular way that you could negotiate but that a child, say, could not. As an analogue, you might imagine raising a molecule level by level from its lowest "ground" state of energy to a higher energy state from which it could fly apart, or photodissociate (Section 3.3.3). The molecule, in

this case, would be moved rung-by-rung from the ground to the top floor. This could be done in stages using a series of "small" photons each of low energy. Every compound would have a specific pattern (actually, a number of definite patterns) of photons that could take it to the top. The rungs of the ladder would be spaced differently for each compound, however. A sequence of photons that could dissociate one compound generally could not dissociate another. A highly selective mechanism for photodecomposition therefore would be available: **multiphoton dissociation**.

Multiphoton dissociation does not occur in daylight because the intensity of sunlight at each wavelength (or energy) is too low. A laser is capable of producing an extremely high intensity of light at one specific wavelength.<sup>11</sup> For the greatest effect, the laser beam would be pulsed, with the light emitted in short bursts lasting a millionth of a second or less.

11. Electromagnetic radiation having a single well-defined wavelength is referred to as **monochromatic** radiation. In nature, radiation from matter typically has a characteristic spectrum, or distribution, of wavelengths. The narrower the spectrum is, the closer the radiation will be to being monochromatic. When the amount of energy carried by a beam of radiation is fixed, the intensity of the radiation at any wavelength is inversely proportional to the width of the spectrum. Monochromatic radiation has a narrow spectrum and a high intensity at the central wavelength. A laser generates radiation with an extremely narrow spectral range by stimulating the emission of a single specific spectral line of a material.

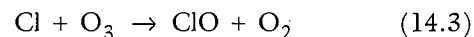
Such a laser beam shining on a parcel of air could produce conditions ideal for multiphoton dissociation. The laser must be tuned to the proper wavelength to select the molecule of interest.

For this scheme to work, the entire atmosphere must be processed by laser beams over a time span that is short compared with the current atmospheric lifetime of CFCs. A period of 10 years is commonly assumed, although a shorter time span would be preferable. In that time, all 5 billion cubic kilometers of air in the lower atmosphere must be blasted with intense laser radiation. Designs have been worked out. Between 1000 and 10,000 sophisticated lasers would be required. The total energy requirements of several gigawatts (GW) to tens of gigawatts have been projected. So what's a few watts between friends? The lasers themselves do not actually exist. The costs of building such machines several meters in diameter to generate megawatt beams of radiation, with the specialized optics needed to deflect and guide the rays, would be high. Even at that, the proposed laser systems would barely keep up with the present emissions of CFCs. To reduce CFC concentrations to negligible amounts in a reasonable time, a project 10 times greater in scale would be called for.

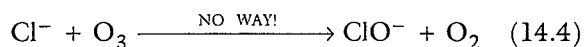
The idea of laser spotlights swinging through the skies all over the world forever is not particularly reassuring. The intensity of the beams would exceed that of sunlight by at least a factor of 1000. Birds flying through a beam would be fried. This solution for the CFC problem, which even makes a little sense technically, makes no sense in the global context.

### *Charging up the Stratosphere*

Another approach to saving ozone is to deactivate chlorine after it is released from CFCs in the stratosphere. This solution might allow CFC production to continue by compensating for its effects within the stratosphere itself. Figure 14.11 offers a plan to nullify the CFC's effect on ozone. The idea is based on the fact that chlorine atoms carrying a negative electrical charge do not react with ozone. Recall from Equation 13.12 that chlorine atoms participate in an important "catalytic" reaction cycle that destroys ozone (Sections 3.3.4, 13.2.2, and 13.5.2). If this reaction could be inhibited, ozone depletion by CFCs would be halted. Indeed, studies of the chemical processes show that whereas the neutral chlorine-ozone reaction occurs rapidly:



the equivalent "electrified" version of this reaction does not:



The challenge then is to charge up the chlorine.

Positive and negative electrical charges are relatively easy to separate. On a dry day, when you shuffle across a carpet and reach for the door, a painful electric spark may jump from your finger to the knob. Shoes rubbing against carpet fibers pick up extra negative charge (electrons) from the carpet fibers, leaving the fibers with an equal positive charge. The electrons travel through your body (which is an excellent conductor of electricity) and jump from your hand to the metal doorknob as you reach for it. From there, the electrons drift through the air to rejoin the positive charges.<sup>12</sup> A **Van de Graaff generator** acts on the same principle.<sup>13</sup> The Greeks discovered that amber (fossilized tree resin) becomes activated when rubbed and attracts bits of paper, styrofoam, feathers, or other similar objects. The Greek word for amber is *elektron*, and so the negative electrical particles later associated with this phenomenon were called *electrons*.

