Designation: A1100 – 16

Standard Guide for Qualification and Control of Induction Heat Treating[1]

This standard is issued under the fixed designation A1100; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the process control and product properties verification of continuous heat treating of material using a quench and temper induction process (surface hardening, surface heat treating, and batch heat-treated products using induction are not considered in this guide). Examples of products covered by this guide may include products covered by API Specifications 20E, 5L, and 5CT.

1.2 This guide indicates some features of induction heat treating compared to furnace heat treating. Induction heat treating processes typically operate at higher temperatures compared to furnace processes.

1.3 This guide addresses the features and requirements necessary for induction heating and ancillary equipment. However, induction equipment may be used in combination with convection heating equipment (for example, gas or electric furnaces).

1.4 *Units*—The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A255 Test Methods for Determining Hardenability of Steel
A751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
A941 Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys
A1058 Test Methods for Mechanical Testing of Steel Products—Metric
E7 Terminology Relating to Metallography
E10 Test Method for Brinell Hardness of Metallic Materials
E18 Test Methods for Rockwell Hardness of Metallic Materials
E112 Test Methods for Determining Average Grain Size
E384 Test Method for Microindentation Hardness of Materials

2.2 *ASM Standards:*[3]

ASM Handbook Volume 4C Induction Heating and Heat Treatment

2.3 *API Specifications*[4]

20E Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries
5CT Specification for Casing and Tubing
5L Specification for Line Pipe

2.4 *ANSI Standard:*[5]

ANSI/NCSL Z540.3 Requirements for the Calibration of Measuring and Test Equipment

3. Terminology

3.1 For definitions of terms used in this guide, refer to Terminologies A941 and E7.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *induction heat treating, v*—process by which an electromagnetic field is used to induce a voltage in an electrically conductive material thereby causing current flow and heat is generated in the electrically conductive material through the Joule heating effect. (See ASM Handbook 4C, p. 18.)

3.2.2 *major rebuild, n*—any rebuild or repair that could alter the temperature uniformity characteristics of an induction heat treat line.

3.2.3 *product, n*—set of similar materials to be heated by passing through induction coils under the same conditions as defined in 6.3 process variables. (Including as examples bar, rod, tube, pipe.)

[1] This guide is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.22 on Steel Forgings and Wrought Fittings for Piping Applications and Bolting Materials for Piping and Special Purpose Applications.

Current edition approved Nov. 1, 2016. Published December 2016. DOI: 10.1520/A1100-16.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society for Metals (ASM International), 9639 Kinsman Rd., Materials Park, OH 44073-0002, http://www.asminternational.org.

[4] Available from American Petroleum Institute (API), 1220 L. St., NW, Washington, DC 20005-4070, http://www.api.org.

[5] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

3.2.4 *quench media, n*—coolant used to quench out the work piece.

3.2.4.1 *Discussion*—Typically, it contains water or water and a polymer-based quench media.

3.2.5 *refractometer, n*—device used to measure the concentration of quench media that is mixed with water.

3.2.5.1 *Discussion*—Typical units are in degrees Brix and are approximately equivalent to half the volume concentration.

3.2.6 *sensors, n*—need to identify the type of sensors as they are already in some standards.

3.2.7 *skin depth, n*—also called depth of current penetration; the depth to which an alternating current will flow in a conductor. (See Appendix X3.)

4. Significance and Use

4.1 This guide helps purchasers assess induction processes including the critical parameters that can affect product quality. It guides the evaluation of heat-treating vendor performance and capabilities to ensure higher and more consistent product quality.

4.2 Refer to Appendix X1 for a flow chart for the use of this guide.

5. Equipment

5.1 *Equipment Capabilities*—Equipment used to produce the desired heat-treated product shall be capable of achieving target heat-treat parameters. Parameters shall be documented as per Section 6, and Section 7 shall be used to verify that the manufacturing procedure has been well developed, proper parameter tolerances have been selected, and equipment is capable of achieving all parameter settings. Documented procedures for the verification of equipment capabilities, calibration, and maintenance shall be maintained. These documented procedures shall address all critical equipment for the induction heat treatment line including, at minimum, the following:

5.1.1 All power supply units including relevant components,

5.1.2 All induction coils,

5.1.3 Quench system and components,

5.1.4 Pyrometers and other temperature-sensing devices,

5.1.5 Material handling as it pertains to line speed control, and

5.1.6 Controls.

5.2 The documented procedures shall address verification, calibration, and maintenance of the equipment as described in the following.

5.3 *Verification and Calibration of Equipment*—Equipment for the heat-treating line shall be verified and calibrated at a level necessary to achieve the tolerances determined in Section 6. It is recommended that calibration of test equipment follow the guidelines in ANSI/NCSL Z540.3. Equipment capabilities are related to the product chemistry, product dimensions, and production rate. It is possible that different products may require different tolerance ranges for parameter settings. These tolerance ranges shall be documented as part of the manufacturing procedures (Section 6). Classification and characterization of a heat-treat line based on equipment accuracy ranges and equipment capabilities may be conducted using the method described in Appendix X4. It is recommended that verification of equipment performance be conducted with heated product. Cold tests (for example, testing material handling, sensors, and controls) are useful, but equipment on an induction heat treating line may behave differently with heated product.

5.3.1 *Power Supply Units:*

5.3.1.1 The power supply units shall be capable of achieving the rated power and nominal frequency designated for the equipment by the manufacturer. Heating capabilities to achieve target temperatures should be verified at the point of installation of new power equipment, including ancillary equipment and devices such as connecting power cables and induction coils, and records of these capabilities should be kept (see 9.1).

NOTE 1—The output power is a function of the voltage and current of the electrical system. If voltage or current is limited (because of high inductance, for example), the maximum power will be limited. For this reason, it is important to ensure that the power supply is evaluated with the induction coil and desired product so that accurate power capabilities are determined.

5.3.1.2 The power level for any given manufactured product may be selected at the heat treater's discretion to achieve the necessary target manufacturing procedure parameters. The output power stability should be monitored at regular intervals to ensure sufficient power stability to achieve the tolerance levels documented in Section 6. Incoming power to the plant can affect output power stability; therefore, incoming power may be monitored to ensure consistent output power capabilities. Various power quality measuring devices are available for monitoring incoming plant power and output power during operation.

5.3.1.3 The frequency at each induction coil should be verified and documented within each manufacturing procedure to ensure heating consistency. Periodic checks of the frequency at the induction coils should be conducted.

NOTE 2—The frequency is affected by the power level and the inductance of the system. Changes to the coil design, size of product, cooling media through the coil, current/voltage ratio, coil cable connections, and other factors can affect the frequency at the output coil. Changes in the output frequency can affect the depth of the induced current in the work piece (skin depth) and, therefore, the thermal gradient within the work piece (see Appendix X3). Frequency can be measured using most standard multi-meters.

