AWS C2.21M/C2.21:2015 (R2024)
An American National Standard

Specification for Thermal Spray Equipment Performance Verification

American Welding Society®

Approved American National Standard
ANSI

AWS C2.21M/C2.21:2015 (R2024)
An American National Standard

Approved by the
American National Standards Institute
October 27, 2015
Reaffirmed: December 5, 2023

Specification for Thermal Spray Equipment Performance Verification

2nd Edition

Revises AWS C2.21M/C2.21:2003

Prepared by the
American Welding Society (AWS) C2 Committee on Thermal Spraying

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This standard specifies the essential elements of a procedure for verifying the performance of thermal spray equipment to ensure it is capable of operating according to the manufacturer's specifications or those established by the User.

American Welding Society®

ISBN Print: 978-1-64322-299-8
ISBN PDF: 978-1-64322-300-1

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Foreword

This foreword is not part of this standard but is included for informational purposes only.

Predictable, consistent, and reliable thermal spray equipment performance is essential for proper application of the thermal spray process. Verifying the thermal spray equipment is operating according to the manufacturer's specifications, and established standards is an important part of a thermal spray quality assurance program.

The first version of this standard, titled *Specification for Thermal Spray Equipment Acceptance Inspection*, was published in 2003 as a response to ISO 14231:2000, *Thermal Spraying—Acceptance Inspection of Thermal Spraying Equipment*. The purpose of the standard was to provide a systematic approach to assure a purchaser the equipment has the capability to operate as the manufacturer intended. While verification of function at the time of purchase was a good first step, the industry also has a need to assure ongoing functional capability.

The change in title of this second edition reflects an expanded scope, which now includes a definition of the ongoing requirements for verification of equipment performance. Prescriptive design and performance requirements have been eliminated. Calibration considerations, processes, and procedures have been incorporated.

In this reaffirmation, the following nonsubstantive changes have been made:

1.1 Scope – "These equipment and systems include" was changed to "The equipment and systems include."

1.3 Safety – The boilerplate text, "Safety Data Sheets (SDS), Material Safety Data Sheets (MSDS), or Product Safety Data Sheets (PSDS), supplied by materials manufacturers" was changed to "Safety Data Sheets supplied by materials manufacturers" and the following boilerplate text was added: "Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program."

2. Normative References – The boilerplate text was changed from "The following standards contain provisions which, through reference in this text, constitute mandatory provisions of this AWS standard. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply." to "The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments or revisions of the publications may not apply since the relevant requirements may have changed." and "M/A3.0" has been added to the normative reference.

3. Terms and Definitions – "provides the basis for terminology used herein." was changed to "provides the basis for terms and definitions used herein."

4.2.2 Inspection Interval – "quality control" was changed to "quality assurance."

5.2 General Housekeeping – "Inspection" was changed to "inspection."

5.4 As-found/As-left Condition – "inspector" was changed to "Inspector" in the second sentence and a colon was deleted from "Some examples are."

5.5 Equipment Isolation – "a" was added before "larger" in the first sentence.

5.6.2 Overtemperature – A comma was added after the text "If the thermal spray equipment incorporates thermal protection."

5.6.4 Gas Flow Rate or Pressure – An erroneous line feed was removed.

5.7 Maintenance – "a" was added before "fully" in the third sentence.

5.10.6 Adjustment – "Users" was changed to "Users'."

6.1 Ambient Conditions – A comma was deleted after "certain" and "the" was added before "DUT" in the second paragraph.

8.2.2 Report Contents (2) – "Customer" was changed to "User."

8.2.2 Report Contents (3) – "number" was added after "serial."

A1. Gas Flow Conversion/Correction – "provided In Table A.1" was added to "Some examples are" and the colon was deleted.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS C2 Committee on Thermal Spraying, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166.

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Specification for Thermal Spray Equipment Performance Verification

1. General Requirements

1.1 Scope. This standard describes the essential elements of a procedure to verify performance of equipment and systems used for thermal spraying. The equipment and systems include the thermal spray gun, gas console, control apparatus, and feedstock supply system. Other external systems and apparatus such as a gas or fuel management system, sound abatement, dust collection, automation, fire suppression, and finishing systems are beyond the scope of this document.

This specification does not address all of the thermal spray process variations or equipment configurations. However, the principles presented may be a starting point for establishing a customized verification procedure.

It is not the intent of this standard to address process validation; to ensure a process is producing, or capable of producing, desired coatings. This specification does not address all of the essential process variables necessary for thermal spray process qualification. This specification does not address equipment design standards, provisions, requirements, codes, or regulations that may apply to the thermal spray equipment or its installation.

The standard can be applied at the time of installation and any other times or intervals the User deems appropriate to ensure the equipment is capable of operating to the manufacturer's specifications or other specifications deemed applicable by the User.

1.2 Units of Measure. This standard makes use of both the International System of Units (SI) and U.S. Customary units. The latter are shown within brackets ([ ]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system must be used independently.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard; some safety and health information is provided, but such issues are not fully addressed herein.

Safety and health information is available from the following sources:

American Welding Society:

(1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

(2) AWS Safety and Health Fact Sheets

(3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

(1) Safety Data Sheets supplied by materials manufacturers

(2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous, and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments or revisions of the publications may not apply since the relevant requirements may have changed.

American Welding Society (AWS) standards:[1]

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions; Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included to accommodate usage specific to this document.

acceptance criteria. The standards a product or process must meet to successfully complete a test phase or to meet delivery requirements.

accuracy. The agreement between a measurement and the true or correct value.

adjustment. Setting or correcting the measured output of a device or system.

calibration. A documented process used to determine, under specified conditions, the performance parameters of a device or system by comparison to standards. Calibration may involve adjustment to assure results are produced, which meet or exceed some defined criteria with a specified degree of confidence.

calibration record. A calibration may be expressed by a calibration certificate, calibration curve, calibration diagram, calibration function, calibration table, deviation chart, or statement. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

certification. A documented statement, by authorized and qualified individuals, that an equipment/system validation, revalidation, qualification, re-qualification, or calibration has been performed appropriately with acceptable results.

Inspector. The individual or company who executes some or all of the thermal spray equipment performance verification specified by the User in accordance with this standard.

performance test. See **calibration.**

performance verification. Evaluation of an equipment, system, or process to ensure it will produce reliable and reproducible results when operated within a specified, predetermined set of parameters under normal production conditions.

precision. The minimum discernible change in the parameter being measured.

process gas. A gas or combination of gases, used to create combustion or a plasma, convey feedstock into the thermal spray gun, or propel the thermal spray feedstock from the thermal spray gun towards the substrate.

qualification. The characteristics or abilities gained through education, training, and/or experience, as measured against established requirements, such as standards or tests that qualify a person to perform a required function.

standard temperature and pressure (STP)**.** A specific value of temperature and pressure established to permit comparison of different sets of data. The STP values typically vary by standards organization and application.

uncertainty. An interval of confidence around a measured value expressing the certainty a measured value will not lie outside the stated interval.

User. The individual or company who specifies the thermal spray equipment performance verification be conducted and who has the authority to order it performed.

validation. Substantiation by examination and provision of objective evidence that verified processes, methods, and/or procedures are fit for their intended use.

verification. Confirmation by examination and provision of objective evidence that specified requirements have been fulfilled.

[1] AWS standards are published by the American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166.

4. Performance Verification Procedure

This standard establishes objectives, requirements, and procedures to verify specified thermal spray equipment performance. Appropriate application of this standard allows the User to minimize the risk of undetected equipment problems or variations which may affect its reliability, consistency, or safe use. The principle elements of the performance verification activity are: definition of the scope of work, establishing the timing, execution of the procedure, and documentation of the results.

