Atmospheric Plasma Coating Removal Demonstration

Final Report

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Table of Contents

Section **Page**

List of Figures

List of Tables

Acronyms and Abbreviations

Term	Definition
APCR	Atmospheric Plasma Coating Removal
APS	Atmospheric Plasma Solutions, Inc.
CTL	Corrosion Testing Laboratory
CTMA	Commercial Technologies for Maintenance Activities
DFT	Dry-Film Thickness
DOD	Department of Defense
EAG	EAG Laboratories
EHS	Environmental Health and Safety
FBW	Fairlead Boat Works
GDEB	General Dynamics Electric Boat
HAVs	Hand-Arm Vibrations
IH	Industrial Hygiene
NCMS	National Center for Manufacturing Sciences
NDT	Non-Destructive Testing
NNSY	Norfolk Naval Shipyard
NSRP	National Shipbuilding Research Program
NSWCCD	Naval Surface Warfare Center Carderock Division
PPE	Personal Protective Equipment
SBIR	Small Business Innovation Research
SPTEP	Sample Preparation, Treatment, and Evaluation Plan
TOC	Total Ownership Cost
TRL	Technology Readiness Level
TWHs	Technical Warrant Holders
U.S.	United States

1. Executive Summary

"A ship in port is safe, but that's not what ships are built for."
-Grace Hopper, former United States Navy RDML

A vessel docked for maintenance is a vessel out of service. For military forces, this significantly affects the readiness of that force, its ability to respond quickly and appropriately to a developing situation. It is for this reason that the United States Navy continues to search for and invest in innovations that improve maintenance turn-around times as well as innovations that keep vessels in service for longer periods of time. In large-scale construction and manufacturing industries such as shipbuilding and naval maintenance, coating removal is an essential but time-consuming process required for constructing and maintaining vessels and other structures. Although some new technologies have emerged in recent decades, the pre-World War II technologies of abrasive blasting, grinding, and needle-gunning remain the dominant coating removal methods employed today. Grinders, needle-guns, or hand tools (such as wire brushes and chisels) are often required for small-scale removal, and each comes with their own drawbacks such as hazards to operator health, slow removal rate, and damage to substrates. In the Naval Engineering Industry, there is a significant need for a tool that will accelerate small-scale coating removal operations without negatively impacting the health of the operator or the underlying substrate. The joint effort detailed in this report was undertaken to evaluate the suitability of the Plasma*Blast*® PB7000-M – developed by Atmospheric Plasma Solutions, Inc. (APS) – to fill this need in small-scale removal operations in an experienced naval shipyard setting.

The Plasma*Blast*® 7000-M is an air-fed Atmospheric Plasma Coating Removal (APCR) device that has repeatedly proven to be effective at removing organic coatings commonly found in shipyard environments. The M model has been packaged and configured as a man-portable, single-beam air and power input-only tool. To evaluate the tool for use in a shipyard setting, a series of representative and comparative tests were conducted in which the tool was operated exclusively by Norfolk Naval Shipyard (NNSY) workers. Comparative tests were performed to compare the PB7000-M to the commonly used needle-gun scaler; in these tests, coating removal tool efficacy, substrate impact, and user experience were evaluated on controlled test samples and decommissioned submarine sections. Through the testing conducted at NNSY, it was demonstrated that the Plasma*Blast*® system significantly outperforms the needle-gunning process in removal rate as well as impact on the user and surfaces' substrates.

In comparative tests on prepared flat panel samples, APCR had a **51% greater Area Removal Rate** than the needle-gunning process. In use-case scenario testing on a section of a decommissioned submarine, APCR was measured to be **between 87% to 291% faster** than the needle-gunning process depending on the thickness of the coating and complexity of the surface; thick coatings and complex surfaces were significantly more efficient to treat with APCR than needle-gunning. It was shown that the APCR process has a broader range of applications than needle-gunning; it is able to get into tighter spaces, does not significantly affect substrate surface profile, can remove tougher and thicker coatings, can effectively remove coatings from nuts, bolts, threads, and welds, can be used on certain sensitive surfaces where needle-gunning would be inappropriate or where more precise control is needed, and requires around the same or less total power than needle-gunning per area of coating being removed. The average maximum temperature measured on test surfaces during APCR treatment was around **160°F**, assuaging concerns about effects on the temper of the steel substrate.

The Plasma*Blast*® system also imparts no noticeable vibrational force into the operator during use, a frequent complaint and source of injuries in workers using needle-guns and grinders; this means that the PB7000-M can be operated for longer periods of time without the need for breaks, while both improving worker quality of life and reducing work-place injuries associated with hand-arm vibrations.

In this effort, the Plasma*Blast*® PB7000-M coating removal tool was demonstrated to have immediate benefits in the naval shipyard setting in which it was tested; it was able to provide these benefits even in the hands of relatively inexperienced operators who had only received a 1-2-day training session and had less than 2 days of total experience with the tool. More experienced operators can be expected to remove coatings even faster and more precisely. Given that the technology has not yet been widely adopted, there are still new application areas constantly being discovered for the tool, and its full potential benefits will not be realized until it is put into the hands of experienced shipyard workers who can better identify new applications of the technology and process.

Funding for the collaborative effort between the APS and the Norfolk Naval Shipyard (NNSY) was secured through the National Center for Manufacturing Sciences (NCMS) Commercial Technologies for Maintenance Activities (CTMA) Program when APS won the 2019 CTMA Technology Competition held during the CTMA Partners Meeting in May 2019.

1.1 Results and Benefits

1.1.1 PB7000-M Consistently Outperformed Needle-Gun Removal

- 51% faster than needle-gunning on flat surfaces
- 87% faster than needle-gunning on a complex surface with a thin coating
- 291% faster than needle-gunning on a complex surface with a thick coating
- Surface revealed without profile or features being visibly altered
- Requires no additional surface treatment before recoating
- Enthusiasm from shipyard workers who generally disliked needle-gun removal

1.1.2 Broad Use-Case Applicability

- Completely revels welds without altering them
- Effective on internal corners
- Effective on flat and complex surfaces
- Effective on nuts, bolts, and threads
- Effective in difficult-to-reach area
- Effective on thick and elastomeric coatings
- More applications than needle-gunning, requiring less tool swapping
- Fills gaps where other tools don’t work well

1.1.3 Same or Better Adhesion of Coatings After APCR on Profiled Surface

- Demonstrated that reapplied coating adhesion after APCR is ***at least as strong as*** on an abrasive blasted surface. All dolly-pull test failures were cohesive failures within the coating

- Previous testing demonstrated a marked **increase** in adhesion strength after APCR

1.1.4 Simple Setup, Operation, Training and Maintenance

- Can be setup in under 5 minutes
- Requires only compressed air and electric power to operate
- No calibrations measurements, or adjustments needed to operate
- Plasma*Blast*® operator training can be completed in one or two days
- The only consumables are the pen nozzle and electrode

1.1.5 Environmental Health and Safety Benefits

Less Damage to Operator than Needle-Gunning

- No noticeable vibrational impact on operator, leading to fewer workman's compensation claims associated with needle-gunning
- Produces less noise than needle-gun, reducing hearing damage, reducing noise pollution, and improving workplace safety
- Can be operated for longer than needle-gun without discomfort or needing operator breaks, allowing for longer coating removal shifts, increased productivity, and improved working conditions

Less Cumbersome Personal Protective Equipment (PPE) and Safety Requirements than Other Techniques

- Compared to laser ablation and abrasive blasting
- Requires no light screens, tenting, tinted glasses, protective suits, or helmets to operate safely
- Requires only appropriate gloves, clear plastic safety glasses, a dust mask or respirator, long sleeve shirt, rubber soled shoes, and adequate ventilation

Environmental Benefits

- Reduces waste stream compared to traditional coating removal methods
- APCR leaves behind only a fraction of the removed coating as waste in the form of dust that can be easily vacuumed up
- Reduces solid waste by up to 90%, depending on the coating chemistry
- Surface requires no solvent cleaning after APCR
- Reduces worker safety risks
- Reduces environmental contamination risks
- Reduces power consumption per square foot of area treated, compared to needle-gunning

1.2 Technology Transition

Technology transfer is a driver of innovation in the Department of Defense (DOD) and the U.S. economy. The DOD's objective of technology transition is to meet the warfighter's requirements at the lowest possible total ownership cost (TOC). To this end, the Navy seeks to leverage the best technology available from both government and commercial sources.

As a result of successful project completion in Small Business Innovation Research (SBIR), Forum for SBIR/STTR Transition, and Cooperative Research and Development Agreement programs, APS has been supported to advance the technical development of the Plasma*Blast*® system. As the data and analysis presented in this report shows, the system has reached a Technology Readiness Level (TRL) 8. The efforts of this project with NNSY were meant to move the technology to TRL 9 by actual application of the technology in its final form and under mission-like conditions as of operational test and evaluation.

This project with NNSY and CTMA and the resulting report provides the Navy and all other Services information to support the acquisition system, the requirements generation system, and financial management system. Through the testing and evaluation conducted, the system has shown interoperability, supportability, and affordability.

Interoperability—the technology can interface with other maintenance and sustainment systems in the shipyard or shipboard. The system is a complement or in some cases a replacement for other coating removal and surface preparation tools

Supportability—the fielded systems will help maintain a high state of readiness and safety. It has been demonstrated that trained operators and maintainers can do so economically and with a small logistical footprint.

Affordability—as this tool addresses sustainment issues as early as possible, the implementation of this new technology offers the potential to reduce the TOC associated with most naval platforms and systems.

1.2.1 Technology Insertion Plan

There is a need for close coordination and support among the military forces, the civilian workforce, and industry workforces. APS seeks to align and support with the DOD on deploying this technology and continuing the integration process.

APS's self-assessment is that there is low-to-medium technical, business and cost risk associated with this integration progress. The company headquartered in Cary, NC has a 15-year history of research and technology development with many completed projects with the DOD (see Section 2.1.2 for examples). The company has the financial, facility and personnel resources for manufacturing, distributing, and supporting the product for use with the DOD at our current forecasted demand. The company also has resources that will allow for scaling up the production of the system as demand increases. While the company does not rule out a partnership with a prime contractor, currently there is no need to partner with another company or subcontract the manufacturing work.

There is awareness of the Plasma*Blast*® system throughout the Navy, Army, Air Force and Coast Guard. To expand knowledge and present information to maintainers and sustainers, APS has conducted demonstrations at all four public Navy Shipyards in the last two years. APS gained recognition from the award of CTMA Maintenance Technology of the Year in 2019 as well as being selected as finalist in the Maintenance Innovation Challenge. Additionally, APS is a participating member of National Shipbuilding Research Program (NSRP) Coating and Paint Panel. Going forward, the Company's continued relationship with CTMA will provide additional opportunities to meet with maintainers and sustainers throughout the Navy. As COVID-19 restrictions ease, APS intends to restart regular on-site meetings and demonstrations.

1.3 Invention Disclosure

Invention Disclosure Report(s):

DD882 Sent to NCMS ☐
No Inventions (Negative Report) ☒

1.4 Project Partners

- U.S. Navy – Norfolk Naval Shipyard (NNSY)
- Atmospheric Plasma Solutions, Inc. (APS)
- National Center for Manufacturing Sciences (NCMS)

Member areas of NNSY that participated were:

- CTDC
- Code 970
- Industrial Hygiene
- Shop 64
- Code 265
- Code 983

2. Introduction

2.1 Background

2.1.1 Motivation for this Project

APS has developed an air-APCR technology that has repeatedly proven to be effective at removing organic coatings commonly found in shipyard environments. This technology has been packaged and configured as a man-portable, single-beam, air and power input-only tool, the Plasma*Blast*® 7000-M. (See Appendix A and Attachment 1). This tool has been demonstrated at multiple DOD locations and industry conferences, which led to an invitation to participate in the 2019 CTMA Technology Competition, which APS won in May of 2019. The award included $50,000 in funding to participate in a one-year project. This report describes the awarded project.

As APS and CTMA leaders considered which project to fund, partnering with NNSY was an obvious strong choice. Members of NNSY had seen demonstrations of the air-APCR technology and were interested in identifying real-world use-cases for the technology and comparing the performance of Plasma*Blast*® 7000 to incumbent tools and techniques. Secondarily, NNSY is located within 200-miles of APS's office in Cary, NC; this proximity would reduce the cost of travel and allow for more interaction between APS and NNSY during the project.

2.1.2 Relevant Previous Projects

While APS has not previously performed any CTMA projects, APS has and continues to conduct research and development projects to advance its technology and to understand the use of APCR in industrial applications. As it relates to the ultimate objective of this project – to appropriately integrate Plasma*Blast*® into Navy shipyard sustainment operations – the results of four recent projects provide valuable background information. These projects were:

1. **GDEB Study:** 2018 General Dynamics Electric Boat (GDEB) study under the NSRP to investigate the capability of APCR for coating removal in shipyard construction applications.

2. **CTL-NSWCCD Study:** 2018 Corrosion Testing Laboratory Inc. (CTL) in cooperation with the Naval Surface Warfare Center Carderock Division (NSWCCD) study (jointly abbreviated CTL-NSWCCD) to evaluate the impact of APCR on weld material, weld heat affected zones, and base substrate materials.

3. **BSI Study:** 2018-2019 BSI EHS Services and Solutions study to conduct environmental health and safety tests to evaluate the levels of noise, dust, and select chemicals emitted by a Plasma*Blast*® 7000 system.

4. **FBW-EAG Study:** 2019 project between APS, Fairlead Boat Works (FBW), and EAG Laboratories (EAG), authorized by GENEDGE, on behalf of NAVSEA, under contract to PEO Aircraft Carriers, to perform a comparative analysis between APCR, grit-blasting, needle-gunning, and rotary wire-brushing.

A summary of these studies is presented in Appendix B and more information about each of these studies can be made available upon request to APS.

In summary, these projects found that APS's Plasma*Blast*® 7000 is: (a) effective at removing organic coatings from a variety of abrasive blasted steels, (b) less detrimental to the surface from a metallurgical impact perspective than needle-gunning and rotary wire-brushing, and (c) safe for the operator with proper ventilation and PPE.

2.1.3 Why was the Project Necessary?

While the previous projects have indicated efficacy and acceptable substrate impact, they have done so in controlled studies on cut-out coupons, often with APCR-treatment performed by an APS employee. These prior studies did not identify the comparative operational benefits that single-beam air-APCR can provide in realistic shipyard settings by shipyard personnel. Moreover, while the prior studies demonstrate that Plasma*Blast*® 7000 produces quality coating removal outcomes on shipyard applications, they do not inform us about the operational (e.g., time saving) benefits that the Plasma*Blast*® 7000 can deliver within the shipyard environment. Additionally, the specific applications (or use-cases or jobs) where Plasma*Blast*® 7000 can outperform incumbent methods needed to be identified and, when possible, characterized.

2.2 Purpose

The general purpose of this project was to advance single-beam air-APCR's implementation (as represented by the Plasma*Blast*® 7000-M product) within the Navy's maintenance and sustainment operations. This purpose was pursued through three objectives:

- The project's first objective was to identify and evaluate potential use-cases where single-beam air-APCR (also referred to as just APCR within this report) is likely to enhance the operational performance of NNSY personnel. The evaluation was to be quantitative when possible, and qualitative otherwise.
- The second objective was to identify any barriers to implementation and propose plans to address these barriers.
- The third objective was to identify any changes or enhancements to the tool that would further benefit the shipyard and/or extend the application of the technology to additional use-cases.

Additionally, as a means to an end, but a valuable means nonetheless, NNSY personnel were certified on the Plasma*Blast*® 7000-M product and had the opportunity to work with and use the product during the duration of the project.

2.3 Scope

2.3.1 Project Approach

The philosophical foundation of this project is that real-world benefits are only to be achieved by the users who will be using a given tool. In other words, any analysis and calculations resulting from laboratory testing or in-field testing by highly experienced APS personnel is likely to over-estimate the expected benefit of the tool when used by more general shipyard mechanics. Therefore, the approach to this project was framed around actual NNSY-personnel performing all coating removal tasks with the Plasma*Blast*® product. To this end, APS provided training to NNSY personnel and allowed them time to gain some experience using the tool. After this occurred, trained NNSY personnel conducted the timed coating removal tasks to evaluate the benefit of this technology to the shipyard.

As such, success on this project required consistent communication and collaboration among NNSY personnel, the APS project team, and other project stakeholders.

- The APS team loaned a Plasma*Blast*® 7000-M to NNSY for the duration of the project, provided training on said system, provided follow-up coaching to the trainees, authored and documented the test plan (formally described as the Sample Preparation, Treatment, and Evaluation Plan, or the "SPTEP"), and produced this final report.
- The NNSY team received training, setup demonstrations with other shops at NNSY, used the loaned Plasma*Blast*® 7000-M in and around the Preservation Shop, provided demonstrations of the technology to various groups (e.g., shops, innovation managers, and visitors to NNSY), identified potential use-cases, worked with APS to develop the SPTEP, and executed a modified version of the SPTEP.
- Other stakeholders provided feedback throughout the duration of the project, primarily through biweekly status meetings

The project was approached in five overlapping segments:

- Segment 1 – Demonstration and training, including follow-up training by APS to NNSY
- Segment 2 – Use-case identification by NNSY
- Segment 3 – SPTEP development by APS with NNSY input and confirmation
- Segment 4 – SPTEP execution by NNSY with APS observation
- Segment 5 – SPTEP results assembly, analysis, and final report preparation by APS

2.3.2 Targeted Outcome

The desired outcomes of the project were to:

1. Demonstrate Plasma*Blast*® 7000-M to multiple codes and >100 persons at NNSY.
2. Train and certify multiple NNSY persons as APS-certified Plasma*Blast*® 7000 operators.
3. Develop and execute the SPTEP (with modifications as required) to gather a time-study and other data on Plasma*Blast*® 7000 use-cases.
4. Evaluate, analyze, and present the results of the SPTEP (with modifications, if any).
5. Outline a Technology Transition Roadmap for single-beam air-APCR insertion into Navy shipyard operations.

2.3.3 Goals and Deliverables

The key project deliverables for APS on this project are listed below.[1]

1. Loan a Plasma*Blast*® 7000-M unit to NNSY for the duration of the project. Ensure that the proper electrical connections and air-fittings are available to be used at NNSY's facilities.

[1] It should be noted that the achievement of these deliverables required NNSY action. However, as NNSY is not a project "Participant" per the definition of "Participation" as defined in the Collaboration Agreement, NNSY deliverables are not listed herein.

2. Certify multiple NNSY personnel on the Plasma*Blast*® 7000-M product for handheld removal through classroom training, practical training, a written exam, and a practical test.

3. SPTEP document which includes the initial identification of use-cases that may be advantageous for shipyard operational efficiency.

4. SPTEP execution.

5. Final report.

3. Project Narrative

3.1 Introduction

As noted earlier in Section 2.3.1., this project was approached in five overlapping segments. The Project Narrative section chronologically describes the performance and key activities of this project while notating which segment(s) the described activity relates to.

In addition to the details provided in the remainder of this Project Narrative section, CTMA hosted biweekly conference calls between project stakeholders. Over time, at least fifteen different persons attended these status and coordination meetings.

3.2 Chronological Description of Key Activities

3.2.1 Project Kick-Off Meeting at NNSY (Segments 1 & 2)

On October 23, 2019, APS hosted a kick-off meeting for this project in the Preservation Shop at NNSY. In the meeting, the group discussed the project scope and the vision for where single-beam APCR technology could improve sustainment and maintenance operations at NNSY and other shipyards. Additionally, APS presented an overview of APCR technology and the Plasma*Blast*® 7000-M system. Facility and safety requirements were reviewed as well. Finally, contact information was shared.

3.2.2 Preparation for System Delivery to NNSY (Segment 1)

Leveraging the information exchanged during the kick-off meeting, APS and NNSY exchanged detailed power and air-fitting requirements to support successful and rapid installation at NNSY. Based on this information, APS built a custom, waterproof junction box. This junction box facilitated easy connection to available 440V power sources in the Preservation Shop area at NNSY. Additionally, the junction box was constructed to be able to power two Plasma*Blast*® 7000-M systems simultaneously.

During a CTMA-NNSY-APS project meeting on October 30, 2019, it was determined that NNSY would like to have at least three NNSY persons Plasma*Blast*® 7000-M certified, with the hope that one of these persons could also be certified to provide training to other NNSY personnel. In this same meeting, PPE and IH/EHS (Industrial Hygiene/Environmental Health and Safety) requirements were reviewed. NNSY posited that APS-specified minimum PPE (dry OSHA approved leather gloves, N95 mask, plastic safety glasses, and single hearing protection) would suffice, except that double hearing protection might be required. It was further noted that data samples would be taken during the November 6, 2019 demonstrations for IH and EHS purposes. After the data was analyzed, NNSY's assessment of safety requirements and other procedures would be adjusted as guided by the data.

3.2.3 Demonstration, Training, and System Delivery to NNSY (Segments 1 & 2)

APS visited NNSY on November 6-8, 2019, to conduct multiple demonstrations to NNSY personnel, deliver classroom and practical training on the Plasma*Blast*® 7000-M system to NNSY personnel, deliver a system for NNSY use during this project, begin ideation of use-cases, and collect feedback from trainees and demonstration observers.

Demonstrations

Over the course of the three-day site visit, APS conducted multiple APCR technology demonstrations with two Plasma*Blast*® 7000-M 3-phase 440-480 VAC systems. It is estimated that approximately fifty (50) different persons saw one or more of these demonstrations. APS demonstrated system setup, system maintenance, system tear down, coating removal on APS-supplied coupons, coating removal on NNSY-provided scrap pieces and small parts, and coating removal on the submarine mockups used for coating removal training. The focus of these demonstrations was to show observers what the Plasma*Blast*® 7000-M could accomplish (organic coating removal), the relative complexity (low) of setup and usage, and the portable nature of the system.

An industrial hygienist in the Hampton Roads Division of the Naval Medical Center Portsmouth attended demonstrations on November 6, 2019 to observe the process and determine the type of sampling that would later be conducted. APS shared the BSI Study[2] to support their planning.

Training

Training consisted of a two-hour lecture course, two hands-on training sessions, hands-on evaluation, and a written exam. As noted in Section 3.2.2, the goal was for three persons from NNSY to complete Plasma*Blast*® 7000-M training and to pass the certification exams to become Plasma*Blast*® 7000-M certified. Three persons were identified for this course; however, five additional persons attended some portion of the lecture.

In the afternoon of November 6, 2019, APS conducted the two-hour classroom portion of the training. The interactive lecture course presented potential users with background information on the science behind the technology, requirements to operate the system, how to appropriately use the system, how to maintain and troubleshoot the system, and safety considerations when operating the system. In total, six persons attended the entire lecture. Many good questions were raised by the trainees. Of greatest interest to APS was learning some of the shipyard-specific safety and process rules that operators will need to follow when using the Plasma*Blast*® 7000-M system. Most significantly was the need for Code 99 to connect the unit to power. The three trainees who planned to take the written exam were given a copy of the lecture slides to study in advance of the exam.

The hands-on portion of training took place over sections of two days, November 6-7, 2019. This portion of the training began with a short demonstration of removal and technique,[3] a review of setup and operating practices, and then time for each trainee to practice setting up the system and performing removal.[4] Practice removal was performed on:

- Flat steel coupons coated with Sherwin Williams Fast-Clad® ER Epoxy
- Lap-welded steel coupons coated with MIL-DTL-24441 epoxy primer

[2] See Section 2.1.2 and Appendix B.
[3] During the demonstrations to a large audience the focus was on “what” can the tool do. In the training demonstration, the focus was on “how” to use the tool.
[4] Two Plasma*Blast*® 7000-M systems were used to allow each trainee more time with the tool in-hand.

- Steel coupons with a welded Pad Eye lifting fixture coated with Sherwin Williams Fast-Clad® ER Epoxy

Throughout their practice sessions, trainees received feedback and guidance on their technique and performance from APS instructors.

On the afternoon of November 7, 2019, the three trainees were evaluated based on their removal performance – looking at speed of removal, cleanliness of removal, and if they tended to overtreat the substrate or misuse the tool – and given a simple pass or fail. All three trainees passed the practical exam.

On November 8, 2019, the trainees were given a written test comprising 50 questions regarding the basics of Plasma*Blast*® 7000-M operation, maintenance, and safety. Participants were given a passing or failing grade, and the test was then reviewed with the participants. All trainees failed the written exam. The exam was not specific to NNSY safety and process guidelines, so some of the exam questions were inappropriate for use by NNSY personnel. It was agreed that APS would revise the exam and administer it on a follow-up visit. [5]

System Delivery

Per the NCMS project, APS loaned a Plasma*Blast*® 7000-M system to NNSY for the duration of this project. The system was to be used by NNSY persons for practice, use-case identification, use-case evaluation, and to provide demonstrations to other Navy persons with or without APS persons present. The specific items delivered were:

- Plasma*Blast*® 7000-M Plasma Power Supply 440-480VAC (MN: PB7000-M-48-PS, SN: APSPB7K00025)
- Plasma*Blast*® 7000-M Ergonomic Plasma Pen for handheld use (MN: PB7000-PP-HH) consisting of the plasma pen, grounding cable with clamp, power cord with junction box, SMC pressure regulator
- Plasma*Blast*® 7000 service manual
- Replacement Plasma Nozzle kit, 5 pack with anti-seize lubricant (MN: PB7000-NZ-HH-ST-05
- Protective eyewear (1)
- Hearing protection earplugs
- Pelican™ 1660 transportation case

All items other than the junction box were packaged in the Pelican case.

Initial Use-Case Ideation and Other Feedback

Throughout the three-day visit, APS persons talked with dozens of NNSY persons about the technology, potential use-cases, possible enhancements to the product, and technology insertion. Here is a summary of the feedback.

[5] Two of the personnel were able to retake and pass the test; the third was unable to retake and never completed their certification process.

Potential Use-Cases

Trainees and demonstration viewers suggested multiple use-cases and possible users at NNSY. Potential use-cases included:

- Weld inspections
- “Pick-ups” identified during inspection after grit-blasting a tank
- Cleaning bolts
- Any location smaller than ~100 square inches where a needle-gun might be used

Possible users at NNSY included:

- Code 700 – Lifting and Handling
- Code 920 – Structural Group
- Code 930 – Mechanical Group
- Code 960 – Pipefitting Group
- Code 970 – Preservation Group

Suggested Product Enhancements

While the product was considered usable as-is, several ideas were mentioned for additional enhancements as noted in the list below:

- Some people suggested adding wheels, others disagreed
- Straps to support the ability to carry the unit on one’s back while going up or down stairs
- Smaller system configuration to fit into smaller-than-hatch openings such as between sections in tanks
- Nozzle clock to help the user know when to change the nozzle (in addition to a visual or performance change observation)
- Physical guide to help users with proper off-set and angling of the pen
- Method to bend the pen or the nozzle to get into smaller spaces

Technology Insertion Comments

Various NNSY personnel also commented on implementation matters; comments included:

- The Temporary Services Shop (Shop 99) or Code 990 may be required to be brought in to connect the system to power and/or compressed air sources.
- Hot-Work Determination for Plasma*Blast*®.[6] It is not believed that Plasma*Blast*® will be considered hot work in many scenarios. However, some NNSY persons indicated that while they did not think that the observed demonstrations were hot work, they did think that others will question whether it is or is not.

[6] Hot work definitions vary by jurisdiction and context. However, at NNSY, hot work includes work which produces heat above 400°F. Also, in the presence of flammables or flammable atmospheres, hot work includes other ignition sources such as spark or arc producing tools or equipment, static discharges, friction, impact, open flames or embers, and non-explosion proof lights, fixtures, motors, or equipment.

3.2.4 NNSY Independent Use of Plasma*Blast*® System (Segments 1 & 2)

Between November 9, 2019 and December 10, 2019, NNSY used the Plasma*Blast*® 7000-M system that was left in their possession. They practiced on scrap parts and conducted informal demonstrations to various NNSY persons and shops. In a project status meeting on November 20, 2019, NNSY reported that "shipyard supervisors who have used/seen the equipment love it and are brainstorming applications."

In the same November 20, 2019, meeting, it was confirmed that there were no additional PPE or safety recommendations at this time.

3.2.5 Additional Demonstrations & Follow-Up Training (Segments 1 – 3)

APS returned to NNSY on December 11, 2019 to conduct additional demonstrations for NNSY personnel, review the performance technique and efficacy of the November 2019 trainees, and administer a revised written exam for certification purposes. APS also worked with NNSY to begin to define the use-cases that would be included in the SPTEP.

Demonstrations

Several groups within NNSY were invited to visit the Preservation Shop area for a morning demonstration and to speak with the APS representatives. An NNSY member setup the Plasma*Blast*® equipment and served as a primary operator during the demonstration. APS operators also participated in hands-on demonstrations, while they spoke to attendees and answered questions about the technology and tool.

