THE WORLD OF CHEMISTRY

Program #16

THE PROTON IN CHEMISTRY

Producers Jack Arnold
and Matt Dibble

Air Script: October 31, 1988

PRODUCED BY

EDUCATIONAL FILM CENTER
and
THE UNIVERSITY OF MARYLAND

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Archival commercial footage, rain, lab demo, archival photograph of Soren Sorenson, pH scale, chemical reactions, graphic

NARRATOR (MUSIC and NAT SOUND under):
Acid stomach, acid rain, acid in your drink? How to measure the relative strength of acids and bases. In 1909, Soren Sorenson, employed by a Danish brewery to measure normal acidity in beer, invented the pH scale. What is pH, and what, in the first place, are acids and bases? To find out, we must uncover the vital role of the proton in chemistry.

SUPER: THE PROTON IN CHEMISTRY

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH at chemical plant

ROALD HOFFMANN (SYNC):
Acid spills, acid rain. Acids have certainly been getting a bad press lately, and that on top of an intuition that we have that acids are destructive, corrosive. Does that reflect the reality of the position of acids and bases in our society? Not at all. There's a list of the top ten chemicals in the world. Number one on that list is a molecule made to the tune of 33 billion kilograms every year in the U.S. alone. And that's a strong acid, sulfuric acid. Among those top ten are no less than 5 acids and bases. The truth of the matter is that acids and bases are enormously beneficial. They are used in almost everything that's manufactured around us. For instance, here is a tank car of sulfuric acid. It's transformed here at Delta Chemical into aluminum sulfate that's used in the paper industry and in purifying water. Over there is a tank car of sodium hydroxide, a strong base, and that is used in the making of sodium hypochloride, a bleach and something also used in clarifying water. Acids and bases can be strong or weak. Sulfuric acid here, or nitric acid, are strong acids. Sodium hydroxide is a strong base. We're much more used to encountering weak acids and bases in our home environment. For instance, vinegar and citric acid are weak acids; ammonia is a weak base.

Shots of chemical plant

NARRATOR (NAT SOUND under):
Bases, the basis of household industry.

MONTAGE: Shots of household cleaners

MUSIC

MONTAGE: Household cleaners, ammonia plants, farm machinery, construction equipment, lime, sewage treatment plant, river, furnace, smokestacks

NARRATOR (MUSIC and NAT SOUND under):
Bases, the opposite of acids, neutralize them. They react with acids. In industry, these acid-base reactions are very important. Ammonia reacts with acids like phosphoric acid to produce fertilizers. The U.S. produces 70 million tons of fertilizer a year, one-fifth of the world's production. This base ranks fifth on the list of most produced chemicals, it's lime. If farmers want to neutralize excess acids in soil, they use lime. Like ammonia, lime cleans up. It's used to precipitate impurities from sewage. If left untreated, the sewage would carry harmful nitrogen and phosphorus compounds back into water. Lime is one chemical to be dumped. (cont.)

NARRATOR cont:
Dumped into rivers like this one in coal-mining country, it will reduce acidity, and dumped into coal-burning power plants, it can neutralize 90 percent of the acidic pollutants that could escape into our atmosphere.

MONTAGE: Chemical reactions, people drinking, plants, fruits, vinegar, fermenter, corn field, orange juice

NARRATOR (MUSIC and NAT SOUND under):
Acids. Strong acids are essential in industry as reactants and catalysts. They're not chemicals for everyday contact. Far too potent are concentrated nitric, hydrochloric, and sulfuric acid that can dissolve metals. Yet weak acids we know well. Citric acid is a weak acid and it's found in many beverages and in plants, and, of course, in citrus fruits. Apples are a natural source of another weak acid, acetic acid, found in vinegar. Such acids not only occur in the natural world. They can also be manufactured. In this fermenter, microorganisms produce citric acid from the raw material, corn starch. So, acids in your drink? Certainly, when they're like citric acid, weak and dilute. Acids and bases, then, vary widely in their properties, as Dr. Donald Showalter is discovering.

DS in lab

DON SHOWALTER (SYNC):
Yuck! Have you ever had a sip of wine that reminded you of vinegar? Or how about taking a bite of a fresh lemon? Boy, is that sour? Both of these are very sour. Now, that's a sure indication of having too much acid. In the kitchen now we can tell if something is acidic by its sour taste, but in the laboratory we don't taste, we test. Let's do a little bit of an experiment. What I'd like to do is to take this piece of blue litmus paper and add to it a little bit of that lemon juice. And watch what happens. The litmus paper turns red. Now, that's an indication of an acid. Now let me help you remember that: blue to red, ac-id. Now let's do our test with this common laboratory acid. Put a little of the acid into this dish. I'm going to put some of it onto this litmus paper, just like we did before. Now watch what happens.

EQUATION

Again, the litmus paper turns red, indicating an acid. Now let's do another experiment with this laboratory acid. What I'm gonna do is pour some of it into this test tube. All right. I'm going to add some magnesium ribbon to it. Let's see what happens. Look at the bubbles being formed. The magnesium reacts with the acid to give off a gas. Pretty neat, huh? All right. Let's try another substance with this acid. (cont.)

DON SHOWALTER cont:
This is limestone. I'm gonna add some of that into this test tube, and let's see what happens when we put a little acid in there. Notice the bubbles. The acid is reacting with the limestone and giving off a gas. Okay. Now that we have seen some acid reactions, I know just what you're wondering. What will bases do with the same substances? Well, let's try it and see. I've got some ammonia, which you know is a base. We'll pour a little bit of that into this glass, and let's test that with some blue litmus paper. Well, you see that it gets a little wet, but it really doesn't have a color change. What if we would try red litmus paper? Here's a piece of red litmus. Wow, look at it. As you see, it turned blue.

EQUATION

So the red litmus paper turns blue, an indication of a base, red to blue. Let's take some of that same base, some of this ammonia, put it into this test tube, and see if it reacts with this, the magnesium. Remember that? Put it in there and presto -- nothing happens. Now, what about if I poured some of this ammonia again into this limestone. Remember the limestone? What's gonna happen over there? What do you think? Nothing. Absolutely nothing. Now, what does that mean to us? It means that bases do not react with magnesium or with limestone.

Lab demonstration

NARRATOR:
Acids and bases change the color of dyes such as litmus. Acids produce hydrogen gas when reacting with metals such as magnesium. Acids produce gaseous carbon dioxide when reacting with limestone. Bases do not react with magnesium or limestone. Acids and bases are opposites. They react to neutralize each other.

DS in lab

DON SHOWALTER (SYNC):
What would happen if we mixed acids and bases? Let's try this one. I'm just gonna take these tops off, put the tops together. Look at the smoke. Definitely a reaction, huh? How about this pair? There's nothing exciting there. I don't see anything happening. How about this pair? Wow! Look at the bubbles. Now, those three reactions certainly were different. But what do you think these reactions have in common?

GRAPHIC: Acid-base reactions

NARRATOR (MUSIC under):
The ammonia and the hydrogen chloride react to form a cloud of solid ammonium chloride. Nitric acid reacts with sodium hydroxide to form soluble sodium nitrate and water. (cont.)

NARRATOR cont:
Acetic acid reacts with sodium bicarbonate to form carbon dioxide gas, water, and soluble sodium acetate. So what do these reactions have in common? To find out, consider the language of chemistry. The reactions still appear different, but look closer. In all three, hydrogen plays a role. A transfer of hydrogen is the common factor, and it can be visualized more clearly on the molecular level. Focus on a single molecule of hydrogen chloride and a molecule of ammonia. Here hydrogen chloride acts as an acid, donating a proton. Ammonia acts as a base, accepting a proton. A proton was transferred.