A Van de Graaff generator could be flown on an airplane. The positive charge it generated could be transferred to water droplets by bringing the drops into contact with an electrode. If the drops were

12. Opposite electrical charges attract each other, and like charges repel, according to Coulomb's law (Section 7.3.1). Electrical charge also likes to move to the outside surface of an object, particularly a good conductor. When a charged object is brought near a conductor, an "image" charge of opposite sign is produced in the conductor. This image charge creates a voltage that may be strong enough to cause a sudden discharge. A charged object exposed to air slowly leaks its charge into the air, forming currents of electrically charged molecules, or ions. The ions readily attach to dust particles, which slows them down considerably. In air, drifting ions represent a weak current that carries electrical charges back to their original source. By nature, positive and negative charges are always seeking routes to recombine. That is why most electrical devices, particularly those working at high voltages, must be carefully insulated.

13. Robert Jemison Van de Graaff (1901–1967) was an American physicist who invented the electrostatic "generator" named after him. He was influenced by Marie Curie's work and began studying atomic physics. He saw the need in experimental physics to generate high voltages to manipulate charged particles. His generators have produced up to 13 million volts simply by rubbing a fabric on hard rubber and collecting the charge on a sphere.

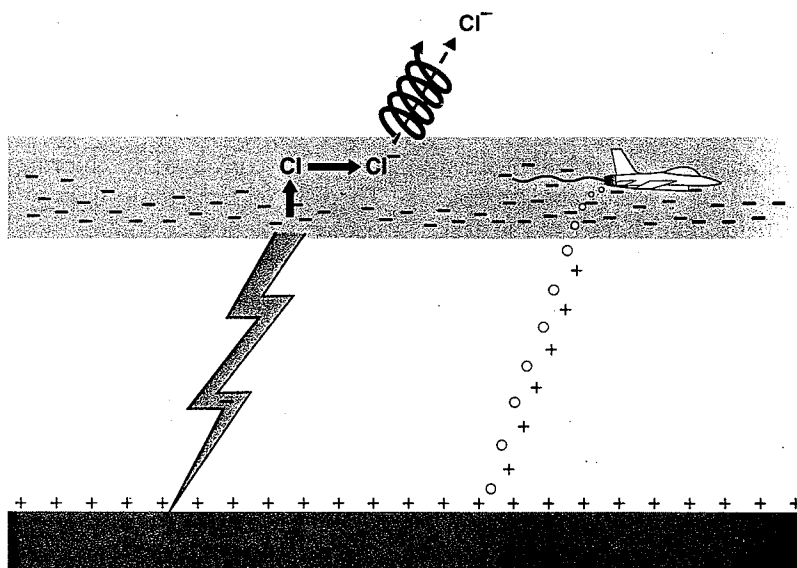


Figure 14.11 A plan to preserve the ozone layer against attack from chlorofluorocarbons, by attaching negative electrical charges to the chlorine released from CFCs, thus chemically deactivating the chlorine. A fleet of jumbo jets would fly through the stratosphere trailing wires that emitted a negative electrical charge into the air. Water carried by the aircraft would be released as artificial rain to carry unwanted positive charges to the lower atmosphere and surface. The charged chlorine atoms would then spiral up the fair-weather electric-field lines and be accelerated into space.

released from the bottom of the plane, the positive charge would be carried downward into the lower atmosphere. The negative charge would remain on the plane, however. As the negative charge accumulated, electric potentials would develop making it difficult for the drops to fall. The solution would be to trail a wire behind the plane. Electrons would flow into the wire and, because of the high potential developed by the accumulating charge, would easily leak into the air around the wire. This leakage of electrons is referred to as a **coronal discharge**. Such discharges, called **Saint Elmo's fire**, can be seen during a storm as glowing light emanating from pointed objects and wires or dancing from the tops of masts on ships. At high voltages, electrons escaping from a surface are accelerated and bang into the surrounding air molecules, exciting them to emit visible radiation.

Chlorine is a very **electronegative** element. It has nothing to do with attitude. Chlorine just likes to acquire and hold onto electrons. Free electrons can be soaked up by free chlorine atoms. The plan outlined in Figure 14.11 to deactivate chlorine might work. Right? Wrong. There are so many problems with this scheme that it would require an entire chapter of this book to explain all of them coherently. Instead, we will just sketch a number of the major objections.

1. Chlorine is not the most electronegative substance in the stratosphere. For example, nitrates and sulfates, which are more abundant, attract electrons more strongly than chlorine. The charging solution would not even have a chance to start up.
2. Less than 0.01 percent of all the chlorine in the stratosphere is in the form of chlorine atoms. The rest is in the form of HCl, ClO, and other compounds. As soon as the free chlorine atoms were charged up, they would immediately be replaced from other chlorine compounds by efficient photochemical processes that operate to maintain a balance among Cl, ClO, and HCl. Indeed, for the scheme to work, all the chlorine in the stratosphere would eventually need to be electrified. That prospect represents an extremely dangerous transformation among chlorine species, similar to the conditions that exist in the ozone hole (Section 13.7.3).
3. Water droplets can carry only a limited electrical charge before they literally explode from Coulomb repulsion. Assuming that the charge-carrying capacity of the drops is optimal and that only 0.01 percent of the chlorine must be electrified, about 10 billion tonnes of water would be necessary to separate the required electrical

charge.<sup>14</sup> Jumbo jets carrying 100 tonnes each would have to fly *100 million sorties* to lift that much water into the stratosphere.

