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Draft Guidelines Document for Cold Spray

1. Introduction and Purpose

When finalized, this draft guidelines document (DGD) will provide U.S. Nuclear Regulatory Commission (NRC) staff with guidelines for conducting reviews of submittals that include the use of cold spray (CS) for both non-structural and structural applications. These guidelines are based on the NRC assessment of the CS process considerations and knowledge gaps associated with using CS for nuclear applications as documented in “NRC Technical Assessment of Cold Spray,” (Agencywide Documents Access and Management System (ADAMS) Accession No. ML22118A090 (hereafter, “NRC technical assessment”), which builds on the Pacific Northwest National Laboratory’s (PNNL’s) technical information and gap analysis, “Assessment of Cold Spray Technology for Nuclear Power Applications,” (ADAMS Accession No. ML21263A107) (hereafter, “PNNL TLR”). This document provides CS-specific draft guidelines under Subtask 2C, “Action Plan for Advanced Manufacturing Technologies (AMTs),” Revision 1, dated June 23, 2020 (ADAMS Accession No. ML19333B973), as a supplement to the AMT generic draft guidelines document, “Draft AMT Review Guidelines” (ADAMS Accession No. ML21074A037) (hereafter, “draft generic guidelines”).

The NRC staff can refer to the generic guidelines once finalized, which can assist the NRC staff’s review of a submittal requesting the use of an AMT. The finalized generic guidelines along with this DGD will identify the generic and CS-specific information that could be necessary in a submittal in order for staff to perform a timely and efficient review. The NRC technical assessment is also available for additional background and technical information to support the review of a submittal.

2. Brief Description of the NRC Technical Assessment of Cold Spray

The purpose of this section is to describe the NRC technical assessment of CS, which provides the technical basis for the technical review guidelines described in this DGD. The primary objective of the NRC technical assessment is to describe important CS process considerations and associated properties and performance characteristics of the CS material. Further, the technical assessment evaluates the state of knowledge and manageability associated with each key process, property, or performance topic for CS applications, and identifies relevant technical information pertaining to each topic. This DGD is intended to build on the NRC technical assessment and provide guidelines, when finalized, to the NRC staff by identifying important considerations when reviewing a submittal requesting the use of CS.

The overall impact to nuclear safety of these key topics (e.g., safety significance) is a function of component performance and the specific component application (e.g., its intended safety function). These reports do not address the impact on nuclear safety, as such an assessment would not be possible without considering the specific component application. In addition to the technical review guidelines in this document, the NRC staff should consider the specific component application and the potential for secondary consequences, such as debris generation and associated impacts, when assessing the impact to overall nuclear safety.

As discussed in the NRC technical assessment, the NRC staff assessed the knowledge gap and manageability and provided relevant technical information for each CS topic by reviewing the information and gap analysis rankings from the PNNL TLR, as well as other relevant technical information (e.g., NRC regulatory and research experience, technical meetings and conferences, codes and standards activities, Electric Power Research Institute and U.S. Department of Energy products and activities).

3. NRC Generic Guidelines for Advanced Manufacturing Technologies and Cold Spray-Specific Guidelines

The finalized generic guidelines will identify the information that could be necessary in a submittal to ensure a timely and efficient review. Appendix A to the generic guidelines (ADAMS Accession No. ML21074A037) identifies the five primary topics to be addressed in a submittal:

(1) <u>Quality Assurance (QA)</u>: process followed during the manufacture and implementation of AMTs to ensure adherence to QA requirements (e.g., Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, “Domestic licensing of production and utilization facilities,” Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants”), established methods (e.g., commercial -grade dedication), or both

(2) <u>Process Qualification</u>: steps taken to demonstrate that the component will be produced with characteristics that will meet the intended design requirements

(3) <u>Supplemental Testing</u>: testing conducted to demonstrate that those material and component properties required to meet the design requirements are acceptable in the applicable service environmental conditions, and thus the performance of the component in service will be acceptable

(4) <u>Production Process Control and Verification</u>: steps taken to ensure that each component will be produced in accordance with the qualified process and, if the production process fails to meet the qualification essential variables, the steps taken to reestablish the qualified process

(5) <u>Performance Monitoring</u>: actions taken to provide assurance that the component will continue to meet its design requirements until the end of its intended service life

Table 1 includes the key CS process considerations and associated properties and performance characteristics of the CS material outlined in the NRC technical assessment, and identifies those principal elements from Appendix A to the generic guidelines that are expected to be most commonly applicable to each of the topic areas. However, the applicable principal elements may vary on a case-by-case basis, depending on the licensee’s approach to demonstrating quality and safety. Therefore, this table provides an example of applicable elements and reflects that not every element in Appendix A to the generic guidelines is applicable to every topic area listed in Table 1.

