AEROSPACE MATERIAL SPECIFICATION

AMS2750™	REV. G
Issued 1980-04 Revised 2022-06 Superseding AMS2750F	

Pyrometry

RATIONALE

AMS2750G results from a Two-Year Review and update of this specification. There were multiple requirements in AMS2750F that became effective 2 years after its release on June 29, 2020, making other requirements obsolete from that point forward. AMS2750G has fully incorporated these 2 year requirements and removed the obsolescent requirements thus preventing their unintended use. The only exception to this, due to equipment availability, is that 3.2.3.2.1 regarding digital recording instruments was added to give users one additional year to comply with the minimum readability. Additionally, this revision has made numerous clarifications to aid the user.

1. SCOPE

1.1 This specification covers pyrometric requirements for equipment used for the thermal processing of metallic materials. Specifically, it covers temperature sensors, instrumentation, thermal processing equipment, correction factors and instrument offsets, system accuracy tests, and temperature uniformity surveys. These are necessary to ensure that parts or raw materials are heat treated in accordance with the applicable specification(s).

1.2 This specification may be used in other non-heat treating applications when specified.

1.3 This specification is not applicable to heating or to intermediate thermal processing unless otherwise specified.

1.4 This specification applies to laboratory furnaces to the extent specified in 3.6.

2. REFERENCES

2.1 Applicable Documents

The issue of the following documents in effect on the date of the purchase order form a part of this specification to the extent specified herein. The supplier may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AS7766 Terms Used in Aerospace Metals Specifications

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For more information on this standard, visit
https://www.sae.org/standards/content/AMS2750G/

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM E29 Using Significant Digits in Test Data to Determine Conformance with Specifications

ASTM E207 Standard Test Method for Thermal EMF Test of Single Thermoelement Materials by Comparison with a Reference Thermoelement of Similar EMF-Temperature Properties

ASTM E220 Calibration of Thermocouples by Comparison Techniques

ASTM E230 Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples

ASTM E608 Mineral-Insulated, Metal-Sheathed Base Metal Thermocouples

ASTM E1137 Industrial Platinum Resistance Thermometers

ASTM E1751 Standard Guide for Temperature Electromotive Force (emf) Tables for Non-Letter Designated Thermocouple Combinations

ASTM MNL7 Presentation of Data and Control Chart Analysis

ASTM MNL12 Use of Thermocouples in Temperature Measurement

2.1.3 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60751 Industrial Platinum Resistance Thermometers and Platinum Temperature Sensors

ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories

2.2 Definitions

Terms used in AMS2750 are defined in AS7766 and as follows:

2.2.1 ACCURACY

The maximum deviation of the instrument or sensor being tested from the values of a traceable standard.

2.2.2 ADJUSTMENT

Any change to an instrument's parameters.

2.2.3 AUTOCLAVE

An oven capable of operating at pressures higher than atmospheric pressure (nominally 760 mm Hg), commonly used in the processing of materials. It may be pressurized with steam, compressed air, or inert gas.

2.2.4 BASE METAL SENSOR

Sensor whose thermoelements are composed primarily of base metals and their alloys. Examples of base metal sensors include Types E, J, K, N, M, and T.

2.2.5 BATCH FURNACE

A furnace where parts or raw material are stationary during the soak. Note: Some batch furnaces may oscillate material within a stationary work zone.

2.2.6 BIAS OR INPUT SHIFT

The act of making an adjustment to an instrument to add, remove, or alter an offset.

2.2.7 BIMONTHLY

See FREQUENCY.

2.2.8 BIWEEKLY

See FREQUENCY.

2.2.9 CALIBRATION

An assessment of the accuracy of a sensor or an instrument to a traceable standard sensor and/or field test or standard instrument, based on one or more measurements, and potentially adjusting an instrument and/or compiling a deviation chart for a sensor or instrument in order to ensure compliance with requirements.

2.2.10 CONTINUOUS FURNACE

A furnace where parts or raw material are conveyed continuously or semi-continuously from the charge area to the discharge area. Examples include bump furnace, shaker furnace, belt furnace, roller furnace, rotary hearth furnace.

2.2.11 CONTROL INSTRUMENT

An instrument connected to a control sensor used to control the temperature of thermal processing equipment. The instrument may or may not also record temperature data.

2.2.12 CONTROL SENSOR

A sensor connected to a control instrument on thermal processing equipment, the temperature of which may or may not be recorded.

2.2.13 CONTROL ZONE

A portion of the working zone in thermal processing equipment having a separate sensor, instrument, and heating or cooling system to control its temperature. This portion of the thermal processing equipment is independently controlled.

2.2.14 CONTROLLED TEMPERATURE LIQUID BATH

A furnace containing a liquid that is heated to the desired heat treat temperature. Parts and raw material are normally immersed in the liquid.

2.2.15 CONTROLLER

A digital, or mechanical device that controls the temperature of thermal processing equipment (e.g., furnace control instruments, quench mechanical thermostat, freezer pressure controls, etc.).

2.2.16 CORRECTION FACTOR

The number of degrees, determined from the most recent calibration that must be added to, or subtracted from, the temperature reading of a sensor, or an instrument, or a combination thereof (system) to obtain true temperature. The correction factors of sensors and instruments are usually kept separately and added together algebraically when a combination is used. Correction factor is the algebraic opposite of deviation (error).

2.2.17 DATA ACQUISITION SYSTEM

An instrument system used to automatically collect and store process data as an electronic record, for example a Programmable Logic Controller (PLC).

2.2.18 DEVIATION/ERROR

In the context of this specification, the difference between the uncorrected indicated temperature and the true temperature (Indicated temperature - True temperature = Deviation/error).

2.2.19 DIGITAL INSTRUMENT

An instrument that records process measurements in a digital (numeric) display format, or an instrument that prints both the scale (graph) and trend line simultaneously. Examples include recorders with pre-printed scales and printed tabular data meeting 3.2.1.4 data collection intervals, and recorders that create scales and trend line or tabular data and also display indicated temperature.

2.2.20 ELECTRONIC RECORD

Any combination of text, graphics, data, audio, pictorial, or other information representation in digital form that is created, modified, maintained, archived, retrieved, or distributed by a computer system.

2.2.21 EXPENDABLE SENSORS

Sensors where any portion of the thermoelements are exposed to the thermal process equipment environment.

2.2.22 EXTENSION WIRE

Wire used for transmitting an unmodified signal from the sensor to the instrumentation system. Wire is generally of the same sensor type, except for some sensor types which allow compensated extension wire.

2.2.23 FIELD TEST INSTRUMENT

An instrument meeting the requirements of Table 7, that has calibration traceable to a secondary standard instrument or better and is used to conduct on-site calibrations or tests of thermal processing equipment.

2.2.24 FLUIDIZED BED FURNACE

A furnace that contains a medium that becomes suspended or fluidized due to atmosphere gas or products of combustion passing upward through the medium. Parts and raw material are normally immersed in the fluidized medium.

2.2.25 FREQUENCY (INTERVAL)

The calendar days between two consecutive calibrations, tests, or sensor replacement. In the context of this specification, the following shall apply:

Frequency	Equal to once every	Shall be completed on or before
Weekly	Week	The same day of the week every week
Bi-weekly	2 weeks	The same day of the week every 2 weeks
Monthly	Month	The same date of the month every month(1)
Bi-monthly	2 months	The same date of the month every 2 months(1)
Quarterly	3 months	The same date of the month every third month(1)
Semi-annually	6 months	The same date of the month every 6 months(1)
Annually	Year	The same date of the year every year(1)

Note:
(1) If the next calibration, test, or sensor replacement is due on a calendar date not contained in that month, then the last day of that calendar month shall be used for the next calibration (e.g., a monthly calibration, test, or sensor replacement performed on January 31st is due on the last day of February).

2.2.26 FURNACE

Equipment used for the thermal processing of parts or raw material. The terms furnace and oven can be used interchangeably.

2.2.27 HEAT SINK

A mass of material with an embedded sensor or sensors which supplies temperature data of that mass to recording instruments.

2.2.28 INTERVAL

See FREQUENCY.

2.2.29 LABORATORY THERMAL PROCESSING EQUIPMENT

Equipment used exclusively for thermal processing of samples, specimens, or test parts as required by materials and processing specifications.

2.2.30 LOAD SENSOR

Sensor that is attached to or in contact with parts or raw material, a representation of parts or raw material, or is buried in the load of parts (e.g., fasteners) or raw material and which supplies temperature data of the parts or raw material to recording instruments that may be used to control the sequence of the production process, such as the start of soak.

2.2.31 MAXIMUM PERMITTED ERROR

A tolerance band for the thermal electric response expressed in degrees or percentages. Maximum permitted error provides a tolerance within which various types of sensors shall conform to standard sensor reference tables, or equivalent.

2.2.32 MATERIAL PRODUCER (METALLIC)

The manufacturer of raw material as stated in 2.2.53.

2.2.33 MEASURING JUNCTION

The location of a sensor where the wire elements are joined together to complete a measurement circuit, which is used to measure an unknown temperature. Also called the hot junction.

2.2.34 MULTIPLE ZONED FURNACES

Furnaces with multiple separate temperature control zones.

2.2.35 NOBLE METAL SENSOR

Sensor whose thermoelements are composed primarily of noble metals (e.g., platinum/platinum-rhodium) and their alloys. Examples of noble metal sensors include Types R, S, B, and RTDs.

2.2.36 NON-EXPENDABLE SENSORS

Sensors having no portion of the thermoelements exposed to the thermal process equipment environment.

2.2.37 NON-METALLIC MATERIALS

In the context of this specification, this term refers to the curing of composite or adhesive bonded assemblies that are typically processed in autoclaves, air ovens, or heated presses.

2.2.38 OFFSET

Any manual or electronic adjustment to an instrument made to alter either the desired set point or the displayed value of the instrument's calculated temperature. Manufacturer specific terminology may also include bias, input shift, etc.

2.2.38.1 CORRECTION OFFSET

Manual or electronic adjustment of an instrument to compensate for known errors of the measurement system (instrument, extension wire/connectors, sensor) to make the system more accurate.

2.2.38.2 MODIFICATION OFFSET

Manual or electronic adjustment of an instrument to compensate for known conditions such as, but not limited to, a skewed TUS result or control thermocouple placement in a retort or muffle.

2.2.39 OVEN

Equipment used for the thermal processing of materials and parts. The terms oven and furnace can be used interchangeably.

2.2.40 OVER-TEMPERATURE INSTRUMENTATION

An independent sensor and instrument combination installed in the thermal processing equipment, which is used to detect any over-temperature occurrence and generate an alarm and/or cut back or shut down heat input. The purpose for this control is to protect parts or raw material and/or the thermal processing equipment from overheating. Integrated control/recording/over-temperature instruments are permitted provided it can be demonstrated that the over-temperature instrument/module of an integrated system is separated from the furnace control/recording system.

2.2.41 PARTS

Usually identified by a part number, produced from raw material in accordance with the requirements of an engineering drawing and are usually tested by non-destructive techniques only. Parts are heat treated, by or for a fabricator, in accordance with a drawing, purchase order, fabrication order, or heat treat specification.

NOTE: The cognizant engineering organization has the authority to assign the terms "parts" or "raw material."

2.2.42 PREVENTIVE MAINTENANCE PROGRAM OR PM PROGRAM

A program for evaluating, taking corrective action as required, and documenting the condition of items that have potential to adversely affect thermal processing equipment conformance to any requirement of this specification. Frequency of PM checks is established based on experience to ensure that no major problems occur between periodic PMs.

2.2.43 PRIMARY STANDARD SENSOR

Sensor calibrated directly against a reference standard and meeting the requirements of Table 1.

2.2.44 PRIMARY STANDARD INSTRUMENT

An instrument that is calibrated directly against a reference standard instrument and meeting the requirements of Table 7.

