U.S. Nuclear Regulatory Commission
Technical Assessment of Cold Spray

1. Introduction and Purpose

This document provides the U.S. Nuclear Regulatory Commission's (NRC's) technical assessment of the process considerations and knowledge gaps related to the application of the cold spray (CS) metal coating process to the nuclear power industry. This assessment is primarily based upon the technical information and gap analysis developed by Pacific Northwest National Laboratory (PNNL) in a technical letter report (TLR) entitled "Assessment of Cold Spray Technology for Nuclear Power Applications," issued September 2021 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21263A107), hereafter referred to as the "PNNL TLR." This assessment, combined with the PNNL TLR, highlights key technical information related to the application of CS in nuclear facilities and fulfills the deliverable for CS under Subtask 1A of the "Action Plan for Advanced Manufacturing Technologies (AMTs)," Revision 1, dated June 23, 2020 (ADAMS Accession No. ML19333B973).

2. NRC Assessment of Cold Spray Technology

This section describes the CS process considerations, highlights knowledge gaps associated with using CS for nuclear applications, and assesses the properties and performance characteristics of CS for both structural and nonstructural applications. The quality of CS is influenced by many process parameters, including the selection of powders, choice of CS equipment, nozzle design, and surface preparation. Careful analysis of the application requirements and suitable process parameters and controls are necessary to achieve the desired coating performance. CS technology for corrosion and wear resistance has been successfully demonstrated in other industries (e.g., defense, aerospace). However, there are considerable knowledge gaps associated with using CS for nuclear applications due to differences in operating environments and substrate materials. The importance of these knowledge gaps depends on the specific CS application requirements. The application categories considered in the PNNL TLR include factory-applied CS coatings for chloride-induced stress corrosion cracking (SCC) mitigation, field-applied CS coatings for chloride-induced SCC mitigation and repair, light-water reactor factory-applied CS for structural fabrication, and light-water reactor field-applied CS for dimensional restoration and corrosion protection.

The results of this technical assessment are provided in two tables. Table 1 includes the CS process considerations, including equipment, process parameter control, powder quality and handling, and quality management. Table 2 includes the properties and performance characteristics for CS materials. In general, an important consideration for any nuclear application of CS is application-specific data for the proposed processing and postprocessing parameters to ensure adequate coating performance in the service environment. Such data should assess the properties required for the application (e.g., adhesion, corrosion resistance) and the effect of aging mechanisms (e.g., thermal aging, irradiation effects, and SCC) on these properties over the intended service life.

Tables 1 and 2 identify and provide technical information for the CS process and the properties and performance characteristics for CS material using the following columns:

- **Topic:** Key aspect of the CS process or property/performance characteristic.
- **Definition:** Brief description of the CS topic.
- **NRC Ranking of Knowledge Gap:**

  Knowledge Gap: State of the knowledge gaps associated with the topic related to CS for nuclear applications:

  - A *large* gap designation indicates that few to no data currently exist.
  - A *medium* gap designation indicates that some data exist, but more are needed to confirm the acceptability of CS for nuclear applications.
  - A *small* gap designation means that the topic is relatively well understood.

  Manageability: Description of how the identified gaps would be managed for nuclear applications.

- **Key Technical Information:** Key technical information associated with the specified topic for use in nuclear applications.

Table 2 identifies and provides technical information for the properties and performance characteristics for both structural and nonstructural applications of CS materials. Several topics in Table 2 are noted as being primarily applicable to the structural applications of CS, but they may also be applicable to nonstructural applications. The primary distinction between structural and nonstructural applications of CS is whether the CS material will be credited with bearing structural load for the component. Data and information on the structural properties and performance of CS are limited. Therefore, the information provided for the structural applications of CS is preliminary and subject to change based on new information becoming available as research progresses in this area.

In general, the structural applications of CS

(1) are likely to be thicker, and

(2) 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.

Meanwhile, the nonstructural applications of CS

(1) are likely to be thinner,

(2) do not credit the CS material for any load-bearing capacity, and

(3) only credit the CS material for nonstructural purposes, such as corrosion mitigation or wear resistance.

Two specific likely applications of CS that may be classified as either structural or nonstructural applications of CS are leak/flaw repair and dimensional restoration. Additional discussion follows to help determine whether such applications are structural or nonstructural. Leak/flaw repair refers to the use of cold-sprayed material to seal a leak or cover a surface-breaking flaw. Currently, limited data are available 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 such coatings do for other applications, such as wear resistance or corrosion protection.