QA comprises all those planned and systematic actions necessary to provide adequate confidence that a system or component will perform satisfactorily in service. QA processes implemented during the manufacture and implementation of AMTs ensure that QA requirements (e.g., 10 CFR Part 50, Appendix B), established methods (e.g., commercial-grade dedication), or both, have been satisfied. For AMTs, a QA program will specifically address novel or unique aspects of manufacturing or implementation specific to the AMT. Therefore, Table 1 does not explicitly include QA as a distinct column, but QA is applicable to each of the topic areas identified in the table and achieved through successful implementation of the other four Appendix A items: process qualification, supplemental testing, production process control and verification, and performance monitoring.

4. Cold Spray Technical Review Guidelines

The technical review guidelines are provided in two tables. Table 2 addresses the CS process considerations. Table 3 covers properties and performance characteristics for CS materials. It is important to note that a given submittal need not address all elements of these tables but only those that are relevant for the particular application. In general, an important consideration for any nuclear application of CS is application-specific data for the proposed processing and post-processing parameters to ensure adequate CS performance in the service environment. Such data should assess properties required for the application (e.g., adhesion, corrosion resistance) and the effects of aging mechanisms (e.g., thermal aging, irradiation effects, and stress corrosion cracking [SCC]) on these properties over the intended service life.

Tables 2 and 3 provide technical review guidelines related to the CS process considerations and component performance through the following columns:

- Topic: identifies the key aspect of the CS process or property / performance characteristic outlined in the NRC technical assessment

- Key Technical Information: summarizes the key technical information documented in the NRC technical assessment for easy reference, including those specific considerations for non-structural and structural applications of CS

- Technical Review Guidelines: provides additional guidelines to support the staff's evaluation of the proposed use of CS, and ensure its adequacy, for the intended application.

Structural vs. Non-Structural Applications of Cold Spray
Table 3 addresses properties and performance characteristics for both non-structural and structural applications of CS. Several topics in Table 3 are noted as being primarily applicable to structural applications of CS but may also be applicable to non-structural applications. The primary distinction between a non-structural and structural application of CS is whether the CS material will be credited with bearing structural load for the component. Data and information on structural properties and performance of CS are limited. Therefore, the information provided for structural applications of CS is subject to change based on new information becoming available as research progresses in this area.

In general, non-structural applications of CS:

- are likely to be thinner,
- do not credit the CS material for any load-bearing capacity, and
- only credit the CS material for non-structural purposes, such as corrosion mitigation or wear resistance.

Meanwhile, structural applications of CS:
- are likely to be thicker, and
- credit the CS material for load-bearing capacity such that either the CS material entirely or the CS material in conjunction with the substrate and the interface meet the full structural strength requirements.

Two specific likely applications of CS that may either be classified as structural and non-structural applications of CS are leak/flaw repair and dimensional restoration. Additional discussion to help determine if such applications are structural or non-structural follows. Leak/flaw repair refers to the use of cold sprayed material to seal a leak or cover a surface-breaking flaw. Currently, there is limited data on this type of application and only exploratory work has been performed. CS repair of an active leak has been demonstrated as a proof-of-concept. However, qualification testing is needed to demonstrate the effectiveness of CS for leak/flaw repair and that the required structural margins have been restored, if applicable. In principle, the use of CS for leak/flaw repair may not claim structural credit for the CS materials but may still require that the CS coatings exhibit greater structural performance than for other applications such as wear resistance or corrosion protection.

Dimensional restoration refers to deposition of CS material to repair a damaged or corroded surface. CS for dimensional restoration has been done in many material systems in the defense, aerospace, and automotive sectors. Lessons learned from these applications can be transferred to nuclear applications. Most of the prior work has been performed using aluminum (Al) or nickel/chrome (Ni/Cr) alloys as the CS powder materials. Like leak / flaw repair, the use of CS for dimensional restoration may not claim structural credit for the CS material; however, such applications can include requirements for material properties such as strength and wear resistance. The determination of whether a particular application is structural or non-structural will largely be dependent on whether the CS material is needed to meet structural requirements.

