**Letter Report**
**TLR-RES/DE/REB-2021-12**

# *ASSESSMENT OF COLD SPRAY TECHNOLOGY FOR NUCLEAR POWER APPLICATIONS*

Date:
September 2021

Prepared in response to Task 1A in NRC Advanced Manufacturing Technologies Action Plan, Revision 1 and Task 2 of User Need Request NMSS-2021-004 , by:

*K. A. Ross*
Pacific Northwest National Laboratory

*J. P. Lareau*
Pacific Northwest National Laboratory

*S.W. Glass*
Pacific Northwest National Laboratory

*R. M. Meyer*
Pacific Northwest National Laboratory

NRC Project Manager:
*Bruce Lin*
Materials Engineer
Reactor Engineering Branch

**Division of Engineering**
**Office of Nuclear Regulatory Research**
**U.S. Nuclear Regulatory Commission**
**Washington, DC 20555–0001**

Pacific
Northwest
NATIONAL LABORATORY

PNNL-30299

# Assessment of Cold Spray Technology for Nuclear Power Applications

September 2021

K. A. Ross
J. P. Lareau
S. W. Glass
R. M. Meyer

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Contract DE-AC05-76RL01830
Interagency Agreement: 31310019N0001

PACIFIC NORTHWEST NATIONAL LABORATORY
*operated by*
BATTELLE
*for the*
UNITED STATES DEPARTMENT OF ENERGY
*under Contract DE-AC05-76RL01830*

PNNL-30299

# Assessment of Cold Spray Technology for Nuclear Power Applications

September 2021

K. A. Ross
J. P. Lareau
S. W. Glass
R. M. Meyer

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Contract DE-AC05-76RL01830
Interagency Agreement: 31310019N0001

Pacific Northwest National Laboratory
Richland, Washington 99354

# Summary

This report provides an overview of cold spray (CS) technology as it relates to repair and fabrication of metal alloys in the nuclear power industry. CS is a relatively new technology with applications established in other industries (e.g., aerospace, defense), and greater use of CS is anticipated within the nuclear power industry. This report is prepared in support of the United States Nuclear Regulatory Commission (NRC) Action Plan for Advanced Manufacturing Technologies (AMTs) Rev. 1, which includes objectives to identify the AMTs most likely to be used for nuclear power applications that require NRC approval, and to prepare NRC staff to review regulatory submittals containing components manufacturing using AMTs. In addition to providing an overview of CS technology, this report highlights engineering and scientific knowledge gaps of CS and rates the size of the knowledge gaps. It also assesses importance rankings of the knowledge gaps as they relate to several application categories. The application categories considered in this exercise include factory-applied CS for chloride induced stress corrosion cracking (CISCC) mitigation, field CISCC repair, light water reactor (LWR) factory structural fabrication, and LWR field dimensional restoration and corrosion protection. The combination of a knowledge gap size rating and importance ranking for an application can be used to prioritize additional data or information gathering efforts.

It is important to recognize that anticipated near term applications for CS in the nuclear power industry are limited to non-structural coatings. CS can deposit material with improved properties, such as wear and corrosion resistance, to enhance performance and extend the service life of new and existing components. Most military work has been performed using aluminum as the CS powder material. Application of CS is expanding beyond the military to component repair and manufacturing in other sectors such as aerospace, medical, electronics, and energy. The recent extension of CS beyond military applications, and the fact that most existing applications are aluminum, leads to considerable knowledge gaps for nuclear applications involving other types of alloys. In the nuclear power industry, some potential applications of CS technology include:

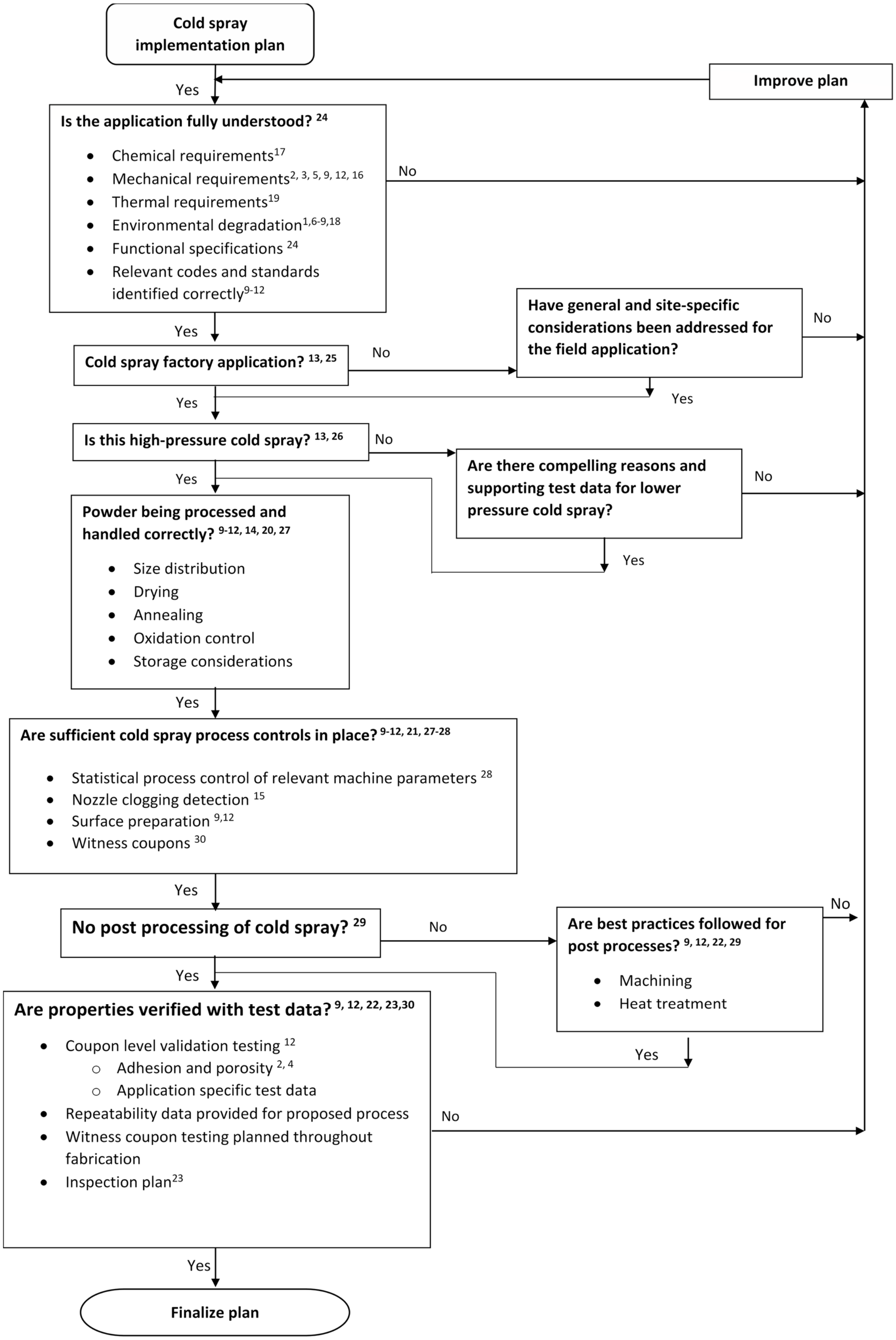
- Mitigation and repair of stress corrosion cracking (SCC), intergranular attack, CISCC, flow accelerated corrosion (FAC), and other types of corrosion by applying a protective coating to isolate the component's structural material from the corrosive environments. Candidate components include primary and secondary steam supply system piping and vessels, fuel cladding, heat exchanger surfaces, and spent fuel canisters.
- Rebuilding and resurfacing valve seats and eroded pipe elbows.
- Plugging and repairing active fluid leaks.
- Fabrication of accident tolerant fuel based on multilayer cladding.
- Additive manufacturing technology for new fleet nuclear power plant fabrication.

CS technology was initially developed in Russia during the mid-1980s. CS has been adopted as a valuable repair and mitigation process and additive manufacturing method promoted by the Army Research Laboratory through the Cold Spray Action Team annual conferences since 2010. Powdered 10 to 100 micron (0.001 to 0.1 mm) diameter metal particles are accelerated to two to three times the speed of sound in a heated gas and impacted on the substrate to be coated. Upon impact, an extreme plastic deformation at the particle-substrate interface produces metallurgical bonding and mechanical interlocking. The standard CS process can produce coatings as thin as 100 microns (0.1 mm). Using specialized equipment and small powder diameters, coatings as thin as 10 microns (0.01 mm) can be achieved. For most

materials, there is no theoretical limit to the thickness that can be applied by CS. Typically, coating thicknesses range between 0.5 to 10 mm (0.02 and 0.4 inches) thick. Thicker builds are common for CS dimensional restoration of components. CS is a technology of interest for near net shape additive manufacturing for specialty applications. CS advantages include:

- Little to no thermal stress associated with the coating surface because powders are not heated close to their melt temperature.
- CS coatings can induce compressive residual stresses in and around CS coatings, thereby minimizing susceptibility to cracking or corrosion when the mechanisms rely on surface tensile stresses.
- CS work hardening can have a beneficial influence on erosion, corrosion, and wear behavior.
- CS is cost competitive with other metal coating and powder based additive manufacturing techniques.
- Vast range of process parameters, materials, and equipment configurations enable broad applicability.

To realize these advantages, careful analysis of the application requirements and suitable implementation of procedures to manage quality is necessary to achieve success. Some key process challenges that can compromise CS coating quality include nozzle clogging, surface oxides that can hinder adhesion, and applying CS on difficult geometries such as inside corners. A more complete illustration of process considerations associated with CS applications is provided through the schematic in Figure S-1. This schematic provides a framework to make sure all relevant considerations are understood and addressed during CS implementation. This framework is based on observed best practices throughout various industries. While this framework (i.e., Figure S-1) is typically followed during CS process development, it is valuable to understand and evaluate a proposed CS implementation using this framework to determine its adequacy for an intended application.



1) ASTM B117
2) ASTM D4541
3) ASTM E92
4) ASTM E2109
5) ASTM F3007
6) ASTM G61
7) ASTM G78
8) ASTM G134
9) MIL-STD-3021
10) MIL-DTL-32495
11) MIL-DTL-32495A
12) UIPI 6320-901
13) Sec. 2.1
14) Sec. 2.2.1
15) Sec. 2.2.3
16) Sec. 2.3.3
17) Sec. 2.3.4
18) Sec. 2.3.5
19) Sec. 2.3.6
20) Sec. 2.4.1
21) Sec. 2.4.2
22) Sec. 2.4.3
23) Sec. 2.4.4
24) Sec. 2.4.5.1
25) Sec. 2.4.5.2
26) Sec. 2.4.5.3
27) Sec. 2.4.5.4
28) Sec. 2.4.5.5
29) Sec. 2.4.5.6
30) Sec. 2.4.5.7

Figure S-1 Guidance for CS process implementation. This schematic provides a strategy to ensure relevant considerations are understood and addressed relative to CS implementation.

# Acknowledgments

The authors express gratitude to external collaborators for their willingness to share information for this report as listed below:

- Dr. Victor Champagne and Aaron Nardi of the Army Research Laboratory provided information, data, and critiques for sections of this report.
- Dr. Lee Friant (Exelon Corporation) and Kyle Johnson (VRC Metal Systems) provided pictures and information regarding their Small Business Innovation Research project on adding a corrosion resistant coating to prevent sea water crevice corrosion for a nuclear plant valve.
- Dr. Arash Parsi (Westinghouse Electric Corporation) provided information on nickel coatings for the prevention of primary water stress corrosion cracking as well as information on oxidation protection for nuclear fuel rods using a chromium coating.
- Thomas Stamey (Puget Sound Naval Shipyard) for providing information on Naval Sea Systems Command qualification processes for cold spray.
- The numerous presenters at the Cold Spray Action Team Conference for sharing their experiences with cold spray applications.

# Acronyms and Abbreviations

| | |
|---|---|
| Al | aluminum |
| AMP | aging management program |
| AMT | advanced manufacturing technologies |
| ARL | Army Research Laboratory |
| ASME | American Society of Mechanical Engineers |
| ASTM | ASTM International (formerly American Society for Testing and Materials) |
| CISCC | chloride induced stress corrosion cracking |
| cm | centimeter |
| COD | crack opening dimension |
| CoC | certification of compliance |
| CPCu | commercially pure copper |
| CPNi | commercially pure nickel |
| CrC | chromium-carbide |
| CS | cold spray |
| CSAT | Cold Spray Action Team |
| CSAM | Cold Spray Additive Manufacturing |
| Cu | copper |
| DCSS | dry cask storage systems |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| ECCS | emergency core cooling system |
| EMAT | electromagnetic acoustic transducer |
| EPRI | Electric Power Research Institute |
| FAC | flow accelerated corrosion |
| HAZ | heat affected zone |
| HPCS | high pressure cold spray |
| IGSCC | intergranular stress corrosion cracking |
| in. | inch |
| ISFSI | independent spent fuel storage installation |
| ISO | International Standard Organization |
| ITNS | important to nuclear safety |
| kg | kilogram |
| ksi | 1000 pounds/square inch |
| lbs | pounds |
| LOCA | loss of coolant accident |
| LPCS | low pressure cold spray |

| | |
|---|---|
| LWR | light water reactor |
| m | meter |
| mm | millimeters |
| MPa | mega pascals |
| m/s | meters per second |
| NAVSEA | Naval Sea Systems Command |
| NDE | nondestructive evaluation |
| NEI | Nuclear Energy Institute |
| Ni | nickel |
| NPP | nuclear power plant |
| NRC | U.S. Nuclear Regulatory Commission |
| NSSS | nuclear steam supply system |
| OD | outside diameter |
| PNNL | Pacific Northwest National Laboratory |
| psi | pounds per square inch |
| PWR | pressurized water reactor |
| PWSCC | primary water stress corrosion cracking |
| RTQA | real time quality assurance |
| s | second |
| SBIR | Small Business Innovation Research |
| SCC | stress corrosion cracking |
| Sec. | Section |
| SEM | scanning electron microscopy |
| SPC | statistical process controls |
| SS | stainless steel |
| Ti | titanium |
| TiC | titanium carbide |
| UIPI | Uniform Industrial Process Instruction |
| $V_{cr}$ | critical velocity |

# Contents

Summary ........ vi
Acknowledgments ........ ix
Acronyms and Abbreviations ........ x
Contents ........ xii
1.0 Introduction and Background/Purpose ........ 1
    1.1 CS Technology Introduction ........ 1
    1.2 Equipment and Carrier Gases ........ 2
    1.3 Powders and Applications ........ 3
2.0 CS Technology Overview/Assessment ........ 5
    2.1 Process Description ........ 5
        2.1.1 Equipment ........ 6
        2.1.2 Robotic and Manual Delivery Systems ........ 11
    2.2 Process Parameters and Control ........ 11
        2.2.1 Powder Size, Shape, and Processing ........ 13
        2.2.2 Deposition Efficiency/Powder Feed Rates ........ 14
        2.2.3 Nozzle Control/Nozzle Clogging ........ 14
        2.2.4 Surface Preparation/Post Cleaning ........ 15
    2.3 Coating Properties and Performance ........ 17
        2.3.1 Adhesion ........ 18
        2.3.2 Water Permeability ........ 18
        2.3.3 Mechanical Robustness ........ 18
        2.3.4 Chemical Resistance ........ 19
        2.3.5 Erosion Resistance ........ 19
        2.3.6 Thermal Considerations ........ 20
        2.3.7 Radiation Resistance ........ 20
        2.3.8 Stress Corrosion Cracking Resistance ........ 21
    2.4 Process Quality Management ........ 21
        2.4.1 Pre-process Quality Management ........ 22
        2.4.2 In-process Quality Management ........ 23
        2.4.3 Post-process Quality Management ........ 24
        2.4.4 In-service Quality Management ........ 27
        2.4.5 Comprehensive Process Quality Management ........ 27
3.0 CS Applications ........ 33
    3.1 Applications in Non-Nuclear Industries ........ 33
    3.2 Nuclear Applications ........ 34
        3.2.1 Application of CS to Hanford Waste Tanks ........ 34
        3.2.2 Investigations of CS Applications by the Nuclear Power Industry ........ 35

3.2.3 Other Potential Nuclear Power Industry Applications of CS ................. 41
4.0 Knowledge Gap Analysis and Importance Ranking of CS in Nuclear Applications......... 48
4.1 Knowledge Gap Analysis ........................................................................ 48
4.2 Importance Rankings for Knowledge Gaps ........................................................ 57
5.0 Summary and Conclusions ........................................................................ 61
6.0 References ........................................................................................ 63

# Figures

Figure 1-1 A schematic of CS process. .......... 3

Figure 1-2 Helium recovery system installation (courtesy of ARL). .......... 3

Figure 2-1 VRC Metal Systems Generation III CS system with a conventional nozzle (courtesy of VRC Metal Systems) in manual handheld operation. .......... 7

Figure 2-2 VRC Metal Systems Generation III CS system at PNNL with a conventional nozzle with CS gun mounted to an industrial robot. .......... 7

Figure 2-3 Portable Generation III CS System for shipboard use with each component capable of fitting through a normal hatchway (courtesy of VRC Metal Systems). .......... 8

Figure 2-4 High pressure stationary industrial CS equipment for factory CS of high melt temperature materials such as MCrAlY (a family of thermal and corrosion barrier coatings where M = Co, Ni or Co/Ni), Ti6Al4V, Inconel, and SS (Plasma Giken 2018). .......... 9

Figure 2-5 Handheld CS nozzle for small area application (courtesy of ARL). .......... 10

Figure 2-6 Miniature nozzle for confined spaces as small as 1.5 in. (38 mm) (PNNL photo). .......... 10

Figure 2-7 Particle velocity versus particle diameter (microns) compared to $V_{cr}$ using He gas with given temperature and pressure. .......... 12

Figure 2-8 Particle velocity vs. particle diameter (microns) compared to $V_{cr}$ using $N_2$ for a given temperature and pressure. .......... 12

Figure 2-9 Alloy 625 Inconel sprayed onto a thin SS alloy 304 substrate, causing distortion (PNNL photo). .......... 14

Figure 2-10 SS 316 CS coating on SS 304L substrates applied with and without nozzle clogging. .......... 15

Figure 2-11 CS coating crack caused by large surface discontinuity on the substrate. (PNNL data.) .......... 16

Figure 2-12 Cavitation damage for various surfaces. .......... 20

Figure 2-13 Examples of photomicrographs of CS; (left) high porosity top layer over lower porosity coating due to clogged nozzle; (center) poor adhesion at substrate interface; (right) crack in underlying layer covered over by uncracked CS coating layer. (PNNL photograph) .......... 25

Figure 2-14 CS process implementation guidance schematic. .......... 29

Figure 3-1 Three conditions required for SCC. .......... 36

Figure 3-2 a) Graphic of in situ CS repair, b) photo of CS mockup trail with Electric Power Research Institute/RTT robotic crawler showing viability of in situ SS CS, (c) cross section of cold sprayed SS 316L, (d) cross section of Inconel 625 (courtesy VRC Metal Systems). .......... 37

Figure 3-3 Horizontal spent fuel dry storage canister resting on steel rails inside concrete overpack (Meyer et al. 2013). .......... 38

Figure 3-4 Seawater corrosion of a sea water check valve flange at a nuclear power plant (courtesy Exelon). .......... 40

Figure 3-5 Flow element flange with severe crevice corrosion (courtesy Exelon). .......... 41

Figure 3-6 Example of CISCC under a pipe hanger in an ECCS piping section. ................. 42
Figure 3-7 Ni coating on a 6 in. Schedule 10 SS304 pipe section. ....................................... 43
Figure 3-8 Repair of active leak using CS by VRC Metal Systems. .................................... 44
Figure 3-9 Ruptured elbow caused by FAC. ........................................................................ 45
Figure 3-10 Ni CS deposit filling a blended region of simulated corrosion in a ¼ in. carbon steel plate (sample courtesy of ARL). ..................................................... 46
Figure 3-11 Sump well and recirculation system. (Generic photo.) ...................................... 46

# Tables

Table 2-1 HPCS property values from various sources....................................................18
Table 2-2 Principal (not all-inclusive) CS process parameters quality assurance mechanism. ...................................................................................................23
Table 2-3 Part properties variables of interest...................................................................25
Table 4-1. Knowledge gap ratings describe the size of the knowledge gap for each topic relative to nuclear applications..................................................................49
Table 4-2 Importance rankings for the knowledge gap topics in Table 4-1 for illustrative CISCC and LWR applications. ..........................................................58

# 1.0 Introduction and Background/Purpose

This report provides an overview of cold spray (CS) technology as it relates to repair and fabrication of metal alloys in the nuclear power industry. CS is a relatively new technology with applications established in other industries (i.e., aerospace, defense), and its greater use is anticipated within the nuclear power industry. This report is prepared in support of the United States Nuclear Regulatory Commission (NRC) Action Plan for Advanced Manufacturing Technologies (AMTs) Rev. 1, which includes the objectives to identify the AMTs most likely to be used for nuclear power applications that require NRC approval and to prepare NRC staff to review regulatory submittals containing components manufacturing using AMTs (NRC 2020).

An objective of this report is to highlight technical gaps related to CS technology implementation in the nuclear power industry. This is performed by providing an overview of CS technology, including a description of CS equipment, process parameters and control, and coating properties and performance. In addition, a summary of CS experience in non-nuclear applications is provided along with a description of potential applications of CS technology in the nuclear power industry.

To date, CS has primarily been developed for non-structural military applications for corrosion or wear resistance. Most of this work has been performed using aluminum (Al) (for corrosion prevention and dimensional restoration of aluminum or magnesium components) or nickel (Ni)/chrome alloys (for wear resistance) as the CS powder materials. Application of CS is expanding beyond the military to component repair and manufacturing in other sectors such as aerospace, medical, electronics, and energy. The nuclear power industry applications present an entirely new set of challenges regarding operating conditions, substrate materials, and powder composition. As such, considerable knowledge gaps exist to demonstrate that CS is viable for the variety of potential applications.

An introduction to CS technology and its history is provided in the remainder of this section, while Section 2.0 provides an overview of CS technology, including equipment, process parameters and control, and coating properties and performance. Section 3.0 includes a summary of non-nuclear applications of CS technology and also describes several applications of CS technology in the nuclear power industry. Section 4.0 presents knowledge gaps associated with the utilization of CS in the nuclear power industry and rates the size of the knowledge gaps using “Small,” “Medium,” and “Large” designations. In addition, Section 4.0 presents an importance ranking of knowledge gaps for some application categories using ranking designations of “Low,” Middle,” and “High.” Finally, conclusions are provided in Section 5.0.

## 1.1 CS Technology Introduction

CS technology was originally developed in Russia in the mid-1980s at the Institute of Theoretical and Applied Mechanics of the Russian Academy of Sciences (Papyrin et al. 2006). The principal inventor, Dr. Anatolii Papyrin, was investigating supersonic two-phase flow over experimental airfoil designs. He noted that the small particles used to visualize the air flow adhered to the leading edge of the airfoil. This led to researching how to utilize this method as a coating process. In the United States, this research has been greatly enhanced under the leadership of the Army Research Laboratory (ARL) and is increasingly applied in naval and aeronautical systems for nonstructural repair or specialty coatings (Champagne 2007).

In simplest terms, the CS process uses preheated and pressurized gas that rapidly expands in a convergent/divergent nozzle to accelerate the micron-range suspended particles to supersonic speeds (Mach 2–3), impinging on the substrate surface and forming a coating. A schematic of the process is shown in Figure 1-1. The gas temperature used is well below the particle melting point, and heating is primarily for enhancing the adiabatic expansion of the gas. The governing process parameter is referred to as the critical velocity ($V_{cr}$), defined as the velocity above which the particles are sufficiently plastically deformed and adhere to the substrate, forming a coating. Critical velocity is a function of the gas temperature and pressure, nozzle design, particle size (and shape, to a lesser degree), and the mechanical properties of the substrate and powder. Both the particles and the impact surface are plastically deformed upon the ballistic impact, creating an interface with metallurgical bonding and mechanical interlocking. The initial bond is particle-to-substrate. As coating thickness increases, bonds are particle-to-particle. The resulting coating can be heavily cold-worked, free from oxidation and with very low porosity. The process parameters can be adjusted to achieve a range of surface hardness and ductility properties.

