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PLANNING, PRODUCTION PROCESSES & FACILITIES

Using Atmospheric Plasma for Enhance Coating Adhesion to Limit the Onset of Corrosion

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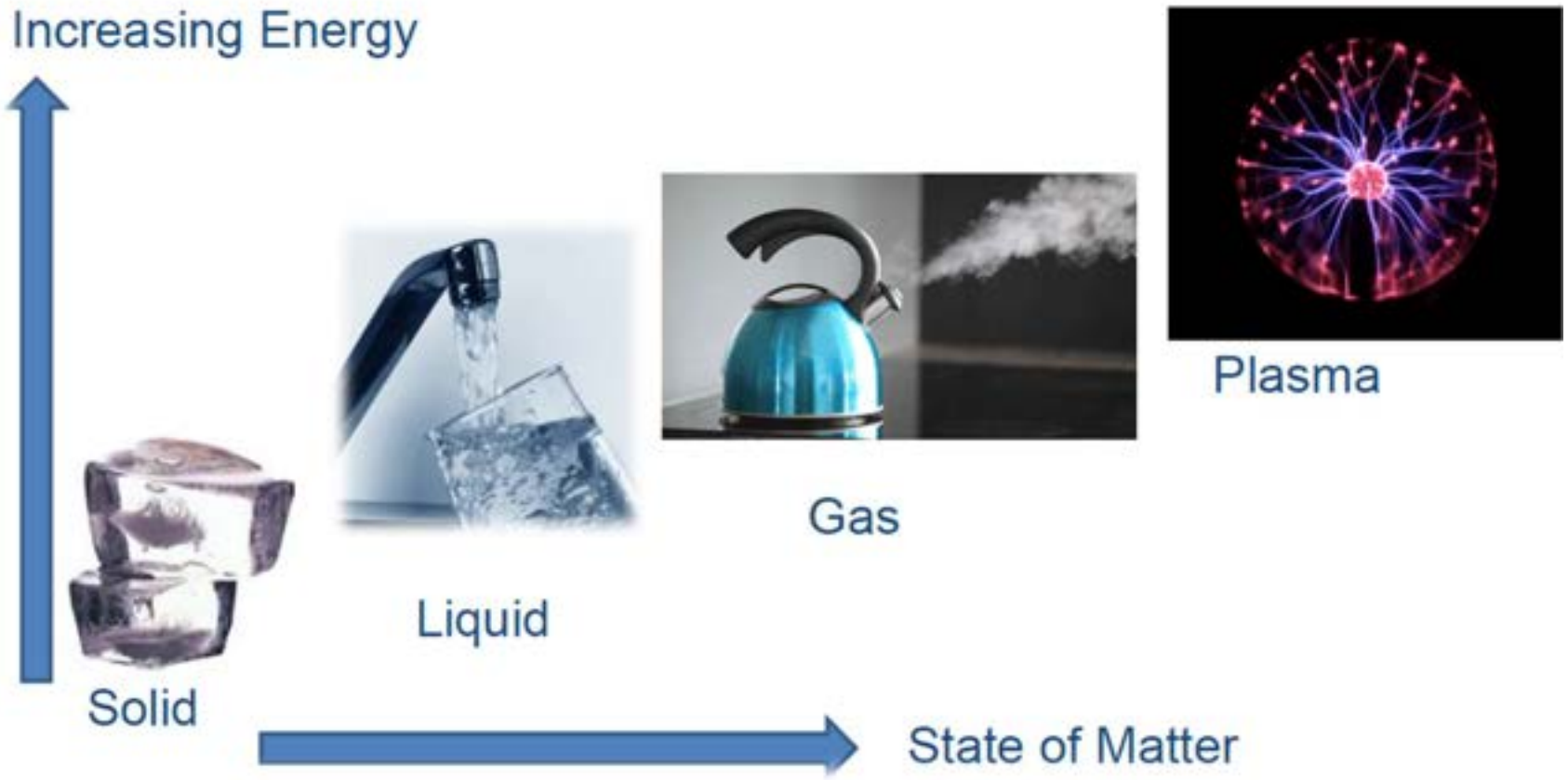
Overview

- What is Plasma
- Differences between Thermal and Non-thermal plasmas
- What is Atmospheric Plasma Adhesion Promotion?
- Atmospheric Plasma Coating Removal
  - APCR vs. Needle Gun (Case Study)
- Atmospheric Plasma Surface Preparation
  - Water Contact Angle
  - Salt Fog Corrosion Testing
- Conclusions
- Additional Testing To-Date

Plasma: Fourth State of Matter



What is Atmospheric Plasma?