Table 1. Relevant Elements from Appendix A to the Generic Guidelines

Topic	Process Qualification	Supplemental Testing	Production Process Control and Verification	Performance Monitoring
Factory Application and Associated Equipment	X		X	
Field Application and Associated Equipment	X		X	
Powder Quality and Processing	X		X	
Surface Preparation	X		X	
Process Parameters and Controls	X		X	
Post-processing	X		X	
Witness Specimens	X		X	
Local Geometry Impacts on Properties and Performance	X	X	X	
Non-destructive Examination	X		X	X
Adhesion Strength	X	X		
Porosity	X	X		
Edge Effects	X	X		X
Corrosion / Erosion Resistance		X		X
Wear Resistance		X		X
SCC Resistance		X		X
Fatigue Resistance		X		X
Irradiation Effects on Properties and Performance		X		X
Tensile Properties	X	X		
Initial Fracture Toughness	X	X		
Thermal Aging		X		X
High Temperature Time-Dependent Aging Effects (e.g., Creep and Creep-Fatigue)		X		X

Table 2 – Technical Review Guidelines – CS Process Considerations

Topic	Key Technical Information	Technical Review Guidelines

Factory Application and Associated Equipment	• The commonly used carrier gases are helium, nitrogen, and air. Helium, with its low atomic weight, provides the most rapid acceleration and generally achieves the best quality coatings.
	• High-pressure CS (HPCS) systems enable high-quality CS of high-melting-point materials that are currently used in the nuclear power industry, such as nickel-based alloys and steels.
	• Low-pressure CS systems are not recommended for high-quality CS of steels, Inconel, and other high-strength and high-melt-temperature materials.
	• Properties of the cold-sprayed material and process considerations need to be validated using equipment and nozzle types that will execute the work on mockups or witness specimens that are representative of the actual applications.
	• For both factory and portable systems, coating quality is influenced by many process parameters, including the selection of powders and their size distributions, choice of carrier gas and temperature, nozzle design, and surface preparation.
	• Sections 2.1.1 and 2.4.5.2 of the PNNL TLR compare field and factory applications and associated equipment in more detail.
	• Figure 2.14 of the PNNL TLR shows a framework describing process implementation, including relevant process considerations and best practices for CS applications.
		Process Qualification
		• Through process qualification, the applicant should provide sufficient data to demonstrate that the cold sprayed materials meet the intended function and requirements.
		• At a minimum, the process qualification should consider the following attributes:
		  ○ Process pressure (i.e., high pressure or low pressure CS)
		  ○ Equipment (i.e. stationary or portable) and nozzle types
		  ○ Delivery systems (robotic vs. manual)
		• The applicant should identify additional application-specific attributes and associated testing as appropriate.
		
		Production Process Control and Verification
		• During production, the applicant should demonstrate that process control and verification will maintain the essential process parameters within the qualified ranges.
		• One possible approach to demonstrate process control and verification is to test the CS process on a mock-up of the actual application to address and resolve potential issues with the CS deposition process and verify that the desired properties can be met using the equipment and nozzle types intended for the application.

Field Application and Associated Equipment	• The commonly used carrier gases are helium, nitrogen, and air. Helium, with its low atomic weight, provides the most rapid acceleration and generally achieves the best quality coatings. • HPCS systems enable high-quality CS of high-melting-point materials that are currently used in	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that the cold sprayed materials meet the intended function and requirements. • At a minimum, the process qualification should consider the following attributes: ○ Process pressure (i.e., high pressure or low pressure CS)

Topic	Key Technical Information	Technical Review Guidelines
	the nuclear power industry, such as nickel-based alloys and steels. • Low-pressure CS systems are not recommended for high-quality CS of steels, Inconel, and other high-strength and high-melt-temperature materials. • Properties of the cold-sprayed material and process considerations need to be validated using equipment and nozzle types that will execute the work on mockups or witness specimens that are representative of the actual applications. • For both factory and portable systems, coating quality is influenced by many process parameters, including the selection of powders and their size distributions, choice of carrier gas and temperature, nozzle design, and surface preparation. • Sections 2.1.1 and 2.4.5.2 of the PNNL TLR compare field and factory applications and associated equipment in more detail. • Field applications may be subject to additional constraints, such as access limitations and radiation exposure. • Figure 2.14 of the PNNL TLR shows a framework describing process implementation, including relevant process considerations and best practices for CS applications.	○ Equipment and nozzle types ○ Delivery systems (robotic or manual) • The applicant should identify additional application-specific attributes and associated testing as appropriate. **Production Process Control and Verification** • During production, the applicant should demonstrate that process control and verification will maintain the essential process parameters within the qualified ranges. • One possible approach to demonstrate process control and verification is to test the CS process on a mock-up of the actual application to address and resolve potential issues with the CS deposition process and verify that the desired properties can be met using the equipment and nozzle types intended for the application.
Powder Quality and Processing	• Best practices for powder processing and handling include sieving to control particle size, drying to avoid clumping, and storage in inert atmosphere to avoid oxidation and contamination. Sections 2.2.1 and 2.4.5.4 of the PNNL TLR discuss these in greater detail. • The selection of the powder is application specific depending on the application requirements, such as tensile strength, corrosion resistance, wear resistance, dimensional restoration, or a combination of these.	**Process Qualification** • Through process qualification, the applicant should identify the essential variables related to powder quality and demonstrate that controlling these variables within identified ranges will ensure reliable and adequate component properties and performance. • At a minimum, the process qualification should consider the following essential variables for powder quality: ○ chemical composition, including trace elements ○ powder size and morphology distribution ○ powder flowability ○ powder oxidation/contamination ○ acceptance criteria or limits for powder reuse

