Cold Spray Mitigation & Repair for Nuclear Applications

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NRC AMT WORKSHOP 2020

This material is based upon work supported by the Government under Contract No(s). DE-SC0017855 & DE-SC0017229. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Government.

VRC Metal Systems

- Cold Spray Equipment Manufacturer and Commercialization Partner, specializing in process development for Repair, Additive Manufacturing, Coating, and Joining applications.
- Veteran Owned Small Business Established in 2012 focused primarily on DoD applications.
- Headquartered in Rapid City, South Dakota. 3 US locations.
- 63 Full Time Staff

Problem – *Seawater Corrosion*

- Corrosion of structural steels in military and industrial applications is a widespread problem
  - Cost to the US Navy:
    - 20-25% of total maintenance costs Corrosion mitigation and remediation –
    - Estimates as high as $4B Annually
  - Cost to Nuclear Energy:
    - Corrosion-related causes of partial LWR outages - $5M/year
    - Corrosion-related causes of zero power LWR outages - $665M/year
    - Contribution of corrosion to LWR operation and maintenance (O&M) - $2B/year

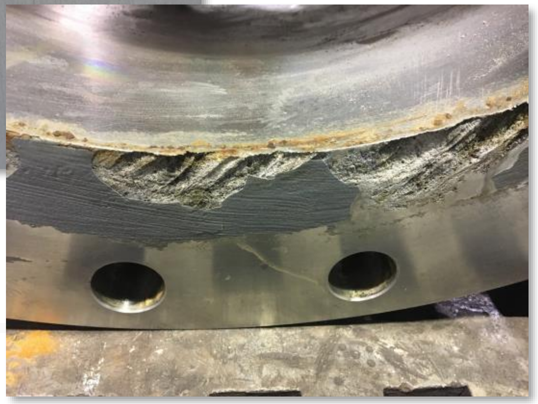
[1]

[1] Griesbach, T. J., Gordon, B. M., "Materials aging management programs at nuclear power plants in the United States," Second International Symposium on Nuclear Power Plant Life Management, Shanghai, China, October 15-18, 7007.

Stainless Steel Materials for Seawater Service

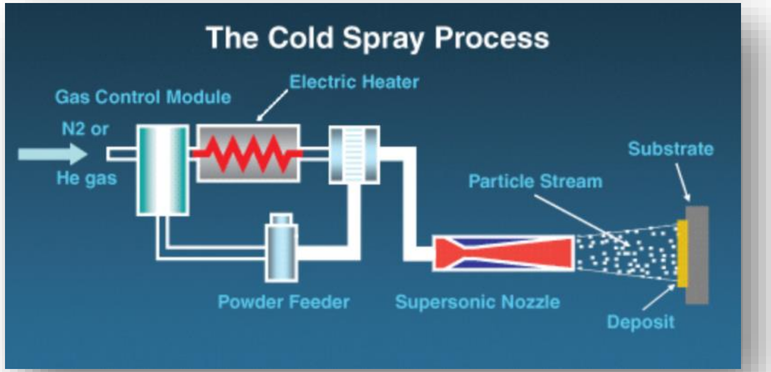
Wrought	Cast
304L	CF3
304	CF8
304H	CF10
316	CF8M
AL-6XN	CN3MN
Alloy 20	CN7M

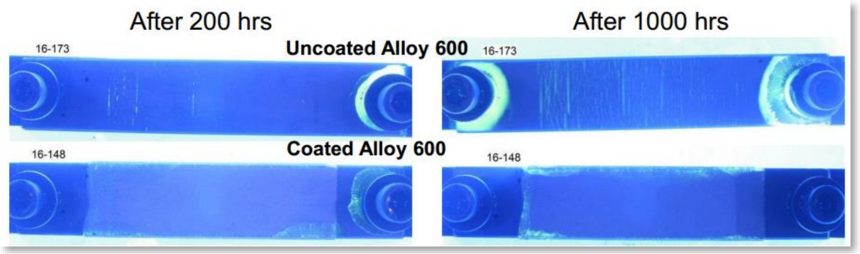
- **Common Austenitic Grades**
  - **304 & 316 most common industrial wrought steels**
  - **CF series most commonly used cast stainless steel**
  - **Cast Austenitic grades can contain up to 40% Ferrite, although higher levels of Ni and C stabilize Austenite in highly alloyed steels**
- **Even the most corrosion resistant grades are susceptible to**
  - **Stress Corrosion Cracking**
  - **Crevice Corrosion**
- **Solution: Cold Spray Corrosion Mitigation**



Solution – Cold Spray Corrosion Mitigation

- Applied at Low Temperatures
  - Coatings can be applied as low as 400 °C
- Dense and Highly Adherent
  - Less than 1% porosity and greater than 10ksi adhesion typical
- Can be applied with Nitrogen for cost sensitive applications
  - Pure Metals (e.g. CP-Ni), Alloys (e.g. 316L) and Metal Matrix Composites (e.g. Ni / CrC) can be sprayed with high Deposition Efficiency.
- Cold Spray contains crack retarding compressive residual stresses
  - Resists stress corrosion cracking
- Corrosion Control Coatings typically non-structural, allowing quicker implementation.