Attendees were excited to see and hear that the Plasma*Blast*® equipment could be used to remove organic coatings of any thickness and color and that consumables were limited to the nozzle (replaced every ~8 hours of plasma-on time) and the electrode (depends on usage, but typically replaced every ~100 hours of plasma-on time).

Follow-up Training and Written Exam

Two of the objectives within this visit were to: (1) provide feedback and coaching to the November 6-8, 2019 trainees, as needed, and (2) to administer the revised written exam to formally certify the trainees on the Plasma*Blast*® 7000-M. Unfortunately, due to trainee availability only a portion of these objectives were met. While it was apparent that experience had been gained by the NNSY personnel on the use of the tool, only one of the three was available enough at the time to pass the exam and complete the formal training.

Use-Case Ideation and Other Feedback

Based on feedback from using the system over the prior month, and insights from other demonstration attendees, additional comments were captured to add to the list of use-cases, possible product enhancements, and technology insertion matters.

<u>Additional Possible Use-Cases from Project Stakeholders</u>

In addition to the use-cases previously identified, several additional use-cases were suggested by demonstration attendees including:

- Tight areas that cannot be easily reached with grit-blasting equipment, or locations in which cleaning up the waste from grit-blasting equipment is time consuming, difficult, or otherwise problematic. (An example was shared in which ~1,000 hours were spent on tight space touch-up work after blasting.)
- NAVFAC: Removing 6" wide strips of lead paint prior to plasma-cutting.
- NAVFAC: Maintenance on decommissioned vessels.
- Cleaning pumps, sprayers, and pressure washers. (Note: While the efficacy may be there, the business case on a per-man hour basis is probably not strong.)
- More than one person suggested usage within nuclear areas.
- In combination with cold spray applications as pretreatment for cleaning and surface preparation.

Suggested Product Enhancements

In addition to some of the suggestions mentioned during APS's prior visit, the following additional ideas for enhancements were made during this site visit:

- Wider-area treatment
- End effector that will allow for rotational cleaning on the inside of a pipe
- Ventilation and/or dust collection in confined spaces

Technology Insertion Comments

While largely excited about the efficacy and applicability of Plasma*Blast*® 7000-M to Navy operations, and NNSY operations in particular, several demonstration attendees expressed concern and identified implementation challenges. These included:

- Can it catch something on fire?
- Will it be considered hot work on/off a boat/ship? What will Code 106 (Occupational Safety, Health and Environment Office) determine?
- A few persons suggested that NNSY may require a half-face respirator instead of just an N95 mask.
- What are the Code 2350 requirements for use in a nuclear space?
- Can APCR-treated surfaces be considered SP10 or SP11?

SPTEP Planning

Escorted by NNSY personnel, the APS team found many use-cases aboard the Ex-McKee. At the end of the day, the group met to consider candidate use-cases for the SPTEP. The draft list was:

On the submarine mockups:

- Outer surface of sub mockup: missed grit-blasted spots
- Hooks and bolts with paint missed during blasting
- Insides of beams in tanks
- Vent tubes and pipes inside tank
- Missed paint spots on inside of tank

On the Ex-McKee:

- Bolts on small hatches
- Bolts on wall in internal room
- Welds up and under beams on walls near doors
- Bolts on ventilation ducts
- Interface between ventilation ducts
- Frame around large hatches/doors
- Strip of removal on walls between rooms
- Spot treatment areas/feathering for recoating

Given the value of evaluating the Plasma*Blast*® 7000-M on a floating vessel as opposed to a mock-up or sample, time was spent planning how to coordinate SPTEP execution onboard the Ex-McKee. Given the location and status of the Ex-McKee, additional shipyard approval and coordination would be required to include it in the SPTEP execution.

3.2.6 **SPTEP Drafts** (Segment 3)

In January and early February of 2020, APS drafted multiple versions of the SPTEP. The intent of the document was to be very precise about the tests to be performed and the measurements to be taken. The document outlined how APCR was to be applied and evaluated in a shipyard setting; identified use-case areas and desired samples to be used during testing; how these areas and samples should be prepared for testing; the procedures for conducting testing; what measurements were to be taken, how, by whom, and their analytical purpose; and outlined a schedule for completing these tests. Meticulous attention was given to describe each process step. Furthermore, templates were prepared for manual data capture of test equipment and sample treatment results. The plan was for APS to observe but not participate in treatment or measurement activities.

The scope of the testing included:

- Flat samples to provide a baseline comparison between APCR-treated, grit-blasted, and needle-gun treatments
- Grease-coated samples
- Salt contaminated samples (high chlorides)
- Miscellaneous test parts
- External submarine mockup spots, some with hard-to-reach locations
- Sub-sail mockup parts, some with complex geometries
- A collection of use-cases on the Ex-McKee

Two drafts were shared with the NCMS and NNSY teams for feedback (January 15, 2020 and February 5, 2020 versions).

3.2.7 **Additional Demonstration, Training, and SPTEP Planning** (Segments 1 & 3)

APS returned to NNSY on February 20, 2020 to conduct an additional demonstration, complete the certification process for an NNSY operator, and review the February 5, 2020 draft SPTEP.

Demonstrations and Feedback

Code 712 of NNSY was invited to visit the Preservation Shop area for a noon-time demonstration and to speak with the APS representatives. The demonstration was well attended and several use-cases for small area removal were suggested by attendees. (These use-cases were described in general terms and were similar to use-cases already documented previously in this report.) The most common sentiment from the demonstration attendees was that with Plasma*Blast*® coating removal would still be hard work, but the job would be able to be performed in a way that was less impactful on the mechanics while improving sustainment for the Navy

NNSY Operator Plasma*Blast*® 7000-M Certification Finalized

In support of achieving the objective of certifying three NNSY persons on the Plasma*Blast*® 7000-M, and since the person identified to use the Plasma*Blast*® 7000-M during the execution of the SPTEP had not completed the training, it was imperative that APS conduct a final testing period. The NNSY member passed the test and achieved certification with the tool.

SPTEP Feedback and Planning

The on-site APS team and NNSY representatives met to review the February 5, 2020 draft of the SPTEP document. During the discussion, edits were identified, the daily plan for the three-day SPTEP execution was worked out, and NNSY preparation requirements were identified. Of note, it was clarified that NNSY would seek to provide all measurement equipment for the evaluation and took responsibility to coordinate the provisions of all test samples. APS would bring their own equipment to be used as a backup only.

3.2.8 SPTEP Finalization (Segment 3)

Based on feedback from the February 20, 2020 visit to NNSY, APS finalized the SPTEP and published it on March 6, 2020. A full copy of this report can be found as Attachment 2.

3.2.9 SPTEP Execution, Round 1 (Segment 4)

NOTE: Segment 4 of this project was scheduled to occur March 11-13, 2020, the same week that significant shutdowns due to COVID-19 occurred in Virginia and North Carolina. While a significant portion of the SPTEP was completed during this time, not all aspects were able to be completed. A second SPTEP Execution event occurred in August 2020.

Sample Preparation

In advance of APS's March 11-13, 2020 visit to NNSY, Code 970, with support from the Paint Shop and Shop 64, prepared samples for treatment. The only treatment targets that did not require preparation were the submarine mockups and the areas on the Ex-McKee. Select pictures of the prepared samples can be seen in Attachment 3.

SPTEP Executed Testing, March 11-13, 2020

From March 11-13, APS worked with NNSY operators to execute the testing outlined within the SPTEP. The following tests were completed:

- Flat plate coating removal comparison of needle-gun and plasma
- Complex geometry coating removal comparison of needle-gun and plasma

- Sub hull mockup coating removal with plasma
- Salt treatments with plasma
- Grease treatments with plasma

The results of these tests are discussed below, with the full data found in Appendix C. Temperature readings were taken at intervals throughout each plasma treatment. Images were taken by NNSY throughout the testing. Unfortunately, all testing planned onboard the Ex-McKee was cancelled due to time limitations, authorization difficulties, and concerns about lead-based paints onboard the vessel. Finally, the outlined adhesion testing was started, with NNSY recoating the samples after either needle-gun or plasma treatment. However, it was decided that more precise results would be achieved by allowing APS to return to their Cary, NC location with the samples and use their adhesion testing equipment.

3.2.10 **Data Analysis** (Segments 4 & 5)

After returning to NC, the APS team performed adhesion testing and began analyzing the collected data. Additionally, formation of the final report was begun. It was made clear as the data was tabulated that several critical tests remained unfinished from the initial visit. The images received from NNSY of the initial visit further supported the desire from both parties for APS to return to NNSY and capture more data with the tool. For this second visit, it was decided to focus most on gathering comparative data between treatments of needle-gun and the Plasma*Blast*®. In addition to the quantitative comparison of these techniques, a goal was set to capture more data on APCR tasks on unique shipboard geometries. Finally, it was determined that neither of the previously Plasma*Blast*® certified NNSY operators would be available, so APS agreed to conduct an additional training class.

3.2.11 **Additional Training and SPTEP Execution, August 25-27, 2020** (Segments 1 & 4)

Training

An additional round of training was conducted during APS's return visit to NNSY for follow-up testing on August 25, 2020; four users from NNSY were successfully trained and evaluated, and one was selected to perform the APCR treatments in the follow-up testing.

SPTEP Round 2 Execution

To complete the series of testing that was started during the March visit, APS worked with NNSY in-person again from August 25-27, 2020. During this time period, data on the effects of both plasma and needle-gun treatments on substrate surface profile, additional complex geometry coating removal data, and further temperature data during treatments were all collected and evaluated. These results are summarized below and found in detail within Appendix C.

3.2.12 **Final Analysis and Final Report Write-Up** (Segment 5)

Data analysis and writing of the final report began after the initial March 11-13, 2020 testing session, and concluded September 2022. Delays were seen during data communications between NNSY and APS, as well as due to general delays during the pandemic. The project decreased in priority for a large portion of this time period. During Spring 2022, APS and CTMA picked the report back up and drove it to completion as of September 2022.

3.3 Summary of Completed Milestones

During this project, two on-site visits from APS to NNSY allowed completion of the following milestones:

- Training of 6 NNSY staff to become certified Plasma*Blast*® users
- Demonstration of Plasma*Blast*® to various Codes (groups) across NNSY
- Evaluation of Plasma*Blast*® coating removal efficacy in direct comparison to needle-gun
- Evaluation of Plasma*Blast*® for surface preparation use-cases specific to Navy Shipyards

4. Results and Analysis

Throughout this project, the Plasma*Blast*® was tested as a tool for coating removal, for surface preparation, and for adhesion promotion. Compared to the current standard method within the Navy for power tool surface preparation, the needle-gun, atmospheric plasma displayed increasing coating removal efficiency as the application increased in complexity, while boasting additional benefits that are not found with the use of other power tools.

4.1 Atmospheric Plasma for Coating Removal

4.1.1 Flat Plate Removal Rate as Compared to Needle-Gun

With removal rate (ft^2/hr) being the metric most widely used to compare efficiencies of coating removal tools, the baseline for both APCR and needle-gun were evaluated via timed removal of a section of 12” x 12” x 0.375” flat steel plates. These plates, prepared ahead of the testing by NNSY, were coated with Fast Clad ER Epoxy (grey or light blue) applied using roller with a 20-30 dry-film thickness (DFT) goal. These samples were also used for the results mentioned in Sections 4.1.3, 4.1.4, and 4.2.1 below. For both tools, the complete coating removal of a 5” x 5”, 6” x 6”, or 5” x 11” section was timed and recorded. Figure 1 displays an example result from each of the two tools.

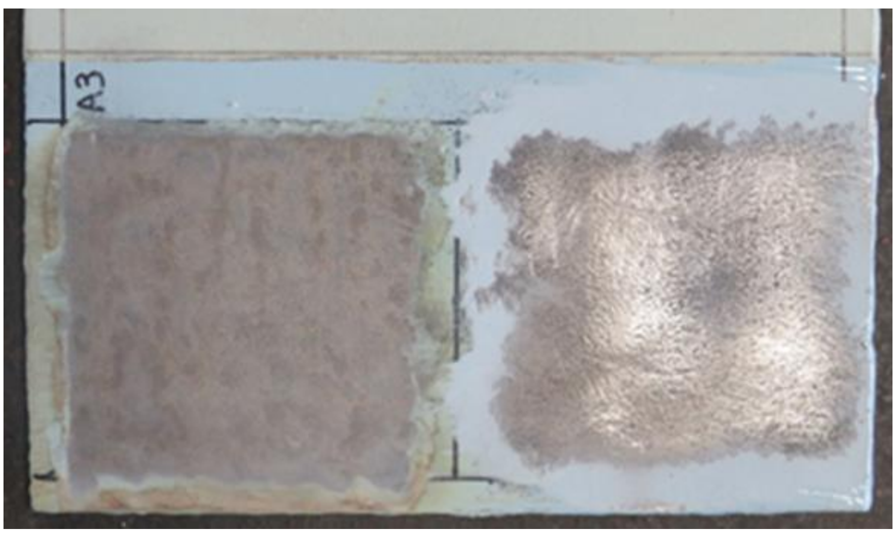


Figure 1. Resulting Surface from Treatment via APCR (left) and Needle-Gun (right)

For the needle-gun process, half of the samples were removed solely with the needle-gun, and the second half of the data included a secondary grinding step, as would be necessary prior to recoating the surface. Table 1 displays the average area and average volume removal rate comparison between the two tools, with the needle-gun data including both mentioned procedures as a single set. Appendix C contains the entire data sampling that these data points were averaged from.

Table 1. Flat Plate Removal Rate Comparison of APCR and Needle-Gun

Removal Method	Avg Area Removal Rate (ft^2/hr)	% Area Rate Improvement Compared to Needle Gun	Avg Volume Removal Rate ($ft^2 \cdot mils/hr$)	% Volume Rate Improvement Compared to Needle Gun
Needle Gun	1.66	+/- 0%	42.60	+/- 0%
APCR	2.52	51.81%	65.10	52.82%

As seen above, the APCR process on flat steel plates was measured to have both an average area removal rate and average volume removal rate of just over 50% higher than the results of the needle-gun. This tool efficiency is found with operators that were trained within two days and had minimal hands-on experience with the Plasma*Blast*® system. Figure 2, below, compares the area removal rate of each sample to its measured average coating thickness. From the graph, APCR is seen to remove 18.5 mils of protective coating just as effectively as 36.0 mils. Although the trends are estimated to be similar across other organic coatings, these removal rates are specific to the tested substrate and coating combination, with the coating chemistry playing a major role in APCR efficiency.

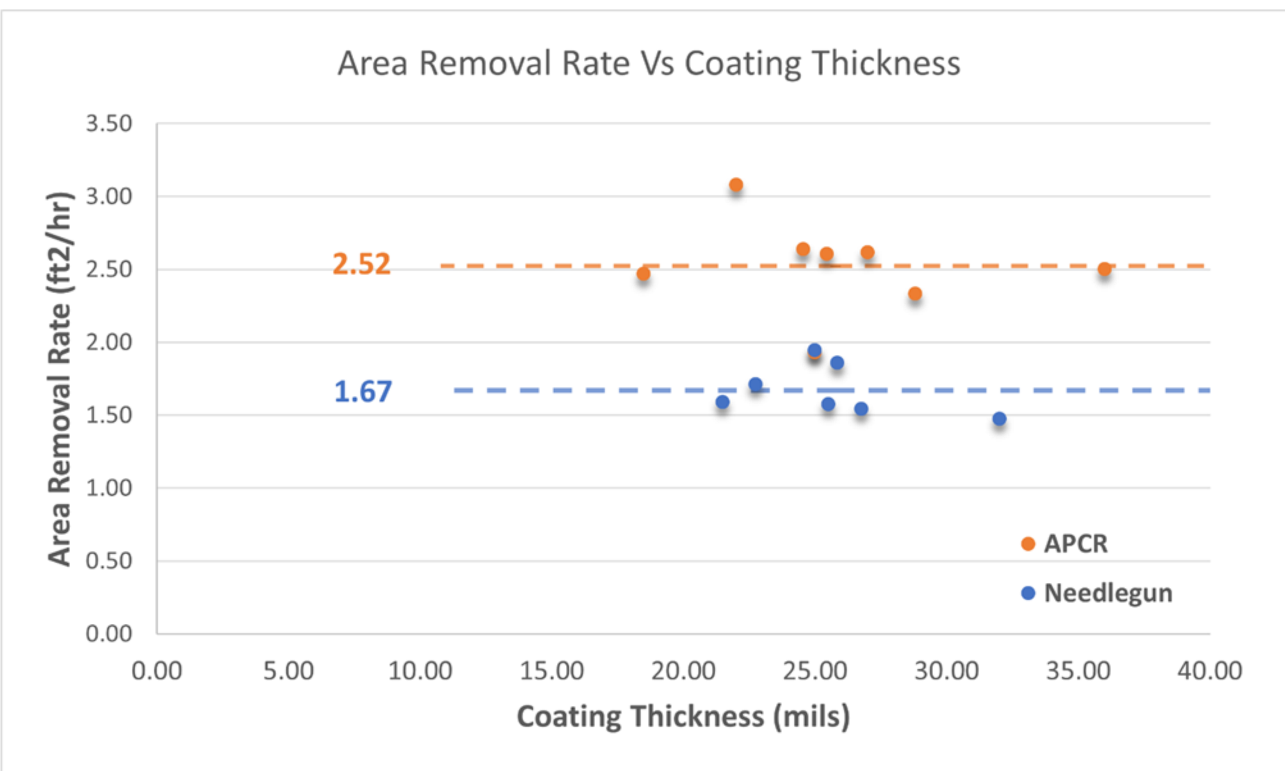


Figure 2. Coating Thickness and Area Removal Rate for APCR and Needle-Gun

4.1.2 Complex Geometry Removal Rate as Compared to Needle-Gun

Moving beyond flat samples, removal rate was measured for both APCR and needle-gun on two sets of surfaces with protruding and complex geometries, located on a section of submarine sail within the Preservation Shop in NNSY. Each set had a combination of Fast Clad-coated nuts and bolts to treat; however, one set had a thin coating of 3-5 mils DFT, while the second set had a thick coating over 50 mils DFT. Table 2 displays the selected area dimensions and geometries, as well as the measured removal time.

Table 2. Coating Removal of Complex Geometries via APCR and Needle-Gun

Removal Method	Treatment Dimensions (in)	Included Geometry	Avg. Coating Thickness (mils)	Total Treatment Time (mm:ss)	Complete Removal (Y/N)
Needle Gun	3”×4.5”	2 Nuts and Bolts	3-5	7:57	N
APCR	3”×4.5”	2 Nuts and Bolts	3-5	4:15	Y
Needle Gun	2” Diameter	1 Nut and Bolt	>50	14:24	N
APCR	2” Diameter	1 Nut and Bolt	>50	3:41	Y

Comparing the treatment times for each removal technique, APCR achieved complete removal 87% faster than needle-gun while treating the thinly coated section and a significant 291% faster while treating the section with thick coating. Figure 3 combines these complex geometry trials with the flat plate results of the last section to compare removal rates for both techniques.

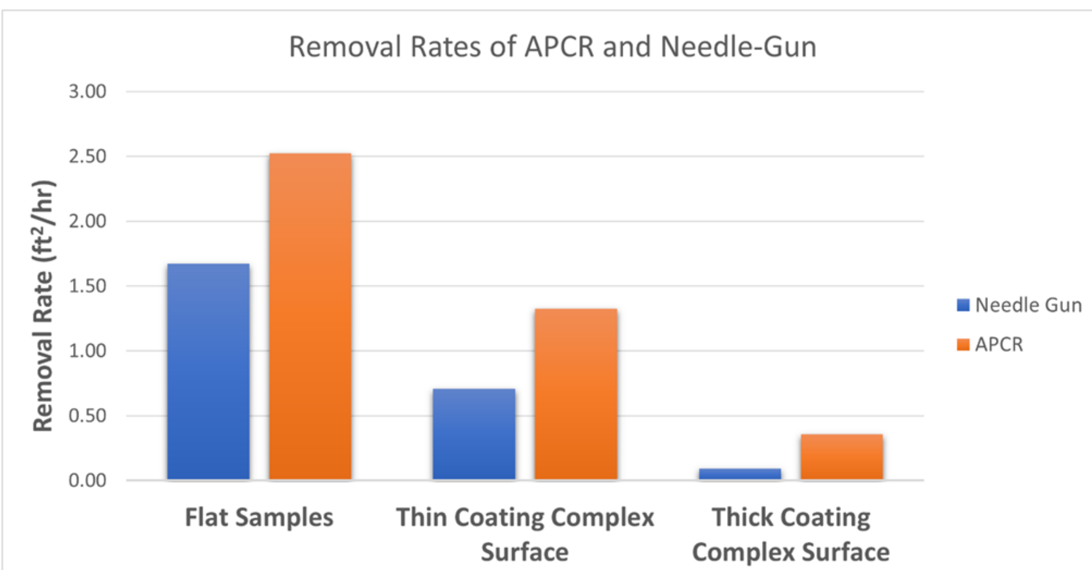


Figure 3. Removal Rates of APCR and Needle-Gun

As the removal scenario increases in difficulty, APCR increases in efficiency compared to the currently used method. Notably, the needle-gun was not able to achieve full removal directly around the complex geometries of the nuts and bolts. APCR was able to achieve results similar to that of the flat plate even along and around the bolts, allowing for less effort spent on surface preparation directly prior to any recoat procedure.

4.1.3 Treatment Effect on Substrate Surface Profile as Compared to Needle-Gun

Using the same samples as mentioned in Section 4.1, surface profile measurements were taken prior to coating and after removal via either APCR or needle-gun. Surface profile measurements were taken by NNSY personnel using either replica tape or a digital profilometer. Table 3 displays the profile averages for before and after each treatment type. Appendix C includes the data from each sample that is averaged below. Because the samples varied among the sets, the difference between before and after is used as the comparative value.

Table 3. Surface Profiles Before and After Either APCR or Needle-Gun

Treatment Type	Average Surface Profile Before Treat (mils)	Average Surface Profile After Treat (mils)	Average Difference (mils)
Needle-Gun	3.25	2.62	-0.63
APCR	3.09	3.14	0.04

APCR is found to have little effect on the surface profile, with the slight measured increase likely to be within the test method's margin of error, while the needle-gun creates a significant reduction in profile as it removes coating. The rough surface profile on steel surfaces, almost always originally created through abrasive blasting, has a significant impact on the performance of any applied coating. A deeper profile increases surface area and allows for more anchor points between the coating and surface, increasing both adhesion strength and corrosion resistance. Using APCR, the original surface profile is kept, reducing the risk of decreased part life or the need for additional profiling procedures.

4.1.4 Treatment Effect on Substrate Temperature

Temperature readings were taken incrementally during and after completion of all plasma treatments and several needle-gun trials. The entire temperature data set, including heating and cooling graphs for many samples, can be found in Appendix C. Needle-gun use had little effect on the substrate temperature, with the max substrate temperature being 76.0°F. Figure 4 displays the maximum temperature reached during each APCR treatment with respect to treatment time.

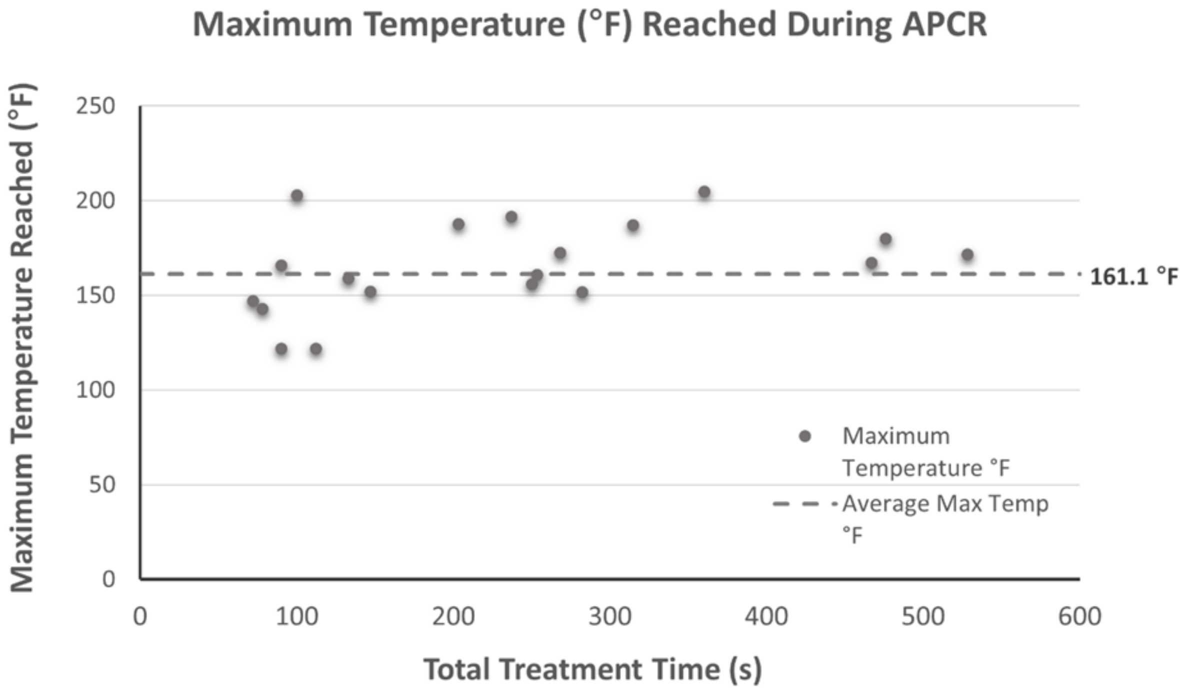


Figure 4. Max Temperatures Reached During APCR Treatment

As seen in the graph, the averaged maximum temperature reached during APCR on the steel samples was 161.1°F. Several samples' temperature data were excluded from the above graph, as they were deemed to have conditions outside of average coating removal application. These excluded data points were from several samples that were both of smaller dimensions and thermally isolated from their surroundings. Seen in Appendix C, a bolt and washer sample was able to reach 383°F during treatment; use of APCR in these types of situations would need to be performed with increased care to avoid excess energy being transferred into the substrate. With a maximum temperature around 160°F for general bulk coating removal, however, APCR is not in danger of damaging the properties of most steel substrates. Also, the recorded treatment times ranged from around 100 seconds to over 500 seconds with very little trend in increasing maximum temperature as time increased. This reinforces the tool's ease-of-use, allowing users a margin of error regarding efficiency without endangering the part, given the piece is not thermally isolated.

4.1.5 Complex Geometry Removal Rate Testing on Mockup Submarine Hull

As a final coating removal evaluation, removal rates were measured as APCR was applied to numerous sections of a mockup submarine hull. These trials included varying coating thickness and complex surfaces as would be found during real use. The complete set of data as well as geometry and area dimensions can be found in Appendix C. Figure 5 shows application of APCR on one of the chosen sections.

Figure 5. Application of APCR on Complex Geometry of Disused Submarine Section

All segments, the largest being 3” x 3”, were completely removed via plasma in 3.5 minutes or less. As seen in Section 4.1.2, as surface geometry increased in complexity, treatment time increased as well. However, unlike how the needle-gun was unable to achieve full removal on bolts as mentioned above, there were no sections that disallowed APCR to achieve complete coating removal across the area.

4.2 Atmospheric Plasma for Surface Preparation and Cleaning

While coating removal was the main application focus for the Plasma*Blast*®, the effects of plasma treatment on coating adhesion as well as surface cleanliness, in the form of oil and salt prevalence, were also investigated. Although these preliminary tests would require further insight to prove specific application feasibility, atmospheric plasma was found to have no negative effect on recoat adhesion, significantly decrease the presence of surface salts, and showed potential in the removal of surface grease.

4.2.1 Post-Treatment Coating Adhesion as Compared to Grit-Blasted

Although plasma treatment is used to remove existing coating, the substrate underneath is rarely left bare for very long after treatment. Therefore, it is important to understand if the coating removal process has any detrimental effects on the adhesion strength of a subsequently applied coating. After the coating removal mentioned in Section 4.1.1, those samples were repainted with Fast-Clad ER Epoxy within the day. For comparison, similar samples that were prepared only via grit-blasting were coated in the same manner. Following ASTM D4541, dolly-pulls were done two months later to test adhesion strength. Table 4 displays the averaged results of the adhesion testing.

Table 4. Comparison of Coating Adhesion Strength Post-APCR or Grit-Blast

Sample ID	Removal Method	Number of Pull Tests	Avg. Coating Thickness (mils)	Avg. Pull Break Strength (PSI)	Number of Coating Adhesion Failures
1-G-1	APCR	6	19.03	2136	0
1-G-2	APCR	6	26.49	1933	0
1-G-5	Abrasive	5*	27.65	1905	0
1-G-6	Abrasive	6	24.06	1924	0

From the table, it is seen that the APCR-treated samples had a slightly higher average adhesion strength of 2034.5 psi, compared to the 1914.5 psi from the grit-blasted samples. However, none of the tests broke at the adhesive interface between the substrate and the coating; they all broke cohesively within the coating layer. One of the tests in the first set on the grit-blasted sample broke entirely at the interface of the dolly and adhesive; that test was removed from the average. As all failures were cohesive, it can only be concluded that APCR had no significant negative effects on the adhesion of the new Fast Clad layer. Additionally, adhesion strength is subject to both the substrate and coating material properties, therefore further testing would be needed for other material combinations. In studies separate from this, however, it has been demonstrated that plasma treatment can enhance adhesion strength by increasing surface energy and promoting chemical adhesion.