- Atmospheric plasma is a plasma produced at one atmosphere pressure—in other words the same pressure as the atmosphere we live in every day.
- Stream of Air is introduced into a region of intense electric field between internal electrodes where the plasma is formed and ejected through a nozzle
- Electrons excited by electric field generate:
  - Ions and secondary electrons (maintains the plasma density)
  - Dissociated molecules (atomic oxygen from air)

- Non thermal plasma - Plasma formed in an active plasma region followed by an afterglow region rich in monoatomic oxygen that exits the plasma pen

Single Beam Plasma Pen

Thermal vs. Non-Thermal Plasma

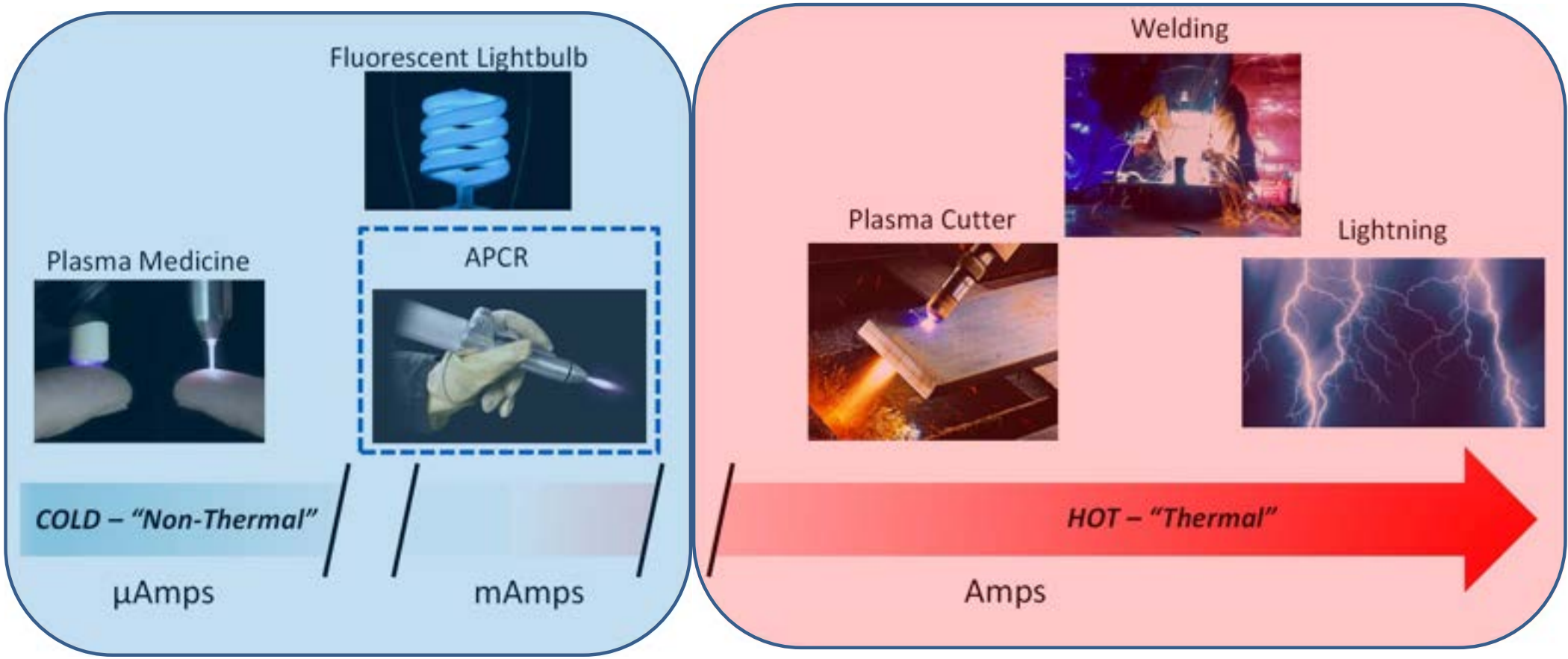
Thermal plasma **-** is characterized as having both its free electron and heavy ion components at high temperatures and in thermal equilibrium with each other.

- Very Hot

Non-thermal plasma **-** the free electron and heavy ion components are not in thermal equilibrium. Typically, the ion components are at a significantly lower temperature than the electrons.

