THE WORLD OF CHEMISTRY

Program #15

THE BUSY ELECTRON

Producers Jack Arnold
and Robert Kaper

Air Script: October 31, 1988

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Annenberg/CPB Project Logo and Music

Funder Credits

MONTAGE: Rusting metal, batteries, graphics, lab demo, chemical reaction, electrolysis

NARRATOR (MUSIC under): Corrosion. Corrosion involves the transfer of electrons. Batteries produce electrical current. How? Through chemical reactions involving the transfer of electrons. Can electrical current split water into hydrogen and oxygen? Yes, through the process of electron transfer. Chemical reactions can produce electrical current. Electrical current can produce chemical change. And it's possible because of the tiny, ubiquitous and, above all, busy electron.

SUPER: THE BUSY ELECTRON

THE WORLD OF CHEMISTRY OPEN: Montage, Music, Logo

RH in botanical garden

ROALD HOFFMANN (SYNC):
Oxygen was discovered just over 200 years ago by Scheele, Priestley, and Lavoisier. It's very reactive, this life-giving element. Things burn in it, metals react with it. The name "oxidation" came into use. In time, it was discovered that many other chemical reactions, not those necessarily involving oxygen, shared with oxidation something much more fundamental, and that's the transfer of electrons. But the old names hang on, and even though oxygen is not essential, we still use the old word "oxidation." Oxidation means the loss of electrons, and its opposite, the gain of electrons, is called reduction.

MONTAGE: Shots of rusting metal

NARRATOR (MUSIC and NAT SOUND under):
Oxidation and reduction. One of their effects we're most familiar with is corrosion. It's a common but complex series of chemical reactions. Metal atoms give up their electrons to other elements, often oxygen. They oxidize. Iron and steel form iron oxide, rust. Rust stimulates the production of more rust. Eventually there are no iron atoms left. But metal corrosion doesn't always lead to inevitable destruction. (cont.)

NARRATOR cont:
The product formed when some metals corrode actually stops further corrosion. The copper in bronze corrodes to a green protective layer. It blocks out oxygen and moisture and protects the underlying metal. Aluminum corrodes to aluminum oxide, a tough layer that stops further oxidation. But the runaway oxidation of iron and steel creates special problems. Billions of dollars are spent annually trying to stop it.

Shots of painting in an automobile factory, close up of corroded pipe

NARRATOR (NAT SOUND under):
An obvious way is to keep oxygen and moisture away from the metal. That's one reason for paint. But corrosion occurs in a lot of places that can't be protected with paint. Hot water races through the tubes inside boilers at extremely high temperatures. Oxidation can eat pits in the metal and cause the tube to burst. Dr. Jack Kelly, of the W. R. Grace Company, studies ways to reduce boiler tube corrosion.

INTERVIEW: Dr. Jack Kelly,
W. R. Grace Company

SUPER: Jack Kelly

DR. JACK KELLY (SYNC):
This is extremely serious, because if you do have pitting attack, you lose metal, and metal, there's no chemical treatment that I'm aware of in which you can replace the metal. Eventually this tube, this pipe, failed and had to be replaced. In this case, the primary corrosion process involves oxygen interacting at the surface with iron ions, and oxidizes it and removes it from the surface.

Chemist at work in the lab,
analyzing and testing,
shot of rust on ship's hull

NARRATOR (NAT SOUND under):
Chemists who specialize in the field, use sophisticated instruments to analyze corrosion deposits. An electron microscope first locates a deposit for investigation. Then the elements that make up the deposit are analyzed by computer. It scans through the periodic table. The symbol for iron indicates the presence of iron oxide, rust. Iron exposed to oxygen alone often corrodes very slowly, but the presence of other elements, such as calcium, can greatly speed up the reaction. Other external conditions can accelerate the process even more. Iron rusts much faster in salt water than in fresh water. (cont.)

NARRATOR cont:
The reason is that salt water is a good conductor of electricity. Electrons are transferred much more rapidly and the rate of oxidation is enormously increased. The oxidation rate can be increased even more by raising the temperature and using a more reactive metal, such as magnesium. Don Showalter.