4.2.2 Treatment Effect on Surface Oils

Related to adhesion strength, oil and grease on a substrate can significantly decrease the effectiveness of a protective coating. Typically, surfaces are cleaned using solvent or degreaser before surface preparation and before any coating procedure. The effects of plasma on surface greases were tested, with the ability to remove a solvent cleaning step as a possible prospect. Two greases commonly used in the shipyard were applied to flat and complex surfaces and removed using the PB7000-M. The results were primarily evaluated visually.

Various amounts of grease were applied, from excessive to thin layers. Because there was no measured metric, the results were not definitive; however, at the end of each plasma treatment, the surface appeared visually clean. For larger buildups of grease, the system displaced the grease before vaporizing it, due to the heated, pressurized air from the nozzle. Plasma did interact with and likely vaporize the thin layer left behind by the air. This testing indicated the opportunity for application of atmospheric plasma for surface cleaning but would require more quantitative results to verify.

4.2.3 Treatment Effect on Surface Salts

Considered more impactful than oils, salts on a surface can severely limit the lifetime of a newly applied coating and negate its beneficial effects on corrosion resistance. Prior to testing plasma treatment, samples were selected and exposed to a marine environment for 5-15 days to allow for salt contamination. The effect of plasma on surface salts was quantified by testing for soluble salts in the form of the Bresle Patch Test, measuring conductivity. Along with plasma treatment, steel-wire brushes and DI water sprays were utilized; further testing information can be found in Appendix C. Table 5 displays results from the testing, with samples 3-1-A and 3-4-A having an additional treatment directly after measuring results from the first.

Table 5. Effect of Plasma Treatment on Conductivity Measurements

Sample ID	Treatment Number	Pre-Treatment Conductivity (µS/cm)	Post-Treatment Conductivity (µS/cm)	Reduction in Conductivity	Total Conductivity Reduction After Both Treatments	
3-1-A	1	95	37	61.05%		86.32%
	2	37	13	64.86%		
3-1-B-1	x	95	22	76.84%	x	x
3-3	x	130	54	58.46%	x	x
3-4-A	1	199	49	75.38%		93.47%
	2	49	13	73.47%		

Each plasma treatment resulted in a significant reduction in surface soluble salt concentrations, with the reduction from a single treatment reaching 76.84% and from two treatments reaching 93.47%. To better quantify this conductivity testing, goals were set at less than 70 µS/cm for atmospheric service and less than 30 µS/cm for immersion service, under the guidance of Navy standards. Seen in Figure 6 below, all tested samples were within atmospheric service levels after a single plasma treatment, with three of the four samples being within immersion service levels by the end of testing. As there are numerous different salts that can be detrimental to surface preparation, further testing on specific salt compounds would be needed to indicate range of applicability and specific efficacy. However, these results indicate that plasma treatment has a clear and significant impact on some soluble salts.

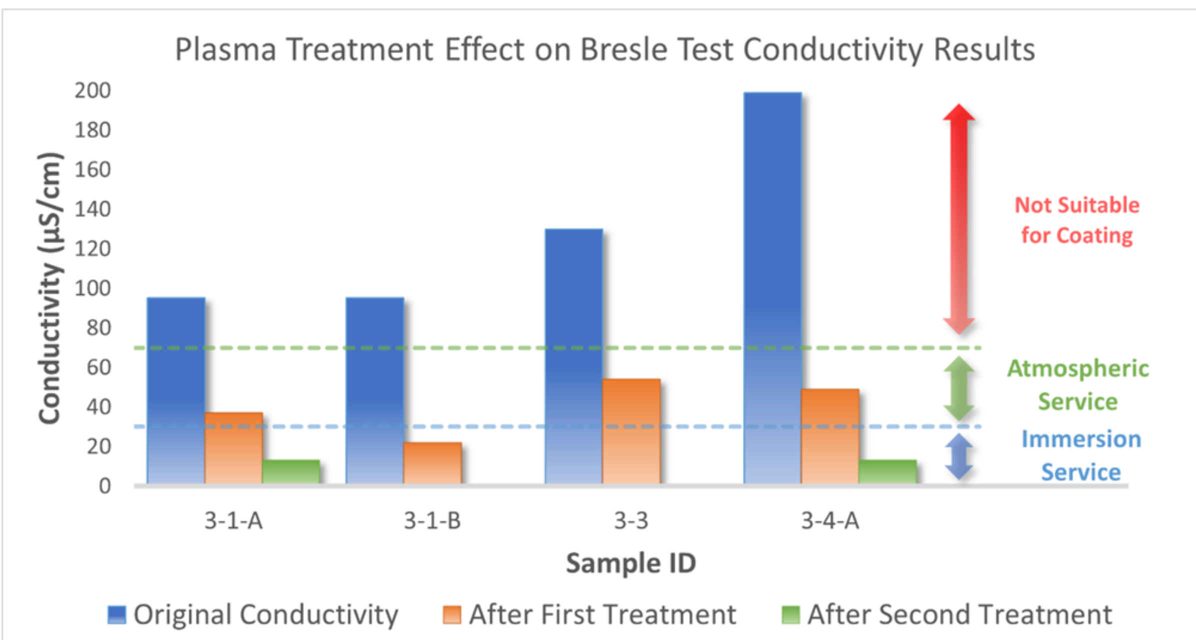


Figure 6. Plasma Treatment Effects on Conductivity Measurements

5. Conclusions

Over the course of several on-site visits, APS worked with NNSY to train their personnel on the operation of the Plasma*Blast*®. A variety of testing was then conducted to evaluate the effectiveness of atmospheric plasma regarding coating removal and surface cleaning in the hands of those newly trained users. Throughout the project, both APS and NNSY also gave demonstrations of the plasma technology and received feedback from operators experienced in currently applied surface preparation methods. Not only was the tool well-received and thought of by operators to significantly improve the quality of life of the user compared to power tools of similar purpose, but it also proved more effective at coating removal than the traditionally used needle-gun while also demonstrating additional benefits such as revealing an unaltered surface profile and reducing the amounts of both oils and salts on the work surface.

5.1 Training and Demonstration Feedback

During the APS on-site visits, six total NNSY personnel were trained on the use of the Plasma*Blast*® system. Not only were the NNSY operators then immediately able to transition and obtain the efficiency data discussed in this report, but also gave several demonstrations across NNSY without assistance from APS. Combined with the various demonstrations that APS gave during the two site visits, NNSY gained significant exposure to the technology, and feedback from numerous different sectors was taken in. Even without a direct comparison during the demonstrations, many of the observers mentioned a visible increase in efficiency compared to currently used power tools, such as the needle-gun or bristle-blaster. The majority of comments and enthusiasm, however, related to the tool's minimal impact on the health and safety of the user. The Plasma*Blast*®'s lack of vibrational impact and decreased noise compared to traditional power tools was mentioned many times as an invaluable benefit. Although improvement recommendations, further discussed in Section 8, were made by observers that would increase the versatility of the tool, there was agreement throughout the demonstrations that the Plasma*Blast*® in its current form would provide benefits over currently used tools for many coating removal applications.

5.2 Atmospheric Plasma for Coating Removal

As the main application in mind for the Plasma*Blast*® was coating removal, a series of tests were conducted to examine the tool's efficiency at the task and any effects on the work surface, with several of the trials including a direct comparison against needle-gun. There was a desire to ensure results were indicative of what would be achieved by personnel at the job site, so an emphasis was made to have the newly trained NNSY operators complete all plasma treatments, instead of an experienced user from APS. Comparatively, all needle-gun trials were done by an NNSY operator with moderate experience with that power tool. Regardless of any gaps in experience, coating removal of Fast Clad on steel was accomplished faster with plasma than when using a needle-gun, with a 51% speed increase on flat plates, an 87% speed increase on thin-coated complex geometries, and a significant 291% speed increase on thick-coated complex geometries. For additional trials, areas were chosen across a submarine mockup within the Preservation Shop of NNSY for timed APCR. Including some difficult-to-reach areas, each trial was completed in 3.5 minutes or less. During removal of both flat and complex geometries, plasma treatment was able to achieve full removal over the entire surface, including areas such as bolt threads, while the needle-gun left visible retained coating in similar spots and crevices. Depending on the application, any retained coating would require additional work and surface preparation, which would be negated by the initial use of atmospheric plasma.

Comparing surface profile before and after each flat plate coating removal trial, the profile of the needle-gun samples were significantly flattened after treatment, while the plasma sample profiles were unchanged. By ensuring no damage is done to the surface profile, maintenance work on a previously well-prepared substrate would require no additional steps to promote the adhesion of an applied coating. This, in many applications, would remove the necessity of an additional grit-blasting step prior to recoating, being especially time consuming for spot-repair maintenance demands.

Additionally, temperature measurements of the substrates were taken at regular intervals throughout the plasma treatment trials. Compared to the measured needle-gun maximum substrate temperature of 76.0°F, the averaged maximum substrate temperature during plasma treatment was notably higher at 161°F. Although in a few cases samples were able to reach higher temperatures, these were pieces of smaller dimensions that had no surrounding connection for thermal conduction. With the treatment times ranging from just over 70 seconds to over 500 seconds, there was little increase in maximum temperature as the time increases, indicating that the 161°F maximum is roughly accurate regardless of treatment time. While some applications may require a user to be mindful of minimizing excess energy transfer into the bare substrate, this temperature is not in danger of damaging most steel's substrate properties, allowing for more user freedom as long as the work surface is not thermally isolated.

5.3 Atmospheric Plasma for Surface Cleaning

As surface cleaning is closely related to coating removal, especially in maintenance and re-coat applications, testing was done to explore the effects of plasma treatment on recoat adhesion, surface oils, and surface salts. The plasma treated flat plates used in prior removal rate tests were subsequently coated with Fast Clad ER Epoxy. For comparison, newly grit-blasted samples were coated in the same manner. Allowing for sufficient cure time, adhesion strength was tested using dolly-pulls as outlined in ASTM D4541. The resulting averages were 2034.5 psi for the plasma treated set and 1914.5 psi for the grit-blasted set, eliminating a single test in the latter group due to adhesive failure. Notably, there were no adhesive failure modes, with each dolly-pull test aside from the one adhesive failure ending with a cohesive break within the coating layer. This testing indicates no negative effects on adhesion of the applied Fast Clad coating post-plasma treatment. Additionally, APS-led testing outside of this project has demonstrated that plasma treatment can enhance adhesion strength by increasing surface energy and promoting chemical adhesion.

Oils and salts on the surface of a substrate can greatly reduce the overall adhesion that an applied coating achieves at the interface, leading to early coating failures such as delamination or blistering. Because common coating removal methods such as needle-gun and grit-blasting are ineffective at removing or reducing both oils and surface salts, and sometimes even make the situation worse by penetrating the salts further into the substrate, added solvent or degreaser cleaning steps are necessary before and after these techniques to ensure proper coating performance. Through visual examination of grease removal results and solubility testing of soluble salt removal results, atmospheric plasma was found to have beneficial effects on both. Having tested two kinds of greases commonly used in the shipyard, plasma treatment displaced large amounts of grease from the work surface and seemed to vaporize any thin layer left behind. Using the Bresle Patch Test after plasma treatment on separate samples exposed to marine contamination, conductivity measurements showed a significant decrease in soluble salts present on the surfaces, with the reduction from a single treatment reaching 76.84% and from two treatments reaching 93.47%. While additional testing would need to be done to understand the effect of plasma treatment on specific oils, greases, and salts, these surface cleaning tests combined with APCR's ability to reveal a substrate's surface profile without damaging it would suggest that there are opportunities for plasma treatment to achieve all the necessary coating removal and surface preparation steps prior to recoating in an application such as spot repair. By doing so, multiple steps in current processes (solvent clean prior to coating removal, solvent clean after coating removal, grit-blasting to re-achieve proper surface profile, water spray to remove dust after profiling) would be removed.

6. Benefits

Not only is atmospheric plasma an effective means of organic coating removal, but the Plasma*Blast*® system offers additional advantages unique from the currently used small-scale surface preparation tools. For both flat and complex geometries regardless of coating thickness, Plasma*Blast*® users within two days of training were able to achieve cleaner surfaces at a faster pace than needle-gun users of moderate experience. APCR reveals the underlying surface profile without any flattening effect and demonstrated the potential to remove both grease and salt contamination from bare substrates. Additionally, the system operates with zero vibrational impact to the user as well as decreased noise compared to industrial needle-guns. These performance enhancements translate to significant economic and environmental health and safety benefits, allowing for assets to be maintained quicker at a higher quality while preserving and effectively employing the workforce.

6.1 Performance

As outlined in the previous sections, the Plasma*Blast*® system offers numerous performance benefits over traditionally used small-scale power tools. Compared to coating removal via needle-gun, APCR was shown to be more efficient while allowing for a cleaner resulting surface. These advantages were true when working on flat plates, but APCR was found to be even more dominant when working on complex geometries. With no reduction in surface profile and no negative effects on re-coat adhesion found from coating removal trials of Fast Clad on steel, atmospheric plasma treatment would require no additional surface profiling tools or steps as long as the pre-existing profile is adequate. Additionally, with promising results for the effects of plasma on both grease and soluble salt surface contamination, the Plasma*Blast*® shows potential to be the only tool necessary for the entire coating removal and surface preparation process.

With such positive results from the Plasma*Blast*® being achieved at the hands of newly trained operators with minimal prior exposure to APCR, the tool is shown to be user-friendly and easy to utilize. Within two days of training, users are able to achieve results that outperform those of a needle-gun. Only requiring air and electricity, the system allows for quick setup and reduces the additional clean-up consideration that comes with the use of a media such as grit or water. During use, there is no vibrational impact to the user, the noise level is lower than that of an industrial needle-gun, and the PPE requirement is minimal. Having only two consumable parts, both of which can be replaced in under five minutes with ease, there is little interruption during work. Weighing under 35 pounds with dimensions of 12” x 14” x 22”, the system allows for use within confined spaces and has a 20 ft cord attached to the pen allowing for further flexibility. Lastly, as APS is headquartered in the United States and all Plasma*Blast*® systems are being manufactured in the U.S, the U.S Navy will have access to quick response maintenance assistance and part shipment.

6.2 Health and Safety

Use of vibrational hand tools exposes workers to hand-arm vibrations (HAVs), which can cause short-term pain, numbness, and reduced motor function. Frequent use of these tools over multiple years can lead to permanent nerve and vascular damage in what is referred to as Vibration (or HAVs) Syndrome. This condition can eventually worsen to the point at which workers can no longer perform certain manual labor tasks due to pain, numbness, and loss of motor function and grip strength in their fingers, leading many to leave the workforce. Frequent use of needle-gun scalers has long been associated with the development of this condition. Since the Plasma*Blast*® imparts no noticeable vibration to the user while in operation, its adoption as a replacement for the needle-gun would eliminate this concern. While reducing the risk of chronic work-related injury, a lack of vibration also allows for higher short-term quality-of-life for the user while getting the job done and allows for work periods to be extended with no detriment to the worker. Having reduced noise levels compared to industrial needle-guns, as well as no associated spent media, adjacent work can typically be done with little concern of any nearby APCR. With the possibility of being the only step in the surface preparation process, there is a potential to eliminate certain addition steps, for example the use of solvent cleaning, and with that any related exposure risks for the operators.

6.3 Environmental

Unlike the waste waters or grit media that require proper containment and disposal after processes like water jetting or grit-blasting, as the Plasma*Blast*® system uses only electricity and air, APCR does not require any additional concern for waste stream management. Since the process actively vaporizes organic material within the coating into water vapor and carbon dioxide, the remaining dust is in smaller amounts compared to the results of traditional power tool coating removal. As the resulting waste is in the form of dust, proper removal of any hazardous materials (lead, chromium) is made significantly easier. These attributes allow for quick setup and breakdown of the system with minimal effect on the environment. Additionally, with reduced noise during use compared to industrial needle-guns, there will be reduced noise pollution levels. Finally, with the possibility of the Plasma*Blast*® removing the need for additional surface preparation steps such as solvent cleaning, any environmental effects these steps would have had are negated.

6.4 Economic

All mentioned performance benefits of the Plasma*Blast*® system lead directly to economic savings when compared to the use of traditional small-scale power tools such as the needle-gun. Increased efficiency allows for either shorter project timelines or fewer man-hours associated with an equal amount of accomplished work. With the ability to be the only step within the surface preparation process, the Plasma*Blast*® eliminates the need for additional tools, along with all the costs associated with them, including additional training, specialized operators, and specialized preparation and cleanup, to name a few. Because of the intensity of vibrational forces in effect when controlling a needle-gun, the user must take frequent breaks throughout the tool's use, with the CDC recommending that workers take a 10-minute break for every hour of work with a vibrational hand tool. As APCR imparts no noticeable vibrational force during use, workers are able to complete the job without these stops. This feature also reduces the costly number of workers' claims for compensation that are filed each year due to HAVs Syndrome. Without additional waste stream needs and by reducing cleanup to a small amount of dust (depending on the coating composition), savings are also found when comparing environmental considerations with other traditional tools. The Plasma*Blast*® as it is currently deployed is estimated to benefit any organic coating removal project with 50-60% reduction in labor times across full coating removal shifts, with increasing efficiency as the removal task increases in complexity, if APCR is adopted as a replacement for needle-gun treatment.

Translated specifically to the Navy and the associated shipyards, APCR facilitates seamless coating maintenance work by efficiently removing coating while reducing downtime and stoppages throughout the entire surface preparation process. This, in turn, allows for increased fleet readiness while simultaneously preserving and effectively employing the workforce.

7. Technology Transition into the Fleet

7.1 Technical Approval

7.1.1 NAVSEA Technical Warrant Holder Approvals

Technology readiness assessments —evaluations that determine a technology's maturity—have been used widely at the DOD since the 1990s. As stated in a January 2020 U.S Government Accountability Office report on technology assessment, "relatively few agencies have guides for assessing a technology's maturity and its readiness for integration into larger acquisition programs, and the federal government has not adopted a generally accepted approach for evaluating technology beyond using TRL measures." Given the status, APS has created their own path making use of the SBIR program, NSRP, and coordination with the CTMA Program.

Since 2006, APS has been on a path to advance the TRL level of the Plasma*Blast*® system and to produce testing data and analysis for review that allow the relevant Technical Warrant Holders (TWHs) to make an assessment of the system and then provide towards approval for use.

A report filed number 341:CW/941399 dated April 10, 2019 was delivered to Program Executive Officer Submarine. This was the Final Report for Evaluation of Plasma Beam Technology for Coating Removal. Completed under the award and direction of NSRP, the evaluation was done in coordination with GDEB. The report found that Plasma*Blast*® was capable of removing representative coatings found in shipyard applications. The metallurgical examination showed no recase, inclusions, or microstructural changes. General Dynamics transitioned the findings to an affordability initiative to develop business cases. See Appendix B for more details.

This information was presented and discussed with TWHs in June 2019. This meeting led to the scoping of the Phase II SBIR project. Of most importance to the TWH was Task 2 Axial Fatigue Testing, having key information needed by the TWHs.

The overarching purpose of this Phase II SBIR project was to produce a deliverable prototype APCR system that effectively removes organic coatings from metal substrates of interest to the Navy while meeting the safety standards and grounding systems required by the Navy. Additionally, the APCR system's impact on the substrate should be characterized to support the consideration of APCR for various Navy coating removal tasks.

Within the scope of the project, there were three technical objectives that were proposed and met over the period of performance. These objectives are as follows:

1. Further develop the existing ("Mk0") APCR system technology to add the following specific capabilities. The resultant system will be called the "Mk1" system.

   RESULT: Safety metrics have been identified and designs have been fabricated and tested per MIL standards. The Mk1 system is ready for testing by the Navy to determine what further refinements are required for a finalized Mk2 system.

2. Characterize the fatigue performance of HY-80 steel using ASTM E466 after coating A is removed using the APCR process.

RESULT: Fatigue testing revealed no discernable difference in fatigue performance when comparing APCR processed samples to uncoated, abrasive blasted samples.

3. Characterize the coating removal performance of the Mk1 APCR system compared to the Mk0 system on coated HY-80 samples.

   RESULT: The Mk1 system performed identically to the Mk0 system, indicating that the safety electronics did not interfere with the performance of the system.

Having satisfied the Phase II objectives, as of May 2022 the TWHs are drafting an "Initial" approve for use of Plasma*Blast*® in specified areas on surface ships, carriers, and submarines. APS is now beginning an Option period on the Phase II SBIR. This additional work and resulting data will fully characterize the usage of the system in highly sensitive areas. Once complete, there is high confidence for full approval and usage across the different Navy platforms.

7.1.2 Transition to Each Navy Public Shipyard, IMF and RMC

In discussions with the personnel at each of the public yards as well as staff at NAVSEA 04 and NAVSEA 05, we see the following steps needed to achieve. Upon receiving acquisition contracts, we will further clarify these actions:

- TWHs to provide approval for use of the Plasma*Blast*® system
- Navy to create Industrial Process Instructions for each yard
- APS to provide information required for a transition document package. This will include details on the system and its use will address:
  - IT
  - Security
  - Safety
- APS to provide information to support each yard in their assessment of EHS and Work Safety (see Section 8.1)
- Demo to yards and Code based on application needs
- Train at each location deploying systems
- APS to identify and log applications
  - By Platform
  - By Yard
  - By Code (welding, pipes, small parts, cranes, etc.)
- Support the process of sharing found applications within the user community

7.1.3 Transition to Other DOD Branches and Allied Nations

As mentioned throughout this report, the Plasma*Blast*® system has opportunities for insertion across the DOD and Allied Nations. Many branches will have similar if not identical use-cases i.e., coating removal for weld inspection. There will also be requirements that are individualized to the circumstances and platforms where the work will be done. APS has made contacts and done demonstrations for all the branches list below:

Marines

Identified use-cases in non-destructive testing (NDT) inspection and maintenance on heavy lift, ground vehicles, and support structure.

NAVAIR

At Cherry Point and Pax River demonstrations identified use-cases in NDT and small area coating removal. More qualification work is needed for certification on “fly-able” parts. See note on Air Force below.

Military Sealift Command

Many applications identical to Navy needs. A key focus area identified was increased repairs on amphibious platforms where paint adhesion is an issue from water exposure and salt spray.

Army

Anniston Army base has purchased two systems from APS for repair and maintenance of group vehicles. This program type of work could be replicated across the Army. Demonstrations have been conducted at Aberdeen Proving Grounds.

Air Force

APS has completed 3 SBIR projects with the Air Force. In 2021, work was done to evaluate the effectiveness of APCR on the F-16 platform. This testing was done in coordination with the University of Dayton Research Institute and the Air Force Research Laboratory.

Space Force

Discussions on NDT heavy life.

Allied Nations

In 2019, APS lent a Plasma*Blast*® system 7000-R to Australian Government Department of Defence. Information has been requested and provided to Ministry of Defence United Kingdom. In 2021, APS provided quotes to contractors working at Fincantierri shipyard in Jacksonville, Florida for work on submarines from an allied nation.

7.2 Transition to Commercial Entities

7.2.1 Navy Prime Contractor Private Shipyards

Through CTMA, the NSRP, and direct sales calls, APS has done demonstrations and presentations to many of the prime contractors. There is substantial interest in acquisition and deployment for both new construction and maintenance repair overhaul work. All of the yards have stated that they required TWH approval before they will move forward on deployment.

Newport News, Electric Boat – Groton, NASCO San Diego, and Fincantieri Marinette Marine have all had systems on-site for testing and evaluation.

7.2.2 Commercial Shipyards

Commercial shipyards both domestically and internally face many of the same challenges as the U.S. Navy public and private yards. APS intends to market the Plasma*Blast*® product as part of Phase 3 funding.

7.2.3 Other Commercial Industries

Beyond the marine applications, Plasma*Blast*® has broad market potential for both its effectiveness in surface cleaning (including coating removal) and adhesion promotion. Current commercial industry focus includes but is not limited to:

- Energy
- Infrastructure
- Transportation
- Aerospace

8. Recommendations

Overarching Recommendation: Integration of the as-is Plasma*Blast*® 7000-M product as an additional coating removal tool available to operators within NAVSEA will increase coating removal task productivity and will help reduce vibrational-injury risk. Moreover, the Plasma*Blast*® 7000-M is a means to increasing the readiness and sustainment of Navy assets. This tool has applicability across naval platforms and weapon systems. The Plasma system can be transitioned across the DOD.

8.1 Additional Studies

8.1.1 Related to Coating Removal

With the testing done in this project displaying the Plasma*Blast*® as a more efficient alternative to the needle-gun, it is important to note that the tool will not achieve the same results with every coating and substrate combination. Although the Plasma*Blast*® is expected to be advantageous for the vast majority of organic coating removal situations when compared to needle-gun, further studies should be done for application-specific verification. All treated samples for this project were Fast Clad on steel, which is an extremely common combination found with Navy applications; other commonly used coatings and substrates should be acknowledged and tested with the tool. Additionally, it is recommended to further understand the effects of atmospheric plasma treatment on the surface and bulk substrate properties. Although this project provided temperature data suggesting little to no effect on bulk steel substrates, there was concern that local surface damage may be occurring in some cases of tool use. A study would be recommended to confirm if any damage can be done to the surface under proper tool use, to what degree, and how to mitigate this risk. Finally, while the Plasma*Blast*® was shown to be a superior match to a power tool such as the needle-gun, the tool cannot currently output removal rates similar to large surface treatment methods such as abrasive blasting or water jetting. Considerable interest was shown by demonstration viewers in the tool's ability to upscale and possibly reach competitive large-scale removal rates. APS believes the technology and tool's design inherently allows for upscaling, but research and development will be needed before a large-scale APCR product is at a deployable state.

8.1.2 Related to Surface Preparation and Cleaning

Along with increased coating removal efficiency, the Plasma*Blast*® demonstrated benefits more general to surface preparation. Similar to the necessity of testing removal efficacy on any applicable coatings, it would also be important to test and verify the adhesion results found within this project with regards to any applicable coating. Furthermore, as APS has seen atmospheric plasma treatment notably increase adhesion strength in certain cases, a study involving more rigorous adhesion testing and use of alternative testing methods would be needed to see the extent of any adhesion promotion specific to Navy-used coatings. Using conductivity tests, atmospheric plasma was shown to decrease the concentration of soluble salts on the surface of a steel sample; however, before this benefit could be fully utilized, in-depth salt-specific testing is required. Some salts may not be reduced to the same extent as those tested in this project, which would be vital information for surface cleaning applications of this type. Additionally, the Plasma*Blast*® visibly removed grease contamination from the surface of a steel sample. Similar to the salt testing, further application-specific testing would be required to prove full efficacy. Also, as the grease testing within this project did not have a true metric connected to the results, further evaluation using a quantitative test method would be beneficial to see the extent of contamination removal.

8.2 Technology Developments

It was agreed among project participants and demonstration viewers that the Plasma*Blast*® would provide benefits to shipyards if deployed in its current form. However, throughout the testing, suggestions were made by NNSY operators, and the product still showed constraints in a few complex-geometry scenarios. These points are summarized in the list below:

- Smaller frame
- Smaller pen and/or bendable joints
- Curved or angled nozzle
- Ease-of-carry enhancements such as wheels or backpack straps
- Stand-off attachment
- Vacuum attachment
- Longer umbilical cord for pen
- Multi-beam

Notably, the system is just large enough to be restricted from a few of the tighter crawl spaces within a vessel, so it was recommended to either look into reducing frame size or increasing the cable length from system to pen end (allowing the operator to work further from the system). Additionally, the plasma pen was too long to allow for navigation around some of the tighter complex geometries. To ensure full surface preparation can be done, it was recommended to look into creation of smaller pens or bendable joints within the part. Additionally, further ease-of-use could be found through the development of various angled nozzles, allowing for the plasma to be effective at many pen-to-substrate angles that currently reduce removal rates significantly. Lastly, it was seen that optimal plasma application height from the substrate became more difficult to hold steady as treatment times lengthened. Suggestions were made to add a stand-off piece to the pen that would allow for a constant height to be achieved throughout treatment, with no need for precise monitoring from the user. These product recommendations would allow for further application of the beneficial Plasma*Blast*® system and have been acknowledged by APS.

Appendix A – Development of Atmospheric Plasma Coating Removal and Plasma*Blast*® Product Line

Brief Technology History: APS's APCR technology evolved from research in plasmas related to deposition, etching, and surface modification of materials at the Center for Advanced Manufacturing Processes and Materials at North Carolina State University. Over the past ~15 years, APS has developed APCR technology into a commercially viable process and product line.

