

>> **Dr. Walsh:** Thank you, Jessica. Good morning, everyone and thank you for participating. I am Mike Walsh from the Materials and Corrosion Lab. And we're certainly happy to have this opportunity to share this technical information with you. This webinar is going to give an overview of both corrosion and some corrosion control methods. In particular, we're going to talk about protective coatings and a technique that we use called cathodic protection. Why do we care? Three reasons, mostly. The first of which is public safety. Corrosion-related failures cause fatalities, and protecting the public is of course a primary responsibility. Second, we got to consider the economic cost. It's big bucks, no doubt. Cost of corrosion in the US alone amounts to about 3% of our total, the total value of our annual goods and services in the country. I should mention that this figure only covers the direct costs, so indirect costs such as gas that you burn as you set out on the highway because corrosion has caused trouble with the bridge and the time that you spend sitting bumper-to-bumper traffic—costs of that sort are not included. The third thing, the third reason that we're very concerned with corrosion is it represents possible loss of utility or capacity. Reclamation supplies water for more than 30 million people, 10 million acres of farmland, and indeed we produce a lot of power also. So, here we are. We know that we should care about corrosion. Now, we'll go into what it is. To put it simply, as you can see that definition there, we say the deterioration of material. In this presentation, we're going to limit materials primarily to metals. A good example of corrosion, of course, something with which we're all familiar, is steel rusting when it's exposed to air and water. Now, I'll get a little more technical here and say that corrosion is a reaction between a metal and an electrolyte. In a little while, we'll define electrolyte and a few other important terms, but for now we just want to look at a few more examples. Pictures show corrosion, few different forms. On the left there, you see corrosion, it's pretty localized. This is in the crevice formed by welding there, next to the ruler. In the middle we see one metal component, the bolt is completely covered with rust, and the other component there, the vertical beam appears to be, for the most part, completely unaffected. On the right-hand side there, you can see corrosion covering the entire structure. It's uniform and consistent over all that we see there. Now of course, there are other types of corrosion. In fact, corrosion engineers typically talk about 8 or 10 different forms. Now, at Reclamation, we don't always see all of these things in the normal course of our operations. So, we're not going to cover all of them in great detail, but we'll look more closely at the ones that are most relevant to us. Moving around counterclockwise from the top there. First off, uniform, or general corrosion, top left. We'll then talk about galvanic corrosion, crevice corrosion, pitting, corrosion in reinforced concrete, and skipping a few there, we'll move on to talk a little bit about selective leaching. First up, general, or uniform corrosion. We've all seen this. Maybe the best example is right there in the middle, of the Statue of Liberty. Copper, of course, is not green, but copper oxide is. The corrosion is very even and consistent, and you can see that there, covering the statue. To the right there, you can see the El Vado Dam spillway. That's the picture that I had up earlier. The rust layer, like I said, it's pretty consistent. In this type of corrosion, general or uniform corrosion, it's generally pretty predictable. And as indicated, in many cases it's expected and even allowable. We know it's going to happen, and we can use materials with greater thicknesses knowing that