2.2.45 PROCESS CHART RECORDER

See RECORDING INSTRUMENT.

2.2.46 PROGRAMMABLE LOGIC CONTROLLER (PLC)

A digital computer control system that continuously monitors the state of input devices and makes decisions based upon a programmed input (recipe) to control the state of output devices.

2.2.47 QUALIFIED OPERATING TEMPERATURE RANGE

The nominal set point temperature range of thermal processing equipment where temperature uniformity has been tested within a qualified work zone and found to be compliant with required tolerances. The qualified operating temperature range represents the temperature range including ± min/max uniformity tolerances within which parts or raw material can be processed.

2.2.48 QUALIFIED WORK ZONE

The portion of a thermal processing equipment volume where temperature variation conforms to the required uniformity tolerance within the qualified operating temperature range as defined by the placement of sensors during the most recent temperature uniformity survey.

2.2.49 QUALITY ORGANIZATION APPROVAL

Objective evidence of review and acceptance or rejection of a calibration or test as defined by a documented process within the user’s quality system which also defines any delegation of this approval.

2.2.50 QUENCH SYSTEM

A system that provides rapid cooling, usually accomplished using oil, water, water/polymer mixtures, or gaseous mediums.

2.2.51 RADIATION SURVEY

Initial survey of aluminum alloy thermal processing equipment used above 800 °F or 427 °C when the heat source (e.g., electrical elements or gas tubes) is exposed to the qualified work zone or only separated by a metal baffle.

2.2.52 RADIATION SURVEY SENSOR

A TUS sensor, typically base metal (Types E, J, K, N, M, and T) sensor used in conjunction with a test panel for determining the heating characteristics of furnaces used for solution heat treating aluminum alloys.

2.2.53 RAW MATERIAL

Usually includes, but is not limited to, such items as sheet, plate, wire, rod, bar, forgings, castings, and extrusions. Raw material is usually identified by a heat or lot number and is usually tested destructively for acceptance. Raw material is heat treated, by or for a material producer, in accordance with a process or material specification.

NOTE: The cognizant engineering organization has the authority to assign the terms “parts” or “raw material.”

2.2.54 RAW MATERIAL FURNACES

Equipment used in accordance with a process or material specification to process raw material.

2.2.55 RECORDING INSTRUMENT

An instrument connected to a controlling, load and/or recording sensor that documents process equipment temperature data and generates a permanent process record. Examples are a chart recorder, electronic data recorder, or a data acquisition system.

2.2.56 RECORDING SENSOR

A sensor that is connected to a recording instrument or connected to a control instrument of an integrated control/recording system.

2.2.57 RECURRENT TEMPERATURE PATTERN

Cycling of furnace temperature due to operation of the temperature control instrument.

2.2.58 REFERENCE STANDARD SENSOR (NOBLE METAL)

A noble metal standard sensor that has been calibrated by NIST or other internationally recognized standards organization meeting Table 1 requirements.

2.2.59 REFERENCE STANDARD INSTRUMENT

A standard test instrument that has been calibrated by NIST or other internationally recognized standards organization meeting Table 7 requirements.

2.2.60 REFRACTORY SENSOR

A sensor whose thermoelements are composed primarily of refractory metals (e.g., Tungsten, Rhenium, Tantalum, Niobium, and Molybdenum) and their alloys. Example: Type C sensors.

2.2.61 REFRIGERATION EQUIPMENT

A compartment, cabinet, or room that may be held below room temperature and >32 °F or 0 °C (refrigerator), or ≤32 °F or 0 °C (freezer) depending on the temperature range of use. This equipment may be used for retarding or advancing metallurgical transformation, or for storage of metallic materials.

2.2.62 RESIDENT SAT SENSOR

A test sensor that remains resident in the test location between system accuracy tests.

2.2.63 RETORT FURNACE

A furnace that contains a retort or muffle which isolates the parts or raw material being heat treated from the heating elements. The furnace normally surrounds the retort.

2.2.64 RESISTANCE TEMPERATURE DEVICE (RTD)

A device (for example, PT100, PRT, etc.) that produces a change in resistance across an element in response to the temperature at the element (usually in the tip).

2.2.65 SALT BATH

A furnace containing molten salt that is heated to the desired heat treat temperature. Parts or raw material are normally immersed in the molten salt.

2.2.66 SECONDARY STANDARD TEST INSTRUMENT

An instrument calibrated directly against a primary standard or reference standard meeting Table 7 requirements and which is operated in a controlled test environment.

2.2.67 SECONDARY STANDARD TEST SENSOR

Sensor calibrated directly against a primary standard test sensor, meeting the requirements of Table 1.

2.2.68 SEMI-CONTINUOUS FURNACE

See CONTINUOUS FURNACE.

2.2.69 SENSOR OR TEMPERATURE SENSOR

In the context of this specification, a device designed to detect or measure temperature (e.g., thermocouple, RTD, etc.).

2.2.70 SPECIAL LIMITS OF ERROR SENSOR WIRE

Sensors and extension wires whose initial calibration accuracy meets or exceeds the requirements of ASTM E230, Tables 1 and 2 for special tolerances.

2.2.71 STABILIZATION (ALSO REFERRED TO AS EQUALIZATION, EQUILIBRIUM, STEADY STATE, OR SOAKED CONDITION)

Equipment stabilization occurs when all control and recording sensors are within the allowable temperature uniformity survey tolerance span and controllers are cycling and/or maintaining the desired temperature in each zone. Temperature uniformity survey stabilization occurs when all temperature uniformity survey sensors have reached the desired uniformity range and are not exhibiting a continual upward or downward trend away from the set point during and after the stabilized period of the temperature uniformity survey.

2.2.72 SYSTEM ACCURACY TEST (SAT)

An assessment of the sum of the combined errors or correction factors of the sensor, extension wire (and connectors), and instrument to ensure compliance with Table 11 or 12 requirements.

2.2.72.1 COMPARISON SAT

An assessment by comparison of the difference between the readings of the thermal process equipment sensor system being tested (sensor, extension wire, and instrument) and the corrected reading of the test sensor system (test sensor, extension wire, field test instrument) after test sensor and field test instrument correction factors are applied (see 3.4.7). Also referred to as a "probe check."

2.2.72.2 ALTERNATE SAT

A mathematical assessment of the sum of the errors or correction factors of the thermal processing equipment sensor and the calibration error or correction factor of the connector, extension wire, and instrument channel (see 3.4.8).

2.2.72.3 SAT WAIVER

Additional requirements and comparisons to be made when the comparison or alternate SAT methods are not performed (see 3.4.9).

2.2.73 SYSTEM ACCURACY TEST SENSOR

A calibrated and traceable sensor meeting the requirements of Table 1 used for an SAT.

2.2.74 TEMPERATURE OVERSHOOT

When any temperature sensor exceeds the upper temperature tolerance as defined by the applicable thermal processing equipment class as stated in Table 8.

2.2.75 TEMPERATURE SENSOR PASS-THROUGH

Installed wiring connecting sensors (typically thermocouples) inside the thermal processing equipment to the instrumentation outside, usually with sockets, jacks, or terminals at each end.

2.2.76 TEMPERATURE UNIFORMITY

The temperature variation (usually expressed as ± degrees) within the qualified work zone with respect to set point temperature. For retort furnaces where a sensor in the retort is used to control temperature, the temperature variation is with respect to the sensor in the retort and not to the furnace set point temperature. The requirement is established by the required thermal processing equipment class in accordance with Table 8.

2.2.77 TEMPERATURE UNIFORMITY RECORDER

Independent digital recording instrument meeting the requirements of Table 7 for a field test Instrument and used to perform temperature uniformity surveys.

2.2.78 TEMPERATURE UNIFORMITY SENSOR

A calibrated and traceable sensor meeting the requirements of Table 1.

2.2.79 TEMPERATURE UNIFORMITY SURVEY (TUS)

An assessment of the temperature variation within the qualified work zone of thermal processing equipment prior to and after stabilization using a field test instrument (TUS recorder) meeting Table 7 requirements and sensors meeting the requirements of Tables 1, 17, and 18, as applicable.

2.2.80 THERMAL PROCESSING

Any process in which parts or raw material are exposed to controlled heating, soaking, or cooling to achieve the specified properties or condition of the parts or raw material for which there is no exception in accordance with 1.3.

2.2.81 THERMAL PROCESSING EQUIPMENT

A term used to refer to any vessel (such as autoclave, furnace, oven, quench and refrigeration equipment, liquid bath, heated press, etc.) used to process parts or raw material at controlled temperatures.

2.2.82 THERMOCOUPLE

A temperature sensor consisting of two wires (thermoelements) of dissimilar thermoelectric characteristics connected at a measuring junction, An EMF is developed between the two junctions in proportion to the temperature gradient.

2.2.83 TRACEABLE OR TRACEABILITY

The ability to relate measurement results through an unbroken chain traceable to the International System of Units (SI) through internationally recognized standards organizations such as, but not limited to:

National Institute of Standards and Technology (NIST)
National Physical Laboratory (NPL)
Physikalisch-Technische Bundesanstalt (PTB)
Swedish National Authority for Testing, Inspection, and Metrology
China National Calibration Technology Specification (CNAS)
National Institute of Advanced Industrial Science and Technology (AIST)
Instituto Nacional de Metrologia, Normalização e Qualidade Industrial (INMETRO)
Bureau International des Poids et Mesures (BIPM)

2.2.84 USE (OF A SENSOR)

One cycle of heating or cooling upon the sensor being placed into service (see 3.1.4.2, 3.1.7.2, 3.1.7.5, and 3.1.11.1 for examples).

2.2.85 VACUUM FURNACE

A furnace that processes parts or raw material at any pressure lower than atmospheric pressure (nominally 760 mm Hg) during soak.

2.2.86 WIRELESS TRANSMITTER

A device for sending electromagnetic waves; the part of a broadcasting apparatus that generates and modulates the radio frequency current and conveys it to a receiver.

2.2.87 ZENER VOLTAGE REFERENCE

A diode which allows current to flow in the forward direction in the same manner as an ideal diode, but also permits current flow in the reverse direction when the voltage is above a certain value known as the Zener voltage.

3. TECHNICAL REQUIREMENTS

3.1 Temperature Sensors

3.1.1 General Sensor Requirements

3.1.1.1 Unless specifically noted, the requirements defined in this specification shall apply to all sensors.

3.1.1.2 All sensors shall comply with the requirements of Table 1. Other sensors that possess equal or better calibration accuracy may be used. Thermocouple composition shall comply with the requirements of ASTM E230 or ASTM E1751, and Table 2.

3.1.1.3 Resistance temperature devices (RTDs) shall be noble metal, shall comply with the requirements of Table 1, and shall be considered non-expendable.

3.1.1.4 Sensors may be made either from bare or coated wire, or mineral insulated/metal sheathed (MIMS) cable as described in Tables 2 and 3.

3.1.1.5 Measuring junctions shall be made by either of the following methods:

- Any combination of twisting and/or welding the thermoelements provided there is no addition of filler metal (including ungrounded and grounded MIMS).
- Spot welding the thermoelements directly to a part, simulated part, or heat sink is permitted for temperatures ≤2000 °F or 1100 °C.