- Relatively Cool

Non-Thermal versus Thermal Plasmas

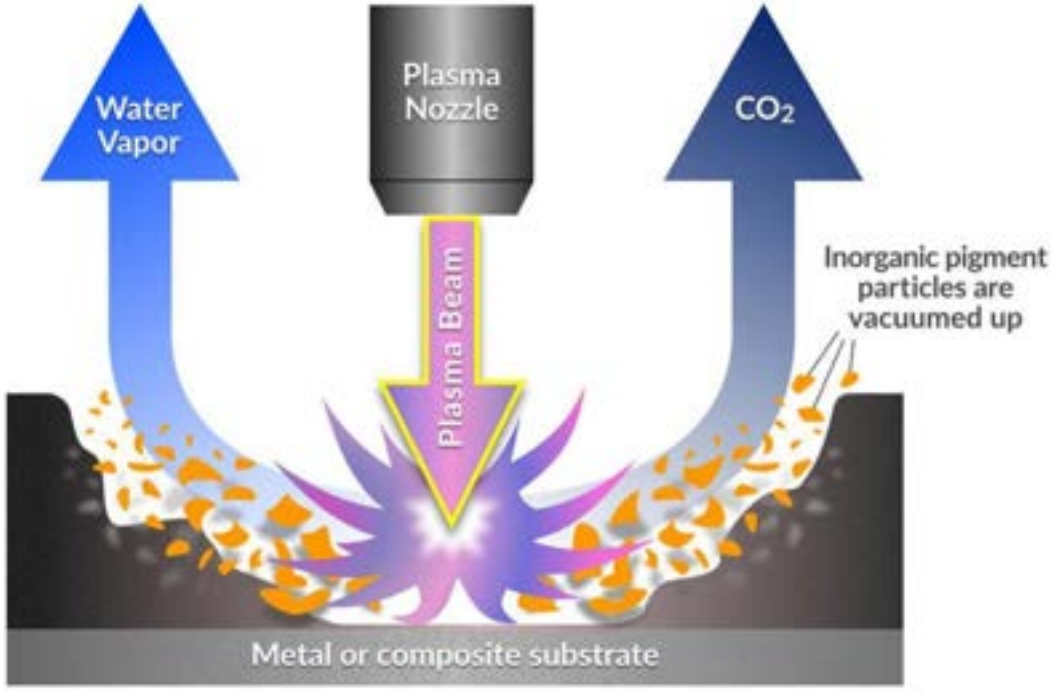


APCR – uses milliAmps of current : energy used to make chemistry instead of heat

Atmospheric Plasma Coating Removal (APCR)

1. Produce atomic oxygen from air
2. Direct the atomic oxygen to the organic surface (coating)
3. Water vapor, CO_2, and inorganic particles are by-products

No change to the existing profile underneath the coating*

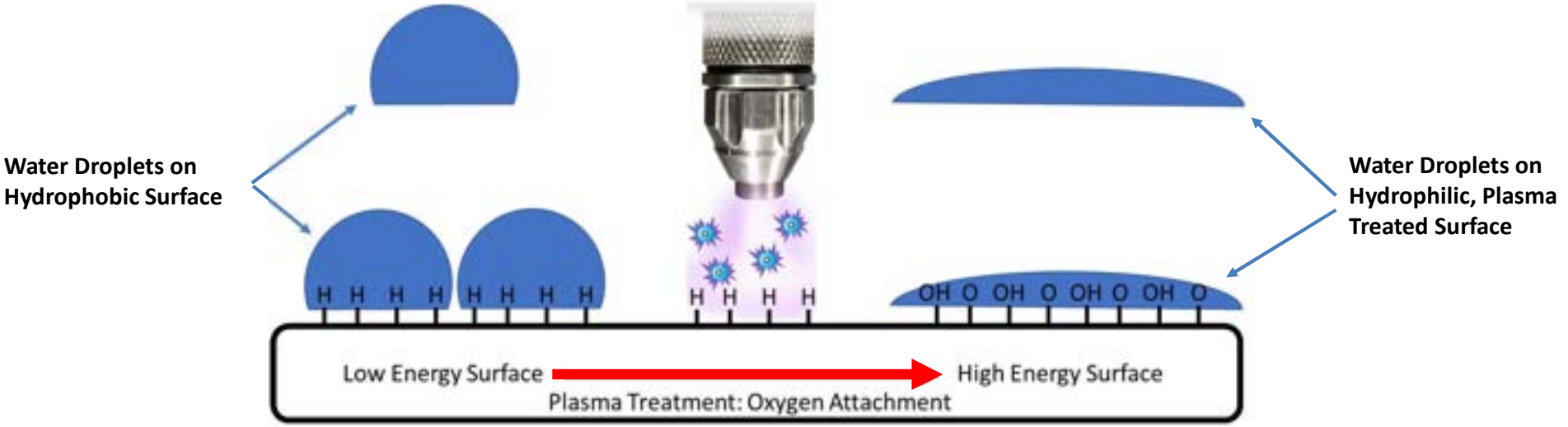


Atmospheric Plasma Coating Removal (APCR) – Not Laser

Both contain plasma – but very different types of plasma lead to different surface treatments

APCR	Laser
Air plasma – non-thermal	Material/metal plasma – thermal
Uses plasma-generated air chemistry to oxidize/etch/remove coatings, clean the surface, and promote adhesion	Vaporizes / ablates coating and contamination by depositing heat on very short time scales
Low thermal energy over long time scales	High thermal energy over short time scales