5.3.1.4 It is not expected that power supply units will require calibration unless otherwise stipulated by the manufacturer of the equipment. Calibration and verification shall follow the manufacturer's recommended schedule or the schedule outlined in Table 1, whichever is more frequent.

5.3.2 *Induction Coils*—Induction coils are an important part of the power supply units. The verified power output and voltage/current match depend on the interconnection of coils and power supply units. For example, connecting coils in series or parallel to a power supply may significantly affect efficiency, inductance, and overall ability to heat the product. Verification of equipment should include consideration of coil connections and interconnect wiring functionality. Reverification of output power capabilities should occur after any changes to the coil designs or the interconnections. In the instance of multiple

TABLE 1 Verification and Calibration Frequency

	Parameters/Features to Verify	Event	Reverification Frequency[A]
Power Supply	• Power Stability • Nominal frequency range	After installation/commissioning of new power supply unit	Once per year
		Creation of a new MP[B]	At time of new MP verification
		After major rebuild[C] of equipment	Once per year
Induction Coils	• Visual inspection of interconnect wiring and coil connections	After installation/commissioning of new coils	Once per year
		After major rebuild of equipment	Once per year
Quench	• Composition	Installation/commissioning of new quench system or component; after flushing quench system	Monthly
		Mill startup	After system remains dormant for more than 14 days
		Creation of new MP	At time of new MP verification
	• Flow	Installation/commissioning of new quench system or component	Once every 3 months for first year, annually thereafter
		Creation of new MP	At time of new MP verification
Pyrometers	• Temperature accuracy	Installation of new pyrometer	Once every 3 months for first year, annually thereafter[D]
		Pyrometer is sent out for repair	Once every 3 months for first year, annually thereafter[D]
		Pyrometer is exposed to conditions not recommended by the manufacturer	After each event
Line Speed	• Speed	Installation of new drive equipment or measurement device[E]	Once every 6 months for first year, annually thereafter
		Major rebuild or repair of drive equipment or measurement device	Once every 6 months for first year, annually thereafter

[A] Verify parameter at time of "event" and after initial verification follow this frequency.
[B] MP = Manufacturing procedure.
[C] See Note 5.
[D] The use of a master pyrometer for verification is recommended.
[E] Line speed measurement device may include tachometer, laser velocimeter, or other suitable means to determine line speed of product.

induction coil designs on the same line, all coils will be properly identified, and design/model number will be specified in the manufacturing procedure.

5.3.3 *Quench System:*

5.3.3.1 Quench media composition shall be documented for every manufacturing procedure. Composition may include documentation of polymer chemistry, supplier, age, brine concentration, water chemistry, and so forth as applicable. Verification of quench media composition, if applicable, shall be conducted at the interval specified in Table 1. Use of a refractometer is recommended, when applicable, to determine the concentration at the start and during the operation. Note that quench media compositions are also affected by waste material in the quench (that is, scale, rust, and so forth). It may be necessary to periodically discard and replace quench media as it becomes contaminated with minerals, oil, scale, rust, and other undesirable materials. The frequency of this refreshing of the quenchant depends on results from periodic monitoring of quenchant chemistry.

5.3.3.2 Quench flow rate shall be verified periodically according to the schedule in Table 1 using a method suggested by the equipment manufacturer or selected by the producer and described in a documented procedure maintained by the heat treater.

5.3.4 *Pyrometers:*

5.3.4.1 Pyrometers shall be placed at positions along the heat treat line to establish heating rates and soak times accurately, as appropriate for the application. Pyrometer position shall be consistent and recorded (see 9.1).

5.3.4.2 Pyrometer calibration by the pyrometer manufacturer typically entails calibration using a blackbody furnace under highly controlled conditions. The tolerance and accuracy of a pyrometer on a heat-treat mill can be significantly reduced compared to measurement of a blackbody furnace in laboratory conditions. The tolerance and accuracy for each pyrometer shall be provided by the pyrometer manufacturer based on the target material composition and temperature for the pyrometer application. In addition, it is recommended that pyrometer accuracy be verified during production with the use of a "master" pyrometer. The master pyrometer may be a hand-held or other unit in which the accuracy of the device has been verified off-line using a target material with similar surface finish, composition, temperature, and ambient conditions compared to the heated product. Temperature accuracy of the master pyrometer is typically verified through the use of thermocouples attached to the off-line target material. Comparison to the master pyrometer should not be considered a replacement for regular calibration of the on-line pyrometers, which should be performed according to the manufacturer's specification. Records of pyrometer calibration and verification shall be maintained (see 9.1). Calibration and verification should follow the manufacturer's recommended schedule or the schedule outline in Table 1.

NOTE 3—Proper selection of an appropriate pyrometer technology is essential to ensuring the accuracy. Single-wavelength pyrometers are most common, but also least accurate. Higher accuracy can typically be achieved with shorter wavelength pyrometers, but pyrometer accuracy is also highly influenced by the emissivity setting. Additional information on pyrometer technologies is provided in X4.1.

5.3.5 *Verifying Line Speed*—Line speed and product rotation are critical parameters that affect the heating and cooling rates as well as the soak time. Line speed shall be documented in the manufacturing procedure as described in 6.3.4. Verification and calibration of material-handling capabilities should include a means for verifying line-speed measuring devices as well as synchronization of rolls and drives (that is, gap control). Synchronization of driven rolls becomes critical for control of uniform rotation of product and control of gaps between products to minimize end effects during heating (see Appendix X3 for additional information on end effects). Methods for verification and calibration of material-handling equipment shall follow the equipment manufacturer's instructions and may include the use of a calibrated off-line measurement device such as a laser velocimeter or other suitable device. Verification of line speed should be conducted at multiple locations along the heat treat line (for example, entry, austenitizing section, tempering section, and so forth) taking into account thermal expansion of the product, as applicable. Calibration and verification records shall be maintained (see 9.1) and shall follow the manufacturer's recommended schedule or the schedule outline in Table 1, whichever is more frequent.

5.3.6 *Controls:*

5.3.6.1 Functionality and calibration of controls should be verified during installation and after any major rebuild (see Note 5) to the heat-treat line and performed according to the equipment manufacturer's recommendation.

5.3.6.2 The heat-treat producer shall have a documented procedure that addresses the verification and maintenance of the controls for each qualified line according to the guidelines of Table 1 or the equipment manufacturers' recommendation, whichever is more stringent.

5.3.7 *Maintenance*—The heat-treat producer shall have a documented and fully implemented preventive maintenance procedure that addresses the following equipment and follows the manufacturer's recommendations:

5.3.7.1 Material handling,

5.3.7.2 Induction coils,

5.3.7.3 Power supply units,

5.3.7.4 Quench systems including regular inspection and cleaning of spray nozzles and maintenance of pumps, and

5.3.7.5 Pyrometers.

6. Procedure

6.1 *Manufacturing Procedure*—A manufacturing procedure shall be established and maintained as a record (see 9.1) by the heat treater for each product. The manufacturing procedure shall include details of the process variables outlined in 6.3.