4.1 Scope of Work. The principle reason for performance verification is to ensure the thermal spray equipment can operate within the established specifications. However, there can be a wide range of expectations for the verification procedure and they can have a great impact on the verification effort and cost, as well as the production availability of the equipment. The scope of work, including the performance verification requirements, procedures, acceptance criteria, and responsibilities of the parties, shall be clearly defined.

4.1.1 Process Capability Requirement. The User must consider the degree to which the capability for process reproducibility is required. If it is acceptable for machine settings to be machine specific, there may be minimal need for certification to a traceable standard. On the other hand, if there is a need to move work and parameters between different thermal spray equipment, standardization of the parameters could be essential. The degree of process capability required may be one of the following:

(1) Process Capable. Confirm the equipment can be adjusted within the range(s) defined by the manufacturer so desired coatings can be applied successfully.

(2) Process Repeatable. Ensure the equipment settings can be restored to known values, such as might be required to perform quick changeovers or to return to previous set values after long intervals or incidents which may have affected the settings or readings.

(3) Process Reproducible. Certify the equipment to known standards to ensure it is capable of being set to prequalified values, such as would be required if applying a prequalified thermal spray procedure or having consistent settings within a group of machines.

It might be ideal to have a calibrated device for the reading, adjustment, or measurement of every essential thermal spray variable, but this may involve costs that are not affordable or justifiable. The User should determine if the machine elements of the original equipment design are sufficient to give the level of process control required or desired. In the event some machine elements are insufficient for the application, an upgrade should be considered. On the other hand, it should also be determined if some of the machine elements serve as references only and do not require calibration or certification. In the end, the User must establish a scope of work congruent with the requirements of the equipment.

4.1.2 Verification Objectives. The extent of the performance verification effort is determined by the desire of the User to satisfy objectives which may include the following:

(1) Verify the equipment is in working order.

(2) Confirm the equipment performance and accuracy meet the manufacturers' specifications.

(3) Demonstrate equipment meets commercial, industry, or other established quality standards.

(4) Document each means of adjustment performs within specified standards of tolerance.

(5) Meet customer or standard requirements for periodic certification of calibration.

(6) Perform preventative maintenance.

(7) Maintain a record of equipment adjustment, maintenance, and service history.

(8) Support warranty claims.

4.1.3 Inspection Activities. The verification process will include procedures and tasks related to the activities listed below, and others as determined by the User, or recommended by the Inspector.

(1) General housekeeping

(2) Visual inspection

(3) Documentation of as-found and as-left conditions

(4) Inspection of the system's protective devices and components

(5) Calibration

(6) Preventive maintenance

(7) Identification and/or implementation of critical upgrades

(8) Preparation of a summary performance report

(9) Provision of operator or technician training

Each activity requires definition of objectives, expectations, specific tasks, and actions necessary if the foregoing cannot be completed within the terms of the agreement or contract. When calibration is specified, the method, tolerance, and location of performance should be described in detail since it can have a significant impact on the cost and timing of the work.

4.1.4 Records Retention. Any specific requirements for the retention, maintenance, and retrieval of documents shall be specified in the scope of work. The specification should include time interval requirements and obligations to protect, store, or destroy documents.

4.1.5 Communication of Scope. While a detailed written procedure or contract is preferred, the User will determine the format of communicating the scope of the performance verification activities.

4.2 Verification Schedule

4.2.1 General. The User shall determine the frequency and timing of the verification process necessary to ensure the thermal spray equipment is capable of operating reliably and consistently. A contract, code, standard, or quality procedure may establish timing requirements and means of execution. It could also establish whether all aspects of the performance verification need to be conducted at one time, location, or at a desired frequency or time interval.

4.2.2 Inspection Interval. Required inspection shall be performed at an interval of one (1) year or less, as determined by the User. The inspection timing may also be event triggered or based on input from the thermal spraying operator, thermal spray engineer, or individual with engineering or quality assurance authority. Examples of a triggering event are a substantial change in the equipment status, equipment upgrades and reconfiguration, or the occurrence of a production quality issue. Common status change events are: putting the equipment in service, including both new installations and reactivation after an extended shutdown, significant relocation, or extensive maintenance; and removing the equipment from service.

4.2.3 Calibration Interval. Required calibrations shall be performed at an interval of two (2) years or less, as determined by the User. When the equipment is used in applications requiring coating reproducibility, annual or more frequent calibration may be recommended by the equipment manufacturer or required by the customer or accreditation (e.g., National Aerospace and Defense Contractors Accreditation Program [NADCAP]) standard. Intervals shall be shortened or may be lengthened when the results of previous calibrations indicate such action is appropriate. Calibration may also be required if there is an incident which creates uncertainty such as contamination, damage, shock, replacement, or relocation of equipment.

4.3 Responsibilities

4.3.1 Responsibilities of the User. The primary responsibility of the User is to define the scope of work and provide other direction and guidance as may be required for the performance inspection to be conducted in a safe and efficient manner. Specific responsibilities and activities are as follows:

(1) Provide clear access to the equipment at the scheduled time.

(2) Communicate User safety policies and procedures.

(3) Provide an operator to run the equipment before the verification process to establish the as-found condition of the equipment.

(4) Provide an operator to run the equipment after the verification process to establish the as-left condition of the equipment.

4.3.2 Responsibilities of the Inspector. The Inspector shall conduct the activities specified by the User in the scope of work with professionalism and diligence. Specific responsibilities and activities are as follows:

(1) Review the scope of work to determine if the User performance expectations are consistent with the thermal spray equipment manufacturer's specifications.

(2) Provide all management, tools, supplies, equipment, and labor necessary to satisfy the verification process requirements defined in the statement of work.

(3) Ensure the test instrument(s) used for certification are within their calibration interval and traceable to known reference standards (see 5.10.3).

(4) When specific records retention requirements are not included in the scope of work (see 4.1.4), the document retention policies employed by the Inspector shall be either compared to the standard requirements of the User to ensure there are no conflicting specifications or communicated to, and accepted by, the User

(5) Upon request, produce records such as certificates, reports, or datasheets, attesting to the suitability of the tools, supplies, and equipment listed in 4.3.2(2) for the intended purpose.

(6) Be knowledgeable and take precautions as necessary to ensure actions will not harm or damage equipment (including voiding any warranties), production parts, or other materials and personnel in the area.

(7) Document set-up, calibration, and maintenance procedures, plus any specialized training required to perform the performance verification process.

(8) Identify any start-up, testing, or commissioning procedures that require User or operator observation or participation to establish a schedule so as to avoid duplication or delay.

(9) Analyze measurement data for identifying abnormalities, trends, and/or predicting future values.

5. Inspection Activities

The inspection activities and their order of performance are at the discretion of those specifying or performing the work.

5.1 Equipment Identification. The equipment must be properly identified by documenting the following items:

(1) equipment manufacturer

(2) model number

(3) serial number

(4) ID or location reference

(5) run time meter reading (if present)

(6) rated duty cycle

(7) configurable items such as powder feeder platen or feed wheel, orifice, or nozzle

5.2 General Housekeeping. The equipment and area must be free of obstructions and dirt, which will interfere with the inspection or increase the risk of introducing contamination into components or systems.