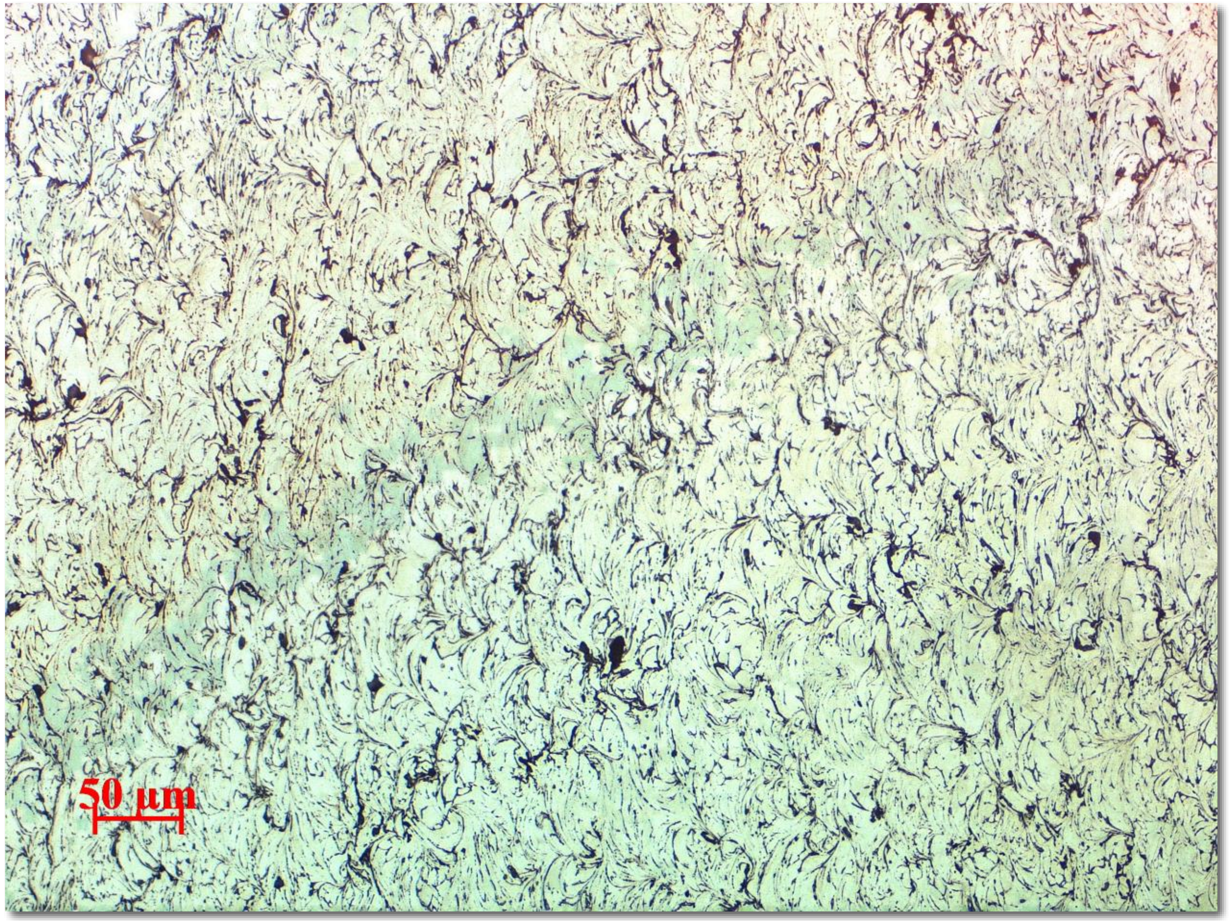
[2]

[2] Parsi, A., Lareau, J., Gabriel, B., Champagne, V., "Cold Spray Coatings for Prevention and Mitigation of Stress Corrosion Cracking," 2013 CSAT Workshop, Worcester, MA, 18-19 June 2013.

Solution – Cold Spray Corrosion Mitigation

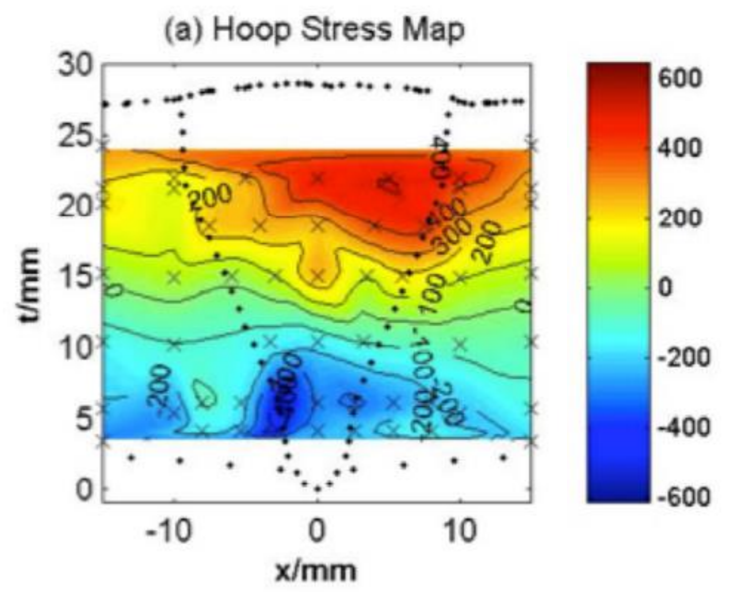
Cold Sprayed Nickel

- Typical Cold Spray coatings exhibit porosity less than 1%.
- Dependent on material and processing parameters
- Polished cross section – No particles can be seen
- Etched cross section shows particle boundaries
- Significant flattening observed