Atmospheric Plasma Adhesion Promotion

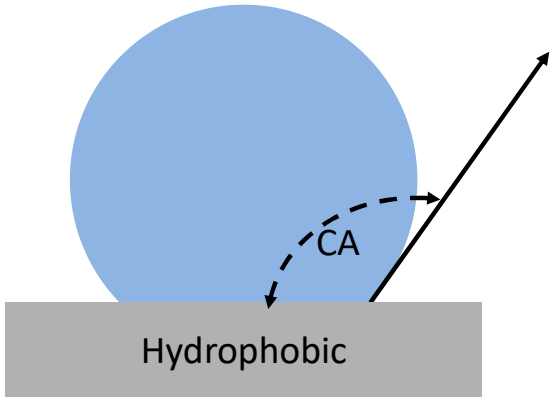


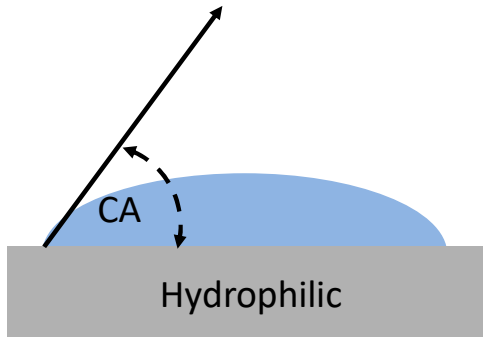
1. Reactive plasma species cleans surfaces (removes carbonaceous materials)
2. Increases surface energy (confirmed through water contact angle measurements)
3. Promotes chemical adhesion (increases chemical bonding with coating)

ASTM D7334 - Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement

Atmospheric Plasma Surface Preparation (Adhesion Promotion)

Automated Water Contact Angle (WCA) Measurement Device





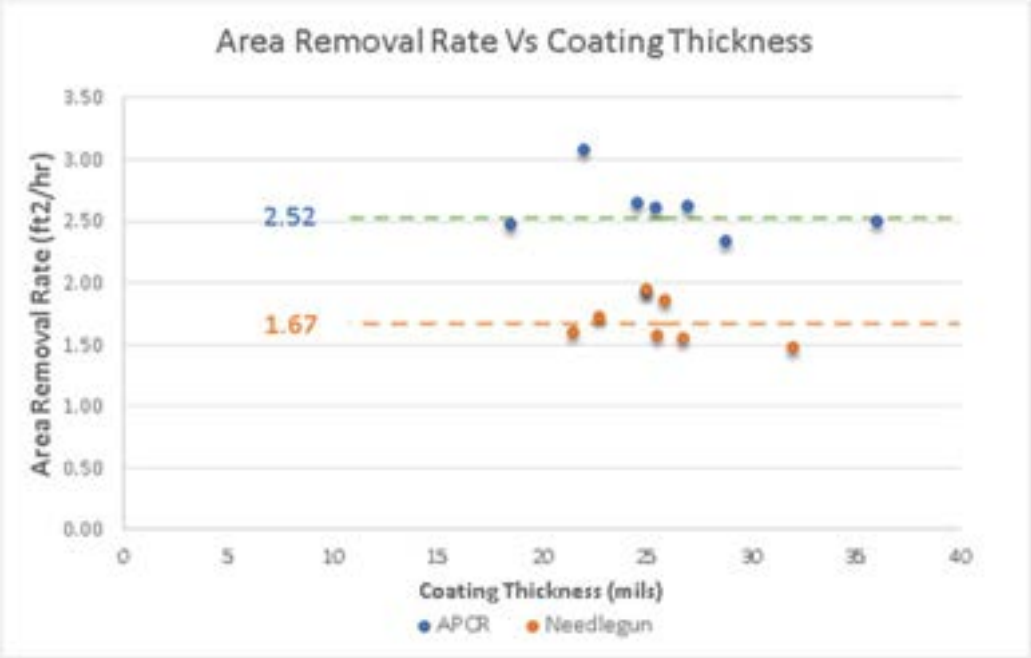
High ---------- Contact Angle ---------- Low
Low ---- Substrate Surface Energy ---- High
Poor ---------- Wettability ---------- Good
Low ------- Adhesive Properties ------ High

Water contact angle (WCA) measurements provide a method to characterize the surface energy of a substrate. A high surface energy correlates to better adhesion between the substrate and an applied coating.

APCR vs Needle Gun

Study evaluated laboratory and in-field testing of ***Atmospheric Plasma Coating Removal*** and highlights its adoption benefits to productivity, worker safety, corrosion control, and fleet readiness.