CS, sometimes referred as a kinetic weld, is a solid-phase process. Therefore, CS avoids oxidation, tensile residual stresses, and other detrimental effects typically associated with melt-based processes such as fusion welding and thermal spray. The CS process is similar to shot peening in that the coating and near-surface region of the substrate typically have compressive stresses. Additionally, powder amalgams can be produced to optimize properties, such as corrosion or wear resistance, using materials that are not compatible with welding processes. Based on a review of recent presentations from the Cold Spray Action Team (CSAT) Conferences (CSAT 2020), a large portion of current research is focused on determining optimal powders for custom applications coupled with application specific performance demonstrations.

A comprehensive treatise of CS principals can be found in *The Cold Spray Materials Deposition Process-Fundamentals and Applications*, edited by Champagne (2007). Several presentations from the annual CSAT Conference were used for information on processes, equipment, and applications included in this text. Most CSAT presentations are available to the public at its website (CSAT 2020). Each year's presentations are listed by the year presented, e.g., CSAT2020 has the presentations from 2020.

## 1.2 Equipment and Carrier Gases

Several commercially manufactured CS systems are now available. Figure 1-1 depicts a generalized schematic of the basic components. Many of the designs are derived from work accomplished at the ARL with its Generation system. The commonly used carrier gases are helium (He), nitrogen ($N_2$), and air. He, with its low atomic weight, provides the most rapid acceleration and generally achieves the best quality coatings. With the cost and sometimes limited supply of He, $N_2$ is widely used for large area spraying projects. Recently, He recovery systems have been developed that capture >90% of the He for reuse (Howe 2017), but these systems are designed for industrial in-house settings and not for field applications.

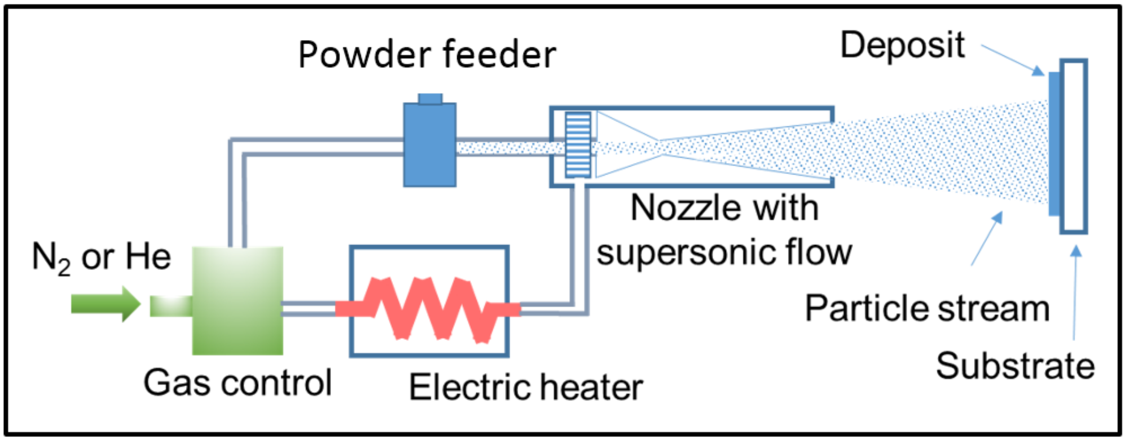


Figure 1-1 A schematic of CS process.

Figure 1-2 below depicts a He recovery system installation. The entire spraying system is contained in a sealed environment and a vacuum system directs the He gas and entrained powder particles into a large hood. A water spray and filters remove the powder particles to achieve He purity >90%, which is then sent to the compressor feed supply.

Figure 1-2 Helium recovery system installation (courtesy of ARL).

## 1.3 Powders and Applications

Powders are selected based on the application (Champagne 2007). The most common applications are related to corrosion or wear resistance for repair and mitigation. A less common use is for dimensional restoration of mating surfaces like flanges. As reported in the opening comments by ARL at the CSAT 2016 conference (Champagne 2016), there have been some novel applications such as using tantalum for a thermal barrier in gun barrels, using copper (Cu) as an antimicrobial surface for hospitals, and coating the outside of nuclear fuel rods with a zirconium-boron mixture to provide a burnable poison. A Ni fillet coating was also developed to reduce electromagnetic radiation leakage from sensitive communications electronics to prevent detection. Please note that many of the applications cited in this report can be found in the addresses from the annual CSAT conferences (https://www.coldsprayteam.com).

For corrosion resistance, the most used coatings are forms of Ni, Cu, Al, or titanium (Ti). Various Inconel® alloys and stainless steels (SS) are also used, with Inconel 625 and SS-316 the most common. Often, these metals are mixed with hard particles to enhance bond strength and reduce porosity. Various carbides (chrome carbide and titanium carbide) and oxides (zirconium oxide) have been used.

For sliding wear resistance, carbides are typically added to a metal matrix. The most common powder is Nickel-Chromium and chromium-carbide (NiCr-CrC), and it has been proven an excellent choice for aerospace applications. For mechanical wear, carbides provide high spots on the surface such that abrasive material cannot reach matrix material without first wearing through or pulling out surrounding carbides. Thus far, for cavitation resistance, Inconel 625 or SS-316 alloy, without carbides, significantly outperform NiCr-CrC blends. Initial results indicate cavitation erosion resistance appears to be limited to the strength of the matrix material, not the carbides. This is likely because cavitation is capable of eroding matrix material around carbides.

The powder and substrate materials with similar ductility values and compatible chemistries are easier to CS. Similar ductility enables a balance of deformation and shear conditions at the interface, resulting in improved mechanical interlocking. CS of dissimilar metals is common and has a tighter process window compared to similar metals. CS of metals to non-metals can be done, but typically relies on mechanical interlocking alone.

There is no limit on the CS deposition thickness for most metals. CS 3d printing equipment for Al, and other soft metals, are commercially available (SPEE3D). For corrosion barrier coatings, a thickness of 0.5 millimeter (mm) (0.02 inch [in.]) is often sufficient. During CS, once the particle has impacted (called a “splat”), due to cold work, it is harder and less ductile than the initial powder, so it differs in mechanical properties from the initial powder. Heat treatments can improve mechanical properties. Using heat treatments to increase ductility is of interest for emergent structural repair or additive manufacturing of structural components using CS. However, heat treating CS coatings is uncommon because the as-deposited coating typically has the required mechanical properties for coating and dimensional restoration applications that dominate CS applications.

# 2.0 CS Technology Overview/Assessment

CS technology involves several process considerations, including equipment, process parameter control, powder selection and treatment, and spray delivery, as described below. How these elements are managed can significantly influence coating characteristics and performance.

## 2.1 Process Description

Metal spray coating processes use heated gas to propel metal particles that bond to a substrate's material surface. Thermal spray is a family of metal spray coating processes where particles are fully or partially melted during the process and re-solidify after impacting the substrate. Thermal spray processes include plasma spray, detonation spray, and high-velocity oxy fuel spray and its variants. Because melting and re-solidification occur during thermal spray, tensile residual stresses exist due to shrinking that occurs during re-solidification. Oxidation and undesirable chemical reactions are produced due to high heat input and melting. Most thermal spray processes are limited in build thickness to 1 mm (0.04 in.) or less. In limited cases, greater build thickness can be obtained. Mechanical interlocking of solidified particles is the primary bonding mechanism for thermal spray (Balić et al. 2009; Luo et al. 2018b; Trompetter et al. 2005; Wang et al. 2005).

CS is a solid-phase metal spray process where no melting occurs. Metal particles are carried by a heated gas stream that propels particles at high velocities. The impact energy is sufficient to bond metal particles to the surfaces they impact. Because particles are solid, they can impart high shear forces. High shear conditions result in improved bond strength. Because it is a solid phase process, CS avoids oxidation effects, tensile residual stresses, and other detrimental effects typical of melting and high heat input that occurs with thermal spray. In addition, the coating typically results in a beneficial compressive residual stress state in both the coating and surrounding substrate, along the edges and beneath the coating.

Some researchers in the thermal spray community describe CS as a type of thermal spray; however, CS has key features and benefits that distinguish it from other thermal spray processes. Melted particles are part of the definition of thermal spray (The Welding Institute 2020). The technical driver for CS development and commercialization was to avoid issues associated with high heat input, melting, and re-solidification that occurs in thermal spray processes. For this report, CS refers to metal spray processes where no melting occurs, and thermal spray refers to metal spray processes where melting occurs.

High pressure cold spray (HPCS) is the metal spray process most relevant for nuclear power applications. During the process, substrate heating is minimal, dimensional stability is maintained, and unwanted thermal effects (heat affected zone [HAZ], thermal stresses, dilution layer formation, etc.) are avoided. HPCS systems operate at pressures typically ranging from 300 to 1000 pounds per square inch (psi) (2 to 7 mega pascals [MPa]) and produce particle velocities typically ranging from 800–1400 meters per second (m/s) (Moridi et al. 2014). High velocity enables high kinetic energy, which is required to create high plastic deformation and shearing at particle boundaries. This results in dynamic recrystallization and metallurgical bonding at interparticle boundaries. Particles are held to each other and the substrate by both mechanical interlocking and metallurgical bonding.

Low pressure cold spray (LPCS) is of less relevance because it fails to propel particles fast enough to achieve the kinetic energy needed for high quality CS deposition of high melt temperature alloys. LPCS systems operate at 300 psi (2 MPa) and lower. They typically produce particle velocities ranging from 300 to 600 m/s (Moridi et al. 2014). Reduced kinetic energy associated with LPCS means less plastic deformation, less interlocking, and no or dramatically reduced metallurgical bonding in high melt temperature materials (VRC Metal Systems 2020). Reduced kinetic energy means reduced mechanical properties relative to HPCS. LPCS systems are not recommended for high quality CS of steels, Inconel, and other high strength/melt temperature materials.

Kinetic metallization, pulsed gas dynamic spraying, vacuum CS, and warm spray are CS variants. This report focuses on HPCS because of its advantages relative to competing techniques (Siopis 2019). A summary of these CS variants is provided by Moridi et al. (2014).

### 2.1.1 Equipment

The authors are aware of four HPCS equipment manufacturers around the world: (1) VRC Gen III, based in America; (2) Impact Innovations, based in Germany; (3) Plasma Giken, based in Japan; and (4) CGT, based in Germany. Portable HPCS technology was developed by the Army Research Lab (ARL) to enable in-situ repair of aging military platforms. The ARL technology was commercialized by VRC Metal Systems. VRC Metal Systems and Impact Innovations are the only companies the authors are aware of that offer portable HPCS equipment. Portable HPCS can be used for repair and mitigation of existing nuclear components in situ. Figure 2-1 depicts a portable HPCS system similar to one acquired by the Pacific Northwest National Laboratory (PNNL), the VRC Raptor. This is shown with the CS gun detached from the robot being used in manual handheld operation. The SS container is the powder mixer, which uses a magnetic stirring mechanism to avoid clumping. The powder feeder typically holds 2–3 kilograms (kg) (4.4–6.6 pounds [lbs]) of powder with feed rates in the range of 4–8 kg/hour (8.8–17.6 lbs/hour). This capacity limits the working time for a spray pass to approximately 30 minutes, thus limiting the area/thickness for practical spraying in a single run. Generally, a segmented spraying plan is developed with several powder loads to complete specific applications. A heating unit is between the operator and mixer. An insulated hose, which can be up to 8 m long, provides the heated high pressurized gas, along with the powder feed. The main part of the powder jet stays within the nominally inert gas flow. Some divergent particles at the edges of the spray plume get exposed to air and immediately oxidize, giving them an appearance like miniature meteors.

Figure 2-2 depicts PNNL's automated CS system. In this case, the CS gun is held by a six-axis robotic arm for fully automated delivery. However, the CS gun can be removed from the robot and used in handheld operation. Figure 2-3 depicts the smaller, more portable high-pressure CS system that was developed for the Navy by VRC Metal Systems. One of the design criteria was that each component could fit through a hatchway on a naval vessel. The temperature and pressure ranges for PNNL and Navy systems are comparable.

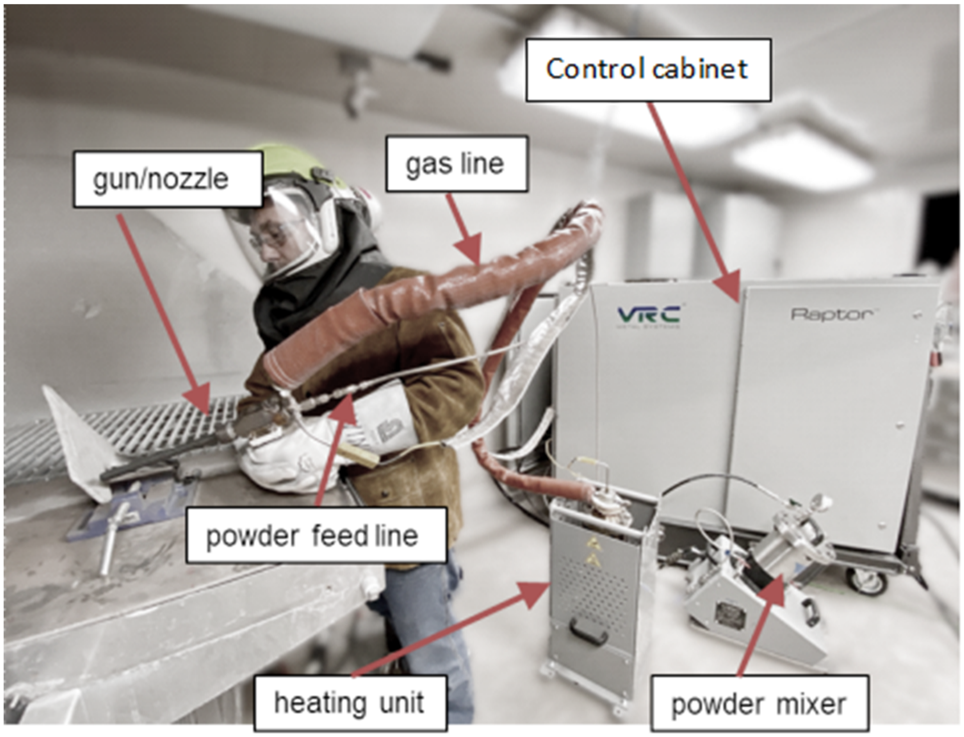


Figure 2-1 VRC Metal Systems Generation III CS system with a conventional nozzle (courtesy of VRC Metal Systems) in manual handheld operation.

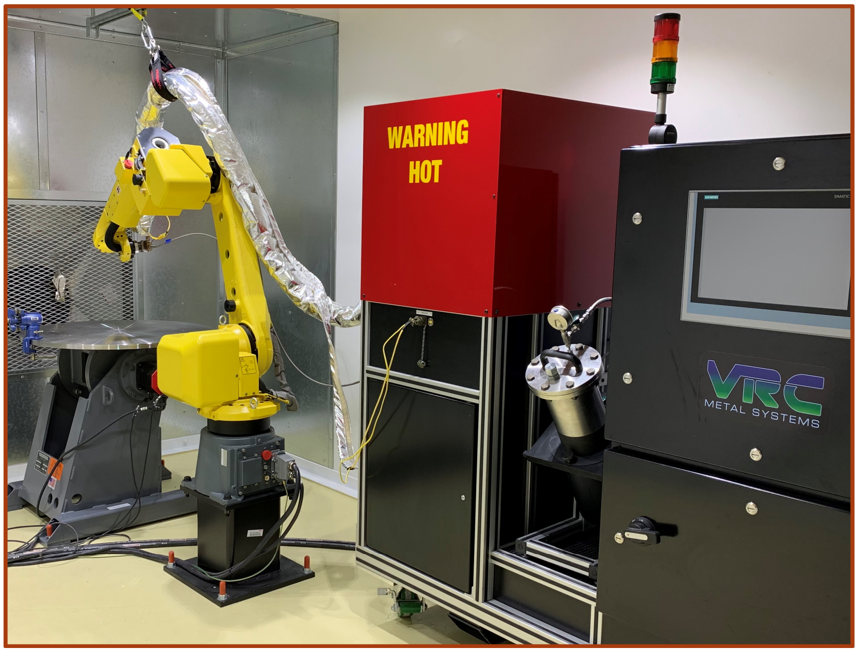


Figure 2-2 VRC Metal Systems Generation III CS system at PNNL with a conventional nozzle with CS gun mounted to an industrial robot.

Figure 2-3 Portable Generation III CS System for shipboard use with each component capable of fitting through a normal hatchway (courtesy of VRC Metal Systems).

An electric heating coil provides temperatures up to 700°C. In some systems, only the carrier gas is heated, and the powder is mixed in at the nozzle entry chamber. In recent designs, there is an option to connect the powder feed line to the gas spray at the heater unit so that the powder is heated and softened. However, heating the powder is only done for specialty, dedicated applications because the heated gas line is a corrugated tube and traps powder particles, so, if multiple powders are used, the gas line would have to be changed in order to avoid powder contamination in the line. The temperature is still well below the melting point of the metallic powder, so this process differs from welding or brazing. The primary purpose of the heating is to provide more rapid acceleration of the gas/powder mixture during adiabatic expansion in the nozzle throat.

A flexible, insulated gas supply tube connects the heated gas to the nozzle. Normally, this feed tube is about 2 m long, but feed tubes up to 8 m long have been used. With longer feed tubes, it is common to add an auxiliary heater at the nozzle entry to make up for line losses.

Stationary industrial HPCS systems typically have gas heating and nozzle cooling systems built into the spray gun. This enables higher gas temperature, higher particle velocities, reduced gas consumption, and improved nozzle technology. Nozzle cooling enables improvements in nozzle lifetime and enables nozzle designs that reduce or eliminate clogging. This equipment configuration results in a spray gun that is too heavy to be operated manually. Stationary HPCS equipment is a more mature technology than recently developed portable HPCS equipment. Figure 2-4 shows a Plasma Giken PCS-1000 CS system. This equipment is used for applications ranging from sputtering targets to in-home cookware (Plasma Giken 2018).

Figure 2-4 High pressure stationary industrial CS equipment for factory CS of high melt temperature materials such as MCrAlY (a family of thermal and corrosion barrier coatings where M = Co, Ni or Co/Ni), Ti6Al4V, Inconel, and SS (Plasma Giken 2018). In general, stationary equipment with large CS guns offer improved properties and economics compared to portable equipment for high melt temperature alloys.

The nozzle assembly comprises an entry chamber, a convergent section, and a final divergent throat, called a de Laval nozzle. The divergent throat section allows for rapid gas expansion and acceleration of the gas and powder up to supersonic speeds. The exit velocity of the powder is in the range of 700–1,000 m/s (Mach 2–3). For coating operations performed in an industrial setting with no space constraints, the nozzle assembly is in the range of 200–250 mm (8–10 in.). For specialty applications, especially for confined spaces, the nozzle throat can be reduced to 40–80 mm (1.5–3 in.). The shorter the nozzle throat, the lower the achievable exit velocity. In general, confined space applications with a miniature nozzle using helium gas can achieve the same level of quality as a conventional nozzle and $N_2$ gas. Since the miniature nozzles would be used for smaller areas, this is generally a reasonable trade-off. The nozzle is maintained close to perpendicular to the coated object, but off-angle spraying up to about 45 degrees is possible, with diminishing efficacy of the coating process. The standard shop nozzles have two basic designs, “block” and “barrel.” In the block design, the gas and powder have a short distance for heating before the entrance to the nozzle. In the barrel design, an extra length is added to provide some powder preheat. The selection of gas line, powder, heating, and block or barrel design are application specific.

Nozzles are typically cylindrical and deposit a coating nominally 2 mm (0.080 in.) wide. There are several variations of nozzle shapes and sizes for specific applications. Figure 2-1 and Figure 2-2 above show conventional nozzles that are used in shop applications. There are also smaller handheld versions of nozzles, as shown in Figure 2-5 and Figure 2-6. Note that the reaction forces from the gas spray are relatively small and do not pose a problem for handheld operation. Figure 2-6 shows a recently developed miniature nozzle for use in confined spaces. The ability to create high quality CS deposits within 1.5 inch (38 mm) diameter bores has been demonstrated for multiple Department of Defense (DoD) applications (Nardi et al. 2019). The initial application for these miniature nozzles was for coating the inner surface of gun barrels, but it is well suited for small area applications in limited access spaces commonly found with installed nuclear components.

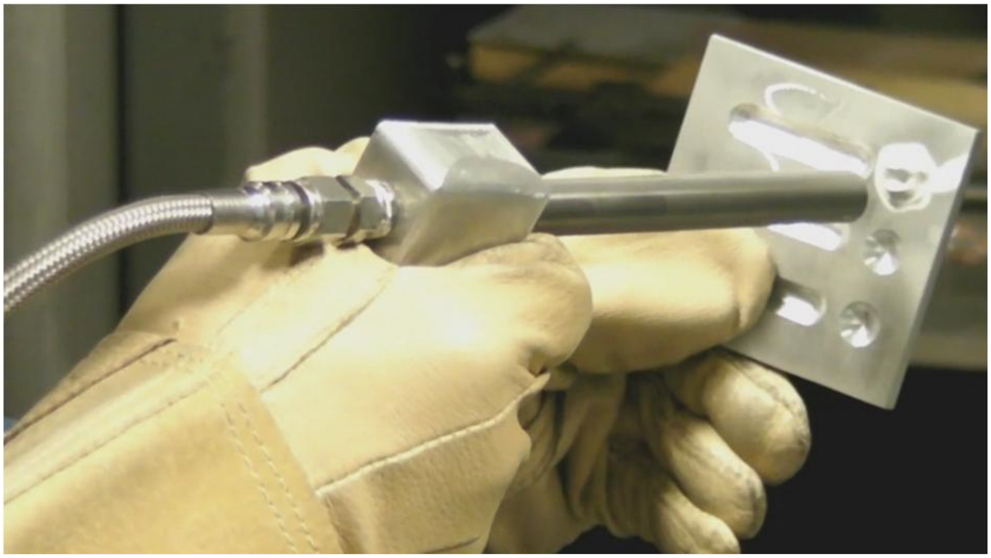


Figure 2-5 Handheld CS nozzle for small area application (courtesy of ARL).

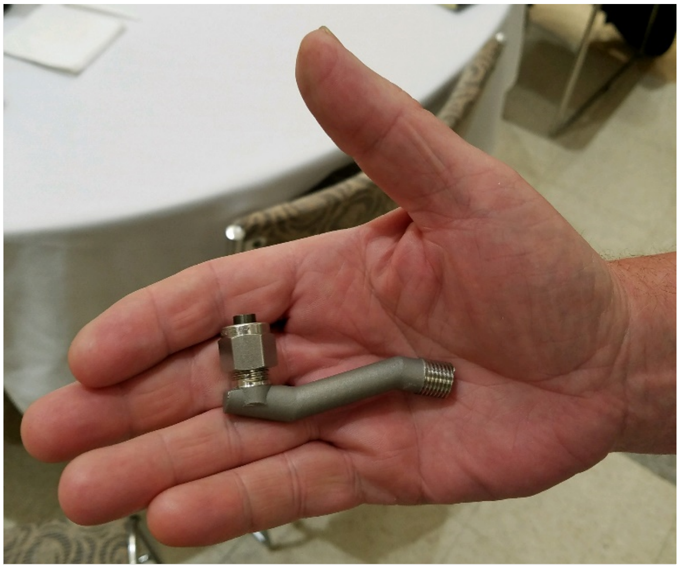


Figure 2-6 Miniature nozzle for confined spaces as small as 1.5 in. (38 mm) (PNNL photo).

Most commonly, nozzles are fabricated from cast tungsten carbide for wear resistance. There are some newer nozzles that use an ordinary glass lining, but these require jacketing and cooling to survive the high velocity particle flow and are therefore used with stationary CS systems. The conventional nozzle has a two-step taper to provide the expansion volume for the gas to accelerate.