5.3 Visual Inspection. The thermal spray equipment shall be visually inspected to identify any issues which may require correction before proceeding with the procedure verification or a change to the inspection plan. The Inspector should look for and act on:

(1) any obvious signs of wear, damage, leaks, or contamination

(2) worn or frayed hoses, cables

(3) all authorized and unauthorized modifications

(4) missing or damaged labels

Action might be limited to documenting the condition. Issues requiring action should be addressed in the manner specified by the scope of work, or as mutually agreed with the User.

At this point in the verification process, it is a good time to verify adjacent activities will not expose equipment or the Inspector to hazards. The impact the Inspector's actions may have on other equipment or personnel in the area should also be considered and mitigated as appropriate.

5.4 As-found/As-left Condition. The Inspector shall determine the operating condition of the equipment, with the assistance of the operator if appropriate. This may involve operation of the equipment by the operator or Inspector. This is a good time for the Inspector to verify that the environmental and operating parameters are within the normal operating ranges specified by the equipment manufacturer. Some examples are supply voltage(s), ambient temperature, humidity, elevation, input water temperature. This shall be done before any maintenance, adjustments, calibrations, or repairs. The as-found operating parameters shall be recorded before the connection or installation of any instrumentation that may affect the as-found condition, and before any maintenance adjustments, calibrations, or repairs.

All of the as-found and as-left machine settings shall be recorded and all issues affecting operation (e.g., missing, disabled, defective, or faulty devices; gas contamination or leakage; insufficient cooling water or supply voltage) shall be documented, reported, and where appropriate, repaired. The Inspector should solicit the operator's input which would aid in the identification of any issues to be addressed during performance verification.

Upon completion of the equipment verification, the Inspector shall verify the system is functional before leaving the installation site. The Inspector shall provide the operator with information regarding the changes made or differences between the system reading and the calibration standard to enable the operator to adapt to any changes made. The Inspector may elect to keep some of the calibration apparatus or instrumentation in place while reviewing any issues or implemented changes with the operator if it aids the discussion. If not done previously, the Inspector shall report to the User any device which required major adjustment or replacement, and those equipment items for which repair and/or calibration were not possible under the terms of the inspection contract. The Inspector will make recommendations for those items which are not functional. If installed, calibration apparatus was left in place to review with the User or operator, an additional as-left cycle shall be run once these devices have been removed.

5.5 Equipment Isolation. If the thermal spray equipment has been integrated into a larger system, it may be necessary to take steps to isolate it from certain systems before performing performance verification. Usually the system integrator would have made accommodations and their established instructions or procedures should be followed. Otherwise, the Inspector will need to have a thorough understanding of the system and seek additional information required to make informed decisions.

If the thermal spray equipment or any component is isolated during a test the Inspector must exercise care to consider how such isolation may impact provisions for health and safety. For example, isolation from a larger system may prevent the activation of a ventilation system, curtains or shields, or fire suppression systems.

The thermal spray equipment shall be tested with all ancillary equipment fitted that could affect the test results.

5.6 Critical Systems Inspection. Systems provided for safe operation of the equipment shall be checked for proper function during the verification procedure.

5.6.1 Console Safeties. The safety functions of the console should be verified by following the manufacturer's procedures. Examples are, operating the emergency stop and purge valve(s).

5.6.2 Overtemperature. If the thermal spray equipment incorporates thermal protection, the manufacturer's instructions should be followed to verify the safety system is operational. This may involve restricting cooling fan airflow or disconnecting the fan to ensure the overtemperature condition is detected.

5.6.3 Insufficient Cooling Water. The proper orientation, connection, and operation of any water flow or water temperature sensors should be verified using the procedures and equipment recommended by the manufacturer.

5.6.4 Gas Flow Rate or Pressure. Before conducting any verification of a gas flow rate or pressure detection that may be part of the thermal spray system the Inspector must verify suitable flashback preventer(s) are properly installed and oriented. Once the flashback preventer(s) have been verified, the pressure and/or flow rate devices should be verified as directed by the equipment manufacturer. This may, for example, involve reducing a gas pressure regulator until insufficient flow or pressure is sensed by the equipment. Verification shall also include confirmation the meter or controller has been programmed or set to the proper gas type, heat transfer coefficient, or other scheme employed by the manufacturer of device.

5.7 Maintenance. Maintenance of the thermal spray equipment includes adjustment, service, and repair to address wear, deterioration, inoperability, etc. Examples of maintenance activities include the replacement of filters, worn gaskets, seals, nozzles, and electrodes. The objective is to return the equipment to a fully functioning state consistent with the manufacturer's specifications. Major repairs or equipment overhauls beyond the scope of the performance verification must be addressed to the User before the work is initiated. Replacement components affecting essential variables must be calibrated before a certification can be issued for the equipment.

5.8 Preventative Maintenance. It is beneficial to determine if there are outstanding or looming preventative maintenance activities that can be completed during the performance verification. Examples include the following:

(1) Filters. The recommended replacement frequency will depend on the manufacturer and application.

(2) Seals. Seals, for example in a feedstock feeder, may be subject to conditions that will affect the service life and require regular replacement.

(3) Flashback Arrestors. The recommended replacement frequency will depend on the manufacturer, but a common interval is five (5) years.

(4) Gas Analyzer/Detector Elements. Each type of sensor will present differing calibration and maintenance requirements. Some devices require sensor elements to be replaced as often as twice yearly and require regular calibration. Consult the manufacturer literature to develop calibration intervals, then follow regular maintenance and calibration procedures and conduct regular performance testing.

(5) Cables. The conductivity of cables in arc spray and plasma systems may deteriorate over time necessitating regular replacement to eliminate the possibility of undesired changes in the voltage and current.

5.9 Upgrades. The performance verification presents an opportunity to implement scheduled upgrades, including the replacement of components, which provide increased adjustment or precision. An example may be replacing a rotameter with a mass flow controller.

5.10 Calibration. The objective is to establish a means to relate a parameter to a standard having a stated accuracy or measurement uncertainty. Where the equipment component does not permit adjustment to establish a direct relationship between a reading, parameter, or measurement, the Inspector will have to present the calibration conversion factor in a chart, table, formula, or offset.

5.10.1 Calibration Scope. In general, every means of indication or method of adjustment having the potential to affect conformance to requirements should be verified. Where the reading or measurement is not important and the device does not require calibration, it should be tagged as "For Reference Only".

5.10.2 Calibration Precision. Thermal spray processes and process parameters vary in their tolerance to performance variations and will therefore dictate the precision of the equipment settings required. Unless otherwise specified in the scope of work or calibration standard, the calibration precision classification shall be designated for the thermal spray equipment. Table 1 establishes expectations for standard thermal spray equipment classifications.

Table 1
Standard Thermal Spray Equipment Classifications

Precision Classification[a]	Feedstock Feed Rate[d] (g/min)[b]	Gas Pressure[d]	Gas Flow[c, d]	Temperature[d]
A	±2	±1.5 %	±1.5 %	±1°C [2°F]
B	±5	±3 %	±3 %	±2°C [4°F]
C	±10	±5%	±5%	±3°C [5°F]

[a] The OEM may specify the acceptable tolerance of individual or full-scale values, or in some instances verification of both types of values will be required.
[b] g/min = grams per minute.
[c] % of setpoint. When % full-scale accuracy is specified in the contract, the values must also be specified.
[d] The minimum measuring instrument accuracy specified in 5.10.4 may be insufficient to calibrate to the accuracy specified.

5.10.3 Calibration Traceability. It is essential that all instruments, equipment, and reference standards used to calibrate in conformance to this standard have metrological traceability. This traceability requires the establishment of an unbroken chain of calibrations to specified intrinsic standards, particularly those of a national metrological lab. It is recommended that each testing and calibration laboratory in the chain of calibrations be accredited to a standard such as ANSI/NCSL Z540-1, *Calibration Laboratories and Measuring and Test Equipment—General Requirements* or ANSI/ISO/IEC 17025: *General Requirements for the Competence of Testing and Calibration Laboratories*.