Farm machinery

NARRATOR (MUSIC and NAT SOUND under):
Proton transfer is the key process in the manufacture of fertilizers.

EQUATION over chemical plant shots

NARRATOR (MUSIC and NAT SOUND under):
Ammonia is reacted with phosphoric acid, accepting a proton, to produce ammonium phosphate, for example.

MONTAGE: Plant shots, phosphate rock, rock being crushed, limestone, smokestacks, furnaces

NARRATOR (MUSIC and NAT SOUND under):
Another way of getting essential nutrients to the soil is to use phosphate rock as a starting point. Sulfuric acid transfers a proton in this reaction, which produces super phosphate. In industry generally, sulfuric acid is used as a catalyst because of its superior proton-donating properties. Another acid-base reaction is now being employed in coal-burning power plants. It has led to a new useful limestone, a base. In the furnace of this power plant, coal is crushed and fluidized. It has been burned in a bed of limestone. Sulfur dioxide from the coal is neutralized and remains in the ash. Why could fluidized bed combustion be so important? Because the pollutants that have usually gone up in smoke are a cause of acid deposition, or, as it is more commonly known, acid rain. Dr. John Malanchuk, of the Environmental Protection Agency.

INTERVIEW: Dr. John Malanchuk, Environmental Protection Agency

SUPER: John Malanchuk

DR. JOHN MALANCHUK (SYNC):
Most acid rain is produced by humans, mainly from two major sources, stationary sources and mobile sources. Stationary sources are exemplified by power plants, electrical generating power plants, which burn coal or fuel oil and emit sulfur dioxide into the atmosphere, which combines with water vapor and forms acid rain, just as it occurs naturally. Mobile sources are actually cars, trains, planes, et cetera, internal combustion engines which burn gasoline and produce mainly oxides of nitrogen, which are emitted into the atmosphere in the same process, combine with water vapor and produce acid rain.

MONTAGE: Forest fires, factories, forests, plants, rain run-off, underwater shots, monuments, buildings, cars, lakes, sampling lakes, dead fish

NARRATOR (MUSIC and NAT SOUND under):
Acid rain can also be caused naturally, by forest fires, for example. But as both humans and nature cause the pollution, so are they affected by it. (cont.)

NARRATOR cont:
Midwestern oaks, maples in the Northeast, the proud ponderosa, all are damaged, nutrients destroyed, leaves and needles lost, shoots appear crooked, deformed, leaves turn out discolored and abnormally small. According to the National Wildlife Federation, one storm in Wheeling, West Virginia, had the acidity of auto battery acid. Monuments, buildings, even the paint on cars can become pitted and discolored from the effects of acid rain. In the Western states, nitrogen oxides are thought to be mainly responsible for the change in the rain. In the East, it's sulfur dioxide transformed into dilute sulfuric that's primarily responsible. Lakes of the Northeast and elsewhere are now the focus of scientific study. Fish and underwater life are threatened. The Environmental Protection Agency is investigating some 3,000 lakes in all. Samples of the water must be taken and rapidly analyzed in mobile laboratories. Some lakes are able to absorb changes in acidity quite well. Other lakes become much more acidic, sometimes irreversibly, such that the damage to life is severe. In other words, acid rain can lead to a range of acidity in lake water. There is a significant principle here. Generally, when it comes to measuring acidity, more acidity, less acidity, the role of water is crucial.

RH in office with chemical models

ROALD HOFFMANN (SYNC):
Water is by far the most common medium in which acids and bases exist and act. What would happen in the molecular world if we were to take an acid, for instance HCl here, and to put it into water? It would immediately transfer a proton to the water molecule, to give a hydronium ion, H3O+. The water is here acting as a base, accepting a proton. On the other hand, if we were to take a base, ammonia, into water, what happens then is that the water gives up a proton to the ammonia, leaving behind a hydroxide ion, OH-minus. Water, in this case, is acting as an acid, a proton donor. The very same substance, water, in one case an acid, in the other case a base. And would there be any proton transfer in water by itself in the absence of any added external acid or base?

GRAPHIC: The hydronium ion in water

NARRATOR (MUSIC under):
Only one water molecule in 500 million accepts a proton. That molecule becomes hydronium ion. The water molecule that lost the proton becomes a hydroxide ion. Chemically speaking, an equilibrium exists among the hydroxide and hydronium ions and water molecules. (cont.)

NARRATOR cont:
Still only one out of 500 million molecules of water becomes a hydronium ion. This corresponds to 10 to the minus-7 moles of hydronium ion per liter.

RH at chalkboard

ROALD HOFFMANN (SYNC):
We've seen that in water itself, there is a tiny amount of hydronium ion in solution. What if we were to add to that water an acid, for instance, hydrochloric acid? That acid would transfer its proton to the water, like a shot, to generate some hydronium ion and there would be much more of that hydronium ion from the acid than there would be from the water equilibrium itself. And if instead of a strong acid, we were to add a weak acid, say acetic acid, that's what CH3COOH is, that weak acid would also transfer a proton, this one, to the water solution to give hydronium ions, but it would do so much less effectively than the strong acid HCl. The number of hydronium ions in the solution of a weak acid is much less than those in a solution of a strong acid. Both of them are bigger than they would be in the water equilibrium itself. We've seen that in a solution of a strong acid, such as hydrochloric, there are many more hydronium ions in solution than there are in the case of a weak acid. (cont.)

ROALD HOFFMANN cont:
The actual range of concentrations of hydronium ions that we normally encounter in chemistry is incredibly large, over 14 powers of 10, 14 orders of magnitude. We need an instrument to measure this incredibly large range of hydronium ion concentrations.

DS in lab

DON SHOWALTER (SYNC):
It's a pH meter. It works on the principle of an electrochemical cell. It consists now of this meter that gives us a number readout, and this electrode which measures the concentration of hydronium ion in solution.

EQUATIONS over lab demo

NARRATOR:
We have to devise a convenient way of representing the range of acidity in water solution. For this we can use a comparatively simple relationship, that the hydronium ion concentration in water equals 10 to the minus-something. That something is going to be what we call the pH. For example, here is a range of solutions of differing acidity. When the concentration of hydronium ion is 10 to the minus-1, the pH will be 1. When the concentration of hydronium ion is 10 to the minus-2, the pH will be 2. (cont.)

NARRATOR cont:
When the concentration drops to 10 to the minus-7, the pH will be 7. And this is the pH of pure water. pH 7 is the dividing line between acids and bases. The value of the pH becomes larger than 7 when the hydronium ion concentration gets even smaller.

DS in lab

DON SHOWALTER (SYNC):
Here we have a chart that shows the pH scale. And as my laboratory assistant will point out, the pH of bleach is just under 13, the pH of milk of magnesia just above 10. Sea water is just below 9. Blood is right at 7.4. And pure water at 7.0. Black coffee about 5. Vinegar just under 3. And then there are stomach fluids.

Archival stomach footage

NARRATOR (MUSIC under):
pH 1. Even in the normal stomach, the acid is hydrochloric acid. An expert on stomach acid is Dr. Paul Maton of the National Institutes of Health.

INTERVIEW: Dr. Paul Maton, National Institutes of Health

SUPER: Paul Maton

DR. PAUL MATON (SYNC):
The stomach produces a small amount of acid all the time, but then that amount of acid may be stimulated by food. Even the sight and smell of appetizing food is enough to make the stomach produce more acid.