The CS process does have occupational safety concerns. The spray process produces high noise levels more than 100 decibel, so ear protection is required. The fine particles of the powder represent a respiratory health concern, so adequate personnel protection equipment is needed. Since the carrier gas is typically inert, confined space breathing concerns need to be addressed. Also, in some cases, the fine powder can have flammability issues that need to be addressed.

### 2.1.2 Robotic and Manual Delivery Systems

Although there are handheld portable delivery systems, the most common approach for CS is some form of robotic delivery. For complex surfaces, a six-axis industrial robot is normally used. For many applications, the nozzle is held stationary, and the work piece is translated or rotated. Stationary nozzles with a linear/rotational feed of the work piece are used for prototype spent fuel canisters (Vo et al. 2015) and nuclear fuel rods (Sevecek et al. 2018). Typically, the CS deposit is applied with relative translational speeds in the range of 1.5–2.0 m/s (60–80 in./s). One issue to note is the stop-start ends of spray paths. In laboratory work fabricating qualification samples, it is common to spray past the ends of the test piece. For actual components, this overspray approach is often not feasible, which can result in the stop/start location typically getting a double thickness. Masking techniques employ a sacrificial material, such as sheet metal, that can be removed after the CS operation to block overspray from the substrate. Coordinated motion of the axis can easily accommodate spraying outside corners of parts; however, inside corners pose more of an issue. At an inside corner, the spray beam can produce complex bounces off the side wall, which can result in increased porosity. It is important to mockup the actual geometry for any CS application to address and resolve potential issues with the CS deposition process and verify that quality objectives can be met.

## 2.2 Process Parameters and Control

The fundamental parameter governing the CS process is the $V_{cr}$. This velocity depends on several material properties, including the composition, density and shape of the powder particles and the substrate material. ARL developed physics-based models that can be used to calculate the critical velocity; however, some of the parameters used in this model are empirically determined (Champagne 2007). Figure 2-7 and Figure 2-8 show a typical $V_{cr}$ and particle velocity as a function of particle size and carrier gas. Curves on these figures are calculated values from the ARL model.

When powder mixtures are used, for example Ti-titanium carbide (TiC), it is important to understand that each component has a different $V_{cr}$ as well as a different exit velocity from the nozzle (larger, heavier particles will be slower). An initial powder composition of 70% metal and 30% carbides may have a deposited composition of 80% metal and 20% carbides, which is not necessarily a problem but should be considered in selecting the powder and process parameters. Deposition efficiency will be different for separate constituents of a powder mixture.

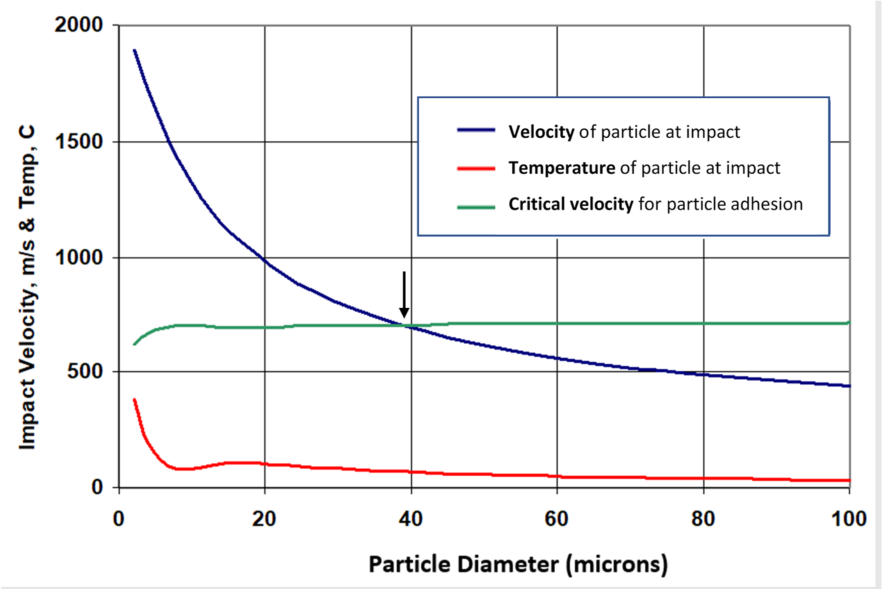


Figure 2-7 Particle velocity versus particle diameter (microns) compared to $V_{cr}$ using He gas with given temperature and pressure. Parameters for CS of CP Ni using He at 400°C at 380 psi resulting in deposition efficiency = 99.7%. The black arrow indicates the intersection for particle velocity at impact and critical velocity required for particle adhesion. Particles with diameters larger than 40 microns may not adhere to the substrate using these parameters (courtesy of ARL).

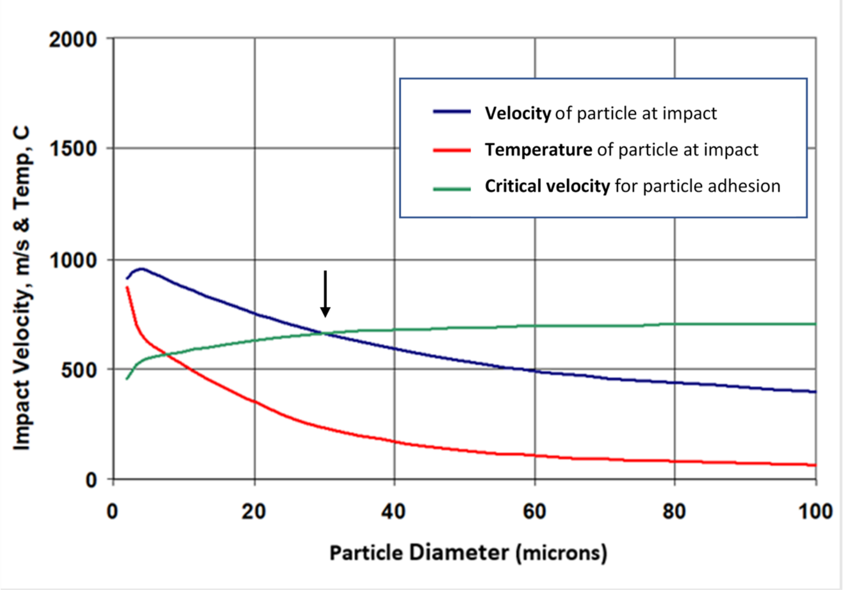


Figure 2-8 Particle velocity vs. particle diameter (microns) compared to $V_{cr}$ using $N_2$ for a given temperature and pressure. Parameters for CS of CP Ni using $N_2$ at 900°C at 650 psi resulting in deposition efficiency = 99.1%. The black arrow indicates the intersection for particle velocity at impact and critical velocity required for particle adhesion. Particles with diameters larger than 30 microns may not adhere to the substrate using these parameters (courtesy of ARL).

The selection of the powder is application-specific depending on whether the goal is corrosion resistance or wear resistance or dimensional restoration. Based on work reported by ARL at CSAT conferences (CSAT 2020), for corrosion resistance, the common choices are commercially pure Ni (CPNi) or copper (CPCu), both of which have well-understood spraying properties and provide both good bond strength and low porosity. Titanium, Chromium, SS (usually alloy 316), and Inconel (usually alloy 625) also have been used in several applications. Titanium is frequently combined with titanium carbide particles to help improve the adhesion strength and reduce the porosity of the coating. Powder mixture selection is a process of using past experience and, to some extent, trial and error down selection.

In most cases, the optimum bond strength is achieved with the nozzle perpendicular to the substrate to achieve the maximum impact velocity normal to the surface. For some materials, particularly powder mixtures with added carbide compounds, an off normal orientation (up to about 30 degrees) improves bond strength by introducing an additional shear component to the impact force. The optimum angle needs to be determined experimentally for a given powder and substrate combination. During the process development, a range of orientation angles are used to determine the process limits for geometric considerations with varying part geometry.

### 2.2.1 Powder Size, Shape, and Processing

Some of the important powder parameters are particle shape, particle size, and oxidation state. Early work experimented with different powder shapes, including spheres, irregular shapes, and flakes. Generally, a spherical shape is preferred. Using standard powder feeders, the functional nominal diameter for powder is between 5 and 100 µm (Champagne 2007). Best results are obtained when powders are sieved to remove large and fine particles, decreasing variation in size to an optimum nominal size which typically ranges between 20 and 50 µm. The presence of particles that are either larger or smaller than the optimum nominal size reduces the velocity of particles in the stream, which negatively impacts coating properties. In general, higher velocities produce improved mechanical properties of cold sprayed coatings. Specialty powder feeder systems exist to enable the deposition of fine particles (~1–5 µm) (Desaulniers 2016). The oxidation state of the powder is a factor for particle-to-particle cohesion and ductility. Low oxide states are preferred, which can lead to a shelf-life issue with some powders. As reported at the CSAT conference, recent advances in packaging (based on freeze-dried food) have increased the powder shelf life from months to years (Champagne 2018; Placzankis et al. 2019). The military maintains a list of approved powders and vendors in MIL-DTL-32495 A, *Powders for Cold Spray Deposition*. This specification also provides guidance for powder storage and handling (MIL-DTL-32495 A 2018).

The yield strength of the powder is also an important parameter when coating a thin substrate. For example, one experiment performed at PNNL used Inconel alloy 625 powder to apply a coating 1.5 mm (0.06 in.) thick on a SS alloy 304 substrate that was 4.8 mm (0.188 in.) thick. The CS process creates compressive stresses, and the stronger Inconel coating buckled the substrate, as shown in Figure 2-9. This effect is comparable to the use of an Almen test for assessing the extent of peening (SAE International 2017).

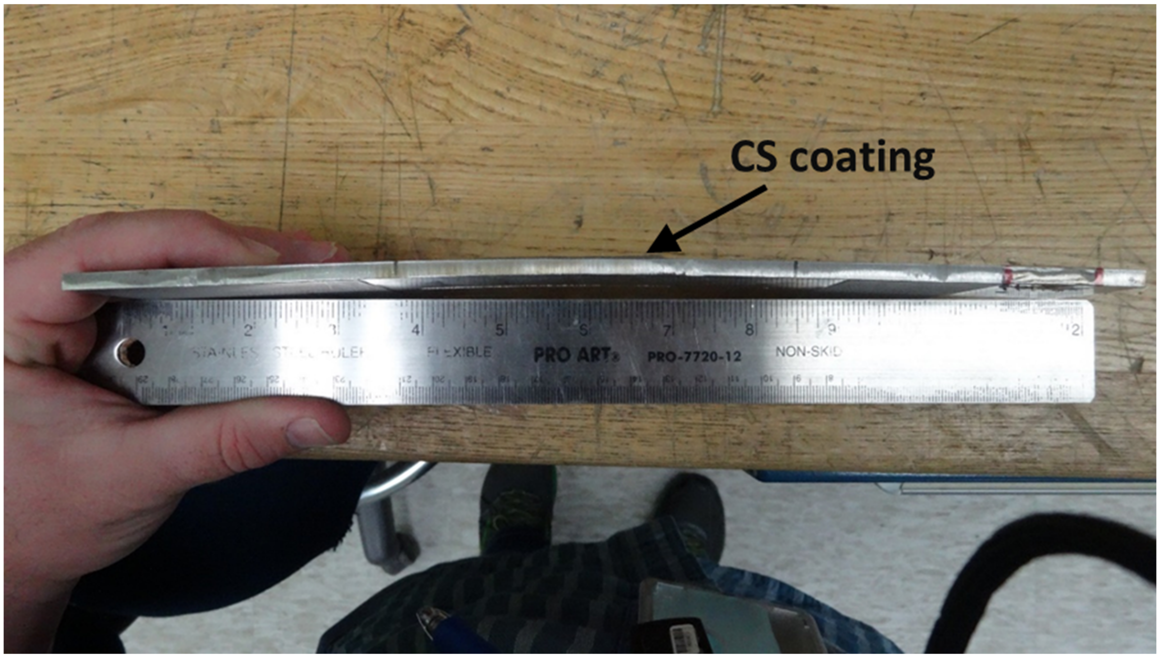


Figure 2-9 Alloy 625 Inconel sprayed onto a thin SS alloy 304 substrate, causing distortion (PNNL photo).

### 2.2.2 Deposition Efficiency/Powder Feed Rates

Powder feed rates typically fall in the range of 4.5–13.5 kg (10–30 pounds) per hour. Using a robotic delivery system, this provides a deposition rate of 100 $cm^2$/min. or 0.01 $m^2$/min (16 $in.^2$/min.) for a typical corrosion resistant layer of 0.25 mm (0.01 in.) thickness. Using the conventional shop nozzle, and with He as a carrier gas, it is possible to achieve up to 99% deposition efficiency, assuming normal incidence of the spray. With the lower velocities achieved with $N_2$ gas, the deposition efficiency drops. Miniature angled nozzles for spraying in confined spaces have significantly lower velocities due to the direction changes of the gas stream. Therefore, materials that can typically be sprayed with $N_2$ using a straight nozzle require He gas when using an angled nozzle (Nardi et al. 2019). Collection and removal of non-deposited powder is a consideration and may be required for some applications, e.g., inside the primary nuclear steam supply system (NSSS).

### 2.2.3 Nozzle Control/Nozzle Clogging

The primary issues with nozzles are wear and clogging. The diverging powder spray provides conditions for wear erosion of the inner surface of the nozzle. Once any wear occurs, the powder spray can impact the inner wall of the nozzle at a better angle for adhesion, thus producing clogging, which is highly detrimental to the coating process. Even without erosion, the random powder collisions can produce the right conditions for powder adhesion, providing a new surface that enhances additional buildup. When clogging occurs, the nozzle must be refurbished, usually by acid dissolution of the buildup or grit blasting. Nozzle clogging is one of the most common problems with the CS process and requires continuous monitoring.

Figure 2-10a and Figure 2-10b shows SS 316 CS coatings on 304L substrates without and with nozzle clogging, respectively. With clogging, exfoliation, high porosity, and cracking are all likely results. One concern is that a final pass may cover a volume of poor coating and preclude visual detection of the condition. A skilled operator knows how to monitor process parameters to detect nozzle clogging. Algorithms to flag operators at the onset of pre-clogging conditions and record clogging conditions in data logs can be developed as an automated quality tool. Typically, a spike in process gas pressure indicates nozzle clogging. A spike in the powder feed gas pressure generally indicates a feed line clog.

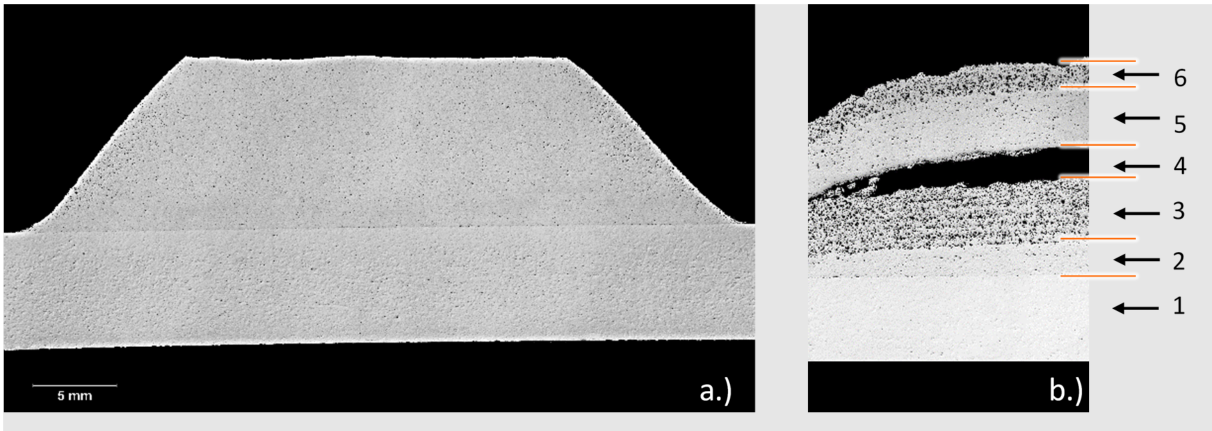


Figure 2-10 SS 316 CS coating on SS 304L substrates applied with and without nozzle clogging. a) CS executed without nozzle clogging using optimized parameters. b) CS where poor parameter selection and extreme operator negligence resulted in a poor coating. Poor parameter selection caused fast nozzle clogging resulting in extremely porous material. Instead of correcting the problem, the machine operator replaced the nozzle and continued spraying over porous CS produced by the clogged nozzle. Label 1 is the base metal, 2 is dense CS coatings, 3 is highly porous CS resulting from clogged nozzle. 4 is a gap resulting from stronger CS breaking off from weak CS during sawing. 5, after a nozzle change dense CS is applied over previous layers 6, the new nozzle soon begins to clog.

Issues associated with nozzle clogging are preventable because the onset of clogging can be detected before coating quality is affected. Automated nozzle clogging detection should be integrated in CS equipment to ensure clogging does not happen in the field. If nozzle clogging does occur, it can be detected by examining recorded pressure from CS equipment data logs, visual inspection of the nozzle, nondestructive evaluation (NDE) techniques or destructive evaluation of a witness coupon. Material sprayed while the nozzle clogged should be ground or machined out and new CS applied. Cold spraying over existing cold spray after grinding out porous cold spray is straightforward.

### 2.2.4 Surface Preparation/Post Cleaning

Pre-cleaning the surface is typically necessary to achieve good bond strength if a thick oxide layer exists. If there is a thick oxide layer, the adhesion strength is poor and limited by the tensile strength of the oxide layer, approximately 1000 pounds/square inch (1 ksi). Therefore, the best practice is to remove oxide layer prior to CS via abrasion. Common methods include grit blasting, abrasive pads (i.e. Scotch-Brite$^{TM}$), and wire brushes or wire wheels. A cleaned surface refers a surface with contaminates and thick oxide layers removed. Adhesion strength of 10–20 ksi is common on a cleaned surface and adhesion strengths greater than 30 ksi are not uncommon for adhesion strength of CS of higher strength alloys.

For CS done in in confined spaces, grit blasting can be done with the CS equipment itself. CS processes have been develop such that large carbide particles break through oxide layers eliminating the need for surface preparation. Based on steam generator tube plugging and sleeving experience, Inconel substrates exposed to primary water conditions have thick, tenacious oxide layers that need to be removed. Depending on the application, the cleaning grit residue may have to be removed to prevent service fouling. Another consideration comes into play with surface contamination, which would become airborne with grit blasting and pose a radiological hazard. Spraying in areas where there are geometric changes requires additional attention. One situation of concern is spraying an inside corner when side wall bouncing of the spray powder can lead to increased porosity and irregular surfaces. Typically, side walls are ground or machined to taper gradually from bottom surface.

Surface texture may be an issue for some combinations of powders and substrates. A small amount of surface roughness may help in the bond strength by producing some shear impact forces along with the predominant normal forces. Similarly, for some powders, a slight off-normal nozzle angle improves the bond strength due to contribution of shear forces. These details have to be determined experimentally for candidate powders, substrate, impingement angle, and surface roughness combinations and the process is application specific. In some cases, the nozzle is only angled for the first cold spray pass for improved substrate adhesion then return to normal to the surface for subsequent passes.

Another surface condition of concern is a crack with a large crack opening dimension (COD). In the literature (Parsi et al. 2012), it has been reported that COD can be sprayed over using CPNi powder sprays. However, a sample was made for PNNL using alloy 625 (Inconel) on an SS substrate that did not contain a crack but did contain a subsurface discontinuity that was separated from the surface by a very thin ligament of 0.025 mm (0.001 in.) thick and 2.5 mm (0.1 in.) wide. The ligament ruptured during spraying, causing it to break through to the surface. The CS coating aggregated porosity at this discontinuity, which continued through several layers of coating, resulting in a through coating crack. This crack was readily detected by penetrant testing but could easily be missed with a standard surface visual inspection. Figure 2-11 shows the crack detected by eddy current testing of the surface (horizontal pink line near the bottom; the vertical pink lines are the response to beveled edge geometry changes).

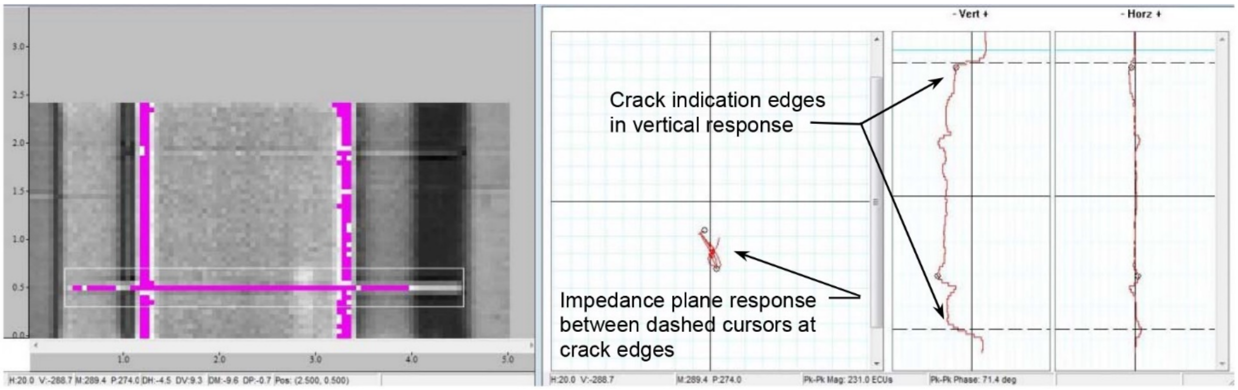


Figure 2-11 CS coating crack caused by large surface discontinuity on the substrate. (PNNL data.)

Using robotic delivery systems, the as-deposited surface is generally acceptable as is with no additional finishing preparation. These surfaces allow for penetrant testing in the as-coated condition. Surface grinding or machining may be required for final dimension control and blending contours. Especially in applications where there are several start/stop locations, the local coating thickness will differ substantially from the nominal due to acceleration and deceleration of the nozzle during cold spray. This can be avoided by masking or path planning that accounts for acceleration and deceleration associated of the cold spray nozzle. The metallic CS coatings act like normal cold worked metals under grinding or machining. A conservative best practice is to reduce feed rates to 1/3 of machining handbook values for plate material when machining cold sprayed material. In the situation where cold spray needs to be partially removed and resprayed, no special surface preparation is required beyond what is described in this section.

## 2.3 Coating Properties and Performance

Discussion of CS properties in the paragraphs below will be relative to CS of high melt temperature alloys such as SS and Ni-based alloys. For alloys with high melt temperatures, the best properties are achieved under the following conditions:

1. HPCS system is used.
2. Helium is used as the carrier gas.
3. Proper surface preparation is implemented.
4. The correct material is selected for the application.
5. Powder is processed correctly.
    a. Sieve powder to remove fines (particles smaller than 5 microns).
    b. Dry powder.

For alloys with high melt temperatures, much of the CS work that has been performed is for coating jet turbine blades and natural gas power generation turbine blades. These blades operate at temperatures of 1,000°C and higher while rotating at speeds greater than 10,000 rotations per minute in corrosive combustion environments. Inconel 718 is an alloy of interest for gas turbine blades. Some reported property values for cold sprayed Inconel 718 are shown in Table 2-1 below. These numbers are based on $N_2$ gas spray tests from several universities. Information about commercial CS coatings for natural gas applications are typically trade secrets and likely have properties superior to what is reported below.

CS coatings with high hardness and strength are being developed to replace electroplated chrome and Ni for DoD combat systems. Properties for one such CS coating, Ni and CrC-NiCr blend, are also shown in Table 2-1 below. These DoD CS coatings are designed for better corrosion and wear resistance than electroplated chrome coatings.

CS has been investigated to form corrosion resistant coatings to prevent primary water stress corrosion cracking (PWSCC) of Inconel alloy 600 components in nuclear reactors. Some properties obtained from testing of commercially pure nickel (CPNi) coatings on Inconel alloy 600 components are provided in Table 2-1.