Case Study – Cold Spray CISCC Mitigation

- **Long term on-site is now being considered.**
  - **Large Existing Fleet Made from welded 304SS - Known for susceptibility to SCC**
  - **Chlorine-assisted SCC threshold in austenitic stainless steel as low as 80-100 MPa**
  - **304 stainless steel girth welds are likely sites for initiation and propagation of SCC**
- **Dry Canisters not readily maintainable**
  - **Difficult to inspect and repair**
  - **Potential for CISCC environment to form, especially near seawater**
  - **Canister removal and replacement or repair costly**



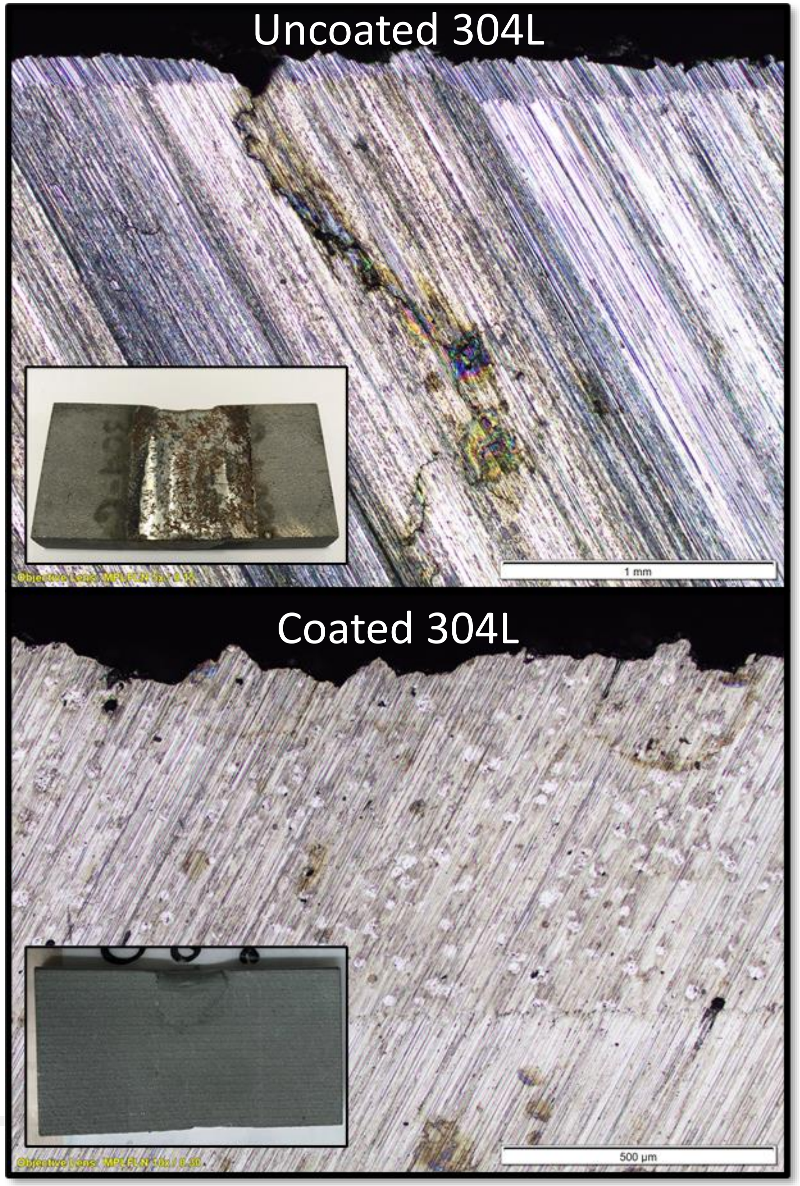
[3]

- **Cold Spray Corrosion Resistant Coatings with Compressive Residual Stresses Offer an Ideal Solution to CISCC Mitigation.**

[3] Haigh, R.D.; Hutchings, M. T.; James, J. A. ; Ganguly, S.; Mizuno, R.; Ogawa, K.; Okido, S.; Paradowska, A.M. and Fitzpatrick, M. E. (2013). Neutron diffraction residual stress measurements on girth-welded 304 stainless steel pipes with weld metal deposited up to half and full pipe wall thickness. International Journal of Pressure Vessels and Piping, 101 pp. 1–11.

Case Study – Cold Spray ClSCC Mitigation

- ASTMG36 Boiling MgCl testing
  - Very effective cracking of 304 and 316 Stainless
  - Boiling point of 140 °C assures cracking efficacy.
    - MgCl Concentration Increased to achieve 140 °C
  - Samples welded to create tensile residual stresses.
  - Uncoated and Cold Spray Coated Samples tested
  - Samples exposed for 24 hours
- Extensive and deep ClSCC on Uncoated 304L
- No cracking observed on Coated 304L



