



Landmark Lesson Plan:

Chlorofluorocarbons and Ozone Depletion

Grades: 9-12

Subject areas: Atmospheric chemistry, chemical reactions, and history.

Based on the [Chlorofluorocarbons and Ozone Depletion](#) National Historic Chemical Landmark

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The following inquiry-based student activities are designed for use in high school lesson planning. The handout, activities, and videos will help students understand the timeline and reasons for the initial development and use of chlorofluorocarbons as refrigerants, but also their eventual banning due to their damaging effect on stratospheric ozone. Students will also explore the chemical reactions related to this damage and the challenges faced by atmospheric researchers.

The activities are designed as a ready-to-go lesson, easily implemented by a teacher or his/her substitute to supplement a unit of study. In atmospheric chemistry, the activities relate to the different regions of the atmosphere and the different roles that the same chemical can play depending on its location, and the work of atmospheric chemistry researchers to educate others about the harmful effects of chlorofluorocarbons (CFCs). In chemical reactions, the activities relate to CFCs and stratospheric ozone. In history, the activities highlight the process of change connected with the use of refrigerants throughout history. An additional science-related concept is the perception of chemicals as positive or negative.

All resources are available online at www.acs.org/LandmarkLessonPlans.

While these activities are thematically linked, each is designed to stand alone as an accompaniment for the handout. Teachers may choose activities based on curricular needs and time considerations.

- Take a few minutes to introduce the lesson with a few conversation starters. When have students used a refrigerant today? Have they used a refrigerator to keep their food chilled and to help prevent it from spoiling? If there is currently hot weather, have they used an air conditioner in their home or car? How does chemistry help to keep us cool? Ask students for their perceptions of the terms CFCs and ozone. Are they positive or negative? What background do they have in connection with the two?
- Show the ACS *Speaking of Chemistry* video "[Keeping Cool Without Killing the Planet](#)" (3 min., 19 sec.). The video gives an overview of the use of refrigerants, from the toxic, flammable compounds used in the 1920s, to the non-toxic, nonflammable CFCs developed in the 1930s to replace them. The video points out that while new compounds solved some of the old problems, they brought new problems, such as ozone depletion. It also extends this point to more recently developed refrigerants.
- Follow up with the ACS *Reactions* video "[How Air Conditioning Works](#)" (4 min., 38 sec.). It provides an explanation of how refrigerants, including CFCs (both mentioned in the Landmark handout), work to keep things cool as part of refrigerators and air conditioners.
- Preview/review vocabulary that students will encounter in the handout and activities. Student groups could also split up the terms to research online or in a chemistry textbook, then share with the entire class.
 - **Refrigerant:** In general, liquid compounds with low boiling points used in refrigerators and air conditioners that are able to conduct/absorb heat well.
 - **Chlorofluorocarbons (CFCs):** Compounds that contain carbon, fluorine and chlorine. Some CFCs are nontoxic and nonflammable refrigerants, developed in the 1930s to replace toxic and flammable options.
 - **Ozone:** A highly reactive molecule made up of three oxygen atoms. It can be found near the Earth's surface as a pollutant in photochemical smog. It is also found higher up in the atmosphere, where it absorbs potentially damaging ultraviolet radiation.

- **Troposphere:** The part of the atmosphere from the Earth's surface up to about 6 miles.
- **Stratosphere:** The part of the atmosphere from 6 to 31 miles above the Earth's surface.
- **Inert:** A substance that is stable and does not tend to react.
- **Volatile:** The tendency of a chemical to vaporize (to turn from liquid to gas).
- Have students read the handout **Chlorofluorocarbons and Ozone Depletion**.
- Distribute the **Activities** selected for the class.
- Use the **Answer Guide** for student feedback and discussion.
- For additional information and discussion related to ozone and atmospheric measurements, show the ACS *ChemMatters* video "[How NASA Keeps Tabs on Air Pollution from Space](#)" (7 min., 34 sec.). The video discusses the AURA satellite and its instrumentation, along with different roles that ozone plays in varying locations in the atmosphere.
- Students could also read the April 2013 *ChemMatters* article "[The Ozone Layer: Our Global Sunscreen](#)" by Mike Carlowicz. It discusses a computer model that simulates what could have happened to our planet if even more ozone-destroying chemicals were present and considers what will happen in our real world "ozone experiment."