Dimensional restoration refers to the 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 previous work has been performed using aluminum or nickel/chrome 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 nonstructural will depend largely on whether the CS material is needed to meet structural requirements.

3. Codes and Standards

Currently, no codes or standards directly address CS for nuclear applications. The PNNL TLR identifies three U.S. Department of Defense (DOD) documents (MIL-STD-3021, “Materials Deposition, Cold Spray,” issued March 2015; MIL-DTL-32495A, “Powders for Cold Spray,” issued November 2018; and Uniform Industrial Process Instruction 6320-901, “Processes and Quality Control of Cold Spray,” issued March 2019) for the CS process, but they generally reference different powder and substrate materials than would be expected in nuclear applications. While specifically developed for DOD applications, these documents may be helpful in informing the development of standards or other guidance documents for CS in nuclear applications. In addition, several American Society for Testing and Materials (ASTM) standards pertaining to coating quality could also apply to CS coatings. Additional standards may need to be developed to support the qualification and implementation of CS for nuclear applications. Such standards should consider CS equipment, powder processing, process parameters and controls, CS test methods, and performance acceptance criteria.

It is also important to note that most current CS applications relate to nonstructural coating. Structural applications of CS will require development of standards that define how CS is to be tested and properties validated. Appendix A to MIL-STD-3021 identifies a number of tests that should be considered for structural applications. The specific test requirements should be tailored to the specific application. Whether the application is structural or nonstructural, qualification of CS for specific nuclear applications should be handled through application-specific requirements and associated test standards.

4. Summary and Conclusion

The staff has identified and assessed the process considerations and knowledge gaps associated with using CS for nuclear applications, as well as the properties and performance characteristics of CS materials for both structural and nonstructural applications. Application-specific data will also need to be generated to demonstrate adequate CS performance to meet the design requirements over the intended service life of the CS component. Because CS is a technology that has been recently developed and applied to only a limited number of applications, the staff has determined that additional codes and standards are necessary to support the use of CS in nuclear applications.

Table 1 Technical Information: CS Process Considerations

Topic (Corresponding PNNL Report Topics)[1]	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
		Knowledge Gap	Manageability	
Factory Application and Associated Equipment (Manufacturing/ factory setting)	Factory application refers to application of CS in a factory setting. The location of where CS will be applied determines the limitations on the type of equipment that can be used to implement CS.	**Small:** There are minor knowledge gaps in how to execute CS on materials and substrates of interest in a factory setting.	CS has been done in many applications for the aerospace, defense, and automotive industries. Nuclear applications would be informed by nonnuclear experience with CS. New and existing codes and standards would address application-specific requirements.	• 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.
Field Application and Associated Equipment	Field application refers to application of CS in a field setting. The location of	**Medium:** Portable HPCS equipment for field application is a newer technology	CS has been done in many applications for the aerospace, defense, and automotive	• 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.

Topic (Corresponding PNNL Report Topics)[1]	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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(Unconfined space field setting, confined space field setting, nozzle technology for portable CS)	where CS will be applied determines the limitations on the type of equipment that can be used to implement CS.	compared to stationary factory HPCS equipment.	industries. Nuclear applications would be informed by nonnuclear experience with CS. Equipment vendors are working to improve nozzle designs and develop new gas-heating strategies to improve performance of portable HPCS equipment. New and existing codes and standards would address application-specific requirements.	• 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. • 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.
Powder Quality and Processing (Powder processing, powder storage and handling)	Powder quality and processing refers to powder selection, drying, sieving, contamination minimization, and other powder processing and	**Small:** Best practices of powder processing and handling such as sieving and drying are well understood and documented in the available	Existing best practices are likely sufficient. These practices may need to be tailored to materials of interest for nuclear applications.	• 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

Topic (Corresponding PNNL Report Topics)[1]	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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	storage and handling practices.	literature and standards.		corrosion resistance, wear resistance, dimensional restoration, or a combination of these. • 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.
Surface Preparation (Surface preparation)	Surface preparation refers to methods used to treat the surface of the substrate before CS application.	**Small:** Best practices for surface preparation are well understood and available in the literature.	Best practices for surface preparation are available that can guide selection of surface preparation techniques. Existing best practices are expected to be applicable to materials and CS applications in the nuclear industry.	• 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 postcleaning in more detail.
Process Parameters and Controls (In-process: statistics process control)	Process parameters and controls refers to key aspects of CS operation that impact CS quality and performance and thus should be monitored and controlled, such as temperature, pressure, and flow rates (in part for nozzle clogging detection).	**Medium:** Process control can be implemented to monitor relevant process parameters. The range of allowable qualified process parameters is expected to depend on the application and materials.	This issue is manageable with appropriate quality assurance requirements and the use of in situ monitoring and environmental sensor data to monitor essential parameters. Allowable ranges for parameters for specific nuclear applications should	• 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