How the Technology Works: The patented APCR process uses a low pressure (90-100 psi) compressed air source and electricity (208-240 volt or 440-480 volt) to produce a special form of atmospheric pressure air plasma. The process is highlighted by three steps:

1. A pulsed electric field is applied to the internal electrodes of the pen.
2. Air is introduced into the electrode region of the pen at high velocity.
3. Plasma generated in the electrode region is directed through a nozzle, which concentrates the plasma flow into a beam.

What it Does: This atmospheric air plasma is highly chemically activated and oxidizes any organic components in paints and other coating materials. The plasma beam can be passed across a coated surface (manually or robotically) to remove the coating layer-by-layer, allowing for full or selective removal, in addition to cleaning and surface preparation. Because the plasma can flow around surface features, it is well suited to treat both flat and more complex surfaces.

The APCR process converts a significant portion of the removed organic coating into water vapor and carbon dioxide, leaving behind a lower volume of solids of mostly inorganic pigments and fillers that can be safely collected with a suitable HEPA vacuum. APS APCR systems have been used to demonstrate the extreme versatility of the technology across a wide range of substrates, coating types, and removal conditions.

Product Models: Plasma*Blast*® 7000 comes in three product configurations: Mobile, Benchtop, and Robotic. All systems generate the same plasma output. Likewise, all three systems come with a pen (either ergonomic for handheld remove or mount-able for machine-controlled removal) attached to a 20' air/power cable. The length of the cable allows the operator to move freely within a region. Each model comes in either 208–240 volt or 440–480 volt version. (The 440-480 volt version was used on this project.)

Figure A1 shows the Mobile model of the product line, the PB 7000-M. This model was designed to be used in rugged conditions and is easily man-carriable. The system weighs 34 pounds is 12" x 14" x 22" and comes with an ergonomic pen

Figure A1: PB7000M Mobile APCR System

for handheld coating removal. As can be seen in the figure, the unit includes an attached “backpack” to hold the pen, cord, spare parts, and basic PPE.

Figure A2 and Figure A3 show the Benchtop and Robotic models of the product line. These two models have the same power supply base. The Benchtop model comes with an ergonomic pen and the Robotic model comes with a mountable pen. Both models are intended to be used in workstations or other fixed locations.

Figure A2: PB7000B Benchtop Handheld APCR System

Figure A3: PB7000R Benchtop Robotic-Mounted APCR System (power-supply not shown)

Appendix B – Relevant Previous Projects

APS has completed four recent projects that provide important background and context for understanding the motivation for this project and the results of this project. Herein below, we present brief abstracts of these studies. Requests for a full copy of each report can be made directly to APS.

2018 General Dynamics Electric Boat Study (GDEB Study)

In 2018, the National Shipbuilding Research Program sponsored a joint project led by General Dynamics Electric Boat titled, "Evaluation of Plasma Beam Technology for Coating Removal and Surface Preparation" to "develop a NAVSEA approved process qualification document to allow the use of the Plasma*Blast*® atmospheric plasma coating removal (APCR) system on a select list of high impact applications (substrates/coatings) developed by Electric Boat."[1] The project team consisted of: GD-Electric Boat, GD-Bath Iron Works, GD-NASSCO, NAVSEA 05 Tech Warrant Holders, NSWC-Carderock, and APS. In this study, the Plasma*Blast*® system was evaluated both for its efficacy of removal and its impact on the treated substrates.

Efficacy: GDEB determined that APCR is capable of effectively removing both MIL-DTL-24441 (an ultra-high solids coating often referred to as "Mare Island") and MIL-RFO-23236 (an epoxy powder coating) from abrasive blasted steel. GDEB additionally noted significantly less dust/debris is generated compared to typical power tool removal.

Impact: Impact on underlying substrate was evaluated through microstructure evaluation, hardness testing, tensile strength testing, Charpy impact testing, hydrogen content evaluation, metallurgical evaluation, and temperature monitoring.

- GDEB ultimately determined that APCR treated samples "showed no significant changes with respect to microstructure, hardness, tensile strength, Charpy impact strength and hydrogen content when compared to untreated samples."
- Additionally, metallurgical examination of the treated samples showed no recast metal, inclusions, or microstructural changes.
- The results of the temperature monitoring revealed that: (1) on small steel sample coupons (4" x 8" x 0.375"), the temperature of the backside of the removal area typically remained below 300°F, with a maximum recorded temperature of 338°F. (2) on larger steel samples (24" x 36" x 0.375") – more representative of real shipboard conditions – the maximum temperature anywhere on the backside of the removal areas was 260°F, and maximum temperature at the edge of the treatment area was 197°F. However, only 2" outside of the treatment area, the maximum recorded temperature was only 102°F. These temperature readings showed that maximum temperatures reached during treatments were below temperatures that would affect the temper or performance of the steel, especially for the larger samples that were more representative of real-world use-cases.

[1] https://www.nsrp.org/project/evaluation-of-plasma-beam-technology-for-coating-removal-and-surface-preparation/

Thus, on all properly APCR-treated sample sets, it was shown that no negative effects were detected for substrate composition, structure, performance, or hydrogen content.

2018 Corrosion Testing Laboratory and Naval Surface Warfare Center Carderock Division Study

In 2018, CTL and NSWCCD conducted a study to evaluate the impact of APS's APCR process on the substrate of the surface being treated. Specifically, this study examined the effects of APCR on weld material, weld heat affected zones, and base substrate material. All treatment, testing, and handling of the samples was done independently of APS.

Impact: Samples were examined microscopically for weld defects and cracks, evaluated using magnetic-particle testing for cracks in the metal, and macro-etching was performed on all samples to inspect for weld defects or irregularities. Metallurgical cross-sectional mounts were prepared for microscopic examination of the weld, heat-affected zone, and base metal. Samples also underwent Vickers hardness testing, tensile testing, Charpy impact testing, and hydrogen content testing. The results of this testing showed no significant difference between APCR-treated samples and controls except for a slight increase in Charpy impact strength on the APCR treated samples. Therefore, no negative effects from APCR-treatment were identified on the tested substrates.

2018-2019 BSI EHS Services and Solutions Study

In late 2018, APS sponsored a study by BSI EHS Services and Solutions ("BSI") to evaluate the environmental health and safety of a single-beam Plasma*Blast*® system. More specifically, BSI evaluated the level of noise, dust, and select chemicals emitted by a Plasma*Blast*® system properly operated in an environment with modest ventilation. Below is the Executive Summary from this study's final report, edited slightly to remove references to graphs and tables, remove the redefinition of abbreviations, and add selective bolding for key point emphasis.

On December 18, 2018 and March 4-5, 2019, BSI conducted a series of tests at the request of APS to evaluate the use of APS's plasma "pen" technology. These tests were conducted within a testing shed located within the APS facility at 11301 Penny Rd, Cary, North Carolina and included an assessment of noise, dust, and select chemicals to determine the safety of the pen technology. Two use conditions were selected for study: static and in-use. Under the static use condition, the pen was clamped to a ring stand and run continually for four hours. Under in-use conditions, the pen was used by an operator to remove Sherwin Williams Type IV, epoxy green primer from DH36 + HY80 steel for four hours. During each use condition, samples were collected for a variety of media including:

- Direct-Reading tests for gases (Ozone, Carbon Monoxide, Carbon Dioxide, and Nitrogen Oxides)
- Area noise levels (both inside and outside the testing shed)
- Chemical samples with laboratory analysis (Aluminum, Copper, Hydrogen Cyanide, Total Hydrocarbons, Respirable Dust, Total Dust, and Sulfur Dioxide)

The results for the direct reading gas indicate all tested gases were well below the established OSHA Permissible Exposure Limits.

Regarding the noise testing, results indicated that during both operating conditions detected noise levels were near or above the OSHA PEL of 90 dBA (approximately 99-109 dBA within in the test booth and 84-89 dBA immediately outside the enclosure). These results are generally in the range of existing technology used to remove paint. For example, typical noise levels with abrasive blasting range from 90 to 119 dBA[2].

Finally, for the analytical sampling, under both operating conditions the sample results were below analytical detection limits for:

- Total Hydrocarbons (VOC)
- Sulfur Dioxide
- Hydrogen Cyanide

Where detected, laboratory analysis found selected contaminants to be well below applicable OSHA PELs including:

- Static Run Mode
  - 0.0018 mg/m3 copper (OSHA PEL = 0.1 mg/m3, Cu fume)
- In-Use Paint Removal
  - 0.019 and 0.024 mg/m3 aluminum (OSHA PEL = 5 mg/m3, Respirable Al)
  - 0.003 and 0.0042 mg/m3 copper (OSHA PEL = 0.1 mg/m3, Cu fume)
  - 4.5 and 1.1 mg/m3 respirable dust (OSHA PEL = 5 mg/m3 Respirable Dust)
  - 1.4 and 3.9 mg/m3 total dust (OSHA PEL = 15 mg/m3, Total Dust)

In summary, this testing effort demonstrated that the APS plasma pen technology provides an effective mechanism by which paint may be removed from steel with minimum potential health impacts via gases, noise, or chemical media.

Update: In 2020, the results from this study were utilized by Anniston Army Base in an evaluation for regulatory compliance with Title 5 of the Clean Air Act which determined that the byproducts produced by the Plasma*Blast*® 7000-M warranted no special considerations or mitigation efforts. In 2022, APS conducted off-gassing testing and data analysis with Newport News Shipyard.

2019-2020 Fairlead Boat Works and EAG Laboratories Study

In 2019 and 2020, APS worked with FBW[3] and EAG Labs under the authorization of GENEDGE, on behalf of NAVSEA, under contract to PEO Aircraft Carriers, to perform a comparative analysis between APCR, grit-blasting, needle-gunning, and rotary wire-brushing. The removal methods were evaluated for their efficacy (cleanliness of removal) and impact on underlying substrate and profile.

Sixteen (16) 4” x 6” x 0.25” DH36 steel coupons were grit-blasted to a 3-4 mil profile and coated with MIL-PRF-23236 FAST-CLAD® at 7-12 mils thickness. Twelve (12) coupons were delivered to FBW for coating removal by grit-blasting, needle-gunning, and rotary wire-brush removal. Skilled

[2] “Abrasive Blasting Hazards in Shipyard Employment.” US Department of Labor – OSHA Guidance Document, Dec. 2006.

[3] FBW is an east-coast marine vessel repair facility whose customers include both commercial and military organizations. FBW is experienced in marine maintenance and coating removal, making them an ideal party for this study.

operators at FBW treated four (4) coupons with each method. A trained operator at APS treated four (4) coupons with a Plasma*Blast*® 7000-M system.

Efficacy: Energy-Dispersive X-ray Spectroscopy ("EDS") analysis was used to determine the cleanliness of removal by detecting the composition of remaining coating. EAG Labs analysis reported that the grit-blasting, followed closely by standard APCR treatment, had the cleanest removal – compared to needle-gunning and wire-brushing – and had the least impact on the substrate profile, revealing the existing profile without altering it.

Impact: Scanning Electron Microscope ("SEM") created images which were evaluated for signs of microfractures, defects, re-melting, and alterations to surface profile. The needle-gunning and rotary wire-brushed coupons both shows significant alterations of the substrate profile, with the coarse peaks flattened down or smoothed out. Plasma*Blast*®-treated coupons preserved the surface profile of the underlying substrate, with the peaks and valleys being clearly revealed. The EAG expert described the handheld and standard plasma-treated samples as "practically indistinguishable" from the grit blasted samples based on the SEM and EDS images.

In summary, EAG Labs observed that APCR achieves a cleanliness close to that of abrasive blasting – and significantly greater than other tested removal methods – without compromising the existing profile on the substrate surface.

Appendix C – SPTEP Experimental Data

APS and NCMS representatives arrived at NNSY on March 11, 2020, to oversee testing, to record measurements and take notes. Equipment and samples were first unpacked, examined, tested, and prepared for taking measurements. Testing started on the morning of March 11 after the testing plan was reviewed by all participants. APS returned to NNSY on August 25 to train an additional group of NNSY personnel and conduct a series of additional tests to further quantify the differences in performance between APCR and needle- gun removal.

The data collected during the execution of the Sample Preparation, Testing, and Evaluation Plan (SPTEP) are presented in this appendix along with other important details about the samples tested, their preparation, and how the experiments were executed. All APCR treatments and needle-gun removals were performed by trained NNSY personnel. Measurements were taken by NNSY and NCMS personnel. Pictures taken during the project can be found in *Attachment 3: Experimentation and Documentation Images.*

C-1: Measure Tools

Table C1: Measuring Tools Used During Projects

			Used on Date/Location			
			3/11/2020 AM	3/11/2020 PM	3/12/2020	3/13/2020
Instrument	**Model/Decsription**	**Property of**	Preservation Shop	NNSY Shop 970	Preservation Shop	Preservation Shop
Stopwatch	Personal Smartphone	NNSY	x		x	
Thickness Probe	Elcometer 456	NNSY X-71		x	x	x
Camera	Canon SX 540 HS	NNSY	x		x	
IR Thermometer	Fluke 568 IR	NNSY 230309	x	x	x	
Temperature Crayons	Tempil, Inc. MSKIT-1	APS		x	x	
Salinity Test Kit	Elcometer 138	NNSY	x		x	
Surface Profilometer	Elcometer 224	NNSY 224819		x	x	x
Adhesion Test Tape	Elcometer ASTM D3359	APS				x
Needle Gun	8000 BPM	NNSY-741		x		

C-2: Flat Panel Comparative Testing Removal Rate Data (2020-03-11 and 2020-08-27)

This round of tests investigated removal rate and removal comparison tests performed on Fast Clad ER Epoxy coated steel samples prepared by NNSY. The samples were all 12” x 12” x 3/8” steel plates that had been prepared several days before testing by first either needle-gunning then grinding the plate or grit-blasting the steel plate to 3-4 mil profile and cleanliness standard specifications; the samples were then coated with either gray or light blue Fast Clad ER applied via roller. Three of the samples were prepared using the needle-gun and grinding method (labeled with an “N” in their sample names) and the other six were prepared by grit-blasting (labeled with a “G” in their sample names). Additional flat panel testing was performed on August 27, 2020. Five samples were prepared for these tests, following the same preparation procedures as the abrasive-blast-prepared samples in the first round of tests. Due to the coating being applied with use of a paint roller, there was a significant amount of variation in coating thickness among the samples as well as across the surface of each individual sample. An NNSY-owned Elcometer 456 Inductive Coating Thickness Gauge was used during the first round of testing to measure coating thickness of each sample prior to removal and an NNSY-owned Elcometer E224C-TI Inductive Coating Thickness Gauge was used during the second round of testing; from this data, an average thickness across each sample was estimated. Timing measurements were taken using a smartphone stopwatch application during the first round of tests and using a 10-ms precision sports stopwatch.

Table C2: Flat Plate Removal Rate Comparison of APCR and Needle-Gun

Test Spot	Treatment Method	Sample Dimensions (in)	Treatment Area Dimensions (in)	Est. AVG Coating Thickness (mils)	Removal Time (min)	Area Removal Rate (ft2/hr)	Volume Removal Rate (ft2 x mils/hr)
1-N-1	APCR	12"×12"×3/8"	6"×6"	36	6	2.5	90
1-G-1	APCR	12"×12"×3/8"	6"×6"	27	5.73	2.62	70.64
1-G-2	APCR	12"×12"×3/8"	6"×6"	25	7.77	1.93	48.28
1-N-2	Needle Gun	12"×12"×3/8"	6"×6"	50	Tool Failed	N/A	N/A
1-G-3	Needle Gun	12"×12"×3/8"	6"×6"	25	7.72	1.94	48.6
1-G-4	Needle Gun	12"×12"×3/8"	6"×6"	32	10.18	1.47	47.14
A-1-TL (G)	APCR	12"×12"×3/8"	5"×5"	18.5	4.22	2.47	45.7
A-1-BL (G)	Needle Gun	12"×12"×3/8"	5"×5"	22.75	6.08	1.71	38.96
A-2-TL (G)	APCR	12"×12"×3/8"	5"×5"	28.8	4.47	2.33	67.16
A-3-TL (G)	APCR	12"×12"×3/8"	5"×5"	24.55	3.95	2.64	64.74
A-4-TL (G)	APCR	12"×12"×3/8"	5"×5"	22	3.38	3.08	67.73
A-2-BL (G)	Needle Gun	12"×12"×3/8"	5"×5"	21.5	6.55	1.59	34.19
A-3-BL (G)	Needle Gun	12"×12"×3/8"	5"×5"	26.75	6.75	1.54	41.28
A-4-BL (G)	Needle Gun	12"×12"×3/8"	5"×5"	25.85	5.6	1.86	48.08
A-1-FH (G)	Needle Gun	12"×12"×3/8"	5"×11"	25.5	14.55	1.58	40.16
A-2-FH (G)	APCR	12"×12"×3/8"	5"×11"	25.45	8.8	2.6	66.28
1-G-3-2	APCR (1800W)	12"×12"×3/8"	3 1/16"×6"	22	4.7	1.63	35.84
1-G-4-2	APCR (2200W)	12"×12"×3/8"	3 1/8"× 3 1/8"	32	4.17	1.91	61.25

C-3: Comparative Use-Case Scenario Removal Testing Data (2020-03-13)

This round of testing was performed at NNSY in the afternoon of March 13, 2020 and comprised another round of comparison trials between needle-gun removal and APCR. The tests were performed on two symmetric sets of test spots selected on the submarine sail mockup in the Preservation Shop. Each tool had to remove coating from one section of the sail that was a roughly 3” x 4.5” rectangular area containing two large, coated bolts and another circular section on an adjacent protruding panel; the circular section was roughly 2” in diameter and encircled another large, coated bolt. Tool operators were tasked with removing all coating from both the flat areas and the bolts down to bare substrate. This trial was designed to test the abilities of the two removal methods to remove coatings from complex surfaces and in difficult to reach spots, namely the area between the side bolts and the adjacent wall. The sub sail surfaces were thick steel walls coated with a multi-coat stack. Removals for each tool were timed and the temperatures of the surfaces were monitored during treatment. Removal operators were instructed to remove as much of the coating as possible down to bare substrate on the flat areas as well as on the nuts and bolts. An NNSY-owned Elcometer 456 Inductive Coating Thickness Gauge was used during the first round of testing to measure coating thickness of each sample prior to removal and timing measurements were taken using a smartphone stopwatch application. APCR removals were completed down to bare substrate with little to no remaining coating, while needle-gun removals were determined to be incomplete on both test areas and would require additional treatment with grinders, solvents, and brushing before the surface could be recoated.

Table C3: Complex Geometry Removal Rate Comparison of APCR and Needle-Gun

Removal Method	Sample ID	Treatment Area Dimensions (in)	Avg. Coating Thickness (mils)	Total Treatment Time (mm:ss)	Complete Removal (Y/N)
Needle Gun	Sail-2-1	3"×4.5" w/two nuts and bolts	3-5	7:57	N
APCR	Sail-1-1	3"×4.5" w/two nuts and bolts	3-5	4:15	Y
Needle Gun	Sail-2-2	2" Diameter w/one nut and bolt	>50	14:24	N
APCR	Sail-1-2	2" Diameter w/one nut and bolt	>50	3:41	Y

C-4: SPTEP Testing Temperature Data

C-4.1 First Round of Flat Panel Testing on March 11, 2020, Temperature Data

These tests were conducted on March 11, 2020 on flat Fast Clad ER Epoxy coated steel samples prepared by NNSY. The samples were all 12" x 12" x 3/8" steel plates that had been prepared several days before testing by first either needle-gunning then grinding the plate or grit-blasting the steel plate to 3-4 mil profile and standard specifications; the samples were then coated with either gray or light blue Fast Clad ER by rolling on the coating. Sample 1-N-1 was prepared using the needle-gun and grinding method prior to coating and the other samples were prepared by grit-blasting prior to coating (labeled with a "G" in their sample names). An NNSY-owned Fluke 568 IR single-point infrared thermometer was used to gather temperature data while a smartphone stopwatch application was used to record times. Temperature measurements were taken directly behind the path of the plasma pen as it treats the surface, avoiding pointing the thermometer directly at the plasma plume as this would give false readings of the substrate's temperature.

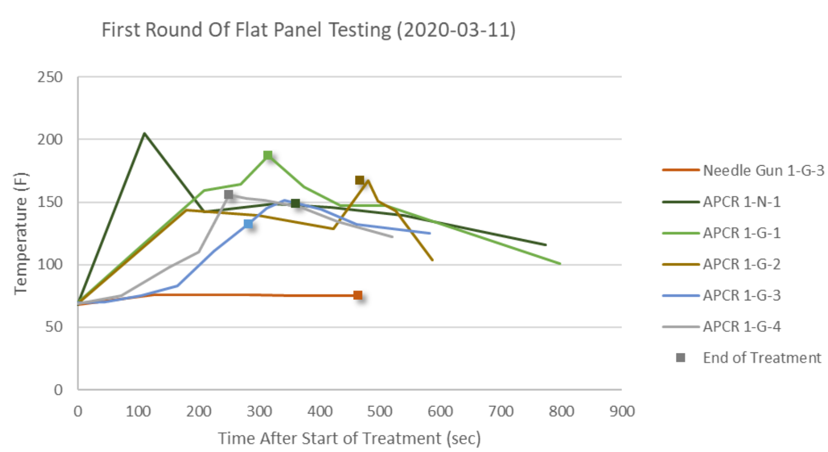


Figure C1: First Round of Flat Panel Testing Temperature Graph

C-4.2 Second Round of Flat Panel Testing on August 27, 2020, Temperature Data

These tests were conducted on August 27, 2020 on flat Fast Clad ER Epoxy coated steel samples prepared by NNSY using the same preparation procedures as the abrasive-blast-prepared flat panel samples used in the first round of flat panel testing. The samples were all 12” x 12” x 0.5” steel plates that had been prepared several days before testing by abrasive blasting the steel plate to 3-4 mil profile and standard specifications; the samples were then coated with gray Fast Clad ER using a paint roller. An NNSY-owned Fluke 568 IR single point infrared thermometer was used to gather temperature data while a 10-ms stopwatch was used to record times. Temperature measurements were taken directly behind the path of the plasma pen as it treats the surface, avoiding pointing the thermometer directly at the plasma plume or effluence as these would give false readings of the substrate’s temperature.

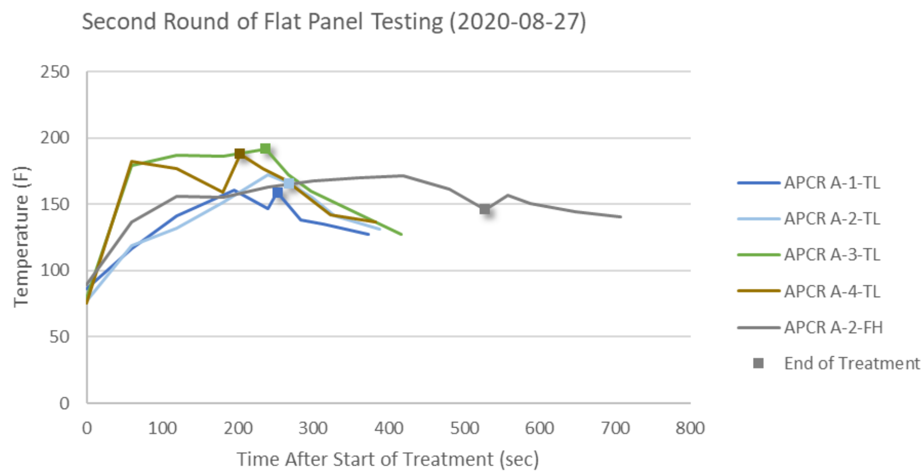


Figure C2: Second Round of Flat Panel Testing Temperature Graph

C-4.3 Submarine Mockup Flat Surface Testing on March 12, 2020, Temperature Data

On the afternoon of March 12, 2020, several use-case test areas were selected for testing on the submarine mockups at the Preservation Shop in NNSY. The sub tank mockup is regularly used to train blasting and painting technicians and is regularly abrasive blasted and repainted as part of the training process. As part of the testing on these realistic use-case scenarios, three 3” x 3” square areas were selected for APCR treatment on an outside surface of the sub tank. The surface was a thick, flat steel wall coated with a gray Fast Clad ER Epoxy measured to be between 19 and 34 mils thick. Treatment of the area comprised removing the coating down to bare substrate using the APCR system and briefly brushing off the surface with a wire brush. An NNSY-owned Fluke 568 IR single-point infrared thermometer was used to gather temperature data while a smartphone stopwatch application was used to record times. Temperature measurements were taken directly behind the path of the plasma pen as it treats the surface, avoiding pointing the thermometer directly at the plasma plume or effluence as these would give false readings of the substrate’s temperature.

C-4.4 Submarine Mockup Complex Surface Testing on March 12, 2020, Temperature Data

This set of tests were also performed on March 12, 2020 on the submarine mockups at the Preservation Shop in NNSY; however, these tests were performed on a series of complex surfaces and difficult to reach areas to evaluate how well the Plasma*Blast*® system could remove coatings from surfaces that traditional removal methods such as needle-gunning, grinding, and wire-brushing might struggle with. The tests spots were all steel surfaces of varying thicknesses and features. Test spots ***SM-19-LL***, ***19-LR***, and ***19-Upper*** were located on right-angle weld interfaces on the inside edges of external beams on the sub mockup and were located on the opposite side of the surface that the Plasma*Blast*® operator had to face while treating them; this forced the operator to reach over the beam into a tight space to treat the test areas; these areas were coated with 18 to 30 mils thick Fast Clad ER Epoxy coating. Test spot ***20-1-LP*** was a roughly 3" x 3" outlined area on the weld interface between a roughly 6" diameter pipe running through and welded to one of the thick external walls on the sub mockup and was coated with 14 to 40 mil thick Fast Clad ER Epoxy; this presented the challenges of treating a curved surface, a right-angle interface, and a weld area. Test spot ***18-1-BL*** was two-inch circular area centered over a roughly three-quarter inch bolt and nut welded to one of the thick external walls of the mockup and coated with 1-2 mil thick LSA White Enamel coating; treatment involved the removal of coating down to bare substrate over the complex surfaces of the welded nut and bolt. Treatments of each area comprised removing the coating down to bare substrate using the Plasma*Blast*® system and briefly brushing off the surfaces with a wire brush. An NNSY-owned Fluke 568 IR single-point infrared thermometer was used to gather temperature data while a smartphone stopwatch application was used to record times. Temperature measurements were taken directly behind the path of the plasma pen as it treats the surface, avoiding pointing the thermometer directly at the plasma plume or effluence as these would give false readings of the substrate's temperature.

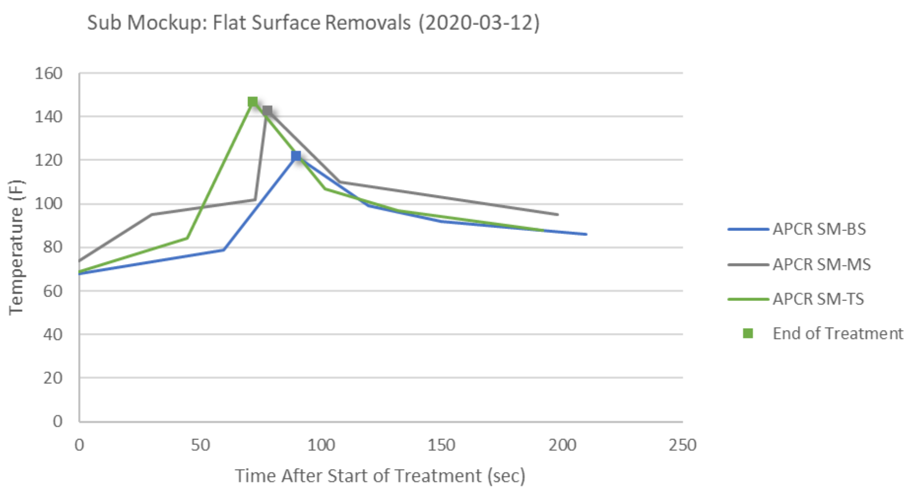


Figure C3: Sub Mockup – Flat Surface Removals Temperature Graph

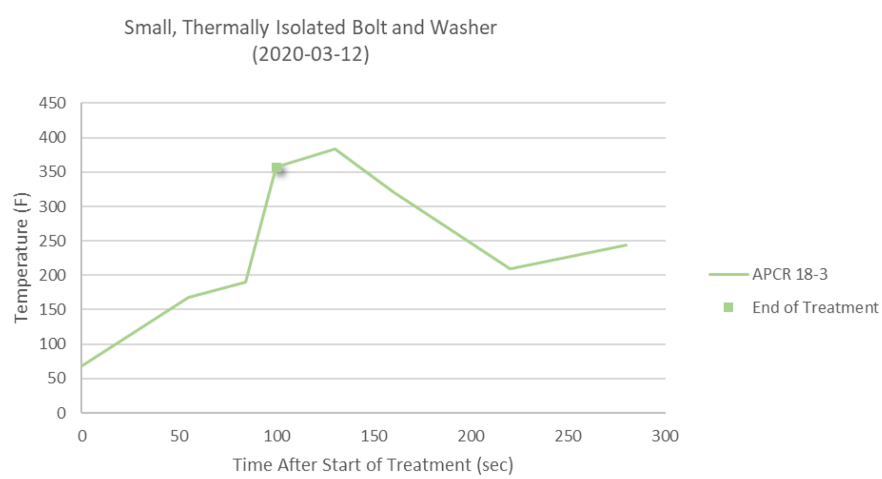


Figure C4: Small, Thermally Isolated Bolt and Washer Temperature Graph

C-4.5 Small, Thermally Isolated Sample on Submarine Mockup March 12, 2020, Temperature Data

Sample 18-3 was another complex surface sample on the submarine mockup at NNSY but has been singled out because it represents a unique scenario and resulted in an outlier in the temperature data gathered throughout this project. The sample was a very small steel object that was effectively thermally isolated from any larger pieces of steel and was insulated on its backside by a honeycomb rubber tile. This resulted in the sample building up heat during APCR treatment and being unable to effectively dissipate that heat leading to it reaching a much higher temperature than what was recorded in any of the other tests. The sample comprised a ¼" nut and bolt and a 2" diameter washer used to mount a honeycomb tile to one of the external walls of the sub mockup. It was coated with a light blue Fast Clad ER Epoxy coating although thickness was not able to be reliably measured due the samples size, complexity, and thickness. Treatment of the area comprised removing the coating down to the bare substrates of the sample using the Plasma*Blast*® system and then briefly brushing off its surfaces with a wire brush. The treatment process took a total of 1 minute 40 seconds to complete, during which the temperature rose from its initial value of 68.5°F to a maximum value of 383.1°F, recorded 30 seconds after removal. An NNSY-owned Fluke 568 IR single-point infrared thermometer was used to gather temperature data while a smartphone stopwatch application was used to record times.