4. The electrical charge separation created—with negative charge in the stratosphere and positive charge in the troposphere—would generate powerful electrostatic fields. The charges would drift in these fields and recombine. The entire system could be discharged within a day by means of atmospheric conduction. Accordingly, the water runs would have to continue unabated at the rate of 100 million trips per day essentially forever. These flights would destroy the ozone layer.
5. If the goal of charging up 0.01 percent of the chlorine were achieved—which, in any case, would have absolutely no ameliorating effect on ozone depletion—the voltage difference between the ground and the stratosphere would be so large that lightning bolts 10 miles long would fly through the atmosphere. Everyone's hair would be standing on end, and corona discharges would be dancing everywhere.

The end result of any attempt to conserve the ozone layer by charging chlorine using artificial rain would most likely be the total destruction of ozone and the end of the world as we know it. This idea for saving the ozone layer was put forward by an intelligent physicist—who apparently does not understand how the atmosphere works. Even respectable scientists make mistakes.

### *Filling the Ozone Hole*

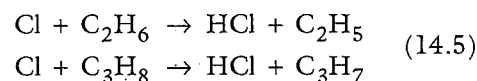
Measures have also been offered to prevent ozone depletion on regional scales. In particular, we describe next a concept to “heal” the ozone hole. (See Section 13.7 for background information concerning this phenomenon.) The basic motivation for intervention rests on the possibility that the ozone hole may become troublesome before the Montreal Protocol has a chance to significantly reduce atmospheric chlorofluorocarbon concentrations (Section 13.8.1). Figure 14.12 depicts the evolution over a year of the ozone hole and a few key parameters

14. The estimate assumes that the water drops are 1 millimeter in radius. This is a minimum size to ensure that the drops would fall into the troposphere before evaporating. Larger drops would be even better, but would carry less electric charge per ton of water.

associated with it. The main action comes in the austral spring, when sunlight returns to the high southern latitudes. Chlorine, which has been activated over the winter on polar stratospheric clouds, is quickly converted to chlorine monoxide (ClO). The ClO participates in destroying the ozone. The ozone depletion continues until ClO is redirected into the normal chlorine reservoirs, mainly hydrogen chloride (HCl).

The high ClO concentrations and deep ozone depletions are maintained by the stability of the southern winter polar vortex (Section 13.7.2). One thought is to destabilize the vortex, which would abruptly end the conditions favorable for ozone depletion. Alternatively, the ClO concentrations could be suppressed. Recall that the critical chlorine catalytic cycles driving ozone destruction entail the chlorine atoms reacting with ozone (Sections 13.5.2 and 13.7.3 and Equations 13.12 and 13.24). Chlorine monoxide is generated in the process. The chlorine-charging scheme discussed earlier proposed deactivating the chlorine atoms by adding an electrical charge. In the concept considered here, the Cl atom would react with light hydrocarbons such as ethane (C<sub>2</sub>H<sub>6</sub>) and propane (C<sub>3</sub>H<sub>8</sub>), converting chlorine to HCl. These common hydrocarbons react vigorously with chlorine and do not produce any unusual or long-lived by-products.

The reactions of interest are



The chemical products on the right-hand side of the reactions would interact further with chlorine. The details are not crucial. The net effect would be to convert Cl and ClO to HCl. Thus the chlorine species would be forced toward a normal partition (Figure 13.27).

In Figure 14.12, the plan would be to add the selected hydrocarbons to the polar vortex in late winter to inhibit the sudden increase in ClO at first light. These hydrocarbons, which are normally gaseous, would be spread across the vortex using aircraft (oops, we've heard a lot about problems with aircraft). The hydrocarbons are stable in polar darkness and would disperse throughout the vortex as winter progressed. When sunlight first appeared in spring to activate chlorine, the hydrocarbons would begin to do their work. The action is depicted in Figure 14.13.

The ozone hole-plugging scheme seems relatively straightforward. Light hydrocarbons like ethane and

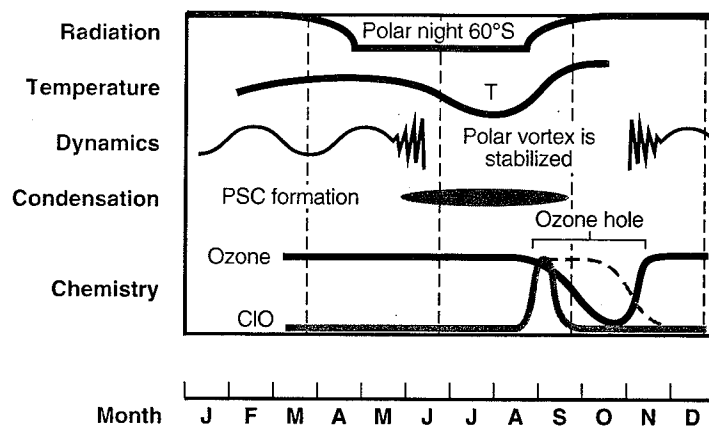


Figure 14.12 The conditions under which the ozone hole forms over Antarctica. The critical period for ozone depletion occurs during a short period of time in September and October. The ozone loss is associated with the high concentrations of the free chlorine radicals ( $\text{ClO}$ ) sustained by the persistent wintertime polar vortex. The idea is to add hydrocarbons to the polar vortex at this time, to quickly suppress the concentrations of  $\text{ClO}$  before catalytic chlorine reactions severely reduce ozone levels. (Information from R. Cicerone, S. Elliott, and R. Turco, *Science* 254 [1991]: 1191)