Table 2-1 HPCS property values from various sources.

| Coating Material | Substrate Material | Carrier Gas | Adhesion Strength (KSI) | Hardness (HV) | Porosity (%) | Residual Stress (psi) | Ultimate Strength (KSI) | Reference |
|---|---|---|---|---|---|---|---|---|
| **SS 304** | SS 304 | $N_2$/He (25/75) | >~12* | 450 | 0.07 | −50.8 to −65 | - | (Yeom et al. 2020) |
| **Inconel 718** | SS 316 | | | 507 | 0.25 | | 67 | (Luo et al. 2018a) |
| **Inconel 718 PWHT** | SS 316 | $N_2$ | | ~410 | <0.5 | | 158 | (Luo et al. 2018a) |
| **Inconel 718** | Inconel 718 | $N_2$ | >~12* | | <2 | −29,008 to -58,015 | | (Fiebig et al. 2020) |
| **Ni, CrC-NiCr blend** | - | He | 38 | 400–500 | <0.5 | | | (Nardi et al. 2019) |
| **CPNi** | Inconel 600 | | >~10* | ~250 | | | | (Parsi et al. 2012) |
| ***Denotes that epoxy-based adhesion tests are used and the epoxy failed before coating.** | | | | | | | | |

## 2.3.1 Adhesion

All reported values in Table 2-1 show adhesion strength greater than ~10 ksi, which is when the epoxy used for adhesion testing fails (ASTM-C633 2017; ASTM-D4541 2017). Triple lug shear testing, described in MIL-J-24445A (1971) can be used to get adhesion values not limited to epoxy strength. Triple lug shear testing is more expensive than epoxy-based adhesion testing and is not often used. Values obtained using a triple lug shear show that adhesion values for CS coatings can be more than triple what can be measured with epoxy-based adhesion tests (Nardi et al. 2019).

## 2.3.2 Water Permeability

CS has no interconnected porosity. When best practices are followed, CS coatings for materials of interest should have porosity values less than 1%. CS is used for corrosion barriers in automotive, defense, and gas turbines. As reported at CSAT 2019, the Canadian National Research Council qualified a process and plans to coat entire carbon steel spent fuel containers with cold sprayed copper for final disposal because they assume it will provide a non-permeable corrosion barrier to protect the carbon steel containers for over a million years (Hall and Keech 2017).

## 2.3.3 Mechanical Robustness

Several mechanical properties of HPCS coatings are summarized in Table 2-1. It is important to understand that some mechanical properties for a part that has been cold sprayed are a combined effect of the substrate and coating and can be affected by coating thickness. These effects can be explored through finite element analysis and laboratory mechanical testing. Typically, CS coatings are less ductile than base metal but much stronger than non-metallic coatings. Ductility and toughness can be improved with post-spray heat treating if needed.

Several tests were performed to evaluate the mechanical performance of cold sprayed CPNi on Inconel alloy 600 (Parsi et al. 2012). Cyclic fatigue was evaluated with 4-point bend testing, and 50,000 cycles with 22.5 ± 21 ksi tensile stress loading. NDE and scanning electron microscopy (SEM) work showed no cracking or debonding. Impact testing was done with a round-nosed weight with 10 J of energy. No cracking or spalling was observed. Vickers hardness testing performed on polished cross sections of coating showed remarkable consistency in hardness (~250 Vickers hardness number).

### 2.3.4 Chemical Resistance

For various applications CS coatings are expected to act as corrosion barriers that protect against chemical attacks. Examples include use of CS to protect structural materials in molten salt environments and prevention of stress corrosion cracking in light water reactors and dry cask storage system (DCSS) canisters for spent nuclear fuel. Galvanic potentials and chemical compatibility must be evaluated when selecting CS powder for use in corrosive environments. Typical hard particles blended into CS powders may need to be replaced if they cause galvanic potentials or lack needed corrosion resistance.

Surface finish is an important consideration for resistance to chemical attacks. Surface discontinuities act as activation sites that accelerate corrosion. For some material and environment combinations, the incubation period for a given material is strongly affected by surface roughness. Buffing surfaces can dramatically improve the incubation period.

In some instances, the interface between the cold spray material and the substrate is exposed to an aggressive environment. Edge effects refer to consideration unique to a CS-substrate interface that is exposed. Galvanic potentials can exist at the edge, stress conditions are altered, crevices can exist if the edge is not properly blended. These are all edge effects that should be considered.

For DCSS canisters fabricated from austenitic SS materials with high CISCC resistance, it may be sufficient to apply CS corrosion resistant coatings just to microstructurally-altered regions in and around welds. If the proper alloy is selected, galvanic effects can be avoided. Alternatively, the entire canister can be CS coated with CISCC resistant materials. ASTM specifications for boiling magnesium chloride testing, crevice corrosion, and salt fog are all useful guidelines to assess chemical resistance. Generally, the approach is to perform a comparative study between an uncoated substrate and a CS coated substrate to determine an improvement factor.

### 2.3.5 Erosion Resistance

CS application parameters can be adjusted to provide a wide range of surface hardness for the coating material. In general, a 316 SS alloy is used to provide surfaces with hardness in excess of Rockwell C 42. There is considerable current research being conducted, led by the ARL, to develop advanced coating technologies that provide an effective erosion-resistant hard facing. PNNL has also worked on processes to reduce cavitation damage with various CS coatings. The ARL and PNNL results are quite different because the ARL study focused on shear force erosion on airframe structures, while the PNNL work used normal impact forces associated with cavitation, as shown below (Figure 2-12).

Several coatings have been evaluated with the similar cavitation damage effects in hydropower water turbines. Figure 2-12 illustrates that cold sprayed coatings of Inconel 625 or SS 316 can improve cavitation erosion resistance for new or repaired components. It also appears that a welded cladding could result in accelerated degradation in the HAZ of the weld edges. CS has extremely low heat input, resulting in no HAZ formation.

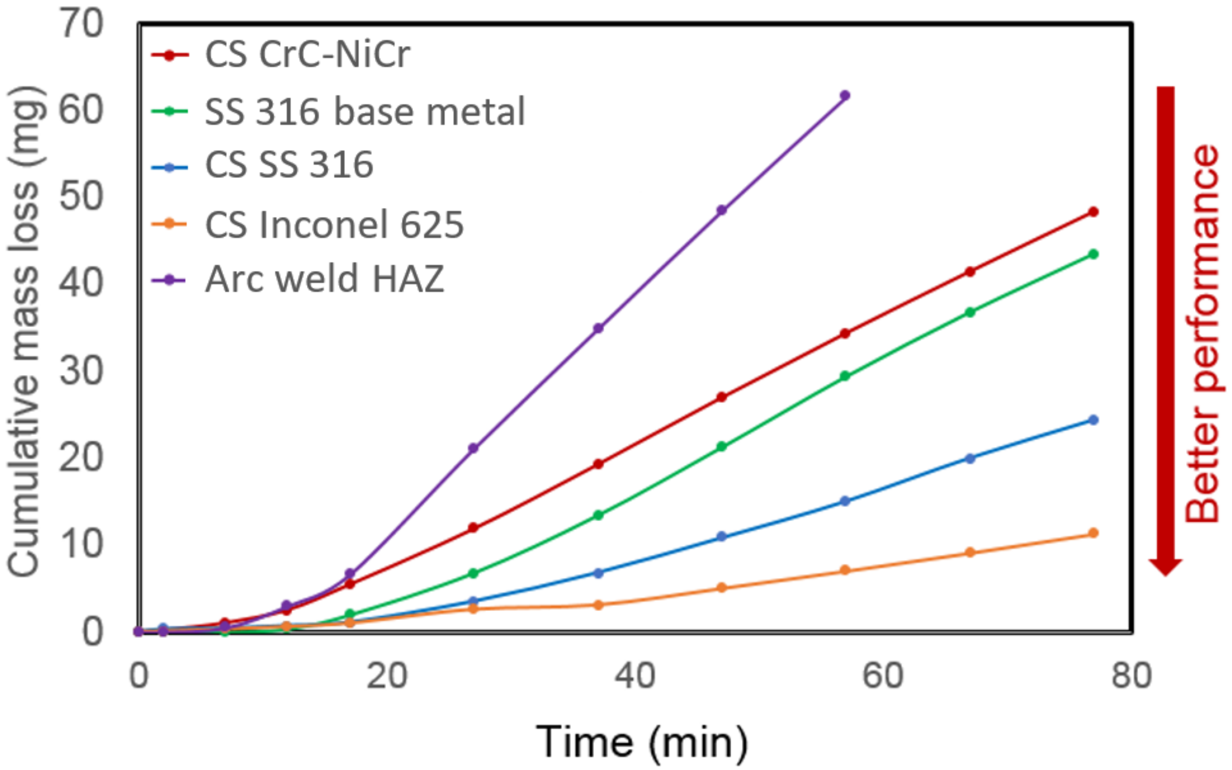


Figure 2-12 Cavitation damage for various surfaces. Using an arc weld repair was inferior, with rapid erosion of the weld HAZ. Cold sprayed Inconel and cold sprayed SS produced 342% and 242% improvements in cavitation erosion resistance, respectively, compared to SS 316 extruded plate base metal (Jiang et al. 2020; Ross 2019).

### 2.3.6 Thermal Considerations

There are two primary thermal failure mechanisms with CS coatings: thermal fatigue and debonding caused by coefficient of expansion mismatch between the coating and substrate. Process development should include testing for both concerns. Thermal fatigue testing requires several heating and cooling cycles that conservatively represent the expected operating conditions and life span. Thermal expansion mismatches between the substrate and coating could result in sufficient shear stresses at the interface to debond the coating. A relatively straightforward test should be performed to check compatibility at a temperature that represents not only normal operating conditions, but also any potential accident conditions.

In a previous process development effort, thermal cycling of cold sprayed CPNi on Inconel alloy 600 was performed by heating coated samples to 400°C and plunging them into water. After 100 cycles, no indications of cracking or debonding were found using NDE techniques and SEM (Parsi et al. 2012). CS of alloy 718 is used for jet turbine blades that operate at temperatures above 1000°C and cool when engines are turned off.

### 2.3.7 Radiation Resistance

Radiation damage is due to several different mechanisms, including weakening of bonds, lattice dislocation, activation, and swelling. Neutron flux is the primary driver for these damage mechanisms, although bond strength can also be affected by gamma radiation. In order of decreasing severity, gamma or neutron flux radiation damage to bonds affects van der Waal bonds, covalent bonds, ionic bonds and metallic bonds (Knief 1981). CS would be expected to be better than organic coatings, such as epoxy or urethane. In situations where neutron flux is a potential concern, activation and swelling should be considered. For example, cobalt alloys could be activated and produce high background radiation. Boron-bearing materials could capture neutrons and cause swelling. Since the likely CS coating candidates are Ni, SS, or Inconel compounds, these materials would be similar to materials that are already used extensively in nuclear plants. Extra consideration should be given to any potential application near fuel, such as reactor internals or spent fuel pools. For spent fuel storage canisters, the neutron levels are likely to be sufficiently low to preclude any concerns (NRC 2019).

### 2.3.8 Stress Corrosion Cracking Resistance

There are several different types of stress corrosion cracking (SCC) that can occur in high alloy steel nuclear components. However, a common effect for all these various forms of SCC is that once the substrate material is isolated from the corrosive environment, it is no longer susceptible to the cracking mechanism. In many cases, sealing the surface will also arrest the growth of existing cracking using an embedded flaw concept.

Several types of SCC that are known to have occurred at nuclear power plants (NPPs) include:

- PWSCC of Ni alloys with less than 24% chrome.
- Intergranular stress corrosion cracking (IGSCC) in oxygenated high temperature environments with 300 series SS.
- ClSCC, which can occur in SS at ambient temperatures if sufficient concentrations of Cl exist.
- Irradiation assisted stress corrosion cracking (IASCC) in reactor internals.

Some qualification testing has been performed using either CPNi or Ti/TiC to demonstrate SCC protection for the various SCC mechanisms with various Inconel and SS substrates. No studies to date have addressed CS for prevention of IASCC.

In the investigation of CPNi coatings applied to Inconel (Alloy 600) materials for PWSCC prevention, doped steam SCC testing was done at 750°F, 5–13 psia $H_2$, with 80 parts per million of $F^-$, $Cl^-$ and $SO_4^{2-}$ (Parsi et al. 2012). 1/8 in. thick CPNi coated and uncoated Inconel Alloy 600 were tested. Also ¼ in. thick Inconel Alloy-182 clad bend bars were tested. Specimens were put into 4-point bend fixtures, and samples of each coating/thickness combination were loaded to 70, 75, and 80 ksi tensile stress. All uncoated samples failed within 200 hours. Testing stopped after 800 hours for the ¼ in. samples and after 1,000 hours for ⅛ in. samples. No cracking was observed on the CPNi CS coated specimens.

## 2.4 Process Quality Management

The quality of CS coatings can be managed by intervention at all stages of the CS process with quality management procedures. These stages are defined here to include the pre-process, in-process, and post-process stages and the in-service stage of the coating lifecycle. Typical quality management procedures include verifying through testing and/or inspection, recording important process parameter values, and adhering to relevant standards. Inspection may include destructive evaluation (DE) of coupons or NDE of the actual part/component.

The International Standard Organization (ISO) publishes standards for quality management documentation, which include processes, procedures, and work instructions. ISO 9001, *Quality management systems – Requirements* (ISO 9001:2015) and ISO 19443:2018, *Quality management systems — Specific requirements for the application of ISO 9001:2015 by organizations in the supply chain of the nuclear energy sector supplying products and services important to nuclear safety (ITNS)* (ISO 19443:2018 2018) are relevant ISO standards for documentation of CS application.

### 2.4.1 Pre-process Quality Management

Initially, the CS application should be defined and understood in detail because requirements determined at this stage will drive considerations such as implementation in factory or field setting, type of powders, feed gas, type of nozzle, and the process parameters.

The implementation of CS in a factory or field setting is important due to trade-offs between equipment performance and portability. Further, the environment under which CS is performed in the factory is often better understood and more easily controlled by the operators. If an application requires the use of CS in the field, then an understanding of site-specific constraints, such as geometric access restrictions, is needed to be sure adequate performance can be achieved through appropriate process selections (e.g., geometry constraints may necessitate the use of He gas instead of $N_2$, increased gas velocities, or other measures to mitigate nozzle clogging).

Another pre-process consideration for quality management includes handling procedures for the CS powders. As noted in Section 2.2.1, the size distribution of the powder needs to be controlled to ensure sufficient velocity and bonding performance. Further, the oxidation state of the powder is relevant to particle-to-particle cohesion and ductility. Therefore, methods for particle size control and protocols for powder storage and handling all need to be implemented.

Surface cleaning may be needed at the pre-process stage to remove surface oxides. As noted in Section 2.2.4, the deposition of CS on top of an oxide layer can significantly reduce adhesion strength.

NDE of the surface prior to coating application may also need to be performed to verify that the substrate does not contain defects that could undermine the integrity of the deposited coating. Section 2.2.4 refers to scenarios in which surface breaking cracks or near subsurface flaws with thin surface ligaments could undermine the quality of the coating deposited over the flaws. Similar concerns have been noted with the surface peening mitigation techniques to reduce surface residual stresses in Ni alloy welds (Lareau et al. 2019a). As a result, an effort was initiated to determine if ET examinations are sufficient for detecting small surface-breaking flaws or near subsurface flaws that could undermine the peening process and component integrity (Lareau et al. 2019a). This report refers to evidence suggesting ET is superior to PT and VT at detecting small surface breaking flaws and determining the adequacy of ET for detecting any near subsurface flaws of potential concern is unresolved. The report also mentions the need for development of acceptance criteria for pre-existing flaws in the component. The application of CS coatings invites similar questions regarding the determination of acceptable vs. unacceptable flaws and understanding if all potential flaws of concern can be detected by ET or if there are scenarios in which other methods (e.g., volumetric UT or RT) should be utilized.

The DoD’s pursuit of CS technology has resulted in the creation of several standards associated with the CS pre-process stage, including:

- MIL-STD-3021 Material Deposition, Cold Spray March 2015.
- MIL-DTL-32495 Aluminum Bead Powders for Cold Spray Deposition August 2015.
- MIL-DTL-32495A Powders for Cold Spray November 2019.
    - MIL-DTL-32495A is helpful since it also establishes a Qualified Product List, which includes allowable contaminant levels, shelf life, and handling requirements along with a specific naming process (part identifying number).
- (UIPI) 6320-901 Uniform Industrial Process Instruction, Processes and Quality Control of Cold Spray.

### 2.4.2 In-process Quality Management

Quality management methodologies, such as Six Sigma and Total Quality Management, are applicable to CS fabrication and repair operations. Quality management is essential to provide process control to ensure that important process parameters remain within qualified ranges and satisfy Appendix B to 10 CFR Part 50 for nuclear applications. A CS quality management plan should include statistical process control (SPC) of relevant process variables, procedures, work instructions and documentation that defines the quality management plan and assures conformance to the plan is documented. SPC can be effectuated real time if vendors apply SPC features into the control system of CS equipment. Alternatively, SPC can be effectuated after fabrication through analysis of process data logs. A table of process parameters and quality assurance methods is shown below in Table 2-2.

Table 2-2 Principal (not all-inclusive) CS process parameters quality assurance mechanism.

| Process Parameters | Quality assurance implication | Quality assurance mechanism |
|---|---|---|
| **Gas temperature** | Gas temperature directly affects particle velocity exiting a convergent/divergent nozzle. Gas temperature also affects heating of powder particles. | SPC of gas temperature as measured by thermocouples. |
| **Substrate temperature** | The heated gas stream can affect substrate temperature. Path planning to avoid local heating may be necessary for CS of temperature sensitive substrates. | Most applications don't need to worry about overheating of substrate material. SPC of path plan or SPC measured surface temperature can be used if needed. |
| **Gas/powder velocity** | Particle impact velocity is the largest contributor to energy available for bonding and therefore effects porosity and mechanical properties of the coating. | SPC of pressure and flow rates are the best practice for ensuring constant velocity. Direct measurement of particle velocity is cost prohibitive. |
| **Particle size** | Particles that deviate from an optimized nominal size disrupt flow and reduce coating properties. | Sieve and classify powder prior to CS to application-specific specifications. |

| Process Parameters | Quality assurance implication | Quality assurance mechanism |
|---|---|---|
| **Powder/particle oxidation** | Aluminum CS powders are highly susceptible to oxidation relative to many oxidation resistant high-melt temperature alloys. Thick oxide layers on particles reduce properties of the deposited material. | Create procedures to prevent corrosion and oxidation of powders in storage (vacuum pack and argon backfill of powders; humidity and temperature control governing storing and handling). |
| **Surface oxidation/ contamination** | Thick oxides and surface contamination reduce adhesion strength of the cold sprayed coating. | Application specific procedures for surface preparation. Destructive testing of test coupons before and after spray. |
| **Angle of powder impact** | Angle of powder impact affects deposition efficiency and mechanical properties of the deposited material. | SPC of angle as measured by instrumentation integrated into CS equipment (encoders, inclinometers, position sensors). |
| **Nozzle distance to surface** | If the nozzle is too far from the surface, particle velocity drops. If the nozzle is too close, gas flow is interrupted. Mechanical properties are reduced if the nozzle is too close to or too far from the substrate. | SPC of nozzle distance to the surface as measured by instrumentation integrated into CS equipment (encoders, inclinometers, position sensors). |
| **Nozzle traverse speed** | Nozzle traverse speed affects thickness of deposited material per pass. | SPC of traverse speed calculated from encoder feedback on CS equipment. |
| **Nozzle clogging** | Increased porosity and reduces mechanical properties of deposited material. | SPC of measure pressure at multiple points. |
| **Post-spray grinding/ machining technique** | Surface roughness can affect corrosion performance. Overly aggressive machining can damage deposited material. | Control application specific surface roughness specifications and validate via handheld or automated surface roughness measurement. Machining or grinding procedures should be qualified or tested. |

### 2.4.3 Post-process Quality Management

Based on reported results from ARL (Nardi et al. 2019), the CS process is reasonably forgiving in terms of nozzle spacing (typically +/- 12 mm) and spray angle (typically +/- 30 degrees), but application specific qualification testing is required to demonstrate this. As long as the process variables are maintained in the desired range, the finished part properties are very likely to be in the expected range. The primary defects in CS are caused by variations in process parameters, such as gas temperature, substrate temperature, powder size, powder oxidation or contamination, nozzle-to-surface distance, nozzle clogging, and powder impact angle.

Parameter variations may cause significant defects, including porosity (small, spatially distributed volumetric discontinuities), voids (larger, typically isolated volumetric discontinuities); surface roughness; and poor surface adhesion (similar to lack of fusion). Part property variables that may be important to evaluate to ensure good coating performance are indicated in Table 2-3, and some typical coating anomalies are shown in Figure 2-13.

The anomalies shown in Figure 2-13 include high coating porosity (left), which can be caused by nozzle clogging and can be an indicator of coating quality. Poor adhesion (center) at the coating/substrate interface can also result from process parameter variations or from failure to remove oxides from the surface prior to the CS deposition. The crack in underlying CS layers (right) can form from defects on the substrate surface that propagate through layers of CS deposit.

Table 2-3 Part properties variables of interest.

| Part property variables of interest |
|---|
| Coating thickness |
| Porosity |
| Voids |
| Substrate adhesion |
| Surface roughness/finish |
| Variation in hardness |
| Young’s modulus |
| Yield strength/toughness |
| Post-machining surface finish |
| Wear/corrosion/crack resistance |
| Residual stress |

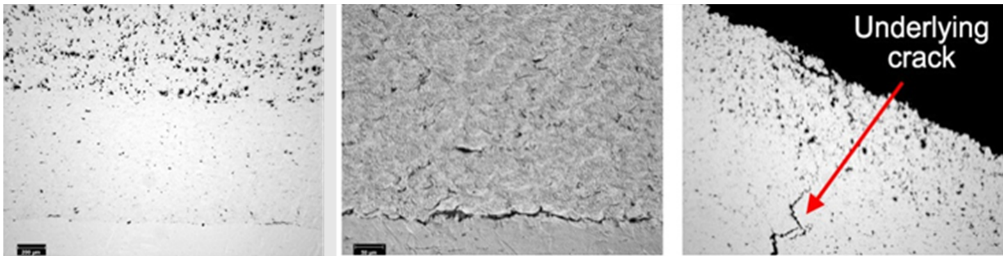


Figure 2-13 Examples of photomicrographs of CS; (left) high porosity top layer over lower porosity coating due to clogged nozzle; (center) poor adhesion at substrate interface; (right) crack in underlying layer covered over by uncracked CS coating layer. (PNNL photograph)

#### 2.4.3.1 Destructive Testing of Witness Coupon

Typically for demonstration and actual application for CS, the process includes placing a witness sample coupon adjacent to the part being sprayed. This coupon is then sprayed along with the primary part, and the coupon may then be subjected to post-process destructive and nondestructive examinations to infer the condition of the part of interest. The most common metric of part quality is the spray thickness and porosity, but other quality metrics can also apply as listed in Table 2-3. Destructive coupon tests can include optical surface profiles, cross-sectional photomicrographs to evaluate porosity, tensile bond/yield strength, hardness, and corrosion susceptibility. Some relevant standards for testing properties of CS coatings include:

- ASTM E92 for hardness testing.
- ASTM D4541 for bond strength using adhesive pull testing.
- ASTM E2109 for porosity measurement.
- ASTM F3007-19 Standard Test Method for Ball Drop Impact Resistance of Laminated Architectural Flat Glass.

Although ASTM F3007-19 refers to laminated architectural flat glass, it has been used by investigators of CS to show that it will dent but not crack or spall. As a destructive testing technique, hardness testing can be applied to surfaces of sectioned pieces of coupons.