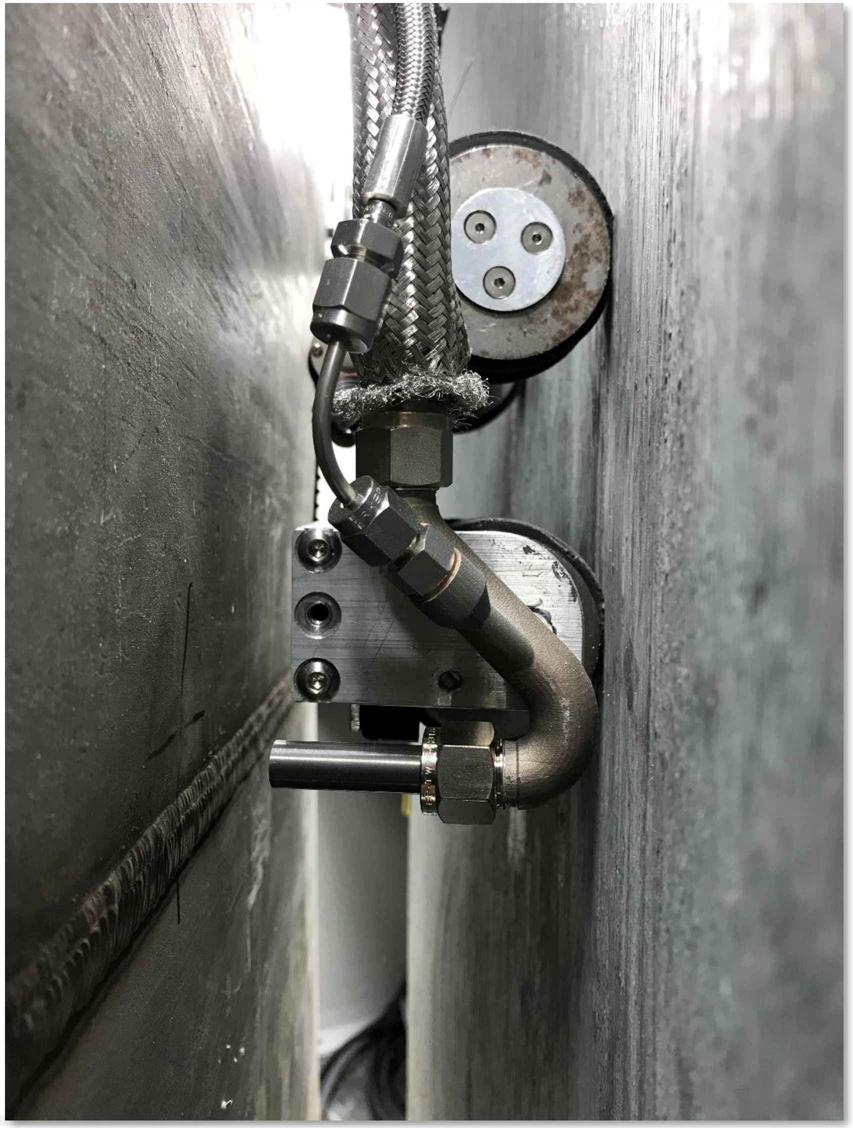
Case Study – Cold Spray CISCC Mitigation

- The Challenge -

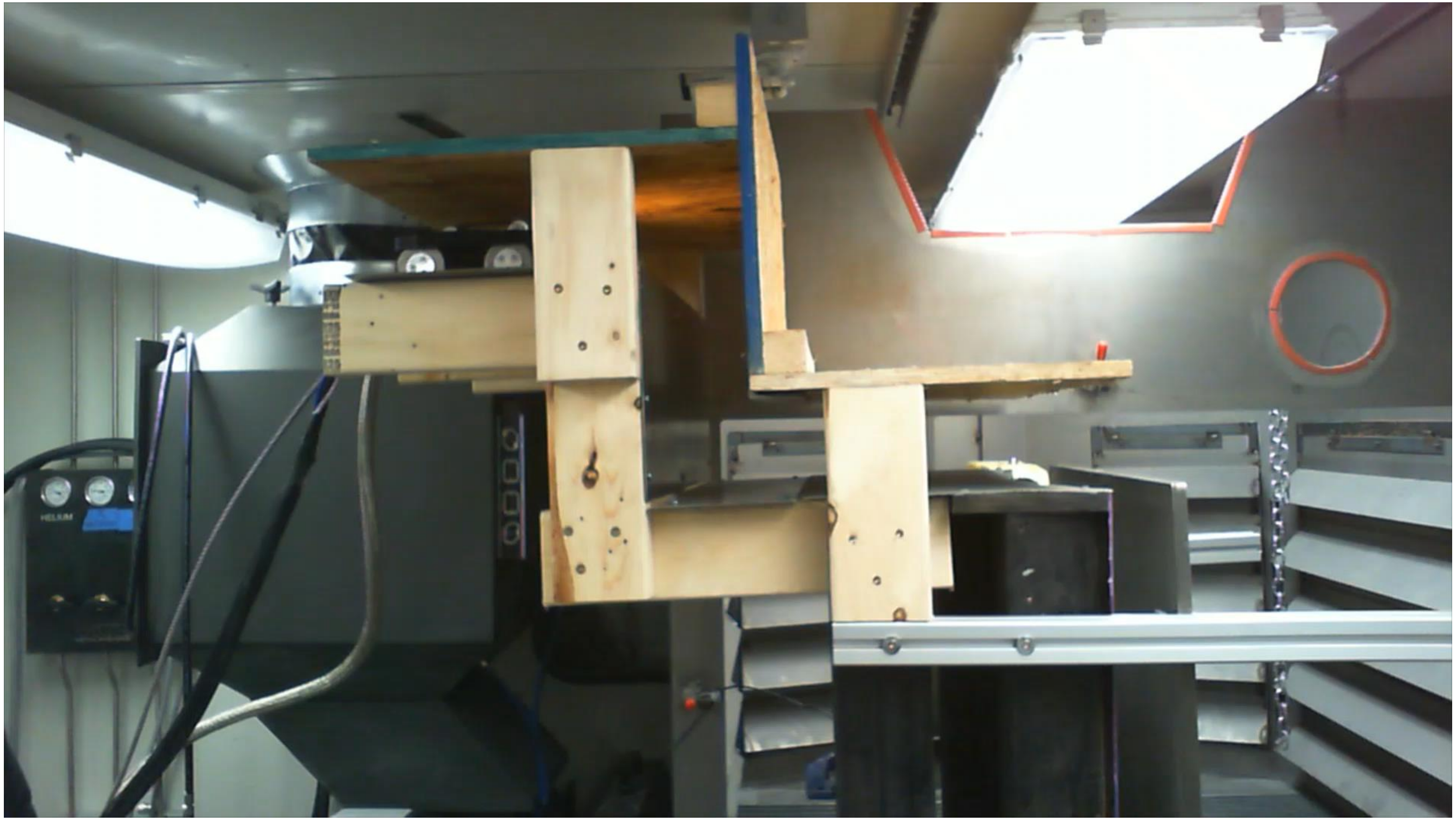
Can the Cold Spray solution be applied in a difficult-to-access application?

