THE WORLD OF CHEMISTRY

Program #13

THE DRIVING FORCES

Producer John Boslough

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: Rocket launch, grapes, match lighting, construction, pouring wine, bread rising, explosion

NARRATOR (NAT SOUND under): We live in a world of molecules interacting with other molecules in chemical reactions. What makes the reactions occur? Why are some fast, and some slow? The rate of a reaction turns out to be critical, whether you're involved in construction, or wine making, or simply preparing food. To understand these dynamics, we must probe the driving forces.

SUPER: THE DRIVING FORCES

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in apple orchard

ROALD HOFFMANN (SYNC):
Chemistry is not just bottles on a shelf. That would be pretty dull. It's about chemical reactions, about compounds changing to make other compounds, about molecules bouncing around. It's a wonderful world of transformations. Take this apple tree. It grew from a seed, but, on the way, it used water from the soil, minerals and fertilizers from the soil. Also it took in carbon dioxide from the air, and the sunlight provided it with the energy to do what? To run a chemical factory making a whole host of marvelous molecules, the chlorophyll in the leaves, the pigments in the skin of the apple, the sugars within, and it's still not static. Those leaves are going to change color. They are going to turn yellow. That's another chemical reaction. This whole tree will die someday. That's another set of chemical transformations.

MONTAGE: Volcano exploding, lava flowing, lake, city street scenes, river rafting, flower blooming, wood burning in fireplace, automobile driving, testing chemical plant water, drop of water in glass

NARRATOR (MUSIC and NAT SOUND under):
Every change has a natural direction in which it occurs, whether in the wilderness, or in the bustling world we've created. Rivers flow to the sea, never the reverse. In a complex series of chemical reactions, a flower blooms, then shrivels and dies, never the reverse. Wood burns, producing carbon dioxide and water. An automobile burns gasoline to carbon dioxide and water, and also produces heat and power for motion. In a vast chemical plant, an array of chemical reactions takes place. Here, for instance, ethylene reacts with water to make ethyl alcohol. Why do all these changes go the way they go? What determines the natural direction of a chemical reaction? When wood burns, the energy of the system decreases and heat is released to the surroundings. This tendency to reach a lower energy is one of the forces that drives all chemical reactions. In the natural direction of most chemical reactions, the energy of the system decreases. Dr. Donald Showalter.

DS in lab

DON SHOWALTER (SYNC):
In this reaction, the reacting materials are potassium permanganate, this dark purple solid on this screen, and glycerine, this thick liquid. Now let's see what happens when we mix them. I'll put the glycerine onto the permanganate. Oop! There's some smoke coming out. Oh, look at the flame. Well, that reaction certainly releases energy, doesn't it? Now, what happened is that glycerine is a combustible organic liquid, and potassium permanganate is a concentrated source of oxygen. So when the two come in contact, they ignite spontaneously. So this kind of chemical reaction releases energy. The key word is "release." This is the type of reaction we call exothermic.

GRAPHIC: Energy diagram for exothermic reaction

NARRATOR:
In an exothermic reaction, the reactants have relatively high energy. The energy is depicted here in kilojoules. The products of the reaction have a lower energy. As the reaction proceeds downhill from high energy to low energy, reactants are converted to products and energy is released by the system, in this case, 300 kilojoules per mole reactant.

Shots of paper burning,
car driving down highway,
bread rising

NARRATOR (NAT SOUND under):
As we have seen, most chemical reactions tend to release energy, usually in the form of heat. An automobile is designed to release energy in the form of motion down the highway and the heat from the engine. What about reactions in which heat is absorbed?

DS in lab

DON SHOWALTER (SYNC):
This time I want to do a reaction that takes in energy. Now, how're we gonna see that? Let's do the reaction and find out. I'm going to mix barium hydroxide, a white solid, with another white solid, ammonium thiocyanate, and before I mix them, I'm gonna put a little water onto this board, and I'll move that water over here, put the beaker onto the board right on top of that water, then I'll put the solids in there, and we'll see what happens. There's the barium hydroxide, and here's the ammonium thiocyanate. I'm gonna mix it. Oh, it's getting moist in there. It's getting liquid. And that's understandable, because one of the products is water. You can also smell a little ammonia coming off of there. That's another product. Oh, the beaker's getting cold down at the bottom now. (cont.)

DON SHOWALTER cont:
I'll keep stirring so that the reaction proceeds, and we'll see if we can tell whether or not energy is taken in. Oop! Look at this! The beaker is frozen to the board. This is an example of an endothermic chemical reaction, one that takes in energy. In this case, the energy is taken in from the surroundings. That's why the beaker got so cold that it was able to freeze that little bit of water that I put on that board. So the beaker is frozen, very tightly, to that board. Look at that!