#### 2.4.3.2 CS Coating Quality Verification with NDE

NDE may be necessary to verify the quality of the actual part/component for some critical applications. An assessment of NDE methods for advanced manufacturing techniques, including CS, is provided in a recent NRC letter report (Jacob et al. 2020). The report documents some knowledge gaps for NDE of CS materials related to applying NDE methods for verifying coating properties such as porosity, coating/substrate adhesion quality, detection of defects in thick CS builds, and inspection of substrate material through the CS coating. Attenuation of ultrasound is influenced by the level of porosity in the CS coating with attenuation increasing with higher levels of porosity. Surface roughness is a property generally correlated with porosity that can affect inspections through effects on coupling for UT, effects of surface conductivity variations for ET, and effects of light scattering for VT. The report also notes that the status of current research of NDE of CS coatings is limited and results are difficult to extract between applications because NDE responses are dependent on the coating and substrate material, their thicknesses, and other special geometry features (i.e., there could be applications where the coating surface is not parallel to the coating/substrate interface).

NDE methods to assess a CS part for overall spray quality and for cracks or flaws are considered in Glass et al. (2018). The principal NDE methods addressed are VT, PT, UT, ET, optical profilometry, and hardness tests. In the context of an NDE method, hardness testing can only be performed on the accessible surfaces of the coating as sprayed. The assessment was performed experimentally on specimens consisting of a 6 mm thick 304 SS substrate with 3.8 mm thick NiCr alloy CS coating. Three such specimens were utilized representing a range of coating quality based on porosity. Some relevant observations from this paper include the following:

- Measurements of porosity by UT and ET are considered based on changes to acoustic attenuation and electrical conductivity with porosity.

- Optical profilometry is considered for measuring porosity using surface roughness as a proxy indicator for porosity.
- UT, ET, and optical profilometry were evaluated for porosity measurement by correlating responses with the samples of varying porosity determined by DE. This implies that NDE measurement of porosity requires a set of calibration specimens to be developed for each application.
- It is noted that an optimal frequency range will exist for ET measurement of porosity because too low of a frequency will result in penetration of the substrate while too high of a frequency will make ET too sensitive to irrelevant surface features. Although not explored, this implies that multi-frequency or pulsed ET techniques may be effective for measurement of coating thickness and the quality of the coating/substrate bond.
- An A-scan from a UT measurement included a response from the coating/substrate interface, which implies UT is capable of measuring coating thickness and discerning the bond quality of the coating/substrate interface. Understanding the possible resolution with which UT can measure coating thickness and coating/substrate interface bond quality requires investigation.
- The effects of coating porosity and acoustic attenuation on ability to inspect for discontinuities in the coating and ability to inspect through the coating for discontinuities in the substrate needs investigation to understand the coating conditions that are prohibitive to these inspections.

### 2.4.4 In-service Quality Management

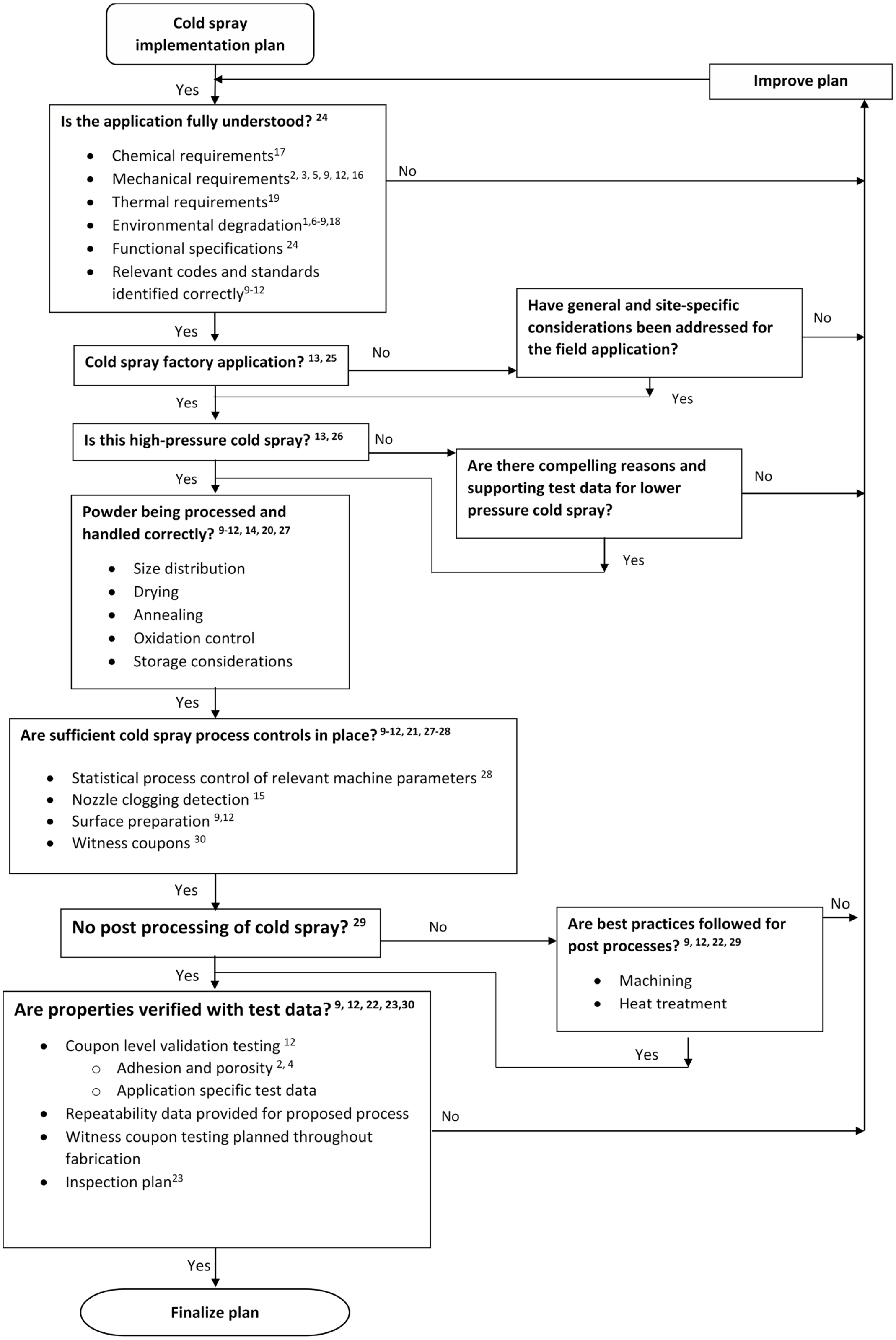
In-service NDE may be applied to manage the integrity of CS coatings very similar to the way in-service inspection (ISI) is applied to manage the integrity of NPP components affected by aging degradation. Visual or surface techniques may be applied to detect surface-breaking cracks in the coating. In this case, surface roughness may be a factor complicating detection by VT, PT, and ET. UT may be applied to inspect the substrate beneath the coating for crack formation. As noted in the previous section, attenuation of the UT signal as it passes through the coating layer could affect detection performance. Finally, debonding at the coating/substrate interface is a type of failure that could be caused in some in-service environments (e.g., thermal cycling). In addition to investigating the capabilities of techniques (i.e., UT and ET) to detect debonding, a definition of acceptable debond conditions, if any, is needed. The debond not only has implications for the integrity of the CS coating, but also the ability to access the substrate beneath the coating for inspection.

### 2.4.5 Comprehensive Process Quality Management

A schematic depicting process implementation guidance for CS applications is provided in Figure 2-14 below. Considerations are depicted in sequence from the pre-process stage to the post-process stage from the top to the bottom of the schematic. This schematic provides a framework to ensure relevant considerations are understood and addressed for a CS implementation. This methodology is based on observed best practices throughout various industries. In the private sector, CS quality plans and work instructions are typically held proprietary and therefore not included in this report.

In addition to observed best practices in the private sector, the implementation guidance presented in the schematic is informed by the DoD CS procedures standardized in several military specification documents. Several of these are referenced in Section 2.4.1. These standards may be limited in their application to the nuclear industry because they are primarily developed for the dimensional restoration of Al components, but they may be helpful in informing a process for qualification and development of standards for CS applications in the nuclear industry.

While the process in Figure 2-14 below is typically used for general CS process development, it is valuable to understand and evaluate a proposed CS implementation with respect to its adequacy for an application.  Each application is likely to require a specifically tailored implementation derived from the process depicted in Figure 2-14.  The subsequent subsections provide additional context to this framework.



1) ASTM B117
2) ASTM D4541
3) ASTM E92
4) ASTM E2109
5) ASTM F3007
6) ASTM G61
7) ASTM G78
8) ASTM G134
9) MIL-STD-3021
10) MIL-DTL-32495
11) MIL-DTL-32495A
12) UIPI 6320-901
13) Sec. 2.1
14) Sec. 2.2.1
15) Sec. 2.2.3
16) Sec. 2.3.3
17) Sec. 2.3.4
18) Sec. 2.3.5
19) Sec. 2.3.6
20) Sec. 2.4.1
21) Sec. 2.4.2
22) Sec. 2.4.3
23) Sec. 2.4.4
24) Sec. 2.4.5.1
25) Sec. 2.4.5.2
26) Sec. 2.4.5.3
27) Sec. 2.4.5.4
28) Sec. 2.4.5.5
29) Sec. 2.4.5.6
30) Sec. 2.4.5.7

Figure 2-14 CS process implementation guidance schematic. This schematic provides a strategy to ensure relevant considerations are understood and addressed relative to CS implementation.

### 2.4.5.1 Understanding the Application

A thorough understanding of the application is necessary to ensure proper implementation and evaluation of CS. A CS integration plan should present clear reasoning and thorough analysis relative to development of requirements for the cold sprayed material. Additionally, the CS integration plan should identify testing necessary to demonstrate that the cold sprayed material is compliant with specifications for the overall part or system. Chemical, mechanical, and thermal requirements and environmental degradation should be included in topics considered when developing specifications.

Systems engineering, product development and other fields commonly use documents called "functional specifications" to define requirements for components or systems. For instances where a component is being coated or repaired, a set of specifications should be developed for the coating or repair. This can be done as a section (or sections) within a functional specification for a given component or as a separate document that references the component's functional specification. Often, the intended function and requirements of a coating or repair are significantly different than that of the surrounding material. A CS integration plan should show that functional specifications are met and quality assured. One way this can be achieved is through a technical proposal with an accompanying quality plan per ISO 9001.

### 2.4.5.2 Field vs Factory Application

The location where CS will be applied determines the limitations on the type of equipment that can be used to implement CS (Section 2.1). For factory HPCS of new spent fuel canisters, large industrial systems with liquid-cooled nozzles can produce high-quality CS deposits economically. He recycling in factory CS enables improved quality at reduced cost. For confined spaces or high rad environments, field repair equipment may be integrated with a robotic crawler. Portable HPCS equipment is a newer technology compared to stationary factory HPCS equipment. It is important to understand the strengths and limitations of the equipment being used.

It is also important to understand that parameters and performance are not directly transferable across significantly different equipment and nozzle designs. For example, it is possible to cold spray with greater than 99.9% deposition efficiency using factory equipment. However, extremely high deposition efficiency has not yet been demonstrated for cold spray of high melt temperature alloys using small angled nozzles (Section 2.1.1) on portable systems intended for field repair applications in confined spaces. Properties of cold sprayed material and process considerations needs to be validated using equipment and nozzle types that will execute the work. It cannot be assumed that the process or properties will be the same across various cold spray platforms and configurations.

Field work may be subject to additional controls and restraints. Examples of items to consider for field repair include but are not limited to:

- Radiation exposure
- Collection of undeposited powder
- Asphyxiation hazards from the carrier gas
- Robotic or manually controlled system (Section 2.1.2)

#### 2.4.5.3 High Pressure vs Low Pressure CS

High velocity enables high kinetic energy, which is required to create high plastic deformation and shearing at particle boundaries. This results in dynamic recrystallization and metallurgical bonding at interparticle boundaries. Particles are held to each other and the substrate by both mechanical interlocking and metallurgical bonding.

Reduced kinetic energy associated with LPCS results in reduced mechanical properties relative to HPCS. LPCS systems are not recommended for high quality CS of steels, Inconel, and other high strength/melt temperature materials if HPCS can be used. There may be applications where LPCS is advantageous due to simpler and potentially smaller equipment configurations.

#### 2.4.5.4 Powder Processing and Handling

Proper powder processing and handling is critical to quality assurance (Section 2.2.1). Powders should be sieved and classified to ensure particle average size and size distribution is within specifications. Minimizing variations in particle size improves deposition efficiency and properties of the coating. Powder should be fully dried to avoid clumping. Al powders are often vacuum packed and argon backfilled to avoid oxidation. Steels and other high melt temperature alloy powders are less sensitive to oxidation at room temperature and require less controls. Some metal powders are flammable or have other hazards and should be stored accordingly.

#### 2.4.5.5 Process Controls

Work instructions are important tools to ensure processes are repeatable and in control. Work instructions that include measurements should be developed for surface preparation (Section 2.2.4). Witness coupons should be fabricated during CS operations to enable destructive testing of representative coupons (Section 2.4.3.1).

All aspects of the CS operation should be monitored and controlled as part of a quality plan. Statistical process control of relevant machine parameters such as those identified in Table 2-2, should be implemented (Section 2.4.2). Nozzle clogging detection through monitoring system pressures should be automated and integrated (Section 2.2.3). Surface preparation and monitoring of line pressure to detect clogging are examples of procedures that can be implemented to improve the likelihood that a CS application will be successful.

#### 2.4.5.6 Post Processing

After a CS operation, post processes such as machining and heat treating may be required. Due to cold working that occurs during CS processing, hardness increases. A rule of thumb is that cutting speed for CS materials should be about ⅓ of a machinist’s handbook values for a given material. Ignoring these guidelines may cause damage to as-sprayed material or tooling.

If heat treating is required, the need should be clearly described. Test data should be provided to show the developed heat treatment results in the desired processing. Heat treating is typically used to increased ductility if needed for the application.

#### 2.4.5.7 Verification testing

The final block in Figure 2-14 calls out steps to verify properties of the CS deposit. Some techniques include coupon testing (e.g., as in Section 2.4.5.5). In this case, coupons can be prepared and tested prior to initiating CS deposit for the intended application to confirm that the process can give the desired results. In addition, witness coupons can be prepared during the CS deposition for the intended application and later tested to confirm the quality of the as deposited coating (Section 2.4.3.1). For scenarios where it is necessary and feasible, NDE of the CS deposit may also be performed to verify the coating quality (Section 2.4.3.2).

# 3.0 CS Applications

Each year, the ARL conducts a conference with the CSAT on CS applications in several industries, including aerospace, naval vessels, additive manufacturing, automotive, and nuclear industries. Most presentations are posted on the CSAT Conference web page (https://www.coldsprayteam.com/), which is public and can be searched by year. A survey of the status of recent applications in aerospace and naval industries is provided in the keynote speech (Champagne 2020), followed by detailed presentations on various topics.

## 3.1 Applications in Non-Nuclear Industries

CS is an approved repair process for dozens of DoD applications. CS-repaired components have been in service on various military aircraft and naval vessels for nearly a decade (Champagne 2018). CS is also used to repair commercial aircraft components. Companies such as Detroit Diesel use CS to repair/rebuild commercial freight engines.

Aerospace applications include corrosion protection (Al alloy coatings of magnesium housings and Ni alloys for seawater flanges), erosion protection (normally NiCr-CrC coatings on fuselages) and dimensional restoration of worn parts. Recent work has also included studies on improved fatigue resistance for aerospace structures so that some level of structural credit can be taken for the coating. However, these applications involve relatively thin components, where the CS is a significant fraction of the total thickness. Refractory coatings (tantalum) have been applied in gun barrels. This effort led to the development of miniature nozzles.

Most of the prior work has been done in the aerospace industry, so the substrate materials and powders differ from what would be encountered for nuclear applications. However, a great deal can be learned and transferred on robotic control, testing methodology, and process parameters. Powder specifications and handling processes are also applicable.

In 2015, the DoD did a detailed analysis of the cost savings associated with CS repair associated with corrosion resistant layers and dimensional restoration with wear resistant layers (Pelsoci 2015). That report estimated a cost savings of more than $250M from fifteen approved repairs. At the annual CSAT conference, ARL (Champagne 2018) summarized the recent applications of CS along with their status (developmental, approved, deployed) and has reported continued savings and salvaging usable life from components with a greatly reduced time frame compared to replacement parts.

The Puget Sound Naval Station has developed procedures for using CS to improve corrosion resistance in several naval applications. These include swing check valves, sea water pump flanges, metering valves and o-ring groove repairs (Stamey 2018). Components that have been successfully repaired include a sea water swing check valve (CuNi 7030 with a Ni coating to prevent corrosion), a metering valve (CuNi 70/30 with a Ni and CrC powder mixture for wear resistance), and a sea water pump shaft and journal (materials not specified). These sea water applications closely resemble similar applications being undertaken by Exelon for sea water valves, although the specific substrate materials differ.

NAVSEA (Naval Sea Systems Command) issued a standardized procedure for qualifying CS repairs: UIPI 6320-901, Processes and Quality Control of Cold Spray (NAVSEA). This procedure addresses personnel qualification and occupational safety as well as process step requirements. In this regard, this procedure is similar to welding procedure qualifications. While this procedure addresses the step-by-step process controls, a separate, application-specific document is required to demonstrate that the coating satisfies the intended purpose, such as corrosion or wear resistance. The procedure does provide generic requirements for porosity and mechanical properties that are applicable to a broad range of uses. It also specifies a comprehensive list of qualification tests covering bond strength, ductility, tensile strength, wear resistance, and others. For many of the test protocols, the acceptance criteria are specified in a related engineering document.

Hydropower plants are investigating dimensional repair of water turbines after cavitation damage (Jiang et al. 2020; Ross et al. 2018). Several potential coating materials were investigated for cavitation resistance. The traditional repair method using weld overlays produces warping and detrimental HAZ. Laboratory testing showed CS can be used to deposit material with more than three times the cavitation erosion resistance of SS overlays.

Automotive applications are mostly dimensional restoration for dents and damaged rims. These generally use lower pressure systems and therefore have little relevance to potential nuclear applications.

## 3.2 Nuclear Applications

In the nuclear field, several applications are being pursued and a survey of potential applications for the nuclear power industry is provided by Lareau et al. (2019b). A summary includes:

- Ni coating for PWSCC protection of alloy 600 Inconel (Parsi et al. 2012).
- CS coated ZIRLO® and Optimized ZIRLO™ cladding tubes, developed by Westinghouse, are currently in service and are being tested in Byron Unit 2 cycle 22 (Sevecek et al. 2018; Shah et al. 2018). These sixteen fuel rods completed their first operating cycle in November 2020 and will be examined visually.
- Depositing a porous coating on the bottom of a reactor vessel for enhanced cooling in case of a loss of coolant accident (LOCA) (Segall et al. 2017).
- Manufacturing subsurface flaw NDE samples (Lareau et al. 2016).
- CS copper cladding of spent fuel storage canister (Keech et al. 2014).
- Mitigation and repair of CISCC in DCSS canisters (Ross et al. 2020; Southern California Edison 2019).
- Repair of material loss due to corrosion (e.g., to fill pits and restore wall loss) in mild steel of Hanford waste tanks.
- Coating the outside of nuclear fuel rods with a zirconium-boron mixture to provide a burnable poison (Lahoda et al. 2007).

There are currently no structural applications for CS anticipated in nuclear plants.

### 3.2.1 Application of CS to Hanford Waste Tanks

PNNL is currently evaluating CS for the restoration of the bottom carbon steel plates of nuclear waste storage tanks at the Hanford site (Enderlin et al. 2020a). CS is a solution of interest for repair of damaged tanks. A modest set of CS conditions were tested to determine if a set of CS parameters exists that leads to dense, robust deposits of mild-steel powder on a mild-steel plate typical of what's found in Hanford tank farms (tanks and pipes). The tests included the deposition of cold sprayed carbon steel material to a pitted surface (simulated flaw) to demonstrate the ability to fill pits and restore wall thickness/corrosion allowance. The tests also included the deposition of carbon steel material to a flat surface opposite a pitted surface (test mockup) as an alternative means of restoring wall thickness/corrosion allowance. Commercially available mild-steel powder was annealed to soften the material such that bonding between the powder and the substrate could be achieved. In addition, screening to remove fines below ~20 µm was performed.

Test results demonstrated mild-steel powder could be bonded to mild-steel substrates (i.e., similar powder/substrate material bonding) via the CS process using commercially available equipment operating within the range of normal process conditions. Measurement techniques used to characterize the CS deposits demonstrated deposit densities greater than 99% (<1% porosity). The best results relative to deposit density, void distribution, and visual appearance were achieved using He gas at an operating temperature of 500°C and a supply pressure of ~4.8 MPa (~700 psi). Surface preparation affected deposit density and appeared to affect bonding/adhesion at the substrate interface and throughout the layer of deposited material. Limited testing demonstrated that the CS process equipment could be used for surface preparation to enhance material bonding.

The feasibility project satisfied the go/no-go criteria that were established to determine whether CS should be considered a candidate tank repair method and, therefore, whether future work would be warranted. Future efforts would (1) identify the range of CS parameters and surface conditions that will lead to dense, robust deposits, and (2) adapt a commercial CS system to perform tank/pipe repairs in an operational environment.

Some specific avenues for future work include:

- determining whether lower deposit densities can be used to create an acceptable repair,
- characterization of the hermetic sealing, powder adhesion and corrosion resistance as a function of deposit density and thickness,
- evaluating modifications to the powder properties that may obtain bonding at reduced pressure or temperature to reduce helium usage,
- and providing final powder specifications to powder vendors to allow production runs of ready-to-use powder to be generated.

Additional information is published in the WM2020 proceedings (Enderlin et al. 2020b). A technology evaluation and down selection for repair of Hanford storage tanks is presented in Ross et al. (2020). Challenges of this repair and proposed specifications are described in the referenced papers.

### 3.2.2 Investigations of CS Applications by the Nuclear Power Industry

This section provides an overview of either previous or ongoing CS activities in the nuclear power industry. Other potential nuclear power applications are discussed in Section 3.2.3.

#### 3.2.2.1 Repair and Mitigation of CISCC in Dry Cask Storage System Canisters

Three conditions must exist for CISCC to occur: tensile stress, a corrosive environment, and susceptible material (Figure 3-1). These conditions must be understood and accounted for while evaluating CISCC susceptibility. Furthermore, non-obvious factors, such as surface conditions and geometric confinement (crevices), can dramatically increase the intensity of one or more of the three listed conditions for CISCC.

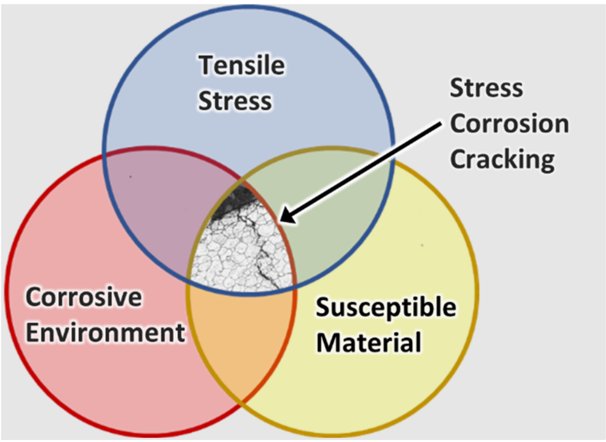


Figure 3-1 Three conditions required for SCC.

CS provides a corrosion resistant barrier coating that has the added benefit of producing compressive residual stresses in the coating and the material immediately beneath the coating. This effectively mitigates two of the three conditions required for CISCC. Nozzles are developed that are capable of spraying in areas with clearances as small as 1.5 in. (Nardi et al. 2019) (Figure 3-2).

As part of an SBIR award from the Department of Energy (DOE), VRC Metal Systems and its team demonstrated the ability to deposit SS and Inconel alloys on SS 304L such that galvanic potential is matched and resistance to pitting is improved. A robotic crawler in a confined environment, representative of the space between a DCSS canister and overpack, executed HPCS using crude manual controls as a proof-of-concept demonstration. This work established the technical viability for CS mitigation and repair within the overpack using remote robotic equipment; however, more development is required for field deployment. Results are shown in Figure 3-2 below.