propane are available, cheap, and, aside from the danger of explosion, fairly easy to handle. Propane fuel is already in wide use in the form of liquefied petroleum gas (LPG). Calculations suggest that to prevent ozone depletion in austral spring, about 20,000 tonnes of liquefied propane or ethane would have to be lifted into the polar stratosphere. A small fleet of specially fitted aircraft could make the flights over a 3-week period; 10 planes might be enough. This seems a rather small price to pay to fill the ozone hole should it become a serious hazard. There is some doubt the plan would work, however.

The ozone hole is quite extensive. It covers an area as large as the Antarctic continent, and is more than 10 kilometers in vertical extent. No aircraft is presently capable of flying over the entire range of altitudes in the vortex where ozone is normally depleted. For the scheme to work, the hydrocarbons must be more or less uniformly distributed throughout this vast region. Here, nature is uncooperative. The atmospheric region of interest has relatively weak mixing. In the stable vortex, little turbulence is present (Section 5.2.1). It is uncertain, therefore, whether the hydrocarbon vapors would be spread uniformly enough to cure the ozone hole.

Under the unusual atmospheric conditions that characterize the southern winter polar vortex,  $\text{HCl}$  derived from active chlorine through the action of injected hydrocarbons would not be secure. In fact

if polar stratospheric clouds were present (Section 13.7.3), the  $\text{HCl}$  could be quickly recycled into active chlorine. In the process, the hydrocarbons would be consumed. Under some not unlikely circumstances, the addition of hydrocarbons might actually exacerbate the ozone-depletion problem. Polar stratospheric clouds have been observed to persist at high latitudes far into the spring, and these lingering clouds might cause the injected hydrocarbons to turn against the ozone. The result could be a prolonged, aggravated depletion of the ozone layer.

We should emphasize that the decomposed polar ozone represents only a small percentage of the global ozone layer. Filling the ozone hole is really global environmental engineering on a minor scale compared with some of the other ideas discussed in this chapter. Nevertheless, all the elements of surprise, uncertainty, and awesome scale can be found there.

#### *Zeolites, Bacteria, and Other Exotica*

Many of the ideas concerning remediation of the ozone layer are simply crackpot. Others, although physically reasonable, are unfeasible because of the global scale or high cost. A few ideas may be reasonable and feasible, but carry too much uncertainty. Is there a winner of a thought, a gem of an idea, lurking

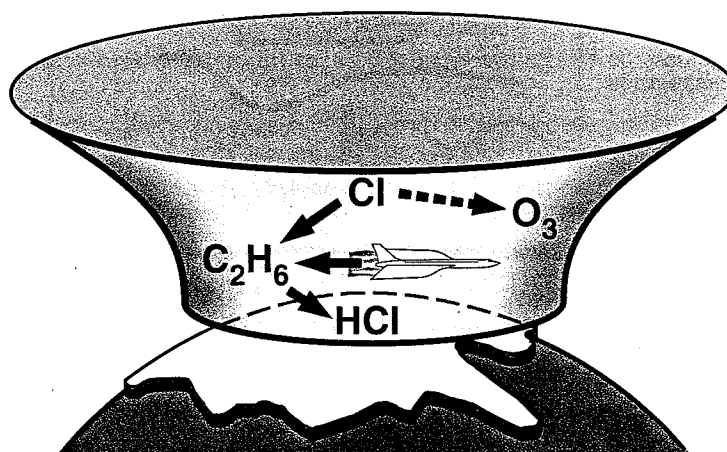


Figure 14.13 A scheme to plug the Antarctic ozone hole by releasing light hydrocarbons (in this case, ethane [ $C_2H_6$ ]) from high-flying airplanes. The hydrocarbon would react with ozone-active chlorine atoms to form HCl, which does not react directly with ozone. The hydrocarbons would eventually be oxidized into carbon dioxide and water, in amounts too small to disturb the global stratosphere.

out there? One cannot eliminate the possibility of a foolproof scheme to stop the loss of ozone while allowing the production of chlorofluorocarbons. It is a long shot. But given the enormous stakes, an army of researchers are thinking hard (some, unfortunately, not hard enough). It is inevitable that a variety of ideas have surfaced, and a few of these are mentioned here.

Think of a zeolite as a microscopic sponge. It is a material having many nooks and crannies that can absorb chemicals from water or gases from air. When a zeolite is exposed to water, for example, it can filter out undesirable chemicals. When it is exposed to air, pollutants can be absorbed inside its labyrinthine structure. Natural zeolites consist mainly of silicate minerals, often of volcanic origin. Pumice is a fine, vesiculated, glassy substance with a huge effective surface area. Special zeolites can also be engineered to attract and hold specific compounds, or families of compounds. Zeolites are used in petroleum refining, in which certain hydrocarbons are absorbed and separated; in the dehydration of gases, in which water is scavenged; and in water softening, in which minerals are adsorbed.