GRAPHIC: Energy diagram for endothermic reaction

NARRATOR:
In an endothermic reaction, the reactants have a relatively low energy. The products have a higher energy. As the reaction proceeds along the uphill slope from low energy to high energy, reactants are converted into products. In this process energy is absorbed, in this example, 400 kilojoules per mold reactant.

Shots of bees in flowers, bread on assembly line, blast sites

NARRATOR (MUSIC and NAT SOUND under):
Many important chemical reactions take in energy. Plants and animals will not grow without an infusion of energy. Reactions involved in cooking food also require that energy be absorbed. (SFX: Blast) But an energy change is not the whole story. There's a second driving force, a tendency towards increased disorder. The scientific name for this disorder is entropy.

DS in lab

DON SHOWALTER (SYNC):
Entropy is a fascinating subject. Let's see how it works. I've got a couple things to do that will show how entropy works as a driving force. Let's do this one first. This beaker has pure water. I'm gonna add a few drops of dye to that. Now, I already know that the dye and the water will not react chemically. Look at that! The dye and the water are mixing slowly in there, and they're doing that by them -- by itself. I'm not helping it out at all. Well, let me speed it up, though, a little bit. Now, any mixture is in a greater state of disorder than it is in the original materials. Now do you think we can get them back into their original containers? (cont.)

DON SHOWALTER cont:
(MUSIC/SFX up and out) But that's just a TV trick. We know that's not the way it happens in the real world. But what does this show us? That going from a state of disorder to a state of greater order is not the natural direction for almost any process. Let's try something else. Here I have some lettuce, and some tomatos, and some peppers. Get all those tomatos in there. Mushrooms, and cucumbers. You know what I'm gonna do. I'm gonna make a salad. I'm gonna toss that salad up here. Oh, it looks pretty good, huh? Stay in here. Looks pretty good to eat. If I kept tossing this now, will the salad go back to its original unmixed state? Well, you know the answer just as well as I do. Like the dye in the water, the salad shows us that the natural direction of change is toward greater and greater disorder, more entropy, increased entropy. Now, this is true for virtually any chemical reaction.

Shots of chemical reactions, lab shots, liquids, gases, chemists working in lab

NARRATOR (MUSIC and NAT SOUND under):
In what ways can entropy increase in a chemical reaction? There is more disorder, or greater entropy, if more molecules are formed. (cont.)

NARRATOR cont:
There is greater entropy if a liquid is formed from solids, or if a gas is formed from liquids or solids. And entropy rises if a mixture is formed, or if the volume of a gas is increased. Look again at the reaction that made the beaker freeze to the board. Why did this reaction occur? Energy was absorbed and the entropy increased. A liquid mixture, with more disorder, was formed in the beaker from two crystalline solids. The increase in entropy was large enough to overcome the absorption of heat. This must be true for all endothermic reactions. In industry, reactions have to work. Both energy and entropy effects determine that. If a reaction does work, if new molecules can be created, then the industrial design is given to the engineers and they focus on energy and materials.

Exterior and interior shots of Union Carbide plant in West Virginia

NARRATOR (MUSIC and NAT SOUND under):
West Virginia. Union Carbide. Chemicals for 500 different products: detergents, adhesives, plastic wraps and car seats, paints and waxes. Probe the panoply of pipes and towers and you find more than a flow of materials.
(cont.)

NARRATOR cont:
There's a flow of energy. Energy. Amidst scores of chemical reactions, the engineers must conserve it. Usually a reaction is exothermic, giving off heat. Plant designers want to reuse this heat to drive other reactions, to minimize waste of energy in the whole plant. So through the red pipes in this scale model, they'll transport steam, and out in the plant, steam is piped from point to point, reaction to reaction. Materials. The basic raw materials coming into the plant are coal or petroleum, both high in energy. First, ethane gas is produced, and then, by selective addition of oxygen to ethane, we get a variety of industrial chemicals.

SUPER (over plant shot):
Ethane, Ethyl Alcohol, Ethylene Glycol, Acetic Acid, Carbon Dioxide

NARRATOR (NAT SOUND under):
The plant is constructed so that each product in the chain of reactions has a successively lower level of energy. Ethane is at the top of the energy ladder. From this, ethyl alcohol is produced. Below that is ethylene glycol, used in antifreeze and adhesives. A further step down the ladder produces acetic acid, for polymers like vinyls and rayon. And at the bottom of the energy ladder are carbon dioxide and water.

RH at construction site

ROALD HOFFMANN (SYNC):
So whether a reaction will go or not depends on the balance of energy and entropy of the reactant and the product. And we can trade off one of these against the other. For instance, human beings like to have ordered things around them. We like to build. Can we construct such a local ordering, a local defeat of entropy in our environment? Yes, we can, if we put in energy. That is what is going on in this construction site in back of me. Energy and entropy tell us whether a reaction will go, but not actually how quickly it does go. For instance, concrete is being set in that building. It's important that it's set in hours and not in seconds, and not in days. Let's look at the rates of chemical reaction and how we can influence them.

