Game-Changing Coatings ™

SilcoTek® CVD Coatings for Improving Heat Exchanger Performance

Company Profile

- 68 employees with a vision of “a better world through our coatings.”
- 130 patents and patent filings for chemical vapor deposition (CVD) technology
- 80,000 ft.^{2} coating service facility in Pennsylvania, USA
- Coating critical components in:
  - Semiconductor manufacturing
  - Analytical chemistry
  - Life sciences, food, and biopharmaceuticals
  - Energy industries

What SilcoTek does

- Improve the value, performance, and usable life of customers' process equipment and products by:
  - Making surfaces chemically inert
  - Increasing corrosion resistance
  - Improving performance at high temperatures
  - Surface engineering (anti-fouling, hydrophobic, hydrophilic, etc.)

How we do it

- Surface coatings and engineering via CVD technology:
  - Amorphous silicon-based foundation layers
  - Surface functionalization and modification
  - Materials characterization and testing
  - Custom solution development

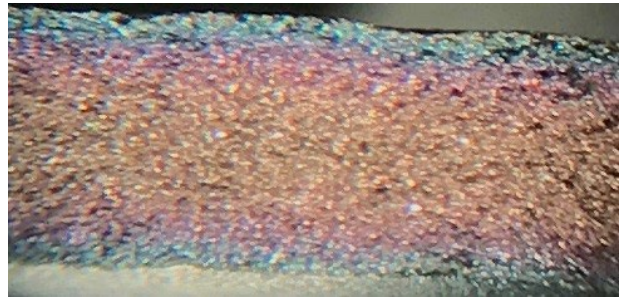
Base Coating Options	Functionalization (Top Layer) Options	
	None	Hydrocarbon (C_xH_y)
Amorphous silicon (a-Si:H)	Silcolloy®	SilcoNert® 2000 (Sulfinert®)
Amorphous silicon oxide (a-Si_xO_y:H)	Dursox®	Dursan®
Amorphous silicon oxynitride (a-Si_xN_yO:H)	Siltride®	Experimental
Hydrophobic Monolayer	Notak®	

Benefits of SilcoTek Coatings over others

Commercialized process	State-of-the-art process control, automation, and traceability.
3-D deposition allows coating of all surfaces	High aspect ratios, complex geometries, filter media.
Bonded to substrate material, superior adhesion	
Wide range of substrate materials	Stainless steels, titanium, aluminum, high nickel alloys
Versatile capabilities	Small fittings and precision needles to large chambers.
Thin coating: ~100 nm up to nearly 2 µm	**Zero effect on heat transfer efficiency!**

General Coating Capabilities

- Variety of common materials for process components
  - Stainless steels, high nickel alloys, Inconel®, Hastelloy®, etc.
  - Most aluminum alloys
  - Titanium
  - Glass and ceramics

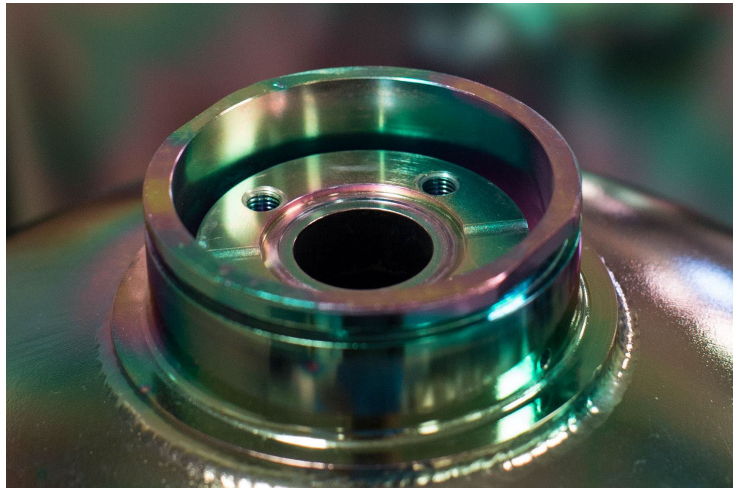


- High aspect ratios and complex geometries
  - .004” ID tubing and larger
  - Porous filter media as small as 0.5 micron (coating self-limits thickness, does not clog pores)

- Several sizes of parts
  - **24 ft. straight tube coating capability coming in 2025**
  - Up to 2,500 ft. per continuous tubing coil
  - Anything from micro-componentry to large vessels

General Coating Capabilities

- Sealing surfaces
  - VCR glands, compression fittings, vacuum, face seals, etc. can all be coated with ease
- Threads
  - Coating has no negative impact on threads or tolerances
- Flexible materials
  - Flex lines, bellows, etc. are easily coated successfully
  - Parts can be flexed/bent without coating damage



Heat Exchanger, Condenser, and other Straight Tube Coating Capability

- Phase 1 system - 24’ length, 10” ID ready for individual tube coating in Q3 2025. Next phase of scale-up is expanding diameter of chamber.
- Designed for coating new heat exchanger, condenser, and cooler tubes.

Value-Added Capabilities

- Expedited processing
- Citric acid passivation
- Class 1000 / ISO 6 clean room cleaning and packaging
- In-house performance testing
  - Gas chromatograph with sulfur detector; corrosion testing; adhesion; more
- Materials characterization
  - SEM, FTIR, FIB, ICPMS, EIS, many more
- Custom packaging
- Supply chain management

Heat Exchanger Coating Value Proposition

- **Improve reliability and availability of energy and power generating facilities while drastically reducing maintenance.**

- How? By enhancing shell and tube materials you already use.
  - Reducing fouling by increasing surfaces' repellency properties
  - Improving ease of removing coke or foulant formation
  - Increasing corrosion resistance of base alloys
  - Preventing catalytic effects with a chemically inert barrier coating

Case Studies

Optimizing Cooling for Highly Corrosive Process Fluids

The Objective

A customer needed a heat exchanger solution to enhance the cooling process of various acids and bases to counteract the heat generated by process equipment such as pumps and reactors.

The Challenge

The process involved highly corrosive fluids that were incompatible with 316L stainless steel, creating a material selection hurdle; LiOH (6 M), HCl (3 M), H2SO4 (3 M), LiCl (4 M).

The solution was to include four heat exchangers and a chiller within their financial limits. The customer was currently using Hastelloy® components in other parts of the system, however their budget constraints required a more cost-effective alternative as they required four heat exchangers plus a chiller to fit within the project budget.

The Solution

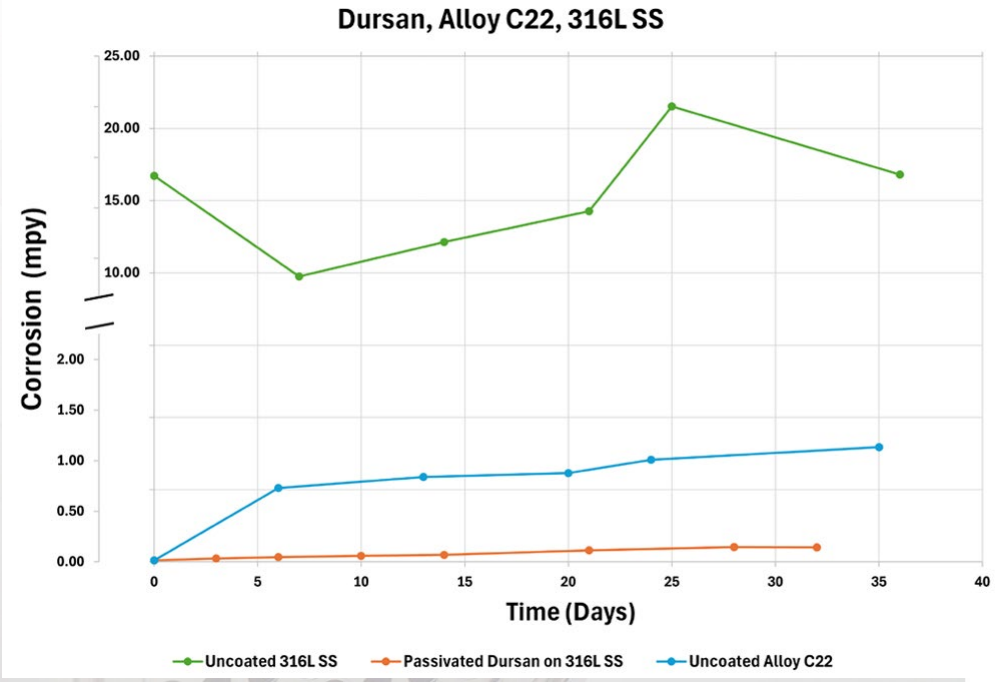
Exergy's 23 Series shell & tube heat exchanger, Model 05211-01, *coated with* SilcoTek *Dursan® 2500,* emerged as the ideal solution due to its compact size, lightweight design, and straightforward installation process. Key features included:

- *1-inch OD shell* x 8-inch length with 0.58 sq. ft. heat transfer surface area, weighing only 1.03 lbs.
- Base material: 316L SST, coated with Dursan® 2500 for enhanced corrosion resistance.