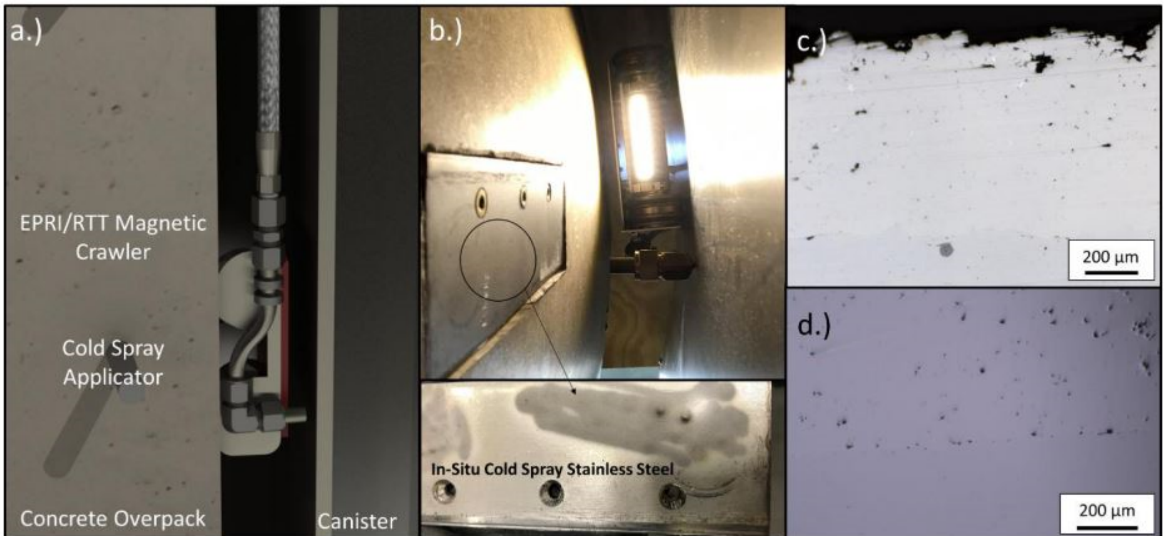


Figure 3-2 a) Graphic of in situ CS repair, b) photo of CS mockup trail with Electric Power Research Institute/RTT robotic crawler showing viability of in situ SS CS, (c) cross section of cold sprayed SS 316L, (d) cross section of Inconel 625 (courtesy VRC Metal Systems).

For situations where tight clearances do not exist, such as factory or pre-service applications of CS for CISCC mitigation, portable CS can be performed by manual handheld operation. Alternatively, the processes can be computer numerical controlled by mounting portable equipment to a portable industrial robot arm or specifically developed coordinated motion tooling.

Hanford contractors are working with a canister vendor, NAC International, and CS vendors to develop CS coatings to enable a 300+ year design life for DCSS canisters to store Cold War-era cesium-strontium (Ross et al. 2020). Externally, the canisters are identical to spent nuclear fuel canisters. Thermal analysis has shown that heat loads produce conditions that resemble those of spent nuclear fuel canisters.

CISCC could occur on regions of the canister surface where the conditions highlighted in Figure 3-1 exist. These regions include the HAZ associated with fabrication welds where the normal corrosion resistance is degraded due to changes in alloy metallurgy and high residual weld stresses. Also, locations with crevice conditions could facilitate initiation of CISCC (see Figure 3-3).

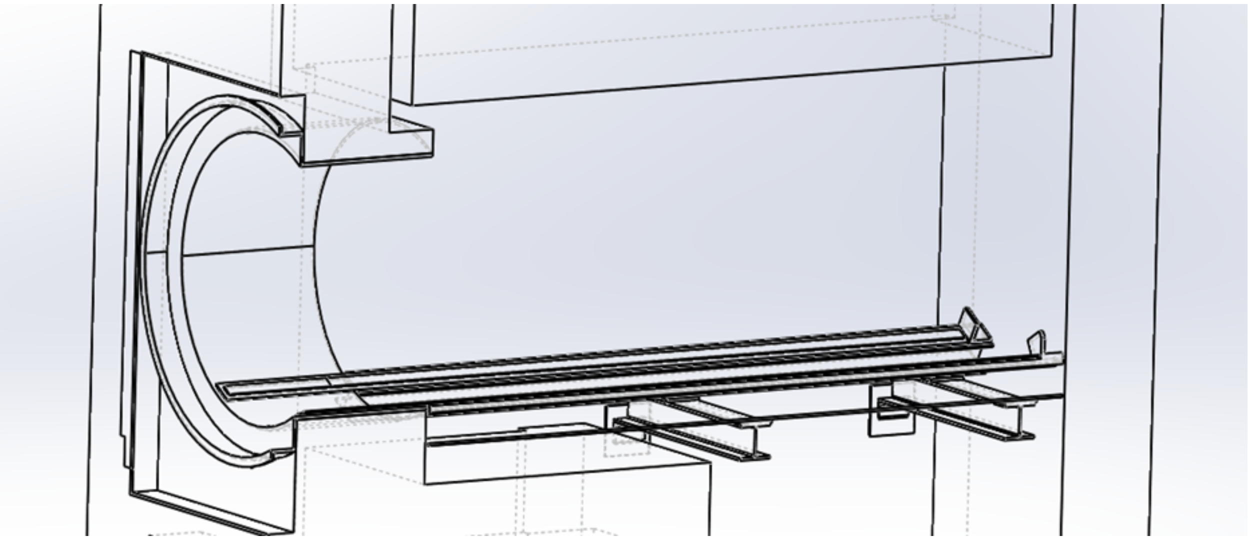


Figure 3-3 Horizontal spent fuel dry storage canister resting on steel rails inside concrete overpack (Meyer et al. 2013).

Applications for a renewed Independent Spent Fuel Storage Installation (ISFSI) license or Certification of Compliance (CoC) include an Aging Management Review that considers various potential aging mechanisms and effects, including corrosion processes that may affect storage system safety functions (NRC (2016). For welded SS canisters, which represent the majority of the DCSSs used in the United States, the primary focus is on CISCC, with special attention required for locations with high residual stresses (weld HAZ, primarily) and crevice locations, which are known to act as concentration sites for chloride salts and also are generally inaccessible for visual testing (Hosler and Hall 2010; Lareau 2014). An Aging Management Program (AMP) is required for credible aging mechanisms that may lead to aging effects that could affect storage system safety functions and which cannot be addressed with a time limited aging analysis (TLAA). AMP elements that describe the recommended content and organization of an AMP are described in NUREG-1927. As an example, the details of the AMP for CISCC of welded SS canisters are included in NUREG-2214 (NRC 2019). CS coatings used as a corrosion protective layer would fall under the preventative actions AMP element. On the inspection program, the example AMP in NUREG-2214 identifies both visual and volumetric inspections to provide complete inspectability of susceptible areas, so the inspectability through a CS layer would need to be addressed as part of any qualification.

It should be noted that existing ASTM SCC tests are designed for base metals (not coatings) and assumed that the material is under high tensile residual stresses representative of those occurring in arc welds. For practical applications, CS would be applied after welding and therefore, CS should be applied *after* the test coupons are placed in a stressed condition to represent realistic conditions for DCSS canisters. Considerations for CISCC testing of CS is described in various DOE reports (Ross et al. 2020; Ross and Alabi 2019).

The canisters are typically housed in a ventilated concrete structure that provides radiation shielding and allows passive cooling but also has geometrically restricted access. One approach to applying CS could be to coat the welds and HAZ with Ni. A separate set of coatings of either Ni or SS 316 could be used for sealing crevices to preclude impurity hide out and concentration. Although the access to the canister housed in the concrete overpack is limited, new miniature CS nozzle designs integrated with robotic crawlers capable of navigating the restricted space could execute these CS operations. A new nozzle developed by the ARL is shown in Figure 2-6.

#### 3.2.2.2 Cr Coating of Fuel Rods (Westinghouse)

One accident-tolerant fuel concept is multilayer cladding (also known as coated cladding). This concept is based on a traditional Zr-based alloy (Zircaloy-4, M5, ZIRLO, etc.) serving as a substrate. Different protective materials are applied to the substrate surface by various techniques, thus enhancing the accident tolerance of the fuel. This study (Sevecek et al. 2018) focused on the results of the testing of Zircaloy-4 coated with pure chromium metal using the CS technique in comparison with other techniques, such as physical vapor deposition, laser coating, and chemical vapor deposition techniques. The CS technique was found to be more cost efficient due to lower energy consumption and higher deposition rates, making it more suitable for industry-scale production. The Cr-coated samples were subjected to different water and steam conditions (500°C steam, 1200°C steam, and PWR pressurization test) and then evaluated by various techniques, such as SEM, energy-dispersive X-ray spectroscopy, or nanoindentation. It was concluded that CS Cr coating has high potential benefits but requires further optimization and out-of-pile and in-pile testing.

CS coated ZIRLO® and Optimized ZIRLO™ cladding tubes, developed by Westinghouse, are currently in service and are being tested in Byron Unit 2 cycle 22 (Sevecek et al. 2018; Shah et al. 2018). These sixteen fuel rods completed the first operating cycle in November 2020 and will be examined visually.

#### 3.2.2.3 Mitigation and Prevention of PWSCC in Ni-Based Alloy Components

PWSCC in Ni-based alloys has been a significant form of degradation in nuclear plants around the world and has led to leaks in the primary system. The release of borated water to exposed carbon steel structures, such as reactor vessel heads, has resulted in secondary corrosion.

Alloy 82/182 dissimilar-metal welds constitute the majority of the primary piping butt welds in which PWSCC has led to leakage in operating commercial nuclear power plants. Several competing mitigation and repair techniques have been pursued, including spool piece replacement, structural outside diameter (OD) weld overlays, corrosive resistant inside diameter weld inlays, and various stress reduction peening methods. A CS layer of Ni over the exposed wetted surface is a viable alternative. Previous work reported by Parsi et al. (2012) demonstrated that a thin (~0.015 in.) pure Ni coating could provide an effective corrosion barrier and compressive residual stress to both arrest existing cracks as well as prevent new PWSCC. The CS delivery system could be adapted to apply to butt welds, nozzle penetration j-welds, and various attachment welds throughout the primary system. Recent equipment enhancements have provided the ability to deliver coatings 10 meters distant from the equipment. For this application, the existing flaw would have to be analyzed to show that the component still had sufficient structural integrity so that CS would only be considered a sealant. A wide range of delivery hurdles would also have to be overcome as piping butt welds are generally under water in high radiation areas. Dissimilar-metal attachment welds would generally be accessible in open air locations, but with high background radiation.

#### 3.2.2.4 Valves: Flanges and O-ring Grooves, Seawater Valves and Flow Element

Several researchers have evaluated using CS to repair flanges and O-ring grooves on various valves comprised of several different substrate materials. Pitting corrosion from borated water or seawater exposure has occurred in several plants. The current practice is to machine down the surface within tolerance limits to provide a new sealing surface. CS could be used to restore dimensional tolerance with some post coating machining (CS coatings generally undergo machining similar to alloyed steels). Case studies of repairs in other industries were recently reported at the 2018 CSAT conference by NAVSEA and Penn State University, among others. The coating material can be tailored for the specific substrate and operational environment so that it can also provide future corrosion protection, in addition to restoring dimensional tolerance. An example of typical sea water corrosion pitting on a valve flange is shown below (Figure 3-4 and Figure 3-5). The first picture is a check valve fabricated from a SS casting (316 SS chemistry modified with the addition of 6% Mo) and has clear instances of crevice corrosion on the flange face. The second picture is a flow element that is fabricated from SS316L, which displays more severe crevice corrosion. For both conditions, the CS coating that was qualified through testing was a powder mixture of Ti and TiC.

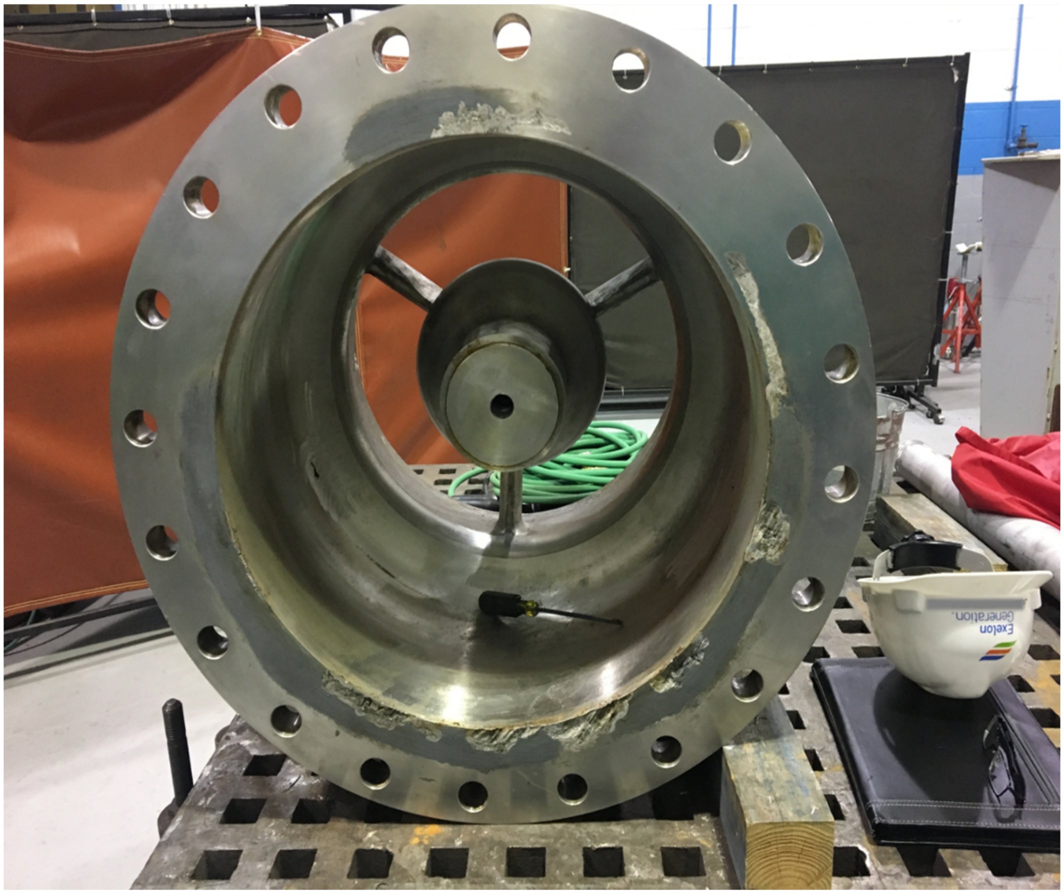


Figure 3-4 Seawater corrosion of a sea water check valve flange at a nuclear power plant (courtesy Exelon).

Figure 3-5 Flow element flange with severe crevice corrosion (courtesy Exelon).

In the nuclear industry, these types of repairs are often performed on valves outside of the nuclear island, which can be removed from service and shipped to a repair site because these components are not contaminated with radioactive materials. This application has the added benefit of eliminating the cumbersome access consideration that exists inside the containment building.

### 3.2.3 Other Potential Nuclear Power Industry Applications of CS

This section describes additional potential applications of CS in the nuclear power industry. Further maturation and adoption of CS technology in the nuclear power industry could happen rapidly and the expansion of CS to applications beyond those discussed in Section 3.2.2 may be anticipated. Although there are currently no active investigations of CS for the applications in this section, it is the opinion of the authors' that the applications appear to be suitable candidates for CS.

#### 3.2.3.1 SCC and Crevice Corrosion of Stainless Steel Components

One potential application of CS is the sealing of crevices. All instances of CISCC in the fielded nuclear applications reported by the Pressurized Water Reactor Owners Group (Hosler and Hall 2010) were associated with crevice corrosion. This can potentially be avoided by cold spraying to seal crevices. This prevents chlorides from entering crevices.

SS components are susceptible to IGSCC, even at low temperatures and stresses. This condition is especially pronounced in seaside plants that are subjected to salt bearing mist, leading to CISCC. An alternate scenario that leads to cracking for inland plants involves the existence of a crevice condition, which, over time, will concentrate any chlorides in this location. Examples of actual plant leakage associated with IGSCC include:

1. **SS Piping Systems:**

   Leaks in SS piping systems have been reported at several plants. An example is the Emergency Core Cooling System (ECCS), which has separate low pressure and high-pressure systems, but is exposed to the corrosive environment on the piping OD in both cases. Manual or robotic spraying could be used while addressing specific access issues, such as pipe hangers.

   Multiple plants, primarily in seaside locations, have experienced leaking welds due to this condition (NRC 2012). Since these are mostly American Society of Mechanical Engineers (ASME) Section XI Class 2 and 3 welds, only visual inspection is required, and cracking is not detected until actual leakage occurs. The piping is often thin walled (Schedule 10) and ultrasonic testing is difficult in thin sections. Penetrant testing would be useful for detection, but only in readily accessible locations, and many times, seismic restraints or pipe hangers interfere (Figure 3-6). A potential mitigation/repair concept is shown in Figure 3-7 with a complete circumferential coating of CPNi. One band was deposited after oxide removal with grit blasting, the other was deposited with no surface preparation. Weld repairs would produce very high residual stresses in these thin-walled pipes (both near and far field) and lead to more cracking in short order.

Figure 3-6 Example of CISCC under a pipe hanger in an ECCS piping section. The pipe hanger provides a concentrating mechanism for chloride entrapment, producing cracking in locations that are not accessible for visual inspection. (PNNL presentation on CISCC)

Figure 3-7 Ni coating on a 6 in. Schedule 10 SS304 pipe section. Two layers of Ni approximately 0.020 in. thick total. Each band is 3 in. wide. The surface was grit blasted for the upper band and was oxidized for the lower band. The yield for Ni deposited with this process was measured at 115 ksi (sample courtesy of ARL).

CS (pure Ni over SS) could seal the leaks and build an actual pipe sleeve around the original pipe. The high yield strength of cold worked Ni used for the coating would make it possible to build up a layer of reasonable thickness to restore the structural strength of the initial pipe. Similar work has been performed at ARL to restore the structures of some naval components. As shown in Figure 3-8, the CS was able to arrest an active fluid leak through a 0.1 in. diameter hole at 100 psi. Leak rates for small cracks in unpressurized piping would be much lower, but this does demonstrate that even a weeping pipe leak could be repaired.

With a 360-degree CS coating, the cohesive strength of the coating is expected to be sufficient so that grit blasting the surface to improve adhesive strength would not be necessary.

Figure 3-8 Repair of active leak using CS by VRC Metal Systems. Left: water leak; right: final repair. Pressure of the pipe was ~100 psi during and 1,000 psi after the repair (Ross and Alabi 2019).

2. **Storage tanks exposed to sea salt mist:**

   Stainless steel storage tanks in seaside locations are also susceptible to CISCC, but the surfaces are generally more accessible compared to piping, allowing for greater flexibility in CS equipment used. In this case, a 360-degree band is unlikely to be practical, so proper surface preparation is necessary to improve the adhesive bond strength.

3. **Spent Fuel Pool Liners**: Spent fuel pool liners are constructed with SS-304 plates that are edge welded together and plug welded to SS struts embedded in the supporting concrete structure. This application of CS would require development for underwater spraying via water exclusion, which has been performed successfully for welding applications. Also, due to high radiation environments, this would necessitate robotic delivery.

   Leaking has occurred in spent fuel pools, most likely in the HAZ of the welds. Both the edge and plug weld HAZ areas are likely the source of the leakage, but no confirmatory testing has been performed. The leaking borated water has been confirmed using drain channels below the pool. The leaking borated water causes leaching of the calcite in the concrete, which eventually creates a blockage in the drainage channel.

4. **Transfer Canals**

   Transfer canals present a challenge similar to spent fuel pools, but without the hydrostatic pressure concern and CS can be performed in open air and moderately low radiation areas.

   There are several operating plants with boron accumulated below the transfer canal. The associated humidity is enough to produce a highly corrosive environment for stainless and carbon steel exposed to these conditions, including the concrete rebar.

#### 3.2.3.2 Mitigation and Prevention of Flow Accelerated Corrosion

One phenomenon that has resulted in several failures is flow accelerated corrosion (FAC) in steam system carbon steel piping elbows (NEA 2015). FAC is the phenomenon where an oxide layer that is normally protective, in this case magnetite, dissolves in fast flowing water. (Figure 3-9). Rapid magnetite growth then consumes more base metal, and the process repeats, rapidly diminishing the pipe wall. Ultimately, the elbow section must be replaced, or a large weld build up must be applied before a catastrophic high-pressure steam rupture occurs, as depicted below.

Figure 3-9 Ruptured elbow caused by FAC. (Ahmed 2012)

A combination of grit blasting to expose an oxide-free base metal and remote CS delivery devices could restore the integrity of piping elbows in lieu of replacement. Additive manufacturing during elbow fabrication could be used to apply an FAC-resistant hard face. The results of tests to evaluate the erosion resistance of several CS coatings are provided in 2.3.8.

#### 3.2.3.3 Steel Containment Shells

Over the years, periodic outage maintenance activities have resulted in the accumulation of boron residue in the containment building floor where the containment steel liner shell is buried into the concrete slab. As a result, the humidity and water used for cleaning during outages interacts with the omnipresent trace boron residue and produces an environment conducive to carbon steel corrosion. This condition has been observed in the bottom few inches of the exposed carbon steel vertical plates.

A SS or Ni coating could provide a suitable barrier to prevent this corrosion. It may be possible to deposit a coating that could also restore the structural strength of the original steel plates because steel plates could be partially excavated so that the CS material forms a tapered plug. Westinghouse presented an example of a containment liner degradation and Ni CS restoration during the CSAT conference in 2012, as depicted in the figure below (Figure 3-10).

Some European regulations also consider the potential for corrosion from borated water seeping between the concrete floor and the embedded vertical carbon steel wall. It might be possible to develop a CS approach to seal the crevice between the carbon steel and concrete. This would require spraying a right-angle corner with the horizontal surface being concrete and the vertical surface being carbon steel.

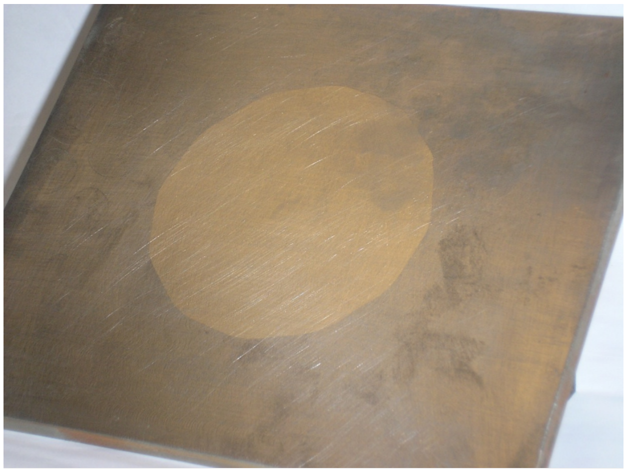


Figure 3-10 Ni CS deposit filling a blended region of simulated corrosion in a ¼ in. carbon steel plate (sample courtesy of ARL). Ni CS deposit is the brighter circular region in the center of the plate.

A similar approach could also be used to deposit a corrosion resistant layer on the containment sump (Figure 3-11). The carbon steel sump is the lowest surface inside containment and invariably is exposed to borated water during outages, which corrodes carbon steel at room temperatures. The sump is a critical safety component in the case of a large-scale LOCA because it supplies the recirculation of emergency cooling water. The current practice for corrosion protection is to apply an epoxy paint. The operating conditions inside containment are such that the epoxy degrades and typically has to be removed and replaced during each outage. CS could be demonstrated to provide permanent mitigation and prevention. The access is relatively straightforward, and CS could be applied with a hand-held nozzle.

Figure 3-11 Sump well and recirculation system. (Generic photo.)

#### 3.2.3.4 Magnetostrictive Electromagnetic Acoustic Transducer (EMAT)

CS technology can be used to deposit a metallurgically-bonded magnetostrictive layer on piping and other structural components to facilitate guided ultrasonic wave monitoring using magnetostrictive EMAT sensors. Instead of using an adhesive, Ni CS or other magnetostrictive powders (like carbon steel, iron, cobalt, iron-cobalt, or iron-gallium alloys [galfenol] with an even higher magnetostrictive coefficient) can be cold sprayed onto the component. These CS sensors are shown to be essentially equivalent to EMAT sensors using magnetostrictive layers applied by adhesive tape (Glass et al. 2019).