Student Activities with Objectives

History Exercise: Chronology of Chlorofluorocarbons and Ozone (15–20 min.)

- Using the handout, students place major events from the development and use of refrigerants from the 1920s to the 1980s, along with their associated environmental effects and a worldwide decision made to limit chlorofluorocarbon use. They also consider the timing of some of the events, such as why it took quite some time to limit CFCs once it was known they were harmful, and how quickly a limit on their use would affect the environment.

Perceptions of Chemicals (15–20 min.)

- Students recognize that our perception of a chemical as positive or negative is not a clear-cut decision. They describe how ozone can have either a positive or a negative effect depending on its location in the atmosphere, then discuss how the perception of chlorofluorocarbons changed over several decades.

Chlorofluorocarbon Debate (15–20 min.)

- Students outline the responses of various stakeholders to F. Sherwood Rowland and Mario J. Molina's 1974 argument regarding CFCs and ozone. They also describe challenges then faced by atmospheric chemistry researchers in obtaining convincing data. Finally, they consider possible causes of a real world 2018 CFC situation.

Atmospheric Reactions (15–20 min.)

- Students explore the reactions that take place between CFCs and ultraviolet light in the stratosphere, and the resulting reactions this triggers with ozone. They also compare these damaging reactions to a similar ozone reaction that is viewed as a positive one.

Chlorofluorocarbons and Ozone Depletion

At the University of California, Irvine, F. Sherwood Rowland and Mario J. Molina discovered that chlorofluorocarbons (CFCs) could deplete Earth's atmospheric ozone layer, which blocks the sun's damaging ultraviolet rays. When the scientists reported their findings in 1974, CFCs were in wide use in refrigeration, air conditioning and aerosol spray cans. The research set off fierce debates, yet the work of Rowland and Molina convinced skeptical industrialists, policymakers and the public of the danger of CFCs.

The scientists' advocacy — and the discovery by other researchers that the ozone layer over the Antarctic was thinning — led to worldwide phaseout of CFCs and the development of safer alternatives. For their work, Rowland and Molina shared the 1995 Nobel Prize in Chemistry with another atmospheric chemist, Paul J. Crutzen.

Widespread Use of CFCs

In the 1920s, refrigeration and air conditioning systems used compounds such as ammonia, chloromethane, propane and sulfur dioxide as refrigerants. Though effective, the compounds were toxic and flammable, and exposure to them could result in serious injury or death. In the 1930s, chemists at Frigidaire led by Thomas Midgely Jr. worked to develop nontoxic, nonflammable alternatives to the refrigerants.

The team focused their effort on compounds containing carbon along with halogens such as fluorine and chlorine. Such compounds were known to be volatile and chemically inert, desirable properties for their use in refrigeration.

The first compound they developed was dichlorodifluoromethane, which they dubbed "Freon." By the early 1970s, CFCs were in widespread use, and worldwide production of the compounds had reached nearly one million tons per year.

The Importance of Ozone

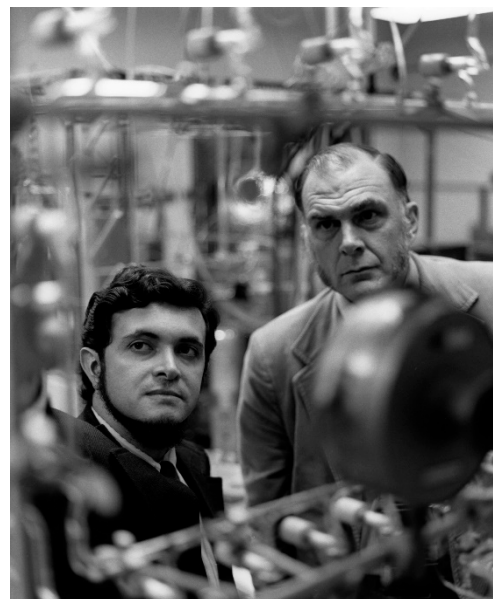
Ozone, a molecule made up of three oxygen atoms, is a confusing molecule from an environmental standpoint. In the troposphere, the region of the atmosphere from Earth's surface up to about 6 miles, ozone is a pollutant that is a component of smog.