Table 1 - Sensors and sensor calibration[12]

Sensor	Use	Type[1][10]	Calibration		Calibration Accuracy[2]
			Interval	Standard	
Reference standard	Primary standard calibration[5]	B, R, S	Before first use; 5 years	NIST[4] reference standard	Refer to NIST or equivalent calibration report
Primary standard	Secondary standard calibration[6]	B, R, S	Before first use; 3 years	Reference standard[5]	Type R, S: ±1.0 °F or ±0.6 °C or ±0.1% Type B: ±0.25%
Secondary standard[7]	Sensor calibration	B, R, S, RTD[10]	Before first use; 2 years	Primary standard[6]	Type R, S: ±1.0 °F or ±0.6 °C or ±0.1%[13] Type B: ±0.25%[13] Refractory[9] Base metal: ±2.0 °F or ±1.1 °C or ±0.4%[11] RTD[10]
System accuracy test[3]		B, R, S, RTD, base metal, and refractory	Before first use[3]	Primary or secondary standard[8]	
Temperature uniformity survey[3]					
Control, and recording[3]	Installation in thermal processing equipment	B, R, S, RTD, base metal, and refractory	Before first use[3]	Primary or secondary standard[8]	
Load[3]	Sensing part or raw material temperature		Before first use[3]		

Notes:

(1) Sensors of equal or better calibration accuracy are acceptable.
(2) Percent of reading or correction factor in °F or °C, whichever is greater.
(3) Sensor recalibration and reuse requirements are provided in Table 5.
(4) NIST or other internationally recognized standards organization.
(5) A reference standard sensor together with a primary standard instrument shall be used to calibrate primary standard sensors.
(6) A primary standard sensor together with a primary standard instrument shall be used to calibrate secondary standard sensors.
(7) Use shall be limited to the calibration of control, recording and load sensors, SAT, and TUS sensors.
(8) A primary or secondary standard sensor together with a primary or secondary standard instrument shall be used to calibrate these sensors.
(9) For refractory sensors Type C: ±8.0 °F or ±4.4 °C or ±1%, the sensor correction factor shall be used for all applications.
(10) RTDs, when used, shall be platinum type and meet Class/grade A tolerances given in ASTM E1137 or IEC 60751. This does not apply to RTDs used in conjunction with a refrigeration equipment controller.
(11) For temperatures <32 °F or <0 °C for Types K, E, and T only, calibration accuracy shall meet the following:
Type K: -328 to 32 °F, ±4.0 °F or -200 to 0 °C, ±2.2 °C, or ±2.0 % for either, whichever is greater.
Type E (MIMS): -328 to 32 °F, ±4.0 °F or -200 to 0 °C, ±2.2 °C, or ±2.0 % for either, whichever is greater.
Type E (all other): -328 to 32 °F, ±3.0 °F or -200 to 0 °C, ±1.7 °C, or ±1.0 % for either, whichever is greater.
Type T: -328 to 32 °F, ±1.8 °F or -200 to 0 °C, ±1.0 °C, or ±1.5 % for either, whichever is greater.
(12) Sensors and sensor materials are normally supplied to meet the tolerances specified in the table for temperatures above 32 °F or 0 °C. The same materials, however, may not fall within the tolerances for temperatures below 32 °F or 0 °C. Two separate sensors may be required, one for each range.
(13) When correction factors are used during production:
Type B sensors shall meet a calibration accuracy of ±0.5%,
Types R and S sensors shall meet calibration accuracy of ±2.7 °F or ±1.5 °C or ±0.25%, whichever is greater.

Table 2 - Sensor and extension wire/connector

Sensor					Extension Wire		
Classification	Type	Positive Element Composition Nominal wt. %	Negative Element Composition Nominal wt. %	Element Color Code	Wire Code Positive/Negative	Jacket Color Code(1)	Connector Color Code(1)
Base Metal	J	Fe	55Cu/45Ni	White/Red	JPX/JNX	Black	Black
	E	90Ni/10Cr	55Cu/45Ni	Purple/Red	EPX/ENX	Purple	Purple
	K	90Ni/10Cr	95Ni/5, Al + Si	Yellow/Red	KPX/KNX	Yellow	Yellow
	N	84.5Ni/14Cr/1.5Si	95.4Ni/4.5Si/0.1Mg	Orange/Red	NPX/NNX	Orange	Orange
	M(3)	82Ni/18Mo	Ni	Yellow/Red	KPX/KNX	Yellow	Yellow
	T	Cu	55Cu/45Ni	Blue/Red	TPX/TNX	Blue	Blue
Noble Metal(2)	R	87Pt/13Rh	PT	Black/Red	RPX/RNX or SPX/SNX	Green	Green
	B	70Pt/30Rh	94Pt/6Rh	Gray/Red	BPX/BNX	Gray	Gray
	S	90Pt/10Rh	PT	Black/Red	RPX/RNX or SPX/SNX	Green	Green
Refractory(2)	C	95W/5Re	74W/26Re	Green/Red	CPX/CNX	Red	Red

Notes:

(1) All color codes stated are in accordance with ASTM E230. Color codes in accordance with other internationally recognized standards organizations are acceptable.

(2) Most base metal extension wires have the same nominal composition as the sensor wires with which they are intended to be used, whereas the compensating extension wires for noble metal (Types S, R, and B) or refractory metal sensors (Type C) are usually of a different, more economical composition whose relative thermoelectric properties as a pair nonetheless closely approximate those of the noble metal or refractory metal sensors with which they are to be used over a limited temperature range.

(3) The designation “Type M” may not be recognized by all international standards. Type K extension wire and connectors shall be used for Type M sensors.

Table 3 - Sensor classification[(2)]

Sensor Cover	Sensor Classification[(1)]
Fiberglass, plastic, or trade name	Expendable
Multiple hard fired ceramic beads	Expendable
Metal over-braid	Expendable
Shielded from the process atmosphere by a closed metal/ceramic protective tube	Non-expendable
Mineral insulated; metal sheathed (MIMS)	Non-expendable
Mineral insulated; metal sheathed (MIMS) with an exposed measuring junction	Expendable

Note:
(1) See definitions for expendable/non-expendable sensors.
(2) The configuration of the sensor at the time of manufacture or assembly shall determine its classification (e.g., fiberglass covered wire inserted into a closed metal protection tube is expendable, bare wire with ceramic insulators purchased installed inside a closed metallic protection tube is non-expendable).

3.1.2 Sensor Temperature Range of Use

Guidelines for sensor temperature range usage can be found in ASTM MNL12, ASTM E230, ASTM E608, ASTM E1137, ASTM E1751, IEC 60751, or other internationally recognized standard and the sensor supplier.

3.1.3 Extension Wire and Connectors

3.1.3.1 Extension wire shall be of the same nominal composition as the sensor and instrumentation used, except when compatible compensating extension wire is allowed (e.g., noble metals). Extension wire shall meet the requirements of Table 2.

3.1.3.2 Extension wire shall not be spliced other than using a compatible connector.

3.1.3.3 Connectors, plugs, jacks, and terminal strips are permitted if they are the compatible type, i.e., they have thermo-electric properties conforming to the characteristics of the corresponding sensor type.

3.1.3.4 Wireless transmitters may be used as an alternative to extension wire.

3.1.4 Sensor Calibration

3.1.4.1 The sensor calibration technique shall comply with ASTM E207 or ASTM E220, or other internationally recognized standards.

3.1.4.2 Sensors shall be calibrated before their first use.

3.1.4.3 Sensor calibration intervals whether based on time, number of uses, or temperatures are the maximums permitted.

3.1.4.4 Users shall have procedures that control the replacement of thermal process equipment sensors including limits on maximum life and/or number of uses based on supporting data such as, but not limited to, SAT, TUS, and re-calibration data, and/or trend analysis.

3.1.4.5 Sensors shall be calibrated or re-calibrated at or lower than the lowest temperature of use and at or higher than the highest temperature of use. Sensors used at a single temperature may be calibrated at the single temperature of use.

3.1.4.6 Intervals between calibration or re-calibration temperatures provided by the calibration agency shall not exceed 250 °F or 140 °C for all sensors.

3.1.4.7 Extrapolation of calibration correction factors above the highest calibration temperature and below the lowest calibration temperature is prohibited by any calibration source except NIST or other internationally recognized standards organization.

3.1.4.8 Interpolation of correction factors between two known calibration points is permitted using the linear method.

3.1.4.9 Alternatively, the correction factor of the nearest calibration point shall be used.

3.1.4.10 Whichever method is used shall be defined and applied consistently.

3.1.4.11 For recalibration of sensors when permitted in Table 5, it is acceptable to use either the date of recalibration, or the date of first use following recalibration as the beginning of the calibration period. Procedures shall identify how the practice is applied and documented to ensure compliance.

3.1.5 Wire/Cable Rolls

3.1.5.1 Calibrated expendable or non-expendable sensors made from rolls may be used in lieu of individually calibrated sensors.

3.1.5.2 The maximum length of wire/cable in a roll at the time of calibration shall comply with Table 4.

Table 4 - Maximum permitted length of wire/cable in a roll

Sensor	Maximum Permitted Length of Wire/Cable in a Roll
Primary standard	200 feet or 60 m
All other noble metal	2000 feet or 610 m
All other base metal	5000 feet or 1525 m
Refractory	2000 feet or 610 m

3.1.5.3 Rolls shall be sampled and calibrated at both ends. The individual correction factors from each end shall be within the requirements of Table 1 and the average correction factor shall be calculated from both ends of the roll at each calibration temperature and used for the entire length of the roll.

3.1.5.4 The roll shall not be used if the difference between the correction factors from each end of the sample sensors at any individual calibration temperature exceeds:

a. 1.0 °F or 0.6 °C for primary and secondary standard sensors.

b. 2.0 °F or 1.1 °C for control, recording, and load sensors, SAT, and TUS sensors.

3.1.5.5 The following shall apply to rolls not meeting the requirements of 3.1.5.4:

a. It is permitted to divide the roll into shorter lengths provided the shorter lengths meet the requirements of 3.1.5.4.

b. It is permitted to use individual sensors from the roll provided they are calibrated to the requirements of Table 1.

3.1.6 General Sensor Reuse Requirements

Reuse of any sensor is not permitted unless the insulation remains intact and the wire/cable including the measuring junction are not damaged (see Table 5).

Table 5 - Sensor reuse and recalibration

Sensor Use	Sensor Type	Form	Recalibration(3)	Reuse(1)(2)
Test Sensors TUS	Base and Refractory	Expendable	Recalibration of expendable base metal sensors is not permitted	• Quarterly when used at or below 500.0 °F or 260.0 °C • M, C, T, K, E: Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.7.3) • J, N: Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.7.3)
		Non-expendable	M, C, T, J & N: Quarterly (see Table 1) E & K: Quarterly; permitted if used at or below 500.0 °F or 260.0 °C; not permitted if used above 500.0 °F or 260.0 °C	No other restrictions
	Noble(4)	Expendable Non-expendable	Semi-annually (see Table 1)	No other restrictions
Test Sensor Nonresident SAT	Base and Refractory	Expendable	Recalibration ofexpendable base metal sensors is not permitted	• Quarterly when used at or below 500.0 °F or 260.0 °C • M, C, T, K, E: Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.7.3) • J, N: Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.7.3)
		Non-expendable	M, C, T, J & N: Quarterly (see Table 1) E & K: Quarterly; permitted if used at or below 500.0 °F or 260.0 °C; not permitted if used above 500.0 °F or 260.0 °C	No other restrictions
	Noble(4)	Expendable Non-expendable	Semi-annually (see Table 1)	No other restrictions
Test Sensors Resident SAT	Base	Expendable	Recalibration of expendable base metal sensor is not permitted	M, E, J, K, T: Shall only be used at or below 500.0 °F or 260.0 °C N: Shall only be used at or below 1000.0 °F or 538.0 °C and is limited by the number of uses, temperature, and calendar days (see 3.1.7.3)

Sensor Use	Sensor Type	Form	Recalibration[3]	Reuse[1][2]
		Non-expendable	M, T, J, N: Quarterly E & K: Quarterly; permitted if used at or below 500.0 °F or 260.0 °C (see Table 1)	M, E, J, K, T: Shall only be used at or below 500.0 °F or 260.0 °C N: No other restrictions
	Noble[4]	Expendable	Semi-annually (see Table 1)	Shall only be used at or below 1000.0 °F or 538.0 °C
		Non-expendable		No other restrictions
Control and Recording Sensors	All	All	Before first use	Replaced in accordance with 2.2.42, 3.1.4.4, 3.4.8, and 3.4.9
Load Sensors	Base and Refractory	Expendable	Recalibration is not permitted	Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.10.1, 3.4.8, and 3.4.9)
		Non-expendable	M, C, T, J & N: Quarterly E & K: Quarterly; permitted if used at or below 500.0 °F or 260.0 °C; not permitted if used above 500.0 °F or 260.0 °C	Limited by number of uses, temperature of use, and calendar days since first use (see 3.1.10.2, 3.4.8, and 3.4.9)
	Noble[4]	Expendable	Semi-annually except as stated in 3.4.8 and 3.4.9 (see Table 1)	No other restrictions except as stated in 3.4.8 and 3.4.9
		Non-expendable		

Notes:
(1) For reuse of any Type E or K sensor used above 500.0 °F or 260.0 °C, the depth of insertion shall be equal to or greater than any previous use (see 3.1.7.1).
(2) See 3.1.6 and 3.1.7 for general reuse restrictions.
(3) Recalibration of any Type E or K sensor used above 500.0 °F or 260.0 °C is prohibited.
(4) Includes RTDs.