NOTE 4—Although API 20E also outlines a "manufacturing procedure" with similar elements, the procedure described here is separate and distinct with no intention to exactly match the format of API Specification 20E.

6.2 *Manufacturing Procedure Qualification*—The manufacturing procedure shall be qualified through product testing as described in Section 7. Product testing as described in Section 7 may also be used to establish the tolerance ranges for the process variables in the manufacturing procedure. Requalification of the manufacturing procedure is required for any major rebuild of the equipment.

NOTE 5—Examples of items that constitute a major rebuild that could change the temperature uniformity characteristics include, but are not limited to: (*1*) Changes in induction coil design or placement; transformer design changes; inverter component changes; or changes to connecting power cables to, between, and from power supply units and coils; (*2*) Changes in the location, type, or manufacturer of temperature-measuring devices; (*3*) New designs for components used to convey parts through the process; and (*4*) Changes to the quench media, design, or position or changes to the quench plumbing that may impact the exit flow and pressure of quenchant.

6.3 *Product and Process Variables*—The manufacturing procedure may be structured in a format determined by the heat treater provided that it contains details on the process variables as stipulated in 6.3.1 – 6.3.9. Tolerances for each process variable are determined by the heat treater based on each individual product physical property requirements.

6.3.1 *Product Composition*—Nominal composition, steel grade, or range of chemistries for any given product shall be included in the manufacturing procedure.

6.3.2 *Product Dimensions*—Nominal dimensions or range of dimensions shall be listed for the manufacturing procedure. Dimensions shall include length, outside diameter and, in the case of tube and pipe, wall thickness and inside diameter.

NOTE 6—Wall thickness variations may require power and line speed adjustment to maintain target temperature.

6.3.3 *Product Prior Microstructure*—Prior microstructure or thermal processing method may be included in manufacturing procedure at the heat treater's choice.

6.3.4 *Line Speed*—Line speed for each stage of the heat-treat process and methods for its verification shall be included in manufacturing procedure. The method for measuring and verifying the line speed shall be described in the manufacturing procedure. The device(s) used to measure the line speed shall be calibrated and maintained as described in 5.3.5.

6.3.5 *Austenitizing*—Target temperature and respective tolerances for austenitizing shall be included in the manufacturing procedure. It is the temperature at which the product is held before quenching. The method for verifying the target temperature shall be described in the manufacturing procedure. The time that product is held at the target austenitizing temperature shall be included in the manufacturing procedure. This may be recorded as a combination of distance (length of coils, number of coils, and space between coils) and line speed or total time at target temperature. Verification of adequate austenitizing soak time may involve the use of in-line or handheld temperature measurement devices (for example, a master pyrometer), modeling and simulation, metallurgical evaluation, or other means at the heat treater's choice.

6.3.6 *Quench Media*—The quench media type (for example, water, oil, emulsions, mill coolant compositions) and the quench media temperature shall be included in the manufacturing procedure. The quench media temperature may be measured at a location convenient to the manufacturer; however, this location shall be consistent to ensure reliable process monitoring.

6.3.7 *Quench Flow and Pressure*—The flow rate and pressure of the quenchant shall be included in the manufacturing procedure, or as an alternative, the as-quenched hardness of the product shall be measured to demonstrate that the flow and pressure are adequate to achieve the desired martensitic transformation.

6.3.8 *As-Quenched Product Temperature*—The target temperature or temperature range at the exit of the quench section shall be included in the manufacturing procedure. The method for verifying the target temperature or temperature range shall be described in the manufacturing procedure. As an alternative, the as-quenched hardness of the product may be measured.

6.3.9 *Tempering*—Target temperature and respective tolerances for tempering shall be included in manufacturing procedure. It is the temperature at which the product is held before exit from the tempering section. The method for verifying the target temperature shall be described in the manufacturing procedure. Time that product is held at the target-tempering temperature shall be included in the manufacturing procedure. This may be reported as a combination of distance (length of coils, number of coils, space between coils) and line speed or total time at target temperature. Verification of adequate tempering soak time may involve the use of in-line or handheld temperature measurement devices (for example, a master pyrometer), modeling and simulation, metallurgical evaluation, or other means, or combinations thereof, at the heat treater's choice.

7. Manufacturing Procedure Validation Testing Requirements

7.1 Upon creation of a new manufacturing procedure, testing should be performed and records maintained (see 9.1) to establish the adequacy of a manufacturing procedure and determine acceptable tolerance ranges for the manufacturing procedure process variables. This testing should be repeated only if the manufacturing procedure is modified or after a major rebuild as outlined in Note 5.

7.2 *Chemical Analysis*—Chemistry of the product should be known. Chemical analysis should be performed in accordance with Test Methods, Practices, and Terminology A751 or a corresponding national standard with all intentionally added and residual elements reported. These analyses are not necessarily performed by the heat treater, and chemistry specifications or heat analyses provided by product supplier are sufficient.

NOTE 7—Ideal diameter (DI) values (measured or calculated based on chemical analysis per Test Method A255 methods) are very useful for each heat-lot material hardenability evaluation. Capability of each lot of material to achieve the required final properties for each size/grade/class of final product should be carefully considered based on reported chemistry, DI, and prior conditions. Test Method A255-calculated DI values are based on average grain size—7 typical for as many as-rolled, fully killed steels with grain refiners such as Al, Nb/Cb, and others. Larger grains tend to increase DI, while smaller result in somewhat lower hardenability.

7.3 *Mechanical Properties:*

7.3.1 Hardness, tensile, and Charpy impact testing of finished product should be used as applicable to validate each product manufacturing procedure and establish acceptable tolerance ranges for process variables. Test Methods A1058 or other suitable standard should provide guidance on these test methods.

7.3.2 Cross-sectional hardness checks on larger diameter bars and thick-walled tube with DI values indicating material limitations for through-hardening can provide valuable data on depth of martensitic transformation and through thickness uniformity of mechanical properties. Test Method A255 may be used for checking hardenability during the creation of a new manufacturing procedure or as a verification step during production.

7.3.3 When performed, bulk hardness measurements may be conducted in accordance with internationally recognized Test Methods such as E10 or E18, as appropriate. Microhardness measurements may be conducted in accordance with Test Method E384. Hardness measurements should be taken in opposite quadrants of a sample cross section and along a sample length as indicated in Fig. 1 to verify process consistency and proper selection of process variables for the established manufacturing procedure. Once a manufacturing procedure is verified, hardness testing should be conducted as required for product specification or purchase agreement as appropriate. For certain materials and products it may be necessary to perform full circumference, through thickness hardness testing. Refer to the standards and requirements for the individual product testing requirements.