MONTAGE: Construction, roads, dam, buildings, concrete trucks

NARRATOR (MUSIC and NAT SOUND under):
Roads, dams, bridges, churches, houses, and offices. There's chemistry in all that concrete. Trucked in slowly turning drums, the mixture of water and cement and gravel cannot set into concrete until it's spread on site. (cont.)

NARRATOR cont:
Boxed in place, it will be left to react slowly, water and cement reacting to produce microscopic bridges of calcium silicate with the gravel. If wooden forms are not left in place long enough, if not enough time is allowed for reaction completion, the consequences can be disastrous.

Still photographs of collapsed apartment building

NARRATOR (MUSIC and Siren SFX under):
In Virginia, in 1973, the rubble remains of a partially collapsed apartment complex. Fourteen died. Too much haste for the slow reaction rate which makes hard concrete. The rate of any chemical reaction depends on several factors. Don Showalter.

DS in lab

DON SHOWALTER (SYNC):
Let's take a look at one of the most common reactions of all, simple burning. Here I have a piece of wood. We all know that wood, if dry, will burn readily in air. Remember, air is about 21 percent oxygen. It's not burning. Oop. We've got to warm it up, don't we, to get it going. Let me warm it up with this match. Oh I'll warm it up, the oxygen of the air reacts with the wood. There it starts going. (cont.)

DON SHOWALTER cont:
Now, that's burning pretty well, but not really well. I wonder if it would burn any better in this 100 percent oxygen. Well, let's see. Oh, look at that. The rate of reaction has drastically increased. Now, what does this tell us? Well, there's a couple of things. The rate of the reaction is increased with increased temperature. Remember the match. And also, the rate of the reaction is increased with increased concentration of ingredients. Remember 20 percent oxygen, 100 percent oxygen.

Interior and exterior factory shots

NARRATOR (NAT SOUND under):
Temperature and concentration. Is there another general way of speeding reaction rate? There is, and it is employed in most reactions in the chemical industry. It involves using substances called catalysts.

DS in lab

DON SHOWALTER (SYNC):
Here I have a white powder, sodium potassium tartrate, about 30 grams. I want to dissolve that into this warm distilled water. The water's at about 70 degrees Celsius. That's a fairly large molecule. I want to perform a chemical reaction for you where I break this big molecule down, degrade it. (cont.)

DON SHOWALTER cont:
The way I do that is by adding hydrogen peroxide, a fairly strengthy solution, 30 percent hydrogen peroxide. Now, if there is a reaction, you should be able to see carbon dioxide given off, bubbles. Let's see if it happens. I'll pour it in there. Oop. Not many bubbles. Even though I heated it, and we know that heat increases the rate of a reaction. It didn't speed it up. So what else can we try? How about a catalyst? Let's add a catalyst. I'll put it into this container just in case it does go pretty fast. Now, here's the catalyst. It's a solution of cobalt chloride. Let's add that to this reaction mixture and see what happens. Now, a catalyst will speed up a chemical reaction. And look what's happening. The carbon dioxide bubbles are being given off, but one other stipulation for a catalyst is it must be the same at the end as it was at the beginning. Look at the rate of reaction. Notice it's green, so the catalyst is actually taking part in the reaction. Look at the steam being given off here. Oh. Now, if it's a true catalyst, what should happen? It should be the same at the end as it was at the beginning. Look at the color. It's back to that original pink color. What's a catalyst? It speeds up a chemical reaction, but it must be the same at the end of the reaction as it was at the beginning. It's pink again.

Slow motion shots of wine being poured into glasses

NARRATOR (MUSIC and NAT SOUND under):
Special biological catalysts, called enzymes, are present in yeast, and that's important to the fermentation process in wine making. It's one interest of food chemists like Dr. Theodore Labuza.

INTERVIEW: Dr. Theodore Labuza, food chemist

SUPER: Theodore Labuza

DR. THEODORE LABUZA (SYNC/VO):
The production of wine from grapes is a fermentation process. In this case, we take grape juice, which contains sugars, and we add a yeast to it.

Shots of wine making

In the ancient days, they didn't add yeast because they didn't know what yeast was, but there's naturally present yeast on the grape skins itself. And under the right temperature conditions, the yeast will ferment the sugars in there, produce alcohol, and the alcohol, in fact, prevents the growth of other microbes that would spoil it. If you didn't hold it under right conditions, you would end up with something that was really God-awful, it would not be a good Cabernet Sauvignon.