3.1.7 SAT and TUS Sensor Reuse

3.1.7.1 During the reuse of Type E or K sensors when used above 500.0 °F or 260.0 °C, the depth of insertion shall be equal to or greater than any previous use.

3.1.7.2 Expendable base metal, noble metal, and refractory SAT and TUS sensors may be reused:

a. Base metal and refractory sensors may be used for up to 3 months from first use, without limit to number of uses, when used exclusively at or below 500.0 °F or 260.0 °C.

b. Noble metal sensors may be used for up to 6 months from first use, without limit to number of uses or temperature of use.

3.1.7.3 Expendable Base Metal and Refractory SAT and TUS Sensors:

a. Types M, C, T, K, and E shall be limited to 3 months or five uses, whichever occurs first, between 500.0 °F and 1200.0 °F or between 260.0 °C and 650.0 °C, and limited to a single use above 1200.0 °F or 650.0 °C.

b. Types J and N shall be limited to 3 months or ten uses, whichever occurs first, between 500.0 °F and 1200.0 °F or between 260.0 °C and 650.0 °C, and limited to a single use above 1200.0 °F or 650.0 °C.

3.1.7.4 Records shall be maintained of the accumulated sensor reuse including sensor batch number, temperature, and use count.

3.1.7.5 Base metal or refractory TUS sensors shall be limited to no more than the maximum number of uses defined in 3.1.7.3 for expendable sensors, Table 6 for non-expendable sensors, or 6 months from first use, whichever occurs first, and may be reused subject to the limitations of 3.1.6 and 3.1.8 that are:

a. Used exclusively ≤1200 °F or ≤650 °C,

b. Identified by the date of installation and by the number and temperatures of accumulated uses, and

c. Preserved/protected from damage (i.e., crimping, excessive moisture contact, corrosion, etc.) between each TUS or remain installed on a rack that is protected between each TUS.

3.1.8 Sensor Salvage

3.1.8.1 Salvage of damaged expendable sensors is permitted if the discrepant portion including any portion previously exposed inside of the furnace is removed and the hot junction remade.

3.1.8.2 The salvaged sensor's original calibration data shall be used.

3.1.9 Control and Recording Sensors

3.1.9.1 Control sensors shall be positioned in thermal processing equipment to ensure control and maintain temperature uniformity of the equipment within the qualified work zone. Recording sensors shall be located in accordance with the applicable instrumentation type (see Table 9).

3.1.10 Base Metal Load Sensors

3.1.10.1 Expendable base metal and refractory load sensors may be used:

a. Up to 3 months after first use without limit to number of uses when used at or below 500.0 °F or 260.0 °C.

b. Types M, C, T, K, and E shall be limited to 3 months or five uses, whichever occurs first, between 500.0 °F and 1200.0 °F or between 260.0 °C and 650.0 °C, and limited to a single use above 1200.0 °F or 650.0 °C.

c. Types J and N shall be limited to 3 months or ten uses, whichever occurs first, between 500.0 °F and 1200.0 °F or between 260.0 °C and 650.0 °C, and limited to a single use above 1200.0 °F or 650.0 °C.

3.1.10.2 The life of non-expendable base metal load sensors shall be limited by the maximum operating temperature and the number of calendar days since the first use.

3.1.10.3 Records shall be maintained of the accumulated load sensor use above 500 °F or 260 °C including sensor batch number, load cycle, temperature, and use count. The use count shall include uses during SAT and TUS.

3.1.10.4 The maximum replacement interval or number of uses, whichever occurs first since first use of non-expendable base metal load sensors, shall comply with Table 6.

Table 6 - Non-expendable base metal load sensor use temperature, interval or uses

Set Temperature		Maximum Replacement Interval or Number of Uses
>2300 °F	>1260 °C	One use
>2200 to ≤2300 °F	>1205 to ≤1260 °C	Quarterly or 10 uses
>1800 to ≤2200 °F	>980 to ≤1205 °C	Quarterly or 90 uses
>1200 to ≤1800 °F	>650 to ≤980 °C	Quarterly or 180 uses
>500 to ≤1200 °F	>260 to ≤650 °C	Quarterly or 270 uses
≤500 °F	≤260 °C	Quarterly unlimited uses

3.1.10.5 When load sensors are used in multiple qualified temperature ranges, the shortest interval or use shall apply.

Example 1: A sensor with nine uses at 2250.0 °F or 1232.0 °C has only one more use allowed in the 2200.0 to 2299.9 °F or 1204.5 to 1259.9 °C range, or any lower operating range. No uses remain at 2300.0 °F or 1260.0 °C or above.

Example 2: A sensor with 50 uses between 1400.0 °F and 1600.0 °F or 760.0 °C and 871.0 °C is then used at 1820.0 °F or 993.0 °C.

The sensor has already exceeded the use limits for all ranges above 2199.9 °F or 1204.4 °C.

The sensor is now subject to the 90 use limit as it has been used in a higher temperature range.

Example 3: A sensor with 50 uses between 1400.0 °F and 1600.0 °F or 760.0 °C and 871.0 °C is then used at 1015.0 °F or 546.0 °C.

The sensor has already exceeded the use limits for all ranges above 2199.9 °F or 1204.4 °C.

The sensor is subject to a 180 use limit as it has been used in the 1200.0 to 1799.9 °F or 648.9 to 982.2 °C temperature range.

3.1.11 Sensor Calibration Results and Records

3.1.11.1 The results of sensor calibration or re-calibration shall be documented. The documentation shall include:

a. Identification of the sensor, batch of sensors or wire/cable rolls.

b. Sensor type, e.g., K, N, E, RTD, etc.

c. Date of calibration or recalibration.

d. Quantity or length of wire/cable rolls represented in calibration report.

e. Identification if the calibration was initial or a recalibration.

f. The required calibration accuracy.

g. Identification of the standard test sensor and standard test instrument used.

h. Nominal calibration temperatures.

i. Actual temperature readings of the sensor(s) being calibrated.

j. Calibration technique referencing ASTM E220 or other internationally recognized standards.

k. Correction factors or deviations/errors for each calibration temperature, including the average correction factor representing both ends for wire/cable rolls.

l. Documentation shall clearly state deviation (error) or correction factor.

m. A statement of traceability to NIST or other internationally recognized standards organization.

n. Identification of the calibration agency.

o. Identification of technician performing calibration.

p. Approval of an authorized agent for the calibration agency.

q. User quality organization approval.

3.2 Instrumentation

3.2.1 General Instrumentation Requirements

3.2.1.1 Conversion from millivolts to degrees or degrees to millivolts shall be in accordance with ASTM E230 or other internationally recognized standards.

3.2.1.2 Output of sensors shall be converted to temperature readings by instruments specified herein or instruments of equal or greater accuracy.

3.2.1.3 Instruments shall be calibrated in accordance with Table 7 and shall be traceable to NIST or other internationally recognized standards organization.

3.2.1.4 Process recording data collection shall be a minimum of six data points for each recorded sensor during each time at temperature processing cycle not to exceed 10-minute intervals.

3.2.1.5 Data collection intervals shall be sufficient to demonstrate conformance to cooling rate requirements.

3.2.1.5.1 The recording instrument shall actively record/collect data during the entire time that parts or raw material are in the thermal processing equipment. In cases where load sensors must be disconnected to transfer the load, users shall have other objective evidence of process compliance (e.g., data showing temperature drop from the temperature of other furnace recording sensor(s) compliant with the soak period).

Table 7 - Instruments and instrument calibration

Instrument	Instrument Type	Maximum Calibration Period[9]	Calibration Standard	Calibration Accuracy[1]	Use
Reference standard	Precision voltage reference	3 years	Precision Voltmeter or Voltage Reference Standard	NIST[6]	Limited to primary standard calibration[8]
Primary standard instrument	Potentiometer, digital voltmeter[1]	3 years	Reference standard	±0.1 °F or ±0.05 °C or ±0.015% of temperature reading, whichever is greater	Limited to laboratory calibration of secondary standard instruments, field test instruments, primary and secondary standard sensors[8]
Secondary standard instrument	Potentiometer or digital voltmeter[1]	Annually	Primary standard instrument	±0.3 °F or ±0.2 °C or ±0.05% of temperature reading, whichever is greater	Limited to laboratory calibration of field test instruments, SAT sensors, TUS sensors, load sensors, and control, and recording sensors[8]
Field test instrument[7]	SAT/TUS portable potentiometer or digital instrument, electronic data recorder or data acquisition system	Quarterly	Primary or secondary standard instrument	±1.0 °F or ±0.6 °C or ±0.1% of temperature reading, whichever is greater	Limited to calibration of control, or recording instruments, performing SAT and TUS[5][8]
Control, over-temperature, recording, data acquisition instrument[7]	Digital instrument	Note[3]	Field test instrument	±2.0 °F or ±1.1 °C or 0.2% of temperature reading, whichever is greater[10]	Limited to control, and recording the temperature of thermal processing equipment
	Mechanical or thermal element[2]	Note[3]	SAT in lieu of calibration	±5.0 °F or ±3.0 °C	Limited to temperature measurement of refrigeration and quench equipment[4]

Notes:
(1) Instruments of equivalent or greater accuracy are acceptable.
(2) Applicable to quench or refrigeration equipment only. (3) Instrument calibration intervals shall be:

Furnace Class	Control, over-temperature, recording, data acquisition instrument Interval	Over-temperature Instruments used solely for furnace over-temperature protection Interval
1	Monthly	May be reduced to Annually
2	Quarterly	
3	Quarterly	
4	Quarterly	
5	Semi-annually	
6	Semi-annually	
Refrigeration and quench equipment(4)	Semi-annually	

(4) When the refrigeration and/or quench equipment sensor is connected to a channel in a furnace recording instrument the interval for calibration of that channel in the recording instrument shall be the same calibration interval as the other channels in the instrument.
(5) Field test instruments meeting the accuracy requirements of secondary standards may be used to calibrate SAT and TUS instruments in the field. These instruments shall be calibrated quarterly using a primary standard.
(6) NIST or other internationally recognized standards organization. Per Manufacturer's Specifications for Reference Standard Instruments (e.g., stability of 2 µV/V per year) and NIST or equivalent Calibration for Reference Standard Instruments.
(7) Includes wireless transmission systems.
(8) Instruments shall be stored and used in the environment specified by the instrument manufacturer.
(9) Calibration periods for instruments shall begin on the date of calibration.
(10) Digital control instruments that only read in whole numbers shall have maximum calibration accuracy of ±2 °F or ±1 °C or ±0.2% of the temperature reading rounded inward towards the smaller whole number.