Topic	Key Technical Information	Technical Review Guidelines
	• Powders should be sieved to ensure that the particle average size and size distribution is within specifications. The presence of either large or small particles reduces the velocity of particles in the stream, which in turn reduces coating properties.	• The applicant should identify additional specific essential variables and their ranges as appropriate. • The applicant should identify methods for particle size controls and protocols for powder storage and handling. • The applicant should identify methods to prevent unacceptable degradation of powders such as corrosion and oxidation of powders in storage. **Production Process Control and Verification** • The applicant can use a variety of powder quality approaches to demonstrate process control and verification, including, but not limited to, the following: ○ testing final components on a sampling basis (e.g., witness specimens with demonstration of applicability) ○ characterizing essential variables by routine sampling after sieving powders before initial use and reuse ○ sieving powder prior to CS to application-specific specifications ○ implement procedures to prevent powder degradation • The applicant should demonstrate that the size distribution of the powder is within the specified ranges.
Surface Preparation	• Poor surface preparation results in poor adhesion, or bonding, to the substrate. • Failure to remove oxide layers from a substrate surface before CS application can negatively impact coating performance. • Surface preparation examples include grit blasting, abrasive pads, and wire brushes or wire wheels. • The surfaces to receive CS deposits should be cleaned to remove oil, grease, dirt, paint, oxides, and other foreign material that could affect CS adhesion. • Section 2.2.4 of the PNNL TLR discuss surface preparation and post cleaning in more detail.	**Process Qualification** • Through process qualification, the applicant should identify the necessary surface conditions including the necessary surface roughness and cleanliness for achieving a good quality coating. Cleaning procedures should not cause any damage to the surfaces that are to be coated that may detrimentally affect CS adhesion or component performance. **Production Process Control and Verification** • During CS application, measures should be employed to protect the surface to be coated from dust, dirt, moisture, and other contaminants that may detrimentally affect CS adhesion. • The applicant can use a variety of post process quality testing such as adhesion testing and NDE to validate the adequacy of surface preparation practices and procedures.

Topic	Key Technical Information	Technical Review Guidelines
Process Parameters and Controls	• One governing process parameter is the critical velocity (V_{cr}), defined as the velocity above which the particles are sufficiently plastically deformed upon impact and adhere to the substrate, or previous coating layers, as appropriate. • Nozzle clogging is one of the most common problems with the CS process and requires continuous monitoring. Nozzle clogging reduces particle velocity, resulting in reduced mechanical properties and increased porosity. • Algorithms to flag operators at the onset of preclogging conditions and record clogging conditions in data logs can be developed as an automated quality tool. • 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. • Process parameters such as those identified in Table 2.2 of PNNL TLR should be implemented.	**Process Qualification** • The applicant should identify the essential CS process parameters and demonstrate that controlling these parameters will ensure reliable, adequate, and repeatable CS properties and performance. • The process qualification should consider application-specific requirements and tailor the essential CS process parameters as appropriate. At a minimum, the process qualification should consider the following essential CS process parameters and controls: ○ gas temperature and pressure ○ substrate temperature ○ powder feed rate ○ particle impact velocity ○ angle of powder impact on substrate ○ nozzle distance to surface ○ nozzle traverse speed • The applicant should identify additional application-specific process parameters as appropriate. **Production Process Control and Verification** • During production, the applicant should demonstrate that process control and verification will maintain the essential process parameters within the qualified ranges. • The applicant can use a variety of approaches to demonstrate process control and verification, including, but not limited to, the following: ○ witness coupons representative of the intended application can be prepared during the CS deposition and tested to confirm the quality of the as-deposited coating. ○ monitor essential CS machine parameters such as gas temperature, powder velocity and nozzle traverse speed.
Post-processing	• For all postprocessing approaches, application-specific demonstration is important to identify adequate heat treatment to achieve the desired improvements in properties. • Heat-treating CS coatings is uncommon because the as-deposited coating typically has the required mechanical properties for coating and dimensional	**Process Qualification** • For process qualification, the applicant should identify appropriate post-processing techniques and demonstrate the intended effects of post-processing on the desired properties of the coating and the substrate. • The applicant should provide sufficient data to identify the essential variables related to post-processing and demonstrate that