There must be a means, such as a label or tag, establishing a link between each instrument, equipment, or reference standard used for calibration and the report or certificate attesting to its certification. The Inspector is responsible for reviewing the calibration documentation to ensure it is accurate before the instrument, equipment, or reference standard is put into service. Upon request of the User, the Inspector shall provide a copy of the documentation (report or certificate) identifying the calibration source, date of calibration, calibration assigned value, statement of uncertainty, and environmental or other conditions under which the calibration results were obtained. Records should also be available for inspection, which document the Inspector's established schedules and procedures followed to maintain the accuracy of the instrument, equipment, or reference standard.

5.10.4 Calibration Instrument Accuracy. An instrument used to determine if the device under test (DUT) is operating or calibrated to the manufacturer's specification shall have an accuracy and measurement uncertainty consistent with the quantity being measured. Generally, there should be between a 4:1 and 10:1 ratio between the instrument accuracy and the desired measurement. Unless otherwise agreed to by the User, the minimum accuracy of measuring instruments shall be as follows:

(1) electrical measuring instruments: ±0.5% of full-scale

(2) temperature measuring instruments: ±1°C [2°F]

(3) flow measuring instruments: ±1% of full-scale

(4) pressure measuring instruments: ±1% of full-scale

In the case of temperature measuring instruments, less precise instruments may be used to identify the optimum or required measurement location(s).

5.10.5 Calibration Procedure. The Inspector shall establish, document, and follow applicable calibration procedures. One source of metrology data, including calibration procedures and technical manuals for test and inspection equipment, is the Government-Industry Data Exchange Program (GIDEP). Qualified individuals can register for free access at: www.gidep.org.

If it is not possible to test or calibrate to the same STP conditions as a component was originally qualified to, it may be necessary to convert the calibration values, using a method such as the formulas in Annex A, or to send the component to a calibration source capable of replicating the conditions. If the component data is not available or there is the potential of an issue related to the STP values, the confusion shall be resolved with the User as necessary before implementation of the calibration procedure.

When calibrating a device across a range, it is preferred the measurements be taken at the upper and lower limits and at increments in between. When not otherwise specified in Clause 6, the minimum number of sample points during calibration shall be five (5).

The thermal spray equipment may not permit the production of calibrated readings such as current and amperage across the range necessary to calibrate display meters. In this case, a calibrated external signal may be used to check these meters using the procedure established by the manufacturer to isolate and protect the control system from the injected signal.

5.10.6 Adjustment. Assuming the element of the machine can be adjusted or tuned to maintain the precision classification specified, the double run calibration method will be used. In this method, an initial run will be performed without undertaking any adjustments (apart from user adjustments, i.e., setting zero) and these results will be recorded. If the initial results show the machine element fails to meet the manufacturer's published accuracy specification, adjustments will be performed with the Users' permission. The after adjustment results will also be recorded along with the performance deviation. This data will allow the long-term drift of the machine element to be monitored.

5.10.7 Calibration Record. The calibration error may be addressed by any method that provides the ability to compensate and correct the discrepancy. Examples are a curve, diagram, table, deviation chart or statement, additive or multiplicative correction function relating the equipment setting to the parameter. Whatever the form of communicating the required correction factor, it must be readily accessible and understandable to the persons who make the adjustments.

5.10.8 Indication of Calibration Status. Upon completion, a label (sticker) shall be affixed to each individual device calibrated showing the date of calibration, the calibration due date, and the Inspector performing the work. If a component cannot be adjusted to tolerance and requires repair beyond the scope of work, the Inspector is required to attach a rejection tag.

5.11 Supplemental Training. When required or desired, the Inspector may provide supplemental training related to the operation of the equipment. An example is to explain how to interpret and apply calibration corrections.

5.12 Performance Report. The Inspector shall prepare a summary report of the performance verification process, data, and results as soon as possible after completion of the field work. Unless otherwise specified by the User, the report shall be delivered within five (5) working days and include all of the elements specified in Clause 8 of this standard. Should there be unresolved issues that prevent successful completion of the verification process, the reasons and proposed resolutions shall be recorded in the report.

5.13 Follow-up. Should there be a need for follow-up actions as a result of postponed repairs, offsite calibrations, or reasons the verification process could not be resolved, the User and Inspector shall determine the effect on the equipment certification status. It might, for example, be agreed that an installation of a replacement certified component will not affect the certification of any other component and therefore the equipment certification will be considered completed once the User makes the installation and returns the equipment to production.

6. Process Controls

The thermal spray process requires control of many process variables critical to the application. The focus of this standard is to ensure the equipment is capable of controlling the equipment-related process variables as intended by the equipment manufacturer or thermal spray system integrator. Examples of equipment-related process variables include the following:

(1) input voltage

(2) gas flow rate and pressure

(3) input energy; for example, input current in amperes

(4) stabilization time

(5) feedstock feed rate, temperature, and velocity

(6) thermal spray equipment condition; for example, orifice, nozzle, or electrode wear

(7) process feedback; for example, spray temperature, particle velocity, acoustic emission, or coating thickness

Other process variables related to the substrate and feedstock, equipment setting values, and spray techniques are beyond the scope of this standard. Examples of these application process variables include the following:

(1) substrate preparation

(2) feedstock size distribution and quality

(3) standoff distance

(4) spray impingement angle

(5) travel speed

As there are many thermal spray processes, process variations, equipment configurations, and manufacturer recommended procedures, the information provided here is of a general nature.

6.1 Ambient Conditions. The ambient conditions must be known to ensure the equipment is being operated within its application limits and to understand how the individual equipment component performance, measurements, and calibration values will be influenced. Temperature and atmospheric pressure can have a significant effect on gas and fluid properties and thus affect thermal spray parameters. Humidity is likely not relevant to equipment operation in typical industrial application but may need to be addressed if operating in extreme conditions.

The terms standard temperature and pressure (STP) and normal temperature and pressure (NTP) are not always provided during application of this standard since they may create confusion about the values used for component or system calibration. If STP, NTP, or other similar acronym or terminology is used at any time, the values on which the standard is based shall be provided. The values of temperature and pressure used to calibrate various equipment components may not be consistent between devices or manufacturers. For example, a temperature of 0°C [32°F], 15°C [59°F], 20°C [68°F], 25°C [77°F] or other may have been used to calibrate the device under test (DUT). It is almost certain the calibration standard does not match the operating environment. Therefore, it is important to know what the standard is and how the difference between the measuring instrument and the DUT will affect the calibration.

Annex A provides formulas for comparing or converting values. Please note the gas property values provided for reference in Table A.2 are based on 0°C [32°F] and the values provided for reference in Table A.3 are based on 20°C [68°F].

When the as-found variance appears to exceed 2% and no obvious issues that might affect performance (e.g., mechanical problems, contamination, or leakage) are evident, the Inspector should take extra precaution before affecting changes to DUT. It is important to verify the error is not based on a mismatch of calibration standards prior to implementing significant changes or adjustments.

6.1.1 Ambient Temperature. Thermal spray processes utilize thermal and kinetic energy in the formation of coatings. Thermal efficiency of the process can be significantly affected by the ambient air temperature and other possible influences such as the process cooling water temperature.