3.2.2 Test Instruments (Primary Standard, Secondary Standard, and Field Test)

3.2.2.1 Primary and secondary standard instruments shall be digital and meet the calibration accuracy requirements of Table 7 in degrees of temperature or in millivolts that can be converted to demonstrate equivalent accuracy.

3.2.2.2 Field test instruments shall be digital and have a minimum readability of 0.1 °F or 0.1 °C for any input and output used.

3.2.2.3 Test instrument calibration shall be performed at a minimum of six simulated sensor input and/or output signals. These shall include the minimum and maximum of the operating range used for test or calibration and a minimum of four points in between either representing areas of normal operation or spaced at approximately equal intervals across the range in which the instrument is used for test or calibration.

3.2.2.3.1 For test instruments used only at a single temperature, the calibration shall be performed at that single temperature.

3.2.2.4 Calibration shall be performed for each type of input and output used, e.g., each sensor type in use and for mV, mA, etc., if the instrument is used for these scales.

3.2.2.5 Calibration shall be performed on each channel in use that can be altered or adjusted individually, or on each group of channels that can be altered or adjusted as a group. Channels not in use shall be blocked or tagged to prevent unintentional use.

3.2.2.6 A test instrument meeting the accuracy of a secondary standard may be used in a production environment as a field test instrument. The calibration frequency shall be the same as a field test instrument and the instrument shall be operated within the environmental conditions specified by the instrument manufacturer.

3.2.3 Control, Recording, and Over-Temperature Instruments

3.2.3.1 All control, recording, and over-temperature instruments shall be digital.

3.2.3.2 Digital recording instruments shall produce permanent records with a minimum readability of 0.1 °F or 0.1 °C.

3.2.3.2.1 Digital recording instruments that only read in whole numbers may be used for 1 year after the release of AMS2750 Rev G and shall have maximum calibration accuracy of ±2 °F or ±1 °C or ±0.2% of the temperature reading rounded inward towards the smaller whole number.

3.2.3.3 Instruments shall receive an unmodified signal from sensors except for analog to digital and digital to analog conversions, or a digitally processed, error-checked equivalent representation of a direct measured value.

3.2.3.4 Calibration shall be performed in the as-found condition taking into account any applied and documented offsets at a minimum of three simulated sensor inputs at the minimum, maximum and at least one point in the middle third of the entire qualified operating temperature range to document the as-found condition.

3.2.3.5 For equipment that does not have a defined qualified operating temperature range (e.g., quench tanks and refrigeration equipment), calibration shall be performed at a minimum of three simulated sensor inputs at the minimum, maximum and at least one point in the middle third of the operating range used.

3.2.3.5.1 Instrument calibration points for equipment with a qualified operating temperature range and an unqualified operating range of use, such as a cryogenic-temper unit, shall be in accordance with 3.2.3.4 for the qualified operating range and in accordance with 3.2.3.5 for the unqualified range of use.

3.2.3.6 For control, recording, and over-temperature instruments used only at a single temperature, the instrument calibration shall either be performed at that single temperature of use, or in accordance with 3.2.3.4 or 3.2.3.5 as applicable.

3.2.3.7 The instrument error is the difference between the readings of the instrument being calibrated and the field test instrument. When any documented modification offsets are used in production, the reading of the instrument being calibrated shall be corrected algebraically.

3.2.3.8 Following any calibration adjustments, the instrument shall be verified in accordance with 3.2.3.4, 3.2.3.5, or 3.2.3.6 as applicable to document the as-left condition.

3.2.3.9 Calibration shall be performed on each channel in use that can be altered or adjusted individually, or on each group of channels that can be altered or adjusted as a group.

3.2.3.10 All active channels of multi-channel digital recording instruments shall be calibrated. Channels not in use shall be identified to prevent unintentional use.

3.2.3.11 When the control and recording system is integrated such that the digitally displayed control value and the digitally recorded value are generated from the same measurement circuit and cannot be different, it is only necessary to document a single displayed/recorded value for the control reading.

3.2.3.12 For retort furnaces, the temperature of the furnace shall be controlled such that the specified temperature is maintained within the retort. As a minimum, the control instrument shall be calibrated across the temperature range of use within the retort.

3.2.3.13 Refrigeration and quench equipment control instruments that display temperature shall be calibrated. All recording instruments shall be calibrated (see Table 7).

3.2.3.14 The timing function for all digital recording instruments and data acquisition systems shall be calibrated at least annually and shall be accurate to ±1 min/h. The calibration may be performed for a time ≤1 hour and the results converted to meet ±1 min/h.

3.2.3.15 External timing devices such as timers, clocks, stopwatches, etc., shall be calibrated at least every 2 years and shall be accurate to ±1 s/min.

3.2.3.16 As an alternative to 3.2.3.14 or 3.2.3.15, a defined digital synchronization of digital recording instruments and data acquisition systems or external timing devices, to NIST or other international equivalent, via satellite, internet, or telephonic systems at least monthly to support a ±1 min/h accuracy is acceptable.

3.2.3.17 Wireless equipment which performs the analog to digital conversion at the furnace and transmits a digital signal to the recording instrument is permitted. However, calibration of the complete wireless system (wireless transmitter, wireless receiver and associated control and recording instruments) is required.

3.2.4 Electronic Records

3.2.4.1 An electronic record is any combination of text, graphics, data, audio, pictorial, or other information represented in digital form that is created, modified, maintained, archived, retrieved, or distributed by a computer system.

3.2.4.2 When using a system (control, recording or data acquisition) that creates electronic records the system shall:

a. Create records that cannot be altered without detection.

b. Provide software and playback utilities as a means of examining and/or compiling the data but shall not allow the user any means for altering the source data.

c. Provide the ability to generate accurate and complete copies of records in both human readable and electronic form suitable for inspection, review, and duplication.

d. Be capable of providing evidence the record was reviewed by recording an electronic review, or a method of printing the record for a physical marking verifying review.

e. Support protection, retention, and retrieval of accurate records throughout the record retention period.

f. Ensure that the hardware and/or software shall operate throughout the retention period as specified in 3.7.

g. Provide methods of protection, such as a password, to limit system access to only individuals whose authorization is documented.

3.2.4.3 Evidence shall be provided that software revisions are verified to ensure continued compliance with the material or process specification requirements and once installed have not altered programs, recipes, or other means used to control thermal processing parameters.

3.2.5 Instrumentation Calibration Results and Records

3.2.5.1 A label or labels affixed to or in close proximity to the instrument shall indicate the most recent successful calibration. As a minimum, the label(s) shall include:

a. Instrument number or furnace number.

b. Date the calibration was performed.

c. Due date of the next calibration.

d. Identification of the technician who performed the calibration.

e. Indication if any limitations or restrictions of the calibration. A notation such as "see report" is acceptable.

3.2.5.2 The results of instrument calibration shall be documented. As a minimum, the documentation shall include:

a. Unique identification of the instrument.

b. Make and model of the instrument calibrated.

c. Unique Identification of the test instrument used during calibration.

d. Identification of each sensor type in use (e.g., Type K, N, etc.) and form (e.g., V, mA, etc.) if the instrument is used for these scales.

e. Identification of location where signal was input (only required for measurement systems employing the alternate SAT).

f. Required calibration accuracy.

g. As-found data at each calibration point and as-left data if any adjustments are made, to include:

    1. Nominal test temperature.

    2. Reading of the instrument being calibrated

    3. Error or correction factor of test instrument (optional or when specified by the customer).

    4. Error or correction factor of instrument under test (corrected or uncorrected for test instrument error when specified).

h. Correction and modification offsets as-found and as-left in accordance with 3.2.6.

i Instrument calibration pass or fail statement.

j. Any limitations or restrictions of the calibration.

k. Date the calibration was performed.

l. Due date of the next calibration.

m. Statement of traceability to NIST or other internationally recognized standards organization.

n. Identification of the technician who performed the calibration.

o. Identification of the calibration agency if calibration is not performed internally.

p. Approval of an authorized agent for the calibration agency if not performed internally.

q. User quality organization approval.

3.2.6 Thermal Process Equipment Instrument Correction and Modification Offsets (see 2.2.38.1 and 2.2.38.2)

3.2.6.1 General Instrument Correction and Modification Offset Requirements

3.2.6.1.1 If instrument correction and/or modification offsets are used, a documented procedure shall exist describing when and how to make instrument correction and/or modification offsets.

3.2.6.1.2 The maximum cumulative correction offset shall not exceed the uniformity tolerance for the thermal processing equipment or ±5.0 °F or ±2.8 °C for refrigeration and quench instruments. (e.g., a Class 2 furnace instrument is limited to a maximum correction offset of ±10.0 °F or ±6.0 °C).

3.2.6.1.3 Instrument correction and/or modification offsets may be either internal (electronic) or external (manual), and shall be included in the calibration, SAT, and TUS documentation.

3.2.6.1.4 Controlling instrument modification offsets for TUS shall not exceed the allowances in Table 15 or 16.

3.2.6.1.5 TUS modification offsets are not permitted on recorder channels other than for the channel recording the control sensor temperature.

3.2.6.1.6 SAT modification offsets are not allowed. Control and recording instrument correction offsets for SAT shall not exceed the allowance in Table 15 or 16.

3.2.6.1.7 For load sensor systems used in production, correction offsets are allowed, but not modification offsets.

3.3 Thermal Processing Equipment:

3.3.1 Furnace classes are defined in Table 8 and are based on the furnace class specified. When not specified, the furnace class shall meet the TUS requirements established in the governing specification for the parts or raw material being processed. Instrumentation types are defined by the level of instrumentation used to control, record, or indicate the desired temperature. Intervals for controlling and recording instrument calibration, SATs, TUSs, are based on the combined furnace class and instrumentation type stated in Table 7, 11, 12, 15, or 16.

Table 8 - Furnace class uniformity tolerances

Furnace Class	Temperature Uniformity Tolerance, °F	Temperature Uniformity Tolerance, °C[(1)]
1	±5.0	±3.0
2	±10.0	±6.0
3	±15.0	±8.0
4	±20.0	±10.0
5	±25.0	±14.0
6	±50.0	±28.0

Notes:
[(1)] Some design authorities require TUS tolerances of ±5.0 °C and ±7.0 °C for Class 2 and Class 3, thermal processing equipment.

3.3.2 Requirements for furnace instrumentation type classification are shown in Table 9.

Table 9 - Instrumentation type requirements

Sensor(s) Required by Instrumentation Type	Instrumentation Type[1]					
	A	B	C	D+	D	E
One control sensor per zone that controls and displays temperature.	X	X	X	X	X	X
The temperature indicated by the control sensor in each control zone shall be recorded by a recording instrument. Alternatively, the recording instrument may be connected to a second sensor contained in the same sheath or holder as the control sensor, and separated from the control sensor by no more than 0.38 inch or 10 mm.	X	X	X	X	X	
At least two additional recording sensors in each control zone shall be located to best represent the actual coldest and hottest temperatures in each control zone at any temperature of use based on the results from the most recent TUS. It is recognized that certain furnace designs/load configurations can prevent the location of these sensors in the precise coldest and hottest locations, but these sensors shall be located as close as practical (see 3.3.5 and 3.3.6). These recording locations may change over time. See 3.5.15 for relocation requirements.[2]	X		X			
At least one recording load sensor in each control zone. During production in multi-zone furnaces, empty zones (i.e., no material is placed in or intrudes into the zone) do not require a load sensor. However, a notation shall be made to the furnace load record that the zone was entirely empty.	X	X				
At least one additional recording sensor in each control zone located at least 3 inches or 76 mm from the control sensor position and of a different sensor type.[2]				X		
Each control zone shall have over-temperature protection (see 2.2.40).	X	X	X	X	X	

Notes:
[1] Instrumentation types are listed in descending order of quality from left to right; i.e., A is better than B, etc.
[2] The over-temperature protection sensor may also be utilized as the recording sensor representing the hottest location for instrumentation Type A or C or as the additional recording sensor for Type D+ if in the proper location.