MONTAGE: Food transportation shots, sheep in New Zealand, food packaging

NARRATOR (MUSIC and NAT SOUND under):
Food is shipped across America and around the world. The rates of food spoilage, the rates of reaction, are vital knowledge for our global economy. A far-off country like New Zealand, for example, is almost wholly dependent on overseas markets for its lamb and butter and cheese. How do scientists study food spoilage and preservation?

Food packaging

DR. THEODORE LABUZA (VO/SYNC):
The kinds of reactions that cause food to spoil are not very different than what chemists study in pure chemical solutions, see.

INTERVIEW: Dr. Theodore Labuza cont.

Where I always like to talk about food, it's the study of messy chemistry. And the reason I say that is that, in a food which has so many different organic compounds and inorganic compounds together, there are lots and lots of different reactions that could have caused spoilage. What we can do, however, is narrow them down to several classes. One, reactions that are enzyme catalyzed. (cont.)

DR. THEODORE LABUZA cont:
For example, when you bite into an apple, you see it start to brown. That's an enzyme reaction. There's reactions that make it go rancid. Potato chips, for example, if they sit around for a long time, the fat goes rancid.

Shots of food preparation and packaging

NARRATOR (NAT SOUND under):
Modern techniques of food preparation and refrigeration have greatly reduced spoilage. Still, the shopper might like further proof that reactions have been retarded, that food is as fresh as possible.

INTERVIEW: Dr. Theodore Labuza cont.

DR. THEODORE LABUZA (SYNC/VO):
One of the more interesting things that we're doing in our laboratory here, which is an application of chemical kinetics,

Food chemists at work in lab, food packaging and spoilage label

is the study of little devices that can be used to monitor time-temperature when a food goes through a distribution cycle. Now, why do you want to do that? (cont.)

DR. THEODORE LABUZA cont:
Well, since foods deteriorate at a faster rate when the temperature goes higher, and at a slower rate when the temperature goes lower, if you had a device that could be put on a package that would essentially integrate the time-temperature exposure and show a color change that could be related to the loss of quality of the food, then, by simply picking up a package and looking at a device that may be on the package, you could tell how much more shelf life is left, so you'd know when to consume it.

Rocket launch shots,
freeze drying foods

NARRATOR (MUSIC and NAT SOUND under):
From supermarket to space. The manned space program has been an exciting challenge for the food chemists investigating rates of reaction. Dr. Labuza.

Astronauts in space,
eating freeze-dried foods

DR. THEODORE LABUZA (VO):
Why would one want a very long shelf life for space foods? The astronauts were only up there for a matter of days to maybe several weeks. Well, in fact, the foods had to be produced maybe six to nine months ahead of time because we never knew when a rocket was gonna go off. (cont.)

DR. THEODORE LABUZA cont:
And so they had to have the foods in storage, and what we wanted to make sure was by the time the rocket went off, the food was still of good quality. And that's why we really had to study the rate at which the quality was lost and the package it in such a way that we could minimize that rate of quality loss.

SUPER: THE DRIVING FORCES

MONTAGE: Chemical reactions, fire, construction workers, food preparation and packaging

NARRATOR (MUSIC under):
To review, in any chemical reaction, substances are transformed into completely different substances. The natural direction of a chemical reaction is determined by the tendency to go in the direction of lower energy and higher entropy. In an exothermic reaction, energy is released. In an endothermic reaction, energy is absorbed. The speed of a chemical reaction is determined by the nature of the substances involved, as well as their concentration and temperature. A catalyst is a substance that increases the rate of a chemical reaction. Sometimes, as in the case of preserving food, it is necessary to slow down a chemical reaction.

RH in field

ROALD HOFFMANN (SYNC):
You know, when I see that reaction that Don Showalter ran in the laboratory, when he mixed hydrogen peroxide with a solution of sodium potassium tartrate and at first nothing happened, and then he added a catalyst and there were color changes and bubbling, when I see that, a terrible urge overcomes me. I want to know what happens in there. I'm not satisfied with seeing the colors. I want to see what the molecules are doing. How can I do that? How can I find out something about those tiny things? Well, those colors can be looked at with a spectrometer. Those messages from within can be decoded. Oh, they happen quickly, those color changes, but I can try to move quickly, I can try to fight nature and slow down the reaction by cooling it. I can build a faster spectrometer. Slowly, laboriously, we can build up a picture of what happens in a chemical reaction, whether it's Don's experiment or in the leaves of that tree. The explanation must lie at the molecular level. This is what we'll see in the next program.