Topic	Key Technical Information	Technical Review Guidelines
	restoration applications that dominate CS applications. Heat treatment is also typically impractical for field mitigation and repair applications, which also represent a sizeable percentage of CS applications. • Thermal postprocessing may also be complicated by application-specific considerations of distortion between the CS coating and the substrate, as well as impacts of heat treatment on the substrate material's properties. • Postprocess grinding or machining may be needed for final dimensional control and blending contours.	controlling these variables within identified ranges will ensure reliable and adequate component properties and performance. • At a minimum, the process qualification for post-processing heat treatments should identify the required time vs. temperature profile, including heating rate, cooling rate, hold times at specific temperatures, and the required environment during heat treatment. • The applicant should identify additional application-specific post-processing requirements as appropriate. **Production Process Control and Verification** • During production, the applicant should demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges for post-processing. • The applicant can use a variety of approaches to demonstrate process control and verification, including, but not limited to, the following: ○ testing final components on a sampling basis ○ witness specimens with demonstration of applicability ○ validated monitoring of post-processing parameters during heat treatment
Witness Specimens	• Table 2.3 of the PNNL TLR indicates CS property variables that may be important to evaluate to ensure good CS performance. • Destructive coupon tests can include appropriate specimens to assess surface profiles, porosity, tensile bond/yield strength, hardness, and corrosion susceptibility. Some relevant standards for testing properties of CS coatings include the following: – ASTM E8/E8M for tensile testing – ASTM E92 for hardness testing – ASTM D4541 for bond strength using adhesive pull testing – ASTM E2109 for porosity measurement	**Process Qualification** • The applicant should identify the material properties, microstructure, and other characteristics for which witness testing will be used to demonstrate process qualification including, for example: ○ adhesion strength ○ porosity ○ hardness ○ yield and tensile strength ○ fatigue resistance ○ fracture toughness ○ corrosion resistance. • The applicant should demonstrate how witness specimens are representative of the end-use component in terms of microstructure and material properties. • The applicant should discuss the witness testing program, addressing aspects such as a description of tests to be performed, associated standards used to perform testing, the acceptance criteria for each test, and the sampling frequency associated with each test.

Topic	Key Technical Information	Technical Review Guidelines
		Production Process Control and Verification • The applicant should indicate how witness testing will be used to demonstrate that process control and verification will maintain the production process within the qualified essential variable ranges during production. • The applicant can use a variety of witness specimen approaches to demonstrate process control and verification, including, but not limited to, the following: ○ confirming that CS process parameters (e.g. gas/powder velocity, powder feed rate) remain within acceptable ranges. ○ confirming required material properties and characteristics (e.g., spray thickness, adhesion strength, porosity, surface finish)
Local Geometry Impacts on Properties and Performance	• Local geometry can impact CS process parameters such as nozzle-to-surface distance and powder impact angle, which can affect the local microstructure and properties. • Geometric features such as obstructions and internal corners may be challenging to obtain necessary coverage and result in significant variation in coating depth. • Properties of the cold-sprayed material and process considerations need to be validated, most likely through qualification on representative mockups, using the planned equipment and process parameters that will be used in the actual application. • Witness specimens developed under conditions representative of the areas of concern within complex geometries could be used to assess the impacts on material properties and performance due to geometries or areas that are difficult to spray.	**Process Qualification/Production Process Control and Verification** • Through process qualification, the applicant should provide sufficient data to demonstrate that local geometry impacts on material properties and microstructure will be addressed to ensure adequate CS properties and performance. • One possible approach to demonstrate process control and verification is to test the CS process on a mock-up of the actual application to address and resolve potential issues with geometric features and verify that the desired properties can be met using the equipment and nozzle types intended for the application. • The applicant should identify additional application-specific considerations as appropriate. **Supplemental Testing** • The applicant should demonstrate that the local geometry impacts on CS process will not unacceptably degrade material properties and performance due to in-service aging.