DS in lab

DON SHOWALTER (SYNC):
That was some chemical reaction, wasn't it? I heated a piece of magnesium ribbon. That was quite a display of chemistry, but what does it have to do with electron transfer?

EQUATIONS

Well, if you think about it, the magnesium lost electrons, and the oxygen from the air gained electrons, and it formed magnesium oxide. There's the connection.

Close up of chemical reaction

NARRATOR (MUSIC under):
Here's another example of oxidation and reduction. A strip of zinc metal is placed in a copper sulfate solution. A reddish deposit of copper metal forms on the zinc. Where has it come from?

EQUATIONS over reaction

NARRATOR (MUSIC under):
Each neutral zinc atom loses two electrons. It's oxidized. The copper ions in solution gain two electrons. They're reduced to neutral copper atoms.

Close up of chemical reaction

NARRATOR (MUSIC under):
The reverse reaction won't go because zinc loses electrons more easily than copper. Can we harness this transfer of electrons to do something useful? Yes, in the electrochemical cell.

MONTAGE: Batteries, uses for batteries, men on the moon, pacemaker, surgery

NARRATOR (MUSIC and NAT SOUND under):
Electrochemical cell, not exactly a household phrase, but in every home we're surrounded by them. Take away the labels and the cover and that's what batteries are. Batteries can raise the garage door, and they can raise the roof. Without batteries at hand, you'd be forced to leave your seat. Without batteries in your smoke detector, you could be forced to leave your home. Batteries. (cont.)

NARRATOR cont:
Other than groping in the darkness, where in the world would we be without them? Certainly not on the moon. But when it's hard to get there and difficult to stay, a light-weight battery makes the going easier. With the heart pacemaker, they can prolong life itself. How do electrochemical cells work? Just how can we make the copper-zinc reaction we saw earlier power an electrochemical cell? Don Showalter.

DS in lab

DON SHOWALTER (SYNC):
I've set one up here for you. This now a copper-zinc electrochemical cell. It consists now of a copper electrode into a copper salt solution, in this case copper sulfate. And then a zinc electrode in a zinc salt solution. Again, it's zinc sulfate in this case. Now, I've connected it with this porous paper bridge. Sometimes you will see people use a porous barrier that's used in the same container rather than have two separate containers, and that will separate the solutions and allow the ions to come through there. We also have an external circuit here, wiring now, that will hopefully carry the product of this reaction. This now is a chemical reaction that's going to occur, and it's going to produce an electric current for us. (cont.)

DON SHOWALTER cont:
Let's see if it does that. I'll connect it here so we finally have a completed circuit, and watch the meter. There's the electric current.

GRAPHIC: Molecular level animation of copper-zinc electrochemical cell

NARRATOR (MUSIC under):
But beneath the surface, deeper into the chemistry of an electrochemical cell, how is an electric current really produced? A good place to start is at the zinc electrode awash in the zinc sulfate solution. Here on the electrode surface, here in the molecular world, there are countless zinc atoms, and as each one moves into solution, two electrons remain on the electrode. This is oxidation. On the electrode, electrons not only accumulate, they move. A constant movement of electrons. They push up into the wire, through the voltmeter, and onto the copper electrode in the copper sulfate solution. Here positive copper ions are pulled to the electrode. They combine with electrons from the zinc to form copper atoms. At the boundary between the solutions, positive zinc ions move toward the copper electrode, and negative sulfate ions move toward the zinc electrode.
(cont.)

NARRATOR cont:
This balance of ions moving through the boundary keeps current flowing in the electrochemical cell. Why should electrons always move externally from zinc to copper? Different metals have different tendencies to give up electrons. Zinc gives up electrons far more readily than does copper.

Batteries on an assembly line

NARRATOR (MUSIC and NAT SOUND under):
Commercial batteries use a variety of electrodes, but each type will always use two metals or compounds with different tendencies to give up electrons. It's what makes a cell work, and when a cell works, a cell sells.