6.1.1.1 Air Temperature. The equipment may be influenced by both the ambient air temperature and forced air cooling efficiency. The ambient air temperature is determined by taking at least two temperature measurements within 1 m [39 in] of the equipment during which the measuring instrument is protected from drafts and abnormal heating. The mean value of the temperature reading is the temperature of the ambient air.

In the case of forced air-cooled equipment, the measuring devices are placed where the air enters the cooling system. Where possible, temperatures are recorded while the equipment is in operation and after shutdown.

On those parts where the recording of temperature is not possible while the equipment is in operation, temperatures are taken after shutdown as described below. Whenever a sufficient time has elapsed between the instant of shutdown and the time of final temperature measurement to permit the temperature to fall, suitable corrections are applied to obtain as nearly as practical the temperature at the instant of shutdown. This may be done by marking the time at the instant of shutdown. Successive temperature readings are taken, and the elapsed time from shutdown noted for each. Plotting a minimum of four (4) temperature readings against time to determine the rate of cooling allows for extrapolation of the temperature at time of shutdown.

6.1.1.2 Coolant Temperature. Liquid-cooled thermal spray equipment shall be tested with liquid conditions as specified by the equipment manufacturer. The temperature measuring instrument or sensor shall be placed as close to the device under test as practical.

6.1.2 Atmospheric Pressure. The atmospheric pressure varies with the weather and with altitude. Consideration of the atmospheric pressure is not normally required unless there is a great deal of variation, or the operating altitude exceeds the manufacturer's recommended limit.

6.2 Input Voltage. The thermal spray equipment will generally accept a range of input supply voltages and the effect of the voltage fluctuations will depend on the type of equipment. It is most important to determine whether the input to the equipment has the capability to adversely affect the set electrical values. The voltage of the main electrical supply should be checked with a digital multi-meter (DMM), equivalent (e.g., analog voltmeter), or a suitable substitute (e.g., power analyzer) by measuring between appropriate test points. The line voltage measurement should be recorded for comparative purposes and if there are fluctuations; measurements should be taken at intervals to determine if the fluctuations might affect process stability. If the measured incoming line voltage is outside of the acceptable range established by the equipment manufacturer, the certification cannot be completed and the equipment should not be used until the source of the problem is determined and addressed.

6.3 Gases. Gases are widely used in thermal spray processes for heating, propulsion, and shielding.

Process heat may be produced by chemical reaction (combustion) or by physical reaction (plasma). Combustion generally involves oxygen and a fuel gas such as acetylene, hydrogen, natural gas, propane, or propylene. In plasma systems, a gas such as argon, nitrogen, hydrogen, or helium is ionized by an electric arc.

In both types of systems, the heat is determined in part by the gas pressure and velocity. In combustion systems, the heating value of the fuel gas and the oxygen to fuel ratio directly affect the temperature, volume of heat, or flame enthalpy.

The primary focus during performance verification is the flow rate of gases. Contamination of process gases will affect the process conditions such as combustion and plasma properties, and can significantly affect component calibration. Gas contamination can alter gas properties and affect the measurement of flow. Any leakage in the gas system should be identified and addressed during the inspection. Air containing moisture and other contaminates can be aspirated into the equipment at a site of leakage.

When working with gas systems, it is necessary to isolate components or interface instrumentation, it is essential to:

(1) Prevent the accumulation of fuel gases to ensure there is no potential for a concentration hazardous to persons or equipment.

(2) Ensure the equipment component(s) and instruments are appropriately bonded or grounded to prevent static or electric discharges that could cause combustion.

(3) Take all appropriate precautions to avoid contamination of the system with chemicals (oil, grease or sealants) or particles that can plug orifices or cause erosion.

6.3.1 Gas Substitution. It is preferred to use the standard process gas for the purposes of the verification since it will eliminate the need for conversion factors or formula. However, alternative gas may be employed for convenience, cost, safety, or to avoid contamination. The selection of an alternative gas or gases for performance verification should be done in accordance with an established procedure or work instruction. If such procedure or work instruction is not available, knowledge of value conversions is required to yield meaningful results, and the interaction of gases is necessary to avoid contamination or hazardous interactions.

The gas supplies provided for the acceptance tests shall be adequate in volume and meeting or exceeding the purity specified by the equipment manufacturer. Since the purity of the gas may influence the test results and the process, it may be preferable to use gases certified to a standard such as AWS A5.32M/A5.32 (ISO 14175 MOD), *Welding Consumables-Gases and Gas Mixtures for Fusion Welding and Allied Processes*, or the appropriate Compressed Gas Association (CGA) commodity specification.

6.3.2 Gas Pressure. Gas pressure measurement is generally accomplished with Bourdon- or diaphragm-type pressure gages or electronic pressure sensors. A manometer may be used for low-pressure measurement. Gage accuracies can range from ±10% full-scale to 0.1% full-scale, so it is important to know the capability of the gage being evaluated. All of these devices are verified by inserting a calibrated master gage in parallel and comparing several values. The reading in both types of gages results from the motion of a pressurized element which is subject to fatigue or hardening, and mechanical wear in service. Tapping on the face of the gage is not recommended as it will tend to falsify actual readings initially presented by the gage. Should it appear the gage has mechanical binding or other impediment, repair or replacement should be considered.

6.3.3 Gas Flow Rate. The apparatus employed to control and/or measure gas flow does so by either volumetric or mass flow principles. Conversion between volumetric and mass flow rates is possible if the material's density is known (refer to Annex A for Useful Gas Flow Calculations). In practice, this conversion is challenging because the density of a gas changes significantly with pressure, temperature, and composition. All meters are subject to contamination, degradation, and leakage as a result of coating, corrosion, cracking, erosion, or pitting. Therefore, regular inspection, validation, and calibration is required.

In addition to degradation, measurement error frequently results from improper device orientation, introduced back pressure, leaks, and visual interpretation. Meters that are influenced by gravity, such as the rotameter or coriolis flowmeter, may have different readings if repositioned. Programmable or adjustable meters may provide incorrect representation or scaling of flow if configured with an incorrect gas type, heat transfer coefficient, or other manufacturer specified variable. Pinched hoses, decreased standoff distance, or obstructed flows can increase the back pressure. Leaks can cause loss of process pressure or gas contamination due to aspiration of air into the process gas.

A typical calibration procedure would involve taking five (5) flow rate readings increasing across the meter range followed by five (5) readings decreasing across the meter range.

6.3.4 Gas Temperature. The measurement of gas temperature requires special consideration since the transfer of heat by convection from the gas to a temperature probe may be less than the radiative interchange of heat between the probe and the surrounding surface(s). Also, the heat distribution across a flow of gas is rarely uniform. The measurement technique recommended by the calibration instrument manufacturer should be followed.

6.4 Liquid-Fueled Systems. Fuels such as kerosene and alcohol may be piped into the thermal spray equipment and utilized in liquid form. Safe storage and leak containment are always concerns when working with such liquid fuels. Supply pressure and/or liquid flow are typically used to verify the liquid fuel delivery system. Verification of filter condition is important to ensure fuel flow is unimpeded. Annex B includes some useful physical property data for common process liquids.

A typical calibration procedure would involve taking five (5) to ten (10) pressure or flow rate readings increasing across the meter range followed by the same number of readings decreasing across the meter range.

6.5 Input Energy. The measure of input energy will depend on the thermal spray process. Measures such as total current, DC arc current, combustion temperature, and feedstock preheat are common.

6.6 Stabilization Time. The interval from spray initiation until the equipment is thermally stable with stable gas and feedstock flow is important for reliable thermal spray coatings. The stabilization time may be addressed by managing the individual process variables. It may be essential, especially if there is process automation, to have an understanding of the stabilization time.