APCR vs Needle Gun – Removal Rate

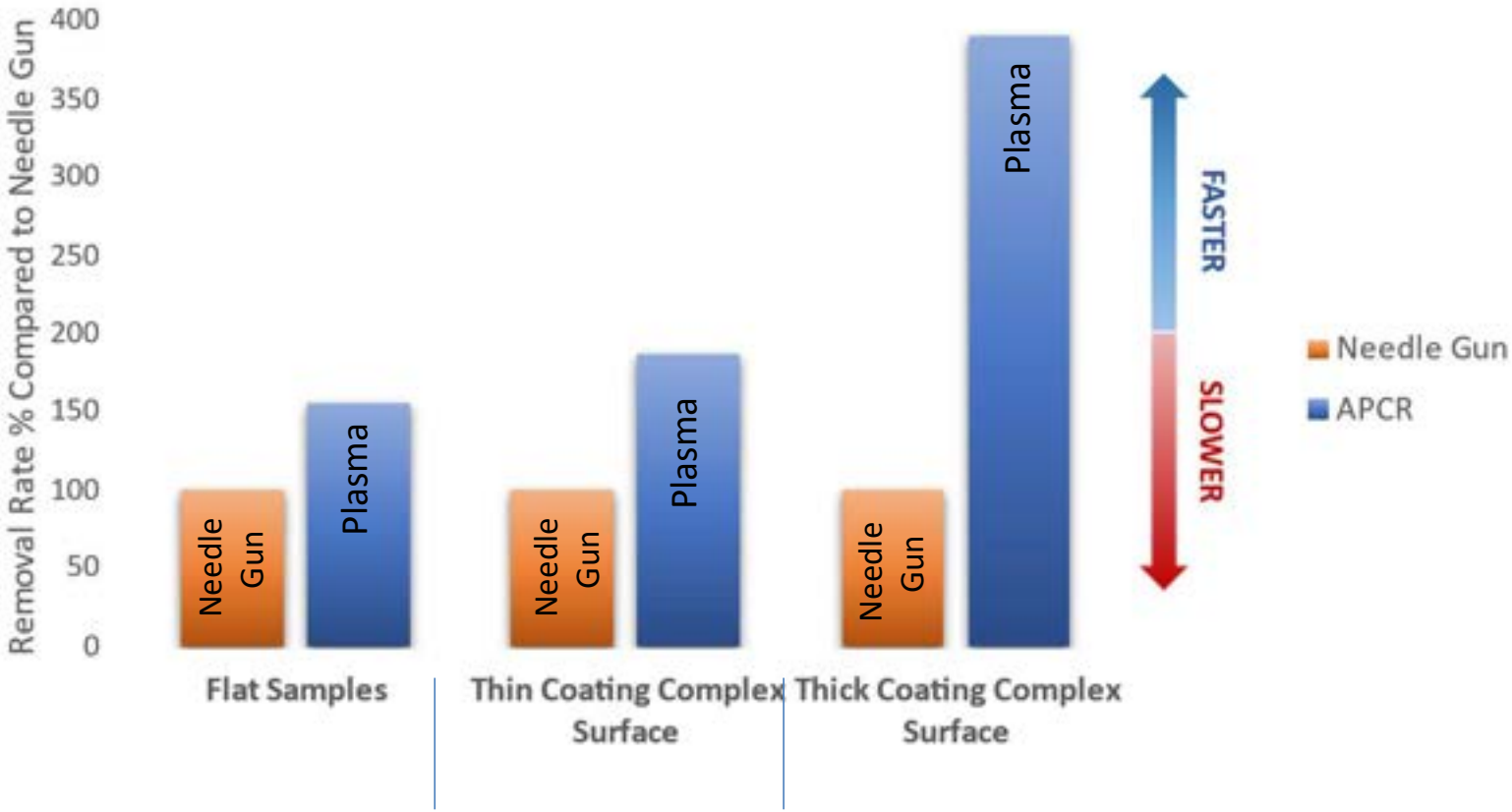


Rates of removal for Plasma*Blast*® APCR and needle gunning were evaluated by measuring the amount of time it took a ***newly trained plasma operator*** to remove the coating down to bare metal in the designated areas.

- Plasma*Blast*® APCR - ***51%*** *faster*
- Average area removal rate of ***2.52 ft²/hr***

Removal Method	Avg Area Removal Rate (ft^2/hr)	% Area Rate Improvement Compared to Needle Gun	Avg Volume Removal Rate (ft^2·mils/hr)	% Volume Rate Improvement Compared to Needle Gun
Needle Gun	1.66	+/- 0%	42.6	+/- 0%
APCR	2.52	**+ 51%**	65.1	**+ 52.6%**