Topic	Key Technical Information	Technical Review Guidelines

Non-destructive Examination	• Visual testing can be used to examine the CS surface for imperfections such as chipping, cracking, and flaking. Penetrant testing can also be used, but surface roughness or porosities may obscure cracks or other imperfections.
	• It is expected that both ultrasonic testing (UT) and eddy-current testing (ET) can be used to examine the quality of CS coatings. Surface roughness may affect the ability to inspect CS depositions. The effectiveness of these methods requires further investigation.
	• UT and ET can penetrate CS coatings and be used to inspect the underlying material. Thick coatings may present problems for inspection, particularly if they contain porosity.
	• It is anticipated that ET is appropriate for thin coatings (i.e., several millimeters); however, additional work should be done to verify the effective thickness limits.
	• Cracks and lack of adhesion can be measured using established UT methods. Understanding the limitations caused by coating porosity and thickness requires further investigation.
	• Section 2.4.3.2 of the PNNL TLR discusses CS coating quality verification with NDE.
		Process Qualification
		• Through process qualification, the applicant should identify the needed NDE methods and demonstrate the capability of the NDE methods to meet the application requirements. The NDE methods should be capable of verifying coating properties such as porosity, coating thickness, coating/substrate adhesion quality, detection of defects in CS materials, and inspection of substrate material through the CS coating.
		• The applicant should demonstrate the capability of the NDE methods to penetrate CS coating and perform any needed NDE of the substrate material.
		• At a minimum, the process qualification should consider the impact of following attributes on NDE performance:
		  ○ powder and substrate materials
		  ○ coating thickness
		  ○ coating surface roughness
		  ○ acceptance criteria
		Production Process Control and Verification/Performance Monitoring
		• Destructive testing of a demonstration or witness specimen following NDE to validate the effectiveness of the NDE methods.
		• Conduct in-service NDE to manage the integrity of CS coatings.

Table 3 – Technical Review Guidelines – CS Properties and Performance Characteristics for Non-Structural and Structural Applications

Topic	Key Technical Information	Technical Review Guidelines
Adhesion Strength	• Adhesion strength of 10–20 kilopounds per square inch (ksi) is common on a properly prepared surface, and adhesion strengths greater than 30 ksi are not uncommon for CS adhesion strength of higher strength alloys. • Thick oxides and surface contamination can significantly reduce the adhesion strength of the CS coating. • Adhesion strength may be limited by the bond strength of the epoxy when epoxy-based adhesion tests (ASTM-C633, ASTM-D4541) are used. The triple-lug shear testing described in MIL-J-24445A can be used to reach adhesion values not limited to epoxy strength.	**Process Qualification/Supplemental Testing/Performance Monitoring** • For process qualification and supplemental testing, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments (e.g. temperature, chemistry, stress), to show adequate adhesion strength of the CS material to the substrate over the intended service life. ○ The corresponding analysis can demonstrate acceptable performance using approaches such as the following: ▪ demonstrating adequate adhesion strength by adhesion tests ▪ experience from previous applications of CS in similar environments using similar process and material ▪ NDE may be used to confirm adhesion quality.
Porosity	• Porosity is known to adversely affect fatigue life, SCC, and irradiation-assisted SCC, though the precise quantitative impact depends on the material and porosity characteristics (e.g., pore frequency, pore size, pore morphology, total void fraction). • Porosity within a qualified process is usually caused by nozzle clogging. Process control to monitor relevant parameters such as gas pressure and flow rate should be implemented to detect nozzle clogging. Automated nozzle clogging detection could be	**Process Qualification** • Through process qualification, the applicant should provide sufficient data to demonstrate that porosity will be managed sufficiently to ensure reliable and adequate properties and performance of cold sprayed materials. • Post-processing through heat treatment may reduce porosity, but this should be demonstrated. Post-processing may not be feasible for field applications of CS. • At a minimum, the process qualification should consider the following key characteristics when establishing acceptance criteria for porosity: ○ pore density ○ pore distribution (e.g., location relative to the surface) ○ pore size ○ pore morphology ○ total void fraction • The applicant should identify additional specific characteristics as appropriate.

Topic	Key Technical Information	Technical Review Guidelines
	integrated in CS equipment to ensure clogging does not happen in the field.	**Supplemental Testing** • The applicant should demonstrate that the porosity in cold sprayed materials will not unacceptably degrade material properties and performance due to in-service aging. • This demonstration could be performed on a witness sample or a mock-up that is representative of, or bounds, the cold sprayed materials' qualified pre-service condition, including post-processing.