some of it might indeed rust away. Galvanic corrosion. Very relevant and very important in a lot of the stuff that we do. The top picture shows a mild steel bolt supporting a stainless steel beam. The bottom picture shows a stainless steel bolt and mild steel washer. What do these pictures have in common? Well, in both cases there are two dissimilar materials that are in direct contact, and one material is corroding faster than the other. In both cases, the corroding metal is mild steel. In cases of galvanic corrosion, we call the corroding metal the anode and the other metal the cathode. We have several options that we can use to avoid this form of corrosion. One, don't use dissimilar materials. What if we need a special property of a material—high strength, low weight—but we can't afford to make an entire structure out of that one desirable material? Well, option two is we can at least avoid a large cathode-to-anode ratio. There are those two new words again. Don't worry, we'll dig into them in a moment here. Right now, look at the bottom picture, the screw and the washer. Here's a question. If one of those is going to corrode and fail faster than the other, which one would we want it to be? Consider the case of a sheet metal roof connected to a frame via small screws. No washers, nothing separating the roof panel from the screws. Then imagine two different scenarios. Stainless steel sheet metal for the roof with mild steel screws, and mild steel sheet metal for the roof and stainless steel screws. We have a sheet metal roof supported by mild steel screws that is, say, the stainless steel roof supported by mild steel screws. The mild steel screws will function as anodes, and they'll corrode. The screws disintegrate and the roof can slide off the side of the building. We'd likely be in better shape if the anodic material, the large mild steel roof, was held in place by small cathodes, stainless steel screws. We can use insulating fittings, washers, that type of thing. We can apply protective coatings, or we can apply, as I mentioned earlier, the technique that we call cathodic protection. We haven't talked about that. Certainly, we will. Now before we move forward, the important question remains, why is the mild steel corroding faster in both cases? And the answer has a lot to do with what we're looking at here. Some metals corrode readily, others don't. The metals that corrode readily, we call them active or anodic. The ones that don't, we call noble or cathodic. Now, this table that you see here shows a bunch of common materials and they're arranged in order of activeness or anodic behavior from top to bottom. You see gold on top. Now gold, we know of course we find it in nature in its pure form. It doesn't corrode much at all. You see down there at the bottom, magnesium. Now we don't find magnesium in its pure form in nature because it's very active and it readily reacts with its environment. Now, you see also up there, stainless steel and mild steel. Stainless steel is more like gold, by comparison mild steel is more like magnesium. If you put these two dissimilar materials in—these two or other two on the chart—in direct contact, the metal that's lower on the table is going to function as an anode and it will corrode. Now, you can see off to the right there, we got some numbers. We attach numbers to this characteristic. The list contains what we call the individual material's "potential," their "potential." And we measure that in volts, as is indicated. Noble materials in this table have more positive potentials. Active materials, the ones near the bottom, have negative potentials, or we'll say more negative potentials. As we go lower and lower on the table, you can see the potential values become more and more negative. Few more pictures. These pictures focus on galvanic

corrosion. I'd like to call your attention to the detail in the second sentence there. The protective environment of concrete grout. We're going to talk about that more in a moment. The concrete chemistry protects the steel, and that's related to one of the things we saw in the earlier slide. Now, crevice corrosion is pretty much exactly how it sounds. And the pictures here show it pretty clearly. Crevices, they develop their own sort of chemistry and they become preferential corrosion initiation sites. To mitigate this type of thing, it's pretty straightforward. You do whatever you can to avoid crevices, either by design or manufacturing technique. Especially if you're welding two pieces of metal together. If you're not familiar with skip welding, that term, skip welding, take a look at the joint on the left. You can see how the welder has made a series of short welds. Some portions of the joint have been skipped. Welders—they'll do this maybe to save time, or maybe save some frustration while welding in maybe an awkward or hard to reach area. Contrast though that with the nice continuous weld bead on the right. The important thing here, remember this—skip welds, bad. Likewise, any crevice—crevices are formed of bolts, rivets, seams, joints, unions, couplings, all sorts of things like that. Pitting corrosion. You can see localized corrosion. Now, we're starting to see a recurring theme here. Localized corrosion is very much more destructive than general or uniform corrosion. Pitting is—it's complex. Two things important to remember here. One, pitting often occurs when coatings break down. And two, some metals are more susceptible to pitting than other metals. Dealloying, we call this selective leaching also. Many materials that we use are pure. Many of the materials that we use are not pure. These are alloys, mixtures of multiple metal types. Now, we use alloys because they can outperform pure metals with regard to strain and weight, ductility, things like that. In some cases though, the use of alloys exposes us to this particular type of corrosion. Remember the galvanic series table, a few minutes ago? Some alloys contain mixtures of both active materials and noble materials. In cases of selective leaching, some of the material corrodes, but some of it doesn't. The corrodible stuff can disintegrate, and it can be carried away by process fluids or aqueous environments. And we're left with a matrix of noble that is inert material. The pictures here give an example, some examples. Graphitic corrosion—iron leeches and graphite is left behind. And here's what you have to remember about dealloying or selective leaching. And that is that what looks like an intact pipe or structure might actually be a pipe filled with holes. Graphite that's left behind is solid, but it's porous and weak. It'll look just like everything around it. We can't tell that the iron has left until we clean the pipe or tap on it or scrape the surface or something like that. You can see in the lower picture, there's a handwritten note on this pipe, this from the Fountain Valley conduit. It says, holes made by tapping with a small rock. So, if you're inspecting a cast iron structure, you'll have to do more than just a visual inspection. In this case, even the minor—a moderate amount of perturbation, tapping on it with a small rock, in this case was enough to knock out that porous matrix that remained and exposed these quite large holes. Here we go, I promised earlier we'd talk about corrosion of steel in reinforced concrete in a little more detail. Chemistry of concrete can protect steel from corrosion. It's very true, very good. But the protection can be lost if the concrete becomes contaminated with chlorides, that is to say, salts, or from a process that we call carbonation. If contamination reaches a certain point, a