YES!

- Cold Spray Mitigation coatings have been demonstrated in laboratory mock-up canisters and in field conditions.
- Coatings can be applied within Overpack from a modified inspection crawler.
- Demonstrations have been performed in laboratory and field environments for vertical canisters using upper vent access.
  - Mockup demonstrations include straight-vent & stepped vent access and direct overpack placement designs.
  - Field demonstrations have been performed on an ISFISI.

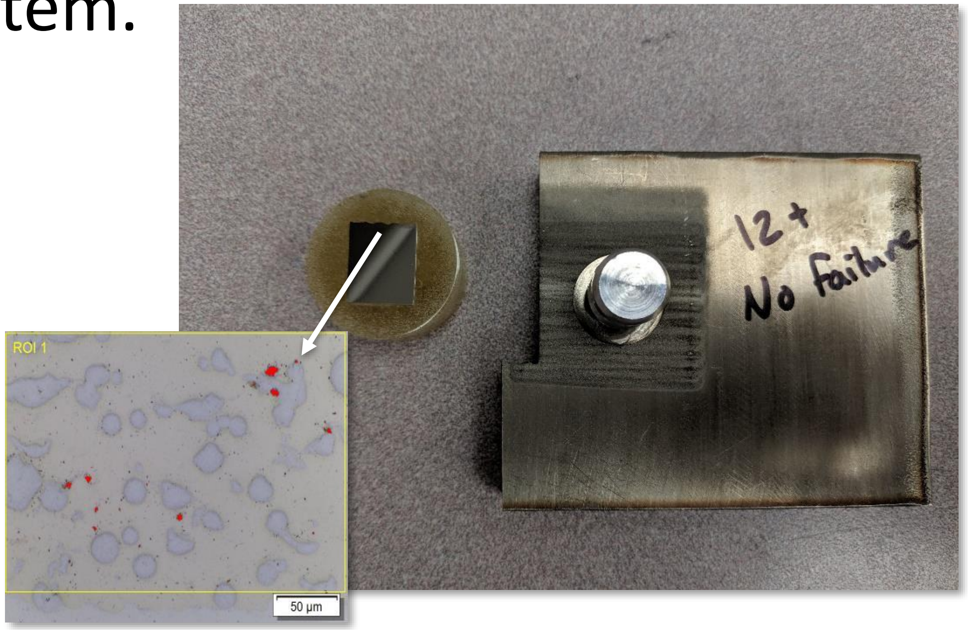


Case Study – Cold Spray ClSCC Mitigation



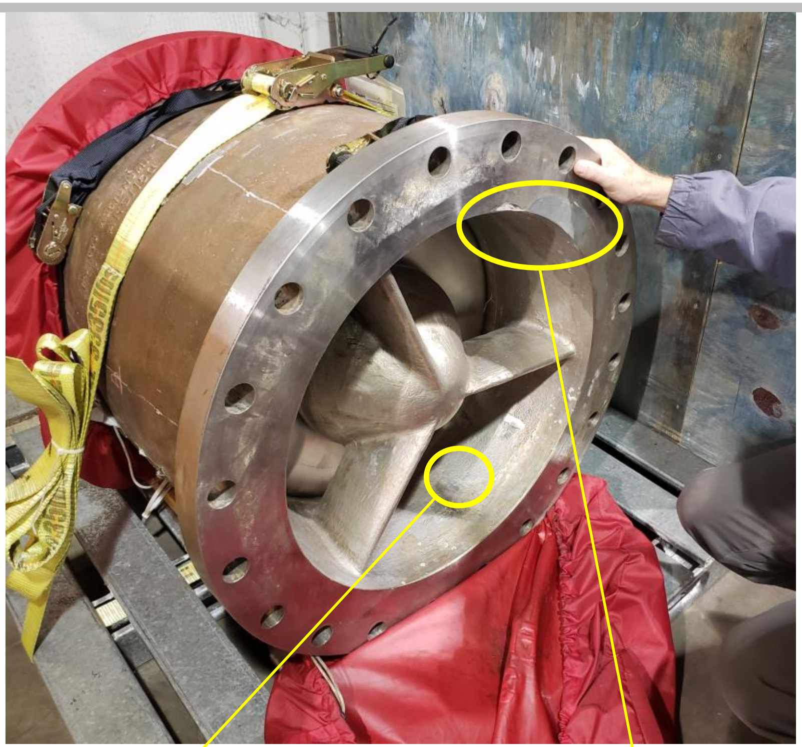
Case Study – Cold Spray CISCC Mitigation

- Cold Spray CISCC Mitigation has been successfully deployed on an active ISFSI within a commercial vertical canister system.
  - Developed with and approved by customer.
  - Independently analyzed and verified.
  - Commercial Grade Dedication Process
  - Deployed within a heated test canister
  - Integrated into Long-Term Inspection and Mitigation Plan



	Stability	Inspect-ability	Adhesion	Porosity	Tensile Strength	Thickness Capability
Tech. Obj.	Y	Y	> 10 ksi	< 2 %	> 36 ksi	> 0.100 in.
Result	Y	Y	> 11.2 ksi	0.6 %	40.6 ksi	0.103 in.