Edge Effects	• Data in representative environments are important to demonstrate that coating edge effects will not lead to unacceptable increases in corrosion susceptibility near the edge of the CS coating.
	• Edge effects due to stress concentration such as effects on fatigue susceptibility (including thermal fatigue) and residual stress should be adequately investigated to ensure sufficient performance in service.
	• Galvanic potentials can exist at component edges and crevices can exist if the edge is not properly blended.
		Process Qualification
		• The applicant should provide sufficient data to demonstrate that edge effects will be managed sufficiently to ensure that the CS materials have reliable and adequate properties and performance.
		• Witness specimens representative of the intended application can be prepared during CS deposition and tested to demonstrate that edge effects can be effectively managed.
		• Post-processing through grinding, buffing or other blending techniques may be used to properly smooth the edges of a deposited coating to reduce edge effects. Best practice should be followed to minimize detrimental cold work or residual stress effects. Any such post-processing should be demonstrated as part of the qualifications process.
		
		Supplemental Testing/Performance Monitoring
		• Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments and loading conditions, to show that the edges associated with the CS coating termination retain adequate adhesion, corrosion, stress, and fatigue performance throughout the service life of the cold sprayed materials.
		  ○ The corresponding analysis can demonstrate acceptable performance by using approaches such as the following:
		    ▪ demonstrating edge effects will not unacceptably degrade essential properties and performance characteristics of the CS component over its intended service life.
		    ▪ addressing uncertainties in the data on edge effects on adhesion, corrosion, stress, and fatigue performance through, for example, conservative design assumptions, additional margins in analyses, use of surveillance programs, in-service inspection, or additional performance monitoring as appropriate

Topic	Key Technical Information	Technical Review Guidelines

Corrosion / Erosion Resistance	• For corrosion resistance, the most used coatings are forms of nickel, copper, aluminum, or titanium.
	• Short-term testing using ASTM standards may be used to screen corrosion and erosion resistance of material combinations in representative environments.
	• Corrosion testing using representative test conditions may be necessary to demonstrate the long-term behavior of CS protective coatings.
		Supplemental Testing/Performance Monitoring
		• Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate corrosion/erosion resistance for the intended function of the CS component over the intended service life.
		  ○ The corresponding analysis can demonstrate meeting design requirements by using approaches such as the following:
		    ▪ demonstrating equal or superior performance by comparison to corrosion / erosion performance for substrate materials (assuming similar in-service inspection frequency and methods)
		    ▪ addressing uncertainties in the data on corrosion / erosion and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate

Wear Resistance	• CS can produce hard surfaces with excellent wear resistance, especially when blended powders with hard particles are used.
	• CS materials generally exhibit higher hardness than those of the corresponding powders and bulk alloys due to the plastic deformation induced during deposition. The CS process parameters can be adjusted to achieve a range of surface hardness and ductility properties.
	• Additional data on wear behavior may be needed if new CS powders or environments with high-wear stressors will be present.
		Supplemental Testing/Performance Monitoring
		• Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate wear resistance for the intended function of the CS materials over the intended service life.
		  ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following:
		    ▪ demonstrating equal or superior performance by comparison to wear performance for substrate materials
		    ▪ addressing uncertainties in the data on wear and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate

SCC Resistance	• Data in representative environments is important to demonstrate that resistance to SCC will be adequate to meet component design requirements and confirm the appropriateness of aging management approaches.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate SCC resistance for the intended function of the cold sprayed materials over the intended service life. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following:

Topic	Key Technical Information	Technical Review Guidelines
	• Limited testing of CS commercially pure nickel appears to show substantial resistance to primary water SCC, as discussed in Section 2.3.8 of the PNNL TLR. • Some qualification testing has been performed using either commercially pure nickel or titanium/titanium carbide to demonstrate SCC protection with various Inconel and SS substrates. • SCC initiation prevention is likely more important in nonstructural applications due to the smaller thickness of the coatings. • For structural applications of CS, SCC growth properties of the CS material are likely to be more important than for nonstructural applications.	▪ demonstrating equal or superior performance by comparison to SCC performance for substrate materials (assuming similar in-service inspection frequency and methods) ▪ addressing uncertainties in the data on SCC resistance and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate
Fatigue Resistance	• CS is expected to improve the 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. • The potential for thermal fatigue due to different coefficients of thermal expansion for the coating and substrate should be considered. • Data in representative environments are important to demonstrate that fatigue resistance will be adequate to meet component design requirements and confirm the appropriateness of aging management approaches. • Fatigue initiation prevention is likely more important in nonstructural	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments and loading conditions, to show adequate fatigue performance throughout the service life of the CS component. ○ The applicant can use current fatigue management approaches supported by sufficient data for the CS component to manage metal fatigue (e.g., cumulative usage factors, cycle counting, environmentally assisted fatigue adjustment factors). ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to fatigue testing for substrate materials (assuming similar in-service inspection frequency and methods) ▪ addressing uncertainties in the data on fatigue initiation and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate

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	applications due to the small thickness of the coatings. • For structural applications of CS, fatigue crack growth properties of the CS material are likely to be more important than for nonstructural applications.	
Irradiation Effects on Properties and Performance	• Data in representative environments are important to demonstrate that irradiation effects will not be significantly greater in CS materials than substrate materials and that CS materials will be adequate to meet component design requirements and to confirm the appropriateness of aging management approaches. • For structural applications of CS, irradiation effects on bulk mechanical properties (e.g., tensile, toughness) of the CS material are likely to be more important than for nonstructural applications.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate performance after irradiation (including irradiation-assisted SCC and loss of toughness) for the intended function of the cold sprayed materials throughout its service life. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to irradiation effects for substrate materials ▪ addressing uncertainties in the data on irradiation effects and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate
Tensile Properties	• Data in representative environments are important to demonstrate that tensile properties will be adequate to meet component design requirements and confirm the appropriateness of aging management approaches. • Tensile properties are primarily applicable to structural applications of CS.	**Process Qualification/Supplemental Testing** • For process qualification and supplemental testing, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate tensile properties for the cold sprayed materials. ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to tensile properties for substrate materials ▪ analyzing design requirements to demonstrate sufficient tensile properties for the cold sprayed material
Initial Fracture Toughness	• Data in representative environments are important to demonstrate that fracture toughness will be adequate to meet component design requirements	**Process Qualification/Supplemental Testing** • For process qualification and supplemental testing, the applicant should provide an analysis, supported by sufficient data in representative or bounding

Topic	Key Technical Information	Technical Review Guidelines
	and confirm the appropriateness of aging management approaches. • For factory applications of CS on new components, thermal postprocessing may be feasible and, with appropriate parameters, would be expected to improve fracture toughness. • Initial fracture toughness is primarily applicable to structural applications of CS.	environments, to show adequate fracture toughness for the intended function of the cold sprayed material. ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following: ▪ Demonstrating equal or superior performance by comparison to fracture toughness for substrate materials ▪ analyzing design requirements to demonstrate sufficient fracture toughness for design and flaw evaluation purposes
Thermal Aging	• Data in representative environments are important to demonstrate that fracture toughness and mechanical properties do not unacceptably degrade due to thermal aging and will be adequate to meet component design requirements and confirm the appropriateness of aging management approaches. • For factory applications of CS on new components, thermal postprocessing may be feasible, and with appropriate parameters would be expected to make material properties and performance more similar to conventional processed materials. • Thermal aging is primarily applicable to structural applications of CS.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate mechanical properties and fracture toughness after thermal aging throughout the service life of the cold sprayed materials. ○ The corresponding analysis can demonstrate acceptable safety margins using approaches such as the following: ▪ demonstrating equal or superior performance by comparison to the mechanical properties and fracture toughness after thermal aging for substrate materials ▪ addressing uncertainties in the data on the mechanical properties and fracture toughness after thermal aging and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate
High Temperature Time-Dependent Aging Effects (e.g., Creep and Creep-Fatigue)	• Data in representative environments are important to demonstrate that high-temperature performance will be adequate to meet component design requirements and confirm the appropriateness of aging management approaches.	**Supplemental Testing/Performance Monitoring** • Through supplemental testing and performance monitoring, the applicant should provide an analysis, supported by sufficient data in representative or bounding environments, to show adequate performance after high temperature time-dependent aging effects (including creep and creep-fatigue) for the intended function of the cold sprayed materials throughout its service life. ○ The corresponding analysis can demonstrate acceptable safety margins by using approaches such as the following:

Topic	Key Technical Information	Technical Review Guidelines
	• High-temperature, time-dependent aging effects are primarily applicable to structural applications of CS.	▪ demonstrating equal or superior performance by comparison to high temperature time-dependent aging effects for substrate materials ▪ addressing uncertainties in the data on high temperature time-dependent aging effects and the implications to in-service performance through conservative design assumptions, additional margins in analyses, surveillance programs, in-service inspection, or additional performance monitoring as appropriate