GRAPHIC, antacid solution and tablets

NARRATOR (MUSIC under):
What actually happens when you eat a meal? Both hydrogen ions and chloride ions, maintaining an electrochemical balance, move through the stomach lining from the surrounding blood plasma. In the stomach the result is a highly acidic medium. That's what it takes to activate certain enzymes for the process of digestion. If the acidity of the stomach becomes excessive, problems can occur, problems which often need antacid solutions.

INTERVIEW: Dr. Paul Maton cont.

DR. PAUL MATON (SYNC):
There are a variety of different compounds that can function as antacids. For example, sodium bicarbonate could be used as an antacid, or magnesium hydroxide, calcium carbonate. There are a variety of compounds.

Antacid solution

NARRATOR (NAT SOUND under):
Basically bases, once more the basis of another household industry.

<u>Alkaseltzer</u> commercial

<u>Rolaids</u> commercial

<u>Tums</u> commercial

INTERVIEW: Dr. Paul Maton cont.

DR. PAUL MATON (SYNC/VO):
All antacids neutralize acid. And if they're given in sufficient amount, any antacid is as good as another at neutralizing acid.

People on street, graphic of stomach

One hears a lot of talk about hyperacidity and too much acid. In fact, there's very little or no evidence that people with ulcers actually produce more acid than many of the rest of us.

Archival footage of antacid solutions

NARRATOR (MUSIC under):
For most of those acid stomach discomforts, then, the tried and tested over-the-counter remedies do their job of neutralization well enough.

SUPER: THE PROTON IN CHEMISTRY

MONTAGE: Lab demonstrations, program graphics, water, equations

NARRATOR (MUSIC under):
To review: In the laboratory, acids are recognized by their ability to change the color of dyes, turning litmus red, for example. They react with metals, like magnesium, to produce hydrogen. Acids and bases react together. Today, acids and bases are defined in terms of hydrogen ion, or proton transfer. An acid donates a proton to a base. A base accepts a proton from an acid. Water is the most important medium in which acids and bases act. The difference between a strong acid and a weak one is the concentration of hydronium ions in solution. In aqueous solution, that concentration of hydronium ions ranges over 14 powers of 10. A strongly basic solution has a pH of 14, and a strongly acidic solution has a pH near zero.
(cont.)

NARRATOR cont:
As the hydronium ion concentration increases, the pH number decreases. Pure water has a pH of 7, the dividing line between acids and bases.

RH at chemical plant

ROALD HOFFMANN (SYNC):
Proton transfer is not just essential business in the molecular world of the chemist. It's really big business. Remember that list of the ten top chemicals, five of which were acids and bases? Someone is making them in tens of billions of kilograms. They're not doing it just for fun. Someone else is buying those molecules. And, in turn, they are being transformed into all the consumer goods around us. Actually, that transformation bears thinking about. Strong corrosive acids are being changed into molecules that are neither acid nor corrosive, nor in any danger of regenerating the acid from which they were made. Does that surprise you? It really shouldn't. Molecules are a thing unto themselves, independent of the history of their production. All that matters in giving a molecule its properties are its component atoms and the way they are arranged in space, the way they are connected to each other.
(cont.)

ROALD HOFFMANN cont:
Let me give you an example, nitric acid, HNO3, is a strong acid, but its component elements, hydrogen, nitrogen, and oxygen are not acid at all. So please don't worry that the bagel that you eat, for instance, which was made from wheat that was grown using a fertilizer, ammonium nitrate, that, in turn was made from nitric acid, that that bagel will spontaneously revert to nitric acid to burn you. It won't.

Credits, Closing Montage, Closing Music

<u>The World of Chemistry</u> Logo

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THE WORLD OF CHEMISTRY

Program #17

THE PRECIOUS ENVELOPE

Producer John Boslough

Air Script: October 31, 1988

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MONTAGE: Earth from space, clouds, smokestacks, weather balloon, mountain range

NARRATOR (MUSIC under):
The atmosphere is essential to all life on earth. What is the atmosphere made of, and how was it formed in the first place? How has our planet's vital supply of air changed in the past, and how is it being threatened by human activities today? Today's scientists are unlocking these and other mysteries as they probe our atmosphere, the precious envelope.

SUPER: THE PRECIOUS ENVELOPE

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH next to water

ROALD HOFFMANN (SYNC):
What does it take to sustain a human being capable of driving a truck, or composing a string quartet, or making a new chemical? Well, let's pare it down to essentials. In one day what it takes is about 2 kilograms of fresh water, about a kilogram of nutritious food, and 16 kilograms of air inhaled. We usually don't think we breathe that much air, but we do. About one-fifth of it is oxygen that we use, the rest nitrogen we mostly exhale. That material's balance is instructive in a number of ways, but what I find in it that is strongest, that comes across most directly, is that it tells me something about the incredible dependence that we have on the air, on the oceans, on the earth under my feet. We live, are sustained on the surface of a planet that is surrounded by a precious and subtle twin atmosphere of air and water that in a thin layer, only 10 kilometers out of the 8,000 from the center of the earth, supports incredible life.

(Air Script)

MONTAGE: Earth from space, sunset, clouds, oceans, storms, flower blooming, airplane, crowd at ballgame

NARRATOR (MUSIC and NAT SOUND under):
The earth is unique. Of all the planets in the solar system, it is the only one with an atmosphere capable of supporting life. This thin membrane not only provides all life on earth with a steady supply of essential oxygen, but it plays other important roles, too. In synchronization with the ocean, the atmosphere brings us the climate and weather that are responsible for our planet's cycles of life. And often to our dismay, dramatic changes in atmospheric conditions bring weather not to our liking. Without a canopy of air, there would be no seasons, airplanes could not fly, and fans could not cheer at a ball game.

GRAPHIC: Diagram of proportions of different gases in the atmosphere

NARRATOR (MUSIC under):
The earth's atmosphere consists of various gases. The major ones are displayed here in their relative proportions. Nitrogen, which is essentially inert, makes up 78.1 percent of the atmosphere. Oxygen accounts for 20 percent. (cont.)

NARRATOR cont:
Other gases are argon, a little under 1 percent, and much smaller amounts of carbon dioxide, neon, helium, krypton, xenon, and hydrogen. Still more gases, not shown here, are present in varying concentrations, such as high-altitude ozone. These all form the gaseous mixture we call the atmosphere.

MONTAGE: Earth from space, Jupiter, steam, smokestacks, mountain range, wheat and wheat fields with farm machinery

NARRATOR (MUSIC and NAT SOUND under):
Without this vital membrane of air, our planet would be as lifeless as the moons of Jupiter. So it is ironic that, since the advent of the industrial age, humans have been pouring unprecedented amounts of pollutants into the sky. The thin and protective membrane of high-altitude ozone is especially at risk. This delicate ozone layer lies 15 to 40 kilometers above the earth's surface. Molecules of ozone, made of 3 oxygen atoms, block a large portion of the sun's potentially harmful ultraviolet radiation. So the ozone protects life on the planet. Dr. Robert Watson is Chief of Atmospheric Sciences for the National Aeronautics and Space Administration.

Program #17 The Precious Envelope

INTERVIEW: Dr. Robert Watson, Chief of Atmospheric Sciences, National Aeronautics and Space Administration

(Air Script)

SUPER: Robert Watson

DR. ROBERT WATSON (SYNC):
The main importance of the ozone layer is it screens the harmful ultraviolet radiation from the sun from penetrating to the surface of the earth. If there was less ozone in the earth's atmosphere, it would mean more ultraviolet radiation would reach the earth's surface with potential adverse consequences for both human health, such as skin cancer, both melanoma and non-melanoma, and probably would have adverse effects on the productivity of both aquatic life and terrestrial life.