7.4 *Metallurgical Evaluation*—Depending on the heat-treating requirements, microstructural evaluation may be used for verification of prior austenite grain size, final grain size (Test Methods E112), martensite transformation depth and completion (on an "as-quenched" sample), or the effects of tempering. (**Warning—**Depending on carbon content, very high stresses (1379 MPa and above) could be present in "as-quenched" samples. Special cutting and grinding equipment and handling care may be necessary to safeguard against unexpected release of internal stress in the material during sample preparation.)

7.5 *Dimensional and Visual Inspection*—As with all heat-treated products, dimensions of finished bar and pipe change depending on prior stress state, cold work, and final microstructure. Induction heated bar and tube ends may exhibit higher hardness and circular ("toe nail") end cracking. For that reason, approximately 1.3 to 5 cm may be removed from each end. Respective dimensional allowances for raw material bars should be considered before heat treating.

8. Report

8.1 The contents of the production report should be decided by purchase agreement.

9. Record Retention

9.1 Records shall be maintained in accordance with the heat-treater's quality system requirements and, at a minimum, for one year from production. Records recommended by this guide include power capabilities (5.3.1), pyrometer calibration (5.3.4), line speed measurement device calibration (5.3.5),

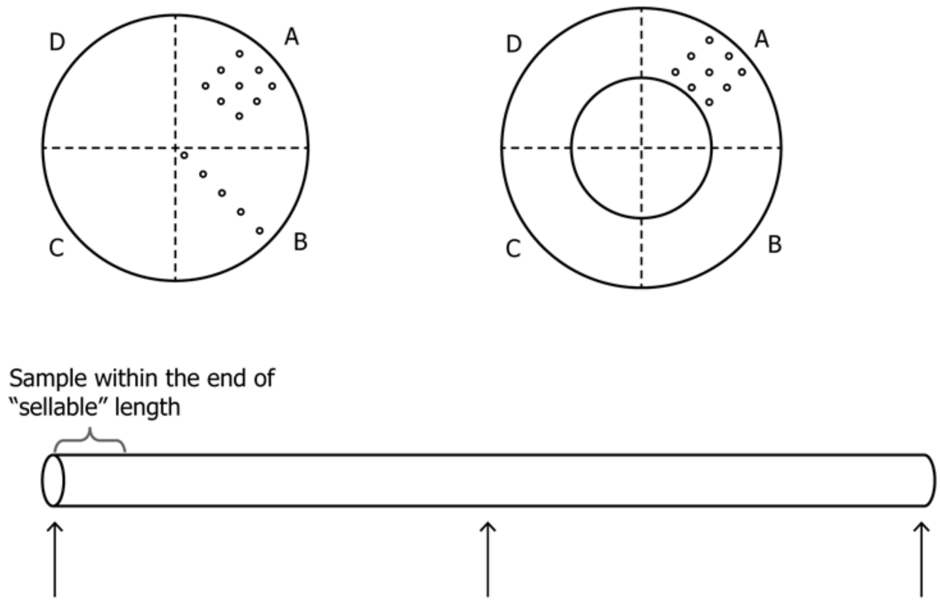


FIG. 1 Hardness Testing May be Conducted in the Pattern Shown in Region A or B as Appropriate, and Testing Should be Conducted in Opposite Quadrants of the Cross Section to Verify Uniformity; Samples from Ends and Middle of a Rod/Bar/Tube/Pipe as Indicated with the Arrows will Provide the Best Verification of Property Consistency along the Length of the Product

manufacturing procedure, product as-quenched hardness (6.3.8 and 6.3.9) as an option, and manufacturing procedure testing (Section 7).

10. Keywords

10.1 austenitize quench and temper; bar; full body heat treat; induction heating; pipe; steel; tube

APPENDIXES

(Nonmandatory Information)

X1. FLOW CHART FOR THIS GUIDE

X1.1 The flow chart in Fig. X1.1 provides a visual guide to the interpretation and use of this guide.