3.3.3 Instrumentation Requirements for Refrigeration Equipment and Quench Systems

3.3.3.1 All refrigeration equipment shall have a temperature controller. This temperature controller requirement is not applicable to liquid nitrogen, dry ice, or dry ice/liquid-cooled containers.

3.3.3.2 All refrigeration equipment shall be equipped with a temperature recording instrument where time-at-temperature (minimum, maximum, or both) is required.

3.3.3.3 Unless otherwise specified, the requirements of 3.3.3.1 and 3.3.3.2 are not applicable during transportation of materials at sub-ambient temperatures.

3.3.3.4 Quench systems (immersion or spray) shall be equipped with a sensor that is recorded by recording instrument where temperature (minimum, maximum, or both) is required.

3.3.4 Additional Sensors

There is no limit to the number of additional recording or load sensors in any control zone, but their use shall be defined in controlled operating instructions, or procedures.

3.3.5 Hot and cold temperature sensors, when required for instrument Types A and C, as stated in Table 10, may be inserted in heat sinks (see 2.2.27), and positioned at the hottest and coldest temperature locations of the control zone based on the most recent TUS when heat sinks of similar configuration are used during the TUS.

Table 10 - Minimum sensors required per control zone

Instrumentation Type	Minimum Number of Sensors Required				
	Hottest Temperature Sensors	Coldest Temperature Sensors	Load Sensors	Over-Temperature Sensor	Additional Sensor
A	1	1	1	1	N/A
B	N/A	N/A	1	1	N/A
C	1	1	N/A	1	N/A
D+	N/A	N/A	N/A	1	1
D	N/A	N/A	N/A	1	N/A

3.3.6 The minimum sensors required are shown in Table 10.

3.3.7 For multiple control zone furnaces with <225 ft^3 or 6.4 m^3 in total qualified work zone volume, it is acceptable to treat the furnace qualified work zone volume as a single control zone for locating hot and cold temperature recording sensors (Type A or C instrumentation) and determining the number of load sensors required, regardless of the number of control sensors (Type A or B instrumentation) when the longest dimension of width, length, diameter, or height is no more than three times any of the other dimensions.

3.3.7.1 For multiple zone furnaces with ≥225 ft^3 or 6.4 m^3 in total qualified work zone volume may be divided into control zones that shall not exceed 225 ft^3 or 6.4 m^3. Each control zone shall contain all the required sensors as defined in Table 10 for a single control zone. For furnaces that have individual control zones 225 ft^3 or 6.4 m^3 or greater in volume, each control zone shall contain all the required sensors as defined in Table 10.

3.4 System Accuracy Test

3.4.1 General SAT Requirements

3.4.1.1 The SAT is an assessment of the sum of the combined errors or corrections of the sensor, extension wire (and connectors), and instrument to ensure compliance with the requirements of Table 11 or 12.

Table 11 - Parts furnace class, instrument type and SAT interval

Furnace Class	Temperature Uniformity Tolerance		Minimum Instrumentation Type	Normal SAT Interval	Extended SAT Interval	Maximum Allowable SAT Difference, Whichever is Greater		
	°F	°C				°F	°C	% of Reading
1	±5.0	±3.0	D, D+	Weekly	Weekly	±2.0	±1.1	±0.2
			B, C	Weekly	Bi-weekly			
			A	Bi-weekly	Monthly			
2	±10.0	±6.0	D, D+	Weekly	Weekly	±3.0	±1.7	±0.3
			B, C	Bi-weekly	Monthly			
			A	Monthly	Quarterly			
3	±15.0	±8.0	D	Bi-weekly	Monthly	±4.0	±2.2	±0.4
			D+	Bi-weekly	Bi-monthly			
			B, C	Monthly	Quarterly			
			A	Quarterly	Semi-annually			
4	±20.0	±10.0	D	Bi-weekly	Monthly	±4.0	±2.2	±0.4
			D+	Bi-weekly	Bi-monthly			
			B, C	Monthly	Quarterly			
			A	Quarterly	Semi-annually			
5	±25.0	±14.0	D	Bi-weekly	Monthly	±5.0	±2.8	±0.5
			D+	Bi-weekly	Bi-monthly			
			B, C	Monthly	Quarterly			
			A	Quarterly	Semi-annually			
6	±50.0	±28.0	E	Semi-annually	Semi-annually	±10.0	±5.6	N/A
Refrigeration and quench equipment				Semi-annually	Semi-annually	±5.0	±2.8	N/A

Table 12 - Raw material furnace class, instrument type and SAT interval

Furnace Class	Temperature Uniformity Tolerance °F	Temperature Uniformity Tolerance °C	Minimum Instrumentation Type	Normal SAT Interval	Extended SAT Interval	Maximum Allowable SAT Difference, Whichever is Greater °F	°C	% of Reading
1	±5.0	±3.0	D, D+	Weekly	Monthly	±2.0	±1.1	±0.2
			B, C	Monthly	Quarterly			
			A	Monthly	Quarterly			
2	±10.0	±6.0	D, D+	Weekly	Monthly	±3.0	±1.7	±0.3
			B, C	Monthly	Quarterly			
			A	Monthly	Quarterly			
3	±15.0	±8.0	D	Bi-weekly	Monthly	±4.0	±2.2	±0.4
			D+	Bi-weekly	Bi-Monthly			
			B, C	Monthly	Quarterly			
			A	Quarterly	Semi-annually			
4	±20.0	±10.0	D	Monthly	Quarterly	±4.0	±2.2	±0.4
			D+	Monthly	Four Months			
			B, C	Quarterly	Semi-annually			
			A	Quarterly	Semi-annually			
5	±25.0	±14.0	D	Monthly	Quarterly	±5.0	±2.8	±0.5
			D+	Monthly	Four Months			
			B, C	Quarterly	Semi-annually			
			A	Quarterly	Semi-annually			
6	±50.0	±28.0	E	Semi-annually	Semi-annually	±10.0	±5.6	N/A
Refrigeration and quench equipment				Semi-annually	Semi-annually	±5.0	±2.8	N/A

3.4.1.2 The SAT shall be performed on all control and recording systems required by the applicable instrumentation type, as well as any additional recording systems used for parts and raw material acceptance in each control zone of each piece of thermal processing equipment used for production heat treatments.

3.4.1.3 When the control and recording system is integrated such that the digitally displayed control value and the digitally recorded value are generated from the same measurement circuit and cannot be different, it is only necessary to document a single displayed/recorded value for the SAT.

3.4.1.4 The SAT shall be performed on additional systems used to justify SAT interval extension (see 3.4.3.2).

3.4.1.5 The SAT is not required for systems whose only function is over-temperature protection.

3.4.1.6 The SAT shall be performed using calibrated and independent SAT sensors meeting the requirements of Table 1 and calibrated and independent field test instruments meeting the requirements of Table 7.

3.4.1.7 Recording instruments used on thermal processing equipment shall not be used as a field test instrument unless it can be demonstrated that the SAT sensor recording channels of an integrated system are separated from the furnace recording system and also meet field test instrument requirements.

3.4.2 Performing a SAT

3.4.2.1 The SAT shall be performed initially and periodically thereafter in accordance with the interval requirements of Table 11 or 12.

3.4.2.2 For equipment that has documented "out of use/service" periods, a new SAT shall be performed on all applicable systems before being returned to service.

3.4.2.3 An SAT (comparison, alternate, or re-establishing the relationship for the waiver) shall also be performed after any maintenance that could affect the SAT difference. Examples include, but are not limited to:

- Replacement of the sensor for the system being tested. (i.e., systems utilizing individually calibrated sensors require an SAT upon replacement of each sensor, but systems utilizing sensors from the same calibrated roll/spool require an SAT upon replacement of the roll/spool).
- Replacement of the control or recording instrument.
- Calibration of the control or recording instrument when any adjustment has been made.
- If an internal correction offset is introduced, removed or an existing internal correction offset is altered.
- After implementation of corrective action due to a failed SAT.

3.4.2.4 The quality assurance organization shall make and document a determination whether equipment maintenance requires an SAT.

3.4.3 SAT Interval

3.4.3.1 The SAT interval shall be based upon the furnace class and instrumentation type (see 2.2.25).

3.4.3.1.1 For furnaces with multiple qualified operating temperature ranges, the SAT shall be performed in accordance with the most stringent interval for the furnace class used.

3.4.3.2 The SAT interval may be extended to the maximum allowed SAT interval in Table 11 or 12, if a preventive maintenance program is in effect as described in 2.2.42, and one of the following conditions is met:

3.4.3.2.1 At least two sensors in each control zone are non-expendable Type B, N, R, or S.

3.4.3.2.2 The relationship requirements of 3.4.9.6, 3.4.9.8, and Table 14 are documented and met.

3.4.3.2.2.1 If the weekly relationship exceeds 2.0 °F or 1.1 °C, a comparison SAT shall be performed prior to returning the thermal processing equipment to production, and the interval shall return to the normal interval until the next TUS is performed to establish the new relationship.

3.4.4 SAT Difference

3.4.4.1 The maximum allowable SAT difference shall be defined by the furnace class as shown in Table 11 or 12.

3.4.4.2 The difference calculated between the readings of the sensor system being tested (instrument/extension wire/sensor) and the corrected reading of the SAT sensor and SAT instrument (after the SAT sensor and SAT instrument correction factors have been applied algebraically) shall be documented as the SAT difference.

3.4.4.2.1 The correction factors for the SAT sensor and SAT instrument may be determined by the SAT set temperature or the observed SAT instrument reading.

3.4.4.2.2 Whichever method is used shall be defined and applied consistently.

3.4.4.3 The temperature readings from the process instrument and sensor being compared with the SAT sensor and field test instrument shall be the temperature reading, read or recorded during production heat treatment. Certain offsets, if consistently applied during production heat treatment in accordance with 3.4.4.4 and supported by documented procedures, shall be algebraically applied to the system being tested.

3.4.4.4 Allowable instrument correction or modification offsets include:

3.4.4.4.1 Internal modification offsets applied to the control and control recording channel instruments solely to correct a skewed TUS result.

Example: Reading from control instrument is 1000.0 °F and there is a -3.0 °F modification offset applied electronically to the control instrument. Then +3.0 °F shall be added to the 1000.0 °F reading before calculating the difference in 3.4.4.2.

3.4.4.4.2 A previously documented and specified manual correction offset to the control or recording instrument to correct an SAT difference.

Example: Reading from control instrument is 1352.0 °F and there is a +2.0 °F correction offset for SAT applied manually. Then -2.0 °F shall be added to the 1352.0 °F control reading before calculating the difference in 3.4.4.2.

3.4.5 Prohibited instrument offsets include:

3.4.5.1 External (manual) modification offset applied to the control instrument that has been specified for production solely to correct a skewed TUS result. These manual modification offsets have no effect on the performance of the SAT or calculation of the SAT difference.

Example: Reading from control instrument is 1905.0 °F and there is a +5.0 °F modification offset for TUS applied manually. Then the 1905.0 °F control reading is used when calculating the difference in 3.4.4.2.

3.4.6 SAT Methods

3.4.6.1 The SAT requirement may be fulfilled using any one of three methods interchangeably, provided the sensor system meets the requirements of the method implemented:

3.4.6.1.1 Comparison SAT (see 3.4.7).

3.4.6.1.2 Alternate SAT (see 3.4.8).

3.4.6.1.3 SAT waiver (see 3.4.9).

3.4.7 Comparison SAT

3.4.7.1 The displayed temperature indication and recording of the sensor being tested as used in production, with appropriate offsets or correction factors, at any temperature within the qualified operating temperature range(s), shall be compared with the corrected temperature indication of the SAT sensor on a test instrument.