C-4.6 Comparison Testing on Submarine Sail Mockup on March 13, 2020, Temperature Data

An additional set of comparison tests between APCR and needle-gunning was conducted on March 13, 2020; for these tests, each tool performed removal on one of two symmetric sets of tests spots inside the submarine sail mockup in the Preservation Shop. Each tool had to remove coating from a roughly 3" x 4.5" rectangular section of and internal sail wall that contained two large, coated, and welded bolts; operators also had to perform removal on one of two roughly 2" diameter circular sections on an adjacent protruding panel with a large, coated bolt roughly two inches in length and welded to the center of the section. The samples had a coating stack comprising an LSA White Enamel topcoat, the rectangular sections had an unidentified primer and the total coating stack measured generally 3-5 mils thick; however, the circular sections on the side panels had a primer, at least five other mid-coat layers, and in total the coating stack was thicker than the 50-mil range that the coating thickness gauge could measure. This made this section a suitable area for testing how well each tool could remove a very thick coating. For removal to be considered complete, the coatings had to be removed down to substrate – to the best of the tool's ability – from the entirety of each area, including the entirety of the protruding nuts, bolts, and welds. An NNSY-owned Fluke 568 IR single point infrared thermometer was used to gather temperature data while a smartphone stopwatch application was used to record times. The figure below displays the temperature readings taken over the total amount of time it took for each tool to remove the coatings from both of their test spots.

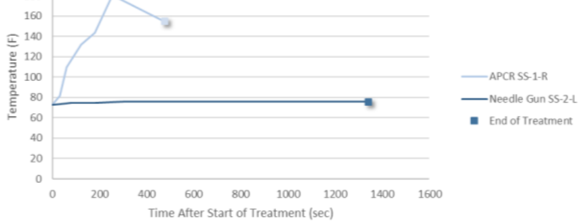


Figure C5: Sub Sail Mockup Comparative Testing Temperature Graph

C-5: Flat Panel Comparative Testing Surface Profile Data

During both flat panel testing trials on March 11 and August 27, 2020, the effects of APCR and the needle-gunning processes on surface profile were investigated. Surface profile depth measurements were taken on the abrasive-blast-prepared samples prior to them being coated and then measured again after removal was completed using the two removal methods being evaluated. The samples were originally prepared via abrasive blasting to a 3-4 mil profile. During the first round of needle-gun removal testing on March 11, the needle-gun was evaluated on its own without the follow-up process of die grinding that is standard process; as such, surface profile depth measurements were unable to be completed due to many small mounds of remaining, well adhered coating being left on the surface after treatment and blocking the profile depth measurement tools from getting an accurate reading. During the follow-up testing on August 27, the entire needle-gunning process was evaluated including the die-grinding process after needle-gunning. Thus, accurate surface profile measurements were able to be taken although the measured profile depths on these samples were likely due to the dents on the surface – caused by the pounding of the needle-gun scaler – and not from a profile remaining from when the surface was originally abrasive blasted. An NNSY-owned Elcometer 124 Tape Thickness Gauge and Testex Press-O-Film Surface Profile Tape were used to take surface profile measurements on sample set 1 prior to coating and an NNSY-owned Elcometer 224 digital surface profilometer was used to measure surface profile during the first testing visit. During the follow-up round of testing, a Testex Tape Thickness Gauge and Testex Press-O-Film Surface Profile Tape kit were used to evaluate profile after removals.

Table C4: Treatment Effect on Surface Profile Comparing APCR and Needle-Gun

Treatment Tool	Sample ID	Treatment Area Dimensions (in)	Est. Avg. Coating Thickness (mils)	Original Surface Profile Depth (mils)	Post-Treatment Profile Depth (mils)
Needle Gun	A-1-BL	5”×5”	22.75	3.0-4.0	2.5
Needle Gun	A-2-BL	5”×5”	21.5	3.0-4.0	2.7
Needle Gun	A-3-BL	5”×5”	26.75	3.0-4.0	2.8
Needle Gun	A-4-BL	5”×5”	25.85	3.0-4.0	2.7
Needle Gun	A-1-FH	5”×11”	25.5	3.0-4.0	2.4
APCR	1-G-1	6”×6”	27	3.1	2.5-3
APCR	1-G-2	6”×6”	25	2.5	2.4-4.2
APCR	1-G-3-2	3-1/16” × 6”	22	3	1.7-3.7
APCR	1-G-4-2	3-1/8” × 3-1/8”	32	3	2.5-3.5
APCR	A-1-TL	5”×5”	18.5	3.0-4.0	3.3
APCR	A-2-TL	5”×5”	28.8	3.0-4.0	3.3
APCR	A-3-TL	5”×5”	24.55	3.0-4.0	3.7
APCR	A-4-TL	5”×5”	22	3.0-4.0	3.6
APCR	A-2-FH	5”×11”	25.45	3.0-4.0	2.6

C-6: Flat Panel Comparison Testing Recoating Adhesion Data

APCR treated Samples 1-G-1, 1-G-2, and abrasive blast treated Samples 1-G-5 and 1-G-6, were selected for recoating and adhesion testing after they each had their 6” x 6” test area removed with their respective removal methods. The samples were sent for recoating the same day that they received their treatments and again coated with grey Fast Clad ER Epoxy, applied with a paint roller. The samples were then allowed 24 hours to fully cure before undergoing adhesion testing. Adhesion of the reapplied coating was first evaluated using the ASTM D3359 cross hatch tape test; however, these tests did not provide any useful information as all samples passed the tape pull-off test without any coating separation or other signs of poor adhesion.

It was decided that APS would take the samples back to their Cary, NC facility to perform pull-off adhesion testing as outlined in ASTM D4541. The samples were prepared for this testing by first identifying areas within the previously treated-then-repainted 6” x 6” area in the center of the sample; the coating was then lightly sanded with 400-grit sandpaper, blasted with compressed air, wiped clean with isopropyl alcohol and paper towels, and then blown off again with compressed air; three 20mm diameter aluminum test dollies were then adhered at the chosen locations on the sample, using Loctite EA-120HP high performance two-part adhesive, and left to cure under downward pressure for 24 hours. The coating and remnant adhesive around the perimeter of the applied dollies were then removed down to the substrate, using a circular hole saw. An APS-owned PosiTest AT-A pull-off tester was then used to measure and record the ultimate force required to separate the dollies from the samples. After the pull-off process was complete, the removed dollies and the test spots on the sample were examined to determine what layer failure occurred in. After this round of testing was completed, another set of three dollies were applied to new locations inside the marked space on the sample; before these dollies were applied, local thickness measurements were taken on each spot a dolly would be applied to, to determine if coating thickness affected the ultimate pull of strength of the reapplied coating. The final pull-tests were completed on May 18, 2020

Table C5: Adhesion Results Post-Treatment of Either APCR or Needle-Gun

Steel Plate ID	Trial Number	Dolly Pull Number	Local Coating Thickness Data (mil)			Avg. Coating Thickness	Pull Break Strength (PSI)	Break Percent in Glue Joint
1-G-1 **APCR**	1	1	Not Taken				2230	0
		2					2289	0
		3					2514	0
	2	1	14.06	11.4	20.5	15.32	1905	5
		2	18.55	22.2	17.1	19.283333	1922	15
		3	23.45	20.9	23.1	22.483333	1956	0
	Average					**19.028889**	**2136**	
1-G-2 **APCR**	1	1	Not Taken				2033	0
		2					2022	0
		3					1968	20
	2	1	22.3	30.85	23.85	25.666667	1773	10
		2	31	31.15	24	28.716667	1866	5
		3	24.4	26.05	24.85	25.1	1938	5
	Average					**26.494444**	**1933.333**	
1-G-5 **Abrasive**	1	1	Not Taken				2013	0
		2					2129	0
		3					1463	100*
	2	1	31.9	26.4	32.35	30.216667	1829	2
		2	21.2	23.85	22.955	22.668333	1835	2
		3	30.3	29.7	30.2	30.066667	1720	10
	Average					**27.650556**	**1905.2**	
1-G-6 **Abrasive**	1	1	Not Taken				1962	0
		2					2070	0
		3					2060	0
	2	1	23.65	25.6	24.65	24.633333	1823	0
		2	28.5	27.45	28	27.983333	1724	2
		3	19.4	20.85	18.4	19.55	1904	30
	Average					**24.055556**	**1923.833**	

*** 100% adhesive failure at dolly-coating interface; data point removed from average**

C-7: Conductive Surface Salinity Concentration Testing Data

These series of tests were conducted on March 12, 2020 in order to determine the effects of plasma treatment with the Plasma*Blast*® system on soluble salt concentrations on a steel surface. The samples for these tests were prepared by submerging them in marine water for several days prior to testing. All samples were first dried-off and then had surface contaminant conductivity measurements[1] performed on them – using an Elcometer 138 Salinity Test Kit and Bresle patch according to the ISO 8502-6 standard – to determine their pre-treatment concentrations of soluble contaminants. The samples used in these tests were then treated with plasma using one of several different treatment procedures and techniques. After the samples had been treated, they were again measured for surface salinity content through the same process as the initial measurements using the Elcometer 138 Salinity Test Kit and Bresle patches according to the ISO 8502-6 standard. Samples ***3-1-A*** and ***3-4-A*** received two full plasma treatments and salinity measurements were taken after each treatment. The treatments that each sample received are presented in Table C6 below. The results of the salinity tests are presented in Table C7 below.

Table C6: Outlined Procedures for Salinity Testing

Sample ID	Treatment Number	Treatment Time (s)	# of Times Plasma Used	Brushing Used	DI Water Used
3-1-A	1	75	Once	After Plasma	Before Plasma
	2	118	Once	Before and After Plasma	No
3-1-B-1	1	118	Once	Before and After Plasma	No
3-3	1	Not Measured	Twice	After Plasma	Before and After Plasma
3-4-A	1	118	Once	After Plasma	Before Plasma
	2	199	Once	After Plasma	Once Before, Once During

Table C7: Effects of Plasma Treatment on Soluble Salts via Conductivity Measurements

Sample ID	Treatment Number	Pre-Treatment Conductivity (µS/cm)	Post-Treatment Conductivity (µS/cm)	Reduction in Conductivity	Total Conductivity Reduction After Both Treatments	
3-1-A	1	95	37	61.05%		86.32%
	2	37	13	64.86%		
3-1-B-1	x	95	22	76.84%	x	x
3-3	x	130	54	58.46%	x	x
3-4-A	1	199	49	75.38%		93.47%
	2	49	13	73.47%		

[1] Conductivity measurements are commonly used throughout many preparation and coating industries to evaluate the degree of soluble salt contamination on a surface prior to coating. It is used because the process is much faster and simpler than the chemical analysis required to determine the specific concentrations of each ion-forming component in a sample (such as Na^+, Cl^-, SO_4^{-2}, K^+, Ca^{+2}, Mg^{+2}, etc.) but can still be used to obtain an meaningful estimate of dissolvable solids that will lead to corrosion or coating failure.

C-8: Grease Removal Testing

This testing was conducted on grease coated, bare steel samples to evaluate the capability of APCR to remove bulk and residual grease from coated samples. The efficacy of APCR treatment was evaluated by recording the total treatment time to remove the grease down to bare substrate, evaluating the cleanliness of the treated surface, and monitoring temperature during treatment. Due to a lack of available evaluation instruments, the samples were determined to be sufficiently cleaned if an operator could run a finger over it without a greasy residue being transferred to the finger. Samples 2-2 and 2-4 were selected for the testing and underwent treatment and evaluation; the samples' dimensions, grease specifications, surface features, and total treatment time are presented in Table C8 below.

Table C8: Grease Removal Samples with Plasma Treatment Times

Sample ID	Grease Used	Sample Dimensions	Sample Surface Features	Total Treatment Time (mm:ss)
2-2	Lubriplate 630-AA	11"×5"×5/8"	Flat Surface with Mill Scale	2:02
2-4	Sherwin Williams Spray Source Packing Saver	12"×8"×1"	Multi-Layer Butt Weld with Backing Bar	4:20

Attachment 1 – Plasma*Blast*® 7000, Model PB 7000-M Data Sheet

PlasmaBlast® COATING REMOVAL SYSTEM

MODEL PB 7000-M

The most advanced coating removal system available

APPLICATIONS:

- ✓ Fast removal of coatings with no damage to the substrate
- ✓ Non-Destructive Examination and Testing, strip back before welding, corrosion control
- ✓ Deploys easily and safely in tight spaces and in high places
- ✓ Replaces needle gunning, grinding and chemical solvents
- ✓ The plasma beam reaches into cracks, crevices, seams, bolt threads or complex surfaces

FEATURES AND BENEFITS:

- ✓ The process is chemical and media free
- ✓ The plasma beam etches away coatings and surface contaminants without damaging the substrate
- ✓ Surface temperatures stay below 100°C
- ✓ The existing profile is unchanged
- ✓ The surface will be ready to re-coat

COMES COMPLETE WITH:

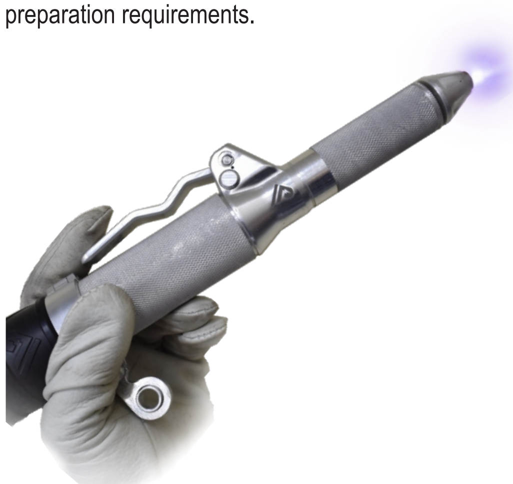
- Ergonomic plasma pen
- 20 ft pen connector cable
- Power cord C19 to NEMA L6-30 (default)
- Grounding cord with clamp
- Input Pressure regulator
- Operating Manual
- 5-pack of replacement nozzles

CONSUMABLES (SOLD SEPARATELY):

- Replacement nozzle kit - 5 nozzles with anti-seize lubricant
- Replacement plasma electrode

ABOUT Plasma*Blast*®

Fast to deploy, simple to operate the portable and rugged Plasma*Blast*® 7000-M quickly and safely removes paint, coatings, sealants, and adhesives without damage to underlying surface. Speed up your job and save money by avoiding the need to set up tarping or containment. Because there is no spent media, there is essentially no clean-up. This tool can get through the toughest and thickest coatings to meet your surface cleaning and preparation requirements.



UNIQUE ADVANTAGES

- ☑ Utilizes patented Cold Plasma Technology
- ☑ Removes coatings effectively with zero substrate damage
- ☑ Demonstrated up to 90% labor savings when compared to traditional methods
- ☑ Sealed system handles harsh environments and temperatures from -14°F to 110°F
- ☑ Protective frame incorporates 8 isolation dampers
- ☑ Only requires air and electricity to operate
- ☑ Hand-held, ergonomic precision pen — No vibrational impact

MECHANICAL SPECIFICATIONS

Dimensions:	12" x 14" x 22"	31 cm x 36 cm x 56 cm
Weight:	34 lbs	15.4 kg
Plasma Cable length:	20 ft	6.1 meters

ELECTRICAL SPECIFICATIONS

Input Power	208-240 VAC, 50-60Hz, single-phase or 440-480 VAC, 3-phase
Input Current	18 Amps, CE-14.5 Amps
Default Plug Type	NEMA L6-30 for 208-240 VAC and NEMA L16-30 for 440-480 VAC
Optional Plug Types	NEMA L6-20, NEMA L14-20, NEMA L14-30, NEMA L15-30 3-phase
Device EMC Status	Class A Group 2
Applicable CE Standards	EN/IEC 61326-1:2013 IEN/IEC 60974-10 IEC/EN 60974-1
Degree of Protection	IP 52

OPERATING PARAMETERS

Operating Temperatures	14°F - 110°F	-10°C - 43°C
Operating Humidity	<95% , non-condensing	
Elevation	<10,000 ft	<3,000 meters
Operating Sound Level	~90 dBa	
Input Compressed Air Pressure	80-100 psi	550kPa-690kPa, 5 -7 bar
Burst Pressure	120 psi	827 kPa, 8 bar
Optimal Input Compressed Air Flow	3.5 CFM	99 SLM

PROVEN EFFECTIVENESS ON COATINGS, SEALANTS, AND SUBSTRATES

The PB 7000-M system has been shown effective in removing a wide range of coatings and sealants from a wide variety of substrates. The technology has been validated by Fortune 100 companies and in projects and related contracts with the US Navy, US Air Force, NATO and the Strategic Environmental Research and Development program (SERDP).

COATINGS

- **Acrylics**
- **Alkyds**
- **Latex**
- **Epoxies**
- **Polyurethanes**
- **Polyesters**
- **Powder Coats**
- **Silicone / Polysiloxanes**
- **Polyurea**
- **Coal-Tar Epoxy**
- **Ultra High Solid**

SEALANTS

- **Elastomeric**
- **Caulking**
- **Polysulfide**
- **Polyether**
- **Butyls**
- **Acrylics**
- **Rubber**
- **Silicones**
- **Polyurethane**

SUBSTRATES

- **Steel alloys**
- **Cast Iron**
- **Aluminum alloys**
- **Titanium alloys**
- **Magnesium alloys**
- **Carbon Fiber**
- **GRP / Fiberglass**
- **Composites**
- **Concrete, Masonry, Brick**
- **Ceramics**

...and more

ATMOSPHERIC PLASMA SOLUTIONS

11301 Penny Road., Suite D
Cary, NC 27518

(919) 341-8325

info@apsplasma.com

https://apsplasma.com

FOR SALES AND RENTALS CONTACT:

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Plasma*Blast*® Global Sales Manager

Mobile: (252) 266-6170

Office: (919) 341-8325 ext. 120

Attachment 2 – March 6, 2020, Sample Preparation, Treatment and Evaluation Plan for NCMS Testing at Norfolk Naval Shipyard

March 6, 2020

Sample Preparation, Treatment, and Evaluation Plan for NCMS Testing at Norfolk Naval Shipyard

Atmospheric Plasma Coating Removal/Sample Cleaning

ABSTRACT

The purpose of this Sample Preparation, Treatment, and Evaluation Plan ("SPTEP") is to provide a framework and instructions for treatment and data collection to demonstrate and evaluate the use of atmospheric plasma coating removal ("APCR") to effectively remove coatings and clean the surfaces of identified samples and surfaces in a shipyard setting. The testing, to occur over three days, will utilize the Plasma*Blast*® PB7000M APCR system[1] developed by Atmospheric Plasma Solutions Inc. ("APS") and the removal will be performed by NNSY personnel trained by APS to use the system.[2] The removal will be on a collection of prepared samples and real or realistic use cases as determined by NNSY personnel (and documented in **Appendix C**). This output of this plan will produce a set of test results that will serve as a baseline for the evaluation of APCR and for comparison to existing removal methods. The evaluation metrics for APCR include removal rate with and without consideration of setup time, visual and temperature impact on substrate, impact on surface profile, cleanliness of removal, salinity changes, and adhesion of a new coating.

[1] Background on the APS Plasma*Blast*® technology can be found in **Appendix A**.
[2] A short description of highlighted interactions between APS and NNSY personnel under the NCMS Collaboration Agreement Number 201911-110417 is presented in **Appendix B**.

Table of Contents

Summary

Samples will be prepared, and ship and mockup areas will be reserved and setup for plasma coating removal. The PB7000M system will be setup along with appropriate ventilation at each treatment site. Measurements and photos will be taken prior to removal. Removal will be performed by NNSY personnel trained by APS to use the PB7000M system. Two additional personnel will be needed to take measurements and record notes during treatment. Measurements on the coating and substrate will be taken before, after, and during removal to include coating thickness, substrate profile, and temperature measurements on all samples treated. Other tests include salinity measurements and adhesion testing on reapplied coatings. Comparative removal will also be performed using the in-use technology appropriate for some use cases. During the testing, APS personnel will be present as observers and to provide instruction and advice if necessary. If available, a representative from the code 133 group will also observe and evaluate the condition of the treated surfaces for repainting. The data from these tests will then be compiled and used to evaluate the usefulness of the APCR process.

Sample Preparation and Description of Testing Targets

This section describes the prepared samples as well as the in-shipyard areas where APCR will be evaluated in this study. Many areas at NNSY were identified as good candidate use cases for the application of APCR technology. The areas presented herein were chosen because the in-use technology is cumbersome, time-consuming, or ineffective at performing removal. In addition to defined use cases, the testing targets will include a baseline test of prepared coupons, and a few day-of-testing user-presented samples.

Shop Area Flat Prepared Sample Plates

Twelve to fifteen test samples[3] will be prepared per the specifications below for testing (see **Appendix C, Table C-1**.). The purpose of including prepared samples in this analysis is to demonstrate the effectiveness of APCR on a controlled surface with the desired target coatings.

- The first set of samples will be made up of nine 8” x 8” plates that have been grit blasted to a 3-4 mil profile and prepared according to standard shipbuilding surface prep procedures and then coated with Fast-Clad ER epoxy to 20-30 mil thickness.
- The second set of samples will include three to six with bolts and fasteners attached to them and then coated with an occupationally encountered grease or oil such as gear grease or way oil.

The sample preparer should document the preparation process and any standards followed and take pictures and surface profile measurements prior to coating.

[3] The steel plates will be provided by Shop 26. It is anticipated that they will be HY80 steel.

Other Prepared Samples and Treatment Areas

NNSY personnel will prepare other parts representative of coating removal challenges at the shipyard. In particular, 3 samples will be exposed to a marine environment for 5 - 15 days in advance of the execution of this plan so that they will be contaminated by salts, leaving them susceptible to poor adhesion of future applied coating. Additionally, Shop 64 will prepare a sectional mockup of tile applied to a submarine will be prepared with multiple tile types used by the shipyard. A list of these parts to be tested can be found in **Appendix C, Table C-2**.

Shop Area Random Parts

A few parts from NNSY personnel will be solicited to be used for testing. These parts will represent miscellaneous use cases that shipyard personnel encounter for which they believe APCR might be a practical solution. The parts should be objects of varying geometries and functions that have acquired through use or construction a coating or contaminant that must be removed for continued use or maintenance. APS would also like to acquire for testing examples of steel that have been exposed to a marine environment and are now contaminated by salts, leaving them susceptible to poor adhesion of future applied coating. A list of these parts to be tested can be found in **Appendix C, Table C-3**.

Use Case Scenario Testing on Submarine Mockup

Several areas were identified on the submarine mockup environment in the NNSY Preservation Shop area. These are areas that would normally be grit blasted but, given the long and cumbersome setup and cleanup associated with grit blasting as well as the difficulty reaching certain areas, Plasma*Blast*® has the potential to be a more convenient and less costly solution. The list of use case areas singled out can be found in **Appendix C, Tables C-4 and C-6.**

Use Case Scenario Testing on Decommissioned USS McKee

Several areas were also identified as good candidates for APCR onboard the decommissioned USS McKee. These areas would likely normally have their coatings removed using needle gun scalers, grinders, or brushes. In these cases, APCR has the potential to be faster, have cleaner removal, produce less dust, and have less of an impact on the substrate material. The list of use case areas singled out can be found in **Appendix C, Table C-5.**

Measurements to be Performed

This section details the measurements and tests to be performed, the purpose of each, and how they are to be performed. The testing team should document what measurement instruments are used during the execution of this plan. **Appendix D** provides a template for recording this list. **Appendix E** presents which measurements are to be taken for each treatment spot listed in Appendix C.

1. **Time**
   - *Purpose:* The amount of time it takes to perform a treatment will be measured to evaluate the speed of treatment compared to existing methods. Time will also be measured from the end of each treatment in order to precisely capture post-treatment readings.
   - *Method:* One of the measurement/note-taking observers will start a stopwatch at the beginning of treatment and leave it running until the designated treatment is completed, at which point the total treatment time will be recorded. The stopwatch will continue to run to allow the data recorders to document the time while capturing post-treatment readings.
   - *Equipment:* Stopwatch, such as a Fisher Scientific Traceable Stopwatch or New Balance Professional Stopwatch.

2. **Dimension Measurements**
   - *Purpose:* The dimensions of the area to be treated will be measured and marked off to determine the total surface area that is treated. This will support a record of accurate treatment rates and allow for an extrapolation to larger treatments.
   - *Method:* Prior to treatment, the area to be treated will be measured with a ruler or tape measure and marked off with a Sharpie® marker as necessary to indicate the designated treatment zone. The dimensions of the treatment area will be recorded in the treatment notes.
   - *Equipment:* Yard-length ruler and Sharpie® marker.

3. **Thickness Measurements**
   - *Purpose:* Evaluate the volume of coating that is to be removed and relate it to removal rate.
   - *Method:* Performed using an induction thickness probe. Prior to removal of coating, touch and hold probe to surface to be measured and record reading in multiple areas to get an average thickness.
   - *Equipment:* Inductive thickness probe such as an ElektroPhysik MiniTest 700 with Inductive probe attachment.

4. **Pictures before, during, and after treatment**
   - *Purpose:* Clear images for documentation, comparison, and evaluation of visual quality of removal.
   - *Method:* To be taken using an appropriate digital camera. Multiple pictures should be taken of each area to be treated before, during, and after treatment under the same lighting conditions and camera settings.
   - *Equipment:* Digital camera such as a Nikon D3400 DSLR camera.

5. **Temperature Measurements**
   - *Purpose:* Sample the temperature variations that the substrate experiences during APCR to determine if there are any potential effects on the structural integrity of the substrate or if other operational safety procedures are needed.
   - *Method:* Performed using an infrared single dot thermometer. Measurements should be taken before, immediately after, and at specified intervals after removal on the area that removal is to be performed on. Point the IR thermometer directly at and perpendicular to the surface being measured. Take multiple measurements around the treated area and get an average and max temperature reached after treatment. Do not point the IR probe directly at the plasma plume as this will interfere with the readings. If possible, temperature measurements should also be taken on the back side of the samples/test areas using temperature crayons.
   - *Equipment:* Single point IR temperature probe such as a Fluke 62 Max Thermometer. Temperature sensitive markers for 200, 300, and 400 deg F such as Markal Thermomelt Heat Sticks.

6. **Chloride Content Measurements**
   - *Purpose:* Evaluate what effect, if any, APCR has on the surface salinity content of the substrate.
   - *Method:* Likely performed using the Bresle Patch Method. Take measurements before and after treatment on a piece of bare steel that has been exposed to marine air and shows signs of salt contamination.
   - *Equipment:* Bresle salt contamination test kit such as an Elcometer 138C kit.