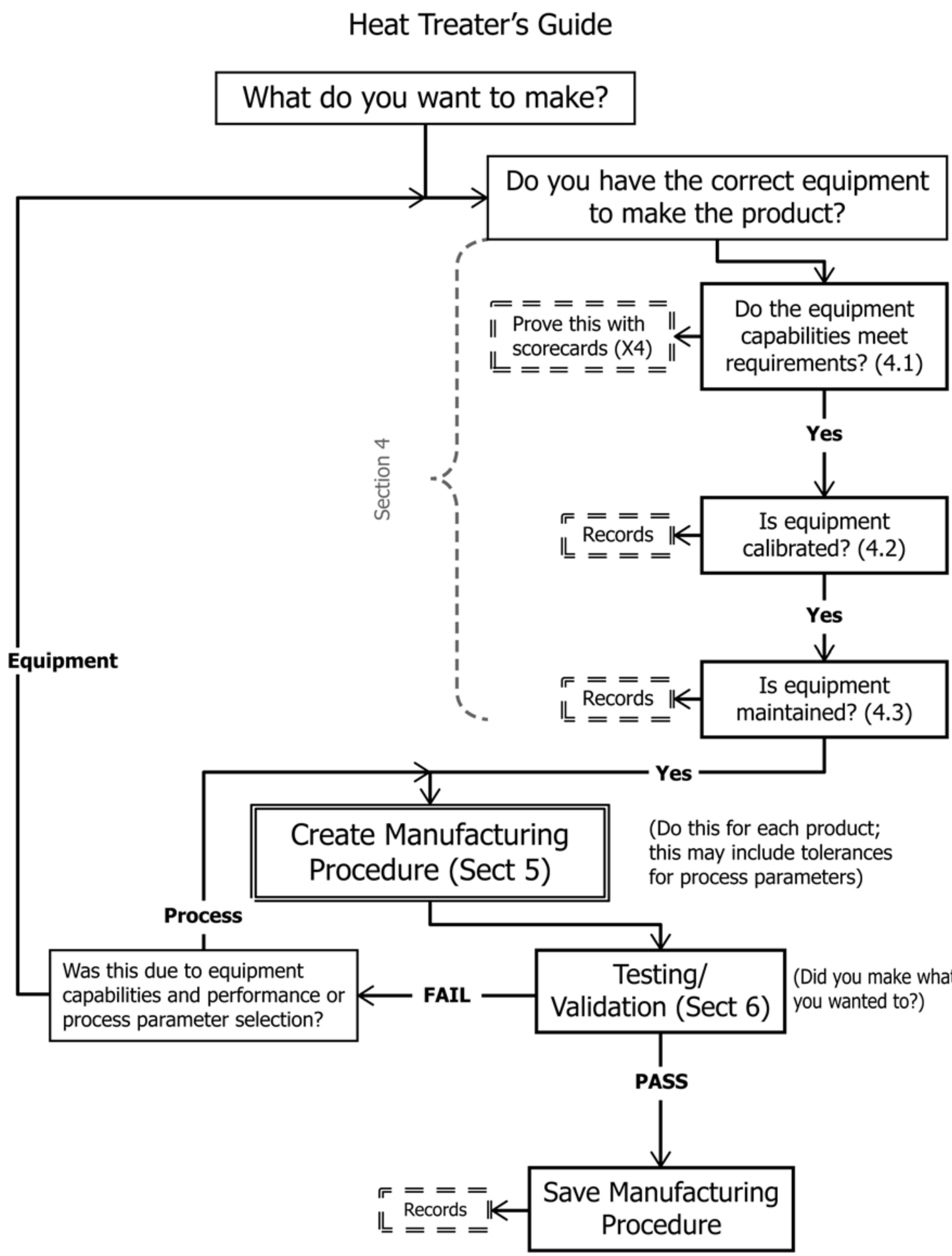


FIG. X1.1 Flow Chart

X2. EQUIPMENT CAPABILITIES SCORECARD

X2.1 This scorecard may be completed for each manufacturing procedure. The output power stability and pyrometer accuracy in particular can be greatly affected by the process variables. For example, voltage-fed power supplies typically have very good output stability when operating above 10 % maximum power (100 kW or greater for a 1000 kW unit), but they may have much poorer stability at very low power levels. The performance of the power supply is, therefore, related to the chosen set point. In addition, pyrometers typically work very well (high accuracy) within a specific temperature range and for a given surface finish and material type. At the high and low limits, this accuracy drops off, and outside of the specified range, the pyrometers are typically not usable.

X2.2 The scorecard in Table X2.1 lists five key areas with five tolerance ranges for each. The score for a specific manufacturing recipe on a particular mill can be obtained by averaging the score (1-5) on each key area. A score of 1 is very poor; a score of 5 is very good. Example of output power stability: there are three 1000 kW power supplies. The first one has a stability of ±10 kW, the second is ±12 kW, and the third is ±35 kW. They would have scores of 5, 5, and 4, respectively. The average scores for each key area should be reported individually (that is, the scores for each key area should not be averaged or added together to create a total score).

TABLE X2.1 Scorecard[A]

Key Area	1	2	3	4	5
Output power stability (for each active power supply on the mill)	>±8 %	±6 to ±8 %	±4 to ±6 %	±2 to ±4 %	<±2 %
Quench flow accuracy	>±12 %	±9 to ±12 %	±6 to ±9 %	±3 to ±6 %	<±3 %
Quenchant temperature stability (°C)	>±46	±36 to ±45	±26 to ±35	±11 to ±25	<±10
Pyrometer accuracy (for each active pyrometer on the mill)	±17°C or worse	±6°C	±6°C	±3°C	±3°C
Line speed stability	>±4 %	±3 to ±4 %	±2 to ±3 %	±1 to ±2 %	<±1 %

[A] Details for obtaining the score: (*1*) *Output power stability*—This is based on stability in kW or % about a set point over a 1 h (60 min) period. Output power may be monitored through the power supply controls, a separate power monitor, or other suitable means. (*2*) *Quench flow accuracy*—This is based on measurement of actual flow versus a set point. Flow can be measured directly (flow meter) or by calculation. (*3*) *Quenchant temperature stability*—This is based on the stability of monitored temperature of the quenchant. Stability should be monitored over the course of a year (winter versus summer month temperatures). (*4*) *Pyrometer accuracy*—This is based on the accuracy rating or calibration results of each pyrometer when it is used according to the manufacturer's recommendation. (*5*) *Line speed stability*—This is based on the actual line speed versus the set point.

X3. INDUCTION HEAT-TREATING FUNDAMENTALS

X3.1 Induction heating occurs when an alternating current is induced in a coil resulting in a magnetic field that couples with the electrically conductive work piece. The magnetic field then generates an equal and opposite current in the work piece which generates heat by the joule heating effect. The magnitude of the heat generated varies as the square of the current and is proportional to the resistance of the material. The subject of this guide is continuous heat treating lines, and for that application the induction coils are typically multiturn solenoid coils.

X3.2 Unlike a direct current (dc) flowing in a conductive work piece in which the current equally distributes through the cross section, an alternating current (ac) is confined to the surface of the work piece in a "skin depth" or "depth of current penetration" as shown in:

$$\xi = \sqrt{\frac{\rho}{\pi f \mu}} \qquad (X3.1)$$

where:

ξ = depth of current penetration in m,
ρ = electrical resistivity of the material in Ohm-m,
f = frequency of the alternating current (Hz), and
μ = relative magnetic permeability.

X3.3 Because the majority of the heat is generated in the skin depth, through wall induction heating shall rely on both induction to generate heat at the part surface as well as thermal conduction to allow heat to transfer to the core or inside diameter. Lower frequency will allow a deeper skin depth and higher frequency results in a shallower skin depth. The selection of the appropriate frequency for the heating application is critical, and factors such as eddy current cancellation, coil efficiency, power factor, product dimensions, and production rate shall be taken into consideration for the selection of a proper frequency.

X3.4 Key Characteristics of Induction Heat Treating

X3.4.1 *In-Line Processing*—The induction coil(s) are placed in line to allow a continuous flow of product. This allows automatic or semi-automatic handling and can reduce labor costs.

X3.4.2 *Rapid Heating Reduces Scale Losses*—The rapid heating rate with induction substantially reduces the surface time at temperature-reducing scale losses and results in minimal decarburization at the surface.

X3.4.3 *Instant On*—The induction process can be run on demand. It is not necessary to preheat induction furnaces or hold the induction furnaces at temperature with the associated wasted energy.

X3.4.4 *Energy Savings and Emissions*—Rapid heating abilities and the "instant on" can lead to lower energy usage. Induction heating can result in no or low emissions from operation.

X3.4.5 *Repeatability*—Once the process control variables are established for a given product (as described in Section 6), the process is precisely repeatable and all products receive the same treatment.

X3.4.6 *Modeling*—Electromagnetic, mechanical, thermal, and multiphysics modeling programs allow the induction heating process to be precisely defined. These models can benefit the design process to optimize production of varying product mixes. Programs are now available for a producer to be able to analyze the optimum setup for a new product on their existing heat-treat line.

X3.4.7 *Flexibility in Product Mix*—With proper induction furnace design, coil design, power and frequency selection, quick changeover, and line layout design, it is possible to change rapidly between products to provide a wide range of flexibility on a single-induction heat-treat line.

X3.5 Considerations for Continuous Induction Heat-Treating Lines

X3.5.1 *Frequency*—One of the most critical considerations in establishing a line to have the maximum combination of efficiency and productivity is the frequency of the power supplies. Selection of the proper frequency while maintaining the optimum efficiency contributes to reduced line length and improved temperature uniformity and product quality. When not properly selected, higher frequencies can contribute to vast thermal nonuniformity, and lower frequencies can cause eddy current cancellation (for solid cylinders, bar, and rod) or artificially high resistance (tube and pipe). The proper nominal frequency for a given material, product size, production rate, coil design, and power supply is essential for optimal heating using induction.