# 4.0 Knowledge Gap Analysis and Importance Ranking of CS in Nuclear Applications

This section ranks technical knowledge gaps associated with CS application in the nuclear power industry and assigns importance rankings to those knowledge gaps for a few illustrative application categories. CS is a relatively new technology that has primarily been developed for military applications. Most of this work was done using Al as the CS powder material. Development of HPCS enables high quality CS of high melting point materials that have broad application within the nuclear power industry such as Ni-based alloys and steels. Portable HPCS of high temperature material is a nascent technology. Although many lessons learned can be gleaned from prior military applications, application-specific demonstration testing is required for nuclear power applications to address the mechanical and corrosion properties of the coatings under simulated field conditions.

The importance of knowledge gaps depends on specific CS application needs. Because CS has several potential applications in the nuclear industry, a generalized ranking of knowledge gaps by importance would have limited utility. Variables that affect knowledge gaps include:

- Application requirements
- CS powder material
- Substrate material
- Physical access conditions
- Post processing.

If any of these variables are modified, applicability and feasibility to perform CS may change. Therefore, in this section, rankings for knowledge gaps are tied to selected application categories. A few sample application categories are considered to illustrate knowledge gap rankings.

## 4.1 Knowledge Gap Analysis

Table 4-1 highlights knowledge gaps associated with using CS for nuclear applications. The knowledge gaps include scientific or engineering data gaps that need to be addressed through additional research. The scientific data gaps are mostly associated with addressing potential concerns with the CS coating quality and performance. Several engineering data gaps are identified in this section that also require further research. The engineering data gaps are mostly associated with the CS process and potential improvements to the CS process. The knowledge gaps fall under the following topic categories: I. Functional Application, II. Physical Access Conditions, III. Pre-process Preparation, IV. Coating Properties, V. Inservice Considerations, VI. Quality Assurance and Inspection Topics, and VII. Technology Improvements.

For each knowledge gap topic in Table 4-1, a rating of the gap is provided using “Small,” “Medium,” and “Large” designations. A “Small” gap designation means that the topic is relatively well understood. A “Large” gap designation describes topics where little to no data currently exists. A “Medium” designation describes gaps where some data exists, but more data would be needed to confirm the knowledge for nuclear power applications. The table also includes callouts to relevant sections of this report that discuss each topic. In addition, rationale for the designated ranking of a topic is provided. Rationale for ratings are provided in the context of available data for a knowledge gap topic and the relevance of that data to nuclear power applications. Finally, additional discussion for each knowledge gap topic is provided in Table 4-1.

For some knowledge gap topics in Table 4-1, the size of the knowledge gap is described by multiple rating levels (i.e., “Small-Medium”). This is because knowledge gap size can vary based on material system and application. For example, the coating property topic of “porosity” is rated as “Small-Medium” because porosity is well understood and usually negligible for coatings applied with stationary, factory-based HPCS equipment. For coatings deposited by portable HPCS equipment, however, less is known about what can be expected with respect to coating porosity.

Table 4-1. Knowledge gap ratings describe the size of the knowledge gap for each topic relative to nuclear applications. Ratings do not reflect importance or impact of the topic. Importance and impacts of gaps are application dependent.

| Knowledge Gap Rating | I. Functional Application Topics | |
|---|---|---|
| | Dimensional restoration | |
| **Small** | Relevant in-document sections | 3.1 |
| | Rating rationale | CS dimensional restoration has been done in many material systems in DoD, aerospace, and automotive sectors. |
| | Discussion | Performance data exists for fielded dimensional restoration repair for DoD applications in many material systems. |
| | Environment-specific demonstration of efficacy | |
| **Medium-Large** | Relevant in-document sections | 2.3 |
| | Rating rationale | In some cases, data exists for repair of military equipment of similar material systems in environments similar to nuclear applications. In many cases, significant effort is needed to test CS coatings in a representative environment because a published analog does not exist. |
| | Discussion | Long term performance data for military CS repair for naval vessels and other equipment exposed to the natural environment can be used to inform expected performance of nuclear components needing repair due to similar environments. For example, anticipated performance of CS repair of seawater valves and flow elements can be informed by existing data for CS repair of naval components. However, specific alloys used for military and nuclear applications may differ. Little to no performance data in nuclear-specific environments exist. |
| | In-situ Leak repair | |
| **Medium-Large** | Relevant in-document sections | 3.2.3.1 |
| | Rating rationale | Exploratory work has been done and data is available. |
| | Discussion | CS repair of an active leak was demonstrated in proof-of-concept work done by VRC metal systems. |
| | Structural applications | |
| **Large** | Relevant in-document sections | 3.1, 3.2.3.1 |

| | | |
|---|---|---|
| | Rating rationale | No data is available for structural applications in materials of interest for nuclear components. |
| | Discussion | DoD is actively working to develop structural applications for CS Al. This work is nascent and has not begun for high melt temperature alloys. |
| | CS Additive Manufacturing | |
| **Large** | Rating rationale | No data is available for structural applications in materials of interest for nuclear components. |
| | Discussion | DoD and others are actively working to develop CS additive manufacturing (CSAM) applications for CS Al. This work is nascent and has not begun for high melt temperature alloys. |
| **Knowledge Gap Rating** | **II. Physical Access Conditions Topics** | |
| | Manufacturing/factory setting | |
| **Small** | Relevant in-document sections | 2.1.1, 2.4.5.2 |
| | Rating rationale | HPCS for industrial factory fabrication in materials of interest is fully commercialized. |
| | Discussion | HPCS for industrial factory fabrication in materials of interest is fully commercialized for many material systems of interest for nuclear components. There are little to no knowledge gaps in how to execute CS on materials and substrates of interest in a factory setting. Parameters and process development must be optimized for new material combinations and geometries per standard practices. |
| | Unconfined space field setting | |
| **Medium** | Relevant in-document sections | 2.1.1, 2.4.5.2 |
| | Rating rationale | Portable CS equipment HPCS is a relatively new development, and some data is available for non-Al materials. |
| | Discussion | Portable CS equipment removes nozzle cooling and heaters from CS guns to enable handheld manual repair. These design changes produce challenges for higher melt temperature materials. Equipment vendors are working to improve nozzle designs and develop new gas heating strategies to improve performance without causing the CS gun to be prohibitively heavy. |
| | Confined space field setting | |
| **Large** | Relevant in-document sections | 2.1.1, 3.2.2.1 |
| | Rating rationale | Portable CS equipment HPCS within confined spaces is a nascent technology. |
| | Discussion | Proof of concept has been demonstrated using portable CS equipment attached to robotic crawlers. While the concept has been demonstrated, there is little published data on performance and properties of the resultant coatings. |
| **Knowledge Gap Rating** | **III. Pre-process Preparation Topics** | |
| | Surface preparation | |
| **Small** | Relevant in-document sections | 2.2.4 |
| | Rating rationale | Best practices for surface preparation are understood and available in the literature. |
| | Discussion | None |

| | | |
|---|---|---|
| | Powder processing | |
| **Medium** | Relevant in-document sections | 2.2.1, 2.4.5.4 |
| | Rating rationale | Best practices of powder processing are understood by industry experts and are described for some material systems in the literature. |
| | Discussion | General powder processing best practices, such as sieving, and drying are well understood and documented in available literature and standards. For CS of materials designed to survive extreme environments, annealing of powders or other non-standard processing is required. Limited information on these techniques are publicly available for high melt temperature CS materials. |
| | Powder storage and handling | |
| **Small** | Relevant in-document sections | 2.2.1, 2.4.5.4 |
| | Rating rationale | Best practices for powder storage and handling are documented in military specifications and other publicly available documents. |
| | Discussion | Best practices may be expanded upon as more work is done in material systems of interest for nuclear applications. Because current best practices are intended for Al powder, they are conservative because Al powder is much more reactive than materials of interest for nuclear applications. |
| **Knowledge Gap Rating** | **IV. Coating Properties Topics** | |
| | Porosity | |
| **Small-Medium** | Relevant in-document sections | 2.2.3, 2.3, 2.3.2, 2.4.3 |
| | Rating rationale | Known for factory equipment, emerging for portable equipment. |
| | Discussion | For stationary equipment, expected porosity is understood and can be negligible for most material systems when done correctly. Portable HPCS of high melt temperature is a relatively new technology. DoD investment is driving equipment in portable CS equipment and driving continuous improvement in porosity and properties of high temperature materials sprayed with portable equipment. |
| | Adhesion strength | |
| **Small-Medium** | Relevant in-document sections | 2.2.4, 2.3, 2.3.1, 2.4.3 |
| | Rating rationale | Known for stationary equipment, emerging for portable equipment. |
| | Discussion | For stationary equipment, adhesion values are known for many powder-substrate combinations. Portable HPCS of high melt temperature is a relatively new technology. DoD investment is driving equipment in portable CS equipment and driving continuous improvement in properties of high temperature materials sprayed with portable equipment. |
| | Tensile strength | |
| **Large** | Relevant in-document sections | 2.3, 2.3.3, 2.4.3 |
| | Rating rationale | Tensile strength of the coating itself is often not tested because most CS applications are non-structural. |
| | Discussion | Most CS applications are non-structural coatings. If mechanical testing is done, it is often combined testing of a coated part or |

| | | |
|---|---|---|
| | | coupon. Tensile strength data is available for a limited set of cold sprayed materials of interest for nuclear applications. |
| | As deposited surface roughness | |
| **Large** | Relevant in-document sections | 2.4.3 |
| | Rating rationale | Surface roughness is typically not measured; |
| | Discussion | For most CS applications, the CS coating is machined, ground, or buffed to remove the outermost layers of deposited material and produce a surface that is smooth and flush with its surroundings. |
| **Knowledge Gap Rating** | **V. Inservice Considerations Topics** | |
| | Fatigue performance | |
| **Large** | Relevant in-document sections | 3.1, 2.3.3, 2.3.6 |
| | Rating rationale | Fatigue data for CS of nuclear applications does not exist. |
| | Discussion | CS is expected to improve mechanical fatigue life of performance because CS can induce compressive residual stresses in the coating and in the base metal directly beneath the coating, like shot peening. Thermal fatigue is of concern if the coating and substrate have different coefficients of thermal expansion. Understanding fatigue performance requires analysis of the part as a whole, not just the coating. |
| | Edge effects | |
| **Large** | Relevant in-document sections | 2.3.4 |
| | Rating rationale | Data is not available |
| | Discussion | Edge effects and interfaces between the coatings and substrates exposed to the environment need to be investigated. For example, deposited coatings could produce geometric discontinuities that enable crevice corrosion. If this is the case, a groove and blend technique can be used to normalize surface geometry. Alternatively, grinding or buffing edges of a deposited coating without a groove may be a solution. Galvanic effects at the interface should be investigated. |
| | Effects of surface finish on corrosion resistance | |
| **Large** | Relevant in-document sections | 2.3.4 |
| | Rating rationale | Limited information on comparing as-sprayed CS to post-processed CS. CS can be machined, ground, or polished to modify surface roughness. |
| | Discussion | Surface roughness/texture effects are expected to affect CISCC initiation and other corrosion mechanisms. CS parameters and powder preparation can affect surface roughness. Testing is required to understand how surface roughness/texture develops as spray affects corrosion initiation for CISCC, cavitation, and other corrosion mechanisms. Post machining could be a possible solution, though the machining might introduce residual stress that could be detrimental for CISCC. Buffing or laser glazing may be a better option to smooth the surface. |
| | Establishing coating requirements and acceptance criteria | |
| **Small-Large** | Relevant in-document sections | 2.3, 3.2.2, 3.2.3 |

| | | |
|---|---|---|
| | Rating rationale | For some applications, this is well understood; for others, it is nebulous. |
| | Discussion | Long term behavior of CS protective coatings over susceptible materials has generally been shown to be effective; however, significantly more work is required for code case justification and broad code acceptance as a repair method, particularly for structural repair of component damage. For example, if corrosion resistance is the end goal, then accelerated corrosion testing in a representative environment is necessary with consideration of residual and service stresses as well as potential crevice corrosion conditions. Porosity limits and adhesion strength need to be quantified during process development and potentially demonstrated with witness samples at the time of application. Representative fatigue and strain conditions need to be considered and documented. If spalling is a concern, then an impact test should be included. For wear resistance application, selecting the correct type of wear test is important. Sliding wear and cavitation are fundamentally different, so one type of wear test is not interchangeable with another. For example, NiCr-CrC coatings have excellent sliding wear resistance but do poorly with cavitation wear. |
| Capture of surface preparation artifacts and CS Overspray | | |
| **Large** | Relevant in-document sections | 2.1.2 |
| | Rating rationale | Information not available in literature |
| | Discussion | Overspray capture needs additional consideration for some applications. Any application inside the primary system would need to address this so that both cleaning and coating particles could not lead to any deleterious effects. Cleaning grit potentially could scratch sensitive surfaces, and metallic particles could potentially plate on fuel rods or produce a source of irradiated particles plating elsewhere in the system and increase background radiation levels. |
| SCC performance | | |
| **Large** | Relevant in-document sections | 2.3.8, 3.2.2.1, 3.2.2.3, 3.2.3.1 |
| | Rating rationale | Initial data is being generated. |
| | Discussion | CS is being investigated for repair and mitigation of CISCC in DCSS canisters. Proof of concept has been demonstrated. Significant work is needed to quantify SCC performance, understand relevant physics, optimize CS parameters/equipment, and develop implementation solutions to maximize life extension of canisters. |
| Irradiation performance | | |
| **Large** | Relevant in-document sections | 2.3.7 |
| | Rating rationale | No experimental work has been completed on this topic |
| | Discussion | CS coatings are expected to have similar radiation resistance to forged or extruded metal of similar chemistry. Some variation may occur due to differences in microstructure between cold sprayed and forged or extruded material. Testing can be done to verify at what dose limit radiation effects become a concern for |

| | | |
|---|---|---|
| | | cold sprayed materials and how associated properties compare to extruded and forged material of the same chemistry. |
| Mechanical wear resistance | | |
| **Small** | Relevant in-document sections | 3.1, 2.3.3 |
| | Rating rationale | Mechanical wear resistance of CS is well understood and documented in the literature. |
| | Discussion | CS can produce extremely hard surfaces with excellent wear resistance, especially when blended powders with hard particles are used. Development of CS coatings for replacing chrome plating on military equipment is in progress. |
| Erosion/corrosion resistance | | |
| **Medium-Large** | Relevant in-document sections | 2.3.4, 2.3.5, 3.1, 3.2.1, 3.2.3.2, 3.2.3.3 |
| | Rating rationale | Data exists showing excellent erosion/corrosion resistance using CS. Nuclear specific material systems and environments have yet to be tested. |
| | Discussion | Exploratory work has shown CS has promise to improve erosion/corrosion resistance for a few specific nuclear applications. Nuclear specific material and environments need to be tested. |
| **Knowledge Gap Rating** | **VI. NDE and Statistical Process Control** | |
| Pre-process: determination of acceptable and unacceptable substrate flaws | | |
| **Large** | Relevant in-document sections | 2.2.4, 2.4.1 |
| | Rating rationale | An isolated example of CS breaking open a surface ligament for a near subsurface flaw is shown in 2.2.4. However, comprehensive understanding of subsurface defects that are susceptible to breaking open to the surface during CS does not exist. |
| | Discussion | An understanding of acceptable versus unacceptable flaws is needed to determine what NDE should be required prior to deposition of a CS coating. This may have application specific dependencies to consider, including substrate material, powder characteristics, and process parameters. |
| Pre-process: NDE of substrate | | |
| **Medium** | Relevant in-document sections | 2.4.1 |
| | Rating rationale | Some investigation of ET has been performed to understand capability to detect small surface breaking and near subsurface flaws in the substrate in consideration of peening mitigation for high Ni alloy welds. More work is needed to understand if ET can adequately detect any flaw that could present a challenge to coating integrity and the extent to which results may generalize across applications. |
| | Discussion | CS deposition over surface breaking flaws can lead to localized coating defects that can propagate through several layers of CS coating. Near subsurface flaws can have surface ligaments break open during the CS application, also resulting in localized coating defects. ET is a good candidate for detection of these flaws but understanding of ET capability is incomplete. |
| Post-process: NDE to evaluate coating porosity | | |

| | | |
|---|---|---|
| **Large** | Relevant in-document sections | 2.2.3, 2.4.3 |
| | Rating rationale | Limited available information showing porosity can be measured by a variety of NDE methods including UT, ET, and optical profilometry. |
| | Discussion | There are several possible approaches for characterizing coating porosity. However, all require the development of calibration specimens that would be specific to the application. Though correlations between surface roughness and porosity would need to be derived, determination of surface roughness by optical profilometry is relatively straightforward. The potential accuracy and precision of techniques also requires investigation. |
| Post-process: NDE of substrate/coating interface adhesion quality (variations in strength of intact bond) | | |
| **Large** | Relevant in-document sections | 2.2.4, 2.4.3 |
| | Rating rationale | No available information demonstrating proof of concept. |
| | Discussion | Nondestructive measurement of the quality of coating/substrate adhesion is a recognized and difficult NDE problem that will likely be a long-term issue. A 2020 funding opportunity has been released by the Army DoD to invite innovative solutions for this issue (DoD 2020). |
| Post-process: NDE of substrate/coating interface debond and coating thickness | | |
| **Medium** | Relevant in-document sections | 2.2.4, 2.4.3 |
| | Rating rationale | Detection of delamination type defects is well established in other application contexts. However, understanding limitations caused by coating porosity and thickness and understanding conditions for which measurements by UT or other NDE techniques is preferable requires investigation.<br>Thickness measurements are also well established in other application contexts. Understanding limitations caused by coating porosity and thickness and achievable resolution of measurements requires further investigation. |
| | Discussion | Complete debond at the substrate/coating interface would result in a discontinuity producing a strong reflection to ultrasound introduced at normal incidence. The strength of the reflection will depend on the size of the debond area and attenuation of the signal in the CS coating.<br>Thickness measurements by UT require the detection of a reflected signal from an in-tact coating/substrate interface, which would be smaller than the signal reflected from a debond interface. The resolution of the measurement would be proportional to the wavelength used. |
| Post-process and in-service: NDE through coating | | |
| **Large** | Relevant in-document sections | 2.4.3, 2.4.4 |
| | Rating rationale | No prior evaluations. |
| | Discussion | Several NDE methods can penetrate coatings and inspect through thin coatings. As coatings thicken, it becomes more difficult to detect and characterize flaws in the substrate when inspecting through the coating. In some cases, it may be important to detect and track underlying flaws through the CS coating. Potential debonding at the coating/substrate interface is another factor that could affect inspectability of the substrate. The |

| | | |
|---|---|---|
| | | potential effects of coating surface roughness on application of UT, ET, and VT technologies require investigations to understand. |
| In-process: statistics process control (SPC) | | |
| **Large** | Relevant in-document sections | 2.4.2, 2.2.3 |
| | Rating rationale | No available data. |
| | Discussion | Statistical process control (SPC) can be implemented to monitor relevant process parameters. SPC can be effectuated real time if vendors apply SPC features into the control system of CS equipment. Alternatively, SPC can be effectuated after processes through analysis of process data logs. Application of SPC for real time monitoring of nozzle clogging is discussed in 2.2.3. |
| **Knowledge Gap Rating** | **VII. Technology Improvements** | |
| Advanced composite powders | | |
| **Medium** | Relevant in-document sections | 1.3, 2.2.1 |
| | Rating rationale | Various efforts are exploring use of advanced powders in other technology sectors. |
| | Discussion | Some hard particles for wear resistance are hard to deposit. However, some particles lend themselves to micro-coating with Ni or other soft metal that is relatively easy to deposit. Hybrid powder concepts could be used to enhance adhesive and cohesive bonding or to provide both corrosion and wear resistance simultaneously. |
| Post processing for mechanical properties | | |
| **Medium** | Relevant in-document sections | 2.3, 2.4.5.6 |
| | Rating rationale | Various efforts are ongoing in other technology sectors and some data is available. |
| | Discussion | Laser annealing has been used in conjunction with CS to eliminate cold working and greatly improve ductility. In some critical applications this may be necessary, although it also complicates the coating process. Other heat treating methods have been investigated and reported in literature but no comprehensive heat treatment studies have been performed in materials of interest for nuclear applications. |
| Nozzle technology for portable CS | | |
| **Medium** | Relevant In-document sections | 2.1, 2.2.3, 1.3 |
| | Rating rationale | Mechanisms causing nozzle clogging are understood, but technical solutions to completely avoid nozzle clogging in angled nozzles still require development. |
| | Discussion | Nozzle clogging is an issue in portable HPCS systems when spraying Ni and Ni-based alloys. This can be solved by developing cooled nozzles for portable systems or adding hard particles, such as carbides, to the powder. Hard particles can improve mechanical properties of the deposited material but could cause localized galvanic effects that accelerate pit formation. Nozzle cooling and effects of hard particles are areas to be investigated. Angled nozzles for spraying in confined space may greatly increase rate of clogging. |

Gaps in the development of codes and standards have not been integrated into Table 4-1. Currently, there are no codes or standards that directly address CS for nuclear power applications. The military has created standards for the CS process, but they are generally developed with different powder and substrate material considerations than would be expected for nuclear power applications. There are also several ASTM standards that relate to evaluating the quality of coatings, generally, and that could also apply to evaluating coatings generated by CS processes. It should be noted that broadly applicable standards are often written for either processes or applications. For CS, it is envisioned that standards will focus on implementing the process. Qualification of CS for specific applications should be handled by application specific requirements and associated test standards, such as the ASTM test standards referred to in Section 3.1.

Finally, it is important to note that current applications of CS have been almost exclusively non-structural coating applications. Structural applications of CS will require development of standards that define how CS is to be tested and properties validated. These standards should be similar to the military specifications/standards in that they consider equipment, powder processing, parameters, and testing. NDE and SPC are areas that need to be further developed and defined in codes or standards to support CS of critical components.

## 4.2 Importance Rankings for Knowledge Gaps

The importance rankings for knowledge gaps for a few application categories are provided in Table 4-2. The application categories used to illustrate knowledge gap rankings are factory CISCC mitigation, field CISCC repair, LWR factory structural fabrication, and LWR field dimensional restoration and corrosion protection. The CISCC applications are motivated by the extended storage of spent nuclear fuel in dry cask storage systems, and this exercise is performed envisioning application of CS to mitigate or repair CISCC degradation in the SS canisters. The LWR categories are meant to capture any application to LWR systems, including those mentioned in Sections 3.4 and 3.5. The “LWR Factory Structural Fabrication” category envisions CS being applied to fabrication of a component and would require the CS deposit to be credited in structural applications. As noted in Section 4.1, current applications of CS have been almost exclusively non-structural coating applications. Taking structural credit for field repairs is possible but not anticipated for near term applications therefore this table assumes repair activities are not taking structural credit.

In addition to the application categories, knowledge gap size ratings are carried from Table 4-1 to Table 4-2 for convenience. Importance rankings for the knowledge gap topics for each application category are given designations of “Low,” “Middle,” or “High.” “N/A” indicates the topic is not applicable to the application. The combination of the importance ranking with the knowledge gap rating can be used to prioritize any further data generating or data collecting efforts. For instance, if the importance ranking of a knowledge gap topic for an application is “High” and the knowledge gap size is “Large,” then that indicates that high priority should be placed towards obtaining additional data. If the importance ranking of a knowledge gap topic is “Low” or if the knowledge gap is “Small,” then collection of additional data would be of a lower priority.

Some of the importance rankings in Table 4-2 have designations spanning multiple levels (i.e., “Low-High”). These designations reflect the variation of potential applications under each application category. For instance, considering the irradiation performance of CS under the LWR factory structural fabrication category, the importance ranking may vary significantly depending on the proximity of the component to the reactor core. Also, several of the post-process NDE topics have “Low-High” ratings because it is anticipated that the coating quality can be inferred from destructive testing of witness coupons for many applications, making the importance of NDE “Low.”  However, for scenarios in which quality can only be determined by direct NDE of the component, the importance of these topics will be “High.”