Case Study – Seawater Crevice Corrosion Mitigation



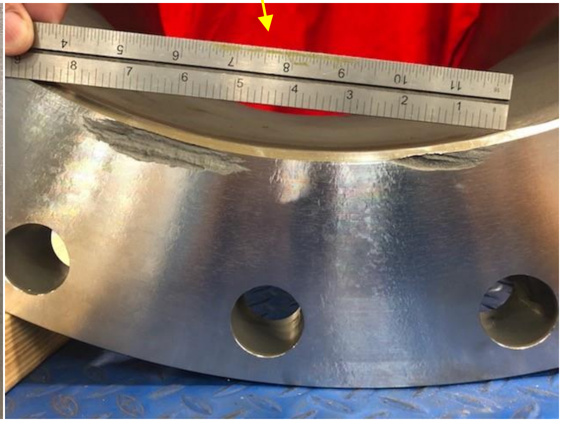
Crevice corrosion plagues even the most seawater corrosion resistant materials

- Especially prevalent in quiescent or slow-moving seawater & brackish water.

Cold Spray offers the ability to apply extremely crevice corrosion resistant materials to isolate structural materials.

Example Seawater Handling Check Valve

- CN3MN – Cast SS, High Mo
- Crevice Corrosion on flange faces
- Casting Defects can lead to pitting and Leakage.

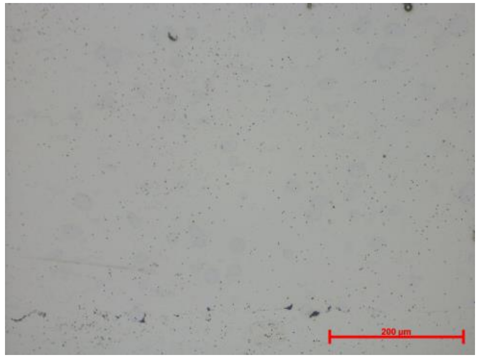


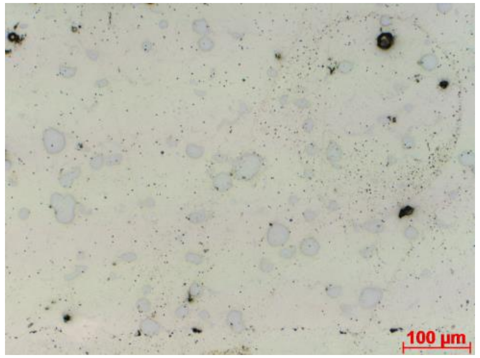
Case Study – Seawater Crevice Corrosion Mitigation

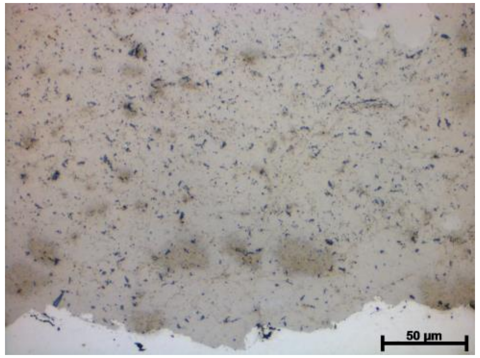
For this application, Focus on Nitrogen-sprayed coatings on AL-6XN

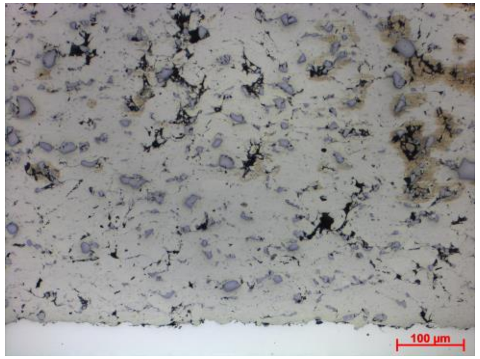
- High Nickel Materials with hard phase blend
- Titanium-based coatings and hard phase blends

Commercially Pure Titanium (CP-Ti) best performer in ASTM G192 re-passivation crevice corrosion tests.









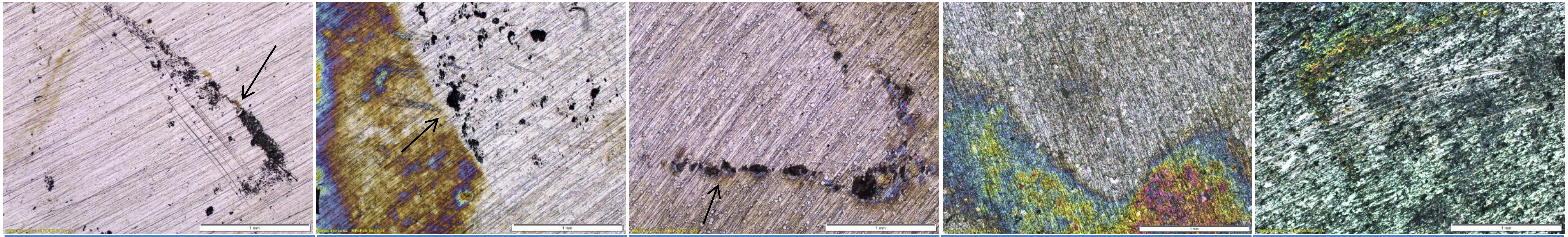
A59/CRC on AL-6XN	C276/CRC on AL-6XN	CP-Ti on AL-6XN	CP-Ti/TiC on AL-6XN
0.05% Porosity	0.75% Porosity	1.00% Porosity	~1.00% Porosity
+10 ksi Glue	+10 ksi Glue	4.61 ksi Adhesion	+10 ksi Glue