7. **Surface profile measurements**
   - *Purpose:* Evaluate the impact of APCR and other removal methods on the surface profile and evaluate their ability to reveal an existing profile.
   - *Method:* Performed using a surface profile gauge or using surface profile test tape and micrometer. Perform measurements after removal. For surface profile gauge, touch and hold probe to surface to be measured and record reading in multiple areas to get an average roughness reading. For surface profile tape, adhere tape to surface to be measured then rub testing spot thoroughly with a burnishing tool. Remove the tape and then measure the thickness of the tape at the testing spot using the appropriate micrometer. After subtracting the film material, this gives you the profile depth measurement.
   - *Equipment:* Surface profile testing equipment such as Elcometer 124 Tape Thickness Gauge, and Testex Extra Coarse Press-O-Film Tape or Elcometer 224 Digital Surface Profile Gauge.

8. **Recoating and adhesion testing.**
   - *Purpose:* The purpose of this test is to evaluate how clean and well prepared the APCR process leaves the surface prior to a new coating being applied.
   - *Method:* A select number of surfaces will be recoated after removal. The coating should be applied within a day after removal. The coating will be applied to standard specifications. The coating will then be allowed to fully cure before adhesion testing. The quality of

adhesion will be evaluated using the cross-cut test, according to ASTM D 3359 or another preferred adhesion test.

- *Equipment:* Painting equipment for applying Fast-Clad ER epoxy, razor blade or cross hatch tester such as Elcometer 1542, ASTM D3359 Cross Hatch Adhesion Test Tape such as Elcometer 99.

9. <u>Code 133 Inspector Evaluation</u>

- *Purpose:* The purpose of this test is to allow for a standard evaluation of the state of the treated surface by a trained professional. They will determine if the plasma cleaned surface is sufficiently cleaned to be ready for recoating.
- *Method:* A representative from the Code 133 group will observe the APCR process and evaluate the quality of the surface after complete removal.

Schedule, Setup, Treatment, and Measurement Procedures

This section details the setup, treatment, and removal procedures for collecting data. These procedures are scheduled to be completed over a three day period. Propper PPE[4] should always be worn during removal by all involved participants and observers. In addition, proper ventilation should be established before removal is performed. For treatments in the shop area, a large fan should be sufficient for the needed ventilation but in more confined spaces, such as the submarine mockup and the USS McKee, a fume extraction system may be needed. A new nozzle should be installed on the PB7000M plasma pen at the beginning of each day, before removal has started. Personnel taking measurements are instructed to fill out the Measurement Recording Template (**Appendix F**) and the Measurement Tools Used Template (Appendix D) during the tests.

Schedule

	Day 1	Day 2	Day 3
Shop Area	• All samples • Repainting		• Adhesion Testing
USS McKee		• All areas	
Submarine Mock-up	• Tile Removal • Exterior Surface (for adhesion testing) • Exterior Surface repainting		• Adhesion Testing on Exterior Surface • All remaining areas

[4] Proper PPE is defined as the more protective of the guidelines documented in the APS provided manual and training documents, or the requirements of the location where treatment is being performed.

Shop Area Testing of Flat Prepared Samples

This section describes the measurements to be taken and/or performed and the treatment of the nine flat prepared samples (Test Spot #1 from Appendix C). Unique only to Test Spot #1, APCR removal will be performed on three of the samples, grit blasting will be performed on three of the samples, and needle gun scaling will be performed on three of the samples. Test Spot #1 will also include adhesion testing.

Personnel needed

1. One PB7000M operator.
2. Two persons taking measurements, notes, and pictures.
3. If available, one Code 133 representative.

NOTE: Representatives from all shops, including but not limited to codes 133, 26, 11, 71, and 64 are requested to attend Day 1 testing. Representatives from these groups are also invited to attend Day 2 and Day 3 testing.

Setup and Before-Treatment Measurements Steps

1. Take stock of all equipment and samples needed to perform treatment and measurements:
    a. *APCR*: PB7000M48 power supply, plasma pen, power cable and adapters, air hoses, grounding cable, brushes, spare nozzles.
    b. *Needle gun scaler*: Any handheld unit currently used by NNSY personnel for spot coating removal purposes. (Be sure to note the specific make and model on the Measurement Tools Used form.)
    c. *Grit Blasting Equipment*: Equipment currently used by NNSY personnel. (Be sure to note the specific make and model on the Measurement Tools Used form.)
    d. *PPE*: Gloves, eye protection, respirators/dust masks, hearing protection, and any other items required for needle gun or grit blasting
    e. *Samples to be treated*: Flat prepared samples as specified in Appendix C, Table C-1.
    f. *Measurement instruments*: Dimension measurement tool, thickness probe, camera, IR thermometer, surface profile gauge, and stopwatch.
2. Document the measurement tools to be used using the form in Appendix D.
3. Prepare six Measurement Recording forms using the template in Appendix F.
4. Setup a treatment area on a table in an open area.
5. Setup proper ventilation in the form of a fan directing air over the testing table away from the operator, measurement persons, and other observes or by setting up a fume extraction system.
6. Ensure all operators, measurement personnel, and observers have on appropriate PPE.
7. Take pictures of setup and samples prior to treatment.
8. Take thickness measurements on painted samples.
9. Take temperature measurements of samples prior to treatment.
10. Apply temperature crayons to the back of the samples to get a reading on temperatures reached.

Treatment Procedure and Measurements Steps

This section and the following section describe the procedure for sample treatment and measurements for Test Spot #1 (the flat Fast-Clad coated prepared samples). In the following two sections, "[APCR | Grit Blast | Needle Gun]" will be used as the placeholder for the treatment type.

1. Pre-treatment Steps
    a. For the APCR samples,
        i. Go through PB7000M setup procedure as outlined in user manual.
        ii. Ensure the sample is properly grounded.
    b. For the Grit blasted samples follow the standard NNSY procedures for grit blasting.
    c. For the Needle Gun scaled samples
        i. Ensure that each sample is secured sufficiently well to stay in place in reaction to the impact of the needle gun.
        ii. Follow any other standard NNSY procedures for needle gun usage
2. Ready one person to take pictures and IR measurements and one to handle timing and recording notes.
3. Simultaneously start stopwatch timer and begin removal.
4. Begin treatment of the sample, aiming for a clean but not overtreated substrate after removal.
5. Take pictures of the sample during treatment.
6. Take temperature measurements of the sample during treatment. For APCR, do not point the IR temperature gauge directly where the plasma is hitting it as it will interfere with the reading.
7. Upon completion of treatment, stop stopwatch and immediately measure the temperature of the area that was treated, then record temperature again after 30 seconds, 60 seconds, and 120 seconds. Keep the stopwatch running.

After-Treatment Measurements Steps

1. Take pictures of samples again under the same camera settings and lighting conditions used before treatment.
2. Brush off sample as necessary.
3. Take pictures of the samples again under the same camera settings and lighting conditions used before treatment.
4. Let sample cool to 100 deg F, record the time when this temperature is reached, and stop the stopwatch. Then perform designated measurements:
    a. Surface profile on painted sample, and
    b. Report the highest temperature reached by the temperature crayon markings.
5. Allow code 133 representative to evaluate the treated surface and record their evaluation.
6. Set aside samples to be re-painted.

Repainting and Adhesion Testing Steps

1. Re paint samples to standard single coat thickness within one day of removal.
2. Take pictures of newly painted samples.
3. When coating has cured fully, perform cross-cut test or other adhesion test, taking notes and pictures of the results.

Shop Area Testing of Oil Contaminated, Salt Contaminated, and Miscellaneous Samples

This section describes the measurements to be taken and/or performed and the treatment of the three to six prepared grease or oil coated samples (Test Spot #2 from Appendix C, Table C-1), the salt contaminated samples (Test Spot #3 from Appendix C, Table C-2), and the Random Parts described in Appendix C, Table C-3 (Test Spots #5 - #6).

Personnel needed

1. One PB7000M operator.
2. Two persons taking measurements, notes, and pictures.
3. If available, one Code 133 representative.

Setup and Before-Treatment Measurements Steps

1. Take stock of all equipment and samples needed to perform treatment and measurements:
    a. *APCR*: PB7000M48 power supply, plasma pen, power cable and adapters, air hoses, grounding cable, brushes, spare nozzles.
    b. *PPE*: Gloves, eye protection, respirators/dust masks, hearing protection.
    c. *Samples to be treated*: Test Spots #2 - #5.
    d. *Measurement instruments*: Dimension measurement tool, thickness probe, camera, IR thermometer, surface profile gauge, salinity test kit, and stopwatch.
2. Document the measurement tools to be used using the form in Appendix D.
3. Prepare Measurement Recording forms using the template in Appendix E.
4. Setup testing area on a table in an open area.
5. Setup proper ventilation in the form of a fan directing air over the testing table away from the operator, measurement persons, and other observes or by setting up a fume extraction system.
6. Measure the dimensions of the non-pre-prepared samples (specifically anything in table C-2).
7. Take pictures of setup and samples prior treatment.
8. Take thickness measurements on painted samples.
9. Take salinity measurements on salt contaminated samples.
10. Take temperature of samples prior to treatment.
11. Apply temperature crayons to the back of the samples to get a reading on temperatures reached.

APCR Treatment Procedure and Measurements Steps

For each sample

1. Ensure all operators, measurement personnel, and observers have on appropriate PPE.
2. Go through PB7000M setup procedure as outlined in user manual.
3. Ground sample to be tested.
4. Ready one person to take pictures and IR measurements and one to handle timing and recording notes.
5. Simultaneously start stopwatch timer and begin removal.
6. Begin APCR treatment of the sample, aiming for a clean but not overtreated substrate after removal.
7. Take pictures of the sample during treatment.

8. Take temperature measurements of the sample during treatment. Do not point the IR temperature gauge directly where the plasma is hitting it as it will interfere with the reading.
9. Upon completion of treatment, stop stopwatch and immediately measure the temperature of the area that was treated, then record temperature again after 30 seconds, 60 seconds, and 120 seconds. Keep the stopwatch running.

After-Treatment Measurements Steps

1. Take pictures of samples again under the same camera settings and lighting conditions used before treatment.
2. Brush off sample as necessary.
3. Take pictures of the samples again under the same camera settings and lighting conditions used before treatment.
4. Let sample cool to 100 deg F, record the time when this temperature is reached, and stop the stopwatch. Then perform designated measurements:
    a. Surface profile on painted sample, and
    b. Report the highest temperature reached by the temperature crayon markings.
5. Allow code 133 representative to evaluate the treated surface and record their evaluation.

Shop Area Treatment of Tiles on Prepared Mockup

This section describes the measurements to be taken and/or performed and the treatment of various tiles (Test Spot #4 from Appendix C, Table C-2).

Personnel needed

1. One PB7000M operator.
2. Two persons taking measurements, notes, and pictures.
3. If available, one approval representative.

Setup and Before-Treatment Measurements Steps

1. Take stock of all equipment and samples needed to perform treatment and measurements:
    a. *APCR*: PB7000M48 power supply, plasma pen, power cable and adapters, air hoses, grounding cable, brushes, spare nozzles.
    b. *PPE*: Gloves, eye protection, respirators/dust masks, hearing protection.
    c. *Samples to be treated*: Test Spot #4.
    d. *Measurement instruments*: Dimension measurement tool, thickness probe, camera, IR thermometer, and stopwatch.
2. Document the measurement tools to be used using the form in Appendix D.
3. Prepare Measurement Recording forms using the template in Appendix E.
4. Setup testing area.
5. Ensure proper ventilation.
6. Take pictures of setup and samples prior treatment.
7. Take multiple dimension measurements of the mockup including overall size, the size of various tiles, and their thicknesses.
8. Mark off treatment targets and measure the dimensions of these treatment target areas.
9. Take temperature of samples prior to treatment.
10. Apply temperature crayons to the back of the samples to get a reading on temperatures reached.

APCR Treatment Procedure and Measurements Steps

For each sample

1. Ensure all operators, measurement personnel, and observers have on appropriate PPE.
2. Go through PB7000M setup procedure as outlined in user manual.
3. Ground sample to be tested.
4. Ready one person to take pictures and IR measurements and one to handle timing and recording notes.
5. Simultaneously start stopwatch timer and begin removal.
6. Begin APCR treatment of the sample, aiming for a clean but not overtreated substrate after removal.
7. Take pictures of the sample during treatment.
8. Take temperature measurements of the sample during treatment. Do not point the IR temperature gauge directly where the plasma is hitting it as it will interfere with the reading.

9. Upon completion of treatment, stop stopwatch and immediately measure the temperature of the area that was treated, then record temperature again after 30 seconds, 60 seconds, and 120 seconds. Keep the stopwatch running.

After-Treatment Measurements Steps

1. Take pictures of samples again under the same camera settings and lighting conditions used before treatment.
2. Brush off sample as necessary.
3. Take pictures of the samples again under the same camera settings and lighting conditions used before treatment.
4. Let sample cool to 100 deg F, record the time when this temperature is reached, and stop the stopwatch. Report the highest temperature reached by the temperature crayon markings.
5. Allow approval representative to evaluate the treated surface and record their evaluation.

USS McKee and Submarine Mockup Use-Case Testing

This section describes the measurements to be taken and/or performed and the treatment of locations on the USS McKee (Test Spots #8 - #16 from Appendix C, Table C-5) and on the submarine mockup (Test Spots #17 - #21 from Appendix C, Table C-6). It is recommended that the submarine mockup testing be performed in one session and the USS McKee testing be performed in a separate session, preferably on a different day.

Personnel needed

1. One PB7000M operator.
2. Two persons taking measurements, notes, and pictures.
3. If available, one Code 133 representative.

Setup and Before-Treatment Measurements Steps

1. Take stock of all equipment needed to perform treatment and measurements:
    a. *APCR*: PB7000M48 power supply, plasma pen, power cable and adapters, air hoses, grounding cable, brushes, spare nozzles,
    b. *Additional Equipment*: Fume extraction system.
    c. *PPE*: Gloves, eye protection, respirators/dust masks, hearing protection.
    d. *Samples to be treated*: Test Spots #6 - #11.
    e. Measurement instruments: Dimension measurement tool, Sharpie®, thickness probe, camera, IR thermometer, surface profile gauge, and stopwatch.
2. Document the measurement tools to be used using the form in Appendix D.
3. Prepare Measurement Recording forms using the template in Appendix E.
4. Mark off areas to be treated using a Sharpie® marker.
5. Setup proper ventilation in each testing area as they are used by setting up a fume extraction system.
6. Measure the dimensions of each treatment area.
7. Take pictures of setup and treatment areas prior treatment.
8. Take thickness measurements (per Appendix E) on painted samples.
9. Take temperature of treatment areas prior to treatment.
10. Apply temperature crayons to the back of the samples to get a reading on temperatures reached.

APCR Treatment Procedure and Measurements Steps

1. Ensure all operators, measurement personnel, and observers have on appropriate PPE.
2. Go through PB7000M setup procedure as outlined in user manual.
3. Ground surface to be tested.
4. Ready one person to take pictures and IR measurements and one to handle timing and recording notes.
5. Simultaneously start stopwatch timer and begin removal.
6. Begin APCR treatment of the surface, aiming for a clean but not overtreated substrate after removal.
7. Take pictures of the area during treatment.

8. Take temperature measurements of the sample during treatment. Do not point the IR temperature gauge directly where the plasma is hitting it as it will interfere with the reading.
9. Upon completion of treatment, stop stopwatch and immediately measure the temperature of the area that was treated, then record temperature again after 30 seconds, 60 seconds, and 120 seconds. Keep the stopwatch running.

After Treatment Measurements Steps

1. Take pictures of samples again under the same camera settings and lighting conditions used before treatment.
2. Brush off sample as necessary.
3. Take pictures of the samples again under the same camera settings and lighting conditions used before treatment.
4. Let sample cool to 100 deg F, record the time when this temperature is reached, and stop the stopwatch. Then perform designated measurements:
   a. Surface profile on painted sample, and
   b. Report the highest temperature reached by the temperature crayon markings.
5. Allow code 133 representative to evaluate the treated surface and record their evaluation.

Appendix A: APCR Technology Summary

APS has developed a revolutionary technology that can effectively remove coatings including paints, sealants, gap fillers and other organic coatings from a wide variety of substrates using only compressed air and electricity. The PB7000M unit being used in this project runs off 440V 3 phase power and 90-100psi 3.5CFM compressed air. The power and compressed air can be supplied by available shipyard 440V power and compressed air or can be provided from a portable, low-pressure air compressor, and a small gas or diesel generator, making this system extremely portable and self-contained.

The APCR process produces a clean, chemically activated surface that is ready for re-coating, presents no undue occupational hazards to the operators, and creates no waste beyond the original coating material. Coatings are vaporized with an air plasma, and the layer-by-layer removal does not damage or alter the profile of the underlying substrate. This process has previously been developed for several other military and commercial specialty coating removal tasks.

The APCR system uses a beam of atmospheric pressure air plasma that can be directed at target coatings. This atmospheric air plasma beam is highly chemically activated and upon contact with a coating oxidizes the coating's organic components. The APCR process converts a significant portion of the removed coating into carbon dioxide and water vapor, leaving behind less solid mass than was present in the original coating. The remaining solids are mostly inorganic pigments and fillers that can be safely collected with a suitable vacuum attachment.

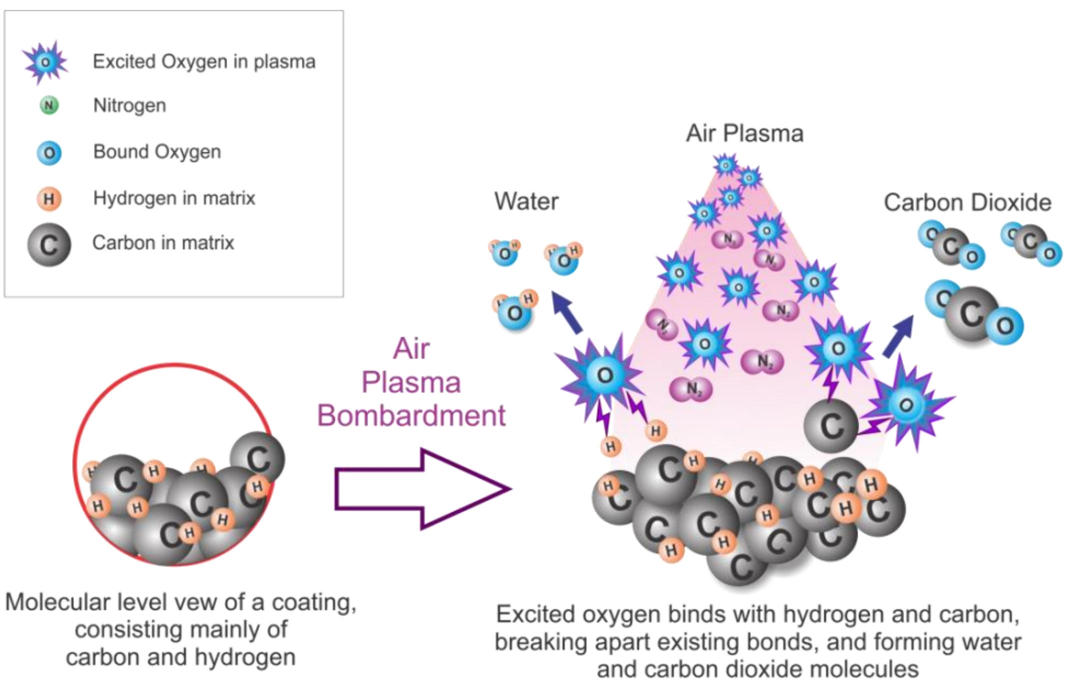

Figure A-1: Example of plasma etching/cleaning process

The two key elements of the APCR process are the pulsed electric field power supply and a plasma applicator or pen, as shown in Figure A-2. The plasma power supply applies a pulsed electric field to the internal electrodes of the pen. Air is introduced into the electrode region of the pen at high velocity to minimize the gas residence time in the electrode region. The plasma generated in the electrode region is directed through a nozzle, which concentrates the plasma flow into a beam and toward the surface to be processed. The combination of short residence time and spatial separation of the electrode region from the substrate produces a non-thermal plasma that is chemically activated at relatively low gas temperature, commonly referred to as a cold or non-thermal atmospheric plasma.

Many atmospheric plasma systems require expensive inert gas additives, such as helium or argon, to achieve stable operation at atmospheric pressure. The APS APCR system is unique in that it provides a high-power, stable discharge using only air as the feed gas. Operation of the plasma beam at high flow rates transports large quantities of atomic oxygen to the substrate surface. Atomic oxygen is the critical ingredient driving the coating removal process by converting the organic component of the coating into CO_2 and water vapor, leaving any pigments or fillers in the coating to be released as a powdery residue.

Figure A-2: PB-7000 APCR system

Appendix B: Project Background

Training of NNSY Personnel

APS visited Norfolk Naval Shipyard on November 6 – 7, 2019 and provided demonstrations to several dozen NNSY personnel and provided classroom training to ~10 mechanics. Due to time limitations, only 3 of the lecture attendees were able to go through hands-on training. Jaime Edwards, Jeffrey Grant, and Josh Harold completed the hands-on training and were evaluated for speed and quality removal by APS on the second day of APS's visit to NNSY. During training, treatment was performed on flat coupons as well as complex parts brought forth by persons in the shop area. The hands-on time trials were conducted on DH36 steel coupons. The specific version that was used for training is the Plasma*Blast*® PB7000M48. A unit was left with Jaime Edwards for use, demonstration, and practice.

On December 11, 2019, APS returned to NNSY to provide follow-up training and to administer a written test. Passage of both the practical and written tests is required to be certified by APS to use a PB7000 unit. Due to travel and sickness, Josh and Jaime were unavailable for this follow-up training and exam. However, Jeffery Grant passed both with high marks.

On February 20th, 2020, APS returned to NNSY to provide follow-up training and for Jaime Edwards. Jaime Edwards passed both the written and practical exams.

Use Case Identification

During the November and December 2019 trips, APS spoke with many NNSY personnel to learn about how the Plasma*Blast*® PB7000M could be used within their jobs. Of particular note, APS worked with Gaston Shaw, Jaime Edwards, Jeffrey Grant, and George Reed to define and document a set of candidate use cases and treatment scenarios for this SPTEP plan. In addition to gaining insights from these discussions, APS explored the submarine mock-up (used for training) and the decommissioned USS McKee (AS-41) to see and identify hands on examples of challenging coating removal operations where mobile APCR could provide comparative value.

Based on these tours and discussions, there are many locations where the PB7000M can be used to quickly deploy to areas for precision or small area coating removal tasks. In several of the use cases, a significant motivating factor is the simplicity of deployment. In other cases, the quality and speed of coating removal is the motivating factor for the use case. As noted elsewhere, a representative list of samples and use case areas have been identified as examples for APCR treatment in a shipyard setting. This list is presented in **Appendix C**.

Appendix C: Samples and Areas to be Treated

Day 1

Table C-1: Prepared Flat Samples

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
1	Shop	Fast-Clad coupons	9	Grit blasting/needle gun
2	Shop	Grease coated samples	3-6	Solvents

Table C-2: Other Prepared Samples

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
3	Shop	Salt contaminated samples	3	?
4	Shop 64 Mockup	Tile removal	3+	Come alongs, chisels, and sawzalls

Table C-3: Random Parts

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
5	Shop	Misc. test parts	?	?
6	Shop	Misc. test parts	?	?

Table C-4: Day 1 Sub Mockup Area

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
7	Sub Mockup	External surface for repainting	3	Grit blasting

Note: Some samples from Test Spot #1 and all samples from Test Spot #7 need to be repainted on Day 1 so that adhesion tests can be performed on Day 3.

Day 2

Table C-5: Treatment Areas on Decommissioned USS McKee

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
8	McKee	Bolts on small hatches on walls	10	Needle gun?
9	McKee	Bolts on walls in internal rooms	10	Needle gun?
10	McKee	Welds inside beams on walls	6	Needle gun
11	McKee	Bolts on ventilation ducts	10	Needle gun?
12	McKee	Interface between ventilation ducts	4	Needle gun?
13	McKee	Frame around large hatches/doors	2	Needle gun
14	McKee	Strip of removal on walls between rooms	4	Needle gun
15	McKee	Spot treatment areas with feathering for recoating	6	Needle gun
16	McKee	Anchor chain or another bio-fouled surface	3	

Day 3

Table C-6: Day 3 Treatment Areas on Submarine Mockup

Test Spot #	Location	Sample	Number of Samples/Instances	Current Technology Used
17	Sub Mockup	Outer surface, spots missed during blasting	3	Grit blasting
18	Sub Mockup	Hooks and bolts with paint missed during blasting	6	Grit blasting
19	Sub Mockup	Inside edges of beams in tank	3	Grit blasting
20	Sub Mockup	Vent tubes and pipes inside tank	4	Grit blasting
21	Sub Mockup	Inside tank, spots missed during blasting	3	Grit blasting

Appendix D: Measurement Tools Used Documentation Template

Date and Time: ______________________________ **Location:** ______________________

Instrument	Model	Property Of
Stopwatch		
Thickness Probe		
Camera		
IR Thermometer		
Temperature Crayons		
Salinity Test Kit		
Surface Profilometer		
Surface Profile Tape		
Micrometer		
Adhesion Test Tape		
Other 1:		
Other 2:		
Other 3:		

Appendix E: Measurements to be Taken

Test Spot	Location	Time	Dimensions	Thickness	Pictures	Temperature	Chloride	Surface Profile	Adhesion Testing	Code 133
1	Shop	Y	Y	Y	Y	Y		Y	Y	Y
2	Shop	Y	Y		Y	Y		Y		Y
3	Shop	Y	Y		Y	Y	Y	Y		Y
4	Shop 64 Mockup	Y	Y	Y	Y	Y				?
5	Shop	Y	Y	Y	Y	Y				Y
6	Shop	Y	Y	Y	Y	Y				Y
7	Sub Mockup	Y	Y		Y	Y				Maybe
8	McKee	Y	Y		Y	Y				Y
9	McKee	Y	Y		Y	Y				Y
10	McKee	Y	Y	Y	Y	Y				Y
11	McKee	Y	Y		Y	Y				Y
12	McKee	Y	Y	Y	Y	Y				Y
13	McKee	Y	Y	Y	Y	Y		Y		Y
14	McKee	Y	Y	Y	Y	Y		Y		Y
15	McKee	Y	Y	Y	Y	Y		Y		Y
16	McKee	Y	Y		Y	Y	Maybe			Y
17	Sub Mockup	Y	Y	Y	Y	Y		Y		Y
18	Sub Mockup	Y	Y		Y	Y				Y
19	Sub Mockup	Y	Y	Y	Y	Y		Y		Y
20	Sub Mockup	Y	Y	Y	Y	Y		Y		Y
21	Sub Mockup	Y	Y	Y	Y	Y		Y		Y

Appendix F: Measurement Recording Template

Test Spot #: ______________________________ Measurement Person 1: ____________________

Date and Time: ___________________________ Measurement Person 2: ____________________

Removal Operator: ________________________ Code 133 Representative: __________________

Pre-Treatment Measurements

Sample Dimensions (in)	Initial Thickness (mils)	Initial Temperature (F)	Other notes about the Sample/Areas

Pictures Taken: [ ] YES [ ] NO

Salinity Measurements: ______________________

During-Treatment Measurements

Time (seconds)						
Treatment Side Temperature (F)						
Back Side Temperature (F)						

Total Treatment Time (mm:ss): _____________________

Pictures Taken: [ ] YES [ ] NO

Post-Treatment Measurements

Time after Removal (seconds)	0	30	60	120		
Temperature (F)						

Pictures Taken: [ ] YES [ ] NO

Chloride Content Measurements: ______________________

Surface Profile (mils): ________________________

Code 133 Comments (use the back side if more space is needed)

____

____

Additional Notes (use the back side if more space is needed)

____

Attachment 3 – Experimentation and Documentation Images

Attachment 3: Experimentation and Documentation Images

This attachment contains compressed versions of the images taken during the experimentation phase of the Plasma*Blast*® Evaluation project. All pictures were taken by approved NNSY personnel and shared with APS by mail after testing visits were completed. Some images have been cropped or edited for visibility. Full resolution, unedited, and additional images may be obtained from NNSY or APS. All images taken during the testing phase have been saved and are available to interested parties upon request.