6.7 Feedstock

6.7.1 Feedstock Feed Rate. Feedstock may be in the form of wire, rod, cord, powder, or liquid suspension so the feed rate will be determined by the means of conveyance. A typical method used to determine actual feed rate is to run the feeder for a known time while determining the quantity of feedstock amount by mass capture or mass loss. This measured feed rate may be correlated to drive roll, feed disk, or pump rotation speed measured with a tachometer. The feed rate may also be correlated to electrical arc current or air motor supply pressure. Load cells may be employed for mass loss feeders. It is important to ensure a false reading of the feed rate is not caused by leaks or misalignment of components.

6.7.2 Preheat Temperature. The temperature of feedstock may be established in the feeder and/or during transit between the feeder and the thermal spray gun. The certification instrument (e.g., thermocouple, I/R sensor) will depend on the temperature controller hardware or temperature feedback method employed.

6.7.3 Velocity. Thermal spray processes requires effective transfer of kinetic energy to the feedstock. A common measure of the effectiveness of this kinetic energy transfer is the feedstock velocity. However, there are many process variables influencing the feedstock velocity, such as feedstock powder or droplet size and shape, which do not relate to the calibration or performance of the thermal spray equipment. Feedstock velocity sensors or monitors cannot be used as a measure of equipment performance and should not be used for equipment calibration.

6.8 Process Feedback Sensors. Special process feedback sensors (e.g., in-flight particle temperature and velocity, acoustic emission, coating thickness) need to be evaluated by the procedures established by the manufacturer.

7. Process-Specific Considerations

7.1 Arc Spraying Systems

7.1.1 Wire Feeding Apparatus. Feed rolls, wire guides, and conduits should be inspected to verify they are not excessively worn or dirty and replaced if necessary.

7.1.2 Contact Tips. Contact tips should be inspected for wear and replaced as necessary.

7.2 Flame Spraying Equipment for Powder, Wire, Rod, and Cord (including HVOF)

7.2.1 Powder Injector. If present, the powder injector should be free from excessive wear.

7.2.2 Wire Feeding Apparatus. Feed rolls and wire guides should be inspected to verify they are not excessively worn or dirty and replaced if necessary.

7.2.3 Nozzle and Air Cap. The nozzle, and air cap if applicable, should be inspected or replaced if worn or damaged.

7.2.4 Hoses. Fuel gas and liquid-fuel hoses should be inspected for signs of deterioration or wear and replaced if necessary.

7.2.5 Sensors. Ensure water and/or flame sensors are properly installed and functional.

7.3 Plasma Spraying Equipment.

7.3.1 Cathode. Testing should be performed with a cathode (electrode) that is not blunted, mushroomed, or cracked. Where applicable, the electrode should be centered. Worn or damaged electrodes should be replaced.

7.3.2 Nozzles. Testing should be performed with a nozzle that is free from excessive wear, cracks, or oxide buildup. The powder port(s) should also not be excessively worn and replaced if necessary.

8. Reporting

8.1 Labeling. For the purposes of this clause, the words *label* and *tag* are synonymous.

8.1.1 Calibration Label. Upon completion, any old calibration label shall be replaced with a new one indicating the date of calibration, the next calibration due date, and the Inspector performing the work. These calibration labels should be in a conspicuous location that does not interfere with the operation or cover required markings. The labels shall be self-adhering, constructed of a durable material, and all markings shall be in permanent ink and legible.

8.1.2 Limited Calibration Label. When all functions or ranges are not calibrated, a supplemental "LIMITED CALIBRATION" label may be affixed describing the functions or ranges not calibrated.

Examples of Limited Calibration include:

(1) A component must be repaired or replaced before the calibration of the equipment is complete.

(2) The equipment has only been calibrated within a specified limited operating range or with a specific process gas.

8.1.3 Rejection Tag. The Inspector shall affix a Rejection tag to all rejected equipment. The Rejection tag shall be red and include the word "REJECTED" and include at least the following information: device model number and serial number, cause for rejection, Inspector's name, and date of rejection.

8.2 Report

8.2.1 Validity of Performance Report. The summary report shall be deemed valid for as long as all criteria of this specification are met.

8.2.2 Report Contents. At a minimum, the report shall include the following:

(1) Name and contact information of Inspector.

(2) User name and site information.

(3) Equipment description including, where appropriate: name, model, ID number, serial number, and location.

(4) A listing of the equipment used to achieve calibration to a traceable standard. The instrument type, brand, model, serial number, accuracy or uncertainty, and the calibration standard and status shall be identified.

(5) Factors and conditions that may have influenced the measurements.

(6) Description of principle components evaluated, including general description, make and range, device ID, serial number.

(7) As-found and as-left values for each system component evaluated.

(8) Reference to the calibration procedure used.

(9) Certification result.

(10) A statement of conformity to relevant specification(s).

(11) Details of any maintenance such as servicing, adjustments, repairs, or modifications carried out.

(12) Any limitations on use of the equipment.

(13) Identification of person(s) performing the calibration.

(14) Date of calibration.

(15) Due date of the next calibration.

8.2.3 Formatting. Where color is used to highlight the inspection results, a color key shall be provided at the point of use to aid in interpretation.

Annex A (Informative)
Useful Gas Flow Calculations

This annex is not part of this standard but is included for informational purposes only.

A1. Gas Flow Conversion/Correction

It may at times be necessary to convert gas flow values between different units of measure, to make adjustments for temperature, or to convert values for one gas type to another. The calculations and conversions can be complex. The properties given for typical thermal spray gases relate to specific gas conditions, which may be different than those of the equipment under test. Therefore, the results of the calculations and conversions given below are subject to uncertainty and should be regarded as approximations.

When conversion between units of measure is required, a general approximation may be sufficient. Some examples are provided in Table A.1.

Table A.1
Example Gas Flow Conversion Constants

To Convert				
From		To		
Unit	Temperature	Unit	Temperature	Multiply By
SLM	21°C [70°F]	SCFH	21°C [70°F]	2.11888
SLM	0°C [32°F]	SLM	21°C [70°F]	1.0773
SCFH	0°C [32°F]	SCFH	21°C [70°F]	1.0773
SCFH	21°C [70°F]	SLM	21°C [70°F]	0.471947
NLM	0°C [32°F]	SCFH	21°C [70°F]	2.283000255
NLM	0°C [32°F]	SLM	21°C [70°F]	1.077000008

where
SLM = Standard liters per minute
SCFH = Standard cubic feet per hour
NLM = Normal liters per minute

NOTE: The approximations are based on a gas pressure of 1 atmosphere (atm) (101.325 kPa [14.7 psia]).

A2. Ideal Gas Law

The ideal gas law relates the pressure, volume, and temperature of a gas to enable a desired value to be determined. Mass and density forms of the formula are provided below for ease of use. Typical values of the specific gas constant and density of gases used in the thermal spray process are included in Tables A.2 and A.3.

A2.1 Mass Form of Ideal Gas Law Equation. This formula provides a linkage between the pressure, volume, mass, and temperature of a gas.

$$PV = m\, R_s\, T$$

where
- P = Absolute pressure, Pa [lb/ft^2];
- V = Gas volume, m^3 [ft^3];
- m = Gas mass, kg [lb];
- R_s = Specific gas constant, J/kg K [ft lb/lb °R]; and
- T = Temperature of the gas, K [°R].

NOTE 1: Absolute pressure (P) = gage pressure + 101.325 kPa [14.696 lb/ft^2].
NOTE 2: K= °C + 273.15; °R = °F + 459.69.