Case Study – Seawater Crevice Corrosion Mitigation

VRC METAL SYSTEMS

- Long-Term Seawater Exposure Crevice Corrosion Testing
  - Candidate Materials Tested on AL-6XN Substrates with Crevice Formers
  - Long-Term Exposure to Chesapeake Bay water, silt, and organic matter.
  - 10 May 2019 – 36 cold sprayed sampled + 9 controls installed
  - 10 Sept. 2019 – Half of the sample set pulled for inspection
  - 3 Feb. 2020 – Remainder of sample set pulled for inspection

- No Crevice or Galvanic Corrosion observed in CP-Ti materials



AL-6XN	C276 / CrC	Alloy 59 / CrC	CP-Ti	CP-Ti / TiC

Case Study – Seawater Crevice Corrosion Mitigation

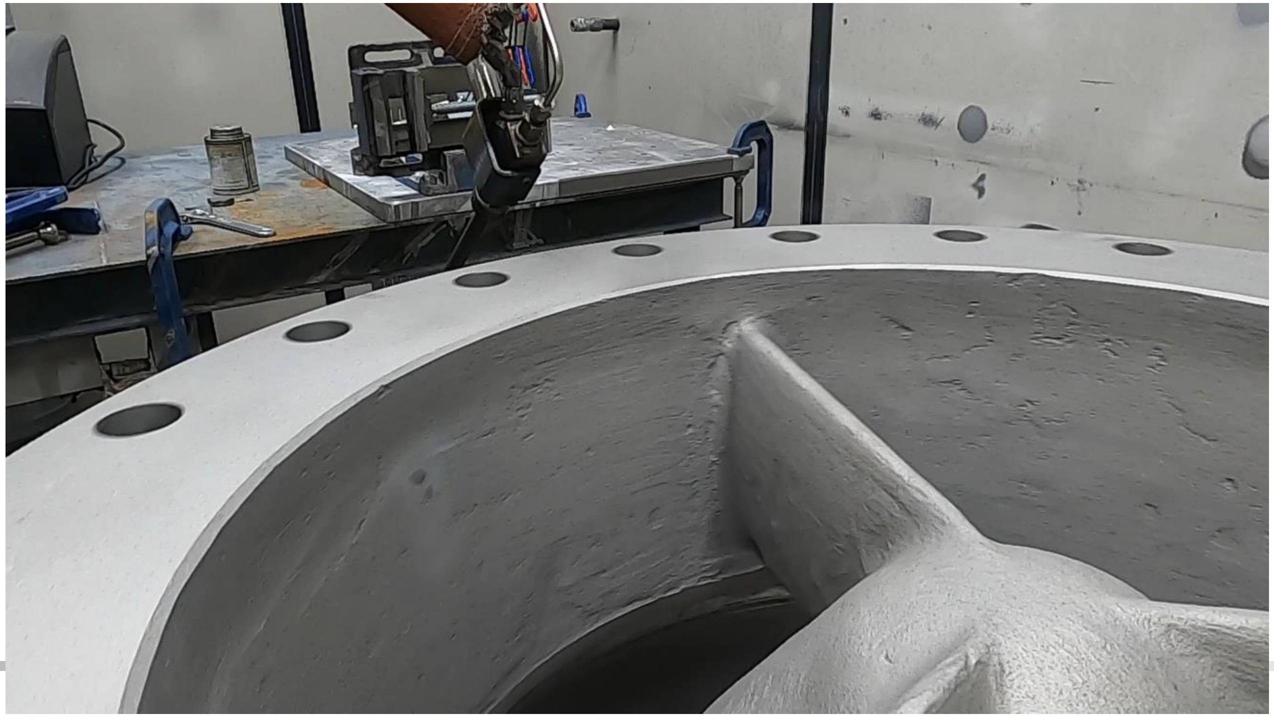
- Application of Ti-based coating for crevice corrosion resistance
  - Excellent adhesion to AL-6XN, low porosity, equivalent or higher hardness, no crevice corrosion
- Qualification Plan developed with and approved by customer
  - Adhesion, Porosity, Hardness, Deposition Efficiency
  - Additional testing for impact resistance, thermal cycling, and salt fog galvanic to ensure no cracking, spallation, or corrosion will occur in the application.

	Adhesion	Porosity*	Hardness	Deposition Efficiency	Impact Resistance	Thermal Cycling	Salt Fog Galvanic
Tech. Obj.	> 10 ksi	< 1 %	None	> 50%	No Cracking	No Spallation	No Corrosion
Result	> 11.3 ksi	0.73 %	188 HV	62%	Pass	Pass	Pass

*Porosity of Metal Matrix between Carbide Hard Phases

Case Study – Seawater Crevice Corrosion Mitigation

- Cold Spray Ti-based coating applied to the flange and internal surfaces.
- Coating application performed at VRC Spray Operations Facility, Box Elder, SD.