Credits, Closing Montage, Closing Music

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THE WORLD OF CHEMISTRY

Program #14

MOLECULES IN ACTION

Producer Stephen Redhead

Air Script: October 31, 1988

PRODUCED BY

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THE WORLD OF CHEMISTRY

Program #14: Molecules in Action
Producer Stephen Redhead
Air Script: October 31, 1988

Annenberg/CPB Project Logo and Music

Funder Credits

Shots of a chemical solution, chemical plant, lab demonstration, random molecule graphic

NARRATOR (MUSIC and NAT SOUND under):
There's more to this solution than meets the eye. It's worth $350,000, for a start, and the start is what gives it that value, for this solution makes other chemical reactions go. It's a catalyst. Giant chemical plants across the country wouldn't be feasible without small amounts of vital and expensive catalysts. What happens during a chemical reaction, and what role do catalysts play? To find out, we must look at molecules in action.

SUPER: MOLECULES IN ACTION

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in laboratory

ROALD HOFFMANN (SYNC):
Something is really going on in here. There is a color change and then the bubbling. One substance is being transformed into another one. In my body there are hundreds of chemical reactions going on. Some of them fast, some of them slow, they are influenced by the substances that are there, by catalysts, by temperature. But how is this really happening? Deep within at the molecular level, what is going on? Well, we know that in reactions bonds are broken or made. And we also know that molecules are constantly moving around. Could it be that reactions are simply the consequence of molecules bumping into each other? What a wonderfully simple idea -- that all this complexity in the beaker or in my body could be simply the consequence of random molecular collisions? What's even more amazing is that it's true.

MONTAGE: City street scenes, cells under microscope, auto plant, gymnastics, ski acrobatics, jet planes flying, random molecule graphic, glider flying, power lines, hydroelectric plant, subway, television sets in store window, cars crashing

NARRATOR (MUSIC and NAT SOUND under):
We are surrounded by objects in motion. Motion has always fascinated scientists. We build machines with moving parts. And marvel at the grace and power of our own movements. Moving objects possess kinetic energy, energy of motion. The faster an object moves, the more kinetic energy it has. If we could peer into the molecular world, we would see a blur of frenetic activity. The thermal energy of gaseous molecules makes them travel at incredible speeds. It is hard to imagine that nitrogen and oxygen molecules in the air are moving at speeds of more than 1500 kilometers an hour. One form of energy can be transformed into other kinds of energy. Energy transformations occur all around us. In hydroelectric power stations, kinetic energy of moving water is converted into electrical energy, which is then used in thousands of different ways. (cont.)

NARRATOR cont:
The kinetic energy of moving objects is transformed when they collide. In a car crash, there is an abrupt transformation of kinetic energy into sound, heat, and the kinetic energy of flying debris. In the molecular world, randomly moving molecules, with no way of avoiding each other, also collide. When molecules meet, one of two things happens. They either bounce like billiard balls or they break and reform, becoming different molecules. And this is a chemical reaction.

GRAPHIC: Collisions and energy

NARRATOR (MUSIC under):
Let's look at a specific example. In one step in the formation of hydrogen bromide, hydrogen molecules collide with bromine atoms. If these particles collide with insufficient energy, they simply bounce off each other. If the particles collide with sufficient energy, a reaction will result. Let's see that in slow motion. The two particles approach each other and collide. An activated complex forms, kinetic energy is converted into vibrational energy, an old bond weakens and breaks as a new one forms. The complex then splits to give the products a molecule of hydrogen bromide and a hydrogen atom.

Shots of blasting rock, balloon lab demo, archival footage of Hindenburg

NARRATOR (MUSIC and NAT SOUND under):
Collision theory helps chemists understand how chemical reactions occur, even the most dramatic ones. But not all collisions result in a reaction. The colliding hydrogen and oxygen molecules in this balloon will not react unless you give them some additional energy. A far more dramatic hydrogen explosion took place on May 6, 1937, over New Jersey. The world's largest hydrogen blimp, the Hindenburg, was preparing to land after another safe Atlantic crossing, but an accidental spark provided the additional energy for a terrifying reaction.

Archival footage of Hindenburg

RADIO ANNOUNCER (VO):
Within seconds, there was a terrific explosion aft and brilliant orange flames formed a backdrop for a tableau of death. The Hindenburg's seven million cubic feet of hydrogen gas had ignited. The ship's tail plummeted to the ground.

DS in lab

SUPER: Donald Showalter

DON SHOWALTER (SYNC):
Now, why did the hydrogen-oxygen reaction require additional energy, that extra push in order to get the reaction to go. Well, the reasoning is that every chemical reaction requires an activation energy. Now, activation energy is the minimum amount of energy needed to initiate a chemical reaction. Now, unless there are enough of the colliding molecules that have sufficient energy to exceed the activation energy, then no reaction will happen. Inside this glass tube is a mixture of two gases, nitric oxide and carbon disulfide. The reaction between those two gases has a fairly high activation energy, so I need to give it some additional energy. Now, in order for you to be able to see this reaction, we're gonna have to dim the lights.