X3.5.2 *Line Length and Power Distribution:*

X3.5.2.1 The product under consideration for this specification is to be through hardened requiring that the part be uniformly through heated and for the core or inside diameter to remain at that temperature for a sufficient time for the carbon to be put into solution. Line length and power distribution are, therefore, critical parameters.

X3.5.2.2 Typical induction heating lines are designed to minimize line length for minimal floor space; to accomplish this, some lines have multiple zones. These zones are designed to allow for efficient ramp up and adequate soak time. The ramp up can be achieved with a high-power zone at the beginning of the line to raise the surface temperature rapidly, which aides in generating a greater temperature differential to increase the heat transfer to the core. Subsequent zones can continue to raise the surface temperature to compensate for the energy transferring to the core and maintain the surface temperature as the core soaks out. This can be achieved in two fundamental ways.

(1) Induction lines with one or two power supplies in which the power banking is accomplished with different coil designs. Lines of this type are sensitive to line speed and work

piece dimensions. Thermal losses are relatively constant at each zone regardless of line speed so, as power is reduced with decreases in line speed, the product could cool in the soak zone and a hot spot in the line can occur at the end of the higher power zones. These lines have natural limitations on product flexibility.

(2) Induction lines with power supplies for each zone or even for each coil are much more flexible and allow wide variation in product mix and line speeds since the power profile can be independently controlled for each coil to maintain the desired surface temperature and thermal gradient in each zone.

X3.5.2.3 In all cases, temperature monitoring should be in place for each power zone.

X3.5.3 *Bar Spacing*—Bar spacing is an important consideration for in-line heating. The best approach is to run with product in continuous contact with each other (end to end) so that the load approximates a continuous bar or tube. Proper material handling, placement of sensors, and temperature monitoring will help to ensure uniform properties.

X3.5.4 *Coil Design*—Coil design is an important consideration for an efficient line. Coil length, turns, turn spacing, and coil inner diameter (ID) all play important roles for voltage/current matching, coil efficiency, and power transfer capabilities. Coils are often designed for a particular zone on a heat-treat line and may not be interchangeable between different zones. Ideally, the optimum efficiency is obtained by minimizing the distance between the work piece surface and the coil ID. Often, the induction coils will include a refractory or liner or both. Increasing the refractory thickness reduces the thermal losses but, at the same time, may decouple the coil from the workpiece thereby decreasing the electrical efficiency of the coil. Refractory plays an important role in minimizing thermal losses during heating, and there are a wide range of refractory materials and designs to insulate the workpiece properly. A key consideration is maintenance of the refractory. Changes to refractory thickness, material, or condition may affect the thermal losses from the product.

X4. INFRARED TECHNOLOGY FUNDAMENTALS

X4.1 There are many manufacturers of infrared thermometers and technologies including single-wavelength, ratio, and multi-wavelength technologies (see Fig. X4.1). Each technology is designed for a specific operating condition (see Table X4.1).

X4.1.1 *Long Wavelength (LW) Technology*—Any pyrometer able to measure ambient temperature values is a long wavelength model. These pyrometers are popular because they are low cost and the only option for measuring at and below ambient temperatures. These pyrometers can produce significant errors when measuring higher temperatures, so they are not appropriate for most applications when the measured temperature is significantly above ambient.

X4.1.2 *Short Wavelength (SW) Technology:*

X4.1.2.1 Short wavelength pyrometers better tolerate emissivity variation, misalignment, and optical obstruction and they are able to view through common window materials. Sensitivity to emissivity variation, misalignment, and optical obstruction increases at higher temperatures and longer wavelengths; therefore, short wavelength pyrometers are most popular for low- to mid-temperature applications in which emissivity variation, optical obstruction, and misalignment are moderate. These products can tolerate a more significant emissivity variation at lower temperatures than at higher temperatures, so these are especially popular for measuring metals at temperatures below 200 to 300°C.

X4.1.2.2 Fig. X4.2 shows the relative sensitivity of various single-wavelength pyrometer wavelength sets to a 10 % change in emissivity, optical obstruction, or misalignment. Note that the shorter wavelength pyrometers produce a more accurate measure of temperature.

X4.1.3 *Ratio Pyrometers:*

X4.1.3.1 There are two types of ratio pyrometers: two color (TC) and dual wavelength (DW). All ratio pyrometers measure temperature at two different wavelengths. The emissivity appears as a factor at both wavelengths so that, when a ratio is taken, the emissivity appears in both numerator and denominator, thus, they cancel out. This is the basis for all ratio pyrometers. In the same way, the ratio pyrometers are able to compensate for misalignment and optical obstruction. Any obstruction that blocks the measured energy at Wavelength A also blocks the same amount of energy at Wavelength B, and when the ratio is taken, the value is unaffected by the obstruction.

X4.1.3.2 All ratio pyrometers make the assumption that the emissivity is the same at both measured wavelengths and any optical obstruction affects both wavelengths the same. Wavelength selection, therefore, can be an important issue when selecting the most appropriate ratio technology.

X4.1.4 *Two-Color (TC) Technology*—Two-color pyrometers use general purpose overlapping wavelength sets. These pyrometers are popular because of their relatively low cost and exceptional speed of response, but their general purpose overlapping wavelength sets can sometimes compromise their accuracy. Because the wavelengths overlap, these models are more sensitive to spectral emissivity variation and surface oxides and scale, and the general purpose wavelength sets are not appropriate for viewing through water, steam, flames, laser energy, or plasma.

X4.1.5 *Dual Wavelength (DW) Technology*—Dual wavelength pyrometers are ratio pyrometers just like two-color pyrometers, except the DW technology allows for the selection of specific wavelengths. Different wavelength sets are available, each optimized for a specific purpose. Some wavelength sets offer exceptionally broad temperature spans. Some wavelength sets tolerate water and steam or laser energy and plasma without interference. Others are optimized for the measure of molten iron and steel. With a greater separation

Single-Wavelength Technologies		
Short-Wavelength (SW)	**Long-Wavelength** (LW)	**Specialty-Wavelength** (SP)
Errors are relatively small for moderate emissivity variation, optical obstruction and misalignment, particularly at lower temperatures. Certain models can view through common interferences.	Low-cost pyrometers ideal for general purpose applications measuring temperatures below 100°C / 200°F.	Used when the target is least reflective and most opaque at a specific wavelength or when optical obstructions are most transparent at a specific wavelength.

Ratio and Multi-Wavelength Technologies		
Two-Color (TC)	**Dual-Wavelength** (DW)	**Multi-Wavelength** (MW)
Ratio Pyrometers designed to compensate for emissivity variation and modest optical obstruction or misalignment.	Ratio Pyrometers designed to measure the hottest temperature viewed. Select wavelength sets tolerate water, steam, flames, plasma, and laser energy. More tolerant of scale, misalignment, and optical obstructions than Two-Color.	Used for non-greybody materials such as aluminum, copper, stainless steel, and zinc. Application specific algorithms adjust for complex emissivity characteristics.