Innovative Material Solution

To address the range of demands from low pH acids to high pH basic solutions, Exergy collaborated with SilcoTek® to coat the stainless steel heat exchanger with Dursan® 2500. Key coating benefits include:

- Enhanced high-pH durability combined with moisture and contamination barrier properties, safeguarding the heat exchanger in LiOH environments.
- Corrosion resistance comparable to the performance of Hastelloy® at a fraction of the cost and lead time.
- Improved corrosion resistance by up to 160x in 6M HCl at room temperature, reducing the risk of equipment failure and extending service life.



The Results / Benefits

Exergy's custom solution successfully met the customer's cooling requirements, while providing a high-performance, economical, corrosion resistant alternative to Hastelloy material. The customer confirmed this with a soak test on both an uncoated 316L SST heat exchanger and SilcoTek Dursan® 2500 coated 316L SST heat exchanger. After 7 days the SilcoTek Dursan® 2500 coated heat exchanger revealed that unlike the uncoated heat exchanger, the stainless steel alloy components (Fe, Ni, Cr) did not leach into the test solution, confirming the coating performed as intended against the corrosive process chemicals.

This case highlights Exergy's capability to tailor solutions for challenging and corrosive environments, ensuring long-term reliability and customer satisfaction.

Cooling Helium – Based Process Gas for 3D Metal Printing

The Objective

A company specializing in laser powder bed fusion (LPBF) metal printing required a sanitary-type shell & tube heat exchanger to cool Helium-based process gas used in their advanced 3D printing process. The process gas, Helistar A1025, is a critical mixture comprising of 90% Helium, 7.5% Argon, 2.5% CO_2.

The solution needed to meet the precise cooling requirements of the printing operation, cooling the process gas from 110C down to 20C.

The Challenge

1. Custom Connections and Cleaning Requirements:
   The customer specified the need for KF50 flanges along with a removable bundle to facilitate cleaning due to soot accumulation, a byproduct of their 3D printing process. Exergy's specific design and manufacturing process does not allow for a removable tube bundle, resulting in a solution that allowed for easy cleaning of the heat exchanger without the removal of a small-diameter tube bundle.
2. Uncertain Soot Properties:
   The customer lacked specific data on the soot characteristics but noted its tendency to agglomerate and coalesce on metal surfaces, posing risks to the exchanger's performance and cleanliness.
3. Material Compatibility and Process Integration:
   The heat exchanger needed to:
   - Resist fouling caused by the soot.
   - Offer surfaces that minimized soot adherence and facilitated cleaning.
   - Maintain compactness and seamless integration into the existing LPBF system.

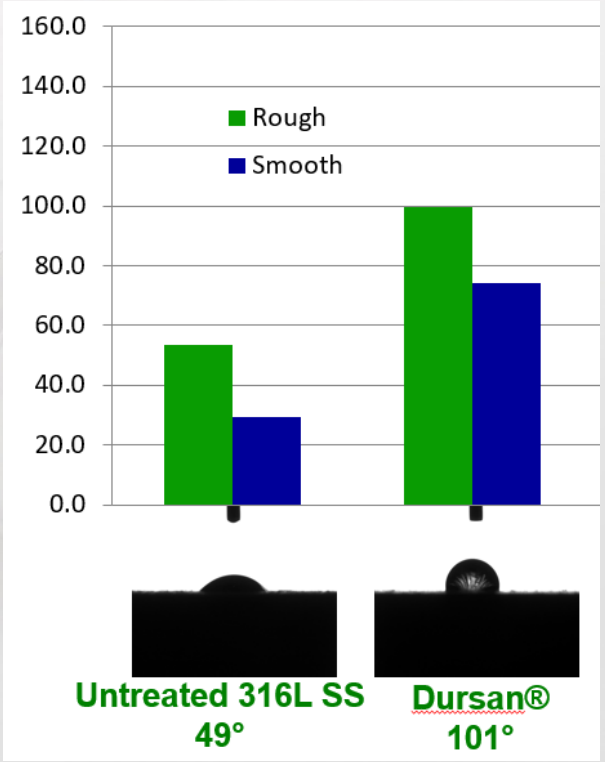
The Solution

Exergy provided a customized 73 Series shell & tube heat exchanger (p/n 05257-03) with the following features:

- *3-inch OD shell* x 20-inch length, offering ample surface area (13.41 ft^2) for efficient heat transfer while weighing just over 10 lbs.
- 316L stainless steel construction coated with Dursan®, providing:
  - Non-stick properties for reduced fouling and easy soot removal.
  - Enhanced corrosion resistance against the Helistar A1025 gas mixture.
  - Improved cleanability, minimizing downtime for maintenance.
- KF50 flanges for seamless integration with the customer's existing system setup.

The Results / Benefits

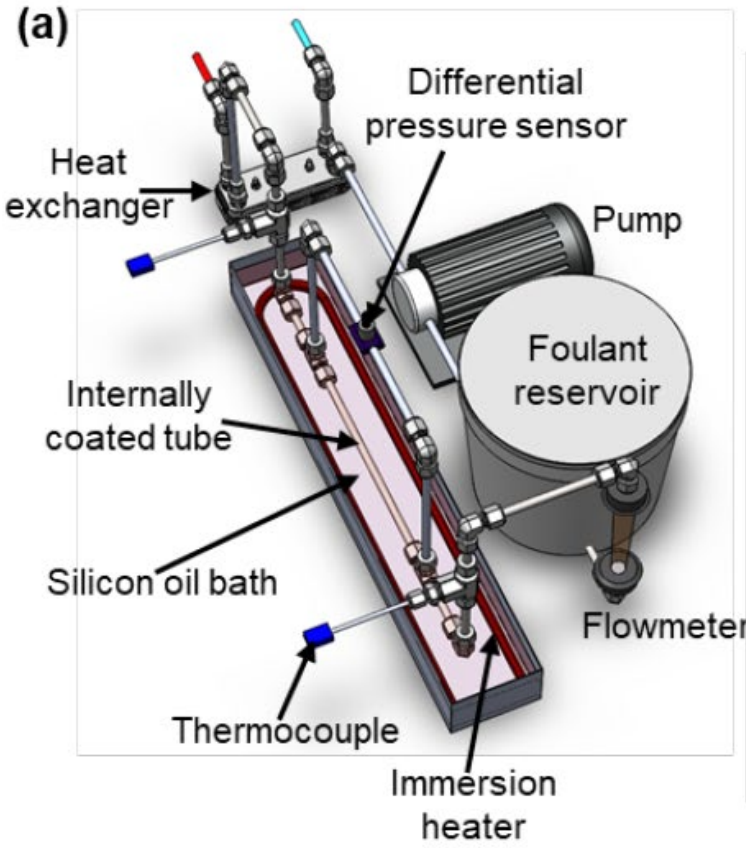
In addition to increasing corrosion resistance, SilcoTek's Dursan® coating drastically reduces the surface energy of stainless steel, rendering coated surfaces hydrophobic, non-stick, and much easier to clean. Non-stick properties can easily be measured by viewing a water droplet under magnification and measuring the angle between the flat metal surface and water droplet. Here is a comparison of untreated stainless steel and Dursan-coated stainless steel:

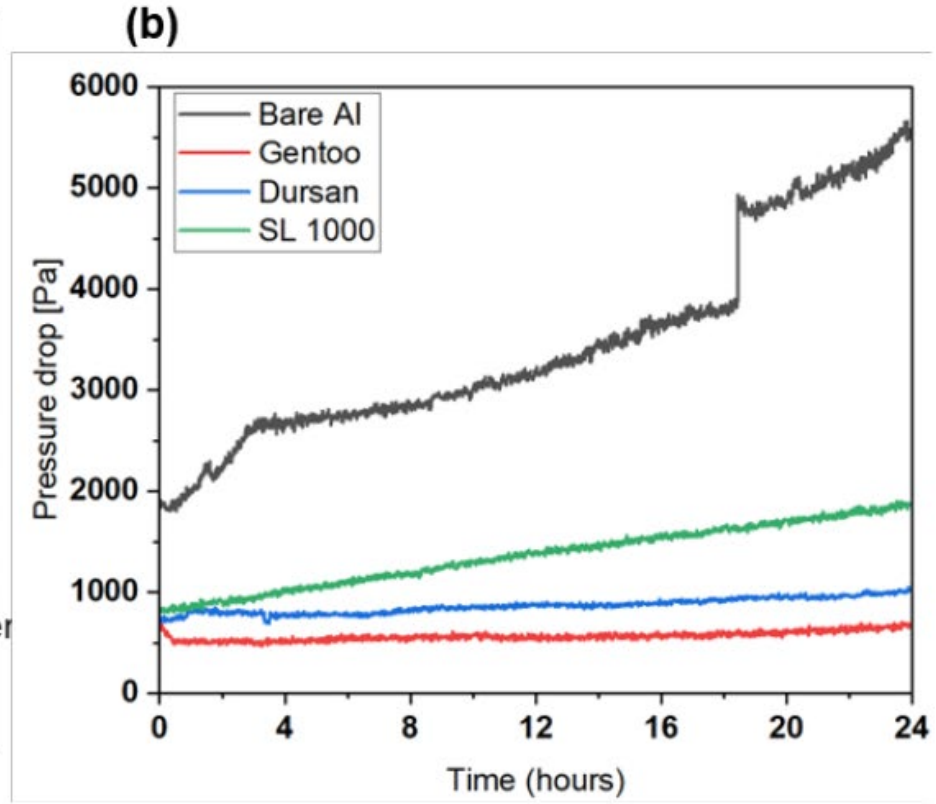


Calcium Sulfate ($CaSO_4$) Fouling

- Bare aluminum (rough) vs. Silcolloy 1000 and Dursan (from SilcoTek) vs. Gentoo (competitor)
- 2L synthetic seawater and 5g calcium sulfate solution
- 80°C

→Dursan showed a 74% improvement in pressure drop vs. uncoated Al



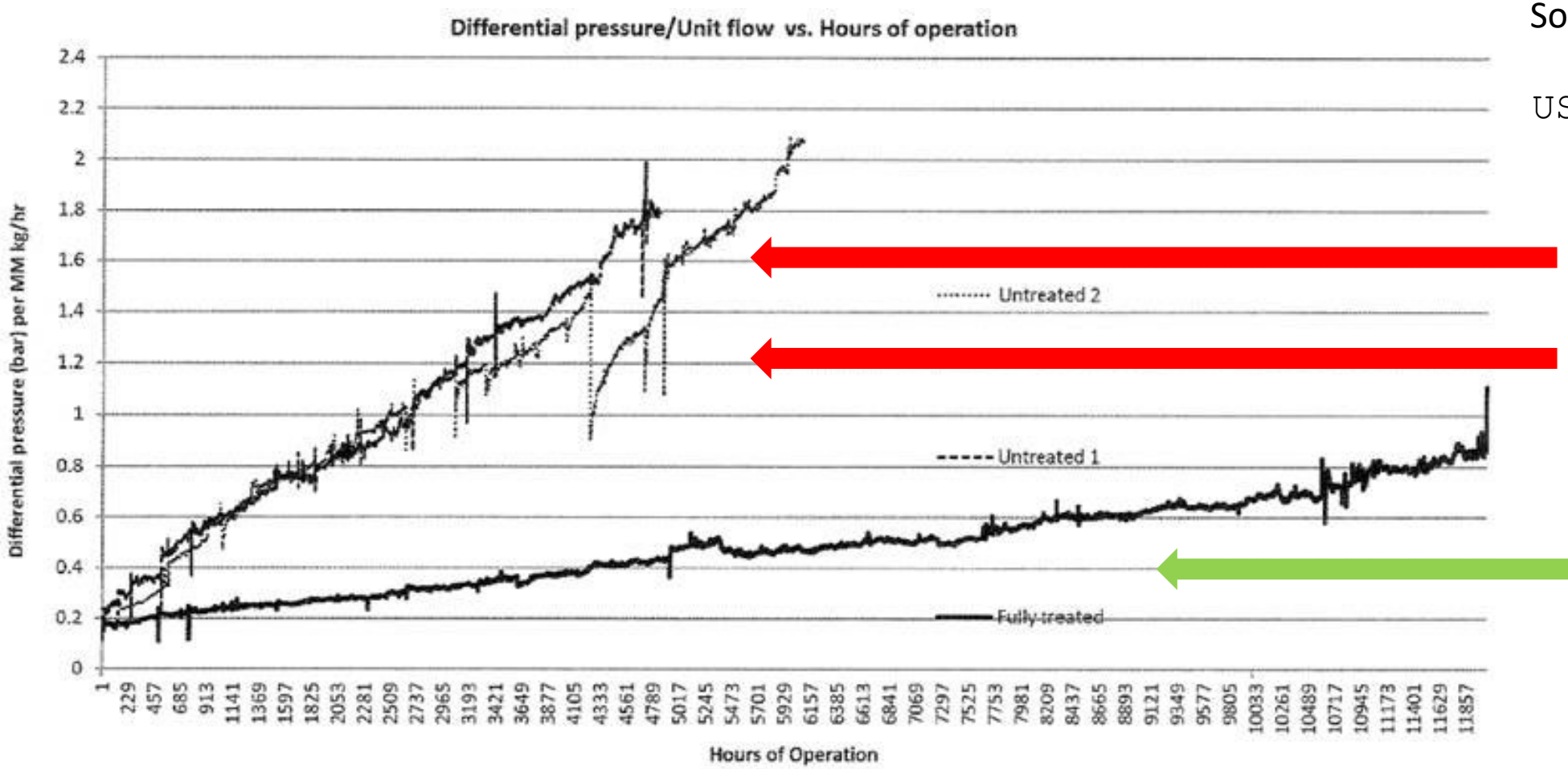


Acknowledgement: Tarandeep S. Thukral, Wentao Yang, Nenad Miljkovic, University of Illinois, Urbana Champaign, IL - USA

Coated Coal Gasification Filters increase Up-time in World's Largest Refinery

- Coating improves fouling and corrosion resistance to harsh gases and in-situ cleaning agents
- 6x lifetime improvement with coating
  - 5 months improved to 2.5 years
- Substantial pressure differential improvements → greater efficiency and less power usage

