>> **Grace Weber:** Alright. Hello everyone and welcome to the Corrosion Webinar Series. My name is Grace Weber and I will be hosting today's webinar. This event is put on by the Materials and Corrosion Laboratory within the Bureau of Reclamation's Technical Service Center, located in Denver, Colorado. We host corrosion-related webinars each year to share topics in areas such as cathodic protection, coatings, geosynthetics, and hazardous materials. Today's presentation will cover research on robotic non-destructive inspection of hydraulic steel structures. Our presenter is Dr. David Tordonato, Materials Engineer. Before we get started, let's go over a couple of housekeeping items. We will be recording today's Corrosion Webinar. If you do not wish to be part of the live recording, please leave at this time. The recording will be available after the webinar at the same link you received in your e-mail. During the presentation, please submit your questions and comments as they come up. You can access the live Q&A chat feature by clicking on the Q&A icon, which looks like a chat bubble with a question mark inside. We will monitor the chat and hold the Q&A session after the presentation. So with that, I would like to welcome our presenter for today. David Tordonato is a Materials Engineer with the Bureau of Reclamation. He performs assessments and specification development for water infrastructure. In addition, David is also a member of the Technical Service Center's rope access team and performs inspections on Reclamation's inaccessible features and structures. He works in the Reclamation Materials and Corrosion Laboratory and holds Bachelor's and Master's degrees in Mechanical Engineering from Virginia Tech, as well as a Ph.D. in Materials and Metallurgical Engineering from the Colorado School of Mines. He is an SSPC certified Protective Coatings Specialist, a NACE certified coatings inspector, a NACE certified Cathodic Protection Specialist, and an AWS certified weld inspector. Dave is interested in additive manufacturing and performs metallurgical failure analysis of hydraulic equipment. And now I will hand this presentation over to Dr. Tordonato.

>> **Dr. Tordonato**: Thanks, Grace and good morning to everyone. Thank you for making the time to join us today. I'm really excited for this opportunity to present to you our findings on this exciting new technology here. So, as Grace mentioned, the title of my presentation is Robotic Non-Destructive Inspection of Hydraulic Steel Structures. Before we get into that, I just want to give a brief introduction on kind of what we do right now and what we're looking to try to do with this project. So first off, we have our Facilities Instructions Standards Techniques, also called FIST. This is our manual that decides when we need to inspect things and for how often. So, right now we're inspecting our penstocks and pressure conduits. The FIST manual recommends this be done every 5, not to exceed 10 years. And our current practice for doing that is shown here on the photographs below. Typically, we do this using a technique called ultrasonic thickness testing, or UT for short. We collect these UT readings manually. Typically we do this on the lower portion of a penstock or a pipe's circumference, as you see here in the lower left. We'll take about 10 readings going across the lower third there. And that's typically where the inspector's able to reach. Especially in these larger pipes, it can be harder to reach the upper areas of the pipe. And then we'll collect those readings going down the pipe approximately