Topic (Corresponding PNNL Report Topics)[1]	Definition	NRC Ranking of Knowledge Gap: Knowledge Gap	NRC Ranking of Knowledge Gap: Manageability	Key Technical Information
			be determined and validated.	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.
Postprocessing (Postprocessing for mechanical properties, as-deposited surface roughness)	Postprocessing includes methods used after the initial deposition of CS material, such as surface grinding, machining, or heat treatments.	**Small**—**Grinding and Machining**: There are minor knowledge gaps related to postprocessing grinding and machining. Best practice should be followed to minimize residual stress effects. **Medium—Heat Treatment:** Postprocessing heat treatment for conventional materials is fairly well understood and reported in the literature, but there is limited experience for CS materials for nuclear applications.	Surface and thermal postprocessing should be demonstrated and the range of postprocessing parameters established through testing, nondestructive examination (NDE), and measurements to ensure conformance with application requirements.	• 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 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.
Witness Specimens	Witness specimens are test specimens that are placed adjacent to the	**Medium:** Witness specimens are commonly used for demonstrating and actually applying	Witness specimens may be subjected to postprocess destructive and nondestructive	• 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

Topic (Corresponding PNNL Report Topics)[1]	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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	part being sprayed and used to provide confirmation of CS quality and performance.	CS to provide empirical evidence of acceptable CS properties such as spray thickness, porosity, and adhesion strength. The representative-ness of the witness specimens to the actual application should be demonstrated.	examinations to demonstrate the process parameters that produce an acceptable CS coating. The specific coating properties of interest can vary depending on application.	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
Local Geometry Impacts on Properties and Performance	The geometry of the component to be sprayed can affect CS material properties and performance. Complex geometries or areas that are difficult to spray (e.g., internal corners or areas with obstructions) are the biggest challenges.	**Medium:** CS has been done in many applications for the aerospace, defense, and automotive industries. Nuclear applications would be informed by nonnuclear experience with CS.	Local geometry impacts are highly dependent on the CS equipment and geometry of the component. They can be managed through process qualification and witness specimens to measure the impacts.	• 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.
NDE (NDE and statistical process control)	NDE refers to methods used to assess the quality of CS coatings, including detection of	**Large:** Limited information is available on the applicability and demonstration of NDE methods for	Further studies of NDE methods to assess CS quality are needed to establish a technical foundation and best	• 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.

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	defects, verification of coating properties such as porosity, bond quality, and inspection of substrate materials through the CS coating.	CS applications, including NDE methods to detect coating properties such as porosity and adhesion quality. Accessibility and harsh environments such as high radiation present additional NDE challenges.	practices for inspection of CS.	• 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.

1 Section 4.1 of the PNNL TLR discusses the corresponding PNNL gaps.

Table 2 Technical Information: CS Properties and Performance Characteristics for Structural and Nonstructural Applications

Topic	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
		Knowledge Gap	Manageability	
Adhesion Strength (Adhesion strength)	Adhesion strength refers to the minimum force needed to separate a coating from the substrate.	**Small—Factory Applications:** For stationary factory equipment, adhesion values are known for many powder-substrate combinations. **Medium—Field Applications:** Portable HPCS of high-melt-temperature materials will require further investigation.	Established test methods are generally sufficient to ensure adequate adhesion strength is demonstrated for new powder-substrate combinations and applications.	• 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.
Porosity (Porosity)	Porosity includes the size, distribution, and total volume of voids. Porosity can have a significant impact on coating performance.	**Small—Factory Applications:** For stationary factory equipment, expected porosity is understood and can be negligible for most material systems when done correctly. **Medium—Field Applications:** Portable HPCS of high-melt-temperature materials will require further investigation.	Appropriate use of destructive testing and witness specimens for process qualification, control and verification should be adequate to manage 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 integrated in CS equipment to ensure clogging does not happen in the field.
Edge Effects (Edge effects)	Edge effects refer to the impacts, such as stress concentration or corrosion initiation, at the	**Large:** Very limited data are available on edge effects at the interface between the coating and substrate.	Edge effects at the interface between the CS material and the substrate would need to be evaluated	• 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.