Reducing Fouling in Coal Gasification Filtration System



Source: US Patent Application Publication
US 2018 / 0318742 A1

Uncoated filters

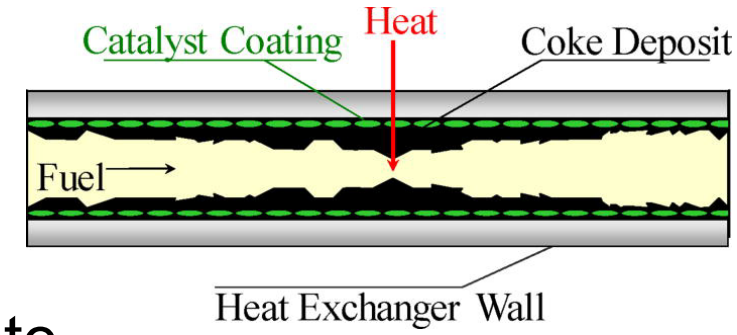
Dursan®

Coated Stainless Steel Filters

Anti-Fouling Data

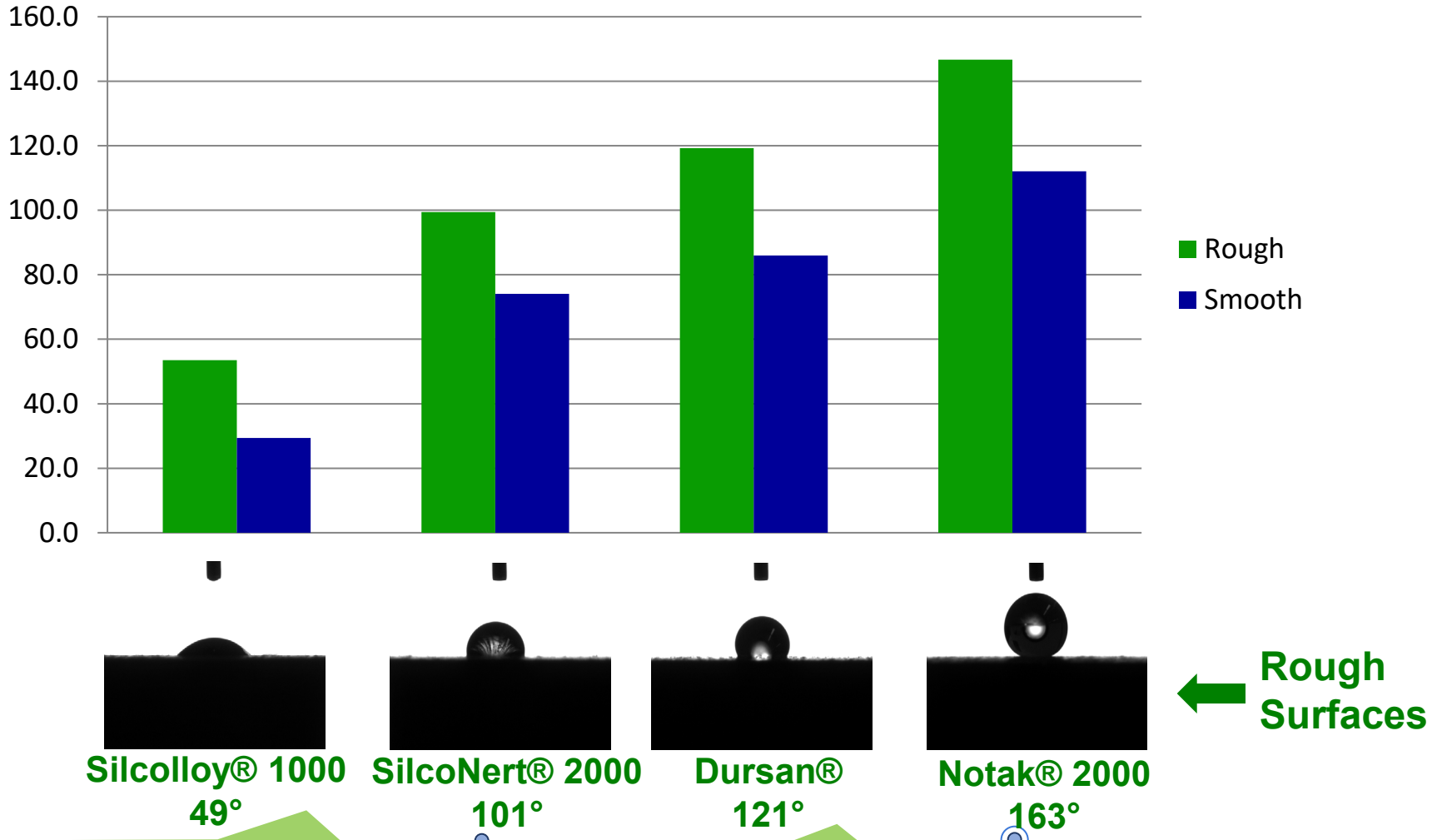
How SilcoTek Addresses Fouling

- Barrier approach
  - Preventing catalytic or chemical interaction with a surface
  - Nickle-containing substrates catalytically form carbon deposits (coke) from petrochemical media



- Chemistry approach
  - Preventing chemical adhesion / adsorption to substrate
  - Using an inert, low energy surface to block unwanted media

Hydrophobic and Hydrophilic Coatings



Siltride

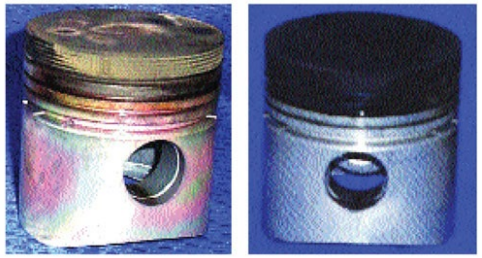
Currently SilcoTek's only hydrophilic coating option. Static water contact angles **~10°**

Catalytic Carbon Coking

- Carbon deposits (coke) form on injection / combustion components from incomplete burning of fuel

- **Solution**: Silcolloy® 2000 high temperature barrier coating

Silcolloy® 2000

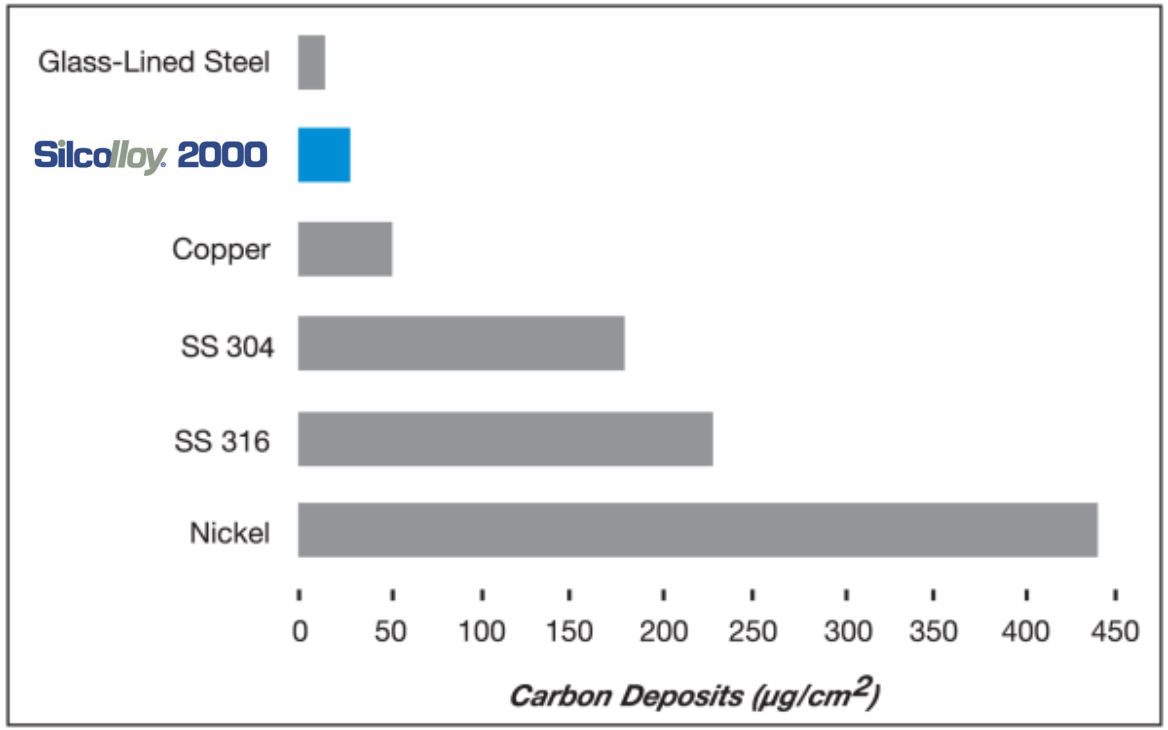


Silcolloy® 2000 drastically reduces carbon coking, boosting efficiency

- Tests by Semih Eser – Penn State Professor of Energy and Geo-Environmental Engineering

  - JP-8 fuel
  - 500° C
  - 500psig
  - 1 ml/min flow
  - 5 hours

Altin, O.; Eser, S. *Ind. Eng. Chem. Res.* 2001, *40,* 596-603



Thermal & Adhesion Data

Thermal Conductivity and Adhesion

- U.S. DOE-sponsored testing by EPRI of 9 steam- and water-side coatings on titanium for thermal power plant condenser application.
- ASTM E1461 for thermal conductivity and ASTM C1624 for adhesion
- SilcoTek coatings Dursan and Notak are only 2 of 9 that received perfect score (actual data proprietary to EPRI and U.S. DOE).