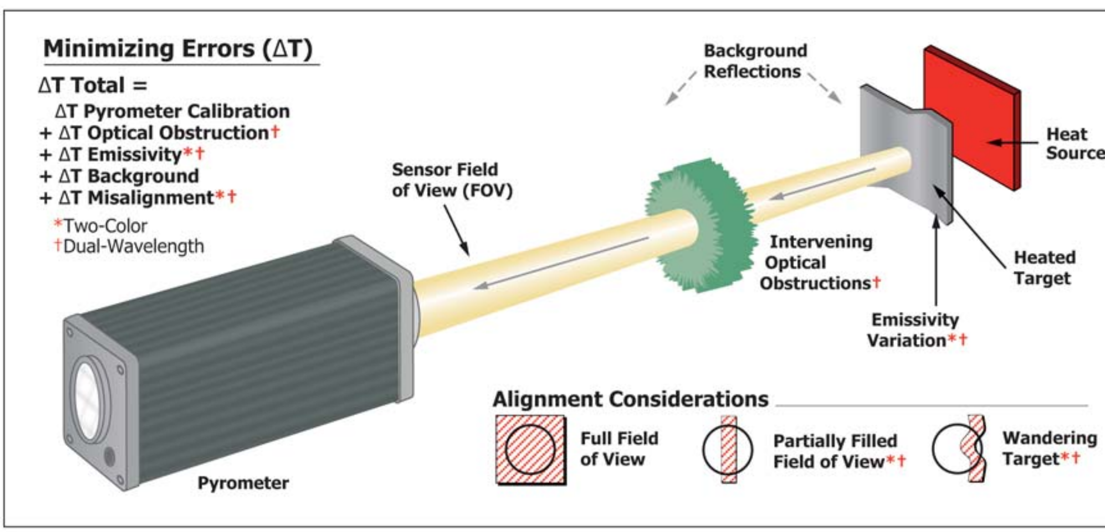


FIG. X4.1 Different Technologies

between wavelengths, dual wavelength pyrometers can be up to 20 times less sensitive to cooler temperature gradients caused by surface oxides and scale or localized heating such as welding and contour hardening.

X4.1.6 *Multi-Wavelength (MW) Technology:*

X4.1.6.1 Multi-wavelength pyrometers are used to measure non-gray-body materials such as aluminum, copper, zinc, magnesium, and low-emissivity steel in which the emissivity varies differently at different wavelengths. For these materials, the SW technology is not appropriate at the higher temperatures because of significant emissivity variation, and TC and DW technology is not appropriate because the emissivity changes differently at different wavelengths. The MW technology was developed specifically for this type of non-gray-body material.

X4.1.6.2 Multi-wavelength pyrometers use an emissivity-versus-wavelength model to characterize the material being measured. For this type of device to produce an accurate and reliable measure of temperature, the model shall accurately represent the true measured conditions, and the hardware shall accurately represent the model.

X4.1.6.3 Various infrared pyrometer technologies are available for steel-heating applications. Pyrometer users may take a "good," "better," or "best" approach that allows each user to select the technology that is most appropriate for his needs.

X4.1.7 *Good: Short-Wavelength Technology:*

X4.1.7.1 Short-wavelength technology provides the good option, which is the lowest cost viable option. Under normal operating conditions when measuring a common steel target, a SW pyrometer will measure within a few tens of degrees of the true temperature as long as the oxide conditions are consistent. Significant variation in the material, alloy, surface condition, or degree of oxidation will produce larger errors. If visible scale forms, then the error can be hundreds of degrees, particularly at hardening or forming temperatures. Typical accuracy is ±17°C.

X4.1.7.2 If water or steam is an application issue, then care should be taken to assure that the wavelength of measurement

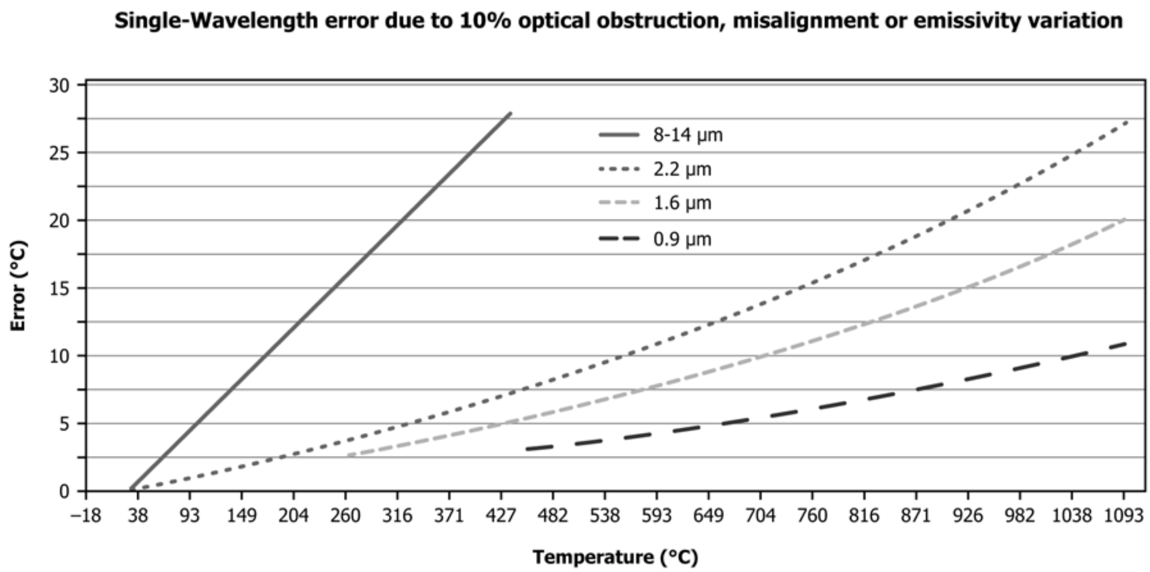


FIG. X4.2 Single-Wavelength Error

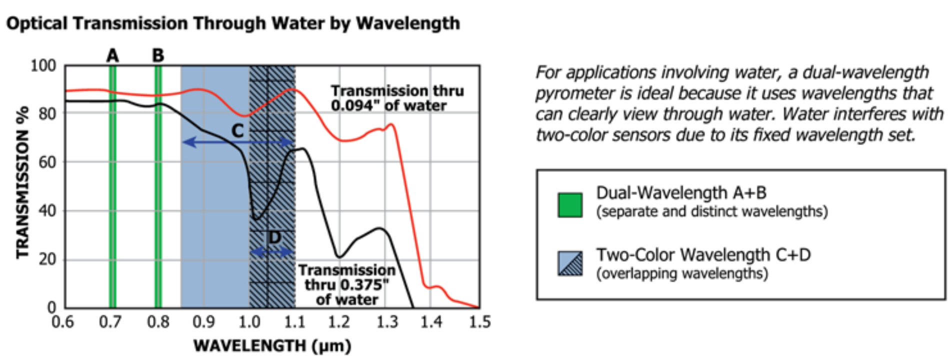


FIG. X4.3 Optical Transmission through Water by Wavelength

can tolerate these interferences without error. Short-wavelength pyrometers often offer an exceptionally broad temperature span and precision optical resolution.