It does not take a great stretch of imagination to try to manufacture a new zeolite that can absorb chlorofluorocarbons. The zeolite could be ground into fine particles and sprinkled into the atmosphere. After scavenging CFCs, the zeolites would settle to the ground, carrying the CFCs with them. The CFCs would remain harmlessly trapped in the zeolite honeycomb.

Such a zeolite does not exist, however. Whether it is possible to design and mass-produce a zeolite that preferentially absorbs chlorofluorocarbons remains to be demonstrated. At a minimum, 10 million to 100 million tonnes of the stuff would need to be spread over the Earth to soak up the chlorofluorocarbons already mucking up the atmosphere. The long-term stability of the zeolites would be a serious issue. If the zeolite particles heated up or decomposed, the CFCs would be released. However, because we don't have an actual zeolite material that targets CFCs to experiment with, this nifty idea must be filed away for future reference.

A biological researcher recently performed an interesting experiment. He scooped mud from the bottom of a pond, and in the laboratory, he bubbled CFCs through the mud. Lo and behold, a smaller amount of CFCs escaped in the bubbles than he had pumped in. Microbes living in the mud were apparently eating the CFCs. Or were they? The researcher took another sample of mud and heated it to kill all the microbes. Bubbling CFCs through the sterilized mud produced a smaller loss. The difference could be attributed to microorganisms consuming the chlorofluorocarbons.

Because CFCs are not natural compounds, living organisms have not evolved in their presence and so have not learned how to use CFCs for food (Section 12.3.3). On the other hand, compounds with similar molecular structures, like methane and methyl chloride, are widely used by living organisms. Moreover, bacteria are known to evolve rapidly when exposed

to novel environmental conditions. Perhaps, living at the bottom of lakes and ponds are organisms waiting to feast on CFCs. As the concentrations of CFCs in the environment—in air, water, and land—continue to increase, microorganisms may appear that can metabolize these inert gases. Better yet, microbes that like CFCs could be genetically engineered and released into the environment. Selective breeding and genetic engineering have resulted in microorganisms that can eat oil spills and toxic wastes. Why not CFCs?

Other possible explanations for the experimental observations were noted earlier. For example, chlorofluorocarbons may have been absorbed on the fine clay particles that compose pond mud. Heating may have altered the properties of the mud and slowed the uptake of CFCs. Bacteria may have had nothing to do with the missing CFCs. Clearly, more work is needed to isolate the actual effects of microorganisms on chlorofluorocarbons and related compounds.

Plans to carry ozone manufactured at the ground into the stratosphere have been proposed. Ozone, condensed for shipment, might explode, however. Another project would pump into the stratosphere smoggy air, containing high concentrations of ozone, from polluted cities. Two serious problems might be solved at once. But the means for pumping smog 15 miles high is left unresolved, and the impact of the filthy smog on the pristine stratosphere is not mentioned. And so it goes. One after another, ideas surface, are poked at, and sink. So many wild ideas, so little time!

#### 14.4 A Rational Approach to Environmental Management

The application of technology to solve environmental problems is often accompanied by problems, especially when human intervention must extend over global distances and span decades and centuries. Some of the examples we cited reflect a lack of basic understanding about, and sensitivity to, the natural environment. Ideas to deep-six CO<sub>2</sub>, grow and bury millions of trees, inject chemicals into the stratosphere, and build huge parasols in space all seem a bit ludicrous. It is apparent that caution must be exercised by those empowered to make decisions regarding environmental intervention, serious mistakes leading to a significantly reduced quality of life in the future.

#### *Science and Nonsense*

All right. The environment is threatened; indeed, it is slowly declining before our eyes. What can be done to prevent a disaster? Consider the following observation about human nature, made seven decades ago, that in a way frames the current debate over the environment: "The optimist proclaims that we live in the best of all possible worlds; and the pessimist fears this is true."

Some people feel that we should do nothing and let events take their course. A few idiots argue that *laissez-faire* has never led to a global disaster. Put aside child labor and sweat shops, urban blight, and Third World poverty. With regard to the environment, simply careening downhill toward a brick wall hoping for a soft landing is no solution. Neither can we "go back to the caves," as some refer to ecological retrenchment. There are not enough caves to go around anymore.

A cadre of clever pseudotechnicians and political hacks have appeared denying that global environmental problems exist in the first place. They find numerous flaws in the generic "disaster" theories of environmental degradation. Thus we hear about the "hole" in the ozone theory or the "cooling down" of the greenhouse-warming effect. These polemicists are outside science. Rather, they exploit the scientific method itself, which at its best doggedly questions accepted ideas and seeks tests of existing hypotheses. By emphasizing the small differences of opinion that often arise among competing researchers and highlighting irrelevant observations that seem to conflict with scientific consensus, the polemicists piece together a phony case. Their nonscientific approach is worse than nonsensical; it is dishonest.