MONTAGE: Clouds, air conditioner, refrigerator, train cars, factory shots

NARRATOR (NAT SOUND under):
But the ozone layer is threatened by synthetic substances called chlorofluorocarbons, or CFCs, that rise into the upper atmosphere. CFCs are used mostly as coolants in air conditioners and in refrigerators, not only in the home, but in large refrigeration systems used to transport perishable food worldwide. (cont.)

NARRATOR cont:
CFCs also are used as solvents to clean computer components and for manufacturing styrofoam. Robert Srubar is environmental coordinator of the Freon Products Division of the Du Pont Company, the world's largest producer of CFCs.

INTERVIEW: Robert Srubar,
Environmental Coordinator,
Freon Products Division,
DuPont Company

SUPER: Robert Srubar

ROBERT SRUBAR (SYNC):
CFCs were first developed in the late 1920s, early 1930s, as replacements for the more toxic or flammable refrigerants. The idea was to have a safer refrigerant for use in your refrigerator at home or in similar machines that are used around the general public. The market value of CFCs in the U.S. is on the order of one billion dollars. Worldwide, it's about three times that much. Products or services related to CFCs in the U.S. are about $27 billion.

(Air Script)

MONTAGE: Earth from space, shots of the South Pole, computer image of the "black hole" at the South Pole, research airplanes

NARRATOR (MUSIC and NAT SOUND under):
During the 1970s, a peculiar depletion of ozone was detected over the South Pole. It was the first clue that something was wrong. By 1985, the Antarctic ozone hole had doubled in size. This image of the globe was taken from a satellite directly above the South Pole. It shows the black ozone hole changing in size. In 1987, Dr. Watson and other scientists used high-altitude research craft, such as this ER-2 plane operated by NASA, to take air samples above Antarctica. These flights confirmed what they already feared, that the size of the ozone hole was increasing at an alarming rate, although it still seemed to be confined to the atmosphere over Antarctica.

INTERVIEW: Dr. Robert Watson cont.

DR. ROBERT WATSON (SYNC):
I was the mission scientist on the DC-8 which actually flew over the South Pole. It was the urgency of the situation that convinced all of us that we had to go down there and devote many months of our lives just to understand what this particular campaign was all about, and specifically what was causing the ozone hole. (cont.)

DR. ROBERT WATSON cont:
I've been concerned for many years that even small changes in ozone could be detrimental to human health and to the aquatic and terrestrial plant life on earth. But when we suddenly see a 50 percent change in ozone in only a 10-year period from 1974 through to the middle of the 1980s, a 50 percent, one has to be concerned. One has to ask the simple question, what is causing the Antarctic ozone hole, and even more importantly, will it spread globally.

GRAPHIC: Ozone and CFCs at the molecular level

NARRATOR (MUSIC under):
Here is a model that describes how ozone might be destroyed in the upper atmosphere. A chlorofluorocarbon is released into the atmosphere from the earth's surface. As the CFC molecules rise into the upper atmosphere, they are bombarded by ultraviolet light, breaking loose a single chlorine atom. The single chlorine atom, in turn, reacts with an ozone molecule, breaking it apart. This creates a molecule of ordinary O2 and a molecule of chlorine monoxide. Free oxygen atoms exist in the atmosphere, created by the action of light on ordinary O2 and ozone. This molecule of chlorine monoxide is broken up when it reacts with a free oxygen atom.
(cont.)

NARRATOR cont:
This creates O_2 and a free chlorine atom. The chlorine atom is then free to attack ozone molecules again. This is a chemical chain reaction. For every chlorine atom released into the atmosphere, thousands of molecules of ozone are removed.

Research airplane, earth from space

NARRATOR (NAT SOUND under):
Evidence shows that the depletion of ozone is spreading worldwide. A 1988 NASA report indicated that there has been a measurable reduction in ozone levels in the Northern Hemisphere.

INTERVIEW: Robert Srubar cont.

ROBERT SRUBAR (SYNC):
That information prompted Du Pont to be consistent with its environmental policy and to come forth with our new position, where we set as our goal the orderly transition to a phaseout of the fully halogenated CFC production.

Chemists working in labs

NARRATOR (NAT SOUND under):
Although the full story about ozone depletion is not yet in, chemical manufacturers, like Du Pont, are developing alternatives to CFCs that will not damage the atmosphere.

INTERVIEW: Robert Srubar cont.

(Air Script)

ROBERT SRUBAR (SYNC):
The alternatives that Du Pont is developing or that Du Pont has announced are all in the fluorocarbon family, meaning they contain carbon, fluorine, some contain chlorine. They also would contain hydrogen. And it's those combinations of elements that give the compound its stability, while at the same time, if it has chlorine, it means a much shorter atmospheric lifetime so as not to affect stratospheric ozone. The addition of a hydrogen atom will cut that atmospheric lifetime drastically.

RH at a chemical plant

ROALD HOFFMANN (SYNC):
This is Du Pont's Chambers Works, where many chlorofluorocarbons are now being made, soon to be replaced by, we don't know what yet. Let's come back to ozone, that wonderful gas which, in the upper atmosphere, protects us from ultraviolet radiation. Here down at sea level, that same molecule is a very nasty actor indeed. It's a blue gas with a characteristic strong odor. It's generated around electrical discharges. And we can smell it in concentrations as small as one part in a hundred million. It ruins tires, damages plant life, and is a component of photochemical smog. And, in another context, it's sometimes used to purify water. (cont.)

ROALD HOFFMANN cont:
The moral of the story? There are no clear heroes or villains in the molecular world. There are only molecules in equilibrium with other molecules. The heroes and villains can only be human. The heroes, for instance, are those people who have puzzled out, with ingenuity and with sweat, the mechanisms of ozone depletion, or who, acting by themselves or in concert with others in society, are willing to modify their ways to preserve this atmosphere.

MONTAGE: Ocean, clouds, volcanos, lava flows, earth's horizon, hot springs, forest, smokestacks

NARRATOR (MUSIC and NAT SOUND under):
How do scientists learn more about the threats to the atmosphere? One way is to study how this precious envelope of air evolved over billions of years. Scientists believe that, when the earth was in its infancy, there were many volcanos, far more than today. Energy produced by radioactive decay deep beneath the surface melted rock and forced lava and gases upwards to the surface. These gases formed a primitive atmosphere consisting mostly of methane, ammonia, carbon dioxide, nitrogen, and chlorine. (cont.)

NARRATOR cont:
Denser gases were held near the earth's surface by gravity. Lighter gases, like hydrogen, escaped into space. There also were vast quantities of water vapor which, because of strong intermolecular forces, eventually condensed to form the oceans. How did the primitive atmosphere and the early oceans evolve together to produce life on earth? Probing for that answer may help us understand how these systems stay in balance, and how human activities threaten nature's exquisite balance. One of the best-known researchers in the field is Dr. Cyril Ponnamperuma.

INTERVIEW: Dr. Cyril Ponnamperuma, University of Maryland

SUPER: Cyril Ponnamperuma

DR. CYRIL PONNAMPERUMA (SYNC):
What we have here is an apparatus that gives us an idea of what could have happened on the primitive Earth four and a half billion years ago.