APCR vs Needle Gun – Removal on Complex Surfaces



APCR outperformed Needle Gun for removing coatings on flat and complex surfaces

APCR - Case Scenarios

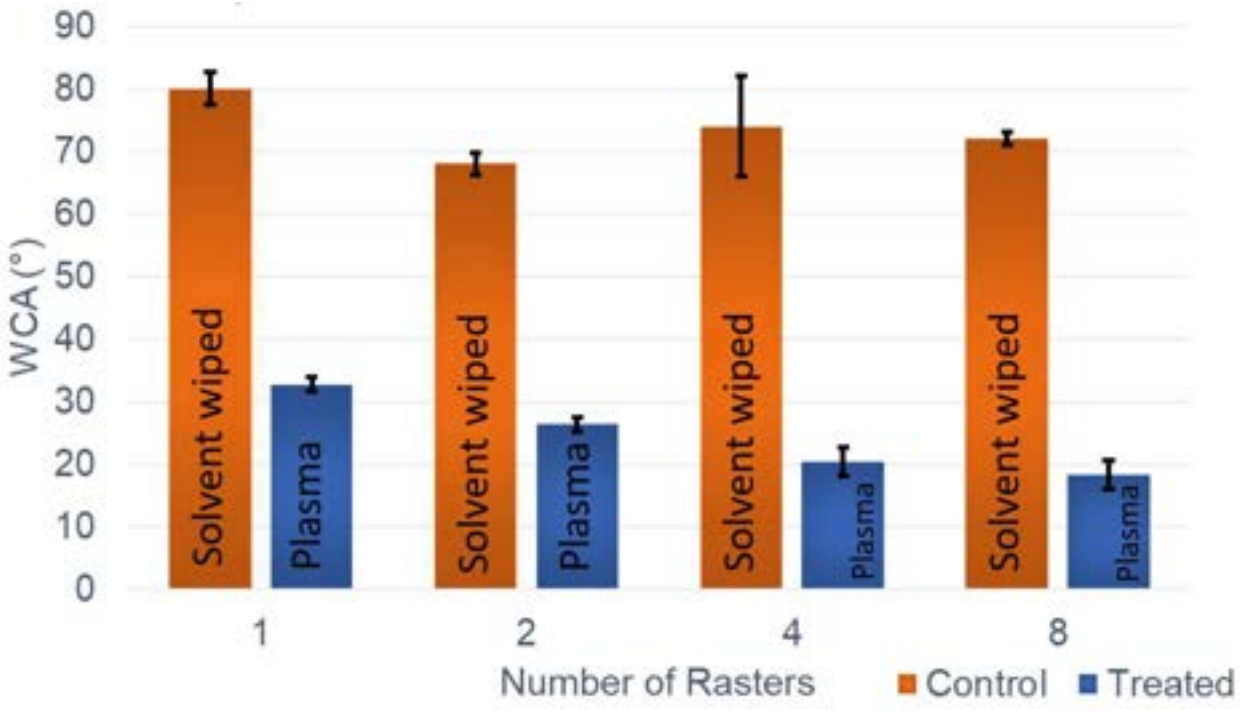
Removal Method	Surface Geometry and Features	Removal Area Dimensions	Key Challenges with Surface	Removal Time (mm:ss)
APCR	Square Area on Flat Surface	3”×3”	None	01:32
APCR	Square Area on Flat Surface	3”×3”	None	01:38
APCR	Square Area on Flat Surface	3”×3”	None	01:30
APCR	Internal Corner Section on Beam	3”×2.5”	Treatment around internal corner, narrow space, treatment on opposite side operator is facing, thick coating	03:32
APCR	Internal Corner Section on Beam	3”×2.5”	Treatment around internal corner; narrow space; treatment on opposite side operator is facing; thick coating	02:27
APCR	Area covering Large Pipe Welded to Surface	3”×3”	Treatment on weld; treatment on complex surface; treatment on right angle interface	02:17
APCR	Bolt and Large Washer Mounting Sound Tile	2” Diameter	Treatment on nut, bolt, and washer; complex surface; small, isolated object	01:40

Demonstrates the APCR process’s ability to remove coatings from complex and difficult-to-reach surfaces quickly.