Who are these people? They range from practicing scientists acting as "the loyal opposition," to extremists on the political right and left, and religious zealots. Unfortunately, some of the loyal opposition rarely submit their scientific "results" for peer review; they would rather publish authoritative editorials in newspapers. An example at the more extreme end of the spectrum is Lyndon LaRouche, an occasional political wanna-be who advocates "Star Wars" and universal fusion power and supports aggressive actions to sell these ideas. A more typical conservative society, organized under the name of the author Ayn Rand, believes that most environmental concerns are unfounded.<sup>15</sup> Society members

15. Ayn Rand (1905–1982), a Russian émigré to the United States, was a writer who believed in *laissez-faire* capitalism and the full freedom of individual persons. Her major novels, *The*



offer evidence to "prove" that CFCs do not deplete ozone and that the greenhouse-warming effect is a deception. Hundreds of similar organizations generate pamphlets and posters and are willing to comment on scientific issues at the drop of a hat. Most of the information dispensed by these groups is distorted or plain wrong. In a related phenomenon, countless public-information groups have surfaced carrying names invoking environmental concern that are organs for special-interest groups that wish to exploit the environment. Examples are the Desert Conservation Institute, sponsored by the mining industry; the Information Council of the Environment, run by coal and utility interests; the National Wetlands Coalition, which seeks to open wetlands to development; the Environmental Conservation Organization, supported by land improvement contractors; and the Wilderness Impact Research Foundation, which seeks to "...educate the public about the damage that wilderness causes to society, the economy, and even wildlife."<sup>16</sup> Again, beware the wolf in sheep's clothing!

Many people exposed to media hype have come to believe that technology will always be available to solve environmental problems. Technology has been known to perform miracles. Behold the atomic bomb. Behold television! During the late 1950s, Walter Cronkite hosted a television show called *The Twentieth Century*. Each week new technological wonders expected to be common in the next few decades were unveiled: limitless nuclear energy, nonpolluting cars magnetically levitated and automatically piloted on tracks, cures for cancer. Few of the wonders promised for this century have actually materialized; instead, the technologies have turned against us. Nuclear energy generates a nightmare of radioactive waste. Automobiles foul the air in cities around the world. Chemicals meant for better living fuel an epidemic of cancer. Television itself devolves into an inane medium of mass marketing.

The examples in this chapter demonstrate that concepts to tinker with the environment are relatively easy to dream up. Their implementation is more difficult, however, usually involving dumb-

foundingly expensive construction projects. Worst of all, dangerous and unforeseen side effects abound. Many of the people who are devising and advocating technological cures are amateur geophysicists. We hear, for example, ideas for preserving the ozone layer from well-meaning engineers and physicists who do not understand how the ozone layer works (unlike the readers of this book). Under cursory inspection, a seemingly creative idea becomes a harebrained scheme. No person or organization has the breadth of expertise required to decipher the full complexity of the natural world, with its interacting biological, physical, and chemical systems. A consortium of experts is needed. Even then, important linkages may be overlooked, and side effects may be ignored. What can be done to ensure that profound, perhaps irreversible, damage is not incurred when dealing with environmental problems and that an enormous sum of money is not wasted chasing phantom technological solutions? How can environmental degradation be limited or reversed?

#### *Behavior and Ethics*

If the world as a whole is to prosper and remain livable, then persons, industries, and nations must develop higher standards of behavior and ethics in dealing with the environment. People must be willing to make sacrifices over the short term to build an environmentally sound infrastructure for the long haul. The environment is not just a fad for today. It is the foundation supporting long-term human survival. Business and industry must develop an agenda for environmental action. The leaders of commerce must *believe* that the environment is worth saving. Faking concern over the environment as a public-relations ploy is unethical and dangerous in these times. Nations must abandon selfish imperatives and join a global effort to preserve key elements of the environment. World civilization must be brought into closer harmony with the natural world. Formulating more equitable distributions of resources worldwide, sharing nonpolluting "clean" technologies with less-developed countries, and negotiating international environmental treaties are important steps.

If this all sounds like "one-world" gibberish, think again. The environment is no longer a matter of concern only for vegetarians and flower children. The global habitat is on the minds of presidents and vice presidents, scientists, baby boomers, beefeaters,

*Fountainhead* and *Atlas Shrugged*, express the conflict of individualism with collectivism and conformism in terms of her philosophy of objectivism, which asserts that "moral" precepts are objectively valid.

16. Information on these societies originally appeared in 19913 in *The Observer*, a publication of the Audubon Society of Whittier, California, in 1993.

and Middle America. It has become a matter of survival—very likely the survival of generations not yet conceived. Every day, we face personal choices in behavior and life-style that will shape the future. It is easy to point an accusing finger at business and its leadership when assessing damage to the environment. Surely, greed is the engine for environmental destruction. Yet it is the public that benefits from, and enjoys the products of, business. Thoughtless consumption encourages industrial activities that pollute. Vocal disapproval of such activities and boycotts of pollution-generating products would stem the tide of environmental destruction. Each of us may realize that that is the right personal choice, but we may be too busy right now to participate. Perhaps the costs appear too dear to pay. More to the point, people like us have little power or influence on the course of events. Nonsense, nonsense, nonsense!