But in the stratosphere, the region of the atmosphere from 6 to 31 miles, ozone absorbs the sun's potentially damaging ultraviolet (UV) radiation. Without this protective ozone layer in the atmosphere, animals and plants wouldn't survive on land.

Rowland's interest in the fate of CFCs in the atmosphere was sparked by a talk he heard at a conference in 1972. The speaker discussed a British scientist's findings that practically all of a particular CFC ever made

was still present in the atmosphere.

Rowland, a chemistry professor, decided to study the fate of CFCs in the atmosphere. Although CFCs are inert in the lower troposphere, Rowland realized that they can be broken down by UV radiation once they drift up into the stratosphere.



Molina (left) and Rowland in their UC Irvine lab in 1974.

Courtesy UC Irvine

In late 1973, Rowland and Molina, who had recently joined Rowland's lab as a postdoctoral fellow, calculated that CFC molecules released near the surface of Earth would, over decades, wind up in the stratosphere where UV radiation would split off chlorine atoms.

Each chlorine atom would react immediately with an ozone molecule, setting off a chain reaction that would destroy thousands of other ozone molecules. They estimated that if CFC use was banned right away, ozone loss would go on for years. If CFC production continued, however, ozone loss would be even greater. They published the findings in *Nature* in 1974.

"When we realized there was a very effective chain reaction, that changed the CFC investigation from an interesting scientific problem to one that had major environmental consequences," Rowland told *Chemical & Engineering News* in 2007. "You don't often get many chills down your back when you look at scientific results," he added, but that had been one of those moments.

From Research to Resistance

In 1976, the National Academies of Science issued a report affirming the destructive effects of CFCs on stratospheric ozone. Congressional hearings reached similar conclusions, and states and the federal government began exploring bans on the use of CFCs in aerosol cans. The chemical industry maintained that the data on CFCs and stratospheric ozone were inconclusive and didn't warrant drastic action.

Rowland and Molina and the other scientists trying to understand stratospheric chemistry faced serious and fundamental challenges. A significant number of chemical species were clearly involved in the interaction of CFCs and ozone in the stratosphere. Most are highly reactive and present in only trace amounts. Their chemistry was difficult to replicate in the laboratory.

Additionally, stratospheric ozone concentrations fluctuate naturally by geography and season. The stratosphere isn't an easy place in which to do research.

Measurements of ozone levels were carried out by instruments carried into the stratosphere by balloons and aircraft. Ozone was also measured by instruments on satellites orbiting Earth, though satellite technology in the mid-1970s was still rather primitive.

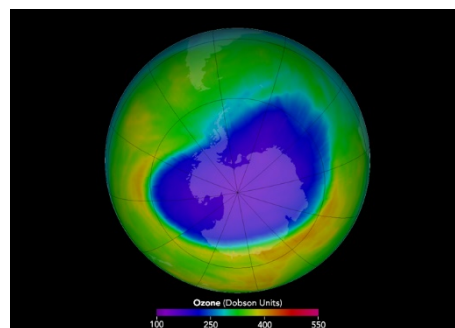
All of these uncertainties gave critics of Rowland and Molina's hypothesis a lot of material to work with. They argued, to many very convincingly, that it simply didn't make sense to take action against a class of highly useful chemicals on the basis of such flimsy evidence. Industry critics, in particular, argued that it was one thing to propose phasing out the use of CFCs as propellants in aerosol cans—a relatively trivial use of the compounds—but quite another to consider banning their use in refrigerators and air conditioners, where obvious alternatives to CFCs simply didn't exist at that time.