3.4.7.1.1 For furnaces with multiple qualified operating temperature ranges, a periodic SAT shall be performed in each range at least annually.

3.4.7.2 The tip (measuring junction) of the SAT sensor shall be as close as practical to the tip (measuring junction) of the control, or recording sensor, but the sensor tip to tip distance shall not exceed 3 inches or 76 mm.

3.4.7.3 The SAT sensor may be inserted temporarily to perform the comparison SAT or may be a resident SAT sensor subject to the limitations of 3.4.7.4.1 to 3.4.7.4.3.

3.4.7.3.1 The resident SAT sensors shall be restricted to Type B, R, S or N at temperatures greater than 500 °F or 260 °C and shall be non-expendable at temperatures greater than 1000 °F or 538 °C (see Table 5).

3.4.7.3.2 The resident SAT sensor type shall be different from that of the sensor being tested as defined by Table 13.

Table 13 - Allowable combinations of resident SAT sensor and sensor being tested for temperatures greater than 500 °F or 260 °C

Resident SAT Sensor Type	Control or Recording Sensor Being Tested				
	B	R	S	N	All Other Sensor Types
B	No	Yes	Yes	Yes	Yes
R	Yes	No	No	Yes	Yes
S	Yes	No	No	Yes	Yes
N	Yes	Yes	Yes	No	Yes

3.4.7.3.3 The resident SAT sensor shall be affixed in position to an assembly to prevent movement in relation to the sensor under test. The position shall be verified on installation and replacement. Alternatively, the resident SAT sensor may be located independently of the sensor under test and its position shall be verified before each SAT to ensure that it has not moved between sensor installation events.

3.4.7.3.4 It is permitted to use the over-temperature sensor as the resident SAT sensor provided it is used only for over temperature protection and meets all of the requirements of an SAT sensor, 3.4.7.3, and Table 13.

3.4.8 Alternate SAT

3.4.8.1 The alternate SAT method shall only be applied to the following sensor systems:

3.4.8.1.1 Load sensor systems (expendable and non-expendable) where the sensor is used only once (single use) at temperatures >500 °F or >260 °C.

3.4.8.1.2 Load sensor systems (expendable and non-expendable) used at temperatures ≤500 °F or ≤260 °C where the sensor is replaced at the same or less than the SAT interval.

3.4.8.1.3 Control and recording sensors (e.g., hot and/or cold recording sensors for instrumentation Types A or C and the additional recording sensor for instrumentation Type D+) where the sensor is replaced at the same or less than the SAT interval. Section 3.1.10 shall also apply to base metal recording sensors when the alternate SAT is used.

3.4.8.2 Periodic calibration of control and/or recording instruments in accordance with 3.2.3.5 and meeting the requirements of Table 7 shall be performed from the point at which the sensor will be connected (including the instrument/extension wire/connector) and one of the following three options are met.

3.4.8.2.1 The sum of the sensor calibration error plus the instrument calibration error or sensor calibration correction factor plus the instrument calibration correction factor shall meet the maximum SAT difference requirements of Table 11 or 12, as appropriate.

3.4.8.2.2 Use the appropriate sensor and instrument correction factors applied manually or via programming, as allowed by the calibration limits of Tables 1 and 7, so that data used from the control and recording instrument combined meets the maximum SAT difference requirements of Table 11 or 12, as appropriate.

3.4.8.2.3 Limit instrument calibration error or correction factor and/or sensor error or correction factor such that the sum of the errors or correction factors cannot exceed the maximum SAT difference defined by Table 11 or 12 accordingly. The sensor lot identification used in the equipment during the alternate SAT period shall be documented.

Example 1: Maximum SAT difference for a Class 5 furnace is the greater of ±5.0 °F or ±3.0 °C or ±0.5% (see Table 11). Limiting instrument calibration to ±1.0 °F or ±.0.6 °C or ±0.1% and limiting sensor calibration to (±2.0 °F or ±1.1 °C or ±0.3%) will always meet the maximum SAT difference.

Example 2: Maximum SAT difference for a Class 2 furnace is the greater of ±3.0 °F or ±1.7 °C or ±0.3% (see Table 11). Limiting instrument calibration to ±1.0 °F or ±0.6 °C or ±0.1% and limiting sensor calibration to ±2.0 °F or ±1.1 °C or ±0.2% will always meet the maximum SAT difference.

3.4.8.3 The frequency of documenting the results of the alternate SAT shall be the lesser of either one of the following:

- The replacement frequency of the control or recording sensor.
- The frequency of calibration of the control or recording instrument.

3.4.8.4 The alternate SAT calculation shall be performed at each temperature on the most recent instrumentation calibration report and using sensor data from the sensor calibration report applicable to the sensor used. Sections 3.1.4.8 through 3.1.4.10 shall apply for sensor temperatures.

3.4.9 SAT Waiver

The SAT waiver requirements are as follows:

3.4.9.1 There shall be at least two recording load sensors in each control zone.

3.4.9.2 Noble metal load sensors shall be either replaced or recalibrated quarterly.

3.4.9.3 Base metal load sensors shall be controlled as follows:

3.4.9.3.1 Expendable base metal load sensors shall be single use only.

3.4.9.3.2 Non-expendable base metal load sensors shall meet the replacement requirements in Table 6 and shall be recalibrated or replaced anytime that observations, made and recorded at least weekly, reveal any unexplainable difference between their readings and the readings of the two recording sensors in 3.4.9.6.

3.4.9.4 Noble metal control and recording sensors shall be replaced at least every 2 years.

3.4.9.5 Base metal control and recording sensors shall be replaced at least quarterly.

3.4.9.6 Weekly readings at one production set point measured within 5 minutes of the end of a production soak period shall be compared. The relationship between the control sensor and an additional sensor in each control zone shall remain within 2.0 °F or 1.1 °C of their relationship determined at the time of the most recent TUS (at the nearest temperature tested during the most recent TUS). The additional sensor may be the over-temperature sensor. Weekly readings shall be taken from the same sensor pair between two consecutive TUS.

3.4.9.6.1 The two sensors chosen shall be different types following the same restrictions as resident SAT sensors in Table 13. The additional recording sensor shall be restricted to Type B, R, S, or N at temperatures greater than 500 °F or 260 °C and shall be non-expendable at temperatures greater than 1000 °F or 538 °C (see Table 5).

3.4.9.6.2 During each periodic TUS, the relationship between the control sensor system and the additional sensor system shall be determined by calculating the temperature of the control sensor minus the temperature of the additional sensor within the final 5 minutes (single reading or average of the last 5 minutes) of the TUS soak period to determine the relationship at each TUS temperature (see Table 14).

3.4.9.6.3 If the weekly relationship exceeds 2.0 °F or 1.1 °C, then 4.4 shall apply.

3.4.10 SAT Difference Pass/Fail Requirements

3.4.10.1 It is not permitted to apply modification offsets to achieve an acceptable SAT.

3.4.10.2 If the calculated SAT difference exceeds the allowable difference of Table 11 or 12, the failure shall be documented, the cause of the difference determined, and corrective action taken before commencing additional thermal processing. The requirements of Section 4 shall apply.

3.4.10.3 If the cause is wholly or partially a result of movement of the sensor being tested from its documented location and depth of insertion, it shall be returned to its original documented location and depth of insertion and the SAT repeated.

3.4.10.4 Instrument recalibration including any correction offset of the control or recording instrument calibration is permitted within the maximum limitations of Table 15 or 16. The effect of this adjustment over the entire qualified operating temperature range shall be evaluated and objective evidence that the correction offset would not cause a failure of any other calculated SAT or TUS shall be documented. The requirements of 3.4.2.2 and 4 shall apply.

3.4.10.5 All corrective actions shall be documented. After corrective action has been implemented and prior to any additional thermal processing, the SAT shall be repeated and yield an acceptable SAT difference. The results of both the failed and acceptable SAT shall be documented.

3.4.11 SAT Results and Records

3.4.11.1 Comparison SAT (see 3.4.7)

The results of the comparison SAT shall be documented. At a minimum, the documentation for each sensor system tested shall include:

a. Identification of the sensor system being tested.

b. Identification of the SAT sensor and depth of insertion when Type K or E is reused.

c. Identification of the SAT instrument.

d. Date and time of the SAT.

e. Set point of the thermal processing equipment during the SAT.

f. Observed control or recording instrument readings and recordings.

g. Observed SAT instrument readings.

h. SAT sensor correction factor.

i. SAT instrument correction factor.

j. Corrected SAT instrument reading.

k. Calculated SAT difference (control and recording instrument readings minus the corrected SAT instrument reading).

l. As-found and as-left correction and/or modification offsets if used during production.

m. SAT difference pass or fail statement.

n. Identification of the technician who performed the SAT.

o. Identification of the agency if SAT is not performed internally.

p. Approval of an authorized agent for the calibration agency if not performed internally.

q. User quality organization approval.

3.4.11.2 Alternate SAT (see 3.4.8)

The results of the alternate SAT shall be documented. At a minimum, the documentation for each sensor system tested shall include:

a. Identification of the sensor system being tested.

b. Identification of the sensor or roll.

c. Date and time of the alternate SAT.

d. Method used:

   1. Sum of calibration errors or correction factors (see 3.4.8.2.1).

   2. Correction factors applied manually or via programming (see 3.4.8.2.2).

   3. Limit instrument/thermocouple calibration errors or correction factors such that SAT is always met (see 3.4.8.2.3).

e. Final SAT results calculated for the method used with supporting documentation.

f. Identification of the technician who performed the alternate SAT, as applicable.

g. Identification of the agency if the alternate SAT is not performed internally.

h. Approval of an authorized agent for the agency performing the alternate SAT if not performed internally.

i. User quality organization approval.

3.4.11.3 SAT Waiver (see 3.4.9)

The results of the SAT waiver shall be documented. At a minimum, the documentation for each piece of thermal processing equipment shall include:

a. Identification of the thermal processing equipment using the SAT waiver.

b. Identification of the control and additional sensor system used for the relationship test.

c. Date of installation of the control and additional sensor used for the relationship test.

d. Date and temperature(s) of the most recent TUS.

e. Documentation of the relationship at each TUS temperature (see Table 14).

f. Documentation of the weekly readings and relationship (see Table 14).

g. Identification of the agency if the SAT waiver is not performed internally.

h. Approval of an authorized agent for the agency performing the SAT waiver if not performed internally.

i. User quality organization approval.

Table 14 - SAT waiver relationship

	Calculation	Examples		
Reference relationship established during TUS (Rref)	Control sensor average = $\bar{C} = \frac{T°_{ctrl\,1} + T°_{ctrl\,2} + \ \dots\ + T°_{ctrl\,n}}{n}$	1000.4 °F 538.0 °C		
	Additional sensor average = $\bar{A} = \frac{T°_{add\,1} + T°_{add\,2} + \ \dots\ + T°_{add\,n}}{n}$	1001.2 °F 538.4 °C		
	Relationship (Rref) = $R = \bar{C} - \bar{A}$	-0.8 °F -0.4 °C		
Weekly Readings Examples				
Relationship established during weekly readings (Rw)		$Week_n$	$Week_{n+1}$	$Week_{n+2}$
	Control sensor reading $T°_{ctrl}$	1000.0 °F 537.8 °C	1000.4 °F 538.0 °C	1000.4 °F 538.0 °C
	Additional sensor reading $T°_{add}$	1001.3 °F 538.5 °C	999.6 °F 537.6 °C	998.3 °F 536.8 °C
	Weekly relationship (Rw) = $T°_{ctrl}$ - $T°_{add}$	-1.3 °F -0.7 °C	+0.8 °F +0.4 °C	+2.1 °F +1.2 °C
	Weekly comparison (Rw) - (Rref)	-0.5 °F -0.3 °C	+1.6 °F -0.8 °C	+2.9 °F -1.6 °C
	Result pass/fail	Pass	Pass	Fail

3.5 Temperature Uniformity Surveys (TUS)

3.5.1 General TUS Requirements

3.5.1.1 The TUS shall be performed using calibrated and independent TUS sensors meeting the requirements of Table 1 and calibrated and independent TUS instruments meeting the requirements of Table 7.