every 10 linear feet, as you see here in this middle figure. So, since each data point represents a discrete location, it's possible that, you know—we're collecting a sampling of data here. So, we may not be hitting all of the worst locations. We're just collecting a sample to try to get an accurate picture of what's going on. And it's also important to point out here that the pipe crown, or the top ceiling of the pipe, is normally excluded from inspection on these larger diameter pipes simply because our inspectors aren't able to physically reach those areas. So you know, it's possible that the way we're doing things right now, we're not getting the most comprehensive picture. And there may be some opportunities for improvement using new technology. And that is where this current project comes into play. So, just to kind of summarize here what we're dealing with, we've got aging infrastructure. We basically—our structures are aging to the point where we want to make sure we're doing a very thorough job. And so, condition assessment becomes more important with these older structures. We've got manual UT, which can miss localized problem areas. It can also miss hard to reach areas. And then in addition, as you can see in these photos here, most of our penstocks are on inclined slopes. And that is going to require rope access, which limits the number of people who can do the inspections and also requires extra safety precautions. And still exposes workers to potential hazards there. So and some—even with all of those mitigations—some of our structures may be difficult and too unsafe to inspect. So, very small pipes can be hard to actually fit a person into. And so, these are areas where we think there's opportunities for improvement. And so that resulted in us making a proposal for our S&T office to fund. And they did. So our research objective here was to evaluate new technologies such as robotic inspection vehicles, or we're calling these RIVs. We wanted to know if these can be used effectively to inspect penstocks, outlet works, and other equipment of interest. If they can be effective, a secondary objective would be where and how to best implement these new, state-of-the-art inspection methods on our aging infrastructure. So with that, we came up with some practical questions here for the technology that we're going to be looking at. We have a lot of very specific challenges with our infrastructure. A lot of it is, you know, coated in coal tar enamel, which tends to be very thick coating. It's also not the smoothest coating. So, we wanted to know how the technology might work on our existing lined penstocks with original lining materials. So, those rough surfaces with coal tar, we wanted to know if there's any limitations related to the surface cleanliness. A lot of our pipes end up with silt, mud, biofilms, and other things in there. So, these things might—robots might look great in a laboratory setting, but in the field, how would they actually perform? We also wanted to know, in situations where we have surface pitting, can that be identified and quantified? So things like localized damage, would a robot be able to pick up on that damage? And then we were looking at logistical limitations, things like: How often do we need access to the pipe? The manhole spacing along the pipe. Power requirements. What kind of minimum diameter requirements are there? And would we be able to have a robot that would inspect and be able to reach all the way up to that pipe crown on larger diameter pipes? Of course, any technology, we want to know what the costs would be and how that would compare to what we're doing now. We also wanted to know about real world setup times, scan speeds, and production rates. Is this something that can reasonably be implemented and performing inspections comparable to what we're doing now? Is it going to take a lot longer or could it potentially speed up what we're doing? And then we also wanted to know, what kind of format would we be getting data in? How easy is it going to be for post-processing and data analysis? A new technology can potentially yield millions of data points as opposed to, you know, a few hundred. So, with that increase in data collection, we need a better way to potentially process and review that data. And then also, is this something that our own engineers might be able to get involved with and do, or is this something that we're going to have to contract out through a third party? So, we did some initial market research to try to understand what is actually out there. And ultrasonics are what we use now. The first three bullets here show some of the ultrasonic technology that we looked at, things like rapid ultrasonic gridding, or RUG for short. Also, we had rapid automated ultrasonic testing. We're gonna call that RAUT for short. And that is usually using some type of a phased array ultrasonic testing, which sounds really fancy, but basically what you need to know there is that it collects a large amount of data, it's very advanced, state-of-the-art type of UT. And it has the capability to see flaws and other defects as well. The last two bullet points here are electromagnetic techniques. These are things like EMAT, electromagnetic acoustic transducers, or EMAT with crack detection. So those are other things that we looked at briefly. We did send out a questionnaire to a few different vendors to try to understand what capabilities were available. We asked about some of the practical limitations that were mentioned on the previous slide. Things like what diameters are you guys able to measure, what type of detection capabilities do you have, resolution, scan speed, all that good stuff. We use this information to help inform a solicitation to be put out to actually have one of these technologies be selected for demonstration at a Reclamation facility. So, just to point out here, the RUG and the RAUT were kind of the two ones that jumped out at us as being the most promising technologies. Most similar to be able to give us the type of data that we're used to getting with our standard manual UT process. And so, we were looking at trying to target, potentially, some of those technologies with our demonstration. And so, we had a plan to do initially two different sites for demonstration at Reclamation. And coincidentally, or maybe not too coincidentally, another facility at Reclamation was also pursuing a similar project for demonstration. And we were able to partner with that facility and add in a third site. I was able to travel down there and witness some of the inspection for that facility. But you'll see that the inspection there was done slightly different. Our goal when we did it was to basically demonstrate the RUG and the RAUT process side-by-side with our manual process to do a side-by-side comparison to see how that data would compare to what we would typically get from a standard inspection. We did not have that rope access, manual UT inspection done for this first facility. So, we just got the robotic data there. So, for our first facility, the good thing is, with the three facilities, each one had slightly different conditions. So, we were able to get an idea of how the technology would perform under a variety of conditions. The goal was to do a limited demonstration at each facility, not an entire penstock. So we wanted to limit it just to, you know, a few thousand square feet, for example. As opposed to trying to do an entire piece of equipment. So, baby steps here. The first facility was a 25-foot diameter penstock with no slope. So, no rope access there. This facility was originally coated and lined with coal tar enamel, both on the inside and the outside. It was also accessible from both the inside and the outside. And the exterior coal tar was smoother than the inside. You can see a photo here that's showing the original coal tar on the upper right corner. And you can also see that some of that original coal tar has been spot repaired with a thinner material. This happens to be a moisture cured urethane, which is much thinner and much smoother. A large fraction of the upper circumference was already repaired and realigned as well. And then, you can see a photograph in the lower right of the exterior of that penstock with a few spot repairs there. So, that's our first facility. Our second facility had a smaller diameter that ranged from 96 inches to 108 inches, so roughly 8- to 9-foot diameter there. This one is 38-degree slope and does require rope access. And then you can also note here from the photographs that there's water and some film present on the surface of the pipe. And you can also see that there's prior pitting. This penstock was recently relined with an epoxy, so we do have that different lining material there, which is much smoother than the coal tar. But you can also see that there's evidence of prior pitting, which made this particular facility a very good candidate for the demonstration. We wanted to see how granular we can get with this data. Would the robotic inspection actually be able to pick up these localized thinning areas in the pipe. And another thing to note here was that this particular penstock was only accessible from the interior. Okay. And then finally, our third facility. This facility was selected for the reason of—the fact that basically it has the original coal tar. This is going to be the situation in many of our facilities that have not been relined yet. So, the original coal tar has some particularities with it. You can see this upper right photo that shows a close up of that material, and it's very rough. You've got undulations there. You've also got some areas where there's missing material. That missing material is actually easier to get a UT reading on than the coal tar itself. Also, another thing about this coal tar, as I mentioned earlier, it is a very thick lining which can also present challenges for UT. When we do this manual data collection, we have to make sure that we pick an area that's smooth enough to be able to get a good coupling for the transducer to sit on. You can also see that there's missing coating showing on the lower two photographs as well. And this pipe had a 96- to 60-inch diameter. So it necks down, so it's got a little bit of complex geometry associated with it. It's also a thicker pipe, 68-degree slope does require rope access. And it's dry, so there's no water coming down the pipe. So a little bit different conditions than Facility #2. And again, this facility is also only accessible from the inside. And it is a very long penstock of over 1,000 feet long. And we were targeting an inspection area of about 150 feet out of that. So, our inspection plan for these three facilities is shown here on this slide. We've got, you know, an arbitrary location selected for each of these facilities. Interior and exterior inspections on the first facility using both RAUT and RUG. The second portion of that was done using RUG on the exterior only because there was no outage available. So, they were not allowed to take that pipe out of service. We had to do the inspection from the outside. On Facility #2 we had a target of 200 square feet to select and demonstrate the RAUT process. Remember, that is the more detailed phased array that gives a lot more data. It's also a slower process. But it can give us potentially a lot more information. We also had a larger area, 3,250 square feet on the slope that was targeted and selected for using a RUG inspection at Facility 2. And then, finally, we were doing a manual UT process, side-by-side comparison with the robotic inspections to try to get an idea of how that compared. Facility 3 was a similar arrangement except we omitted the RAUT from that. So, we were just doing RUG inspection and manual UT. Similar amount of inspection, about 3,800 square feet there. And then all of the remote inspection also captured an encoded video to be able to review later. So the results for the first facility RAUT scanning showed—basically, we were able to get a good scan, approximately 950 feet in an 8-hour shift. The rivets, weld seams, and rough lining presented some challenges for driving across and scanning over. This was particularly the case for the RAUT, which you had to basically do this on one side of the girth seam at a time. And I have a video that we'll show in a second here. These photographs here show the setup where you have the phased array readout on the screen here. A controller on the left side. And then this is the robot. It's got a head here that can raster back and forth to collect data. And then this robot will advance. Both RAUT and the RUG have robotic—or have magnetic wheels that allow the robot to crawl up the pipe and adhere to it. They also use water as the couplant, whereas our manual processes use a gel to connect the sound and allow the sound to penetrate into the metal substrate. We're using water here. You'll see that on this slide here where you can see that there's some wet on that wall surface. You can see this robotic inspection crawler is able to adhere to the pipe and go up. This photograph on the right is showing what we're really after here, is the ability to inspect a hard to reach part. So, guarantee that nobody's ever done a UT measurement up here on the ceiling of this pipe. But we're able to do that using this magnetic crawler. I've got some videos here. Video can be hit or miss with our internet connection. So, I'll play the video and then I'll just kind of talk through as it's going. This is the RAUT robot. It's gonna, you're gonna see that head rastering back and forth. And this was one issue that we ran into here. When you have a rough surface, you can see as it goes across into the rough surface, that transducer kind of flips up. And when that happens, the water sprays out laterally and you lose the connection to the pipe. So you're not gonna get data wherever the surface gets too rough there. And the second video is just showing the robot crawling up near that pipe crown. And very short video there. And then this one on the right, you should be able to see the head that's rastering back and forth. That's collecting data every time it goes back and forth. And then it advances a few inches after each raster. Alright, this is just showing a screenshot of what we're getting for data. This is from the phased array. You can see each one of these little boxes on the image on the right is a file. So that's one aspect of this data collection, is it's collecting a lot of data, it has to be broken up into smaller files and then essentially presented that way. So that's one thing, one potential limitation with the RAUT. The RUG data on the other hand is—we're able to get into an actual web portal and look at the data in a three-dimensional sense. Each one of these is a little 6-inch by 6-inch square that you can target with your mouse or cursor in the portal. The portal also gives access to basic statistics. Things like number of data points, the lowest data reading, average readings, and a histogram. And then we can download the data from there into Excel for additional processing. Alright, so for this first facility, what did we learn? We had initial limitations on the metal thickness for RUG that was around 0.75 inches. However, the engineers were able to increase that limitation to allow for additional scanning up to 2.25 inches thick. So that was a really nice improvement there. We were able to scan—some of our penstocks have very thick material, and so that was a nice advancement there. As far as the RUG versus RAUT, So, RUG data provided—RUG provided the data with a much lower level of spatial density than the RAUT. But that tradeoff was worthwhile because we were able to overcome some of the logistical limitations that the RAUT had. So, things like the maneuverability issues that I showed, where the head was translating across. So, with RUG there's not an actual raster that happens, you've just got a series of transducers. And the robot just drives at a constant speed down the pipe. The RUG robot still couldn't go over some of the things like rivets, but you could drive over welds with it. And the report and the data portal provided a way to access the data that was more intuitive than the RAUT. And that was due to, you know, potentially the software, but also the large file sizes associated with that RAUT. So RAUT is really good for targeting a very small area that we know there might be problems with, that we need to do further investigation. But RUG is gonna be the better option for doing general inspection work. And then the thicker coatings, the coal tar enamel, still make this thing challenging to use. Newer and thinner coatings are a lot easier. And then overall, the dam staff was pretty pleased with the inspection. They felt like there was merit to getting baseline data for some of their penstocks. So, moving on, we'll go through Facilities #2 and 3 and then we'll come up with some overall discussion points and summaries here. So, for the Facility #2, we also had our rope access team involved with this process here. So you can see our team of three was used to do a manual inspection. We have our gauge here that's shown in the center photograph. It's a little handheld portable unit that we picked out specifically to work through coal tar enamel coatings. That doesn't mean that we don't have some problems. We have to make sure we have a nice clean surface. Sometimes we have to scrub the surface to get a data point. Overall, it's still a very time consuming and laborious process. And then sometimes if we see a pit or anything, we'll use a pit depth gauge like what is shown here in this middle photograph as well. And then, this photograph on the right is showing the robot. This is the RAUT robot that they did, scanning. You can see where the surface is wet going up the pipe, so they were actually scanning in the circumferential direction using this RAUT robot. And then with the rug, they were—you can see these lines going down the axial direction of the pipe. That's where the RUG scanning took place. So they were able to drive that along the direction of the pipe. And I've got another video here that just shows that process of data collection using the RAUT robot. And this is scanning right now, the head is going back and forth along—inside the pipe invert. And this robot is able to operate in that wet environment with water on the bottom of the pipe. These aren't designed to be completely, you know, in full immersion. But it was able to work in these conditions here. And then the results here for Facility 1. So, this is a photograph, on the left, showing the RUG robot. So you can see the difference here. Instead of having a single head that goes back and forth, we've got a series of 24 discrete UT transducers. Each one of those transducers has a little jet of water that sprays out. And that's how the coupling works between the transducer and steel. It's able to collect data even fully upside down, as you can see in these other two photographs here. So that was one of the questions we had is, would we be able to get good, sound coupling when you're spraying a jet of water completely up in the air? And the answer was yes, we were able to get good data that way. And this video on the right is just showing the data collection process as it's going forward. And you can see water dripping down from those jets as the RUG is being driven down the pipe length. So, I'll show you some additional data from that facility. So, the initial—as I mentioned, the initial target area was only looking at the 96-inch diameter pipe. However, there was another smaller portion. We weren't sure if we'd be able to get data there because the limitations—this was kind of pushing the limitation on the pipe circumference there. But we were able to get some data on the 73- or 72-inch pipe section. This is an example of what you would see if you were to log into that web portal to look at the data. So, there's a heat map that gets generated. And this is a color-coded data collection in two dimensions, and also in three dimensions, that shows an area—that shows individual areas by thickness. Each color has a different thickness associated with it. And the areas that are white are blank. So that was areas where we weren't able to get any data for that particular location. And another aspect of this pipe was that there was some silt and also film accumulation there. So that was another practical question we had was, what would the data collection look like for those areas? And for the most part, we were able to generate data there. And here's another screenshot showing the RAUT data that we were able to collect. You can see here, this is almost 17.5 million readings taken in 200 square feet. That's an enormous amount of data. And this was taken over 16 different files. And this is just an example showing the data collection that occurred on one file here. And I mentioned—I should have mentioned last time—for the RUG collection, we were able to generate—collect data from about 3.5 million data points over 1,900 square feet in three different areas. So, still a substantial amount of data. Orders of magnitude more than we would be collecting using a manual process. But much less than what we would get from the RAUT. So, how does this data stack up to what we're getting? Those are just numbers of data points, but we wanted to know how the data would actually compare. So we had our engineers do a manual inspection. They were able to find that this particular area that we inspected, they found a max decrease of about 11%. So, wall thinning there. And then, using the manual pit depth gauge measurements, those averaged around 70 thousandths of an inch up to 180 thousandths of an inch on the 0.5 nominal wall thickness. And so that 180-mil-deep pit would be about a 36% wall loss. So, we wanted to know, would those scans using RUG and RAUT also pick up any of those pitting areas? And the answer is they were able to look at getting more data—or sorry, they were able to show that there was more wall loss than what our manual UT process showed. So we were getting 24.4% loss up to—um, maximum. And the other scan on a different section showed 26.8, so about 27% wall loss. And then the data generated—that was from RUG—and then the data generated from the RAUT showed about 26%. So they were very close even though the RAUT collected substantially more data. The numbers were very similar between the two. It's hard to know if the data was—if those maximum loss measurements were taken in pits. There was some concern that due to the geometry of a pit, the sound may reflect in a different direction and not come back to the transducer. So, unless the sound entered the pit directly perpendicular to it, we may not get any data back. But it seems like we were able to get a little bit at least because we're seeing data that was showing a decrease in wall thickness that was more than what we saw with the UT just taken in general locations. So, that is a good sign. And then our third facility here. We had, again, just the RUG on this one. We didn't go with the RAUT inspection here. This one was done on the coal tar enamel. So another big question we had was whether we would be able to get good data on this very rough coal tar enamel surface. And one interesting aspect of the coal tar enamel when it gets daubed on—this is done using a hot molten process. And usually what happens is that you end up with a relatively smooth surface on the upper half of the pipe above 3 o'clock and 9 o'clock. And then below that, you end up with drips, runs, sags, and other things that cause that surface to be very rough to scan over. And sometimes difficult to even find a place to take a manual UT reading on. And so the result of scanning in those conditions is shown here on this screenshot. This is basically showing that we have a lot of data missing in the middle here. And that is where that coal tar is very rough. So, that's the area that's below the spring line. We were still able to get 1.2 million readings despite missing a bunch of that data. And a total of about 2,700 feet was scanned. They did however decide to omit that vertical reducing bend where the pipe constricts down to the 60-inch diameter, just due to the complications associated with processing that. So, it's much easier to process data when you have a constant diameter. So for Facility #3 here, the manual UT inspection showed that there was a maximum wall loss of just 2.5%. And the RUG showed that there was a maximum wall loss of 8.7%. So, RUG was still able, even though we weren't able to scan the lower half of the pipe, it was still able to show that there was maybe some areas that we were missing with the manual process. And there was potentially a little bit more wall loss than we were able to realize with the manual method. Again, as I mentioned, you know the portal shows that there's still images as well. So if there was an issue with a particular measurement, it makes it possible to go back and look and see if there's something different at that location. You know. Any potential reason to think that that data point could be suspect. Even with the data collection issues, RUG scanning was able to collect more data than a manual process. And also reveal localized wall thickness that the manual scan did not detect. So, there was potential, I would say uncertainty, with the reason why we were not able to get data on that lower part. So, the hypothesis that we were working with is that it was just too rough. But there could potentially be some troubleshooting with air in the lines for where the water jets were shooting out. So, we're not 100% sure that it was just due to the roughness, but that is one theory that we have. So, those were the results from all three locations. What did we learn from these inspections and these demonstrations? First of all, I wanted to touch on some of the limitations that we're seeing here. So, the robot was able to go through the water, but it is not designed to be completely immersed. So, we always have to be careful of what conditions we would use something like this in. Whereas the manual UT instruments that we have are pretty ruggedized. The tether length was something that we haven't talked about yet. But that tether provides a connection to the control. It also provides that robot with water to maintain that connection of the sound between the robot and the substrate. And then it provides power. So, the tether length used in this particular demonstration was 150 feet. So, this could potentially be an issue if we have longer assets where we're looking to do an entire, you know, 1,000-foot penstock. We also ran into some issues with water that we did not expect. The facility, one of the facilities that we had a demonstration on, was out of service. And there was no domestic water available. So we actually had to bring in a water trailer to use. It turned out that a 500-gallon water trailer was plenty of water to use for this particular inspection, so we were able to work around that challenge. The coating limitations. The rough texture, runs, drips, and sags, we think do present a challenge for the RUG scanning. But it is inconclusive due to those air bubbles and troubleshooting that the vendor experienced. And then the complex geometries can create additional challenges during both the scanning and the data analysis that we need to address. And then the limited analysis. We do have the portal, which makes data interpretation possible. But it also, due to the number of data points, there's some, probably, opportunities for improvement there. For example, the reports that we were receiving, some of those didn't always include the asset's nominal wall thickness. And I think one of the reasons is that the wall thickness changes as you go down the pipe. So, in the portal it seemed like there was only—it was only really set up to have a single nominal wall thickness. So that might be one area for improvement there. Especially for our situation where we've got a continuously changing nominal wall thickness. So, in summary, we were able to successfully demonstrate the capabilities of these remote inspection vehicles on Reclamation penstocks at three different facilities. We think the technology does show some promise. Both RUG and the RAUT provided useful metal thickness data in much greater quantities than was possible using a manual data collection process. The data was collected through different coating materials as well. So we had the coal tar enamel, that's a legacy lining in many of our existing facilities. We also have newer coatings like a thick, thicker 100% solids epoxy and a very thin moisture cured urethane. We had surface deposits that sometimes did interfere with data collection and also attraction of the robot. But RUG was able to get around fairly well. The RAUT had more issues than the RUG did. And then for the RAUT, the transducer shoe did visibly deflect on small features such as runs, drips, and sags from the new lining. So that, I think, is going to be more limited where we can use it than the RUG would be. And during the project, the RUG was optimized for scanning through coal tar enamel. And also we were able to—they were, the vendor was able to optimize this for thick steel substrates up to 2.25 inches thick. And RUG is much faster than RAUT and better suited just for scanning large areas and navigating around welds and things like that. But we do see some potential additional development that could be needed, both in the short and the long term. So I've got three different things here to potentially be useful to improve this technology. The first would be just to update that portal to allow assets to have multiple nominal wall thicknesses. And then that would be a lot easier to be able to tell what the wall loss is, as opposed to having to do some data reconstruction to try to figure it out after the fact. In the midterm, it would be nice to see some iteration done to ensure that we could get reliable data collection on lining systems with rough textures. So this is really the most critical element here if we wanted to adopt this technology for use like, you know, universal use at Reclamation. We want to make sure we can get good data on very rough linings. And then in the long term—this was a limited study that only targeted, you know, several 100 square feet. But if we wanted to do this for an entire pipe, it may need some longer tethers or potentially even a wireless setup in order to allow that robot to move unimpeded through the pipe length. So, maybe this is a little pie in the sky, but maybe they could try doing something like onboard water recycling to try to keep—allow that water to last longer so we don't need to be tethered as much. So, for next steps here, we think that RIVs have the potential to be a useful inspection tool and that RUG could potentially supplement or eventually replace some of the existing inspection methods. I think the next steps we would recommend would be to do some additional targeted demonstrations on specific applications. And these are things like penstocks and other assets with areas that are considered unreachable by rope access. So, anything with diameters larger than about 8 feet, we're not able to reach the pipe crown. So, that would be a nice area to start using the robotic inspection for. And one nice thing there, is that that tends to be the smoother surface for the coal tar enamel. So that could potentially be deployed right away. Second, penstocks and other assets with areas that are considered unsafe for humans. So, these are things like smaller diameter pipes that we can't fit a person into. Or there's other hazards present that can't be mitigated. That's another really good opportunity for RIVs. And then three, so this is an inspection technique that, you know, generates a lot more data. So, we think that if given the additional expenses, it makes sense to also think about using it for facilities that we need a reason to. So things like, there's a history of corrosion damage. Or we need just a more comprehensive dataset for an aging asset. And then another thing to do would be just to look at areas where it's more conducive to automated, just to make it easier. Things like pipes that have already been relined with epoxies, or we have a relatively smooth surface that's free of any surface deposits. And then fifth, any applications that would open up as the technology matures. So, this is only gonna get better. And as it does get better, there's gonna be more opportunities to use it throughout. So, that would be good to keep in mind. And thank you very much for your attention. I would open the floor to any questions at this time.

>> **Grace Weber:** Thank you, Dave. So, as Dave said, we're going to now begin the Q&A session. So, any attendees, please continue to submit your questions and comments and we will address as many as we can. So, the first one is from Lee, who asks: The automated scans appear to consistently show greater thickness loss than the manual process. Has this been independently verified to actually be the case, or is it potentially just an artifact of the measurement technique?

>> **Dr. Tordonato:** Well, that's a good question. We are comparing two different UT techniques. The thing to do would just be to make sure that we are calibrated properly. That's really the only variable, is the sound velocity. But in general, most of the measurements that were showing on the data portal and during the data collection process were very close to what we measured using the manual process. So, the measurements that were the lowest ones were the outlier

measurements. But in general, it seems like we were getting measurements that were close to what we were reading with our manual gauge. Good question though.

>> **Grace Weber:** Alright. Next question: Were the RIVs operated in-house or by the vendor? And which would be your preference for future inspections?

>> **Dr. Tordonato:** Yeah, good question. So, this was a contract that was awarded to a vendor. They were responsible for doing the inspection. We were on site to witness it and do our manual UT inspection after they were done. But no, we were not trained to operate this equipment. And so, that would be something that if we were to start using this technology more, could be an opportunity for Reclamation engineers to work with the vendor to try to get trained up and use that equipment. I think if we were going to be doing this frequently, that would probably be the more cost effective option than contracting out each inspection.

>> **Grace Weber:** Alright. Next question: How fast does the robot travel when it is scanning?

>> **Dr. Tordonato:** So the setup time, once they're done setting up and they actually start scanning it, the scanning process goes really quickly. I think that for the third facility, they were done in a matter of just a couple of hours of actual scanning. The robot travels across the surface at 0.5 feet per second. And it has 24 transducers that go across the width of it. And each one is—they're at like a one-inch spacing, I believe. You can adjust that spacing and get a smaller width of scan. But for that particular demonstration, the width of the scan was two feet. And so... they were able to get that scan done quite quickly at half a foot per second.

>> **Grace Weber:** Okay. And the next question: I'm assuming the bot is magnetically attached as it moves over the surface.

>> **Dr. Tordonato:** Yeah, that's correct. Both the RAUT and the RUG robots use really powerful, permanent magnets on the wheels, I believe. Actually, I'm not sure if it's permanent or if they're electromagnets, but they do adhere pretty well even through the thicker coal tar. And that was one question that we had too, is, obviously as the lining gets thicker, that's gonna weaken the magnetic strength. Coal tar enamel can be up to, you know, over 100 mils thick. So, it was able to adhere to the surface, for the RUG robot, all the way up to the pipe crown.

>> **Grace Weber:** Okay, you mentioned that the robot can go through some water. Do you know how much? Also, how much sludge or biofilm can they measure through?

>> **Dr. Tordonato:** I'm not sure. That's a good question. It seemed like it was able to go through the amount that was in the invert, which was at least a few inches of water. My bigger concern would be on some of the steeper pipes where we've inspected, the water actually travels pretty

quickly. And so the velocity, more than the actual depth of the water, could be an issue. That's something that we would need to answer. As far as the biofilm or sludge, it did look like they were missing a little bit of data on Facility #2 where we did have some sludge. But overall, I would say the amount of data they were able to collect was satisfactory. Despite that presence of that material. The sludge or the biofilm probably would create more of an issue of traction, especially if they're trying to scan in the circumferential direction. The water at least has the ability to kind of look like it could wash away some of that. But that's one reason why I think it would be better—or it would be a good idea to just continue to try to demonstrate this and get more experience with it, to try to get a better idea of what limitations there are and how they can be improved.

>> **Grace Weber:** Alright. And I don't know if you'll be able to answer all the parts of this question, but: How many vendors were used, who were they, and how were they selected?

>> **Dr. Tordonato:** There was just one vendor that was selected. We developed a statement of work. And the statement of work was looking at, you know, doing an inspection on two different facilities that were described in there and how many data points we wanted to get, roughly how many square feet. And there was a vendor that met our requirements that was selected. And if you're interested in learning more, feel free to send me an e-mail and we can talk more offline about that and the particulars of the inspection.

>> **Grace Weber:** Okay. Thanks, Dave. I'm not seeing any more questions. So, we'll just wait another minute and see if anything else comes in. And I'm not seeing anything else. So, I think that's going to be all for today. If anyone does have any remaining questions, please reach out to Dr. Tordonato. His e-mail address is up on that slide. And keep an eye out for the next webinar in our series. Thank you everyone for joining!

>> **Dr. Tordonato:** Thanks everyone!