Adhesion Promotion Study

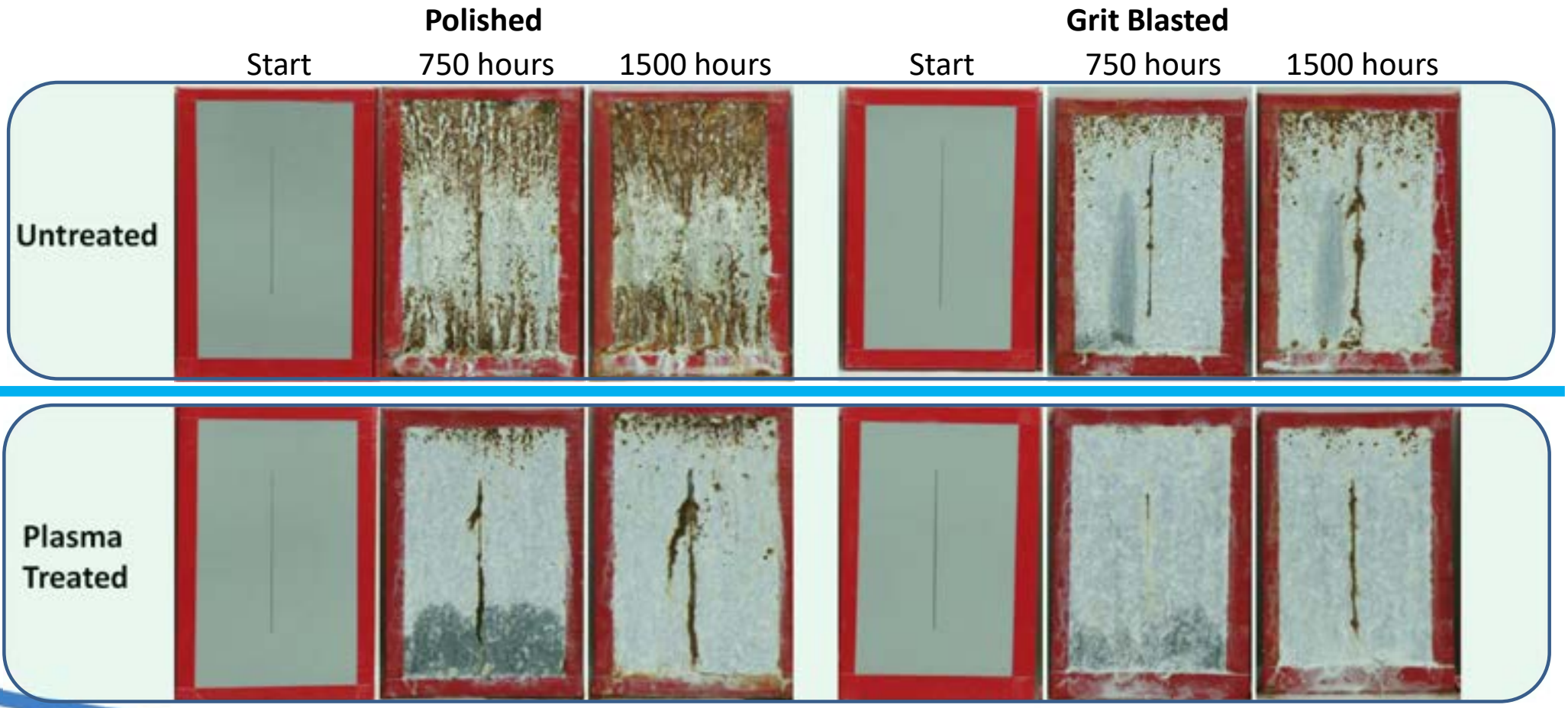
- Water Contact Angle – for qualitative analysis of surface wettability
- ASTM A709 Grade 50 Bridge Steel Specimen Panels
- Coating: 5 mils, SW Zinc Clad 4100 – epoxy, zinc-rich primer
- 2 specimen surface finishes,
  - Polished to 400 grit finish
  - Grit Blasted to SSPC-SP 10 with 2 mil surface profile
- Before coating application, test the surface energy via WCA
- After coating, panels exposed to 1500 hours of ASTM B117 Salt Fog
- Preliminary Cathodic Disbondment Testing ASTM G95

Atmospheric Plasma – Water Contact Angle



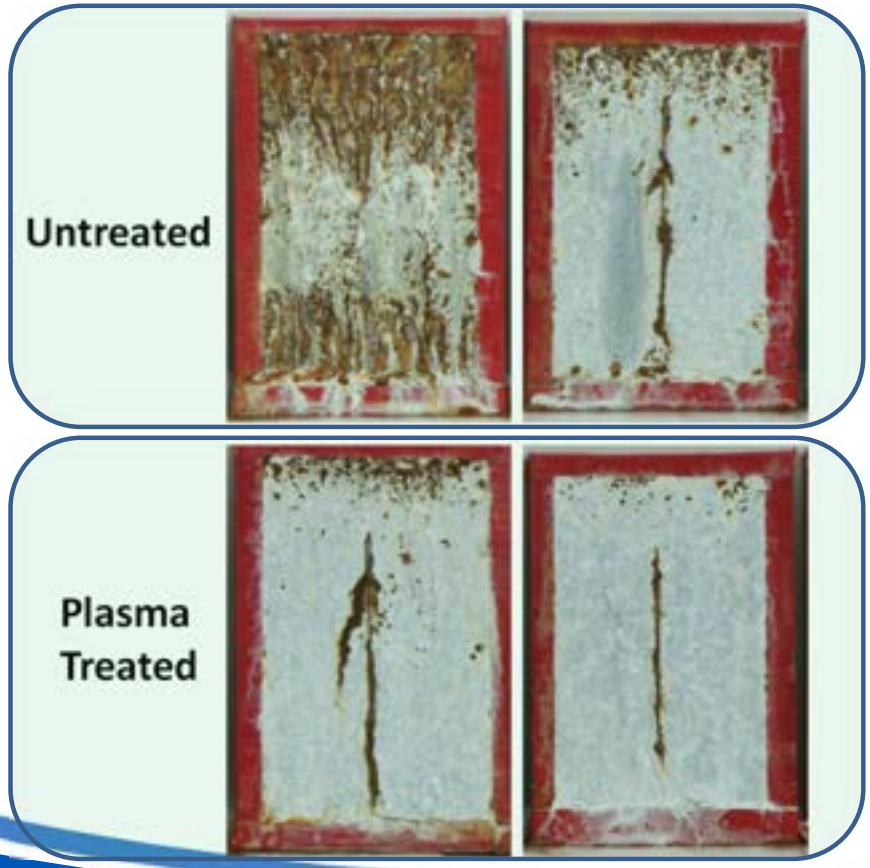
Higher flux of plasma-generated species leads to faster reduction in water contact angle indicating higher surface energy and better adhesion promotion.