A2.2 Density Form of Ideal Gas Law Equation. This formula provides a volume-independent linkage between pressure, density, and temperature of a gas.

$$P = \rho\, R_s\, T$$

where
- P = Absolute pressure, Pa [lb/ft^2];
- ρ = Density, kg/m^3 [lb/ft^3];
- R_s = Specific gas constant, J/kg K [ft lb/lb °R]; and
- T = Temperature of the gas, K [°R].

NOTE 1: Absolute pressure (P) = gage pressure + 101.325 kPa [14.696 lb/ft^2].
NOTE 2: K = °C + 273.15; °R = °F + 459.69.

Table A.2
Properties of Common Process Gases at 0°C [32°F][a]

		Density[b], ρ			Specific Gas Constant[c], R_s		Specific Heat[b], c_p		
Gas	**Molecular Weight, M kg/mol**	**kg/m^3**	**lb/ft^3**	**Dynamic Viscosity, μ Pa·s**	**J/kg K**	**ft lb/lb °R**	**kJ/kg K**	**Btu/lb °F**	**Specific Heat Ratio[d], k**
Acetylene, C_2H_2	0.02604	1.162	0.0725	9.54×10^{-6}	319	59.34	N/D	N/D	1.232
Air	0.02897	1.293	0.0807	16.95×10^{-6}	287	53.35	1.01	0.24	1.400
Argon, Ar	0.03995	1.782	0.1112	21.2×10^{-6}	208	38.65	0.522	0.125	1.667
Carbon Dioxide, CO_2	0.04401	1.964	0.1225	13.8×10^{-6}	188.9	35.10	0.815	0.195	1.289
Helium, He	0.00400	0.179	0.1111	18.7×10^{-6}	2077	386.3	5.204	1.243	1.667
Hydrogen, H_2	0.00202	0.090	0.0056	8.4×10^{-6}	4124	765.9	14.20	3.392	1.405
Methane, CH_4	0.01604	0.716	0.0447	10.4×10^{-6}	518.3	96.40	2.165	0.517	1.304
Natural Gas	0.01900	0.774	0.0483	N/D	500	79.10	N/D	N/D	1.270
Nitrogen, N_2	0.02801	1.250	0.0780	16.6×10^{-6}	296.8	55.15	1.039	0.313	1.400
Oxygen, O_2	0.03200	1.428	0.0891	19.2×10^{-6}	259.8	48.29	0.915	0.219	1.395
Propane, C_3H_8	0.04410	1.967	0.1228	7.5×10^{-6}	189	35.07	1.549	0.370	1.127
Propylene, C_3H_6	0.04208	1.810	0.1130	7.84×10^{-6}	180	36.80	1.426	0.341	1.150

[a] Values are approximate.
[b] Values given at 0°C [32°F] and 1 atm (101.325 kPa [14.7 psia]).
[c] N/D = Values corresponding to the temperature and pressure of this table have not been determined.
[d] The specific gas constant relates the specific heats for a calorically perfect gas and a thermally perfect gas. $R_s = c_p - c_v$; where c_p is the specific heat for a constant pressure and c_v is the specific heat for a constant volume.
[e] The specific heat ratio $k = c_p/c_v$; where c_p is the specific heat for a constant pressure and c_v is the specific heat for a constant volume.

Table A.3
Properties of Common Process Gases at 20°C [68°F][a]

Gas	Molecular Weight, *M* kg/mol	Density[b], ρ		Dynamic Viscosity, μ Pa·s	Specific Gas Constant[c], R_s		Specific Heat[b], c_p		Specific Heat Ratio[d], *k*
		kg/m³	lb/ft³		J/kg K	ft lb/lb °R	kJ/kg K	Btu/lb °F	
Acetylene, C_2H_2	0.02604	1.093	0.0682	10.22×10^{-6}	319	59.34	1.47	0.35	1.232
Air	0.02897	1.205	0.0752	18.1×10^{-6}	287	53.35	1.01	0.24	1.400
Argon, Ar	0.03995	1.661	0.1037	22.3×10^{-6}	208	38.65	0.520	0.12	1.667
Carbon Dioxide, CO_2	0.04401	1.842	0.1150	14.7×10^{-6}	188.9	35.10	0.844	0.21	1.289
Helium, He	0.00400	0.166	0.0104	18.7×10^{-6}	2077	386.3	5.19	1.25	1.667
Hydrogen, H_2	0.00202	0.084	0.0052	8.8×10^{-6}	4124	765.9	14.32	3.42	1.405
Methane, CH_4	0.01604	0.667	0.0417	10.33×10^{-6}	518.3	96.40	2.22	0.59	1.304
Natural Gas	0.01900	0.803	0.0502	10.95×10^{-6}	500	79.10	2.34	0.56	1.270
Nitrogen, N_2	0.02801	1.165	0.0727	17.4×10^{-6}	296.8	55.15	1.04	0.25	1.400
Oxygen, O_2	0.03200	1.331	0.0831	20.0×10^{-6}	259.8	48.29	0.919	0.22	1.395
Propane, C_3H_8	0.04410	1.881	0.1175	7.6×10^{-6}	189	35.07	1.549	0.39	1.127
Propylene, C_3H_6	0.04208	1.748	0.1091	8.7×10^{-6}	180	36.80	1.426	0.36	1.150

[a] Values are approximate.
[b] Values given at 20°C [68°F] and 1 atm (101.325 kPa [14.7 psia]).
[c] The specific gas constant relates the specific heats for a calorically perfect gas and a thermally perfect gas. $R_s = c_p - c_v$; where c_p is the specific heat for a constant pressure and c_v is the specific heat for a constant volume.
[d] The specific heat ratio $k = c_p/c_v$; where c_p is the specific heat for a constant pressure and c_v is the specific heat for a constant volume.

A3. Combined Gas Law

The combined gas law is useful for comparing the same gas under two different sets of conditions.

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

where

p_1 = Pressure at state 1, Pa [lb/ft²];
p_2 = Pressure at state 2, Pa [lb/ft²];
V_1 = Volume at state 1, m³ [ft²];
V_2 = Volume at state 2, m³ [ft²];
T_1 = Temperature at state 1, K [°R]; and
T_2 = Temperature at state 2, K [°R].

A4. Mass Flow Conversion

One method of converting the flow of a calibration gas to the standard flow rate of a different process gas is to use the following mass flow formula. The molecular weights of common process gases are included in Tables A.2 and A.3.

$$Q = \sqrt{\frac{(M_1 \cdot P_2 \cdot T_1)}{(M_2 \cdot P_1 \cdot T_2)}} \cdot F$$

where

M_1 = Molecular weight of calibrated gas, kg/mol;
M_2 = Molecular weight of gas flowing, kg/mol;
P_1 = Pressure of calibration gas, Pa [lb/ft²];

P_2 = Pressure of gas flowing, Pa [lb/ft^2];
T_1 = Temperature of calibration gas, K [°R];
T_2 = Temperature of gas flowing, K [°R];
F = Direct reading of flowmeter, m^3/min [ft^3/min]; and
Q = Standard volumetric gas flow rate, m^3/min [ft^3/min].