Dr. Ponnamperuma's model

NARRATOR (NAT SOUND under):
The upper flask represents the primitive atmosphere, while the lower one represents the ocean. The early atmosphere was made up mainly of methane, ammonia, and water vapor. This side arm is kept warm, while this condenser is kept cold. Water vapor rises through the warm side arm to the upper flask, much like water evaporating from the ocean, and it falls back through the condenser as if it were rain. This electrical discharge simulates lightning through the primitive atmosphere. When the lightning discharges, a number of reactions take place that could result in the formation of organic matter, which collects in the ocean below.

INTERVIEW: Dr. Cyril Ponnamperuma cont.

DR. CYRIL PONNAMPERUMA (SYNC):
Students of chemical evolution who study the origin of life call that the primordial soup. It is believed that the early oceans had an accumulation of organic molecules, the very building blocks of life, amino acids, the bases that occur in the nucleic acid. (cont.)

DR. CYRIL PONNAMPERUMA cont:
In this laboratory, in this very experiment, we have synthesized all five of the genetic bases. Now here we have a wonderful way of simulating the atmospheric conditions of the early earth.

MONTAGE: Lightning, storms, ocean, cells under microscope, misty forest, swamp, space shots, measuring tree rings, sampling ice, tundra, iceberg, research ship, weather balloon, wheat field, flood

NARRATOR (MUSIC and NAT SOUND under):
With the building blocks of amino acids in place, primitive life could begin to develop, first as single-celled organisms originating in the primordial soup of the sea, later as more complex and adaptable organisms capable of leaving the water and living on land. Gradually, some organisms developed the ability to release oxygen into the atmosphere. And from then on, life could begin to evolve in more complex forms, which, in turn, helped produce more oxygen for the atmosphere. To predict how the atmosphere might change in the future, scientists today try to discover how it has changed in the recent past. (cont.)

NARRATOR cont:
One way to measure these changes is by taking samples of tree rings that reflect climatic changes over centuries or even thousands of years. Atmospheric scientists also can track past changes by taking samples of buried ice that formed on the surface long ago. By testing such samples, scientists have shown that the earth was a little warmer about a thousand years ago, and from the 16th to the middle of the 19th centuries, it was about one degree Celsius colder than it is today. For an even deeper look into the past, scientists sample layers of sediments that have settled on the floor of the ocean. Scientists also monitor subtle, but significant, changes occurring in the atmosphere today, since these changes have the potential to enhance life or seriously disrupt global cycles.

GRAPHIC: The hydrologic cycle

NARRATOR (MUSIC under):
One of these cycles is called the hydrologic cycle, the constant movement of water, evaporating from earth to sky as water vapor, and from sky to earth as precipitation. The hydrologic cycle has existed for millenia. It's even possible that, when you take a drink of water, you may be swallowing a molecule or two once drunk by Julius Caesar.
(cont.)

NARRATOR cont:
Powered by the heat of the sun, this slow but steady cycle of evaporation and precipitation is always in balance for the earth as a whole. About 10 percent of all precipitation falls on land and provides us with the supply of fresh water that we depend on.

DS working in lab

NARRATOR (NAT SOUND under):
In the laboratory, series demonstrator Donald Showalter shows how carbon dioxide plays an important role in another cycle vital to life on earth.

DS in lab

DON SHOWALTER (SYNC):
This is bromothymol blue, a nice pretty blue color. Remember the blue. Now, this acid base indicator will change color if there is a change in the acidity of the solution. Let's add some of our carbon dioxide, the dry ice, and see what happens. Notice the dry ice bubbles -- oh, look at that. There's a color change to this beautiful yellow color. Now, what does that mean? Remember, we said this was an acid base indicator. So the carbon dioxide not only dissolved in the solution, but it also changed the acidity of the solution.

Misty forest

NARRATOR:
Photosynthesis by plants also depends on carbon dioxide. An experiment with bromothymol blue demonstrates this vital role.

DS in lab

DON SHOWALTER (SYNC):
Now I have three test tubes here that are filled with water, and then I saturated them with carbon dioxide, just dropped it in there and let it bubble away. I also put some indicator, remember that same indicator, bromothymol blue, so it turned yellow. And then I put a water plant in two of these. Now, this is actually the experiment here. We want to see if the plant will absorb that carbon dioxide, and then the acid content will decrease and we will see a color change, if it happens. What I am gonna do now, I'm gonna take this tube with the plant, and this one over here without, and expose it to an intense light source. I'm going to take this tube out in front here with the plant in it and put it into a dark area where it's not exposed to light. Now, what do you think's gonna happen? Well, there's going to be some change now, we hope, because of the absorption of the carbon dioxide. But that's gonna take quite a bit of time, certainly more than a day. (cont.)

DON SHOWALTER cont:
So I can't sit here and let you watch it while it happens. I've already done that part. Now let me show you what happened. After at least 24 hours now, look what's happened. The solution has turned blue. Now, that means that this water is now less acidic, right? The blue color means less acidic. What happened to the other two, though? Now, remember, this one was in the dark, didn't have any light exposed, and it didn't turn color. And this one now has no plant in it. It was exposed to the light. But it didn't turn color either. Okay. Now, what does this all mean? It means now, for the plant to absorb the carbon dioxide, we need to have the plant, we need to have water, and we need to have light. And if all those are present, the carbon dioxide will be absorbed and the solution will be less acidic.

Lab demo, waves

NARRATOR (MUSIC under):
Carbon dioxide's ability to dissolve in water and its reaction with plants are part of what is called the carbon dioxide cycle. Much of the carbon dioxide gas released throughout geological times by volcanos, and today by respiring animals and plants, is dissolved into the ocean.

GRAPHIC: Carbon dioxide cycle

NARRATOR (MUSIC under):
In water, carbon dioxide forms a bicarbonate ion and a carbonate ion. Some of these end up as calcium carbonate, an insoluble compound found mainly in plankton whose skeletal remains eventually settle to the ocean floor. Photosynthesis is an important part of the carbon dioxide cycle. Green plants use solar energy to convert water and carbon dioxide into glucose and oxygen. Oxygen is released into the atmosphere in enormous quantities. So as long as there are plants and sunshine on earth, there will be a never-ending supply of oxygen in the air.

Water at sunset, smokestacks, factory shots, automobile exhaust, airplanes

NARRATOR (MUSIC and NAT SOUND under):
It has taken eons for the atmosphere to evolve, but as our experience with ozone has shown, only a short time for humans to disrupt this precious envelope. Since the industrial revolution began over a century ago, massive amounts of coal and other fuels have been burned. Unprecedented amounts of carbon dioxide have been pumped into the atmosphere. (cont.)

NARRATOR cont:
Today our species is an agent of nearly geological magnitude. In addition to producing CFCs in vast quantities, another way human activities may be changing the atmosphere is through a mechanism called the greenhouse effect.

INTERVIEW: Dr. Robert Watson cont.

DR. ROBERT WATSON (SYNC):
We're concerned that, through the greenhouse effect, the earth's system may warm up by only a few degrees, three to five degrees during the next few decades. If there were to be an increase, even of only a few degrees, the concerns we have are simply there might be an increase in sea level, erosion of the coastal areas. There may be change in precipitation patterns. There may be a change in the severity of storms. For example, certain models would predict that the American Midwest may become quite dry, it would go back to the dust bowl of the 1930s, wheat will not grow efficiently there. Whereas the warmer temperatures in Canada and the USSR will mean that there will be far more productivity of grain in the high northern climates. One could envisage out of one's scenario very simply that instead of America being an exporter of wheat, it may become an importer from countries such as Canada and the USSR.