Antarctic Ozone Hole

The crucial evidence supporting the CFC hypothesis came from British scientists working at the

Halley Bay Station of the British Antarctic Survey (BAS), who had been taking ground-based measurements of total ozone for decades. In 1984, Joseph C. Farman and his colleagues at BAS studied the raw data and found that stratospheric ozone had decreased greatly since the 1960s. In 1985, the scientists published an article in *Nature* announcing that stratospheric ozone over Antarctica was reduced 40% in September, the end of the austral winter.

The Antarctic ozone hole, as it came to be known, made depletion of the ozone layer a real and present danger to lawmakers and the public at large. Predictions of significant increases in the incidence of skin cancer resulting from continued use of CFCs spurred international action. In 1987, 56 countries agreed under what became known as the Montreal Protocol to cut CFC production and use in half. In subsequent years, the protocol was strengthened to require an eventual worldwide phase-out of production of CFCs and other ozone depleting chemicals. As a result of Rowland and Molina's work, humans for the first time realized that their activities could affect Earth's environment on a planetary scale.



NASA began measuring levels of ozone in Earth's stratosphere by satellite in 1979.

History Exercise: Chronology of Chlorofluorocarbons and Ozone

Chlorofluorocarbons (CFCs) used as refrigerants in refrigerators and air conditioners, and as aerosol propellants, have changed over the past 100 years. Some of these changes were spurred by the harmful effects of the compounds.

1. Using the handout provided, briefly describe the major events that occurred in the area of refrigerants and other CFCs during each of the time periods listed below.

Time Period	Event(s)
1920s	
1930s	
1940s–1970s	
1972	
1973–1974	
1984–1985	
1987	

2. Discuss potential reasons why there was more than a 10-year gap between Rowland and Molina's report that CFCs destroy atmospheric ozone and the Montreal Protocol agreement to cut CFC production and use.

3. If the Montreal Protocol had immediately banned all CFC use and production, would this have solved the problem of ozone depletion the same year it was enacted? Explain why/why not.

Perceptions of Chemicals

We can have a positive or negative perception of a particular chemical. This can depend on different factors, such as location of the chemical, and its uses and effects. For example, ozone and chlorofluorocarbons (CFCs) can be particularly useful in one environment, but can have damaging effects in another.

1. Add labels to the diagram of the Earth's atmosphere below.

a. In the two boxes, write the names of two atmospheric regions: the one 0 to 6 miles above the Earth's surface, the second 6 to 31 miles.

b. Write "ozone layer" in the appropriate location.

31 miles _____

6 miles _____

Earth's
surface

0 miles _____

2. Complete the table below. One source of ozone is the ozone layer. It can also be produced elsewhere in the atmosphere. Decide whether to label ozone as having a positive or negative effect, including reasons to support your decision.

Atmospheric Region	Ozone Source	Effect of Ozone + or -?
0–6 miles		
6–31 miles		

3. In question 2, is the ozone molecule itself different in each of the two atmospheric regions? How is it able to have both positive and negative effects?

4. Describe how/why the perception of CFCs changed over time.

Time Period	Positive/Negative Perception	Reason for perception
1940s		
Late 1970s		
Late 1980s		

Chlorofluorocarbon Debate

Imagine yourself in 1974. Rowland and Molina's paper in *Nature* has jolted the scientific world and various groups disagree about the information and what to do next.

1. In the box below, summarize the key argument that Rowland and Molina made in their paper.

Rowland and Molina's argument

2. In the table below, outline the reaction and reasoning of different stakeholders to Rowland and Molina's argument.

Stakeholder	Agree/Disagree with Rowland & Molina	Counter-argument or supporting argument
National Academies of Science		
Government		
Chemical industry		
Scientists at British Antarctic Survey		

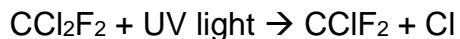
3. Describe several challenges faced by atmospheric chemistry researchers to obtain results that would convince other groups that the use of chlorofluorocarbons (CFCs) was harmful.