certain depth, the steel becomes just as vulnerable as it would be without the concrete. And in this case, the corrosion starts to rust, and the rust can start to cause other problems that we see in this type of corrosion. Rust itself is expansive, it takes up more space than the original steel did. And this expansion causes stress, and stress causes cracks, and cracks causes spalls. Spalls, or spalling, that's what we call the occurrence of concrete chunks breaking away from the surface of the structure. And you might have seen that type of thing, maybe as you roll down the highway, you might see a bridge. You might see some of the supports where rust stains are visible on the surface and some concrete is missing. Here we've got some photos. Again, the thing to remember here is the cracking and spalling effectively exposed the steel reinforcement to all the elements, and exposed steel is vulnerable steel. Take a look at the photos in the lower right corner. Two pictures of the same area. Rust staining is visible on the surface of the concrete in the left photo. Poking at the surface caused the fractured concrete to break free. Take a look there, notice how close the embedded steel is to the concrete surface. Not very deep at all. The distance between the outer concrete surface and the steel is known as cover or cover depth, and it's typically greater than what you see. Often, maybe 3 or 4 inches in bigger structures. Now, cover is indeed one of the best ways to protect steel reinforcement from corrosion, steel that is in concrete. Here's how we keep the steel safe. High quality concrete. This implies a low water to cement ratio. Beware, out there on construction sites, it's common for crews to add water on the job site to improve fluidity and consolidation. The added water leads to higher concrete permeability. The higher permeability enables contaminants to penetrate to the steel more quickly. A higher water content than expected or designed also, of course, makes the concrete weak. Now, coatings can be applied to the outer surface of concrete. And cathodic protection can also be applied. You can use, instead of regular or what we call plain steel rebar, you can use galvanized rebar. You can use stainless steel rebar. These other materials, galvanized and stainless steel, are both more expensive, certainly when compared to the very common and inexpensive mild steel rebar. Alright, we've talked about corrosion. We've talked about why it should catch our attention. We've talked about what it is. Then we've shown the most common forms of corrosion in Reclamation structures. Now we'll spend a little time talking about what we can do to prevent it from starting, and also what we can do to prevent it from getting worse. We're not going to cover material selection very much in this presentation in any great detail. We'll give a solid overview of protective coatings and of cathodic protection. Let's first, though, look at the corrosion mechanism itself. Now earlier, we said that corrosion is a process by which metal deteriorates, given an adverse interaction with its environment. Four things are needed in order for metal to do this. That box on the right, look at the box, think "ACME"—that little mnemonic to help you remember the four things that are needed in order for corrosion to initiate and in fact for it to continue. A for anode, C for cathode, M for metallic path, and E for electrolyte. Now, let's take a moment, think about the table we saw earlier, the one with the gold and stainless steel, magnesium, all the other metals. We call it the galvanic series. We said that more active materials will corrode, and indeed that's true. Consider this, the anode and the cathode can be present on a single material. Indeed, we don't always need two different materials, like say