GRAPHIC: The greenhouse effect

NARRATOR (MUSIC under):
Here is how the greenhouse effect works. The atmosphere allows most visible and ultraviolet radiation from the sun to penetrate to the surface. Thermal radiation is emitted from the surface and absorbed by molecules of atmospheric gases such as water vapor and carbon dioxide. These molecules serve as energy banks, releasing energy in the form of heat and making the earth habitable. But this greenhouse effect can become too strong if excessive carbon dioxide accumulates in the air, trapping additional heat and raising the temperature at the surface.

Shots of the sun

NARRATOR (MUSIC under):
As a result, the mean global temperature has risen about one-half degree Celsius during the past century.

SUPER: THE PRECIOUS ENVELOPE

MONTAGE: Volcanos, oceans, program graphics, "black hole" image, chemists at work in labs, sun over ocean, airplane flying

NARRATOR (MUSIC under):
To review: Current evidence indicates that our atmosphere developed initially from gases pouring out of volcanos. The oceans formed as water vapor condensed from the early atmosphere. A series of cycles, such as the hydrologic and carbon dioxide cycles, maintain the ongoing relationship between the atmosphere and the oceans. Photosynthesis is part of the carbon dioxide cycle and provides life-giving oxygen. The possible depletion of the protective ozone layer is one serious threat to the atmosphere today. Chemists are developing substitutes for the CFCs that seem to be damaging the ozone. An increase in the greenhouse effect, caused by an overabundance of carbon dioxide in the air, is another danger to our planet. The atmosphere is absolutely essential to life on earth. This precious envelope must be protected at all cost.

RH at weather station

ROALD HOFFMANN (SYNC):
Okay, let it go! We use weather balloons like this one to probe what goes on in the atmosphere. (cont.)

ROALD HOFFMANN cont:
And what goes on is not just a function of local weather patterns, but of all those global cycles. These marvelous cycles, on carbon dioxide, on water, they are actually examples of something more general, what we might call budgets, global balances, telling us how the elements and compounds are distributed on the earth, how they are transformed, how they are conserved. You might think of other balances of this type, on phosphorous, on sulfur, on nitrogen, on iron, on other elements essential to the earth. These global cycles reflect the equilibrium that the earth has reached. It's an equilibrium that has evolved with time. And then we came. When we were few, it didn't matter, but now we are a multitude, and our tools enhance the effects of what we do.

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THE WORLD OF CHEMISTRY

Program #18

THE CHEMISTRY OF EARTH

Producer John Ketcham

Air Script: October 31, 1988

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THE WORLD OF CHEMISTRY

Program #18: The Chemistry of Earth
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Air Script: October 31, 1988

Annenberg/CPB Project Logo and Music

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MONTAGE: Valley, lava flows, volcanos, miners, computer chips

NARRATOR (MUSIC and NAT SOUND under):
Look at any corner of our planet and it looks like it's been there forever, but the earth is dynamic, it's been continuously changing for four and a half billion years. The earth's chemicals have been mixed, separated, and deposited unevenly throughout the globe. The earth's surface is different from its interior. Why? And what are the forces that redistribute the elements and minerals? Rare and valuable minerals can be found in a few widely scattered areas. Scarcity inspires a search for substitutes, and today our advancing technology can find new exotic uses for the most common of substances. Both our past and our future is rooted in the chemistry of earth.

SUPER: THE CHEMISTRY OF EARTH

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH next to globe

ROALD HOFFMANN (SYNC):
The American philosopher and historian, Will Durant, observed civilization exists by geological consent. Think about that. Since everything that we use ultimately derives from the earth, the geographical distribution of minerals and ores determines directly global economics, politics, patterns of trade. Here is a sample of stainless steel. An important component in it is the metal chromium. Chromium is also used in alloys that make hub caps and jet engines. And where does chromium come from? From ores from deposits that are found mainly, as are those of platinum, as are diamonds, in South Africa, or in the Soviet Union. Another strategic metal, tin, is found mainly in Southeast Asia. There is oil under Saudi Arabia. There is very little oil under Israel. How did valuable minerals come to be in one place and not another? Well, there's a lot that we don't know about this yet. (cont.)

ROALD HOFFMANN cont:
We don't know why one part of the globe was chosen to be rich in chromium and not another, but we've learned a great deal about how nature concentrates minerals, how it does it on the floor of the ocean, or on the top of land. We've learned about how ore deposits are formed, the underlying chemistry of this planet.

MONTAGE: African bush veldt, mining shots, English ruins, rock blasting, construction machinery

NARRATOR (MUSIC and NAT SOUND under):
Here in the African bush veldt, an area the size of New England, located in Southern Africa, interesting chemistry has been at work. Just beneath the surface lies some of the world's richest deposits of platinum, rhodium and chromium. A mineral is a naturally occurring substance with a characteristic chemical composition. When minerals are concentrated and are economically valuable, they're called ores. Because some places are rich with ores and minerals, like South Africa, and others are not, the fortunes of whole countries, of people and their governments, can rise and fall based on the wealth found in their natural treasuries. (cont.)

NARRATOR cont:
Since prehistoric times, we have recovered and used a variety of minerals. How did our ancestors obtain the minerals and elements they needed from the earth? One of the early techniques used in this ancient tin mine in Cornwall, England, was to build large fires at the base of the rock cliffs. The intense heat cracked the rocks, exposing the tin ore, which was then mined. Today we use dynamite and ammonium nitrate to blast rock away from ore-rich veins. But while we blast and drill and probe at the earth, whatever we're able to extract is limited by our technology, our needs at the time, and cost. How have the minerals and elements come to be located where they are? To find out, we must begin at the beginning, billions of years ago.

GRAPHIC: Formation and differentiation of Planet Earth

NARRATOR (MUSIC under):
Scientists believe that within the swirling dust of the primordial cloud, chemical reactions were occurring. Most of the elements and a variety of minerals were there. Some minerals were decomposing, and others were forming. Gravity was drawing the planet together. Initially, the earth was a homogeneous sphere. (cont.)

NARRATOR cont:
In time, because of the natural radioactivity of some of the elements deep within the earth, the temperature rose, and iron, one of our most common elements, melted and sank to the center of the earth. The earth's core was forming. This was the beginning of differentiation. Different rocks and minerals began emerging from the single homogeneous sphere. Lighter molten materials floated up to the surface, where they cooled to form a primitive crust. The earth was becoming a layered planet, with a dense iron core in the center, just above it the mantle, which is composed of dense silicates, and a crust of lighter rocks and minerals.

GRAPHIC: Element abundance bar chart

NARRATOR (MUSIC under):
The whole earth itself is rich with iron and oxygen, silicon and magnesium, and minor amounts of other elements. But we can only conveniently obtain the elements which are abundant in the crust. Generally, the abundances in the crust are different from the whole earth, as this graph shows. Notice, only about six percent of the earth's iron is in the crust where we can mine it. The rest is at the earth's core. (cont.)

NARRATOR cont:
On the other hand, there are large numbers of combined oxygen, silicon, and aluminum in the crust.

Cliffs, volcano, lava flows

NARRATOR (NAT SOUND under):
But minerals aren't evenly distributed across the earth. In a few scattered places, rare and valuable elements have been concentrated. How? Ore deposits form in three basic ways. One way is by the crystallization of magma, molten rock, in huge chambers beneath the earth's crust. The magma rises and comes in contact with cooler rock near the surface. Dr. Phillip Candela.

INTERVIEW: Dr. Phillip Candela, University of Maryland

SUPER: Phillip Candela

DR. PHILLIP CANDELA (SYNC):
It loses heat to the surrounding cold rock and, therefore, it begins to crystallize. Now, when this molten rock begins to crystallize in the subterranean chamber that we call a magma chamber, there's not just one chemical substance crystallizing, but sometimes five to ten different chemical substances are crystallizing out of this molten rock.