Duracell commercial

Energizer commercial

NARRATOR (MUSIC and NAT SOUND under):
Head to head, Duracell and Eveready, alkaline batteries account for 70 percent of the industry. Annually, a multi-billion-dollar business.

Duracell commercial cont.

Energizer commercial cont.

Batteries and their uses, Wilson Greatbatch working in shed

NARRATOR (NAT SOUND under): Claims of longer life and more power abound. In competition, technology can thrive, but sometimes an advance in science can come from an unlikely source. Several years ago, this inventor had an outrageous dream to prolong life, human life. Wilson Greatbatch.

Wilson Greatbatch working in shed

WILSON GREATBATCH (VO/SYNC): I quit all my jobs, and with the two thousand dollars, I went out in the barn in the back of my house and I built 50 Pacemakers in two years.

INTERVIEW: Wilson Greatbatch

SUPER: Wilson Greatbatch

I started making the rounds of all of the doctors in Buffalo who were working in this field, and I got a consistently negative result. The answer I got was, well, these people will all die in a year, you can't do much for them, why don't you work on my project, you know. (cont.)

Archival photographs

WILSON GREATBATCH cont:
When I first approached Dr. Shardack with the idea of the Pacemaker, he, alone, thought that it really had a future. He looked at me sort of funny, and he walked up and down the room a couple times. He said, "You know," he said, "if you can do that," he said, "you can save ten thousand lives a year."

Newspaper clippings, archival photographs

NARRATOR:
In 1958, a medical team implanted the first heart pacemaker, but for the next few years there was one major problem.

INTERVIEW: Wilson Greatbatch cont.

WILSON GREATBATCH (SYNC/VO):
After the first ten years, we were still only getting one to two years out of pacemakers, two years average, and the failure mechanism was always the battery. It didn't just run down, it failed. The human body is a very hostile environment, it's worse than space, it's worse than the bottom of the sea. You're trying to run things in a warm salt water environment. The first pacemakers could not be hermetically sealed, and the battery just didn't do the job. (cont.)

WILSON GREATBATCH cont:
Well, after ten years, the battery emerged as the primary mode of failure, and so we started looking around for new power sources. We looked at nuclear sources, we looked at biological sources, of letting the body make its own electricity, and we looked at rechargeable batteries, we looked at improved mercury batteries.

Photographs of lithium battery and the pacemaker

And we finally wound up with this lithium battery. It really revolutionized the pacemaker business. The doctors have told me that the introduction of the lithium battery to pacemakers was more significant than the invention of the pacemaker in the first place.

Exterior of Wilson Greatbatch, Ltd., shots of lithium batteries

NARRATOR (MUSIC and NAT SOUND under):
From the Greatbatch origins, new applications of the lithium battery have expanded way beyond the first specialized use. Certain companies are pushing the lithium technology into broad consumer markets. Peter Clark is a scientist at Kodak's subsidiary, Ultra Technologies.

INTERVIEW: Peter Clark,
scientist, Ultra Technologies
(Kodak subsidiary)

SUPER: Peter Clark

PETER CLARK (SYNC/VO):
Basically, our lithium battery operates much the same way that other primary batteries operate that we're familiar with. Now, we need two electrodes in the battery. The first is the anode, and it's made of lithium metal. The second electrode, we call the cathode, and it's manganese dioxide. We also need to have an electrolyte solution that these two electrodes are immersed in, and its job is to allow ions to flow from one electrode across to the other. The other very important part of the battery is the separator, and it's a membrane which is suspended between the two electrodes in the electrolyte and its job is to also allow ions to pass very freely through it, but to prevent the two electrodes from physically touching, because if that happens then we have a short circuit and the battery doesn't perform.

Interior shots of
Ultra Technologies

Lithium is a very light metal, and also very reactive metal, likes to be oxidized very readily. It has the capability to provide more electron activity than other materials.

INTERVIEW: Peter Clark cont.

PETER CLARK cont:
Therefore, it can supply much more electrical energy per unit volume or per unit weight, since it's a very light material. That makes it very desirable for batteries because today everybody would like to have more energy, less weight, less space, and lithium helps to do that.

MONTAGE: Uses for batteries, graph

NARRATOR (MUSIC and NAT SOUND under):
Indeed, the claimed advantages for lithium batteries as against alkaline or zinc-carbon batteries, depend on the highly reactive nature of lithium metal, its exceptional ability to transfer electrons. So, whereas the standard single-cell battery produces 1.3 volts of electricity, the single-cell lithium battery produces 3.4 volts, and it has twice the life of the alkaline battery.

Archival footage of antique cars

NARRATOR (MUSIC under):
Out on the open road we use a wholly different type of battery. These are the batteries which have started our cars and kept them running, from coast to coast, past and present, morning, noon, and night.

Car batteries on assembly line, close-up of car battery cells

NARRATOR (MUSIC and NAT SOUND under):
There's a wide range of labels, but all are lead storage batteries and all differ from the single-cell batteries we've seen so far. For a start, each one has several cells. Inside the battery are different electrodes, lead and lead dioxide. They're immersed in sulfuric acid. In use, a reaction forms lead sulfate on both electrodes. Atoms on the lead electrode are oxidized to a white coating of lead sulfate. Lead dioxide is reduced to lead sulfate.

GRAPHIC: Lead storage battery diagram

NARRATOR:
Electrons released from the oxidized lead can do work, such as turn a car's starter motor. They travel on to the lead dioxide and reduce it. White lead sulfate gradually coats both electrodes. To recharge the battery, an alternator pushes electrons in the opposite direction. The chemical reaction reverses, and the battery is recharged.

RH in electroplating company

ROALD HOFFMANN (SYNC):
So batteries are marvelous devices to harness electron transfer to generate electricity. And we can do the reverse. We can use electrical current to effect chemical change. Let me show you. This is electrolysis. What I've done here is to plate copper onto a silver spoon. Beverly. The process of electrolysis has been used to plate gold and silver onto other metals in shops and factories for over a century. There is a lot of driving force in electrolysis. What could it do to a substance as stable as water?

DS in lab

DON SHOWALTER (SYNC):
Let's split some of it apart and see if we can find out. I'll pour some of the water into this electrolysis apparatus. There's already some water in there. In electrolysis, an electric current is passed through two electrodes. At the negative electrode, we see some gas being given off. That's hydrogen gas. The hydrogen ions are gaining electrons and then providing hydrogen gas. So this is a reduction process, the gain of electrons. At the positive electrode, oxygen gas is given off. Now, in the process, electrons are lost. The loss of electrons is oxidation. (cont.)

DON SHOWALTER cont:
What we're seeing now is the decomposition of water. So what we have done is we have taken electrical energy and converted it into chemical energy, electrolysis.

MONTAGE: Aluminum factory and smelter shots, graphic (equation over video), jet taking off, electrolysis and gold-plated devices, electrochemistry in lab

NARRATOR (MUSIC and NAT SOUND under):
In industry, electrolysis is used to make aluminum from aluminum oxide. In these smelters, cells are lined up side by side with electric current running through them. The aluminum oxide is dissolved. The cells are lined with carbon, which serves as the cathode. A carbon anode is lowered into the solution, and a direct current is applied. The electric current converts the aluminum ion to aluminum metal, which is deposited at the cathode. Electrolysis is not alchemy, but it is an almost magic method of plating gold. The trick is to maintain precise temperature and current control, and to use highly refined plating solutions. Gold-plated devices are not only beautiful, they're smart. This one is bound for a computer. And these laser reflector units will fit nicely into a missile guidance system. (cont.)

NARRATOR cont:
Equally decorative on the surface, this shield will be fixed onto the exhaust cone of a jet engine and thwart heat-seeking missiles. Overall, electrochemistry brings together high tech applications with fundamental research. One futuristic application is to use electrodes as sensors to measure ion concentrations in living cells. The electrode voltage changes as the ion concentration changes. Dr. Henry Blount.

INTERVIEW: Dr. Henry Blount, National Science Foundation

SUPER: Henry Blount, National Science Foundation

DR. HENRY BLOUNT (SYNC/VO):
But we are poised in a very enviable position, with many, many exciting new areas of research and new areas of discovery before us. Electrochemical sensors will enable us to detect trace quantities of substances at levels that we have not conceived of before. This is exciting in diagnosis, it's exciting in environmental control, it is exciting in so very many ways, in manufacturing, in technology, understanding trace contaminants and its impact on a variety of processes. A more generic area of excitement is in the area of bioprocesses. Sensors certainly are relevant there.
(cont.)

DR. HENRY BLOUNT cont:
It's interesting, too, that sensors have now been miniaturized to the point that we can take a single sensor and insert it within an intact living cell, to measure constituents within that cell as the cell functions.

Shots of solar cells

Another very interesting application, and one with tremendous technological promise is the use of electrochemistry to couple light energy to electrical energy.

INTERVIEW: Dr. Henry Blount cont.

This is done through solar cells, in which light energy is absorbed in a chemical system, chemical reactions are caused to happen, which give rise to a transfer of electrons, and that transfer of electrons, that electrical current, is used to perform useful functions.

Shots of the Sun Raycer

NARRATOR (NAT SOUND under):
The Sun Raycer, a winner for General Motors and for the busy electron. Powered by solar cells, it converts sunlight directly to electricity. When it's cloudy, or when it needs an uphill boost, silver-zinc batteries help. Future transportation and electron transfer in action.

SUPER: THE BUSY ELECTRON

MONTAGE: Chemical reactions, lab demonstrations, rusting metal, batteries in use, batteries on assembly line, program graphics, electrolysis, electroplating, solar cells, pacemaker, Sun Raycer

NARRATOR (MUSIC under):
To review: Oxidation reduction reactions involve the transfer of electrons. The transfer of electrons occurs in corrosion when metals are oxidized and oxygen is reduced. The energy from electron transfer can be harnessed, for example, in batteries of different types. Electricity produced by chemical reactions. So, in the lab, in the zinc-copper electrochemical cell, zinc from the zinc electrode enters the solution as ions. The transferred electrons travel externally to the copper electrode. Different electrodes are employed because different metals and compounds have greater or lesser tendencies to give up or accept electrons. The electrolyte remains electrically neutral by the migration of ions. While chemical forces can drive electrical current, the reverse is also true. Electrical current can cause chemical change. Electrons from a DC power source can decompose water into hydrogen and oxygen. (cont.)

NARRATOR cont:
Reduction occurs at the cathode, producing hydrogen. Oxidation occurs at the anode, producing oxygen. This is called electrolysis, and electrolysis is used to make aluminum from aluminum oxide and in electroplating. The phenomenon of electron transfer is ubiquitous and exciting. It's at the heart of present and future invention.

RH in botanical garden

ROALD HOFFMANN (SYNC):
I'm still here with electron transfer going on around me in these plants busy photosynthesizing, in me as I breathe. And why did this program concentrate so much on electrolysis and batteries? The reason is that, in those applications of electron transfer, the electrons were explicit, they were doing their dance in public. We could put them in. We saw them coming out. In other parts of chemistry, the electron's motions may be obscured. It's very hard to stick an electrode into a magnesium strip burning, or into our cells as a copper one is going to a copper plus-two. But there is another reason for our focus. Electricity generated and delivered has become our primary way of transporting energy. It powers every machine that we have. It comes out of nearly every wall. (cont.)

ROALD HOFFMANN cont:
And so, what we try to do today is to convert other forms of energy, heat, light, chemical energy, into electricity. It was not that way a hundred years ago, when the transport of raw materials, of coal, of wood, of oil was the primary interest, and that drove the development of steamships and of trains. It may not be that way a hundred years from now, when, I actually think, that the transport of certain kinds of chemicals, such as hydrogen, and of light will be the way that energy is shipped. But right now it's electricity, and it's chemistry that gets those electrons moving.

Credits, Closing Montage, Closing Music

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