Pole vaulter

NARRATOR (MUSIC and NAT SOUND under):
Activation energy is like an energy hill. Few reactions will occur unless they are given a push to get them over this hill.

GRAPHIC: Activation energy diagram

NARRATOR:
Here is an energy diagram showing the endothermic reaction between hydrogen and bromine. The reactants are on the left and the products are on the right. We can represent the activation energy as an energy hill separating reactants from products. In order to react, the colliding particles must have enough total kinetic energy to overcome the activation energy hill. An activated complex forms. Once the activation energy has been overcome, the complex splits and the reaction proceeds to completion, the products are formed.

Shots of furnaces, blowtorches

NARRATOR (NAT SOUND under):
Collision theory explains the effect of temperature on reaction rates. When you heat a chemical system, the reactants gain energy and move faster. Now the collisions are more energetic, more likely to overcome the activation energy hill. Therefore, more collisions result in a reaction and the reaction rate is increased.

GRAPHIC: Activation energy diagram

NARRATOR:
If we could lower the activation energy hill, we would get the same effect without having to raise the temperature. The lower the hill, the higher the reaction rate, because less energy is required for collisions to result in a reaction and the formation of product.

MONTAGE: Model with photographer, fabrics, aspirin, plastics, interior and exterior shots of Tennessee Eastman Kodak plant, oil platform, gas station, coal

NARRATOR (MUSIC and NAT SOUND under):
Fabrics, plastics, film, and aspirin. What do all these synthetic products share in common? Tennessee, Eastman Kodak. These products are all made using acetic anhydride manufactured here. There's something even more unusual down there. Local coal provides the chemical raw materials to make acetic anhydride. Yet without this rare South African metal, rhodium, there would be no plant at all. They used to make acetic anhydride from oil. With the rise in oil prices in the early '70s, the company began looking for alternative inexpensive materials. Coal was the obvious choice. (cont.)

NARRATOR cont:
First, it is gasified, producing hydrogen and carbon monoxide. At a later stage, carbon monoxide is reacted with methyl acetate to produce acetic anhydride. It is this crucial step which requires the rhodium. A rhodium compound acts as the catalyst. Catalysts are substances which increase the rate of a reaction without being consumed by the reaction. Catalysts do this by lowering the activation energy.

GRAPHIC: Effect of catalyst on activation energy diagram

NARRATOR:
Here again is our activation energy hill. With a catalyst, a new activated complex forms with a lower activation energy. More colliding molecules now have sufficient energy to overcome the hill, so the reaction rate is increased.

Exterior and interior shots of Tennessee Eastman Kodak, rhodium mining, lab work with rhodium

NARRATOR (NAT SOUND under):
The reaction to produce acetic anhydride has a very high activation energy. Without a catalyst present, the reaction would not be feasible. Rhodium is an extremely expensive and rare metal. It costs nearly $50,000 a pound. (cont.)

NARRATOR cont:
It is bought as a powder by specialized catalyst companies, and kept under lock and key until it is ready to be used. This batch of soluble rhodium trichloride is worth over $350,000. Stan Polichnowski is an industrial chemist with Eastman Kodak, and the co-inventor of their rhodium-based catalyst.

INTERVIEW: Stan Polichnowski, industrial chemist, Eastman Kodak

SUPER: Stan Polichnowski

STAN POLICHNOWSKI (SYNC):
We don't purchase rhodium metal. We need to purchase a soluble precursor that we can use to make our catalyst. There are companies that will take the metal and convert it to something that we can use directly in our, in our system. An example of that is rhodium trichloride, which we can use to make our catalyst, and it's a dark crystalline material, soluble, so we can make our homogeneous catalyst. From the rhodium precursor, we, in our process, produce an organometallic compound. This is an example of an organometallic compound. And by that I mean it has a central metal atom, with organic ligand attached to it. And in this case, the red are oxygen atoms, the blue are nitrogen atoms of pyridine rings.

Chemist at work in lab, plant shots

NARRATOR (MUSIC and NAT SOUND under):
If the rhodium is so expensive, how can it be profitable to use the catalyst in such a large-scale reaction? The answer lies in the fact that catalysts are not used up in reactions. Each catalyst molecule may react with thousands and thousands of molecules of reactant. So this catalyst need only be present in tiny amounts. In addition, as the mixture is drawn off, the catalyst is carefully separated from the acetic anhydride and recycled back into the reactor. Very little rhodium is lost.

INTERVIEW: Stan Polichnowski cont.

STAN POLICHNOWSKI (SYNC):
Without the development of a viable catalyst system for producing acetic anhydride from methyl acetate and carbon monoxide, we would not have built this complex at all.

Aerial shot of plant

NARRATOR (NAT SOUND under):
Because of their remarkable chemical properties, catalysts are used throughout the industry. Dr. Norman Hochgraf, Vice President, Exxon Chemical.