Topic	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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	interface between the CS material and the substrate that is exposed to the environment.	The relevant phenomena and their impact depend on the material combinations and environmental conditions.	considering the specific nuclear material combinations and environmental conditions in the intended application.	• 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.
Corrosion/ Erosion Resistance (Erosion/ corrosion resistance, effects of surface finish on corrosion resistance)	Corrosion/erosion resistance refers to the material's ability to resist the loss of material due to corrosion/ flow-assisted corrosion or cavitation erosion processes.	**Medium:** While data exist that show excellent erosion/corrosion resistance using CS, nuclear application-specific material combinations and environments have yet to be evaluated.	Exploratory work has shown CS may have the ability to improve erosion/corrosion resistance for a few specific nuclear applications. Nuclear-specific material combinations and environments need to be tested.	• 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.
Wear Resistance (Mechanical wear resistance)	Wear resistance refers to the ability to avoid the removal and deformation of material from the surface when in contact with another component.	**Medium:** Data exist that show excellent wear resistance using CS in nonnuclear applications. Nuclear application-specific material combinations and environments have yet to be tested.	Mechanical wear resistance of CS is well understood and documented in the literature. Nuclear-specific CS materials and environments need to be tested.	• 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.
SCC Resistance (SCC performance)	SCC resistance refers to the ability to resist stress corrosion crack initiation and growth	**Large:** Very limited data are available on the use of CS for mitigation and prevention of SCC.	Significant work is needed to quantify SCC performance, including SCC initiation and arresting	• 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.

Topic	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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	in susceptible materials under operating conditions of roughly constant stress due to the corrosive environment.		preexisting SCC flaws, for any SCC mitigation or repair applications.	• 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.
Fatigue Resistance (Fatigue performance)	Fatigue resistance refers to the ability to resist initiation and propagation of cracks due to cyclic loading with or without environmental effects playing a significant role in the process.	**Large:** Fatigue data for the range of material combinations likely for CS of nuclear applications do not exist.	Understanding fatigue performance requires analysis and testing of the component with CS material. Testing needs to be representative of the conditions that the component will see in operation.	• 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 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.

Topic	Definition	NRC Ranking of Knowledge Gap		Key Technical Information
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Irradiation Effects on Properties and Performance (Irradiation performance)	Irradiation effects refer to the impact of neutron irradiation on various aspects of material properties and performance, including (but not limited to) loss of fracture toughness, irradiation-assisted SCC, and void swelling.	**Large:** No experimental work has been completed to evaluate the irradiation performance of CS coating.	Irradiation effects are known for substrate materials in nuclear applications. Evaluation of CS materials may be required where data are insufficient.	• 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.
Tensile Properties (Tensile strength)	Tensile properties refer to the ultimate tensile and yield strength of the material.	**Large:** Very limited data are available on bulk CS material tensile properties.	Tensile property requirements may be application specific. Applications of existing standard testing methods to CS materials need to be validated. Application-specific testing should also consider anisotropic and inhomogeneous properties of CS materials, especially in areas more difficult to spray.	• 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.
Initial Fracture Toughness	Initial fracture toughness refers to the material's starting fracture toughness upon entering service after fabrication.	**Large:** Very limited data are available on fracture toughness for CS materials.	Evaluation of CS materials fracture toughness may be required for some applications. Postprocessing may improve fracture toughness.	• Data in representative environments are important to demonstrate that fracture toughness 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

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				feasible and, with appropriate parameters, would be expected to improve fracture toughness. • Initial fracture toughness is primarily applicable to structural applications of CS.
Thermal Aging	Thermal aging refers to changes in microstructures after a significant time at elevated temperature, which can alter mechanical properties, including reducing fracture toughness and ductility and increasing hardness and strength.	**Large:** Very limited data are available on thermal aging effects for CS materials, but the initial fracture toughness is expected to be lower than that of conventionally processed materials. Thermal aging impacts will depend primarily on the operating temperature and time for the component in service.	Data in representative environments will be needed to assess the potential for thermal aging effects in a given application.	• 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.
High-Temperature, Time- Dependent Aging Effects (e.g., creep and creep-fatigue)	High-temperature, time-dependent aging effects refers to mechanisms relevant to elevated temperatures (as discussed in ASME Boiler and Pressure Vessel Code, Section III, Division 5), including creep, creep-fracture, and creep-fatigue.	**Large:** High-temperature, time-dependent aging effects are of high importance to component integrity for the elevated operating temperatures expected for many advanced reactor designs, and there are no known data for CS materials in these environments.	Significant data in representative environments will be needed to assess the suitability of CS materials for these applications.	• 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. • High-temperature, time-dependent aging effects are primarily applicable to structural applications of CS.

[1] Section 4.1 of the PNNL TLR discusses the corresponding PNNL gaps.