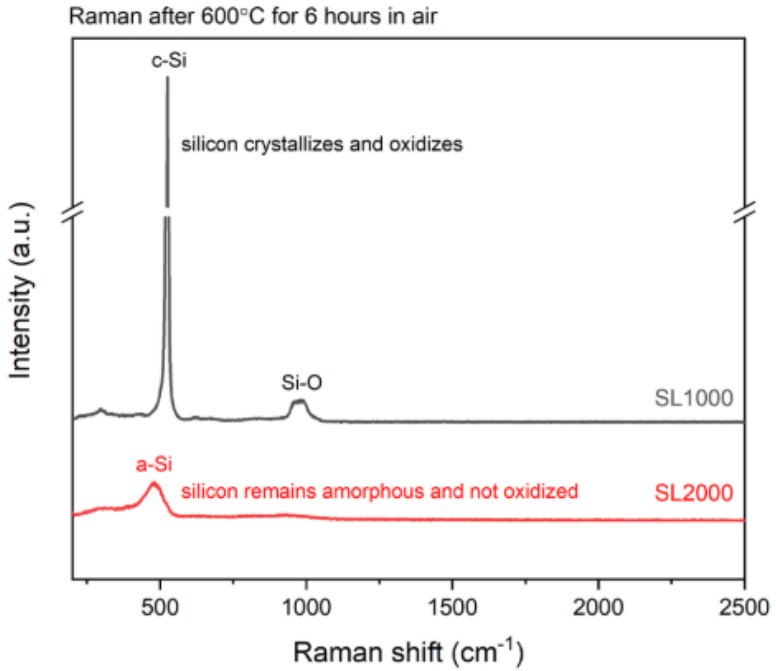
5 = Good; 3 = Fair; 1 = Poor

Coating	Thermal conductivity ASTM E1461	Adhesion ASTM C1624	Total	Rank
Internal Tube Coatings (Titanium Sample)				
A	3	3	6/10	2
B	1	3	4/10	4
C	5	--	5/10	3
Dursan	5	5	10/10	1
D	3	1	4/10	4
E	5	1	6/10	2
External Shell Coatings (Titanium sample)				
E	5	1	6/10	2
F	5	1	6/10	2
Notak 2000	5	5	10/10	1

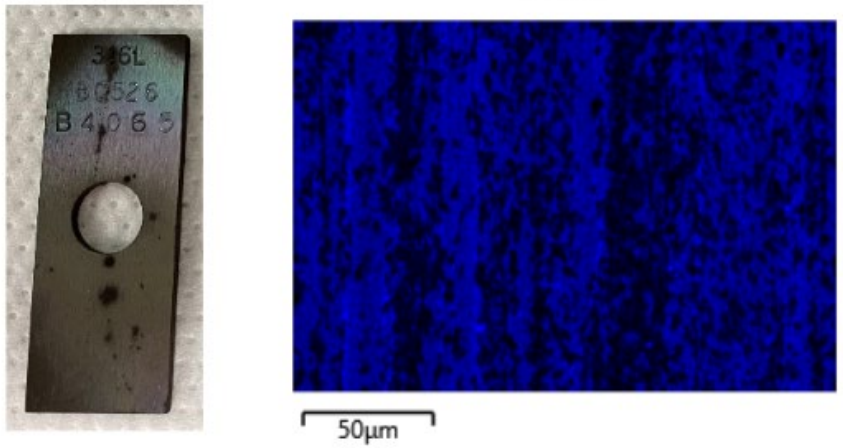
Howell, Andrew. 2021. DE-FE0031762 Status Report. Investigation of Technologies to Improve Condenser Heat Transfer and Performance in a Relevant Coal-Fired Power Plant. Electrical Power Research Institute.

High Temperature Stability

Silcolloy 2000 (SL2000) maintains its chemical composition and performance up to 800° C making it SilcoTek's best high temperature coating.



SL1000 after 800° C for 6 hours: silicon EDS map shows incomplete coating coverage



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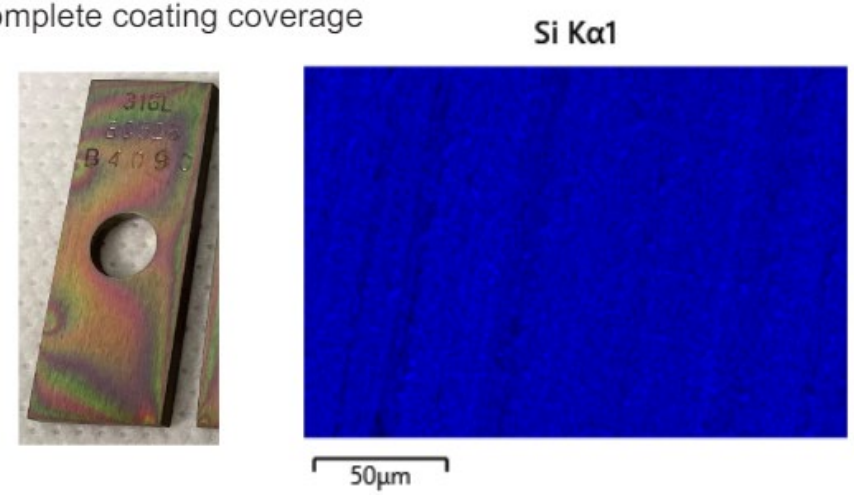


Mechanical Data

SilcoTek Coatings' Mechanical Properties

- All our coatings are <2 micron, so they typically mimic the hardness and wear resistance of the underlying substrate.

- Heat exchanger coatings show at least 2x improvement in hardness and wear rate over bare stainless steel.

→ Coatings can withstand routine handling, installation, and particle abrasion. Excessive scratching or metal-on-metal wear should be avoided to maximize coating lifetime.

Pin-on-disk test data

- Commercialized coatings: Siltride, Dursan, Silcolloy
- Experimental coatings: RD13, RD14

	Test conditions 1N and 15minutes					
surface	RD13	Siltride	Dursan	uncoated	SL1000	RD14
wear track cross section (μm^2)	42.819	44.411	66.587	113.132	154.107	241.136
wear rate x 10^{-5} (mm^3/Nm)	**3.568**	**3.701**	**5.549**	**9.428**	**12.842**	**20.095**

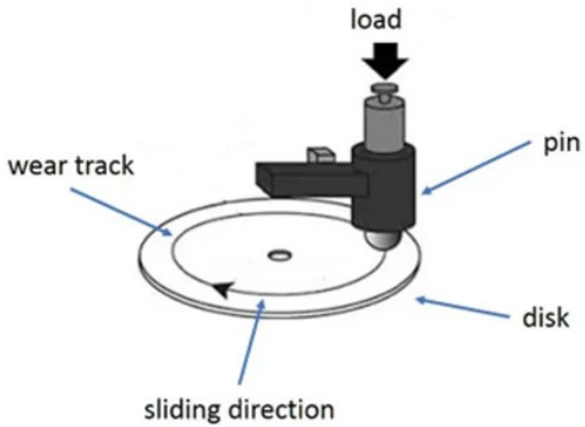
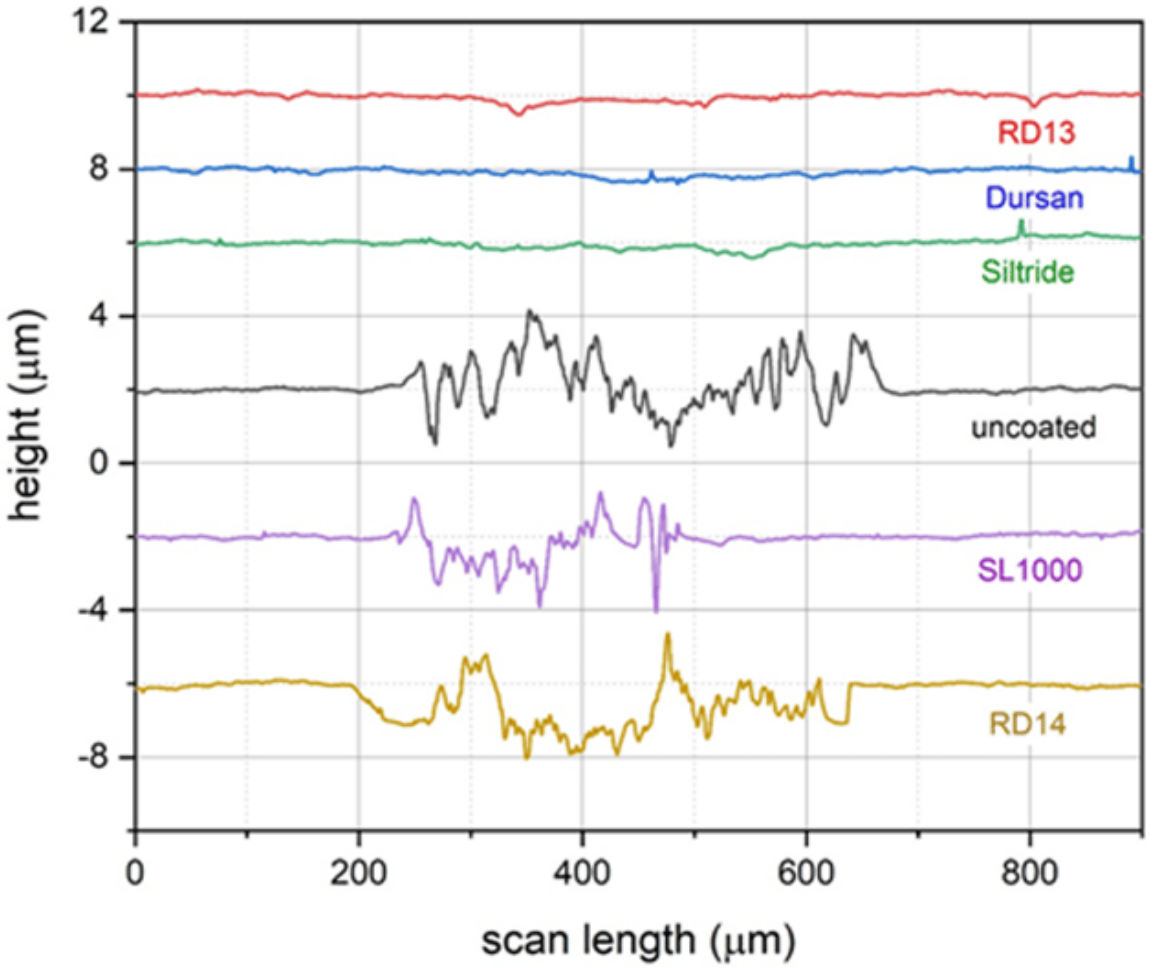
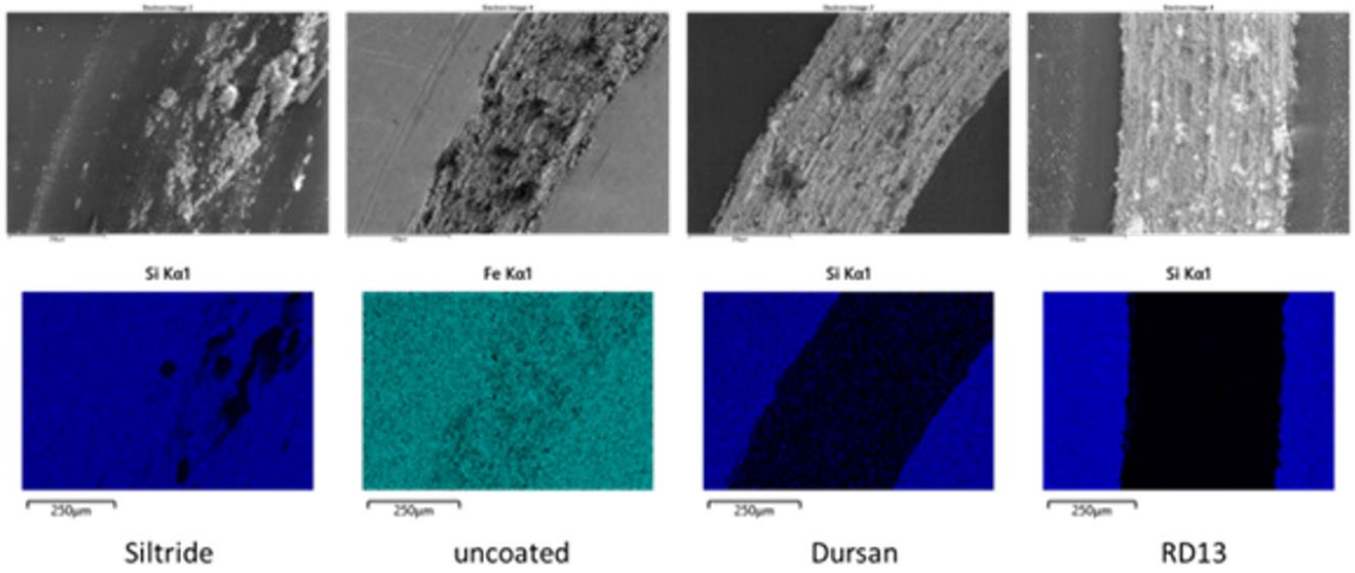