Table of Contents

1. Flat Panel Samples from Comparative Testing

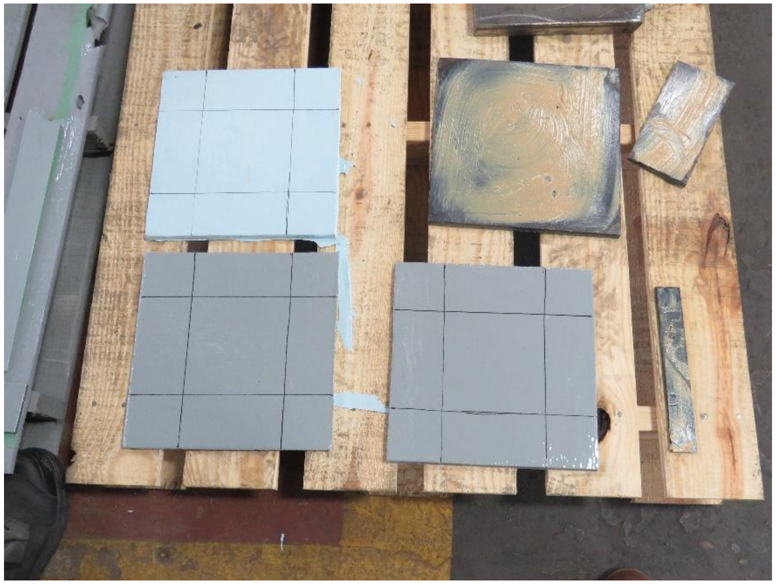

Figure 1: Flat Panel Samples 1-N-1, 1-G-1, and 1-G-2; Selected for APCR Treatment
March 11, 2020

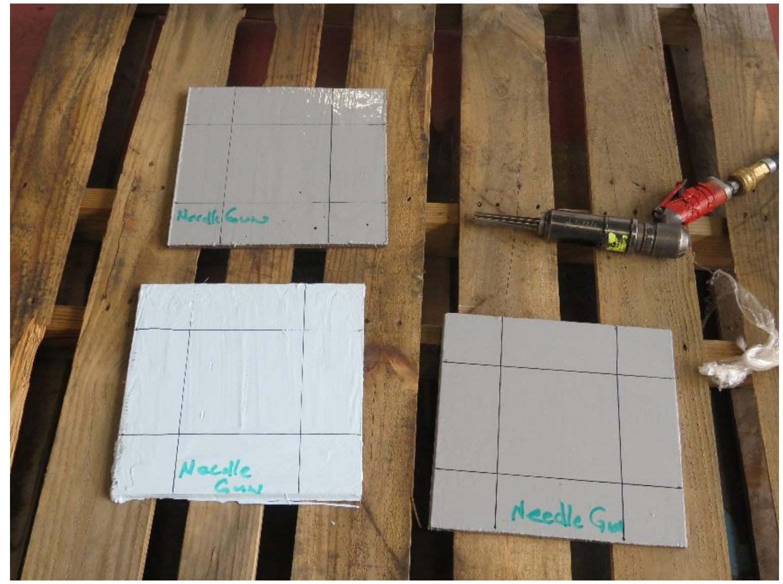

Figure 2: Flat Panel Samples 1-N-2, 1-G-3, 1-G-4; Selected for Needle Gun Removal
March 11, 2020

Figure 3: Flat Panel Samples 1-N-3, 1-G-5, 1-G-6; Coating Removed Via Abrasive Blasting
March 11, 2020

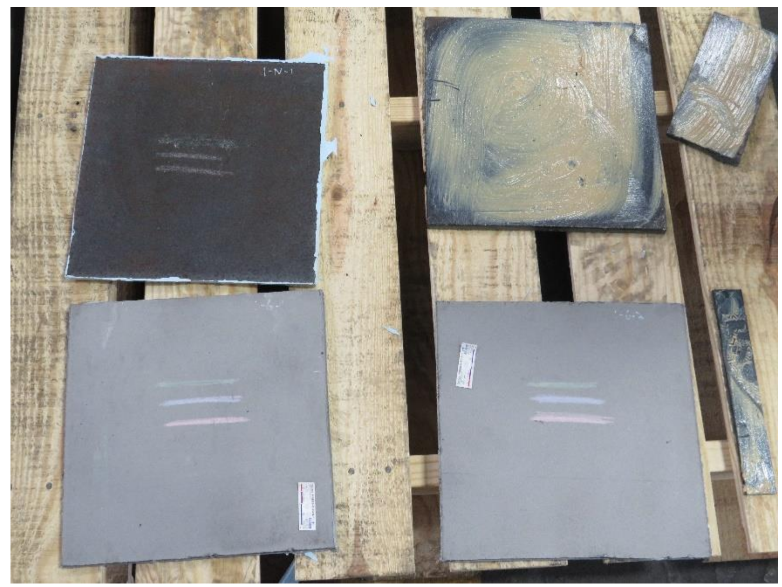

Figure 4: Backsides of Flat Panel Samples 1-N-1, 1-G-1, and 1-G-2 Before Treatmenet
March 11, 2020

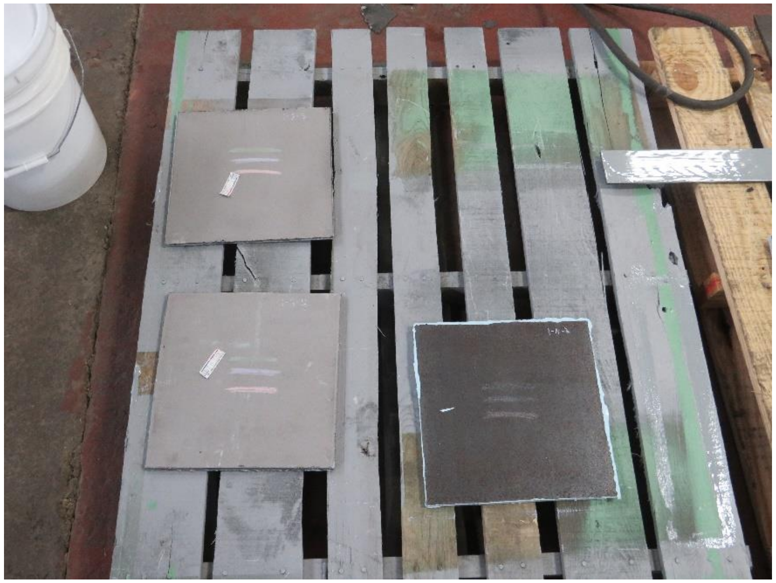

Figure 5: Backsides of Flat Panel Samples 1-N-2, 1-G-3, and 1-G-4 Before Treatment
March 11, 2020

Figure 6: Flat Panel Sample Receiving APCR Treatment
March 12, 2020

Figure 7: Flat Panel Sample Receiving Needle Gun Treatment
March 12, 2020

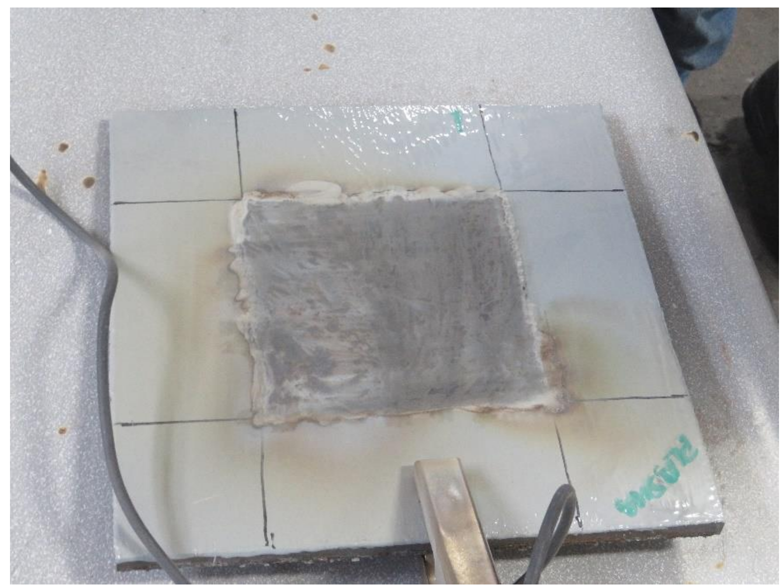

Figure 8: Flat Panel Sample 1-G-2 After APCR Treatment
March 11, 2020

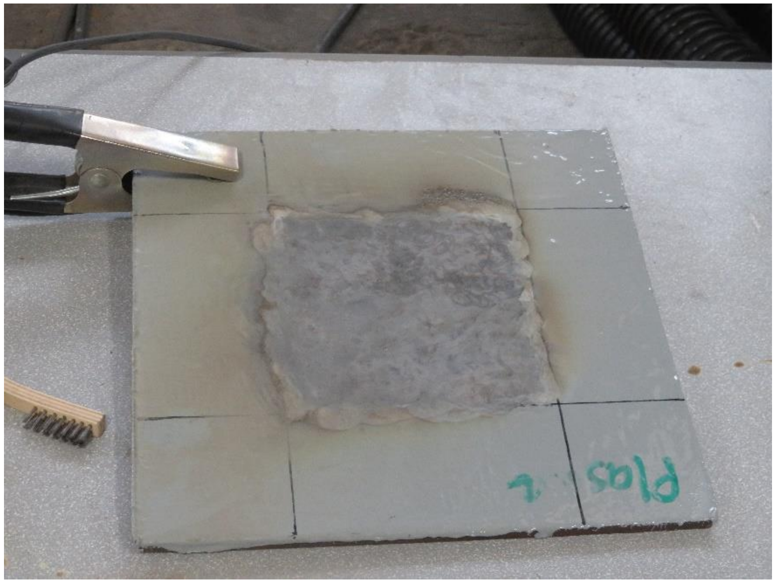

Figure 9: Flat Panel Sample 1-G-1 After APCR Treatment
March 11, 2020

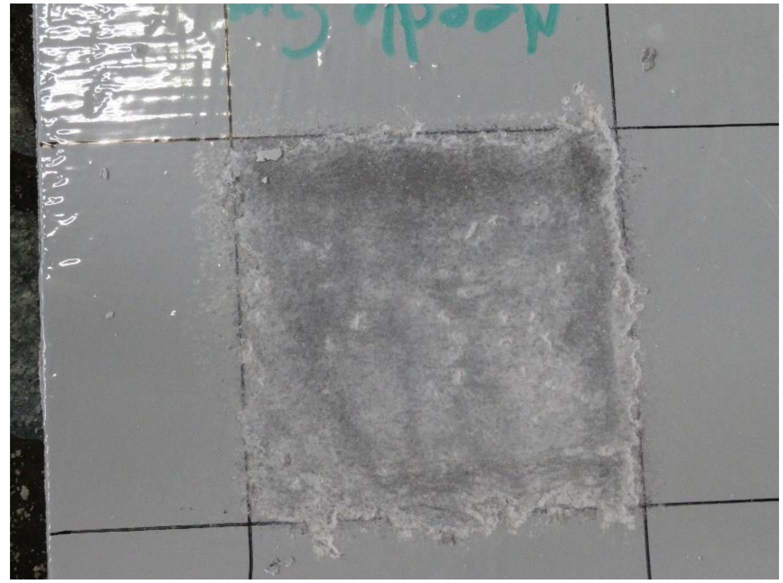

Figure 10: Flat Panel Sample 1-G-3 After Needle Gun Removal
March 11, 2020

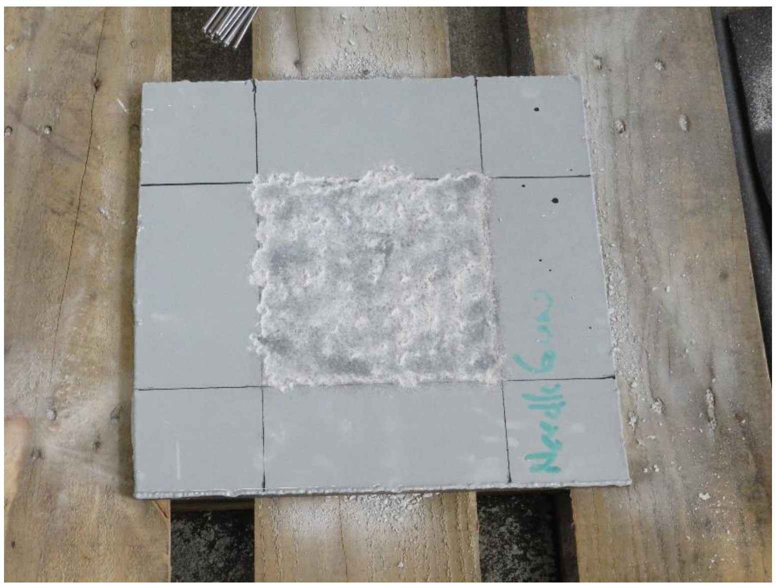

Figure 11: Flat Panel Sample 1-G-4 After Needle Gun Removal
March 11, 2020

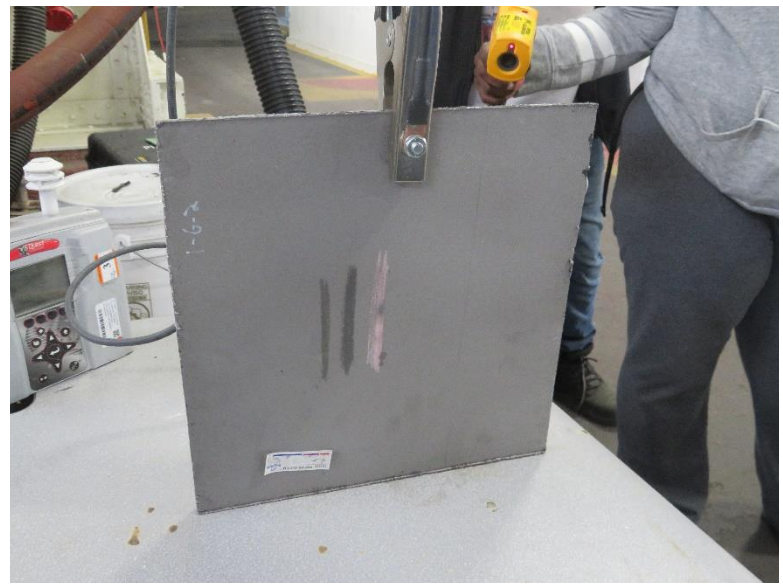

Figure 12: Backside of Flat Panel Sample 1-G-2 After APCR Treatment
March 11, 2020

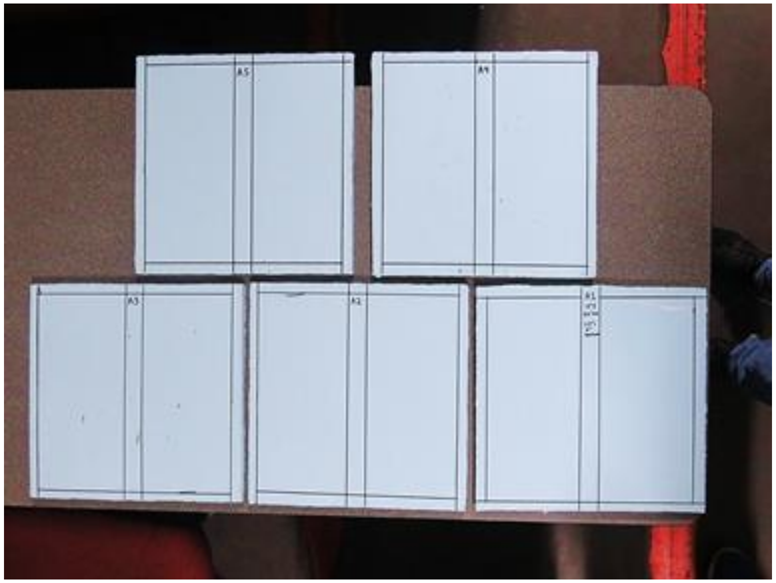

Figure 13: Flat Panel Samples A-1, A-2, A-3, A-4, A-5; Prepared for Second Round of Comparative Tests
August 26, 2020

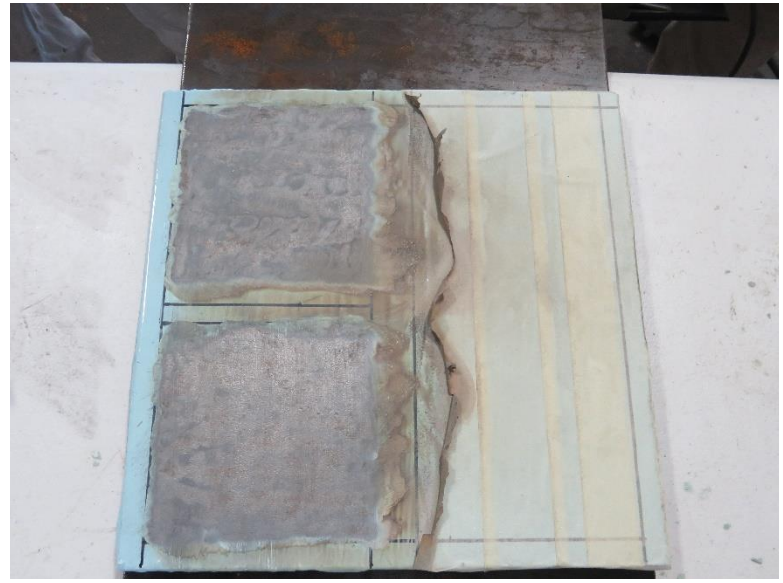

Figure 14: Sample A-5 After APCR Practice Treatment
August 27, 2020

Figure 15: Sample A-1 After APCR Treatment
August 27, 2020

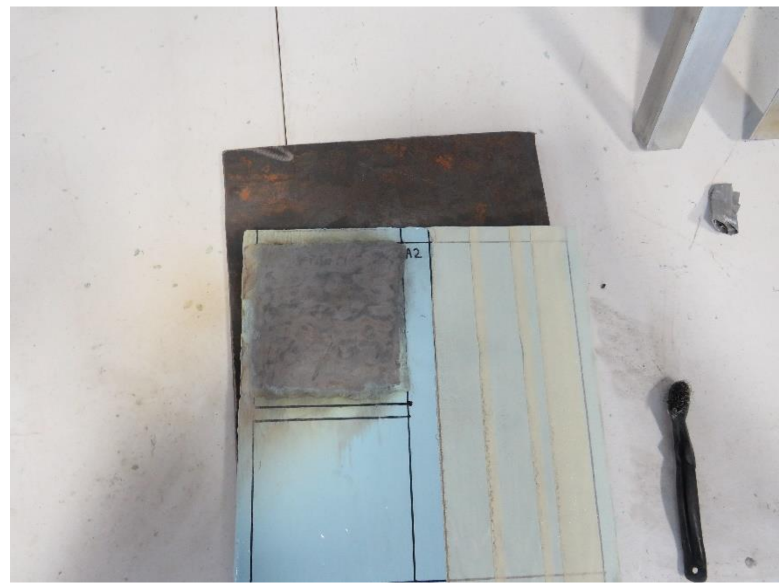

Figure 16: Sample A-2 After APCR Treatment
August 27, 2020

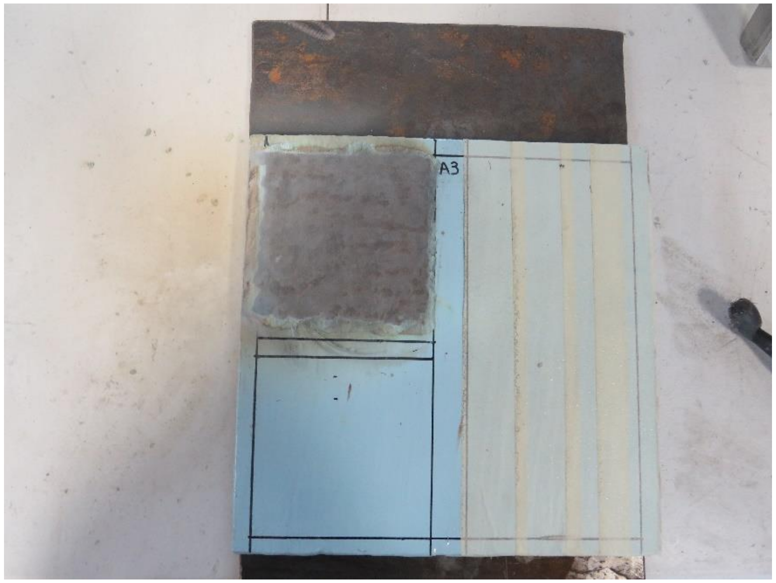

Figure 17: Sample A-3 After APCR Treatment
August 27, 2020

Figure 18: Sample A-4 After APCR Treatment
August 27, 2020

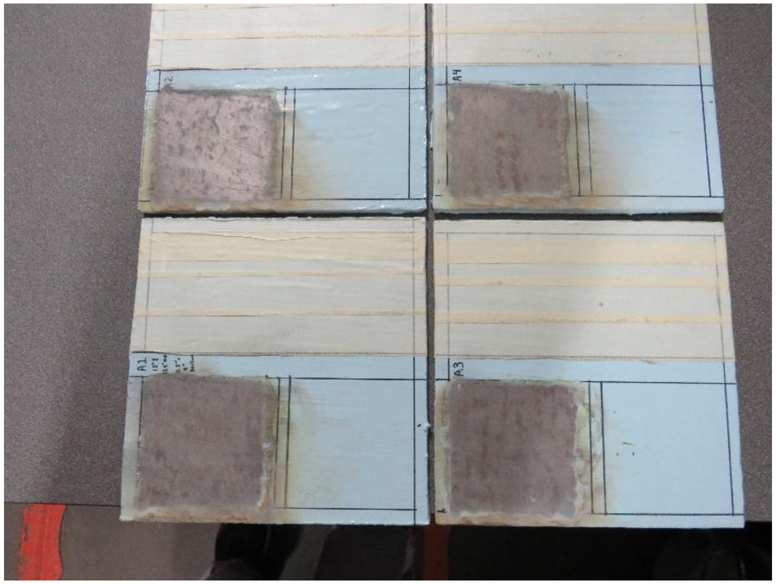

Figure 19: Samples A-1, A-2, A-3, A-4 After APCR Treatment
August 27, 2020

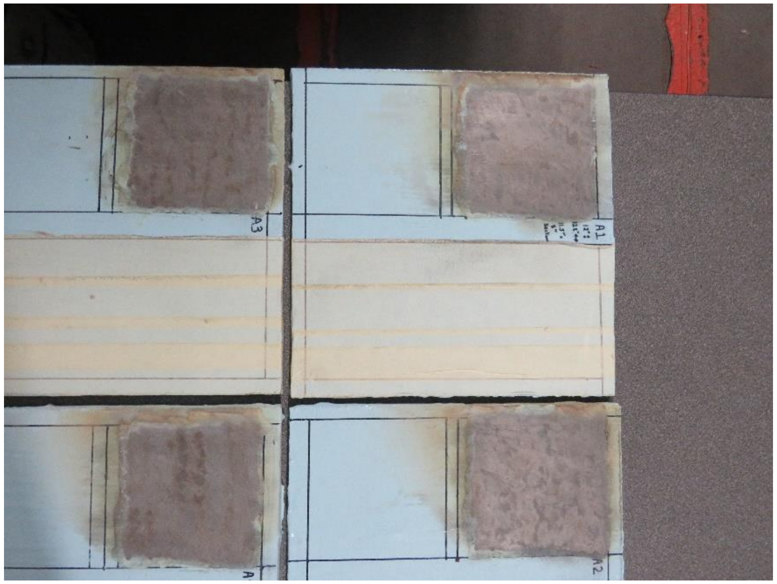

Figure 20: Samples A-1, A-2, A-3, A-4 After APCR Treatment
August 27, 2020

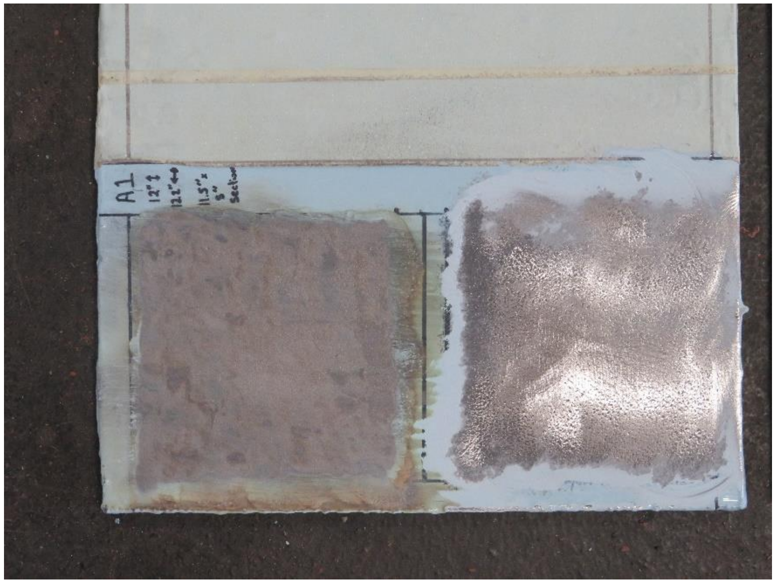

Figure 21: Sample A-1 After APCR (left) and Needle Gun and Grinding (Right)
August 27, 2020

Figure 22: Sample A-2 After APCR (right) and Needle Gun and Grinding (Left)
August 27, 2020

Figure 23: Sample A-3 After APCR (Left) and Needle Gun and Grinding (Right)
August 27, 2020

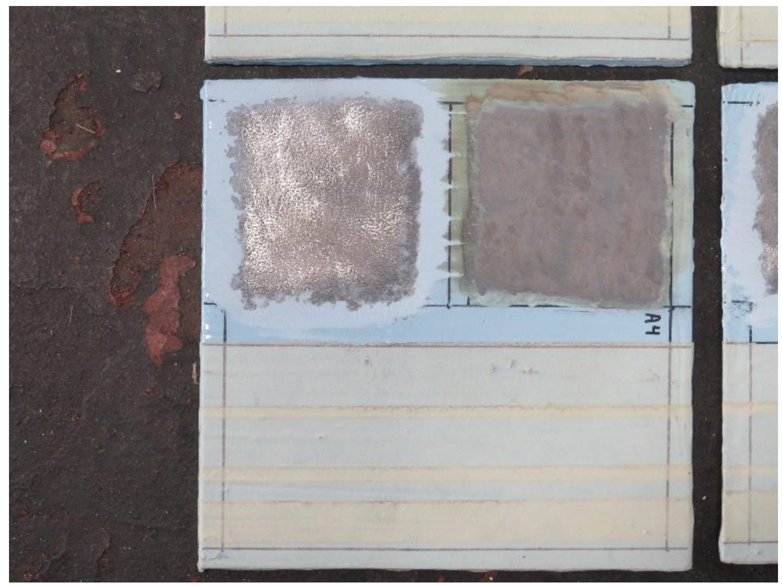

Figure 24: Sample A-4 After APCR (Right) and Needle Gun and Grinding (Left)
August 27, 2020

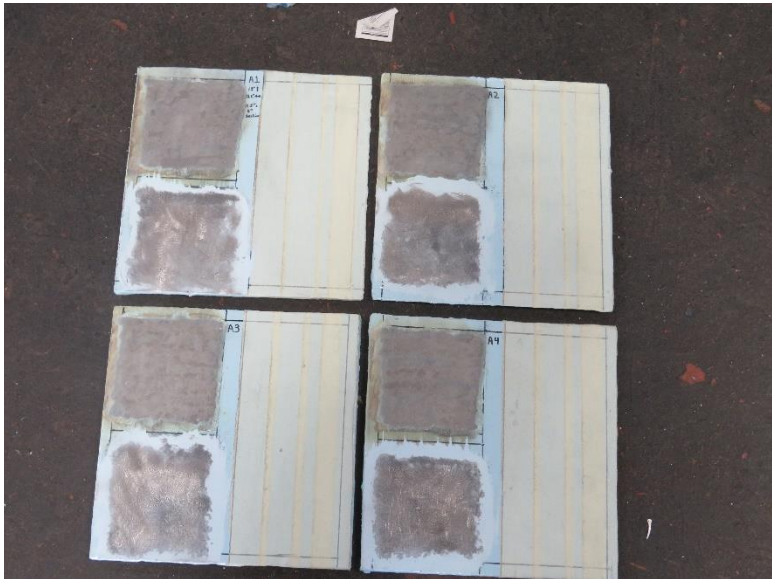

Figure 25: Samples A-1, A-2, A-3, A-4 After APCR and Needle Gun Treatments
August 27, 2020