Education is the key to saving the environment. High schools and colleges should be places where students learn how the environment works. Everyone should gain a basic understanding of the natural world, which ultimately feeds and nurtures our species. Each of us should be aware of the need for a healthy environment. Sensitivity to environmental deprivation should be taught universally. Information is a powerful stimulant. Environmental activism should become a normal part of our lives. An appreciation of the benefits of a clean, healthy environment would make the cost of conservation palatable. Every person would have a role in nurturing that lovable global organism called the biosphere.

Individual citizens can have a positive influence on the state of the environment if they express themselves and are heard. But unless leaders of countries and corporations believe that the environment is a cause worth championing, it will be difficult to halt the downward slide of the quality of life worldwide. The more desperate the situation becomes, the more attractive technological fixes will become. Leaders who understand the environment are less likely to be misled by seemingly attractive proposals by technologists. It is reasonable to expect the world's leaders to become familiar with the technical issues concerning the environment at a level comparable with the descriptions in this book. It would be irresponsible to expect from leadership any less vigilance today with regard to the environment than was expected in the recent past with regard to nuclear weapons and their potentially devastating effects on civilization.

### *Treaties and Laws*

The Montreal Protocol controlling the production of chlorofluorocarbons to save the global ozone shield is an astounding milestone in international environmental law (Section 13.8.1). For the first time in history, the Earth's collective population has recognized a serious threat to the global environment and has acted to fix it. The solution that was finally adopted is *not* a technological cover-up. The source of the ozone depletion problem—chlorofluorocarbons—is being eliminated. This mandates large and permanent changes in a major global industry under unprecedented international oversight and regulation. Personal life-styles will be changed by the treaty (which will affect the costs for refrigeration, air conditioning, dry cleaning, and so on [Sections 12.3.3 and 13.5.2]). Luckily, in this instance, the changes are likely to be relatively painless. The offending industry is small. New, ozone-safe compounds are available to replace the older ozone-depleting chlorofluorocarbons. Nevertheless, over the next decade, the transition to a CFC-free world under the treaty's guidelines will require sacrifices, ingenuity, and huge investments of capital. Despite the costs and inconvenience, world leadership is in essential agreement with the decision to proceed.

Imagine the complexity of the treaty that will be drafted to control the emissions of greenhouse gases, including carbon dioxide. To forge such an agreement, all the creativity and ingenuity of the human species will be required. More important, a consensus of leadership is necessary. Such a consensus must be built on sound science. The geophysical, biological, and chemical basis of global climate change has been under intense development for several decades and is documented in a mountain of technical reports and assessments. Polemicists lingering at the margin of science hoot at this work, calling it biased and selective. They seek, and often attract, the attention of policymakers. Technological "fixers" feed at the outskirts, promising answers for money. An army of lobbyists representing myriad special-interest groups argue against forceful actions. As in any legal proceedings, "experts" on both sides of each issue are paraded before the world court. The media often seek sensationalism rather than balance in pitting the arguments of fringe elements against the conclusions reached by the central body of science.

Laws are imposed on all aspects of life to control a broad range of unacceptable activities and behaviors. The environment must be protected by laws, just as other facets of our lives are, and for the same reasons. To be effective, laws must be fair and equitable. They also must be enforced. The Montreal Protocol is fair and equitable, but it remains to be seen how well it can be enforced. A treaty to control greenhouse gases is still in the formative stages, yet the battle to win the hearts and minds of world leaders is well under way.

### *Technology for the People*

Technology and its underlying science and engineering should be applied to provide life-enhancing experiences while preserving or improving the quality of life. Too many technologies that have been established by industry and government are dirty and dangerous. The world badly needs clean, safe technologies, which are exactly what a new breed of engineers and scientists, sensitive to the fragility of the environment, are seeking: nonpolluting energy sources, renewable fuels, safe waste disposal, toxin-free foods, pristine air, drinkable water, fumeless transportation. Rather than just the "cheapest" and "easiest," another adjective has been added to the design lexicon, the "cleanest." Technology is being designed with the environment in mind from the outset, not merely as an afterthought; technology that is sensitive to the ecology of the land and water; ultimately, technology for people.

In applying clean technology for the purpose of conservation, we are practicing preventive medicine. Pollution of the body over time—say, through exposure to tobacco smoke—leads to health problems such as lung cancer. Pollution of the environment during this century has created serious life-threatening problems for people and for countless other living organisms as well. Clean technology can help eliminate these problems in the future. Imagine a gas leak in your home. You can throw open the windows to let the gas out. You might even live with the windows open for a while without fixing the leak. Of course, you would get wet when it rained and cold during the winter. Better yet, why not fix the leak and close the windows? Stop the pollution at the source. That is the philosophy of clean technology. But unfortunately, it is not usually the philosophy of environmental engineering.