Figure 1: A schematic diagram of a pin-on-disk test[1]

2.5x and 1.7x improvement vs. uncoated stainless steel

Wear track cross-sectional profile





Anti-Corrosion Properties

SilcoTek Coatings and Corrosion

- Our CVD coatings can dramatically increase service life of stainless steel in harsh environments.
  - Not achieved by greater thickness
  - Instead, chemical inertness to corrosive agents
- SilcoTek coatings not suitable for improving lifetime of carbon steel or lower-grade alloys
- Substrate + coating selection are both critical.

→ SilcoTek-coated 316L stainless steel is a much more economical, higher ROI solution than Hastelloy, Titanium, or Inconel materials

Salt Spray (ASTM G85)

- 8,064 hours of acidified salt spray per ASTM G85-A2
  - Dursan coating is unaffected and provides excellent protection on stainless steel in a salt spray environment. Silcolloy shows minor rust.

Uncoated 316L

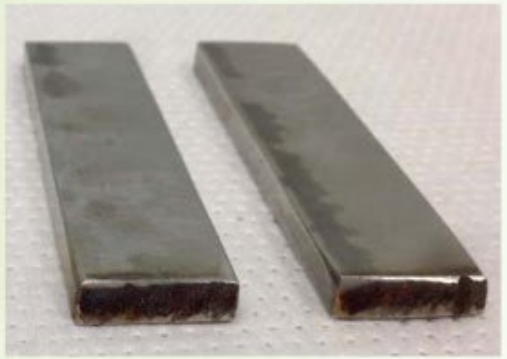
Silcolloy-coated 316L

Dursan-coated 316L

Salt Spray (ASTM G85)

(continued from previous slide)

- Dursan-coated 316L SS is completely unaffected by 168 days of acidified salt spray
  - Even corrosion resistant duplex alloy 2205 showed moderate corrosion under these conditions