Atmospheric Plasma – Adhesion Promotion – Salt Fog Test



Atmospheric Plasma – Adhesion Promotion – Salt Fog Test

1500 hours



Condition (n=10)	Creep (mm)	Rating
Polished – Untreated	N/A – excessive corrosion	
Polished – Plasma Treated	2.43	6.6
Grit Blasted - Untreated	2.25	6.4
Grit Blasted – Plasma Treated	0.82	8.1

The chemical adhesion promotion of plasma treatment delays the onset of corrosion.

The combined (plasma and grit blast) effect is greater, substantially delaying corrosion.

Preliminary Cathodic Disbondment (ASTM G95)

Control – abrasive blast (3-4 mil) / cleaned / coated with Duraplate (~25mils)

Net Disbonded Area
7004 mm²

APCR coating removed (Duraplate) / plasma surface activated / coated with Duraplate (~25mils)

Net Disbonded Area
759 mm²

Conclusions

- In a specific study APCR has a 51% greater Area Removal Rate than the needle-gun process.
- Thick coatings and complex surfaces were significantly easier to address with APCR.
- Effectively removes coatings from nuts, bolts, threads, and welds, can be used on certain sensitive surfaces.
- APCR process imparts no vibrational force into the operator during use.
- Atmospheric Plasma surface treatment functionalizes surfaces for enhanced adhesion confirmed with water contact angle.
- Adhesion promotion occurs over 300 times faster than coating removal.
- Salt Fog Testing revealed that using a plasma surface treatment reduces onset of corrosion over traditional methods.
- Preliminary cathodic disbondment testing suggest enhance adhesion limited early onset of corrosion.

AMPP SP21523-2022, Non-thermal Plasma Surface Preparation of Metals

This standard contains the general requirements for the safe and effective use of APC equipment, operated either manually hand-held or through use of automation, to prepare various metallic surfaces for maintenance, repair, recoating, or lining. This standard does not address surface preparation of concrete.

Questions ?

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Additional Testing To-Date

- ***Microscopic Surface Profile Comparison*** – SEM analysis of plate surfaces were examined post Plasma coating removal were found to be superior to traditional mechanical techniques and indistinguishable from grit blasting to SP10 standards.
- ***Metallurgical Examination*** – Plasma was used to remove epoxy coating from lap-welded HY-80 steel plate. Cross-sections of the HAZ, weld metal, and base metal showed that all three zones were unchanged in both surface and subsurface regions. No discontinuities, voids, recrystallization, or other irregularities were observed in any of the polished metallurgical cross-sections.
- ***Vickers Hardness Testing*** – Compared to control samples, samples treated with Plasma system displayed no difference in average hardness at the surface as well as ~30 mils into the subsurface.
- ***Tensile Testing*** – Tensile testing was performed comparing control and Plasma treated areas of weld, HAZ, and base material. No difference in tensile strength was shown.
- ***Charpy Impact Testing -*** Charpy Impact Testing was performed on samples in the weld, HAZ, and base metal areas. The results showed a negligible increase in Charpy Impact strength in the Plasma area.
- ***Axial Fatigue Testing*** – Characterization of fully-reversed (R=-1) axial fatigue testing on HY-80 steel of Plasma overtreated bare surfaces and coating removal showed no fatigue degradation compared to controls.

Additional Testing To-Date

- ***Hydrogen Embrittlement*** - ASTM F519 Hydrogen embrittlement testing performed on Plasma treated samples showed no embrittlement to high yield, 1530 MPa (222ksi), 4340 landing gear steel.
- ***Hydrogen Content Testing*** – Both Control and Plasma treated samples indicated hydrogen content was low, and changes caused by plasma processing were seemingly insignificant. The values detected were considerably below, <2ppm, the maximum solubility of hydrogen (15 ppm) in steel.
- ***SEM Surface Morphology & Composition Comparison*** - Plasma coating removal was compared to common coating removal methods such as Needle Scaling and Grinding on DH36 steel. Plasma coating removal produces a surface that is most similar in surface composition and morphology to a SSPC - SP10 grit blasting prepared surface preparation.
- ***Surface Temperatures*** - On 60 cm X 91 cm X 0.95 cm steel plate samples, the maximum temperature recorded during treatment of a 10.1 cm X 10.1 cm section was 130°C at the center of the removal area and 91°C at the edge of the removal area. Two inches away from the treatment area, the maximum temperature measured was 39°C.

TESTING COMPLETED WITH:

CORROSION TESTING LABORATORIES, INC.

NAVSEA NAVAL SEA SYSTEMS COMMAND

AFRL THE AIR FORCE RESEARCH LABORATORY

PlasmaBlast® proven on coatings and substrates

Atmospheric Plasma Surface Preparation

- ✓ Tool for <u>both</u> coating removal; surface preparation; and adhesion promotion
- ✓ Removes industry coatings from 1 mil thick to 100's mils effectively
- ✓ Enhances adhesion of coatings to substrates
- ✓ Precision jobs
- ✓ Portable to any job on the platform or yard
- ✓ Media and chemical free
- ✓ Only requires air and electricity to operate