Case Study – Seawater Crevice Corrosion Mitigation

- Cold Spray Application Process
  1. Apply targeted cold spray non-structural fill to crevice sites and blended defects.
  2. Apply uniform cold spray coating robotically.
  3. Post-Machine, as necessary.
  4. Repeat for all component sections.
- Applicable to various seawater handling components.
- Process travelers and quality control processes developed and maintained.
- Witness Coupons collected and tested.
  - Results within Acceptance Criteria

Conclusions

- High Pressure Cold Spray can be used to generate coatings of extremely corrosion resistant materials at low temperatures.
- Compressive residual stresses present in the coating help prevent stress corrosion cracking.
- Cold Sprayed coatings can be applied in critical applications to protect sensitive materials in corrosive environments, key points:
  - Material Selection is Critical!
  - Process Parameter development, process control, and in-process monitoring are important to achieve desired coating performance and quality assurance.
- Select applications that make sense for cold spray
  - High Value, Temperature Sensitive Components for Critical Applications
  - Applications where In-Situ restoration / mitigation is necessary
- Potential Future Applications
  - High Capacity, High Level Waste Tanks
  - In-Situ Dimensional Restoration of Steam Erosion in Secondary Systems

Thank You!

DOE SBIR Program Sponsors
-John Orchard, Prasad Nair,
& Sue Lesica

Exelon Generation
-Lee Friant

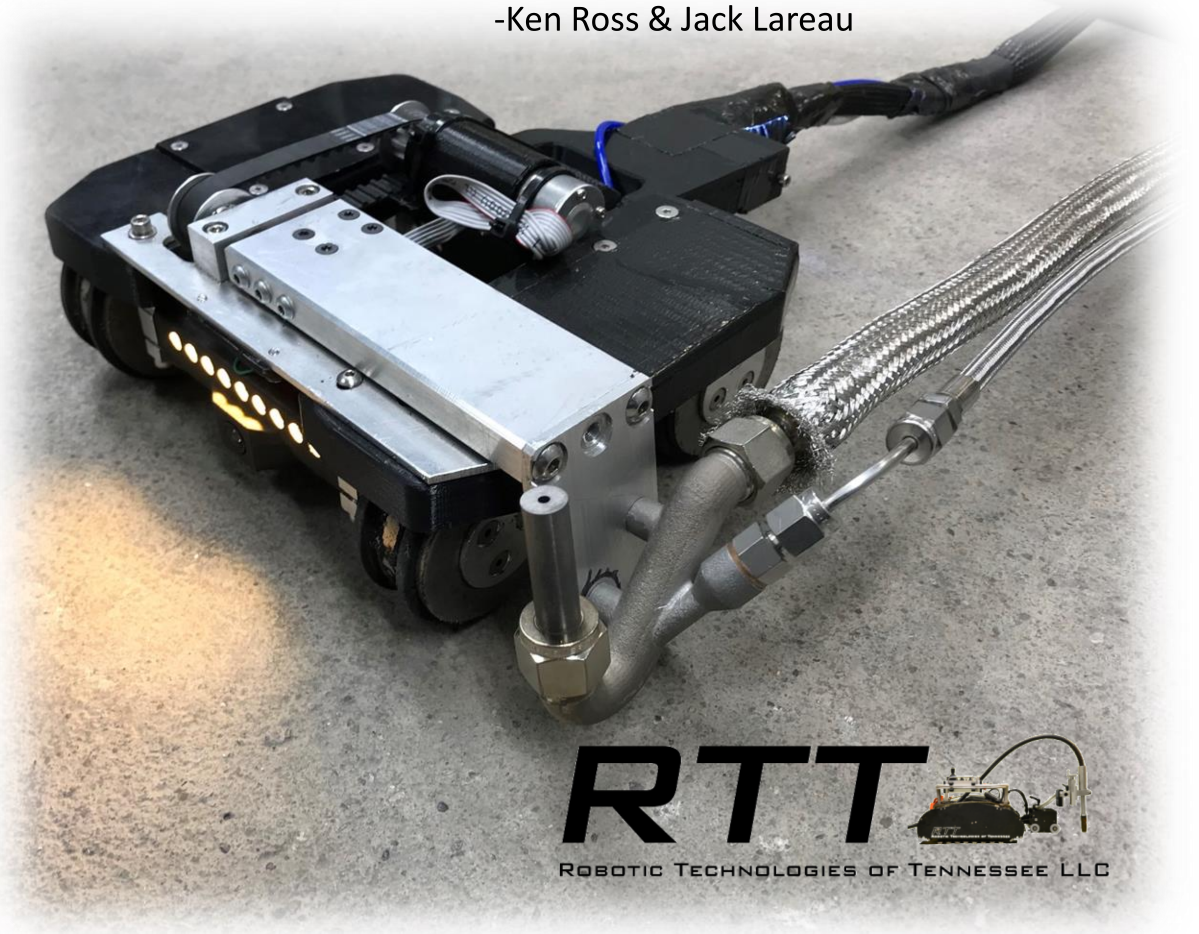
Robotic Technologies of Tennessee
-Jamie Beard & Andrew Braynt

South Dakota School of Mines & Technology
-Bharat Jasthi & Team

Southern California Edison
-Allen Williams & SONGS Team

Electric Power Research Institute
-Jeremy Renshaw & Jonathan Tatman

Pacific Northwest National Lab
-Ken Ross & Jack Lareau



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