In referring to the possibilities for engineering the environment of Earth and the other planets, Carl Sagan and his colleague James Pollack; pointed out that

... a short-term imperative for planetary engineering exists for only one world in the solar system, our own. Careless or reckless applications of human technological genius have put the global environment at risk in several different ways. The Earth is not a disposable planet ... The first step in engineering the solar system is to guarantee the habitability of the Earth.

—J. Pollack and C. Sagan, "Planetary Engineering," in *Near Earth Resources*, University of Arizona Press, 1993.

From what has been said in this chapter, I hope it is evident that the application of technological schemes to fix environmental problems is generally a mistake. Nonetheless, the use of technology as a tool in environmental remediation must not be abandoned. In some cases, the environmental risks associated with the small-scale application of a particular technology are well understood. In such cases, small-scale tests could be performed to determine potential safe uses of the technology. Nevertheless, in almost every instance of environmental pollution discussed in this book, the first and most logical approach to remediation is to identify and eliminate the *source* of the pollution. Technology applied to mask or correct undesirable environmental conditions while leaving the cause undiminished should be second, third, fourth—or last—on the list of remedial options.

### **Questions**

1. Discuss the difference between a "positive-feedback loop" and a "negative-feedback loop." The brake pedal and accelerator pedal in a car are designed to be worked alternately, using the same foot. Would you consider this design to have positive or negative feedback? Some people drive with one foot on the brake pedal and the other foot on the gas pedal. Why could this be dangerous?
2. Summarize the physical and biological foundations for the concept of reducing atmospheric carbon dioxide by fertilizing the oceans with iron. What other schemes involving living organisms could you dream up to bury carbon in the deep oceans (consider the fact that many

marine organisms construct hard shells or skeletons composed of calcium carbonate)? How might you imagine using genetic engineering of marine organisms to enhance the ocean's carbon biological pump?

3. In the ocean iron-fertilization scheme, phytoplankton are fed extra nutrients to accelerate the absorption of carbon dioxide in the oceans. Suppose that the same planktonic species emitted dimethyl sulfide (DMS) as they grew. What would be the overall effect on global climate of ocean fertilization under these circumstances (describe the relevant processes and effects in a general way)? Would the DMS emission cause a positive or a negative feedback on the global temperature change associated with carbon burial?
4. Discuss three schemes to cool the Earth's climate using the *albedo effect*. In your answer, describe the material that will be used, the manner in which the albedo will be affected, and the possible side effects of the proposed activities. Also outline the possible quantitative aspects of the projects, in terms of the needed amounts of materials, the necessary infrastructure to carry out the work, and the relevant size and time scales.
5. Discuss two geotechnological-engineering concepts that have been proposed to prevent chlorofluorocarbons from damaging the stratospheric ozone layer. Explain why these schemes might be impractical. If someone had suggested replacing all the chlorinated fluorocarbons (CFCs and HCFCs) with chlorine-free compounds that contain bromine in place of chlorine, would you be relieved of your anxiety about ozone depletion? Explain.
6. Someone has bubbled chlorofluorocarbon vapors through mud collected at the bottom of a lake and found that the concentrations of CFCs were reduced. Assuming that a particular kind of bacteria in the mud have consumed and destroyed the CFCs, how might this discovery be used in a geoengineering project to save the ozone layer? Discuss in a general style how you would use these bacteria. What problems might you encounter in making this scheme operational? Consider issues related to the biological aspects of this idea and the requirements to reduce CFCs on a global scale.

## Problems

1. Someone has proposed that we transport ozone into the stratosphere on jumbo jets to fill in any holes that are found. The process would be like filling potholes in a street. According to current estimates, perhaps 5 percent of the total normal amount of stratospheric ozone would need to be replaced every month. Calculate how many jumbo jet flights, each carrying 100 tonnes of stabilized liquid ozone, it would take each day to keep the ozone layer full in this case. Is this a practical solution?
2. You have decided to use sand particles to reflect sunlight from the top of Venus's atmosphere in the hopes of cooling its climate to a habitable level. Someone has calculated that you will need a layer of particles with an optical depth of 2 at visible wavelengths. She has also calculated that if the sand grains have a radius of 0.5 micrometer, you will have to build an aerosol layer with a mass loading of 1 gram for every square meter of (planetary) surface to obtain that optical depth. The results will vary with the size of the particles. The optical depth,  $\tau$ , of the layer is proportional to the mass loading,  $M$ , divided by the particle radius ( $\tau \propto M/r$ ). (a) If the surface area of Venus is 400 million square kilometers, how many metric tons of 0.5-micrometer particles will be required to create a global aerosol layer of the proper optical depth? (b) If you can only make dust grains that are 1 micrometer in radius, how many tonnes of these would be needed to achieve the same optical depth? (c) You can use the space shuttle to transport the particles from Earth to Venus. Each shuttle flight will carry 100 tonnes of dust. How many flights will be needed to construct the aerosol layer in (a)? (d) If each shuttle round-trip to Venus takes an average of 6 months to complete, and the dust layer needs to be replaced once a year, how many shuttle vehicles will have to be flying at any given time?

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