4. Although the Montreal Protocol's ban on CFC production and use is still in effect, a 2018 report in *Nature* stated that while some CFC atmospheric levels are declining as expected, CFC-11 levels are not. What are some possible reasons for this surprising observation?

Atmospheric Reactions

A quote from Rowland and Molina's 1974 *Nature* scientific paper reads, "Photodissociation of the chlorofluoromethanes in the stratosphere produces significant amounts of chlorine atoms, and leads to the destruction of atmospheric ozone." These atmospheric reactions can be explored in two stages.

1. The first chlorofluorocarbon (CFC) developed was dichlorodifluoromethane (CCl_2F_2), or Freon. It can be broken down by ultraviolet (UV) radiation:

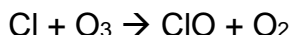


In 1972, Lovelock reported that all the trichlorofluoromethane, or CFC-11, ever manufactured was still in the atmosphere. It undergoes a similar reaction there.

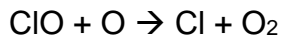
- a. The name of a compound is useful in writing its chemical formula. Dichlorodifluoromethane has the chemical formula CCl_2F_2 . Write the chemical formula for trichlorofluoromethane (CFC-11).

- b. Write the chemical equation that shows how UV light similarly breaks down CFC-11.

2. When a CFC is broken down, the chlorine generated is a free radical, which has an unpaired electron and is highly reactive. It is sometimes shown as $\bullet\text{Cl}$. This chlorine can react with ozone:

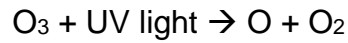


The ClO is also highly reactive and can itself react with an oxygen free radical in the atmosphere:



After these two reactions occur, a chlorine free radical is regenerated. What can it then do in the atmosphere? Why are chlorofluorocarbons so damaging because of this?

3. The ozone layer in the stratosphere protects us from most UV radiation. It absorbs the radiation, breaking down in the process:



The resulting oxygen free radical can either combine with another oxygen free radical to form O_2 , or it can recombine with an O_2 molecule to form O_3 .

This reaction is destructive to ozone. Why is this viewed positively while the breakdown of ozone in the reactions in step 2 is not?

Chlorofluorocarbons and Ozone Depletion Answer Guide History Exercise

History Exercise: Chronology of Chlorofluorocarbons and Ozone

Chlorofluorocarbons (CFCs) used as refrigerants in refrigerators and air conditioners, and as aerosol propellants, have changed over the past 100 years. Some of these changes were spurred by the harmful effects of the compounds.

1. Using the handout provided, briefly describe the major events that occurred in the area of refrigerants and other CFCs during each of the time periods listed below.

Time Period	Event(s)
1920s	Toxic and/or flammable compounds such as ammonia, chloromethane, propane and sulfur dioxide are used as refrigerants.
1930s	Team of chemists develops nontoxic, nonflammable refrigerant alternatives, the first of which is Freon (dichlorodifluoromethane).
1940s–1970s	Use of CFCs as refrigerants increases, reaching a worldwide production of nearly one million tons per year in the early 1970s.
1972	Lovelock reports that atmospheric measurements suggest that practically all of the CFC-11 ever manufactured is still in the atmosphere.
1973–1974	Rowland and Molina report that CFC molecules end up in the stratosphere, where they react to destroy ozone.
1984–1985	Farman and colleagues report that there is an ozone hole over Antarctica.
1987	56 countries agree to cut CFC production and use in half under the Montreal Protocol.

Chlorofluorocarbons and Ozone Depletion Answer Guide History Exercise

2. Discuss potential reasons why there was more than a 10-year gap between Rowland and Molina's report that CFCs destroy atmospheric ozone and the Montreal Protocol agreement to cut CFC production and use.

Rowland and Molina's 1974 report set off fierce debate. The National Academies of Science, along with congressional hearings, reached conclusions similar to Rowland and Molina. However, the chemical industry disputed the claims. In addition, there were no replacements for CFCs at that time.