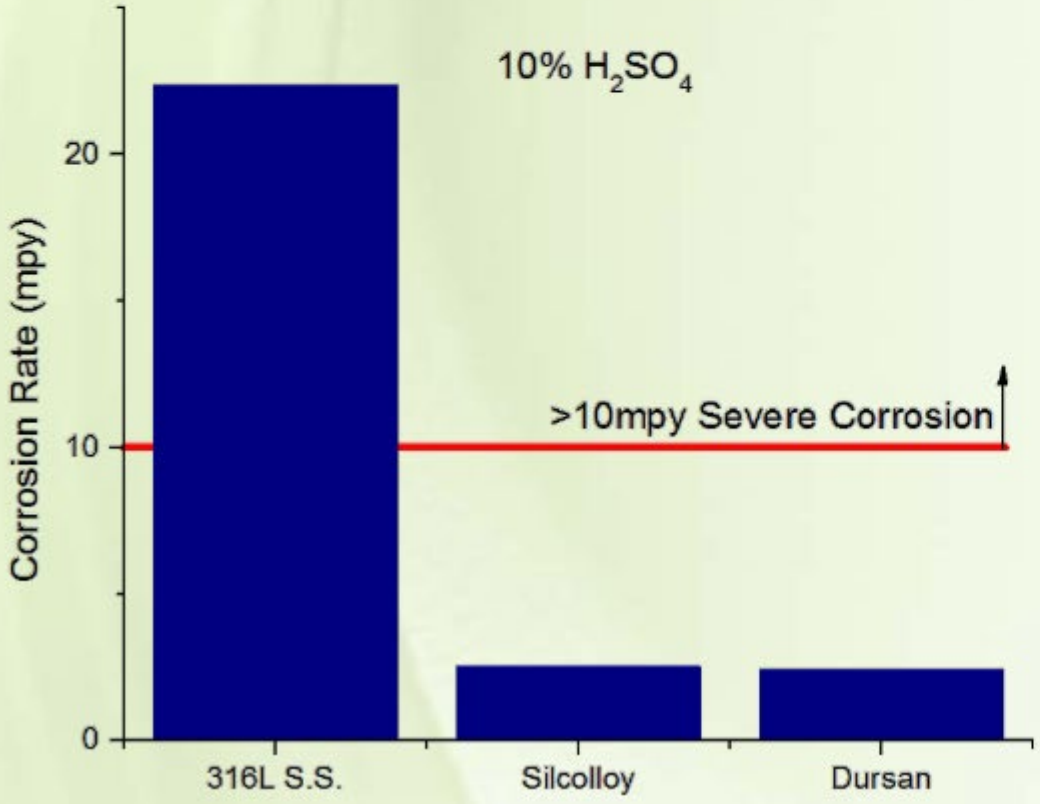


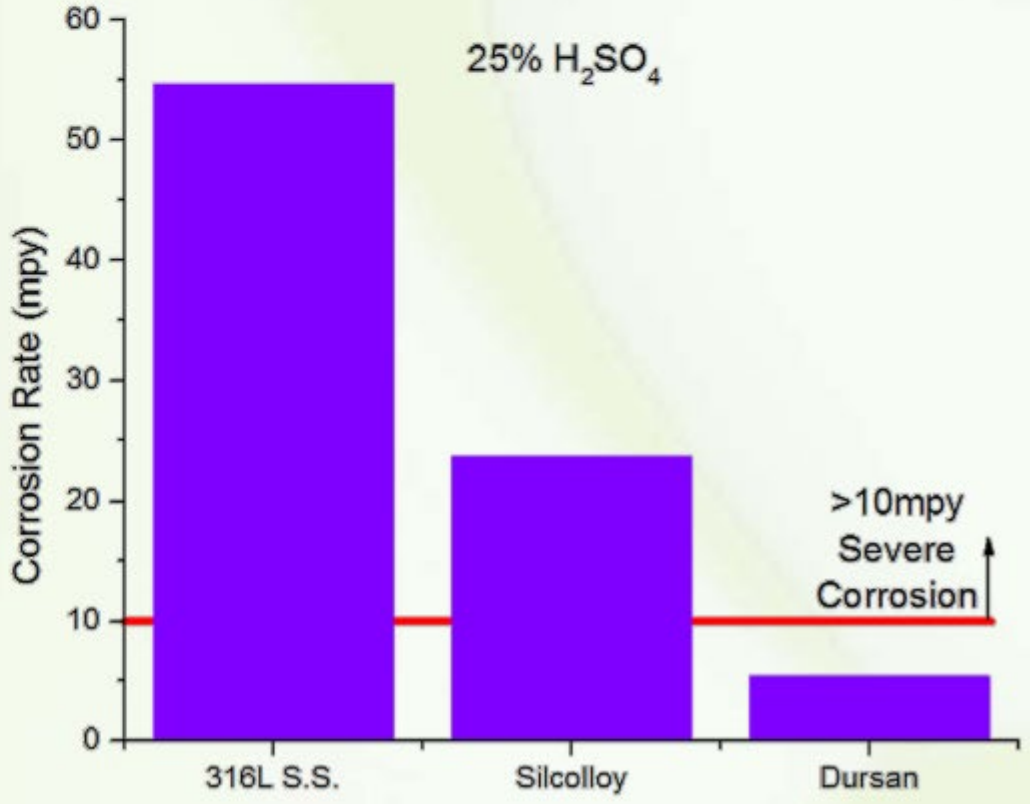
Uncoated Duplex Alloy 2205

Dursan-coated 316L

Sulfuric Acid (H_2SO_4)

- ASTM G31 Guidelines
- Sufuric Acid Exposure
- 24 hrs at Room Temperature





Silcolloy 1000 coating vs. 5% HCl

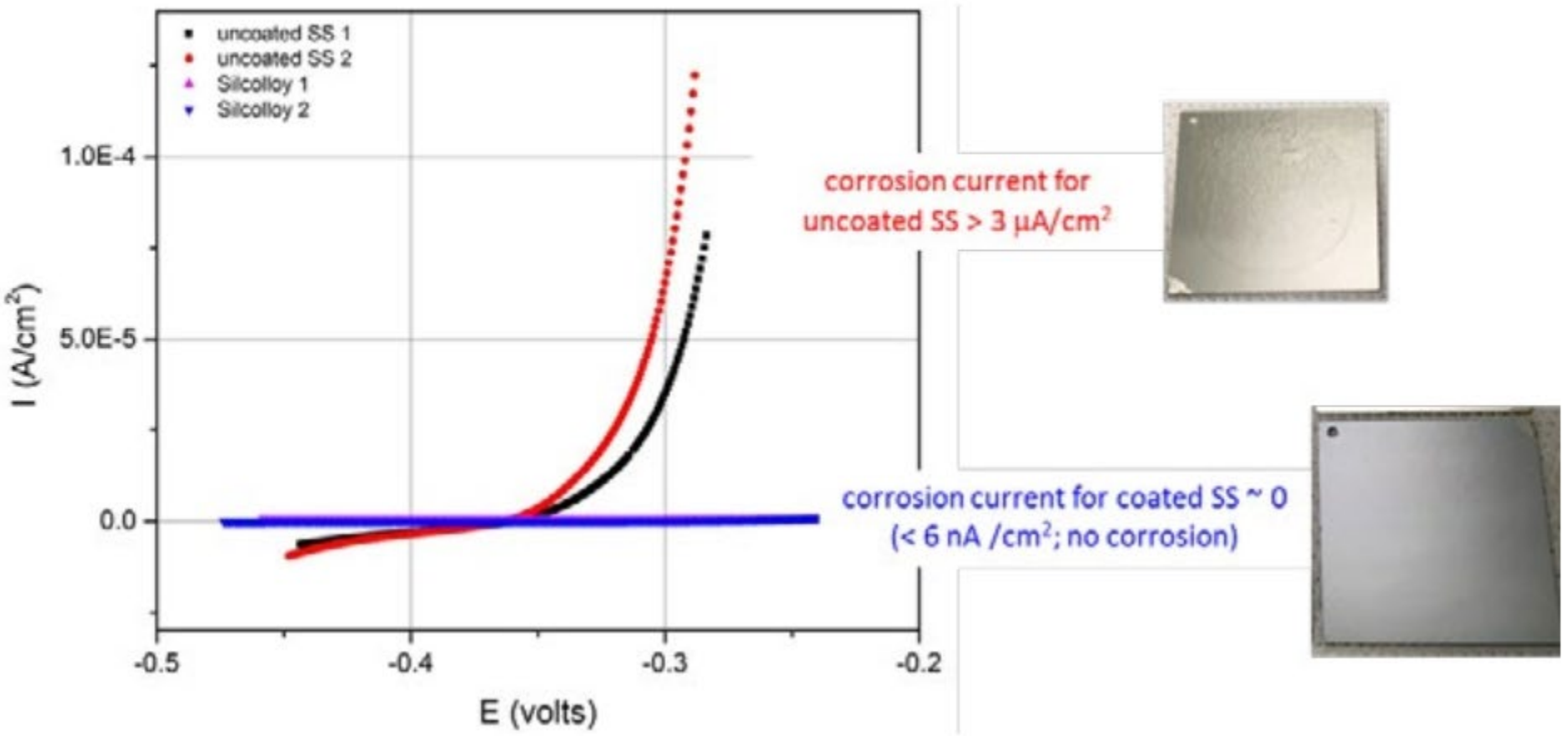
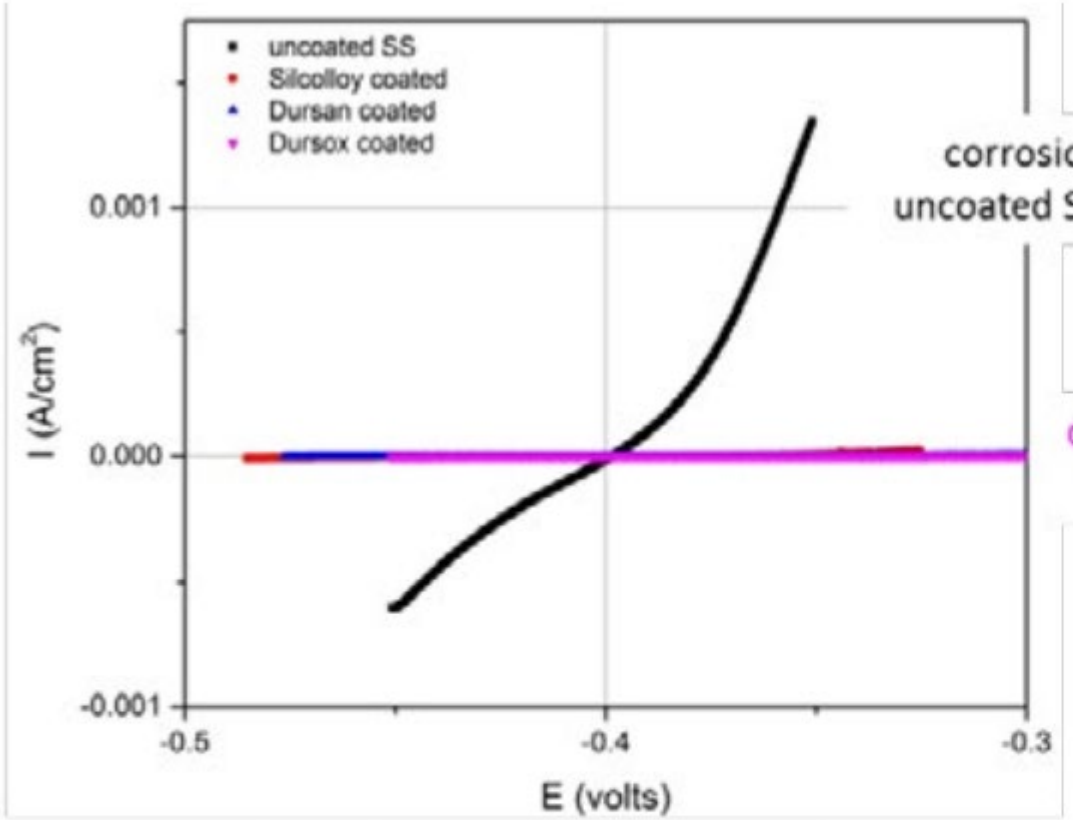


Figure 2: Polarization resistance scan shows that the Silcolloy® coating reduces corrosion by 3 orders of magnitude in 5% HCl. Corrosion current was estimated from the slope in the linear polarization scan (not shown here).