INTERVIEW: Dr. Norman Hochgraf, Vice President, Exxon Chemical

SUPER: Norman Hochgraf

DR. NORMAN HOCHGRAF (SYNC):
Within the petroleum industry, where most of the feed stocks for chemicals come from, catalysts are used to produce motor gasoline, heating oil, and feed stocks for chemicals. And within the chemical industry, catalysts are used not only to purify those feed stocks, but they're also used to polymerize the feed stocks, to make plastics, to make rubbers, and to make synthetic fibers. This industry not only wouldn't be profitable without catalysts, but in a sense, it wouldn't exist. Almost everything we do is the result of catalytic activity, which has been carefully designed, carefully selected, and built into our commercial operations.

RH in laboratory

ROALD HOFFMANN (SYNC):
But there is one problem that not even the most efficient catalysts can overcome. This is that few reactions run in only one direction. Oh, we'd like them to, but nature doesn't cooperate. Most reactions are reversible which means that they run in both ways, from reactant to product and then back again from product to reactant. (cont.)

ROALD HOFFMANN cont:
Both reactions go on at the same time, not in one molecule, but if we have a lot of molecules in a reaction flask, then some of the molecules are going from reactant to product and some of the other molecules are going back to the reactant.

Ski resort shots

NARRATOR (MUSIC under):
Reversible reactions often reach a balance, or dynamic equilibrium, where the rate of the forward and reverse processes are equal and the amounts of reactant and product remain constant. It's like an efficient ski resort. While some people are enjoying the descent, others are riding the chair lift back to the top. Despite all the coming and going, when the number descending equals the number returning on the lifts each minute, then an equilibrium is established. The number of people at the top and bottom of the slope remains constant.

GRAPHIC: Chemical equilibria -- a graphic analogy

NARRATOR (MUSIC under):
Chemical equilibria are based on the same principle. Here's another model. In this hydraulic model, fluid in Tank A represents reactant, and fluid in Tank B represents product. (cont.)

NARRATOR cont:
Let's follow a reversible reaction, beginning with just the reactant. Initially, with a large concentration of reactant present, the forward reaction proceeds quickly. Gradually the forward reaction slows down as the reactant is converted into product, but the reverse reaction now starts to increase as the product concentration rises. Eventually, an equilibrium is reached, the forward and reverse reaction rates are equal, and the amounts of reactant and product remain constant. Here the equilibrium favors the product over the reactant. In another system, the rate of the forward reaction is reduced. Notice the narrower pipe leading from Tank A to Tank B. Now at equilibrium the reactant is favored over the product. So the position of an equilibrium varies under different conditions.

RH in laboratory

ROALD HOFFMANN (SYNC):
Left to their own devices, molecules run reactions in both directions. But when we get into the lab trying to make something, we want the reactions to run in just one direction, forwards. How do we do it? Well the equilibrium system have certain restoring forces built in -- if you disturb it, it responds. (cont.)

ROALD HOFFMANN cont:
For instance, if we have a reaction running and then remove the product, the system will run on to produce more of it. If we raise the temperature, then the system will run in the direction of absorbing the heat. This idea was formulated by the French chemist, Henri La Chatelier in 1884 into the following principle.

Archival photograph of Henri Le Chatelier

SUPER: If a system at chemical equilibrium is disturbed, that system will respond by attempting to counter the disruption.

NARRATOR:
Le Chatelier's principle is one of the most important in chemistry. If a system at chemical equilibrium is disturbed, that system will respond by attempting to counter the disruption.

RH in laboratory

ROALD HOFFMANN (SYNC):
This principle allows chemists to manipulate reversible reactions.

DS in lab

DON SHOWALTER (SYNC):
Let's see Le Chatelier's principle in action by looking at this reversible chemical reaction. In each of these two beakers, I have two cobalt compounds. In this one, almost all of the cobalt ions are attached to water molecules. That's why it's pink. Over here, in this beaker, almost all of the cobalt ions are attached to chloride ions. That's why it's blue. Now, since this is a reversible reaction, we ought to be able to interchange between these two colors. I want to put some of that pink solution into this beaker. And then I'll add chloride ion. Oh, there's the blue color. And then watch what happens if I add water. It goes back to pink. Le Chatelier's principle tells us that if we add chloride ion, a reactant, then the equilibrium will shift to the product side to use up as much of that chloride as possible. And then if we add water to the system, the equilibrium will shift to the reactant side to use up as much of that excess water as possible.

Chemical manufacturing plant shots, farm machinery towing ammonia tank

NARRATOR (NAT SOUND under):
The ability to shift the position of the equilibrium in every action has important consequences for chemical manufacturers. Consider ammonia, the world's number two industrial chemical. Most of the 60 million tons produced annually makes fertilizer. Without it, farmers would not be able to grow enough food to feed us all.