3. If the Montreal Protocol had immediately banned all CFC use and production, would this have solved the problem of ozone depletion the same year it was enacted? Explain why/why not.

No. It takes time for CFCs to travel from the Earth's surface up to the stratosphere. A more important reason is that CFCs have a long lifetime (multiple decades) in the atmosphere.

Chlorofluorocarbons and Ozone Depletion Answer Guide

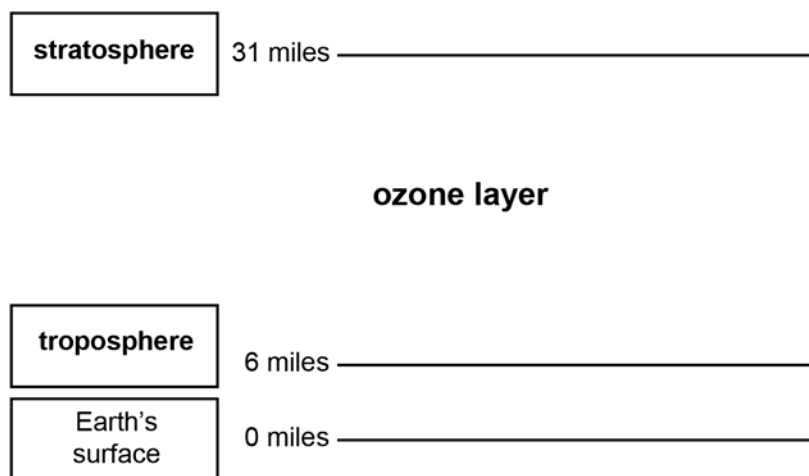
Perceptions of Chemicals Exercise

Perceptions of Chemicals

We can have a positive or negative perception of a particular chemical. This can depend on different factors, such as location of the chemical, and its uses and effects. For example, ozone and chlorofluorocarbons (CFCs) can be particularly useful in one environment, but can have damaging effects in another.

1. Add labels to the diagram of the Earth's atmosphere below.

- In the two boxes, write the names of two atmospheric regions: the one 0 to 6 miles above the Earth's surface, the second 6 to 31 miles.
- Write "ozone layer" in the appropriate location.



2. Complete the table below. One source of ozone is the ozone layer. It can also be produced elsewhere in the atmosphere. Decide whether to label ozone as having a positive or negative effect, including reasons to support your decision.

Atmospheric Region	Ozone Source	Effect of Ozone + or -?
0–6 miles	smog	(–) It is considered a pollutant. It can negatively impact plant growth.
6–31 miles	ozone layer	(+) It absorbs ultraviolet light, preventing this potentially damaging radiation from reaching Earth's surface.

Chlorofluorocarbons and Ozone Depletion Answer Guide

Perceptions of Chemicals Exercise

3. In question 2, is the ozone molecule itself different in each of the two atmospheric regions? How is it able to have both positive and negative effects?

The ozone molecule is identical (O_3) in both regions. It can have both positive and negative effects depending on its location. When it is near Earth's surface, interaction with ozone is harmful to plants and animals. When it is far above Earth's surface, it can protect plants and animals from ultraviolet radiation that would otherwise reach the surface.

4. Describe how/why the perception of CFCs changed over time.

Time Period	Positive/Negative Perception	Reason for perception
1940s	Positive	CFCs replaced toxic and flammable refrigerants.
Late 1970s	Negative/Positive	CFCs had a destructive effect on the ozone layer. Some felt data were inconclusive and there were no alternative refrigerants to use at that time.
Late 1980s	Negative	The ozone layer was greatly affected. 56 countries agreed to cut CFC production and use in half and eventually phase out these chemicals.

Chlorofluorocarbons and Ozone Depletion Answer Guide

Chlorofluorocarbon Debate Exercise

Chlorofluorocarbon Debate

Imagine yourself in 1974. Rowland and Molina's paper in *Nature* has jolted the scientific world and various groups disagree about the information and what to do next.