regular carbon steel and stainless steel, or magnesium and gold. A material can corrode by itself. One spot could be an anode and the other spot could be cathode. Why would this be, that one spot has to be the anode while the other areas get to be the cathode? It could be that the anodic spot, maybe it had a scratch in the surface or some sort of neck or maybe an impurity in the metal itself. And any one of those things can make that spot maybe a little bit more active than another spot. That's an important thing to remember. Now, before I start describing this detail here, you can see it's—there's a lot going on there. We got numbers, we got colors and arrows, all sorts of things. But before we do that, visualize a plain—a steel bar, just a bar. Any cross section, any size. Take the steel bar and drop it in a bucket of water. Now, we'll look at the drawing. First off, before we relate this to our steel bar in the bucket of water, you can see on top there, we say water or soil. That of course is our electrolyte. Steel structure, those two words you see at the bottom, that's something that is active metal. That's something that is subject to corrosion. Now, think of this figure here as a side view of the steel bar, that we mentioned moments ago, lying on its side at the bottom of the bucket. Now, imagine the top surface of the bar, the surface directly exposed to the electrolyte, is initially smooth, corrosion free. There again, we see ACME up there. We don't have an anode or cathode yet. Again, we're imagining that the steel structure is devoid of corrosion. We've just dropped the bar in the bucket with no anode, no cathode. The idea of a metallic path isn't relevant yet. All we have here is electrolyte on top and an active material, active metal on the bottom. Now look just at the left-hand side of the figure over here. Now, before our surface became messed up with all of this stuff, say we had a nick, a scratch, an impurity of those things that I mentioned. Say it was right here on this formerly smooth surface. We see this number here, minus 0.7 volts. The bar went into the bucket, iron ions at this scratch or nick or impurity, they started jumping off the steel into the electrolyte, there. Now, nearby we had some nice clean spots, unscratched. These things, where the ions were jumping off, this is of course our anode. These clean spots over here, the cathode. When the iron starts jumping off into the electrolyte, electrons start moving from the anode to the cathode through the metallic path formed by the metal itself. And they come on over here, interact with some oxygen, combine with oxygen in the electrolyte, and combine with the iron ions out here. And they start—uh, coming to rest on the surface. Uh, something from the, something from the audience, but I think we're alright. We'll continue. Red spots here. It's rust, formed just as I described there. That's corrosion. That's the deal. Is there trouble out there in the audience?

>> **Dr. Torrey:** Can you please remember to mute your phones? We can hear someone, one of the participants, over the line. Thank you.

>> **Dr. Walsh:** So, that is that. That's the mechanism of corrosion. And here's our primary defense against it. It is a coating. We coat the active material. We prevent it from coming in direct contact with an electrolyte, and thereby prevent or slow down corrosion. Are coatings perfect? Of course, the short answer is no. We'll talk about this more shortly. Here's our