Table 4-2 Importance rankings for the knowledge gap topics in Table 4-1 for illustrative CISCC and LWR applications.

| **I. Functional Application Topics** | **Factory CISCC Mitigation[1]** | **Field CISCC Repair[1]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
|---|---|---|---|---|---|
| Dimensional restoration | Low | Low | High | High | Small |
| Environment-specific demonstration of efficacy | High | High | High | High | Medium-Large |
| Leak repair | N/A | High | N/A | N/A | Medium - Large |
| Structural applications | N/A | N/A | High | N/A | Large |
| CSAM | N/A | N/A | High | N/A | Large |
| **II. Physical Access Conditions Topics** | **Factory CISCC Mitigation[1]** | **Field CISCC Repair[1]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
| Manufacturing/factory setting | High | N/A | High | N/A | Small |
| Unconfined space field setting | N/A | High | N/A | High | Medium |
| Confined space field setting | N/A | High | N/A | High | Large |
| **III. Pre-process Preparation Topics** | **Factory CISCC Mitigation[1]** | **Field CISCC Repair[1]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
| Surface preparation | High | High | High | High | Small |
| Powder processing | High | High | High | High | Medium |
| Powder storage and handling | High | High | High | High | Small |

---

[1] The consideration of CISCC is in the context of application to stainless steel canisters in dry storage systems for spent fuel.

| **IV. Coating Properties Topics** | **Factory CISCC Mitigation[1]** | **Field CISCC Repair [2]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
|---|---|---|---|---|---|
| Porosity | High | High | High | High | Small-Medium |
| Adhesion strength | High | High | High | High | Small-Medium |
| Tensile strength | Middle | Middle | High | Middle | Large |
| As Deposited Surface roughness | Middle | High | Low | High | Large |
| **V. Inservice Considerations Topics** | **Factory CISCC Mitigation[2]** | **Field CISCC Repair[2]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
| Fatigue performance | Low | Low | Low–High | Low–High | Large |
| Edge effects | High | High | Low | High | Large |
| Effects of surface finish on corrosion resistance | High | High | Low | High | Large |
| Establishing Coating requirements and acceptance criteria | High | High | High | High | Small to Large |
| Overspray capture | Low | High | Low | High | Large |
| SCC performance | High | High | Low–High | Low–High | Large |
| Irradiation performance | Low | Low | Low–High | Low–High | Large |
| Mechanical wear resistance | Low | Low | Low–High | Low–High | Small |
| Erosion/corrosion resistance | High | High | Low–High | High | Medium to Large |
| **VI. NDE and Statistical Process Control** | **Factory CISCC Mitigation[2]** | **Field CISCC Repair[2]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
| Pre-process: Determination of acceptable substrate flaws | High | High | High | High | Large |
| Pre-process: NDE of substrate | High | High | High | High | Medium |
| Post-process: NDE of porosity | Low–High | Low–High | Low–High | Low–High | Large |
| Post-process: NDE of adhesion | Low–High | Low–High | Low–High | Low–High | Large |

---

[1] The consideration of CISCC is in the context of application to stainless steel canisters in dry storage systems for spent fuel.

| | | | | | |
|---|---|---|---|---|---|
| Post-process: NDE of coating/substrate debond and coating thickness | Low–High | Low–High | Low–High | Low–High | Medium |
| Post-process and In-service NDE through coating | High | High | High | High | Large |
| In-process: Process monitoring | High | High | High | High | Large |
| **VII. Technology Improvements** | **Factory CISCC Mitigation[1]** | **Field CISCC Repair[3]** | **LWR Factory Structural Fabrication** | **LWR Field Dimensional Restoration and Corrosion Protection** | **Knowledge Gap Size** |
| Advanced Composite powders | Low–High | Low–High | Low–High | Low–High | Medium |
| Post processing for mechanical properties | Low | Low | High | Low–High | Medium |
| Nozzle technology for portable CS | Low | Low–High | Low | Low–High | Medium |

---

[1] The consideration of CISCC is in the context of application to stainless steel canisters in dry storage systems for spent fuel.

# 5.0 Summary and Conclusions

CS technology for corrosion and/or wear resistance has been successfully demonstrated in several applications for the aerospace, naval, and automotive industries. To date, these applications have avoided claiming any structural credit for pressure-retaining repairs (except for valve flanges, which are in compression during service). Current activities in aerospace and naval applications include initial work to determine the ability of CS coatings to improve fatigue resistance in accordance with applicable codes and standards. Most of this work has been performed using Al or Ni/chrome alloys as the CS powder materials. The nuclear power industry applications present an entirely new set of challenges regarding operating conditions, substrate materials, and powder composition.

HPCS has been developed into both factory-based and portable equipment. Factory CS application is more amenable to achieving high quality coatings because the constraints on component access and on the size and weight of equipment are usually less restrictive compared to applications for which a portable system is required. For both factory and portable systems, coating quality is influenced by the many process parameters, including the selection of powders and their size distributions, choice of carrier gas and temperature, nozzle design and surface preparation. Coating quality can be negatively affected by poor parameter selections or inadequate process controls. The oxidation of powders due to poor storage conditions, nozzle clogging, and failing to remove oxide layers from a substrate surface prior to CS deposition are examples of issues that negatively impact the resulting coating quality.

The coating quality can be defined by several coating properties, depending on the application. Coating porosity and the coating/substrate adhesion strength are important quality indicators for most applications. Other properties that may be important are identified in Table 2-3 and include surface roughness, mechanical yield strength, Young’s modulus, resistance to wear or erosion, radiation resistance, chemical resistance, or resistance to SCC.

Currently, there are no industry-wide accepted practices for qualification of CS applications in the nuclear industry. Several standards have been developed for CS applications in the military. These standards may be limited to their application to the nuclear industry because they are primarily developed for the dimensional restoration of Al components. However, they may be helpful in informing a process for qualification and developing standards for CS applications in the nuclear industry. In other sectors, CS is qualified on an application specific basis that is typically proprietary.

The quality of CS can be managed through several stages of a CS process including pre-, in-, and post-process stages. Different procedures may be implemented to manage quality at each stage and can include careful handling and storage of powders, surface preparation, coupon testing, NDE of the as-sprayed coating, and automated monitoring of process parameters. Process implementation guidance is summarized by the schematic in Figure 2-14, which is provided to assist readers in understanding aspects of an application that can affect quality (e.g., factory vs. field) and determine best practices that can be implemented during stages of a CS process.

The knowledge gap analysis and importance ranking of knowledge gaps for application categories in Section 4.0 is provided to assist in prioritization of efforts to collect additional information or data. In this case, a knowledge gap rated as “Large” and having an importance ranking of “High” for an application would suggest placing higher priority on additional data and information gathering. Conversely, a knowledge gap that has a “Small” rating or an importance ranking of “Low” for an application would indicate a low priority. The knowledge gaps are organized into seven topic categories and the importance ranking of the topics within each category consider four general application scenarios, which cover field LWR plant, field dry storage system, factory LWR, and factory dry storage system application scenarios.  Most of the topics are given a rating of Medium or Large.  This is reflective of the emerging state of the technology in the nuclear industry.  Further, the development of portable technology for supporting in-field applications is currently at a nascent state.  Therefore, many topics have Large knowledge gap ratings because relevant data or experience that may be drawn from military applications does not exist or is sparse.  Further, topics associated with utilization of portable equipment result in Medium or Large knowledge gap ratings, including the properties of coatings generated with portable equipment.

# 6.0 References

Ahmed, W. H. 2012. "Flow Accelerated Corrosion in Nuclear Power Plants." In *Nuclear Power - Practical Aspects*.

ASTM-C633. 2017. *Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings.*

ASTM-D4541. 2017. *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.*

Balić, Edin E., Mousab Hadad, Partha P. Bandyopadhyay, and Johann Michler. 2009. "Fundamentals of adhesion of thermal spray coatings: Adhesion of single splats." *Acta Materialia* 57 (19): 5921-5926. https://doi.org/https://doi.org/10.1016/j.actamat.2009.08.042. https://www.sciencedirect.com/science/article/pii/S1359645409005205.

Champagne, V. 2016. "Workshop Objectives & New Developments." (CSAT) Cold Spray Action Team Meeting. https://www.coldsprayteam.com/csat-2016.

Champagne, V. 2018. "Advancements in Cold Spray & Army Vision." (CSAT) Cold Spray Action Team Meeting. https://www.coldsprayteam.com/csat-2018.

Champagne, V. K. 2007. *The Cold Spray Materials Deposition Process: Fundamentals and Applications*. Woodhead Publishing Limited.

Champagne, V. K. 2020. "DoD Wide Cold Spray Technology Roadmap." CSAT (Cold Spray Action Team) 2020.

CSAT. 2020. "CSAT past workshops: https://www.coldsprayteam.com/past-workshops." https://www.coldsprayteam.com/past-workshops.

DoD. 2020. "Non-Destructive Evaluation of Bonded Interface of Cold Spray Additive Repair." Army-SBIR-STTR. Army SBIR. Department of Defense. https://www.sbir.gov/node/1696703.

Enderlin, C.W., C.B. Smith, G.J. Grant, K.M. Denslow, K. Boomer, and Wooley T. 2020a. "Assessment of Cold Spraying Mild-Steel Powder onto Mild-Steel Substrate for Development of Waste Tank Repair System." WM2020Phoenix.

Enderlin, C.W., C.B. Smith, G.J. Grant, K.M. Denslow, K. Boomer, and T. Wooley. 2020b. "Assessment of Cold Spraying Mild-Steel Powder onto Mild-Steel Substrate for Development of Waste Tank Repair System." WM2020, Pheonix, Arizona, USA.

Fiebig, J., E. Bakan, T. Kalfhaus, G. Mauer, O. Guillon, and R. Vassen. 2020. "Thermal Spray Processes for the Repair of Gas Turbine Components." *Advanced Engineering Materials* 22 (6): 1901237. https://doi.org/10.1002/adem.201901237. <Go to ISI>://WOS:000513074200001.

Glass, S. W., M. R. Larche, M. S. Prowant, J. D. Suter, J.P. Lareau, Jiang X., and K. A. Ross. 2018. "Cold spray NDE for porosity and other process anomalies." AIP Conference Proceedings. doi.org/10.1063/1.5031507. https://aip.scitation.org/doi/pdf/10.1063/1.5031507.

Glass, S. W., J. P. Lareau, K. S. Ross, S. Ali, F. Hernandez, and B. Lopez. 2019. *Magnetostrictive Cold Spray Sensor for Long Term or Harsh Environment Ultrasound.* ASNT. Proceedings of ASNT Research Symposium ASNT.

Hall, D. S., and P. G. Keech. 2017. "An overview of the Canadian corrosion program for the long-term management of nuclear waste." *Corrosion Engineering, Science and Technology* 52 (sup1): 2-5. https://doi.org/10.1080/1478422X.2016.1275419. https://doi.org/10.1080/1478422X.2016.1275419.

Hosler, R., and J. Hall. 2010. PA-MSC-0474. *Outside Diameter Initiated Stress Corrosion Cracking.* PA-MSC-0474. PWR Owners Group. https://www.nrc.gov/docs/ML1104/ML110400241.pdf.

Howe, Christopher. 2017. *Economics of Helium Recovery for Cold Spray.* Cold Spray Action Team Workshop 2018. http://www.coldsprayteam.com/Howe_2017%20CSAT%20-%20Chris%20Howe%20-%20Moog.pdf.

ISO 9001:2015. 2015. *Quality Management Systems - Requirements.*

ISO 19443:2018. 2018. *Quality management systems — Specific requirements for the application of ISO 9001:2015 by organizations in the supply chain of the nuclear energy sector supplying products and services important to nuclear safety (ITNS).*

Jacob, R E, R Montgomery, J M Harrison, M Komarasamy, H Jiang, and K Ross. 2020. PNNL-30759. *Surevy of Pre-Service and In-Services Nondestructive Evaluation Techniques of AMT-Fabricated Components.* Pacific Northwest National Laboratory. Richland, WA.

Jiang, X., N. Overman, C. Smith, and K. Ross. 2020. "Microstructure, hardness and cavitation erosion resistance of different cold spray coatings on stainless steel 316 for hydropower applications." *Materials Today Communications* 25: 101305. https://doi.org/https://doi.org/10.1016/j.mtcomm.2020.101305. http://www.sciencedirect.com/science/article/pii/S2352492820323163.

Keech, P., P. Vo, S. Ramamurthy, J. Chen, R. Jacklin, and D. Shoesmith. 2014. "Design and development of copper coatings for long term storage of used nuclear fuel." *Corrosion Engineering, Science and Technology* 49: 425-430. https://doi.org/10.1179/1743278214Y.0000000206.

Knief, R. 1981. *Theory and Practice of Commercial  Nuclear Power*. McGraw Hill Publishing.

Lahoda, E J, W R Junker, J P Lareau, and T V Congedo. 2007. Method of applying a burnable poison onto the exterior of nuclear fuel rod cladding. United States.

Lareau, J P, M Larche, and AA Diaz. 2019a. PNNL-29113. *Baseline Evaluation of Eddy Current Testing for PWSCC Susceptible Materials.* Pacific Northwest National Laboratory. Richland, WA.

Lareau, J. P. 2014. "Operating Experience with Chloride Induced Stress Corrosion Cracking (CISCC)." EPRI ESCPCharlotte, NC.

Lareau, J. P., S. W. Glass, C. L. Friant, X. Jiang, and K. A.  Ross. 2019b. "Potential Cold Spray Applications for Mitigation and Repair in Nuclear Power Plants." Cold Spray Action Team (CSAT) 2019, Massachusetts https://55922c16-bbf4-4650-aa4d-6d5bfb8c7a14.filesusr.com/ugd/0ebd9c_4577401715e845cea52ac133d9d582c9.pdf.

Lareau, J. P., S.W. Glass, and A. Diaz. 2016. "The Use of Cold Spray Deposition for the Fabrication of NDE Qualification Samples." Cold Spray Action Team (CSAT) 2016. https://55922c16-bbf4-4650-aa4d-6d5bfb8c7a14.filesusr.com/ugd/0c16db_dcca81521de44c07a050d9d9626d6ea4.pdf.

Luo, X.-T., M.-L. Yao, N. Ma, M. Takahashi, and C.-J. Li. 2018a. "Deposition behavior, microstructure and mechanical properties of an in-situ micro-forging assisted cold spray enabled additively manufactured Inconel 718 alloy." *Materials & Design* 155: 384-395. https://doi.org/https://doi.org/10.1016/j.matdes.2018.06.024. http://www.sciencedirect.com/science/article/pii/S026412751830491X.

Luo, Xiaotao, Gregory M. Smith, and Sanjay Sampath. 2018b. "On the Interplay Between Adhesion Strength and Tensile Properties of Thermal Spray Coated Laminates—Part I: High Velocity Thermal Spray Coatings." *Journal of Thermal Spray Technology* 27 (3): 296-307. https://doi.org/10.1007/s11666-018-0695-1. https://doi.org/10.1007/s11666-018-0695-1.

Meyer, RM, AF Pardini, JM Cuta, HE Adkins, AM Casella, A Qiao, M Larche, AA Diaz, and SR Doctor. 2013. PNNL-22495. *NDE to Manage Atmospheric SCC in Canisters for Dry Storage of Spent Fuel: An Assessment.* Pacific Northwest National Laboratory.

MIL-DTL-32495 A. 2018. *Detail Specification: Powders for Cold Spray Deposition.* http://everyspec.com/MIL-SPECS/MIL-SPECS-MIL-DTL/MIL-DTL-32495A_55925/.

MIL-J-24445A. 1971. *Joint, Bimetallic Bonded, Aluminum to Steel.* Military Standard Specification. Department of Defense.

Moridi, A., S. M. Hassani-Gangaraj, M. Guagliano, and M. Dao. 2014. "Cold spray coating: review of material systems and future perspectives." *Surface Engineering* 30 (6): 369-395. https://doi.org/10.1179/1743294414Y.0000000270. https://doi.org/10.1179/1743294414Y.0000000270.

Nardi, Aaron, Victor Champagne, Gehn Ferguson, Isaac Nault, William Story, and Dan Nikolov. 2019. "Chrome Replacement and Recent Advancements." Cold Spray Action Team Meeting. https://55922c16-bbf4-4650-aa4d-6d5bfb8c7a14.filesusr.com/ugd/0ebd9c_638d644acea54db3b7695142978f938a.pdf.

NAVSEA, UIPI 6320-901.*Processes and Quality Control of Cold Spray* (Restricted reference).

NEA. 2015. *CODAP Topical Report Flow Accelerated Corrosion (FAC) of Carbon Steel and Low Alloy Steel Piping in Commercial Nuclear Power Plants.* Nuclear Energy Agency; Committee on the Safety of Nuclear Installations. https://www.oecd-nea.org/nsd/docs/2014/csni-r2014-6.pdf.

NRC. 2012. *INFORMATION NOTICE 2012-20: POTENTIAL CHLORIDE-INDUCED STRESS CORROSION CRACKING OF AUSTENITIC STAINLESS STEEL AND MAINTENANCE OF DRY CASK STORAGE SYSTEM CANISTERS. .* U.S. Nuclear Regulatory Commission. ML12319A440. https://www.nrc.gov/docs/ML1231/ML12319A440.pdf.

NRC. 2016. NUREG-1927. *Standard Review Plan for Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel.* ML16179A148. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML1617/ML16179A148.pdf.

NRC. 2019. NUREG-2214. *Managing Aging Processes in Storage (MAPS) Report.* ML19214A111. U.S. Nuclear Regulatory Commission.

NRC. 2020. "Action Plan for Advanced Manufacturing Technologies (AMTs), Revision 1." ML19333B980. U.S. Nuclear Regulatory Commission.

Papyrin, A., V. Kosarev, S. Klinkov, A. Alkhimov, and Fomin V. 2006. *Cold Spray Technology*. Elsevier Science.

Parsi, A., J. Lareau, B. Gabriel, and V. Champagne. 2012. "Cold Spray Coatings for Prevention and Mitigation of Stress Corrosion Cracking." (CSAT) Cold Spray Action TeamArmy Research Lab Connecticut

Pelsoci, T. 2015. *Benefit Cost Analysis: ETSCP Funded Cold Spray Technology for DoD Applications, DoD Report.*

Placzankis, B, G Ferguson, W Lum, A Nardi, and V Champagne. 2019. "Process of CS Powder Qualification to MIL-DTL-32495A." (CSAT) Cold Spray Action Team. U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY. Worcester Polytechnic Institute.

Plasma Giken. 2018. "The Next Generation In Cold Spray Technology." Accessed 10/28/2020. http://www.artostw.com/uploads/products/enfiles/ProductsDocs_EN_20180329163947.pdf.

Ross, K. 2019. *Solid State Processing for Improved Performance of current and Next-Generation Hydropower Components Agreement #31902.* Water Power Technologies Office 2019 Peer Review. Pacific Northwest National Laboratory. U.S. Department of Energy - Energy Efficiency & Renewable Energy.

Ross, K, H Jiang, M Alabi, and C Enderlin. 2020. PNNL-30484; M3SF-20PN010207091. *Investigation of Cold Spray as a Dry Storage Canister Repair and Mitigation Tool: Spent Fuel and Waste Disposition.* Pacific Northwest National Laboratory.

Ross, K. A., and M. Alabi. 2019. PNNL-29217. *Update on Investigations of Viability of Cold Spray and FSW as a Spent Nuclear Fuel Dry Storage Canister Mitigation Tool.* U.S. Department of Energy Office of Scientific and Technical Information. 10.2172/1580110

Ross, K., X. Jiang, N. Overman, J. P. Lareau, and D. Anderson. 2018. "PNNL-SA-135735 Cold Spray Repair and Mitigation for Hydropower Parts." (CSAT) Cold Spray Action Team, Massachusetts.

SAE International. 2017. *Procedures for Using Standard Shot Peening Almen Test Strip.* J443.

Segall, A. E., F. A. Sohag, F. R. Beck, L. Mohanta, F.-B. Cheung, T. J. Eden, and J. Potter. 2017. "Microporous Coatings and Enhanced Critical Heat Flux for Downward Facing Boiling During Passive Emergency Reactor Cooling." *Journal of Pressure Vessel Technology* 139 (5). https://doi.org/10.1115/1.4037001. https://doi.org/10.1115/1.4037001.

Sevecek, M., A. Gurgen, A. Seshadri, Y. Che, M. Wagih, B. Phillips, V. Champagne, and K. Shirvan. 2018. "Development of Cr cold spray–coated fuel cladding with enhanced accident tolerance." *Nuclear Engineering and Technology* 50 (2): 229-236. https://www.sciencedirect.com/science/article/pii/S1738573317307283.

Shah, H., J. Romero, P. Xu, R. Oelrich, J. Walters, J. Wright, and W. Gassmann. 2018. WAAP-10756. *Westinghouse-Exelon EnCore® Fuel Lead Test Rod (LTR) Program including Coated cladding Development and Advanced Pellets* Westinghouse Electric Company.

Siopis, M. 2019. "A Comparison of Low and High Pressure Cold Spray Systems." Cold Spray Action Team. https://55922c16-bbf4-4650-aa4d-6d5bfb8c7a14.filesusr.com/ugd/0ebd9c_91d8ae7c7d624c579238de7548689ec2.pdf.

Southern California Edison. 2019. "SONGS Inspection and Maintenance Program." CALIFORNIA COASTAL COMMISSION. https://documents.coastal.ca.gov/assets/banner/report/Appendix%20C%20to%20staff%20report%20CDP%209-15-0228%20Special%20Condition%207.pdf.

SPEE3D. "About Page." https://spee3d.com/about/.

Stamey, T. 2018. "Cold Spray Case Studies and Implementation." Cold Spray Action Team (CSAT). https://55922c16-bbf4-4650-aa4d-6d5bfb8c7a14.filesusr.com/ugd/0c16db_4fd2dc47a88f44f2abbbcd58abaaca70.pdf.

The Welding Institute. 2020. "What is Thermal Spraying?". The Welding Institute. Accessed 07/08/2020. https://www.twi-global.com/technical-knowledge/faqs/faq-what-is-thermal-spraying.

Trompetter, W. J., A. Markwitz, M. Hyland, and P. Munroe. 2005. "Evidence of mechanical interlocking of NiCr particles thermally sprayed onto Al substrates." *Journal of Thermal Spray Technology* 14 (4): 524-529. https://doi.org/10.1361/105996305X76568. https://doi.org/10.1361/105996305X76568.

Vo, P., D. Poirier, J. G. Legoux, P. G. Keech, D. Doyle, P. Jakupi, and E. Irissou. 2015. "Development of cold spray technology for copper coating of carbon steel used fuel container prototypes for CANDU fuel." *Nuclear Waste Management organization*. https://www.nwmo.ca/~/media/Site/Reports/2017/01/30/12/00/NWMO_TR_2015_29.ashx?la=en.

VRC Metal Systems. 2020. "COLD SPRAY VS THERMAL SPRAY – AN OVERVIEW." Accessed July 13,2020. https://www.vrcmetalsystems.com/blog-post/cold-spray-vs-thermal-spray/.

Wang, Y. Y., C. J. Li, and A. Ohmori. 2005. "Influence of substrate roughness on the bonding mechanisms of high velocity oxy-fuel sprayed coatings." *Thin Solid Films* 485 (1): 141-147. https://doi.org/https://doi.org/10.1016/j.tsf.2005.03.024. https://www.sciencedirect.com/science/article/pii/S0040609005002841.

Yeom, H., T. Dabney, N. Pocquette, K. Ross, F. E. Pfefferkorn, and K. Sridharan. 2020. "Cold spray deposition of 304L stainless steel to mitigate chloride-induced stress corrosion cracking in canisters for used nuclear fuel storage." *Journal of Nuclear Materials* 538: 152254. https://doi.org/https://doi.org/10.1016/j.jnucmat.2020.152254 http://www.sciencedirect.com/science/article/pii/S0022311520305286.

**Pacific Northwest National Laboratory**

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

***www.pnnl.gov | www.nrc.gov***