Dursan coating vs. 5% HCl



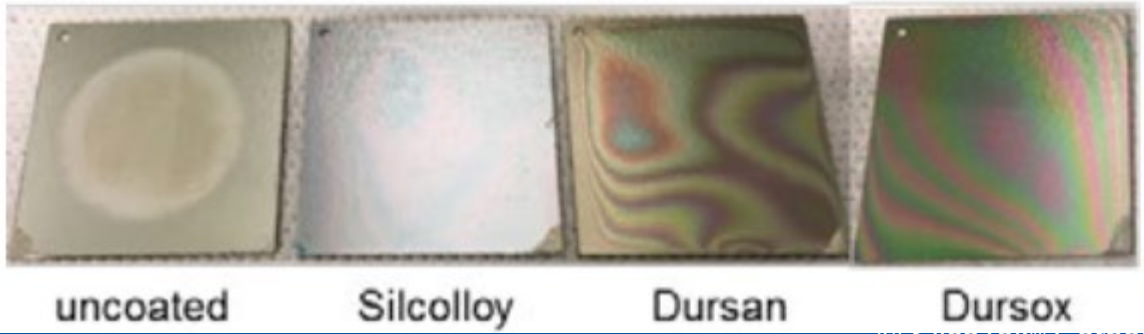
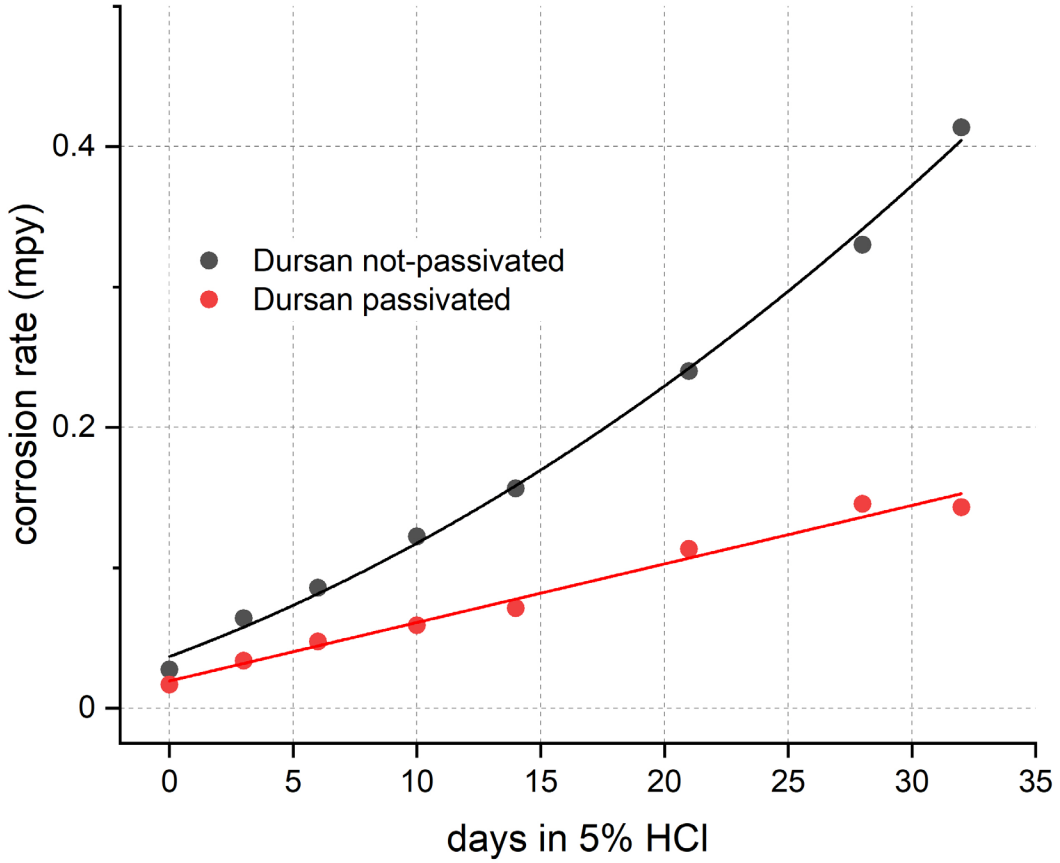
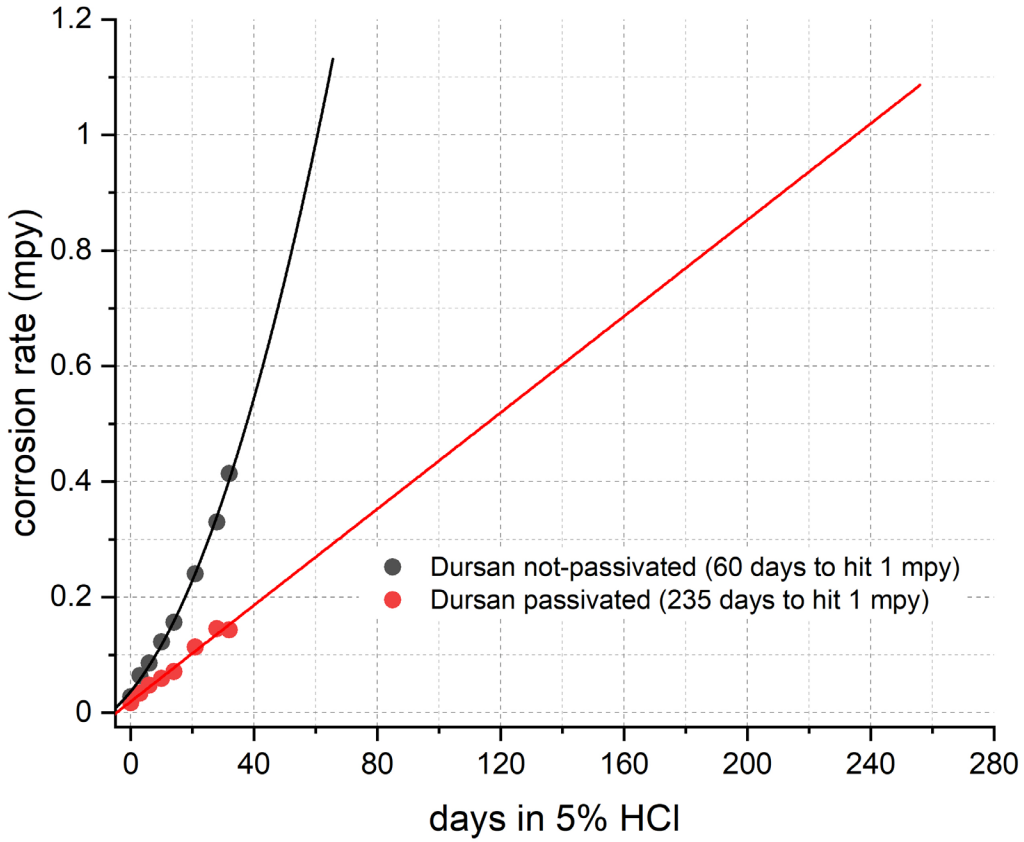


Figure 3: Polarization resistance scan shows that Silcolloy®, Dursan®, and Dursox™ coatings are all effective in reducing corrosion in 5% HCl. Corrosion current was estimated from the slope in the linear polarization scan (not shown here).

Corrosion Rate Comparison of Dursan-coated 316L SS and Citric Passivated + Dursan-coated 316L SS



Extrapolated from ~30 days to ~280 days



Conclusion

- SilcoTek coatings offer far superior surface properties vs. traditional spray or in-situ options **without sacrificing any heat transfer efficiency**.

- When paired with the appropriate alloy, customers enjoy **substantially higher ROI** through less maintenance downtime while reducing spend on exotic alloys.

- SilcoTek's coatings are **already specified** by major exploration and refining companies throughout the oil and gas industry.

Contact

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