secondary defense, cathodic protection. This is that term that I've mentioned a bunch of times already. You'll hear me, and you'll hear others, often abbreviate cathodic protection to CP. In fact, from this point forward in the presentation, I'll refer to cathodic protection as CP. And what we do to effect this cathodic protection, what it's all about is this. We hardwire a more active material to our structure, the structure that we want to protect. We complete a circuit through the electrolyte. And in the case of galvanic anode cathodic protection, we allow this anode that we hardwired over here, we allow it to corrode and to disintegrate. And it protects our metal that we call our cathode down here. Now, the best defense against corrosion, of course, is a combination of these things. We'll use a coating and CP. Take a look at the second point there, the load on the CP system, it can be pretty low because in the case where we have a coating applied, the CP system only has to protect defects in the coating, places where the surface is exposed. There we go, another summary. Apply a coating. And then implement cathodic protection. And now I owe you a little more info I promised regarding protective coatings earlier. Coatings can be pretty expensive, but the fact is they're very effective. Two things to take away from this slide. First, Coatings are Reclamation's primary corrosion defense. We've mentioned that earlier. And second, the most important aspect of an effective coating application is proper surface protection. Now, the cost of the material itself. Take a look on the left. There you'll see the cost of the material only amounts to about 20-30% of the total cost. Surface prep and application each costs a whole lot more than that. You can see moving over to the right there that, in fact, surface prep is the most expensive part. It's okay because the most success of the coating depends on—as we mentioned just a moment ago—first of all, surface preparation, secondly, surface preparation, and third, you guessed it—surface preparation. Without regard to corrosion protection, there are two types of coatings, barrier coatings and sacrificial coatings. Barrier coatings, as we talked about earlier, they simply isolate the metal, the protected metal, from the electrolyte. Sacrificial coatings, they actually serve as an anode for the coated material. Now, in the lower left, we see coating being applied to concrete floor. In this particular case, it could serve as a barrier to contaminants like chlorides or CO₂. In the middle, what you're looking at there, granted a little unusual, is some serious quagga mussel accumulation on a structure. This picture pretty clearly shows the importance of non-corrosion related use of protective coatings, and that is to serve as a fouling release. We can put coatings on our structures to prevent mussels and other things from accumulating in the first place. On the right hand side there, you see a sacrificial coating being applied in a technique that we call metalizing. Earlier, if you remember, we talked about material being used sacrificially. This is how a metal might be applied directly—a sacrificial metal might be applied directly to the thing that we desire to protect. Surface preparation. We mentioned that earlier, didn't we? You see along the left there, surface blasting, whether we're using water or an abrasive material. And there, as we move across the right, a couple examples of different ways that we can prepare a surface or evaluate a surface before applying the coating. We will look a little more closely on these things—over there in the right corner and above that, indications of surface profile that we measure, observe. Surface profile, of course, is a very important indicator of the ability of a surface to maintain a good coating. Here's some more examples of surface

preparation techniques. Again, we see blasting there. On top, we've got a regular wire brush. Next to it, equipment that does a little more intense job. Down there in the lower right-hand corner, we would have abrasive blasting in a very controlled environment. Now, you yourself of course might not be applying coatings in the field. But here's some things to remember in case you are maybe managing a coatings project, or maybe even just walking by and noticing some things. First off, follow the instructions. The manufacturers took a lot of effort and spent a lot of time coming up with those instructions, and the fact is, they're very, very important. The second point there, if you can apply the coatings or have them applied in a shop where the environment can be much better controlled than it ever could be in the field. And last and certainly not of least importance is, know the hazards before you start. Protective coatings, they involve, often, some hazardous materials.

>> **Dr. Torrey:** If I could interrupt one more—Miguel, I believe your sound is on and we can all hear you. So, could you please mute your headset or your speakers? Thank you.

>> **Dr. Walsh:** There we go. Many ways, of course, to apply coatings. The choice of a particular type of technique for application, it'll depend on things like structure size, the operating environment, the structure, material, accessibility of the part that you want to coat, availability of equipment, maybe availability of people specially trained to use any one of those techniques described in the list. Now, earlier I said coatings are good, they're not perfect. They can be damaged during application, they can be damaged by exposure to weather, maybe just exposure to time, other things maybe in their operating environment. And because coatings are not perfect, we'll use CP. Now, we can use CP in cases, of course, where a coating has not been applied also. Now, we see—we use CP anywhere and hopefully everywhere that an active material or metal maintains direct contact with an electrolyte. Note that anodes have to directly contact the electrolyte that the structure is contacting. Here we see buried applications, things like pipelines and maybe some fittings and equipment that is below the surface. In the lower right-hand corner, those things, they look odd. Those are anodes, those are anodes that are going in the ground. In this case, of course, in buried applications, the soil and the liquid in it constituting the electrolyte. And the anodes that you see there in the ditches, they'll be in direct contact via the electrolyte to the structure that we intend to protect. Here we have some immersed applications. Dam and canal gates, equipment, individual subsystems that are in direct contact with the water. You see the list there. Things like trash racks, fish screens, and things like that. All cases wherein we'd want to use CP. Now, with cathodic protection, there are in fact two types. I mentioned earlier, galvanic anode CP systems. That, for our purposes here, is very easy to understand. Just as we talked about galvanic corrosion earlier, we have one very active material, say the anode over here in direct contact with a non-active material, or maybe the thing that we want to protect. Now, when this goes in the ground, the anode is sending protective current through our circuit here. You can see a test station up there on the surface of the ground. Note though, the anode there, it has decreased in size. I'm going to go back here and start our little animation over. The