Shots of lava flows, mining, geysers, hot springs

NARRATOR (NAT SOUND under):
Scientists believe that magma originates within the mantle itself. When conditions are right, the solidifying rocks can contain elements like chromium and platinum. This must have been the case in the bush belt of South Africa, where the ore deposits formed are both profitable and internationally strategic. The second way which mineral ore deposits form is through the action of superheated water. Deposits of tin, lead, and zinc minerals usually originate this way.

INTERVIEW: Dr. Phillip Candela cont.

DR. PHILLIP CANDELA (SYNC/VO):
As this hot water is rising, it dissolves metals, it can dissolve sulfur from the surrounding rock, and as this water rises to cool the levels within the earth's crust, it loses heat to the surrounding rock.

Shots of geysers and hot springs

Also, this rising fluid can boil the metal and sulfur dissolved in the water can combine to form sulfide minerals. These sulfide minerals may plate themselves along the walls of a fracture and form a mineral vein.

INTERVIEW: Dr. Phillip Candela cont.

For example, here we have a mineral vein. This is a granitic type of rock here that obviously had fractured. Hot rising fluids filled the fracture. Dissolved in that water was silicon dioxide, which precipitated out from the solution to form crystals of quartz, which is some of the clear glassy material within the vein. Also the solution contained a metal called molybdenum, and also contained sulfur. And, upon cooling, the molybdenum and sulfur united and precipitated from the solution, along the walls of the vein, to produce a vein which we now find in this rock of molybdenite, molybdenum disulfide and silicon dioxide, or quartz.

Geysers, hot springs, black smokers

NARRATOR (MUSIC and NAT SOUND under):
Scientists think beneath these geysers and hot springs, ore deposits may be actively forming. These hydrothermal vents are also common on the ocean floor. This is a black smoker, a geyser at the bottom of the sea. While we have just recently been able to see them up close, they are already yielding new clues about how ore deposits form. It's a fascinating process.

GRAPHIC: Hydrothermal ore genesis

NARRATOR (MUSIC under):
At the oceanic ridges, running north and south, in the Mid-Atlantic, and in the Pacific, hot magmas are pouring out, renewing the earth's crust. As these magmas cool, they contract and crack. Ocean water then penetrates down to the molten magma. The water heats and it rises. Sulfur and metallic compounds from the adjacent rocks dissolve in the rising water, and they react. When the hot mineral-rich solution comes in contact with the cooler waters, a temperature difference of nearly 400 degrees, minerals precipitate out, often collecting in the cracks and fractures of the rocks.

INTERVIEW: Dr. Phillip Candela cont.

DR. PHILLIP CANDELA (SYNC):
They gave us direct visual proof that our ideas of the circulation of water around magma chambers and the stripping of metals from surrounding rocks, actually is a valid process in the formation of hydrothermal ore deposits.

River sedimentation

NARRATOR (NAT SOUND under):
The third process by which ore and mineral deposits form is sedimentation. Sedimentation is a physical, not a chemical, process.

DR. PHILLIP CANDELA (VO):
Bits of rock and mineral matter can be carried by flowing water. In areas where the velocity of water has decreased, the particles of rocks and minerals that are carried by the flowing water may settle out.

Rock quarry, building construction, ancient Greek buildings

NARRATOR (NAT SOUND under):
Because they are at the surface, and because they are relatively soft, sedimentary rocks have been mined, cut, and shaped throughout civilization. In many ways sedimentary rocks have shaped our history. Our cities were built with them. We make roads, skyscrapers, and statues of limestone and marble. Our ancestors built with it, too. They wanted their buildings to last, so they used rock. They couldn't have known the chemical environment would change to conspire against them.

DS in lab

DON SHOWALTER (SYNC):
Here we have a couple of pieces of common sedimentary rock. They're limestone. They're both made of calcium carbonate. This limestone came from Indiana. This one is Italian marble. Again, both of them calcium carbonate. (cont.)

DON SHOWALTER cont:
Now, we've used that material to build buildings, to make monuments, statues. But we have a problem now in modern day. Certainly you've heard of acid rain. On acid rain, the problem with that is the acid will react with that calcium carbonate, with that limestone, and cause deterioration of that substance. Let's do a test and I can show you how that works. What I'm going to do is add a little hydrochloric acid to the limestone. Now, geologists use this as a test for limestone, because you'll see why, there's certainly a reaction. Put a little bit of acid right on the limestone. Watch what happens. Oh, see the bubbles coming off of that? Now, here's the marble piece, Italian marble. It does the same thing. Of course it should, they're both calcium carbonate. The reaction now that is happening is that the calcium carbonate reacting with the hydrochloric acid, to produce carbon dioxide gas given off, as well as some water, and it's left then with some calcium chloride, some salt that's left on there.

MONTAGE: Buildings and sculptures in Venice, Italy

NARRATOR (MUSIC under):
Limestone and marble have always been important building materials, but they are both calcium carbonate. These sculptures and renaissance buildings in Venice, Italy, are priceless treasures from our past. Because they are made out of marble, the past is crumbling before our eyes. These works of art are being exposed to acid rain, which reacts with the calcium carbonate, turning these sculptures into soluble calcium salts.

MONTAGE: Plants, caves

NARRATOR (MUSIC under):
The same chemical reaction involving acidic rain and calcium carbonate, has been going on naturally for millions of years. It's how caves are formed. Although carbonate minerals are nearly insoluble in water, they are readily dissolved by the carbonic acid which is in the ground water.

EQUATION

As this diluted carbonic seeps through the joints of the rock formations, the limestone can be dissolved away. Over time, a cave is made. In this reaction, an equilibrium is reached. Calcium carbonate and bicarbonate exist together in the solution. It's a reversible reaction, which we can duplicate in the lab.

DS in lab

DON SHOWALTER (SYNC):
What if I took some of this calcium oxide, calcium carbonate minus the carbon dioxide, and put it into this distilled water, just plain water. You form a cloudy solution of calcium hydroxide. Now, what could we do with this in an interesting way? Now, there's another process that goes on here. What if I took this solution, poured it through the filter paper there. I would then have a solution of calcium hydroxide, or really, a solution of calcium oxide, if you look at it that way, too. One of the things I can do, I can add that carbon dioxide back onto there. Let's see if I can add it back on. So I can take that filtered -- I already did the filtering process for you -- take some of this filtered solution of calcium oxide, really calcium hydroxide, a base, and blow into it. Now, I'm not gonna drink it, am I? I'm gonna blow into there. So blowing in means now that I'm adding carbon dioxide. We breathe in oxygen, we breathe out carbon dioxide. Watch what happens.

EQUATION

There it goes. Now, the cloudiness is calcium carbonate. I put the CO2 back on to that calcium oxide. Now, let me speed this process up a little bit for you by adding in some dry ice. (cont.)

DON SHOWALTER cont:
The ice is solid carbon dioxide, so it's a more concentrated form. Put that in there. I want to put quite a bit of it. So initially what you will see is that solution getting more cloudy, forming more calcium carbonate. But there's an interesting phenomena that occurs, and what that is is that bicarbonate will be formed.

EQUATION

Now, the bicarbonate is soluble. It will dissolve in the solution. And hopefully we'll see it clear up. Now, this process that we've talked about is a reversible process. We've shown a little bit of that, calcium oxide into a water solution, and then we can add the carbon dioxide back into there. Oh, look, it has cleared up. So now that we see that the bicarbonate must have been formed. This sounds like a fairly complicated procedure, but it's really not that complicated. In fact, nature does this very, very well underground.