X4.1.8 *Better: Two-Color Technology:*

X4.1.8.1 Two-color technology provides the better option, which is the intermediate cost option. Under normal operating conditions when measuring a common steel target, a TC pyrometer will measure within about 6°C of the true temperature as long as the oxide conditions are not too severe. The TC pyrometer will produce an error when viewing some high-alloy steels and wing a surface with visible scale.

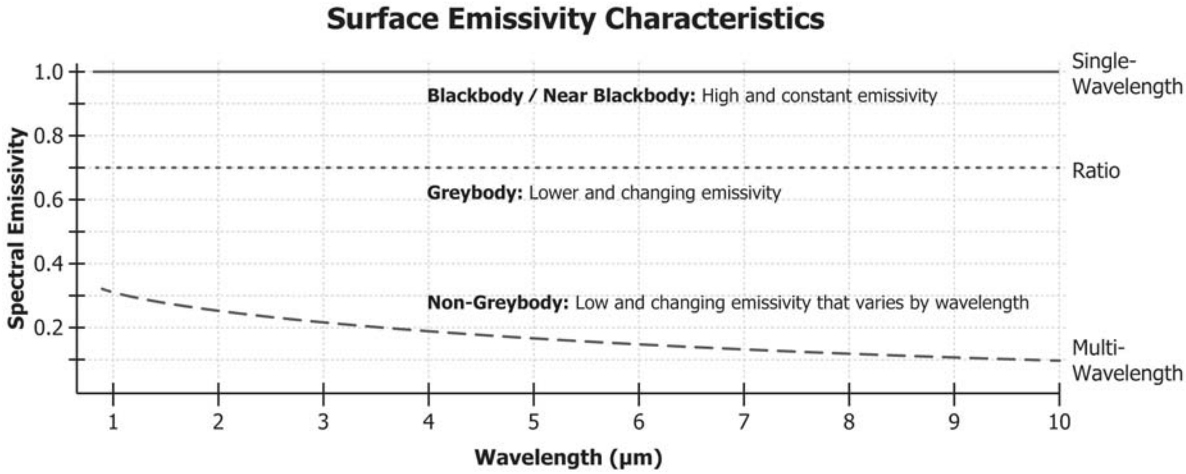
X4.1.8.2 Two-color pyrometers are commonly used to measure temperatures above about 700°C. Lower temperature two-color models are available, but they are not common at this time.

X4.1.9 *Best: Dual-Wavelength Technology:*

X4.1.9.1 Dual-wavelength technology provides the best option for common steel alloys. Under normal operating conditions when measuring a common steel target, a DW pyrometer will measure within about 3°C of the true temperature. The DW pyrometer is also 20 times less sensitive to surface oxides and scale because of a greater separation between wavelengths.

X4.1.9.2 Dual-wavelength pyrometers are similar to two-color pyrometers, except they use narrow-band wavelength sets with a greater separation between wavelengths. Much as a table with a wider separation between the legs, this greater separation between wavelengths makes the DW technology 20 times more stable when interference exists.

X4.1.10 *High-Alloy Steels: Multi-Wavelength Technology*—Multi-wavelength technology provides the best option for many high-alloy steels, including high-strength steels. Whereas, single-wavelength pyrometers assume that the emissivity is constant and known, and two-color and dual-wavelength pyrometers assume that the emissivity is equal at both measured wavelengths, for some high-alloy steels, these are invalid assumptions. For oxide-free stainless steels and high-silicon, high-nickel, or high-magnesium steel alloys, the emissivity is variable and it varies differently at different wavelengths. As a result, for optimal accuracy, a multi-wavelength pyrometer shall be used. Under normal operating conditions when measuring a high-alloy steel target, a MW pyrometer will measure within about 3°C of the true temperature. MW pyrometers do not tolerate heavy scale, and so in some cases, a dual-wavelength model may be more accurate.



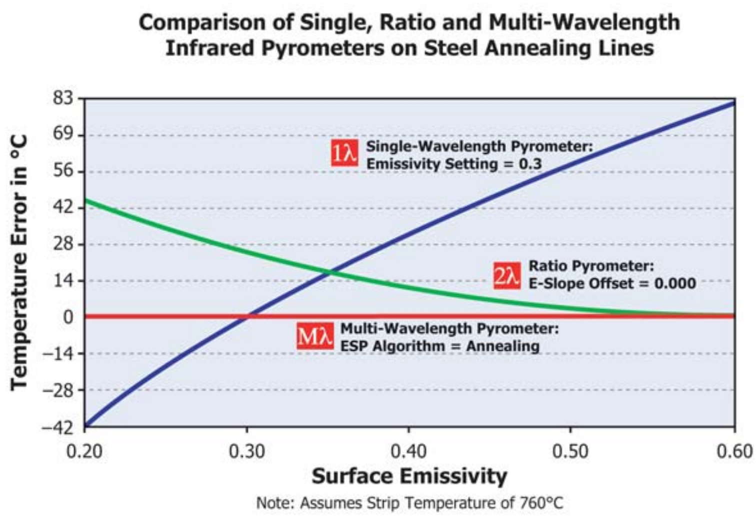


FIG. X4.4 Surface Emissivity Characteristics

X4.1.11 *Recommendations*—If the surface condition is tightly controlled, then the SW technology may be used with confidence. If the measured target is free from scale and heavy oxide, then the TC technology may be used with confidence. If the measured target has significant oxide or scale, then the DW technology is recommended. If the target is a high-alloy steel, then the MW technology is recommended.

X4.1.12 *Pyrometer Maintenance:*

X4.1.12.1 *Electrical Interference*—Pyrometer housings should be electrically isolated. Cable shields should be terminated to a true ground. If the pyrometer housing or cable shield is electrically common with a surface at an elevated voltage, then measurement error or hardware failure or both may occur.

X4.1.12.2 *Alignment*—The pyrometer alignment should be confirmed routinely, perhaps as often as once per shift.

X4.1.12.3 *Lens Cleaning*—The pyrometer lens should be cleaned periodically. The frequency depends upon the environment, but this is something that shall be done routinely.

X4.1.12.4 *Fiber-optic Integrity*—For fiber-optic pyrometers, the integrity of the fiber-optic cable should be confirmed periodically.