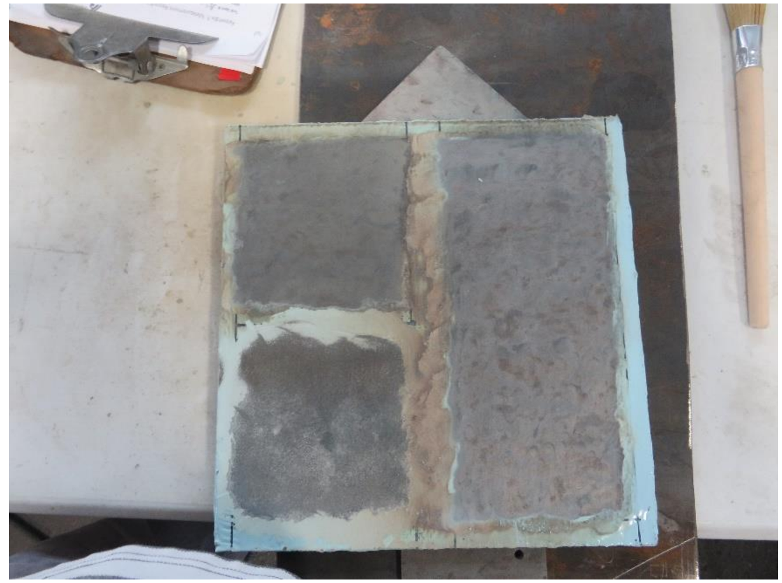

Figure 26: Sample A-2 After APCR Treatment on Full Right Half
August 27, 2020

2. Recoating Adhesion Test Samples

Figure 27: APCR Sample 1-G-1 After Dolly-Pull Coating Adhesion Testing

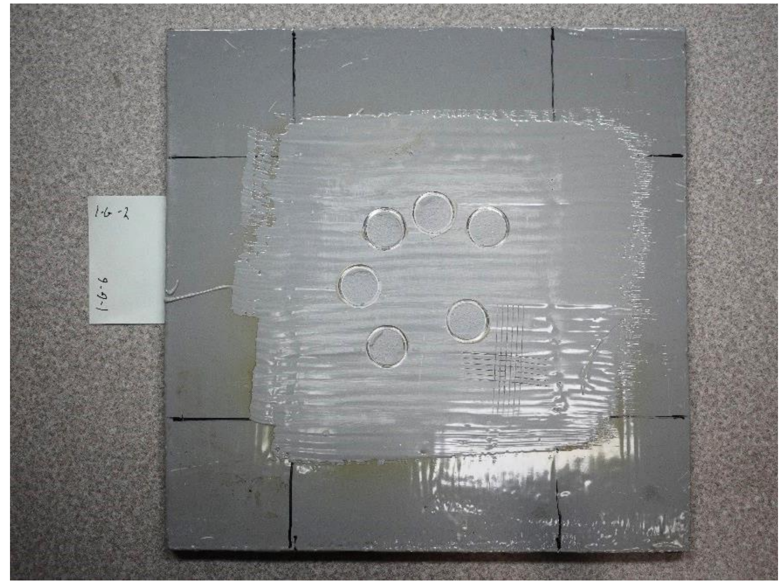

Figure 28: APCR Sample 1-G-2 After Dolly-Pull Coating Adhesion Testing

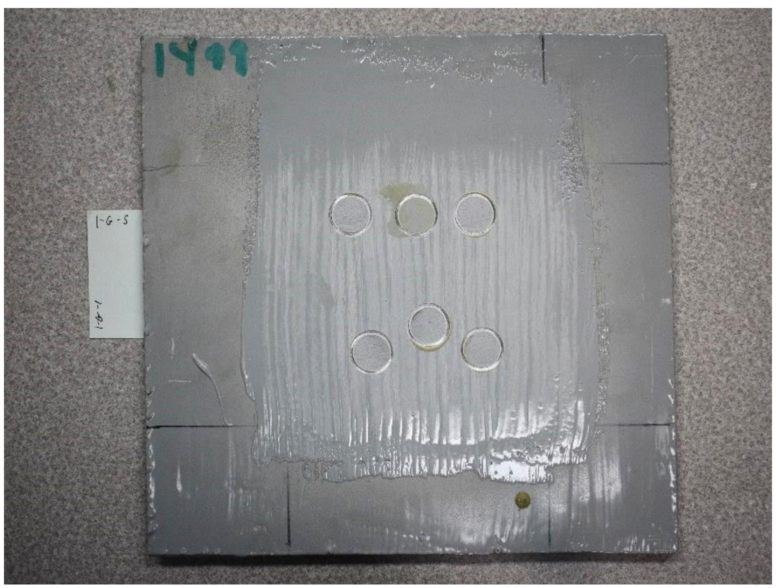

Figure 29: Abrasive Blasted Sample 1-G-5 After Dolly-Pull Coating Adhesion Testing

Figure 30: Abrasive Blasted Sample 1-G-6 After Dolly-Pull Coating Adhesion Testing

Figure 31: APCR Sample 1-G-1 Dolly-Pull Locations; All Failures were Cohesive Failures in the Body of the Coating

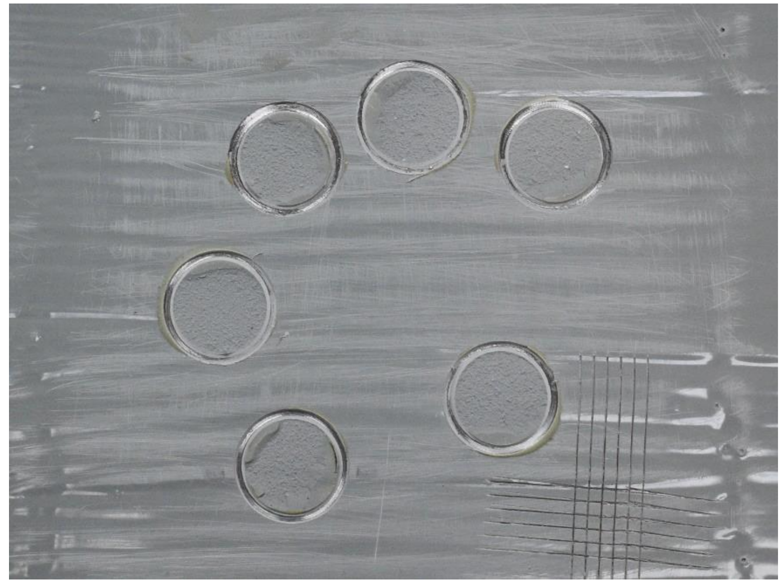

Figure 32: APCR Sample 1-G-2 Dolly-Pull Locations; All Failures were Cohesive Failures in the Body of the Coating

Figure 33: Abrasive Blasted Sample 1-G-5 Dolly-Pull Locations; One Failure Occurred in the Dolly Epoxy Adhesive

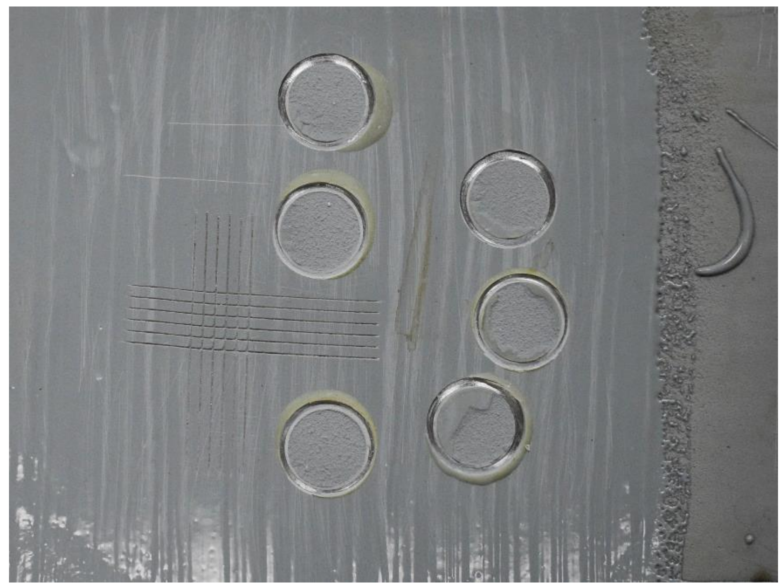

Figure 34: Abrasive Blasted Sample 1-G-6 Dolly-Pull Locations; All Failures were Cohesive Failures in the Body of the Coating

3. Testing Locations from Use Case Scenario Testing

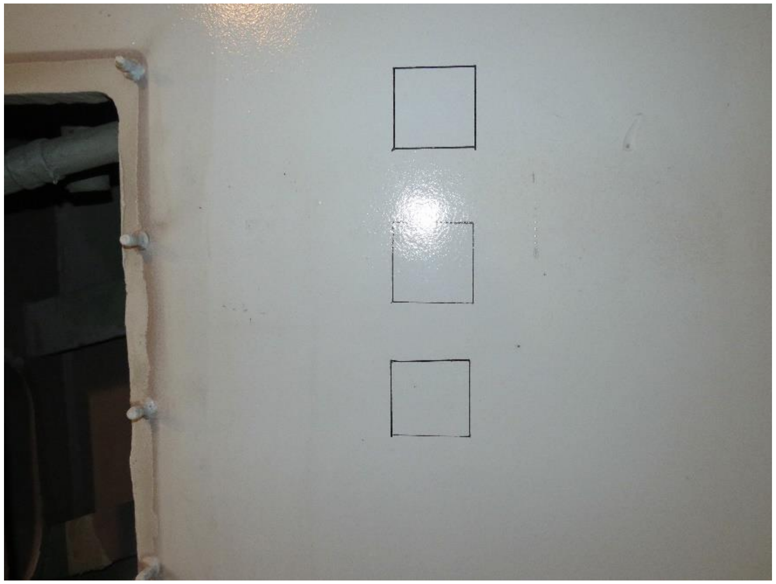

Figure 35: Sample Spots 17-1-B, 17-1-C, 17-1-T on Sub Tank Mockup Before Treatment March 12, 2020

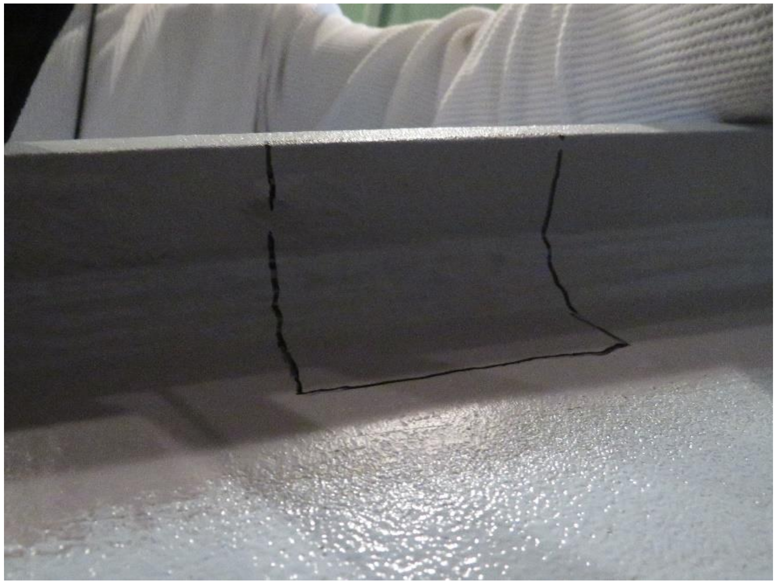

Figure 36: Sample Spot 19-1-Left on External Beam on Sub Mockup Before Treatment March 12, 2020

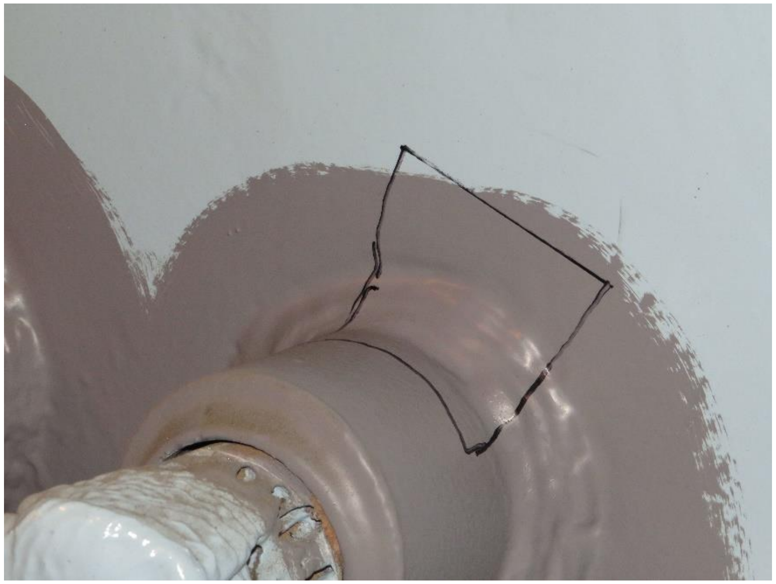

Figure 37: Sample Spot 20-1-Left on Welded Steel Pipe Section on Sub Mockup March 12, 2020

Figure 38: Sample Spot 18-3 (Center Left) Washer and Bolt Sound Tile Mount on Sub Mockup March 12, 2020

Figure 39: Sample Spot 17-1-Bottom Being Removed Via APCR
March 12, 2020

Figure 40: Sample Spot 19-2-Left Being Cleaned Using APCR
March 12, 2020

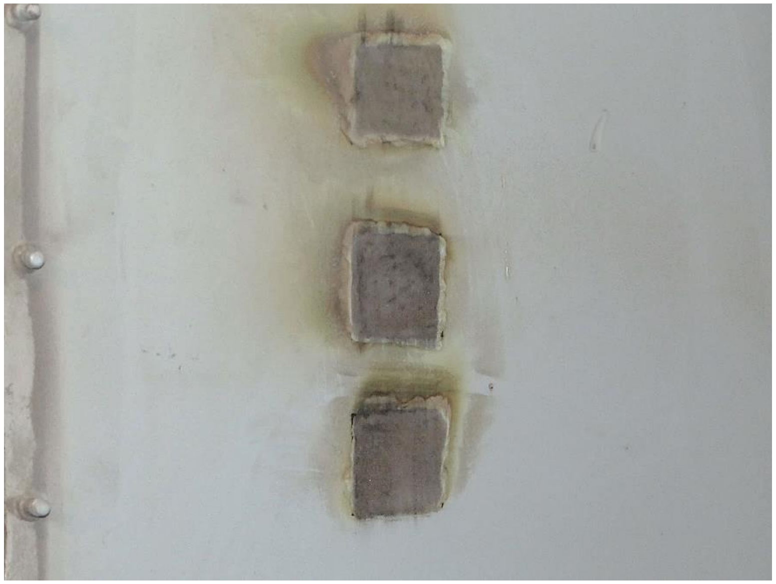

Figure 41: Sample Spots 17-1 After APCR Treatment
March 12, 2020

Figure 42: Sample 19-2-Left After APCR Treatment
March 12, 2020

Figure 43: Sample Spot 20-1-Left After APCR Treatment
March 12, 2020

Figure 44: Sample Spot 18-1-BL After Attempted Removal Using APCR
March 12, 2020

Figure 45: Sample Spot 18-3 After APCR Treatment
March 12, 2020

Figure 46: Welded Bolt Area Used for APCR Practice
March 12, 2020

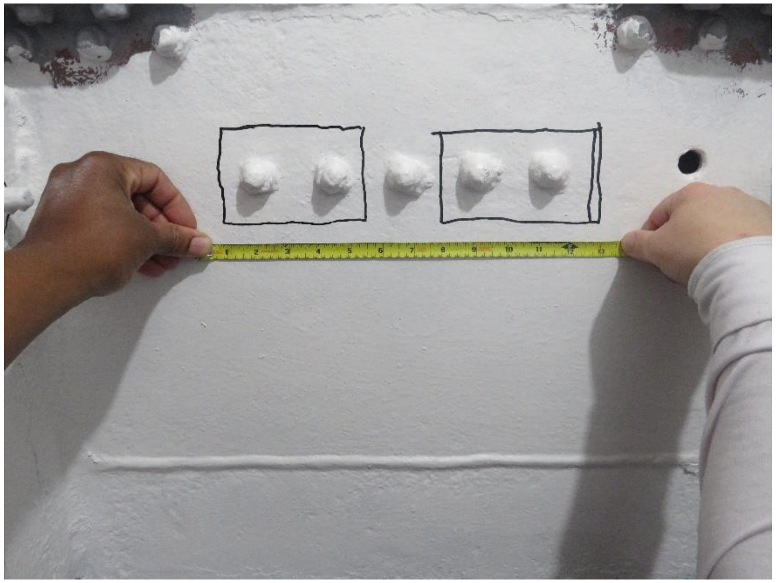

Figure 47: Sample Spots Sail-1 and Sail-2 on Sub Sail Mockup Before Removal
March 13, 2020

Figure 48: Sample Spot Sail-2-2 Welded Steel Bolt on Sub Sail Mockup
March 13, 2020

Figure 49: Sample Spots Sail-1 and Sail-2 Welded Nuts and Bolts on Sub Sail Mockup
March 13, 2020

Figure 50: Sample Spot Sail-1-2 Welded Steel Bolt on Sub Sail Mockup
March 13, 2020

Figure 51: Sample Spot Sail-2-1 Being Treated with Needle Gun Scaler
March 13, 2020

Figure 52: Sample Spot Sail-1-1 Being Treated with APCR
March 13, 2020

Figure 53: Sample Spot Sail-2-1 After Removal via Needle Gun. Underlying Surface Altered by Needle-Gunning Treatment
March 13, 2020

Figure 54: Sample Spot Sail-1-1 After APCR Treatment. Underlying Surface Revealed
March 13, 2020

Figure 55: Sample Spot Sail-2-2 After Removal via Needle Gun
March 13, 2020

Figure 56: Sample Spot Sail-1-2 After APCR Treatment
March 13, 2020

Figure 57: Sample Spots Sail-2 After Needle Gun Treatment
March 13, 2020

Figure 58: Sample Spots Sail-1 After APCR Treatment
March 13, 2020

4. Rubber SHT Sound Tile Removal Tests

Figure 59: Rubber SHT Sound Tile Samples Prepared on Bare Steel Sheet
March 11, 2020

Figure 60: Sample Tile 3-R-7 After Removal Via APCR
March 11, 2020

Figure 61: Steel Sheet Substrate After Removal of Sample 4-R-7 via APCR
March 11, 2020

Figure 62: Steel Sheet Substrate After Removal of Sample 4-B-5 via APCR
March 11, 2020

Figure 63: Honeycomb Tile on Sub Hull Mockup
March 11, 2020

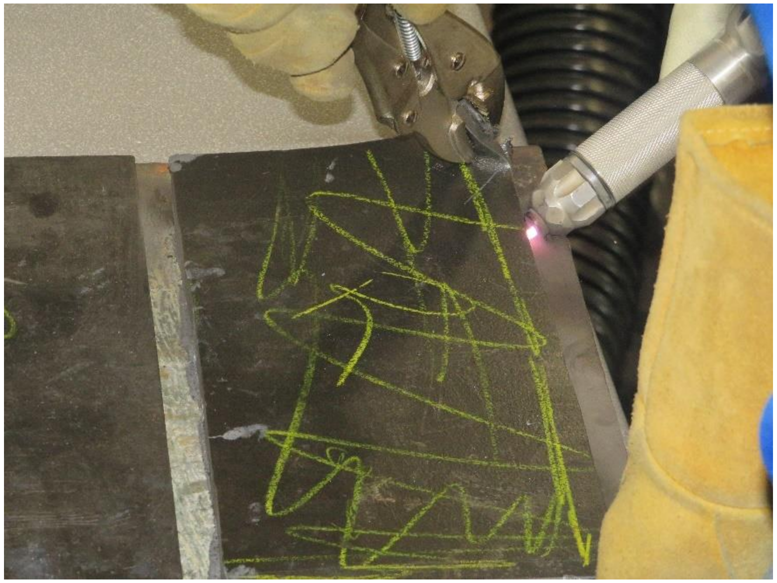

Figure 64: Sample Tile 4-R-7 Being Removed via Flensing with the PB7000M Tool
March 11, 2020

Figure 65: Sample Tile 4-B-5 Being Removed via Flensing with the PB7000M Tool
March 11, 2020

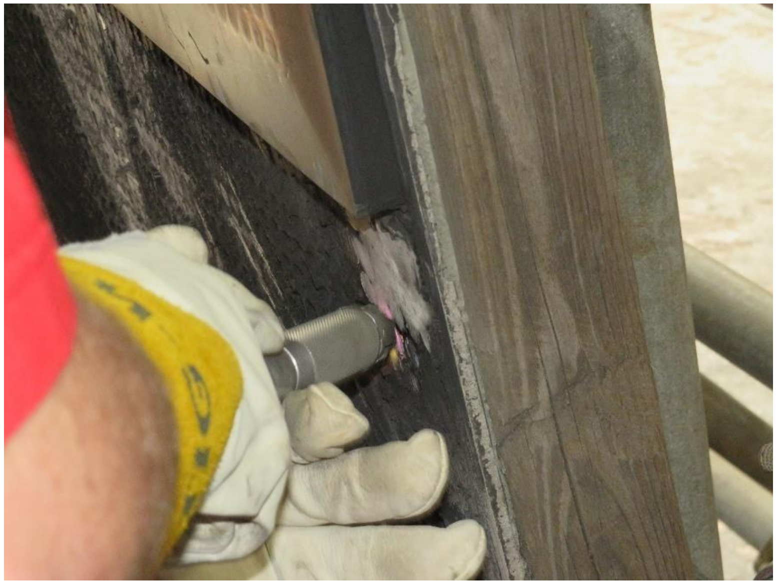

Figure 66: Leftover Honeycomb Tile Being Removed via APCR
March 11, 2020

5. Salt Concentration Effects Testing

Figure 67: Salt Contaminated Sample 3-4 After First Plasma Treatment
March 12, 2020

Figure 68: Salt-Contaminated Sample 3-4 After Second Plasma Treatment
March 12, 2020

Figure 69: Salt-Contaminated Sample 3-1 After Bresle Patch Test, Before Plasma Treatment
March 12, 2020

Figure 70: Salt-Contaminated Sample 3-1 After Plasma Treatment
March 12, 2020

6. Grease and Oil Removal Testing

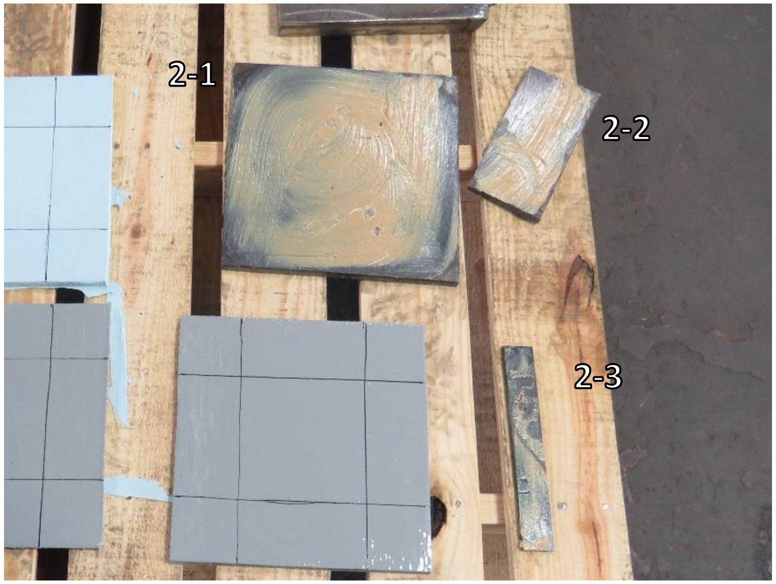

Figure 71: Grease Coated Samples 2-1, 2-2, 2-3 Before Treatment
March 11, 2020

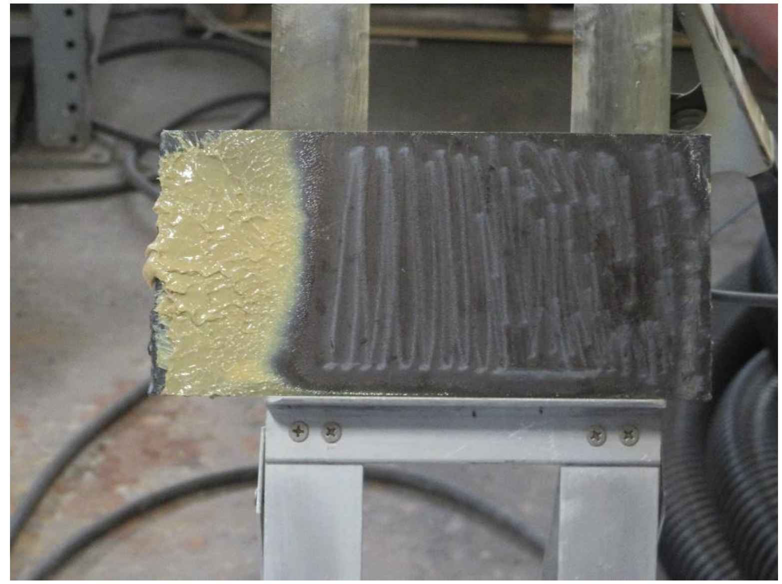
Figure 72: Grease Coated Sample 2-2 After Cleaning via APCR
March 11, 2020

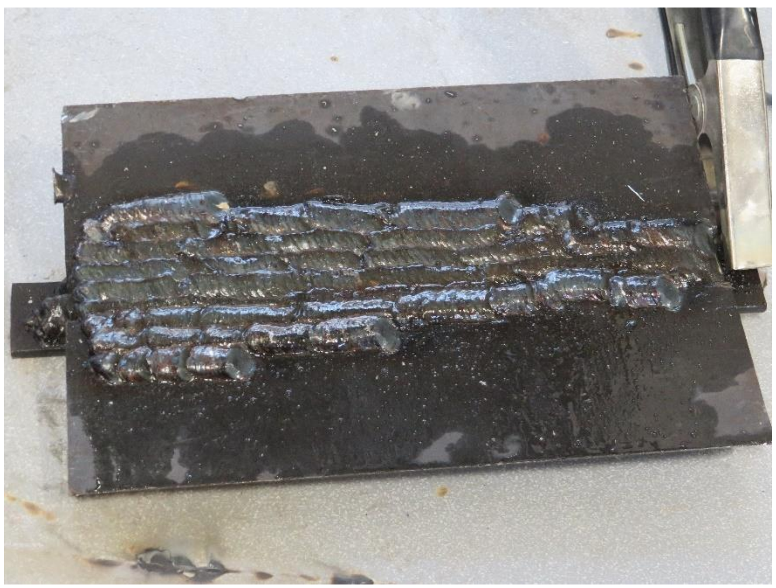
Figure 73: Grease Coated Sample 2-4 Before Treatment
March 12, 2020

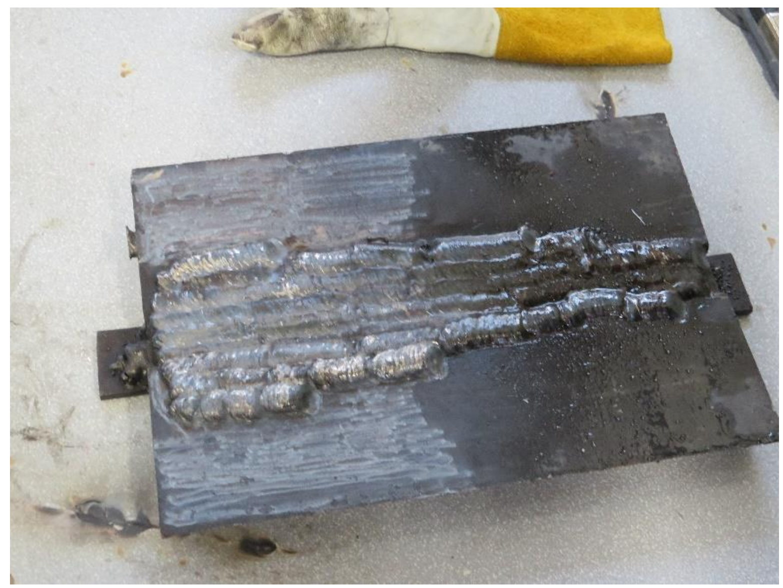
Figure 74: Grease Coated Sample 2-4 After Partial Treatment via APCR
March 12, 2020

7. Miscellaneous Images

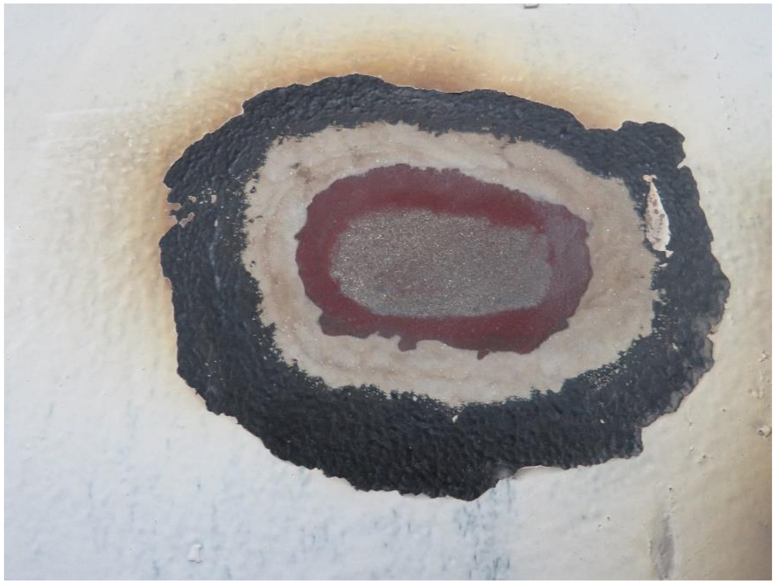

Figure 75: Demonstration of Feathered Removal via APCR on Sub Sail Mockup
March 13, 2020

Figure 76: Demonstration of Selective Layer Removal with PlasmaBlast® Tool
March 13, 2020