Mammoth Cave, Kentucky,
desert shot

NARRATOR (MUSIC and NAT SOUND under):
Here in Mammoth Cave, Kentucky, the same natural processes we saw in the laboratory are at work. Wherever the water drips, stalagmites form on the cave floor, and stalactites form on the ceilings around the source of the dripping water. The building process is slow. It takes over 100 years to form a single inch of a stalagmite or a stalactite. Another common compound, like calcium carbonate, which forms sedimentary rock and is found nearly everywhere, is silica, silicon dioxide or, as we know it, sand.

RH at quarry

ROALD HOFFMANN (SYNC):
Sand. It not only feels good between my toes at the beach or running through my fingers. What a simple material, and thousands of years of use. What is sand? Sand is quartz, finely divided, and quartz is a compound of silicon and oxygen, bound extremely strongly together. And it's only in this century that we've learned how to break apart that bond efficiently and economically, and to make large quantities of pure, very pure silicon. It's changed our lives. The silicon revolution is only 40 years old. Isn't it ironic, the new information age being shaped from simple sand?

Desert shots

NARRATOR (NAT SOUND under):
Sand. It's even more common than limestone. It contains two of the most abundant elements on earth, silicon and oxygen. Pure silicon doesn't exist in the elemental state, and it's been only recently we have been able to extract the silicon from the silicon dioxide.

MONTAGE: Computers and their parts

NARRATOR (MUSIC under):
The new revolution of silicon technology has been built on these discoveries. If silicon and oxygen are the two most abundant elements in the earth's crust, how do they combine with each other to form a variety of substances, and what structure do they have?

GRAPHIC: Silicate structure

NARRATOR (MUSIC under):
A look at the basic structure of a silicate reveals a silicon atom covalently bonded to four oxygen atoms, forming a tetrahedra, with the silicon in the center. This is the basic unit of silicate minerals. Two tetrahedra can link together by sharing an oxygen atom. A chain starts to form, as two oxygen atoms are shared by two silicon atoms. (cont.)

NARRATOR cont:
This chain is the unit in fiber silicates, like asbestos. Two chains might link together with every other silicon sharing oxygen atoms. And the chains can now link up, using the silicon-oxygen-silicon bonds. Sheets form, as in the structure of mica. The sheets can then stack one on top of another. Now each of the tetrahedra share all oxygen atoms with other tetrahedra, forming a three-dimensional framework like quartz. The length of the bonds between the silicon and the oxygen atoms are all the same. On this atomic scale, it's a symmetrical structure of indefinite length. Silicates are hard to melt. The covalent silicon-oxygen bonds are strong. To extract elemental silicon out of quartz, one has to mix it with carbon and heat it to a high temperature. But the silicon obtained that way still isn't pure enough for application in today's technology of chips and solar cells.

Exterior: AT&T Bell Labs, archival photograph of William Pfan

NARRATOR (NAT SOUND under):
AT&T, Bell Labs, in Short Hills, New Jersey. It was here a scientist named William Pfan advanced the technique of purifying silicon, called zone refining.

Dr. Winslow walking down hallway

DR. FIELD WINSLOW (VO):
We had a remarkable collection of brilliant people here when I first showed up on the scene in '45.

Dr. Winslow with lab worker

NARRATOR (NAT SOUND under):
Dr. Field Winslow is an organic chemist.

LAB WORKER (SYNC):
We have to seal off the tube with a monomer in the next couple hours before it explodes.

NARRATOR (NAT SOUND under):
Although not directly involved in the semiconductor project, he remembers the day William Pfan came into his office.

INTERVIEW: Dr. Field Winslow, organic chemist, AT&T Bell Labs

SUPER: Field Winslow

DR. FIELD WINSLOW (SYNC):
Came up to visit me one day and said he had this new idea, that what I want to do is to purify silicon and germanium by placing these materials in a boat and sweeping a hot zone repeatedly over this boat, so that you melt the material in the boat in zones, and sweep these zones along the length of the boat, and repeat it. And in the hopes of driving the impurities ahead of this hot zone.

Archival photographs of William Pfan

NARRATOR:
The principle William Pfan employed was, when a liquid solidifies, the crystal doesn't easily incorporate foreign materials. As a result, the impurities concentrate in a liquid zone.

INTERVIEW: Dr. Field Winslow cont.

DR. FIELD WINSLOW (SYNC):
And the object is that when this silicon resolidifies, the impurities in this molten zone are pushed ahead of the solidifying material. And each time more and more of the impurities are swept toward one end of the boat.

Archival footage and photographs of work at Bell Labs, transistor, silicon crystal pulling, computer chip

NARRATOR (MUSIC under):
Bell scientists knew the electrical properties of silicon depended on its purity. They knew if they could obtain pure silicon and then dope it, that is, add trace amounts of other elements to it, they could precisely control its conductivity. As a result of Pfan's work in purifying silicon, it became possible to design and build transistors which replaced the vacuum tube. That was nearly 40 years ago. Techniques have changed. Now they pull silicon crystals, slice them up, and then dope them with small amounts of the trace elements. In this way, changes in technology and demand can, in turn, change our needs for different elements and their minerals.

SUPER: THE CHEMISTRY
OF EARTH

MONTAGE: African bush veldt, lava, volcanos, black smokers, river sedimentation, quarry, Venetian sculptures, cave, desert, pulling crystals, computer board

NARRATOR (MUSIC under):
To review: We live on a dynamic planet, and the differentiation of materials in the planet is still occurring. The elements and minerals found at the earth's core are different than those found at the surface. And different chemical compounds and minerals are still being formed and deposited in widely scattered places. The three processes at work are magmatic action, where minerals are crystallized out in underground chambers of molten rock; hydrothermal action where, from superheated water, chemical compounds are deposited; and sedimentary action, where, through physical rather than chemical processes, rivers and streams transport minerals and deposit them in new areas. One of the common sedimentary rocks is limestone, calcium carbonate. It's been used throughout civilization as building material, but acidic rain reacts with the calcium carbonate, turning ancient works of art into calcium salts. The same reaction is responsible for caves. (cont.)

NARRATOR cont:
Another common substance, sand, has only recently been put to a more exotic use than building. By first obtaining silicon from the silicon dioxide and then purifying it, the information revolution was made possible.

RH at quarry

ROALD HOFFMANN (SYNC):
This quarry is a symbol of our dependence on the earth. We take from it its riches, some given to us simply like sand, some that have to be torn from its innards, like the rock or iron ore, some that are released by our ingenuity, like silicon. We are very successful at what we do, and so I don't doubt for a minute that under your feet there is another technological revolution waiting to be released by your hands, by your mind. But there is more, and this quarry also symbolizes that. The earth, the oceans, the atmosphere, we ourselves have been part of a grand enterprise, a living planet. It's not been a static one, it's changed. Remember those marvelous cycles of carbon dioxide, of water that we talked about in an earlier program? They've evolved with time. (cont.)

ROALD HOFFMANN cont:
But then we come on the scenes, masters of transforming a technology, and we have modified the cycles, not just one of them but many of them, and we intrude on them with a chemical shock, with a perturbation that is introduced in the geological equivalent of a blink of an eyelid, a mere 100 years or so. The perturbations that our civilization, our culture, have introduced to the earth may exceed the repair mechanisms that this marvelous organism, chemical system, has evolved for itself. This excellent canopy, our home in matter and in spirit, it deserves our best.

Credits, Closing Montage, Closing Music

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