1. In the box below, summarize the key argument that Rowland and Molina made in their paper.

Rowland and Molina's argument
Chlorofluorocarbon (CFC) molecules released near the Earth's surface move to the stratosphere. There, ultraviolet (UV) radiation splits off chlorine atoms to start a chain reaction that destroys ozone molecules.

2. In the table below, outline the reaction and reasoning of different stakeholders to Rowland and Molina's argument.

Stakeholder	Agree/Disagree with Rowland & Molina	Reasoning/argument
National Academies of Science	Agree	Issued a report affirming the destructive effects of CFCs on stratospheric ozone
Government	Agree	Reached similar conclusions to Rowland and Molina
Chemical industry	Disagree	Maintained that data on CFCs and stratospheric ozone were inconclusive and didn't warrant drastic action; stated CFCs would be hard to replace
Scientists at British Antarctic Survey	Agree	Data showed that stratospheric ozone had decreased greatly since the 1960s

3. Describe several challenges faced by atmospheric chemistry researchers to obtain results that would convince other groups that the use of chlorofluorocarbons (CFCs) was harmful.

Chlorofluorocarbons and Ozone Depletion Answer Guide

Chlorofluorocarbon Debate Exercise

- **Chemicals involved in the CFC and ozone interactions are highly reactive and present in only trace amounts.**
- **CFC and ozone atmospheric chemistry is difficult to replicate in the laboratory.**
- **Stratospheric ozone concentrations fluctuate naturally by geography and by season.**
- **It is difficult to gather data from the stratosphere. Measurements had to be made with primitive satellite technology, or instruments needed to be carried into the stratosphere by balloons or aircraft.**

4. Although the Montreal Protocol's ban on CFC production and use is still in effect, a 2018 report in *Nature* stated that while some CFC atmospheric levels are declining as expected, CFC-11 levels are not. What are some possible reasons for this surprising observation?

Answers will vary. Scientists originally speculated that someone could be selling a stockpile of CFC-11 from before the ban, or that, for some reason, a factory was manufacturing it again, despite the presence of other inexpensive and effective alternatives. Instructors and students could research the situation online. One link is <https://www.livescience.com/62906-ozone-cfc-mystery-china-xingfu.html>.

Chlorofluorocarbons and Ozone Depletion Answer Guide

Atmospheric Reactions Exercise

Atmospheric Reactions

A quote from Rowland and Molina's 1974 *Nature* scientific paper reads, "Photodissociation of the chlorofluoromethanes in the stratosphere produces significant amounts of chlorine atoms, and leads to the destruction of atmospheric ozone." These atmospheric reactions can be explored in two stages.

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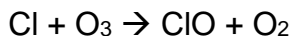
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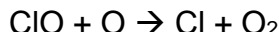
- b. Write the chemical equation that shows how UV light similarly breaks down CFC-11.



2. When a CFC is broken down, the chlorine generated is a free radical, which has an unpaired electron and is highly reactive. It is sometimes shown as $\bullet\text{Cl}$. This chlorine can react with ozone:



The ClO is also highly reactive and can itself react with an oxygen free radical in the atmosphere:



After these two reactions occur, a chlorine free radical is regenerated. What can it then do in the atmosphere? Why are chlorofluorocarbons so damaging because of this?

The regenerated chlorine free radical can then begin the reaction sequence again, to break down additional ozone. This makes CFCs so damaging because they can destroy a large number of ozone molecules during their lifetime.

Chlorofluorocarbons and Ozone Depletion Answer Guide

Atmospheric Reactions Exercise

3. The ozone layer in the stratosphere protects us from most UV radiation. It absorbs the radiation, breaking down in the process:



The resulting oxygen free radical can either combine with another oxygen free radical to form O_2 , or it can recombine with an O_2 molecule to form O_3 .

This reaction is destructive to ozone. Why is this viewed positively while the breakdown of ozone in the reactions in step 2 is not?

Although the reaction destroys ozone, this process absorbs UV radiation that would otherwise harm humans and plants on the Earth's surface. The oxygen products can also recombine to form ozone.