3.5.1.2 Recording instruments used on thermal processing equipment shall not be used to record TUS sensor temperatures unless it can be demonstrated that the TUS sensor recording channels of an integrated system are separated from the thermal processing equipment recording system and also meet field test instrument requirements.

3.5.1.3 An initial TUS shall be performed to determine the temperature uniformity and establish the qualified work zone(s) and qualified operating temperature range(s).

3.5.1.4 During initial and periodic TUS, the dimensions of the measuring junction locations of the corner sensors for a square or rectangle work zone or the periphery sensors of a cylindrical work zone shall define the extremities of the work zone such that no material heat treated extends beyond these boundaries.

Table 15 - Parts furnace class, instrument type, and TUS interval

Furnace Class	Temperature Uniformity Tolerance °F	Temperature Uniformity Tolerance °C	Minimum Instrument Type	Normal Periodic TUS Interval	Required Number of Consecutive Successful Periodic TUS	Extended Periodic TUS Interval	Maximum Permitted Offset[(1)(2)(3)] °F	Maximum Permitted Offset °C	Maximum Permitted Offset Percent of Maximum Qualified Operating Temperature
1	±5.0	±3.0	D, D+	Monthly	8	Bi-monthly	±2.5	±1.5	N/A
			B, C	Monthly	4	Quarterly			
			A	Monthly	2	Semi-annually			
2	±10.0	±6.0	D, D+	Monthly	8	Bi-monthly	±5.0	±3.0	N/A
			B, C	Monthly	4	Quarterly			
			A	Monthly	2	Semi-annually			
3	±15.0	±8.0	D, D+	Quarterly	4	Semi-annually	±8.0	±5.0	0.38
			B, C	Quarterly	3	Semi-annually			
			A	Quarterly	2	Annually			
4	±20.0	±10.0	D, D+	Quarterly	4	Semi-annually	±10.0	±6.0	0.38
			B, C	Quarterly	3	Semi-annually			
			A	Quarterly	2	Annually			
5	±25.0	±14.0	D, D+	Quarterly	4	Semi-annually	±13.0	±7.0	0.38
			B, C	Quarterly	3	Semi-annually			
			A	Quarterly	2	Annually			
6	±50.0	±28.0	E	Annually	None	Annually	N/A	N/A	0.75
Unless otherwise specified, a TUS of refrigeration and quench equipment is not required							±10.0	±6.0	N/A

Notes:
(1) The maximum permitted offset shall be the same for manual and electronic methods.
(2) °F or °C or % of reading, whichever is greater.
(3) The maximum is permitted for TUS modification offsets and SAT correction offsets separately.

Table 16 - Raw material furnace class, instrument type, and TUS interval

Furnace Class	Temperature Uniformity Tolerance		Minimum Instrument Type	Normal Periodic TUS Interval	Required Number of Consecutive Successful Periodic TUS	Extended Periodic TUS Interval	Maximum Permitted Offset[1][2][3]		
	°F	°C					°F	°C	Percent of Maximum Qualified Operating Temperature
1	±5.0	±3.0	D, D+	Monthly	8	Semi-annually	±2.5	±1.5	N/A
			B, C	Quarterly	4	Semi-annually			
			A	Quarterly	2	Semi-annually			
2	±10.0	±6.0	D, D+	Monthly	8	Semi-annually	±5.0	±3.0	N/A
			B, C	Quarterly	4	Semi-annually			
			A	Quarterly	2	Semi-annually			
3	±15.0	±8.0	D, D+	Quarterly	4	Semi-annually	±8.0	±5.0	0.38
			B, C	Semi-annually	3	Annually			
			A	Semi-annually	2	Annually			
4	±20.0	±10.0	D, D+	Quarterly	4	Semi-annually	±10.0	±6.0	0.38
			B, C	Semi-annually	3	Annually			
			A	Semi-annually	2	Annually			
5	±25.0	±14.0	D, D+	Quarterly	4	Semi-annually	±13.0	±7.0	0.38
			B, C	Semi-annually	3	Annually			
			A	Semi-annually	2	Annually			
6	±50.0	±28.0	E	Annually	None	Annually	N/A	N/A	0.75
Unless otherwise specified, a TUS of refrigeration and quench equipment is not required							±10.0	±6.0	N/A

Notes:

[1] The maximum permitted offset shall be the same for manual and electronic methods.

[2] °F or °C or % of reading, whichever is greater.

[3] The maximum is permitted for TUS modification offsets and SAT correction offsets separately.

3.5.2 Initial TUS Temperatures

3.5.2.1 The initial TUS shall be performed at the minimum and maximum temperatures of each qualified operating temperature range(s).

3.5.2.2 Additional TUS temperatures shall be added to ensure that there are no more than 600 °F or 335 °C increments between adjacent TUS temperatures.

Example: If a furnace is used from 800 to 1800 °F or 425 to 980 °C, the furnace shall be surveyed at 800 °F or 425 °C, 1800 °F or 980 °C, and one intermediate temperature to meet the maximum permitted 600 °F or 335 °C range requirement. Performing a TUS at any temperature from 1200 to 1400 °F or 645 to 760 °C would satisfy the 600 °F or 335 °C range requirement.

3.5.2.3 It is not required to include hottest and coldest recording sensors for instrument Type A and C equipment during the initial TUS. The initial TUS defines the location of these sensors.

3.5.3 Periodic TUS Temperatures

3.5.3.1 Periodic TUS shall be performed at any temperature within each qualified operating temperature range(s).

3.5.3.2 A periodic TUS shall be performed at the minimum of each qualified temperature range and at the maximum temperature of each qualified operating temperature range at least annually.

3.5.3.3 TUS Temperatures for Equipment with Single Qualified Operating Temperature Range

3.5.3.3.1 For single operating temperature ranges greater than 600 °F or 335 °C, during each periodic TUS, temperatures shall be selected so that one temperature is within 300 °F or 170 °C of the maximum and another temperature is within 300 °F or 170 °C of the minimum of qualified operating temperature range(s) and there are no more than 600 °F or 335 °C increments in between adjacent TUS temperatures.

Example: If the qualified operating temperature range is 200 to 1200 °F ±10 °F or 90 to 650 °C ± 6 °C, a TUS temperature shall be selected between 200 °F and 500 °F or 90 °C and 260 °C and between 900 °F and 1200 °F or 480 °C and 650 °C. No two adjacent TUS temperatures shall be greater than 600 °F or 335 °C apart.

A TUS at 350 °F or 177 °C and at 950 °F or 510 °C would be acceptable. However, a TUS at 250 °F or 121 °C and 1000 °F or 538 °C would not be acceptable since these temperatures exceed the 600 °F or 335 °C separation increment.

3.5.3.4 TUS Temperatures for Equipment with Multiple Qualified Operating Temperature Ranges

3.5.3.4.1 For equipment with multiple operating temperature ranges, each sub-range shall be treated as a single operating temperature range and the requirements of 3.5.3.1, 3.5.3.2, and 3.5.3.3 apply to each sub-range.

Example 1: A furnace may be qualified to operate within from 600 to 1000 °F ± 10.0 °F or 315 to 540 °C ± 6.0 °C and from 1000 to 1800 °F ± 25.0 °F or 540 to 980 °C ± 14.0 °C. The furnace contains two separate qualified operating temperature ranges.

A furnace meeting ±10.0 °F at 1000 °F or ±6.0 °C at 540 °C automatically meets ±25.0 °F at 1000 °F or ±14.0 °C at 540 °C; therefore, a duplicate TUS at 1000 °F or 540 °C is not required.

Example 2: If the qualified operating temperature ranges are 800 to 1025 °F ± 10.0 °F or 425 to 550 °C ± 6.0 °C, 1025 to 1400 °F ± 15.0 °F or 550 to 760 °C ± 8.0 °C and 1400 to 1600 °F ± 25.0 °F or 760 to 870 °C ± 14.0 °C.

Annually, the TUS would be performed at: 800 °F and 1025 °F or 425 °C and 550 °C and meet ±10.0 °F or ±6.0 °C, 1400 °F or 760 °C and meet ±15.0 °F or ±8.0 °C and 1600 °F or 870 °C and meet ±25.0 °F or ±14.0 °C.

3.5.4 Equipment Modifications and Repairs

When maintenance is performed on thermal processing equipment, the maintenance task shall be documented, and a determination shall be made and documented by the user quality assurance organization whether any testing is required before returning the equipment into service. This determination may require a new initial TUS, performing an additional TUS, or no testing at all.

3.5.4.1 Major Modifications and Repairs

3.5.4.1.1 A new initial TUS and SAT shall be performed after any of the following equipment modifications, repairs, or adjustments that could have altered the thermal characteristics of the equipment. Examples where an initial TUS and SAT is required include, but are not limited to, the following:

a. Relocation of thermal processing equipment. The initial TUS may be waived if the thermal processing equipment is designed to be portable—i.e., the thermal processing equipment has permanent wheels or other means of portability—but in some cases, a new periodic TUS can be necessary.

b. Increase in the maximum qualified operating temperature or decrease in the minimum qualified operating temperature.

c. Burner size, number, type, or location change.

d. Heating element number, type, or location change.

e. Changes to airflow pattern/velocity such as baffle positions, fan speed, fan quantity, etc.

f. Change of refractory thickness.

g. New refractory with different thermal properties.

h. Change of vacuum furnace hot zone design or materials.

i. Change of control sensor (e.g., type, thickness of sensor assembly, gauge of the sensor elements, or hot junction construction).

j. Change of the control sensor location.

k. Change of combustion pressure settings from their original settings.

l. Change of furnace operating atmosphere damper system settings from their original settings.

m. Control instrument or program change:

  1. Proportional versus high-low/off-on.

  2. Change of the control instrument model or type.

  3. PLC logic program change to the furnace heat control scheme.

  4. Adjustment of control instrument tuning constants, parameters, or rheostats.

n. Qualified work zone volume increase covering a volume not previously surveyed.

o. Qualified work zone location change covering a volume not previously surveyed.

3.5.5 Periodic TUS Intervals

3.5.5.1 A periodic TUS shall be performed at the normal periodic TUS interval in accordance with Table 15 or 16 based on furnace class and instrumentation type.

3.5.5.2 Extended periodic TUS intervals may be used based on furnace class, instrument type, and history of the required number of consecutive successful periodic TUS shown in Tables 15 and 16 after an initial TUS. In addition, a documented equipment preventive maintenance program, in accordance with 2.2.42, shall be in effect.

3.5.5.3 If equipment modifications, repairs, or adjustments as described in 3.5.4.1.1 are made the TUS interval shall revert to the normal periodic TUS interval until the required number of consecutive successful periodic TUS are completed.

3.5.6 Equipment Parameters During the TUS

3.5.6.1 During each TUS, except as outlined in 3.5.8 and 3.5.9, all parameters shall reflect the normal operation of the equipment during production. Examples of normal equipment operation include, but are not limited to, the following:

a. If the doors of a continuous furnace are normally open during production, they shall also be open during the TUS.

b. If slow heat up rates and stabilization temperatures are not used during production, they shall not be used during the TUS.

c. