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Robotic Non-Destructive Inspection of Hydraulic Steel Structures

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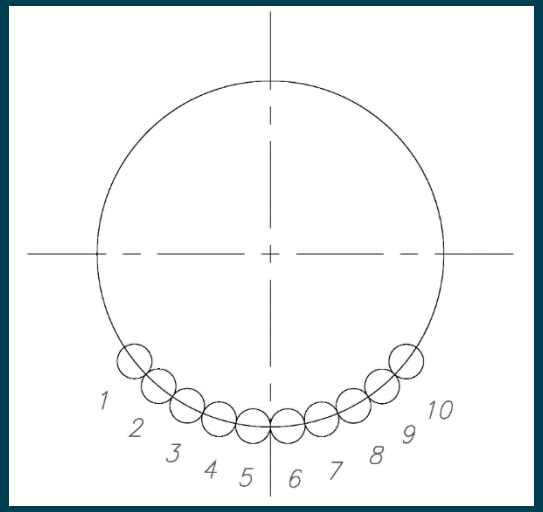
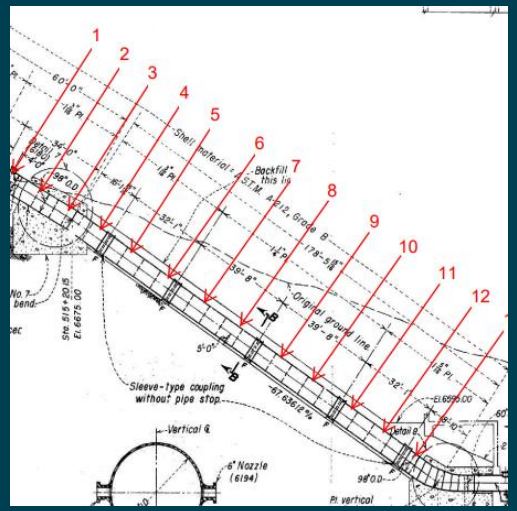
Introduction

- FIST Manual 4-1A requires that detailed inspections be conducted on penstocks and pressure conduits be inspected every 5-10 years.
- Current Practice:
  - Currently collect ultrasonic thickness (UT) readings manually and typically on the lower portion of the penstock's circumference.
  - Inspectors typically collect 5-10 readings every 10 linear feet.
  - Since each data point collected represents a discreet location, it is possible (and likely) that worst locations are not sampled.
  - Pipe crown is normally excluded from UT inspection in larger diameter pipes.





Problem Statement

- Aging Infrastructure makes thorough condition assessment more important
- Manual UT can miss localized problem areas
- Manual UT can miss hard to reach areas
- Manual UT can require rope access and expose workers to hazards
- Some structures cannot be safely inspected by humans i.e. smaller pipe

Research Objectives

- Can new rapid robotic inspection vehicles (RIVs) be used effectively to inspect penstocks, outlet works, etc
- Where and how best to implement new state of the art robotic inspection methods on aging infrastructure.

Practical Questions:

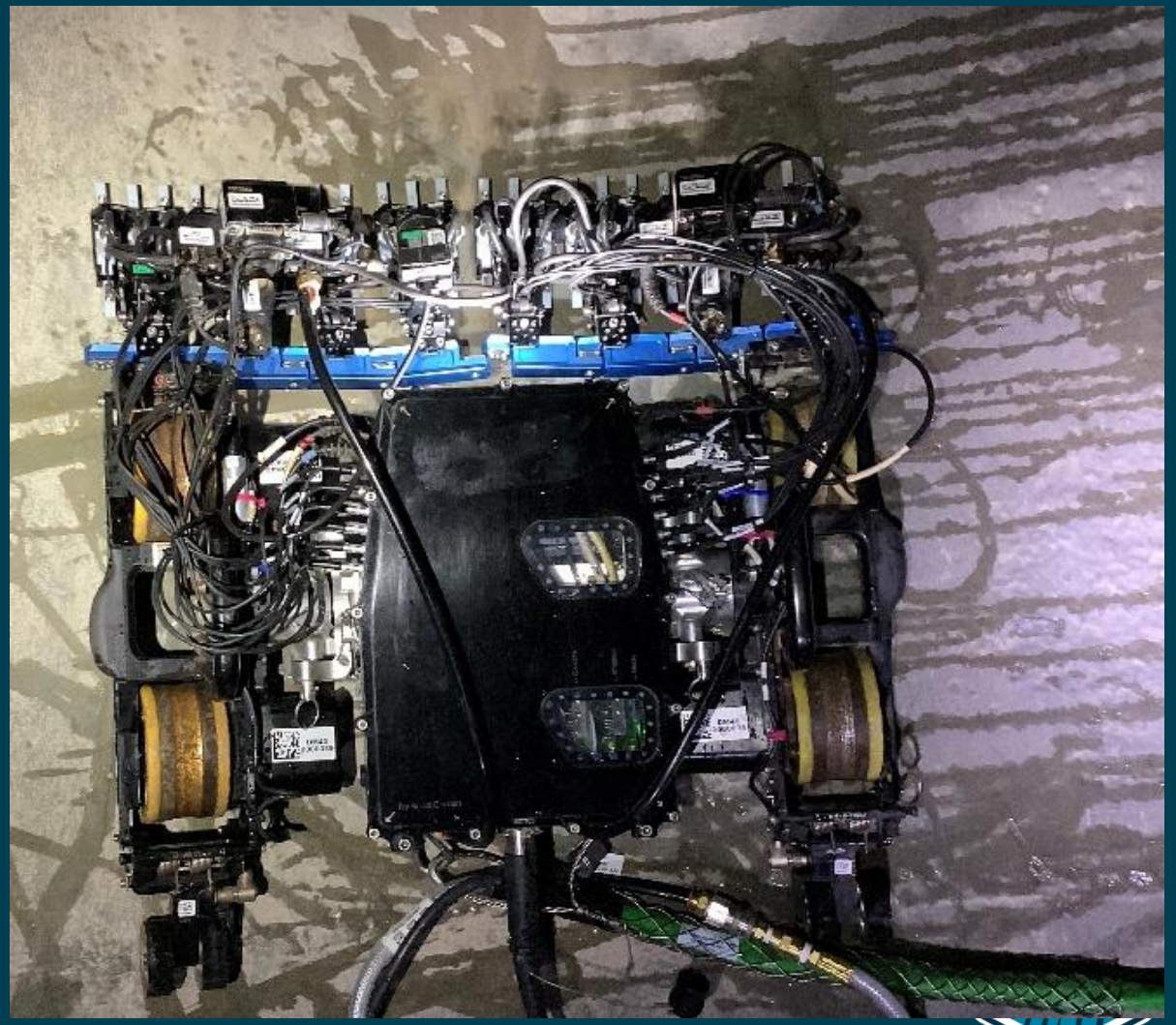
1. Rough surfaces or damaged coatings? Limitations related to surface roughness? Surface cleanliness?
2. Thick coatings i.e. coal tar enamel?
3. Can surface pitting be identified and quantified?
4. Logistical limitations (manhole spacing, power requirements, minimum diameter requirements, pipe crown)?
5. Costs
6. Real-world setup times, scan speeds, and production rates?
7. Format of data collection and ease of use for post-processing?
8. Can this be done in-house?

Technology & Vendor Selection

- Rapid Ultrasonic Gridding (RUG)
- Ultrasonic Technology (UT)
- Rapid Automated Ultrasonic Testing (RAUT) with Phased Array Ultrasonic Testing (PAUT)
- Electro Magnetic Acoustic Transducer (EMAT)
- Electro Magnetic Acoustic Transducer Crack Detection (EMAT CD)

One Vendor was selected to provide inspection using:

- RUG:
  - Marketed as a tool for general corrosion scanning
  - Fast, relatively inexpensive
- RAUT:
  - Uses a phased array ultrasonic transducer.
  - Collects data at a spatial density that is higher than RUG
  - More costly, and sacrifices speed for greater resolution.
  - Appropriate for evaluating a smaller area of concern.



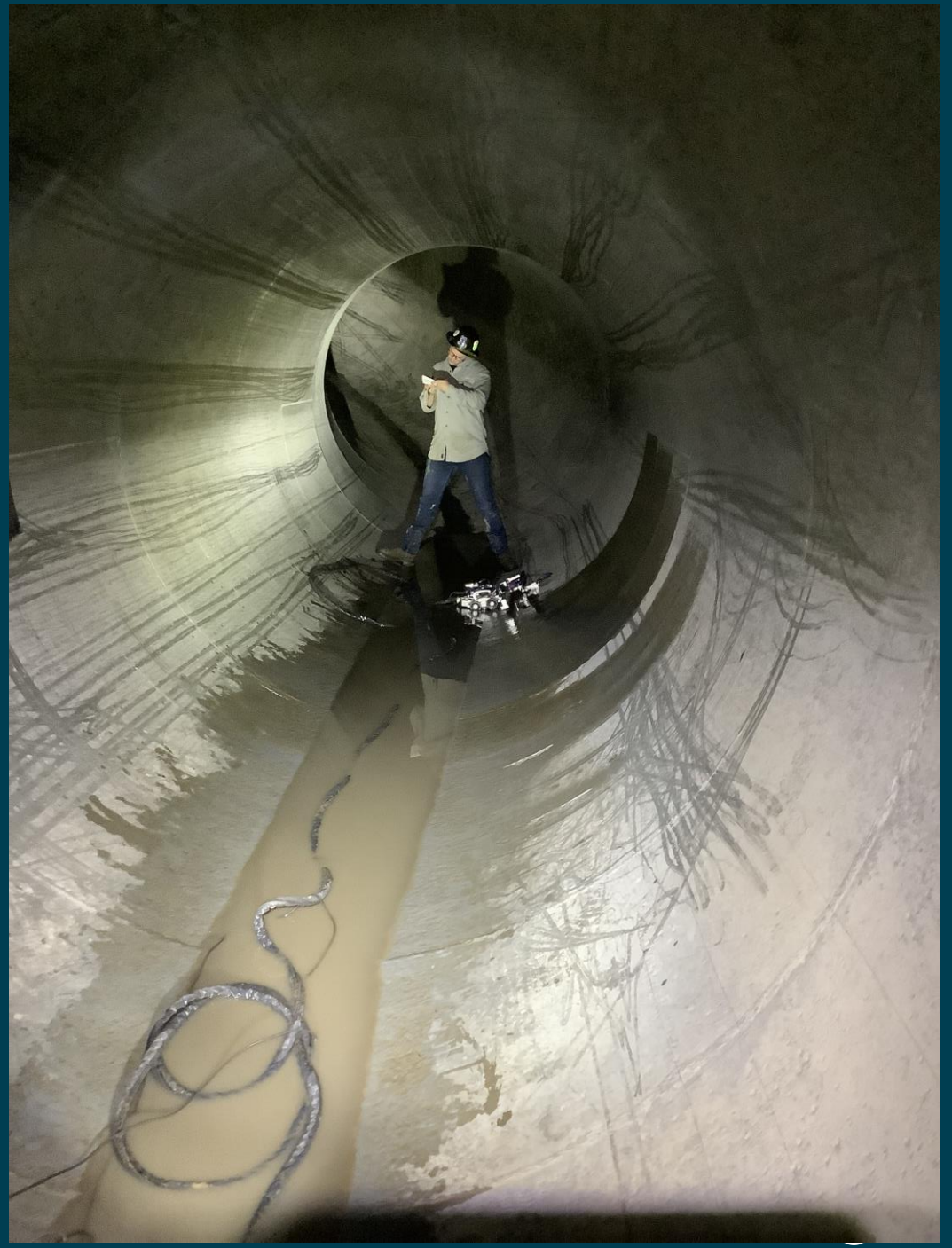
Methods – Site Selection

Three facilities were selected for the demonstration

- Facility 1:
  - 25-foot diameter penstock, no slope.
  - Originally coated and lined with coal tar enamel.
  - Accessible from both inside and outside.
  - The exterior coal tar was smoother.
  - Some of the original coating/lining has been spot repaired with a thinner urethane tar material.
  - Large fraction of the upper circumference was already repaired/relined.

Methods: Facility 2

- 96-inch to 108-inch diameter penstock.
- 38-degree slope, requires rope access
- Water and sludge present on the surface
- Relined with epoxy 50-60 mils
- Only accessible from interior
- Prior pitting visible.



Methods: Facility 3

- 96-inch to 60-inch diameter penstock.
- 68-degree slope, requires rope access, dry surfaces
- Original coal tar present in degraded condition
- Accessible from inside only
- 1,000+ feet long (150 feet targeted)

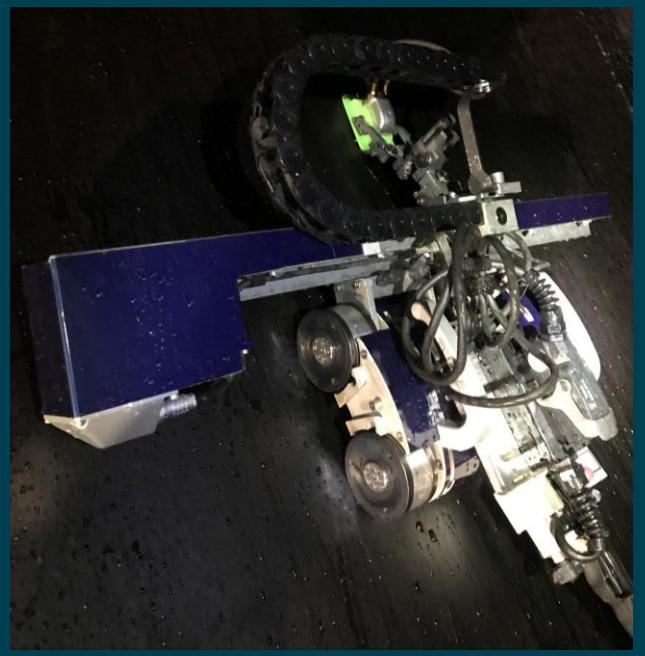
Methods – Inspection plan

- Facility 1: RAUT followed by RUG
  - Arbitrary location selected
  - Interior and Exterior for RAUT
  - Exterior only for RUG (no outage)
- Facility 2: RAUT, RUG, and Manual UT
  - 200 ft^2 select area for RAUT
  - 3250 ft^2 on slope using RUG
- Facility 3: RUG and Manual UT
  - 150 linear feet, 3,775 ft^2
  - Includes vertical reducing bend

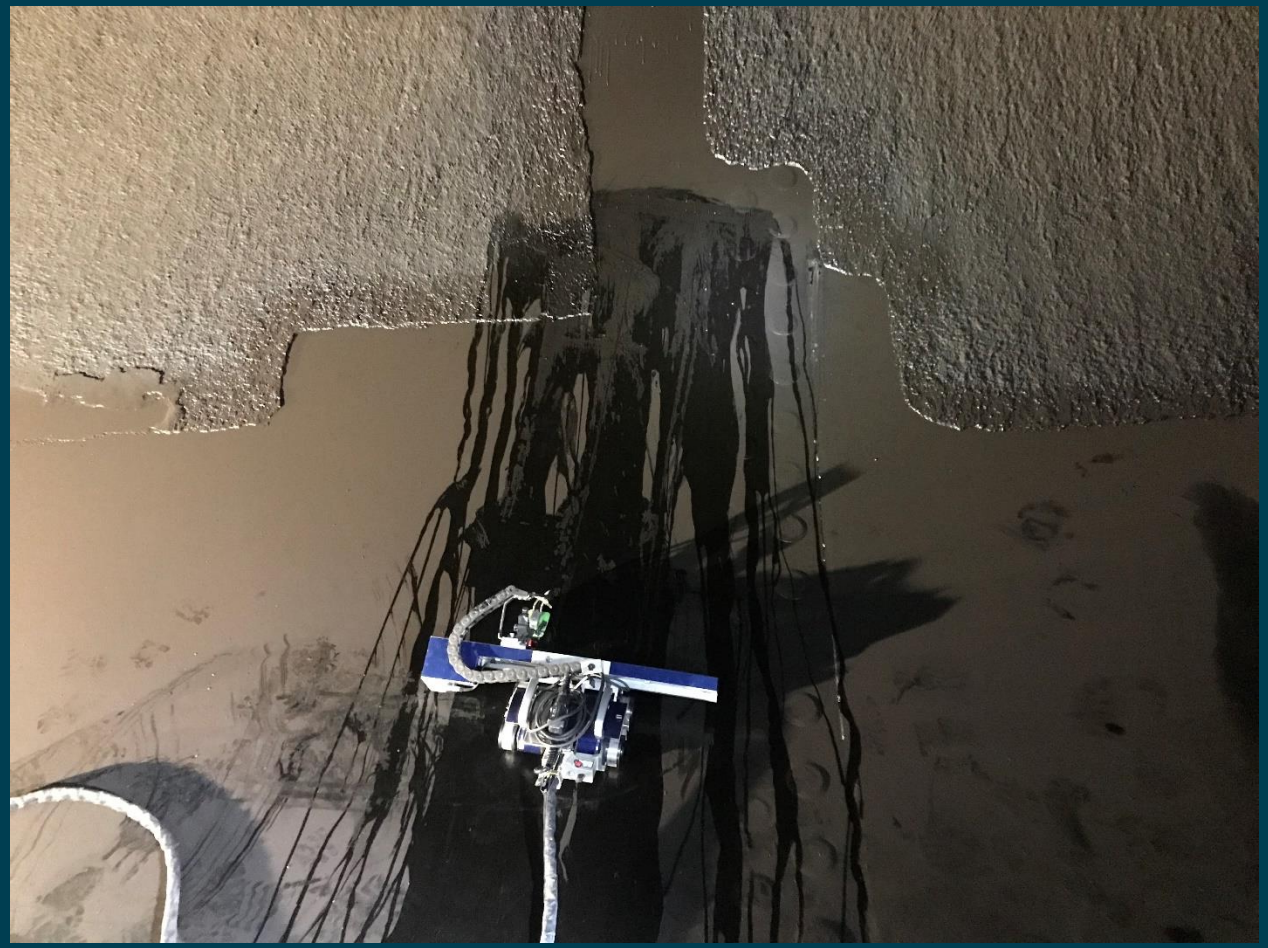
All RIV inspections capture encoded video and provide a series photos available in the vendor’s portal.

Results – Facility 1

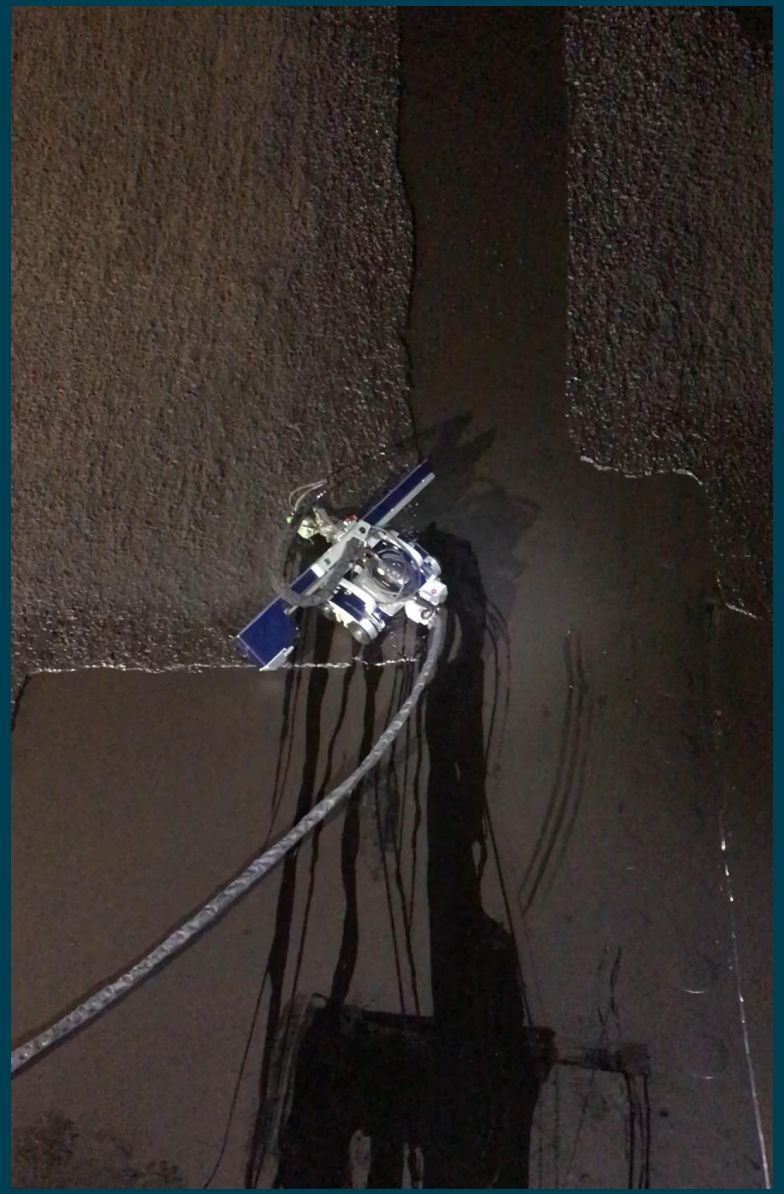
- RAUT scanning over the spot repaired area (10-14 mils)
- Original CTE too thick and rough to scan
- Rivets, weld seams, and rough lining presented challenges for both driving across and scanning over.
- Performed scanning on one side of the girth seam weld at a time.
- RUG scanning: 945 ft2, 8-hour shift

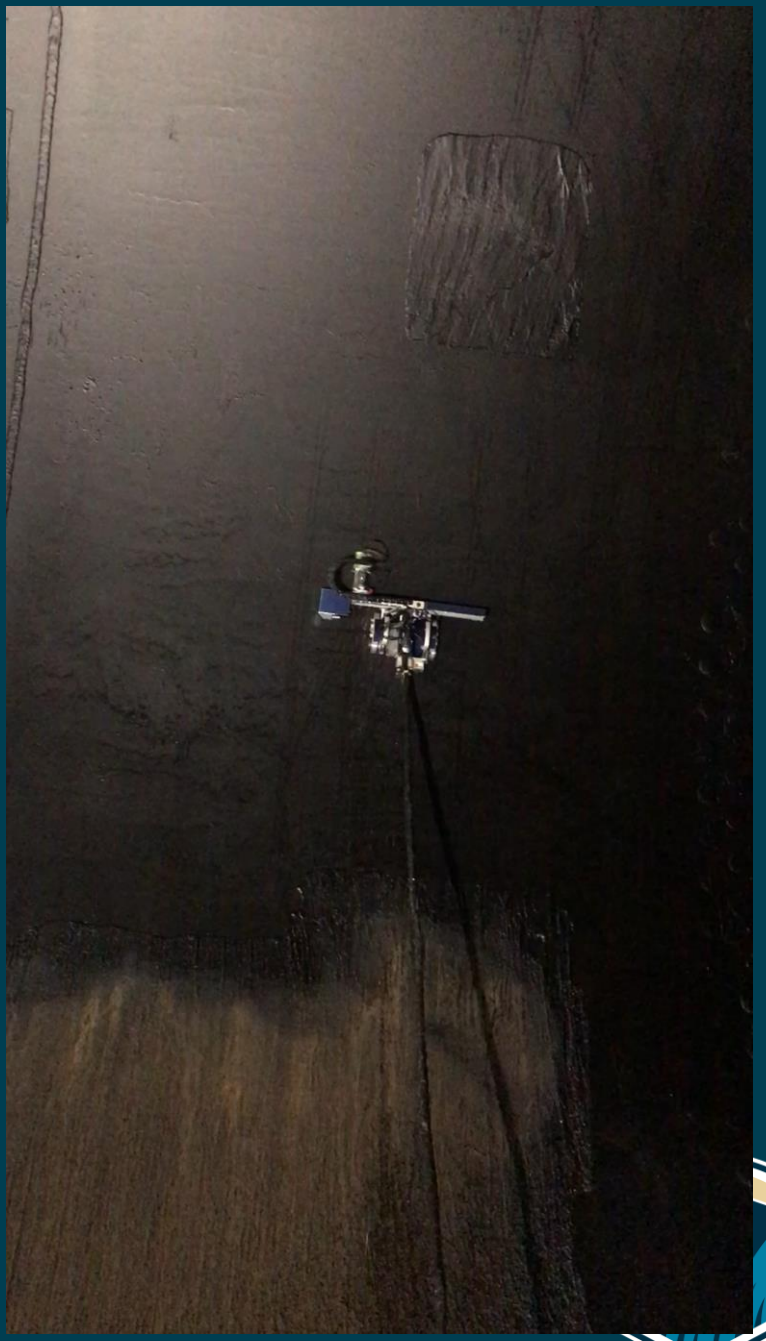


Results – Facility 1

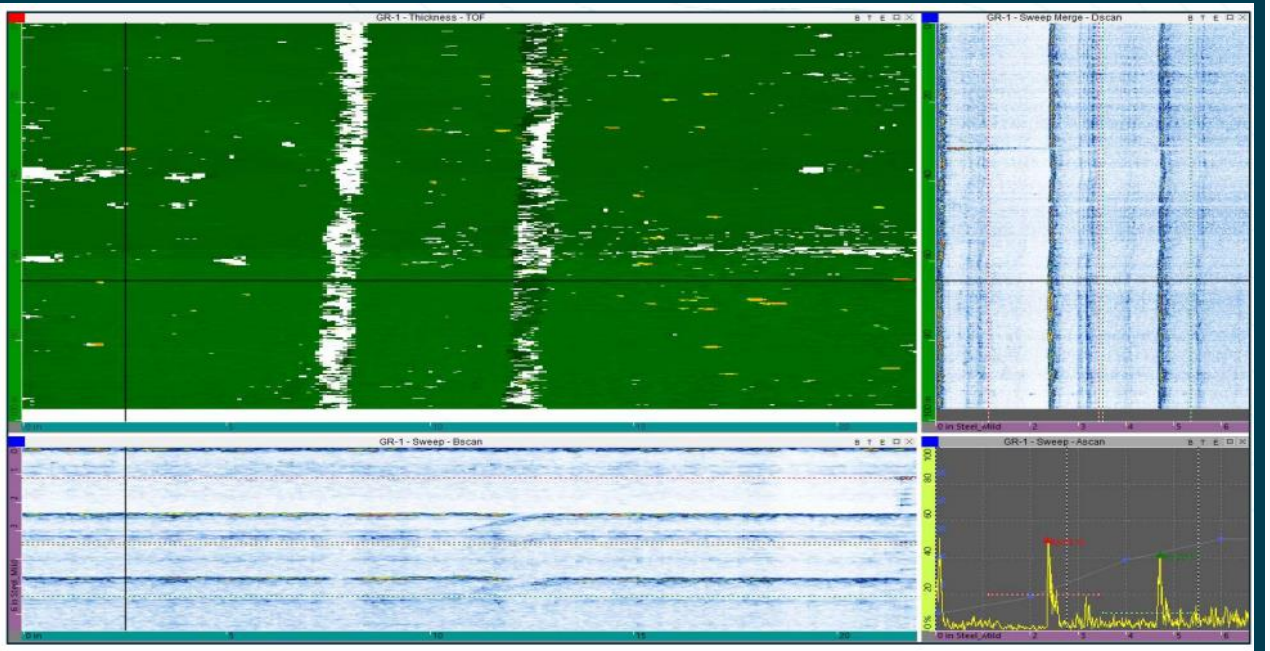


Results – Facility 1





Results – Facility 1

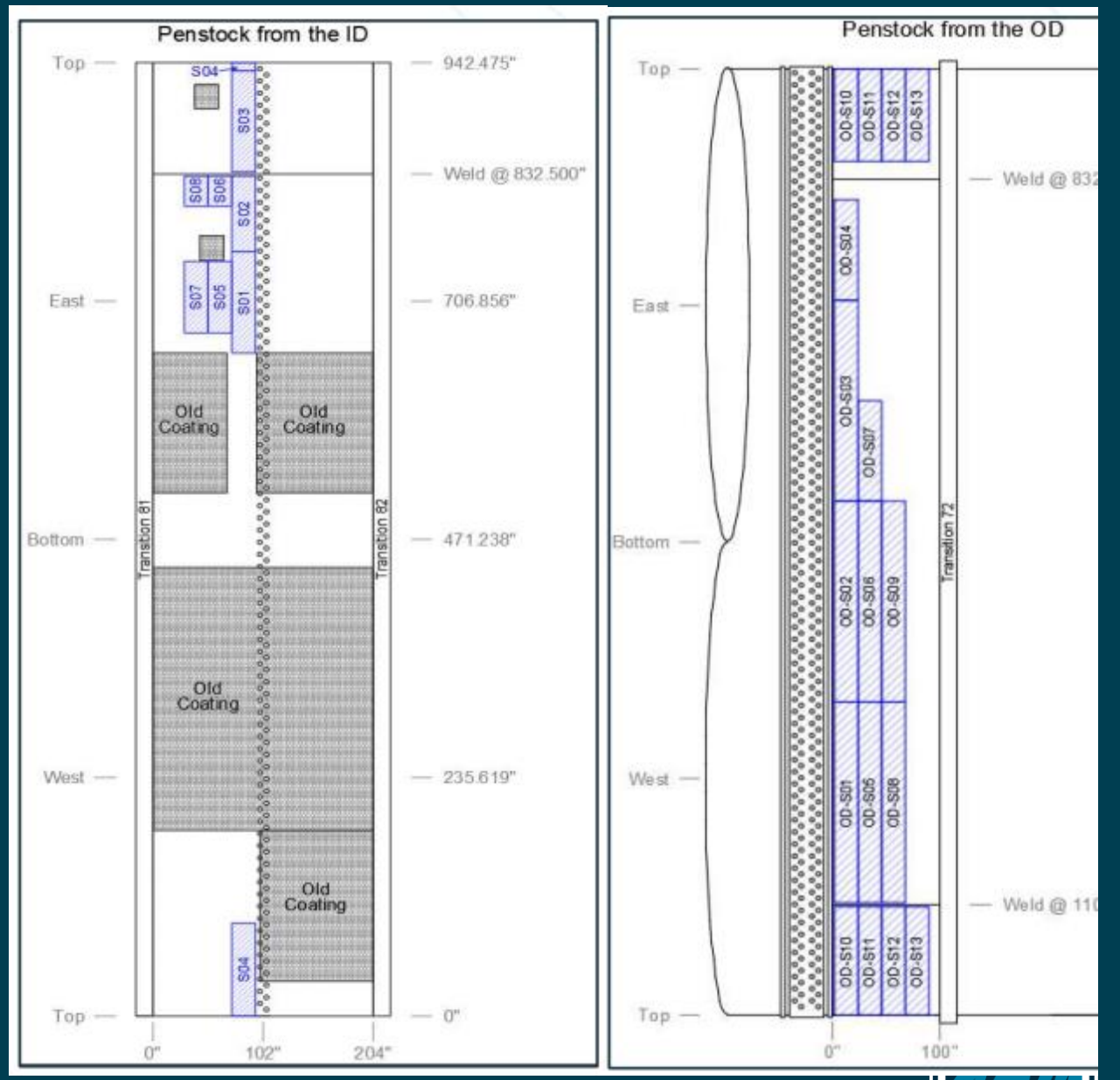


Measurements		Note: Coating & Temp. correction is subtracted from readings below.	
Minimum thickness detected:		Actual Min. Thickness:	
Average thickness detected:		Wall Loss (%):	
Average coating thickness:		Remaining Wall (%):	
Temperature (F°):		Actual Avg Thickness:	
Nominal Thickness:			

Comments

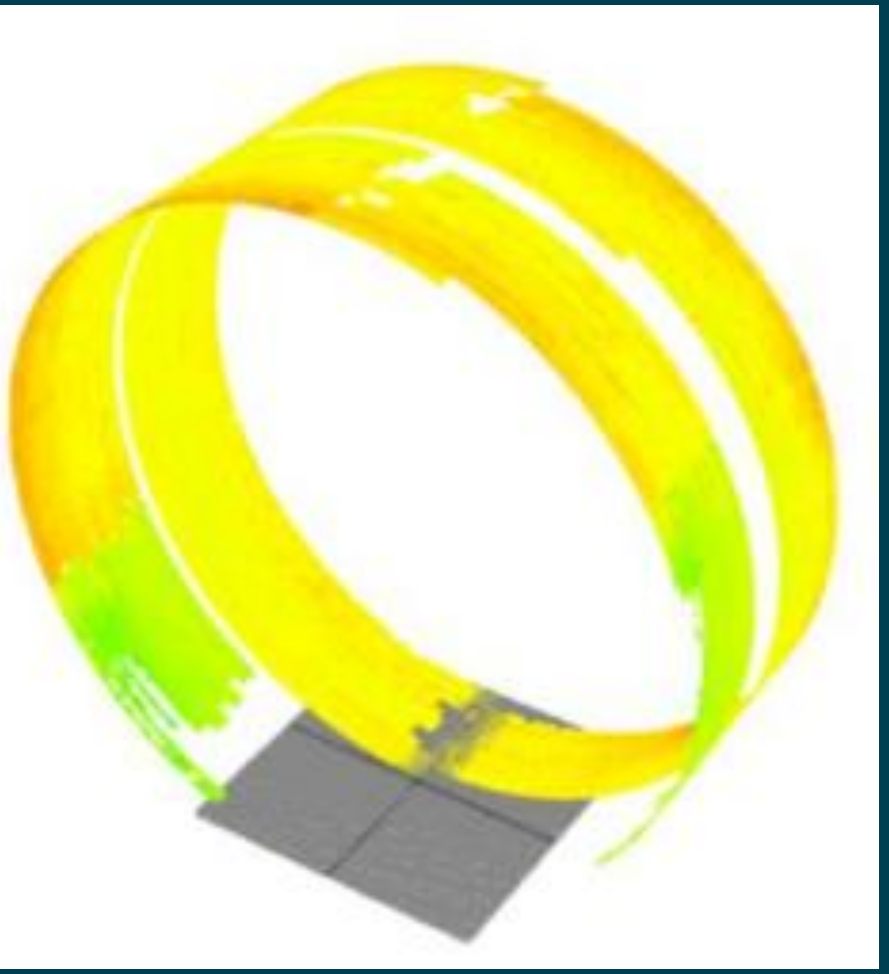
Though there is a coating, because it is on the OD and the ID, the traditional method of Echo to Echo to determine the coating thickness could not be used. Therefore, the Average Coating Thickness calculation is 0 and the readings collected are the thickness of the ID coating, base metal and OD coating.

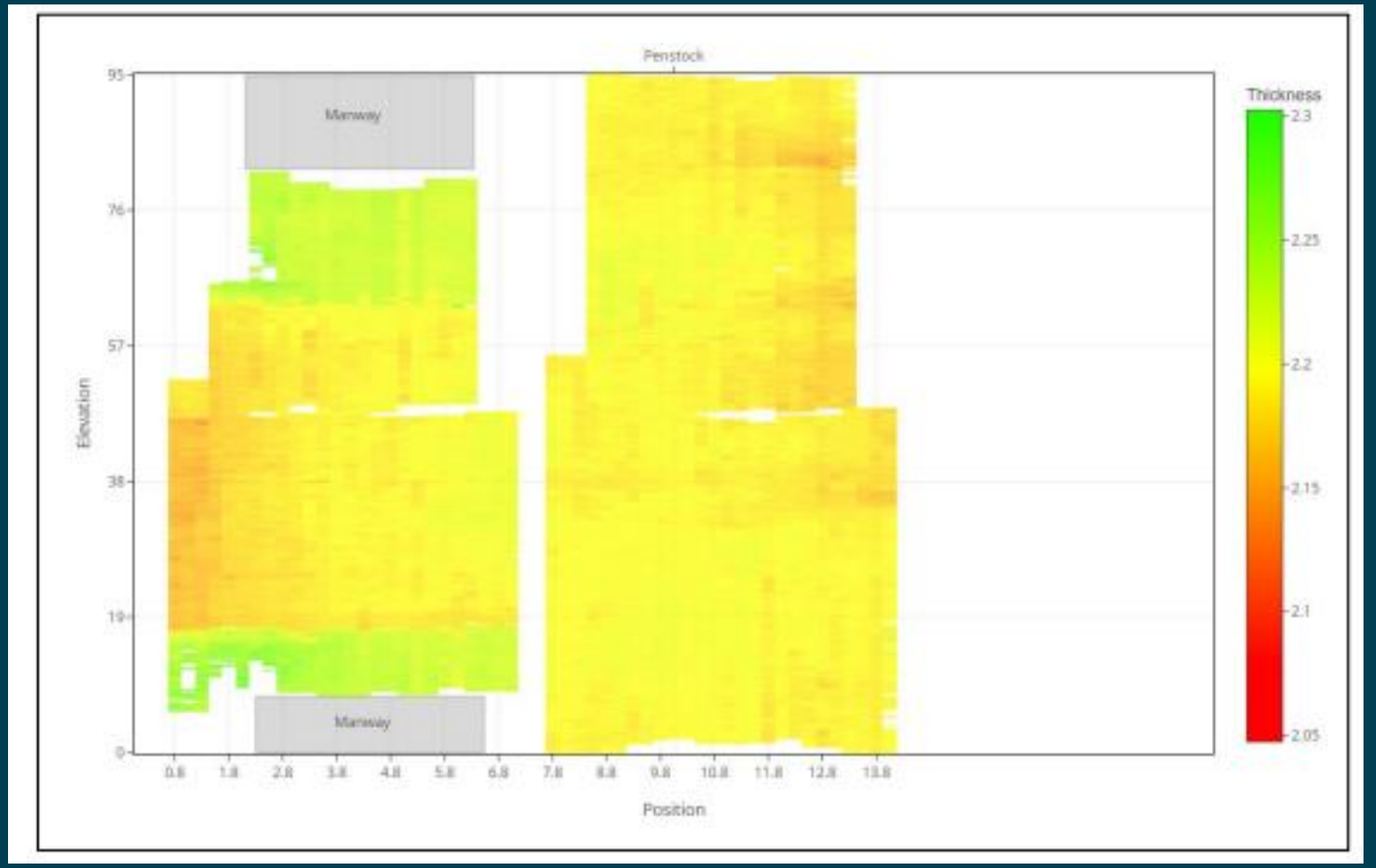
Multiple laminar inclusions are seen here



RAUT Data

Results – Facility 1





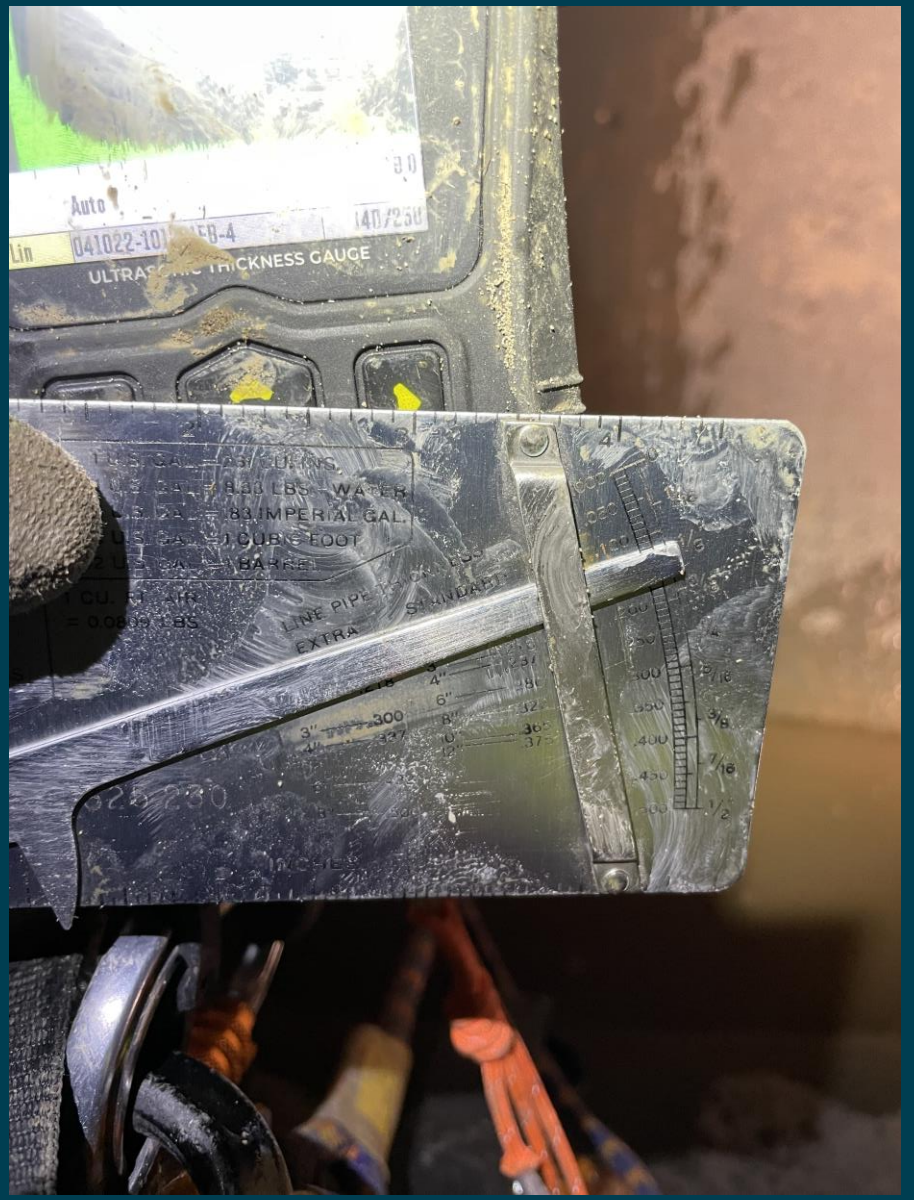
RUG Data

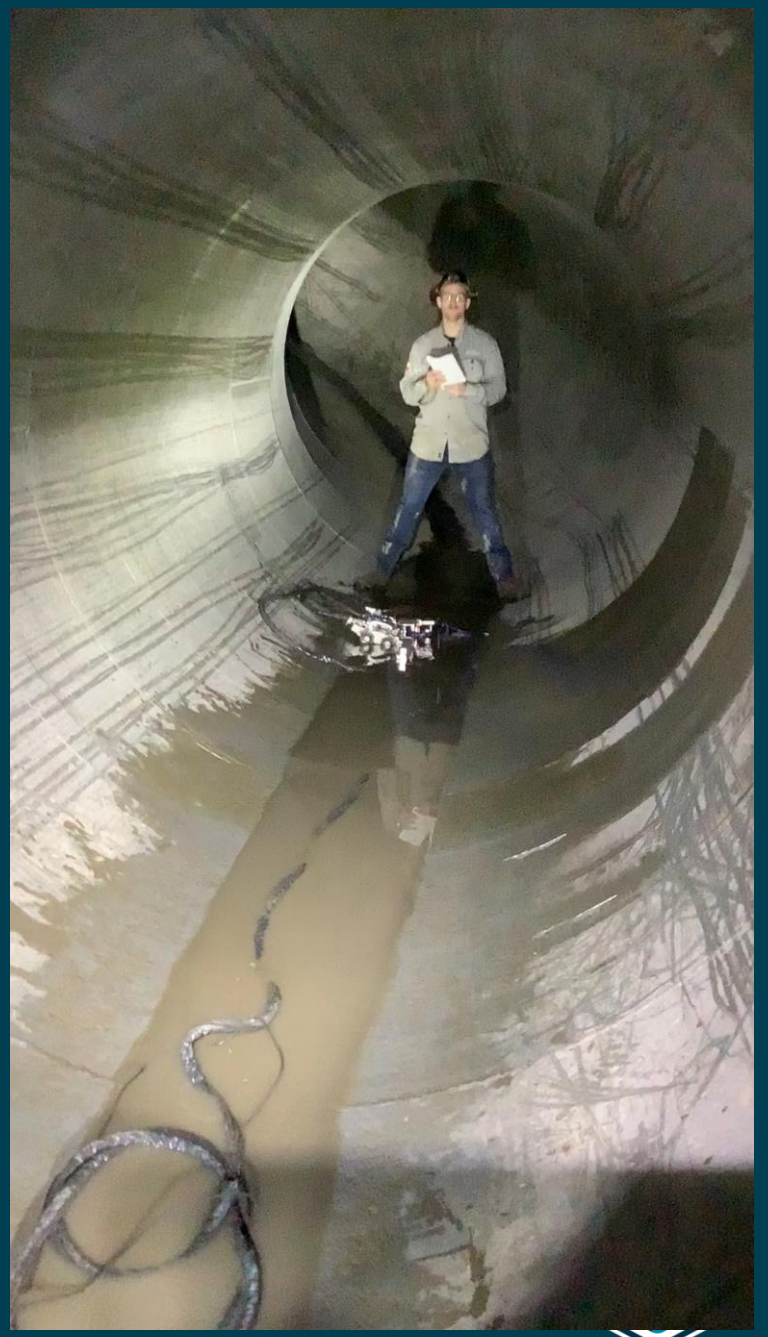
Discussion – Facility 1

- Initial limitation on metal thickness for RUG was around 0.75 inches. Was able to increase the limitation on substrate thickness to allow for scanning of material up to 2.25 inches thick.

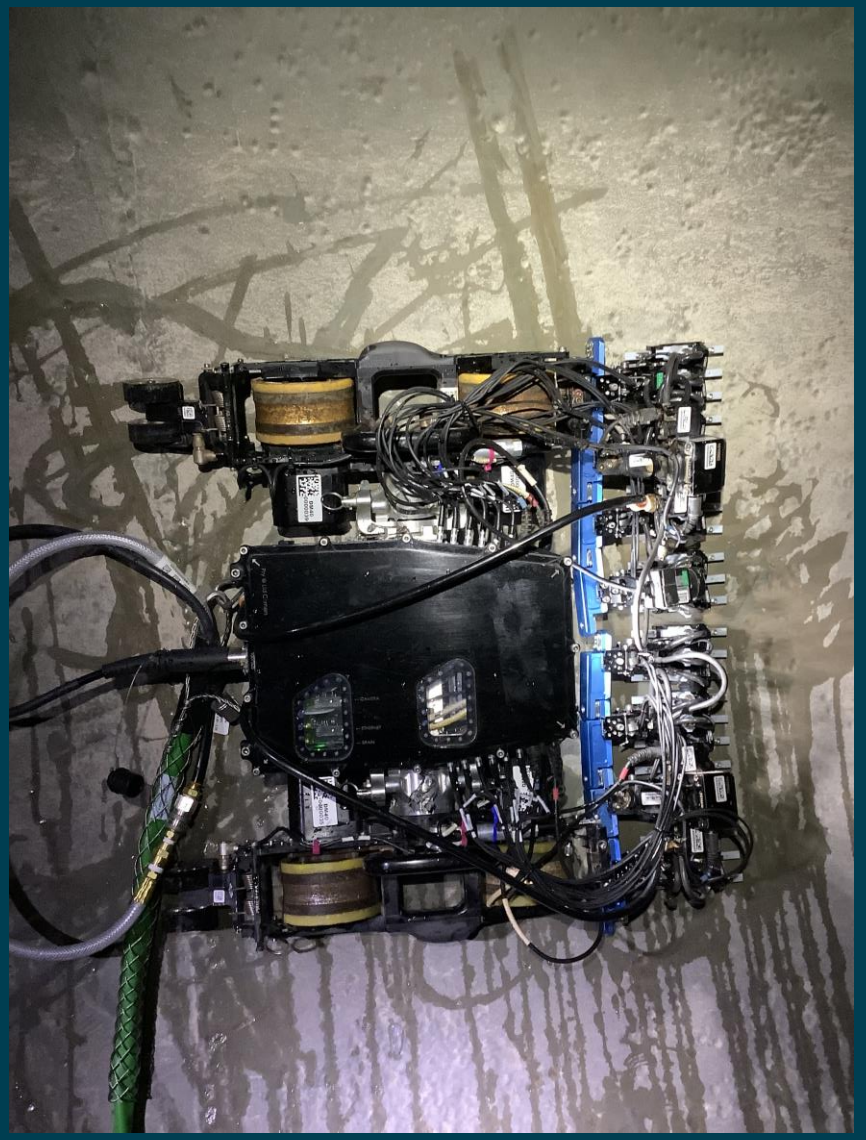
- RUG vs RAUT: RUG provided data with a much lower level of spatial density than RAUT but the tradeoff is worthwhile if some of the logistical limitations of automated RAUT are mitigated.
  - Less maneuverability issues with RUG vs RAUT.
  - The RUG robot still could not go over features such as rivets but likely can go over welds.
  - The RUG report mapped was more intuitive than RAUT. May be due to software used.
  - Able to discern coating thickness from metal thickness with RUG.
  - Interior of the penstocks have thicker coating. Newer/thinner coatings will make scanning easier.
  - Dam staff felt there is merit to getting a baseline data for the penstock thickness.

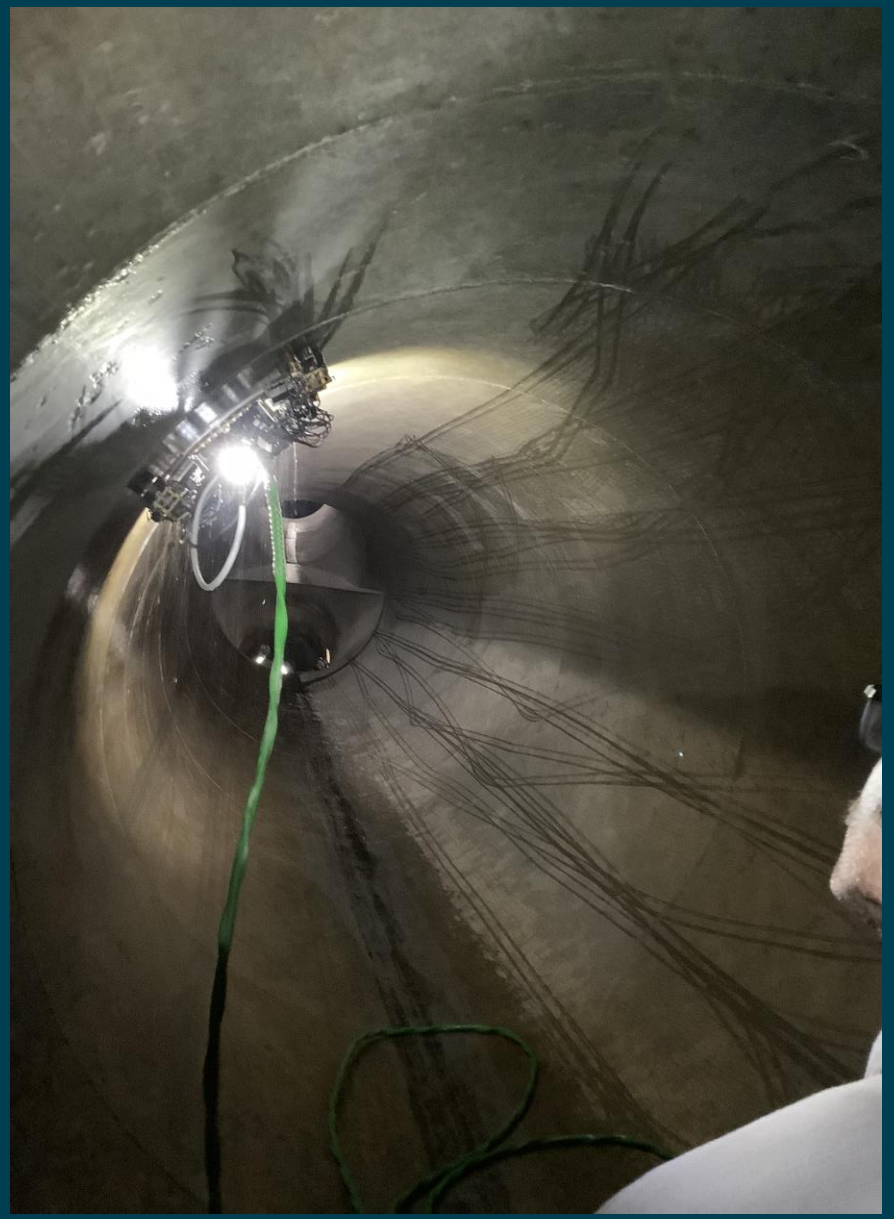
Results – Facility 2

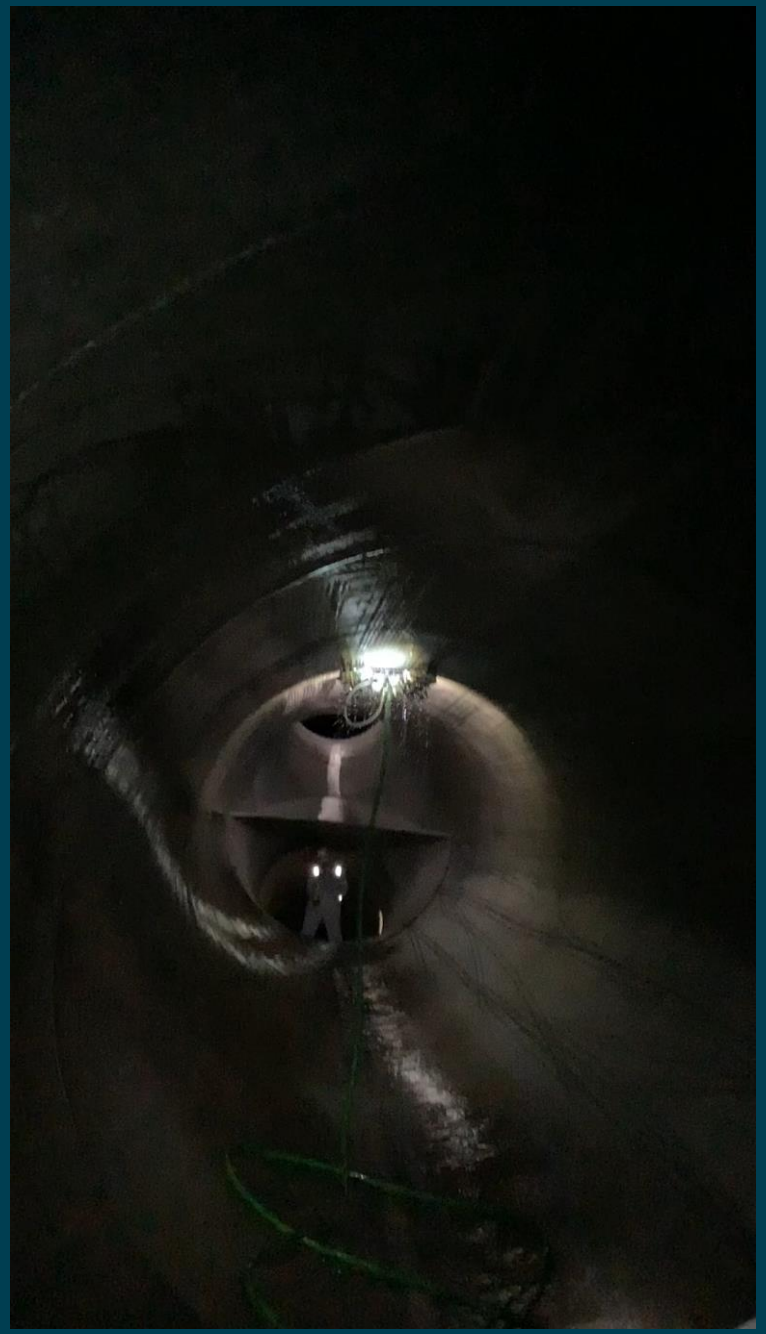




Results – Facility 2



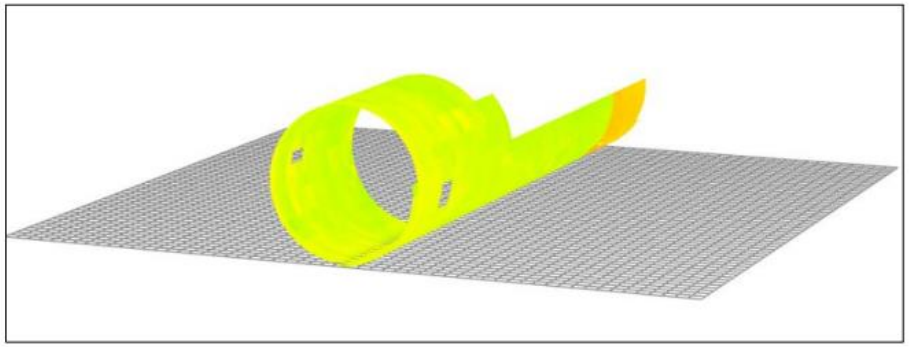




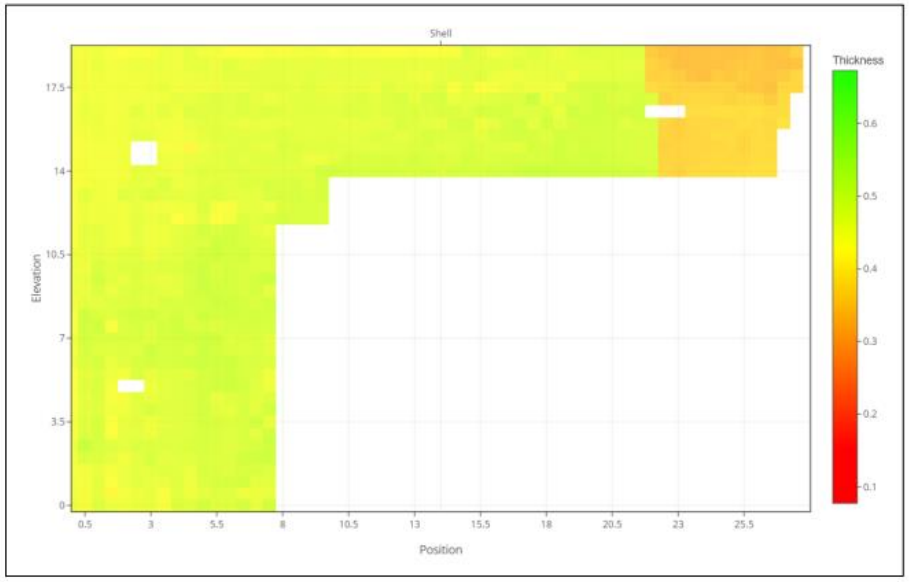
Results – Facility 2

3,477,222 readings taken
1,900 ft^2 and 3 areas

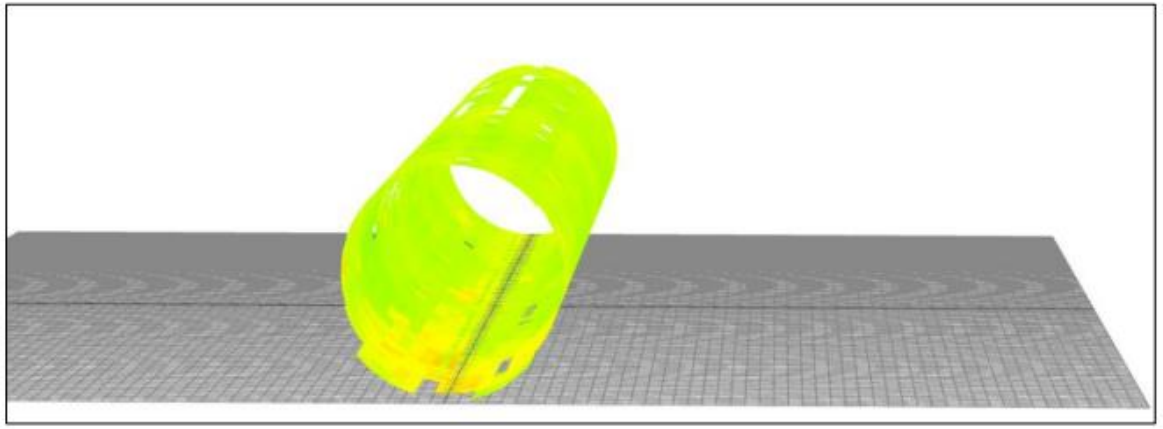
73" ID PENSTOCK 3D MAP



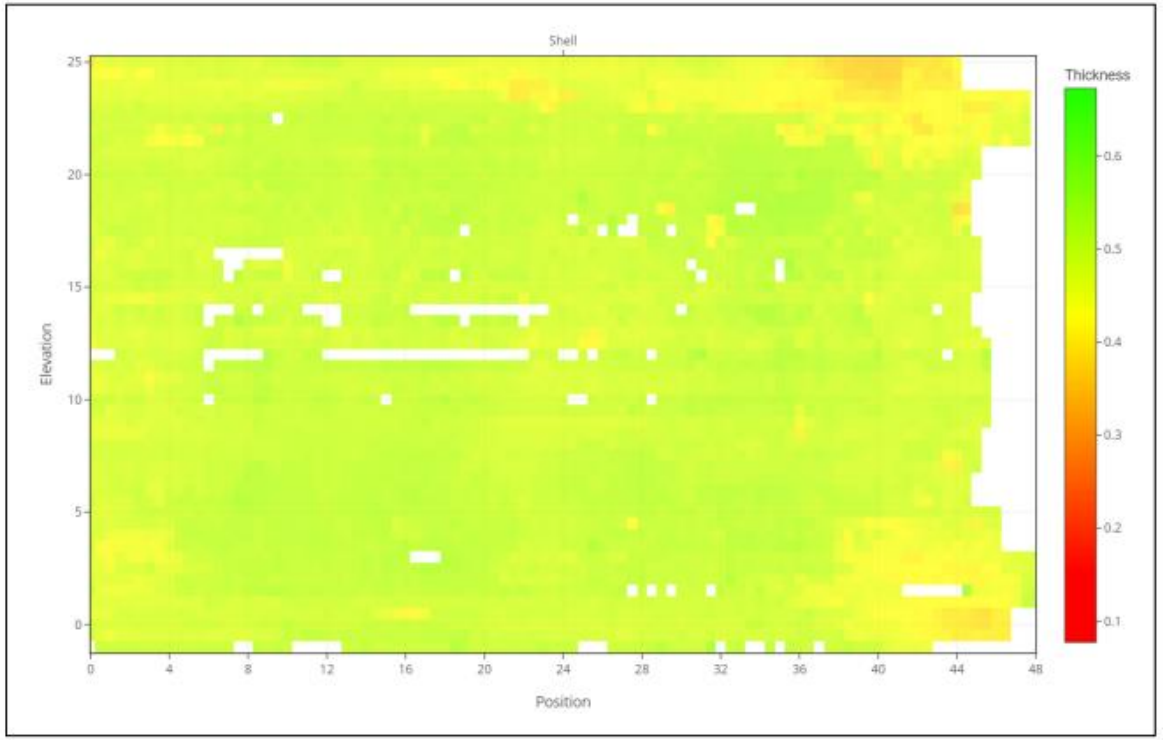
73"ID PENSTOCK C-SCAN MAP



SECTION 2 3D MAP

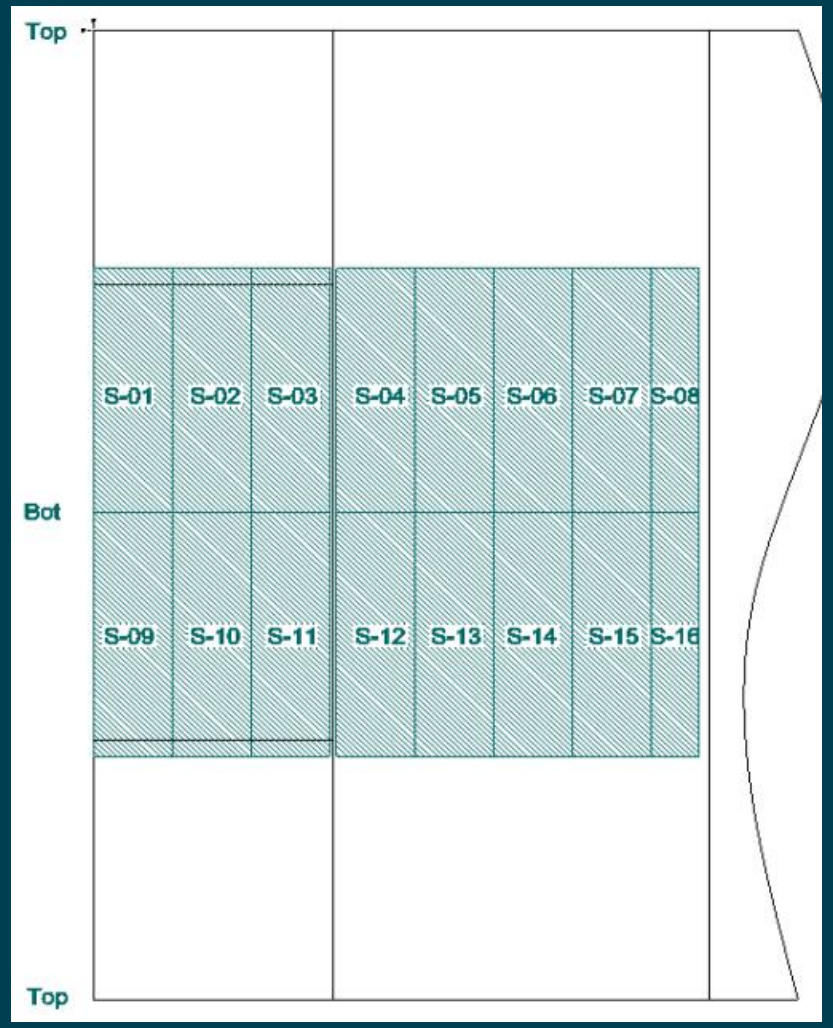


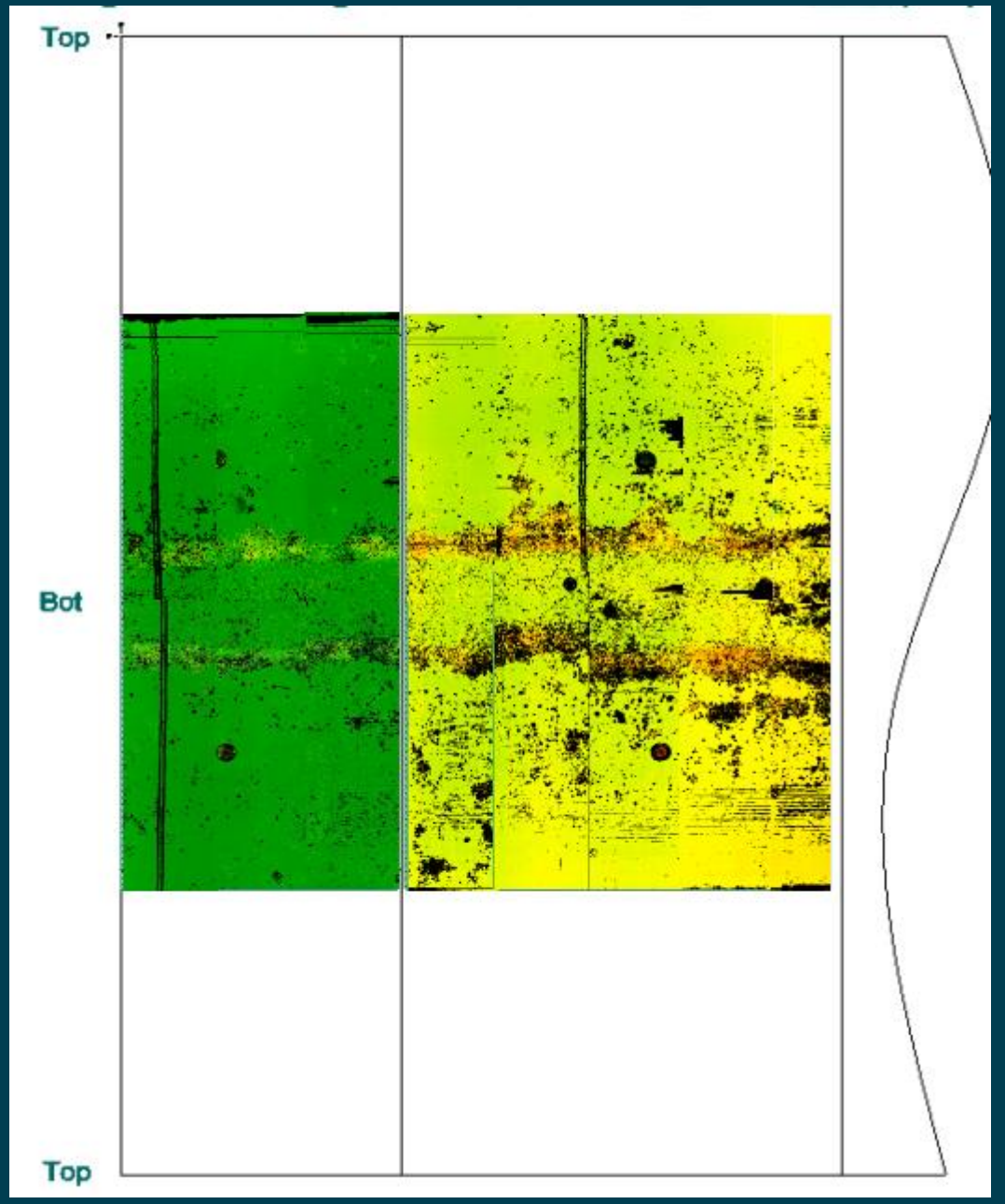
SECTION 2 C-SCAN MAP



Results – Facility 2

17,488,494 readings taken
185 ft^2



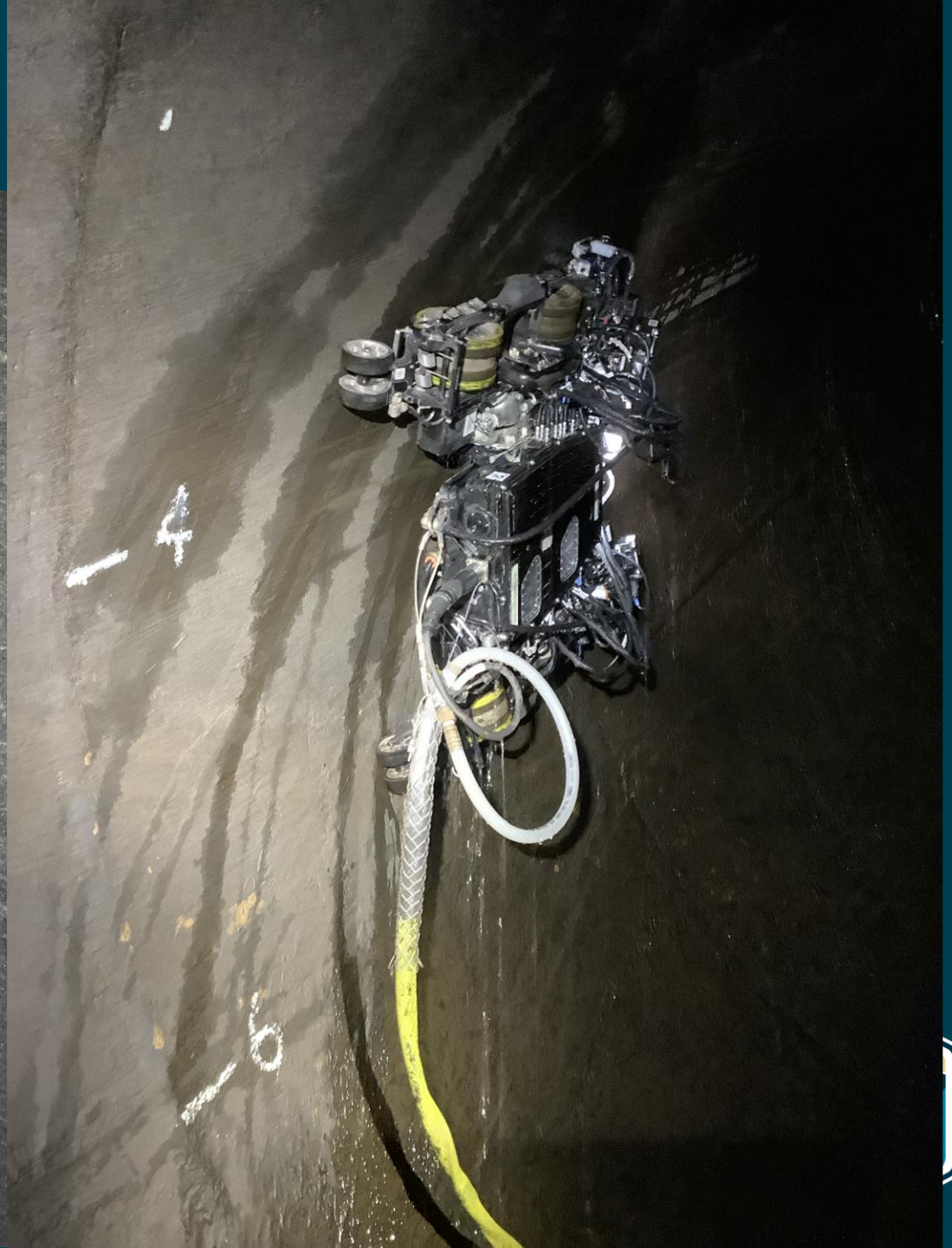


Discussion – Facility 2

- The manual UT inspection found a max decrease of 11% (0.445” with 0.500” nominal).
- Pit gage measurements taken found pits averaged 0.070” with a 0.180” maximum pit depth on 0.500” nominal wall thickness.
- 0.180” deep pit on a 0.500” section would result in 0.320” thickness and 36% wall loss.

- Both the RUG and RAUT detected lower readings than the manual UT.
- The RUG scanning revealed several low readings:
  - 0.379” in Section 1, flat portion on 96” ID section (24.2% loss)
  - 0.366” in Section 2, sloped portion of the 96” ID section (26.8% loss)
  - Note: wall loss not provided in the RUG report.
- RAUT results in the flat portion of the pipe were similar with minimum thickness of 0.369” on the flat portion of 96” ID penstock where the reported nominal 0.500” (26.2% wall loss).
- It is unclear if RAUT & RUG readings were taken in the pits.

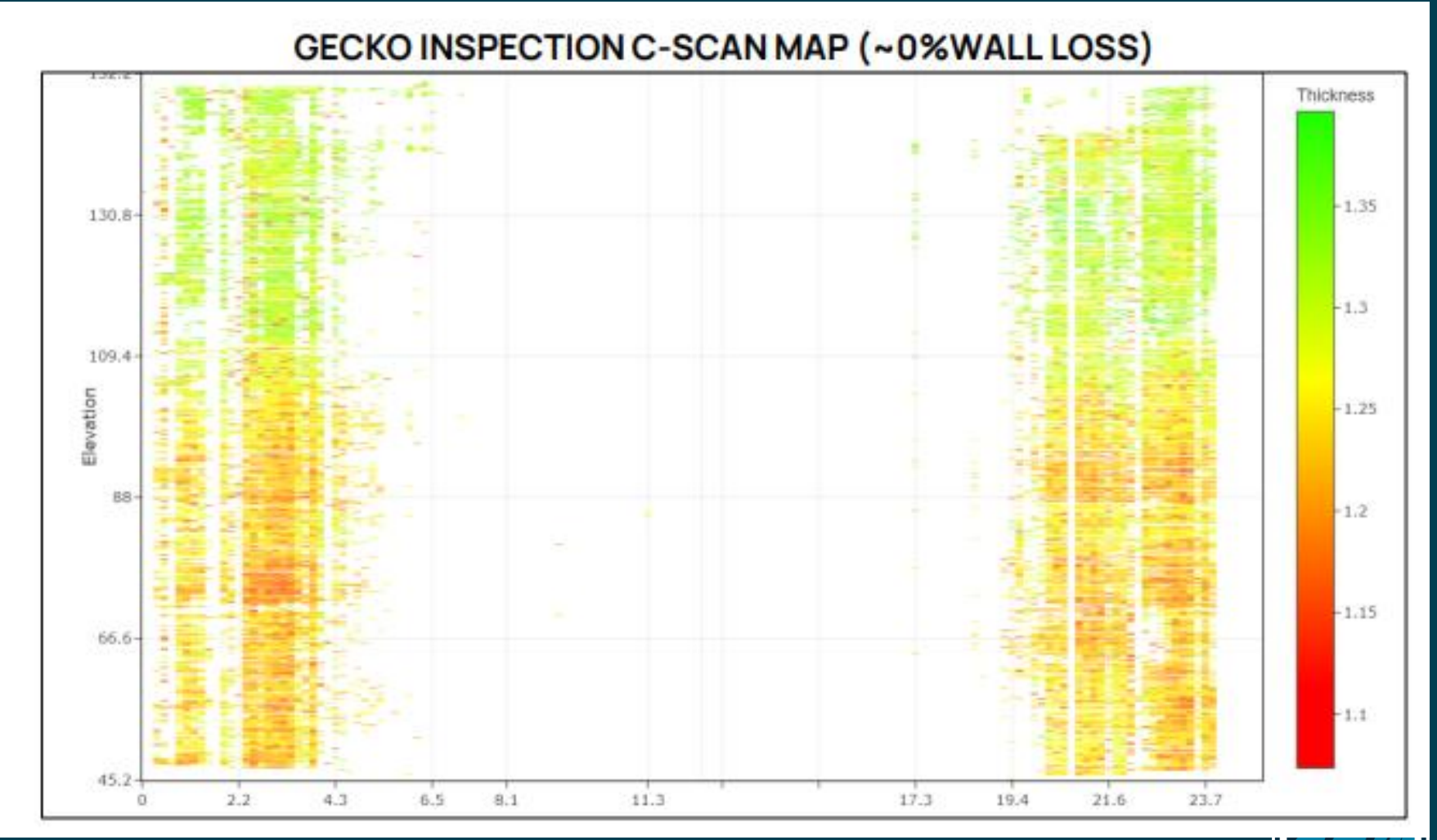
Results – Facility 3



Results – Facility 3

~1,200,000 readings taken
~2690 ft² covered
Vertical reducing bend omitted

RUG Target:
150 linear feet, 3,775 ft²
Included vertical reducing bend



Discussion – Facility 3

- The manual UT inspection showed a maximum wall loss of 2.55% (1.2790” with 1.3125” nominal).

- Vertical converging bend was omitted from scope.
- RUG was missing significant amounts of data on the lower circumference of the pipe. Air entrapment or surface?
- The RUG portal and report provided thickness data only. Data re-construction was needed for analysis.
- The portal includes still images, a histogram, low, and average thickness, whereas the report analysis was limited to listing the lowest 3 readings.
- RUG showed a max wall loss of 8.7% (1.141” with 1.25” nominal)
- Even with the issues associated with data collection, the RUG scanning was able to collect more data than a manual process and reveal localized wall thickness that the manual scan process failed to detect.

Limitations for RIV (RUG and RAUT)

1. Many penstocks have a stream of water in the invert when dewatered. The robot can get wet and go through some water, it is not designed to be completely immersed which may make it necessary to omit the invert from the inspection in some cases. Submerged areas with fast flows are typically omitted from a manual scanning process as well for practical reasons.
2. Tether length was 150-foot. This could be an issue for longer assets.
3. Water requirements
4. Coating limitations (rough surface texture, runs, drips, and sags) presents a challenge for the RUG scanning. Inconclusive because the vendor also experienced challenges with air bubbles in the water column on the penstock sides and bottom.
5. Complex geometries create additional challenges during scanning and data analysis that must be addressed.
6. Limited analysis. Data interpretation was difficult, the report did not always include asset's nominal thickness.

Summary

- Successfully demonstrated the capabilities of RIV on Reclamation penstocks
- Technology shows promise. Both RUG and RAUT provided useful metal thickness data in greater quantities than possible with manual data collection. Data was collected through several coating / lining types.
- Surface deposits sometimes interfered with data collection and traction.
- Thick lining prevented RAUT from being used above the springline.
- When using RAUT, the transducer shoe visibly deflects on small features such as drips/runs from the new lining.
- During the project, RUG was optimized for scanning coal tar enamel and for thick steel substrates up to 2.25”.
- RUG is much faster than RAUT and better suited for scanning large areas and navigating welds.

<u>Additional Development Needed</u>:

- Short term: Update Portal to allow assets to have multiple nominal thicknesses.
- Mid term: Iterate to ensure reliable data collection on lining systems with rough textures i.e. below the springline inside pipes with coal tar.
- Long Term: Longer tethers or wireless… onboard water recycling?

Next Steps

RIVs have the potential to be a useful inspection tool and RUG could supplement or eventually replace existing Reclamation inspection methods. We recommend additional targeted demonstrations in specific scenarios such as:

1. Penstocks and other assets with areas that are considered unreachable via rope access
2. Penstocks and other assets with areas that are considered unsafe for humans
3. Assets with a history of corrosion damage or where a more comprehensive dataset is needed for a condition assessment
4. Other assets where conditions are conducive to automated RUG scanning (relatively smooth surface free of surface deposit buildup).
5. Other applications as the technology matures.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Questions?
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