A5. Mass Flow Rate

To calculate the mass flow rate of a compressible gas through an orifice, the following formula can be used. Typical values of the gas density, molecular weight, and specific heat ratio of gases used in the thermal spray process are included in Table B.1.

$$\dot{m} = \rho_1 Q = C\ A_2 P_1 \sqrt{\frac{2M}{Z\ R T_1}\left(\frac{k}{k-1}\right)\left[(P_2/P_1)^{\frac{2}{k}} - (P_2/P_1)^{\frac{(k+1)}{k}}\right]}$$

where
$\dot{m}$ = Mass flow rate;
ρ_1 = Gas upstream density, kg/m^3;
Q = Volumetric flow rate, m^3/min;
C = Orifice flow coefficient, dimensionless;
A_2 = Cross-sectional area of the orifice hole, m^2;
P_1 = Gas upstream pressure, Pa;
M = Molecular weight of gas, kg/mol;
R = Universal gas constant = 8.3145 J/(mol•K);
T_1 = Absolute upstream gas temperature, K;
k = Specific heat ratio, dimensionless; and
P_2 = Gas downstream pressure, Pa [lb/ft^2].

NOTE: For rough approximations, an orifice flow coefficient (C) between 0.60 and 0.75 may be used. A value of 0.62 will give an approximation of fully developed flow.

A6. Laminar Flow Conversion

The relationship between pressure drop and flow in laminar flowmeters is linear. Within the operating range of a typical meter, the dynamic (absolute) viscosity of a gas changes very little. Therefore, the conversion factor required to measure the flow of different gases is linear and determined simply by the ratio of the viscosity of the gases. Typical values of dynamic (absolute) viscosity of gases used in the thermal spray process are included in Tables A.2 and A.3. This comparative flow rate for two different gases can be approximately calculated as follows:

$$Q_{ag} = Q_{cg}\ [\mu_{cg}/\mu_{ag}]$$

where
Q_{cg} = Flow rate indicated by the flowmeter with the calibrated gas, m^3/min [ft^3/min];
μ_{cg} = Dynamic viscosity of the calibrated gas at the measured temperature, Pa·s;
Q_{ag} = Flow rate of the alternate gas, m^3/min [ft^3/min]; and
μ_{ag} = Dynamic viscosity of the alternate gas at the measured temperature, Pa·s.

Annex B (Informative)
Liquid Properties

This annex is not part of this standard but is included for informational purposes only.

Table B.1
Properties of Common Process Liquids

Liquid	Density, ρ		Specific Heat		Vapor Pressure, Vp		Boiling Point		Vapor Density, Vd	Viscosity	
	kg/m^3	lb/ft^3	kJ/kg·K	Btu/(lb·°F)	kPa	mmHg	°C	°F		Pa·s	lbf·s/in^2
Alcohol, ethyl (ethanol)	789.2	49.3	2.84	0.678	5.87	44	78	173	1.49	1.198×10^{-3}	0.174×10^{-6}
Kerosene	820	51.2	2.00	0.478	0.5	3.75	204–293	399–560	0.79	2.71×10^{-3}	0.393×10^{-6}
Water	998.2	62.3	4.19	1.001	2.34	17.5	100	212	1.61	1.003×10^{-3}	0.145×10^{-6}

Note: Values given at 20°C [686°F] and 1 atm (101.325 kPa [14.7 psia]).

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Annex C (Informative)
Informative References

This annex is not part of this standard but is included for informational purposes only.

ASM Handbook of Thermal Spray Technology, ASM International.

ASTM D3195/D3195M: *Standard Practice for Rotameter Calibration*, ASTM International.

ASTM E2847: *Standard Practice for Calibration and Accuracy Verification of Wideband Infrared Thermometers*, ASTM International.

AWS A5.32M/A5.32 (ISO 14175 MOD), *Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes*, American Welding Society.

CGA-G4: *Oxygen*, Compressed Gas Association.

CGA-G5: *Hydrogen*, Compressed Gas Association.

CGA-G6: *Carbon Dioxide*, Compressed Gas Association.

CGA-G6.3: *Carbon Dioxide Cylinder Filling and Handling Procedures*, Compressed Gas Association.

CGA-P-1: *Safety Handling of Compressed Gases in Containers*, Compressed Gas Association.

CGA-P-9: *The Inert Gases: Argon, Nitrogen, and Helium*, Compressed Gas Association.

ISO 17662: *Welding——Calibration, verification, and validation of equipment used for welding, including ancillary activities,* International Organization for Standardization.

ISO 11095: *Linear calibration using reference materials,* International Organization for Standardization.

NFPA 51B: *Standard for Fire Prevention During Welding, Cutting, and Other Hot Work,* National Fire Protection Association.

SG001-02: *Safety Guidelines for the Handling and Use of Gases in Thermal Spraying*, ASM International.

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Annex D (Informative)
Requesting an Official Interpretation on an AWS Standard

This annex is not part of this standard but is included for informational purposes only.

D1. Introduction

The following procedures are here to assist standard users in submitting successful requests for official interpretations to AWS standards. Requests from the general public submitted to AWS staff or committee members that do not follow these rules may be returned to the sender unanswered. AWS reserves the right to decline answering specific requests; if AWS declines a request, AWS will provide the reason to the individual why the request was declined.

D2. Limitations

The activities of AWS technical committees regarding interpretations are limited strictly to the interpretation of provisions of standards prepared by the committees. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on (1) specific engineering problems, (2) requirements of standards applied to fabrications outside the scope of the document, or (3) points not specifically covered by the standard. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

D3. General Procedure for all Requests

D3.1 Submission. All requests shall be sent to the Managing Director, AWS Standards Development. For efficient handling, it is preferred that all requests should be submitted electronically through standards@aws.org. Alternatively, requests may be mailed to:

Managing Director
Standards Development
American Welding Society
8669 NW 36 St, # 130
Miami, FL 33166

D3.2 Contact Information. All inquiries shall contain the name, address, email, phone number, and employer of the inquirer.

D3.3 Scope. Each inquiry shall address one single provision of the standard unless the issue in question involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the request along with the edition of the standard (e.g., D1.1:2006) that contains the provision(s) the inquirer is addressing.

D3.4 Question(s). All requests shall be stated in the form of a question that can be answered 'yes' or 'no'. The request shall be concise, yet complete enough to enable the committee to understand the point of the issue in question. When the point is not clearly defined, the request will be returned for clarification. Sketches should be used whenever appropriate, and all paragraphs, figures, and tables (or annexes) that bear on the issue in question shall be cited.

D3.5 Proposed Answer(s). The inquirer shall provide proposed answer(s) to their own question(s).

D3.6 Background. Additional information on the topic may be provided but is not necessary. The question(s) and proposed answer(s) above shall stand on their own without the need for additional background information.

D4. AWS Policy on Interpretations

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all official interpretations are approved by the technical committee that is responsible for the standard. Communication concerning an official interpretation is directed through the AWS staff member who works with that technical committee. The policy requires that all requests for an official interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the procedures that must be followed, some requests for an official interpretation may take considerable time to complete.

D5. AWS Response to Requests

Upon approval by the committee, the interpretation is an official interpretation of the Society, and AWS shall transmit the response to the inquirer, publish it in the *Welding Journal*, and post it on the AWS website.

D6. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning AWS standards should be limited to questions of a general nature or to matters directly related to the use of the standard. The *AWS Board Policy Manual* requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

List of AWS Documents on Thermal Spray

Designation	Title
C2.16/C2.16M	*Guide for Thermal Spray Operator Qualification Programs*
C2.18	*Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and their Alloys and Composites*
C2.19/C2.19M	*Specification for the Application of Thermal Spray Coatings to Machine Elements for OEM and Repair*
C2.20/C2.20M	*Specification for Thermal Spraying Zinc Anodes on Steel Reinforced Concrete*
C2.21M/C2.21	*Specification for Thermal Spray Equipment Performance Verification*
C2.23M/C2.23	*Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel*
C2.25/C2.25M	*Specification for Thermal Spray Feedstock—Wire and Rods*

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