anode's getting smaller, it's being consumed. And that's a reality in galvanic anode CP systems in the field. And this does, of course, necessitate periodic replacement of anodes. Now, I mentioned it's also called sacrificial anode cathodic protection. Look down in the lower left corner there. One of the reasons, or a bunch of the reasons we would use galvanic anode CP instead of impressed current CP are those things there. If your current requirement is low, maybe typically associated with a smaller structure or smaller surface area, galvanic anode CP might be a good place. In addition, it doesn't need any external power source and there's low or no maintenance at all. Those are cases where we want to use galvanic anode CP. The placement of the anodes, as I mentioned earlier, in this case buried—you can see earthworks being moved there. You know, often if we have a pipeline or something like that, there might be limited space in the area right next to it, in the right-of-way. Remote earth is a term that refers to a location far away from the protected structure, such that the pipe-to-soil resistance is no longer changing much as we get further away from the structure. In immersed applications, you know, again, think about the soil—the protected structure's in the soil, the anodes are in the soil. In immersed cases, the structure is in the water, the anodes are in the water. And you can see on something—take a look at this middle photo here. All these little things here, these are all sacrificial anodes. They're in direct contact—it's more down here—in direct contact with the structure. And of course, they're not doing anything at all, or much of anything at all, when the structure's out of the water. There might be some moisture on the surface. But when they go into the water, thereby we get the direct contact through the electrolyte between the structure to be protected and the anodes. Now, our other type I mentioned earlier, impressed current CP systems. Here, the thing to note in our little animation—here, the anode is not consumed. There's a reaction taking place at the surface of the anode. The anode that is in direct contact with the electrolyte, in this case soil. The reactions taking place there is affording us this measure of protection. The anode is not consumed. You see above the surface there, a rectifier. The rectifier is changing, rectifying, AC current to DC current. With regard to galvanic anode cathodic protection, you remember I mentioned we don't need any external power source. That is not true in the case of impressed current CP. That power that's coming in from the line is being rectified there and it is driving the reactions that support our cathodic protection. Now, off on the left there, you see two wires going into something. That is our test station. That's the same thing that we showed earlier in our galvanic anode CP system. Now, impressed current CP systems, they're used in different cases. You remember, I mentioned a bunch of the reasons why we might choose our galvanic anode system. Here we see, down there in that lower left corner, again, reasons that we might choose an impressed current over galvanic. And indeed, if we've got the electrolyte moving, high flow, say in the canal or even on the inside of a pipeline. If high current requirements are present. And of course, that would be associated with a large structure. Or in the case where, you know, we've got coated structures where there might be a lot of exposed area. Impressed current CP might be a better application. So, here we've hit the high points. We've covered corrosion, we've talked about the mechanism by which things corrode. And we've talked about some of the ways that we use technology to either prevent corrosion from happening in the first place or to prevent it from

getting too bad. And we mentioned the use of coatings and cathodic protection, present in two different forms, galvanic anode and impressed current CP systems. That brings us to the end of today's webinar. And the webinars are certainly something we enjoy doing, and we enjoy conveying and transferring this technical information. And there's a list there on the left, you see many of the different topics. And these are topics that will appear at different times of the year. And you'll see Jessica's name down there, and she's our primary contact if you do want to get on the mailing list for webinars in the future. And so, this being this and all of that, who wants to be a corrosion engineer? Well, if I've not effectively converted anyone in our audience today, we'll all have to rely on all of these people that we see here. Those e-mail addresses there, naturally, I don't expect you to write them down very quickly here before I end the presentation, but once this thing is published and appears on the web, you'll be able to refer to these names, e-mail addresses, and phone numbers to get additional information or some help, maybe even, if you need it. So, that is that. I thank you, I appreciate you participating today. And that wraps up the corrosion webinar for now.