EQUATION over plant shot

NARRATOR (NAT SOUND under):
Ammonia is produced by reacting nitrogen gas with hydrogen gas, quite straightforward. But there's a problem. The reaction is reversible.

Plant shots

NARRATOR (NAT SOUND under):
Now, the ammonia manufacturers are only interested in the product, so using Le Chatelier's principle, they must create the conditions to favor the forward reaction. This horizontal ammonia converter at IMC's plant in Sterlington, Louisiana, is one of the world's most efficient. The nitrogen for the ammonia reaction is obtained directly from the air, and most of the hydrogen comes from natural gas, which is reacted with steam in this huge reforming furnace. (cont.)

NARRATOR cont:
The nitrogen-hydrogen mixture is then piped to the ammonia reactor. The process uses an iron-based catalyst. This increases the rates of both the forward and reverse reactions. Therefore, it does not shift the position of the equilibrium. But the equilibrium is sensitive to temperature, pressure, and concentration. So the engineers manipulate these factors to favor the forward reaction as much as possible.

ANIMATED EQUATIONS
over plant shot

NARRATOR (MUSIC under):
First, temperature. The forward reaction is exothermic, heat is released. Now, if we lower the temperature in the reactor, more ammonia is produced as the system generates additional heat.

Shots in laboratory,
plant shots

NARRATOR (NAT SOUND under):
So the reactants enter the reactor at a relatively low temperature, about 590 degrees Fahrenheit. At lower temperatures still, the forward reaction would be favored more. But the rate of the reaction would become too slow. Therefore the engineers compromise between the rate and the yield of the reaction. What about the effect of pressure?

ANIMATED EQUATIONS
over plant shot

NARRATOR (NAT SOUND under):
In the formation of ammonia, one mole of nitrogen combines with three moles of hydrogen to form two moles of ammonia. Therefore, the pressure in the system drops. By increasing the reactor pressure, more ammonia is formed as the system responds by reducing the pressure.

Reactor and plant shots

NARRATOR (NAT SOUND under):
This reactor, then, is run at a very high pressure, over 2,000 pounds per square inch. The gas mixture is passed quickly over the catalyst, withdrawn, and the ammonia removed by cooling. Removal of the ammonia also favors its formation.

ANIMATED EQUATIONS
over plant shot

NARRATOR:
Here again is the ammonia synthesis reaction. If we remove some of the ammonia, the equilibrium shifts to the right as more nitrogen and hydrogen react to moderate that loss.

Reactor and plant shots

NARRATOR (NAT SOUND under):
After the ammonia is removed, the unreacted nitrogen and hydrogen are recycled through the reactor. It is extraordinary that over all, about 99 percent of the reactants are converted to ammonia, a very efficient process, thanks to Le Chatelier's principle.

SUPER: MOLECULES IN ACTION

MONTAGE: Lab demonstrations, pole vaulter, program graphics

NARRATOR (MUSIC under):
To review, chemical reactions occur as a result of molecular collisions. All chemical reactions have an activation energy. In order to react, colliding molecules must have enough kinetic energy to overcome that activation energy. Catalysts speed up reactions by lowering the activation energy. Most reactions are reversible. In a closed system, reversible reactions come to a dynamic equilibrium. According to Le Chatelier's principle, the position of an equilibrium will shift when the system is disturbed, so as to moderate that disturbance.

Archival photograph of
Fritz Haber

ROALD HOFFMANN (VO/SYNC):
The modern industrial synthesis of ammonia was devised by Fritz Haber, a German/Jewish scientist, a university professor.

RH sitting on steps
of building

I want to tell you his story because it illustrates so well how chemistry interacts with the economics and politics of its time. As a young man at the turn of the century, Haber witnessed the agricultural revolution, the systematic use of chemical fertilizers. The natural supplies of these, for instance from South America were limited and so Haber devised ingeniously in 1909 using his knowledge of gas reactions and Le Chatelier's principle, the modern synthesis of ammonia. And he did it just in time to assure Germany's agricultural independence during the first world war, when its supply lines to South America were cut. That same ammonia was used for making explosives. Haber's contributions to mankind were not all positive. A strong patriot, nothing wrong with that, he devoted his intellect and energies during the war to the making of poison gases, to chemical warfare. And his life ended in a personal tragedy. (cont.)

ROALD HOFFMANN cont:
In 1933, the Nazis came to power with a weird baggage of ideology, including anti-semitism. Overnight the great German patriot and chemist Fritz Haber became the Jew Haber. He was forced to resign his post in Berlin. He left the country. The next year he died of a heart attack, let's say it was a broken heart, in exile abroad.

Credits, Closing Montage, Closing Music

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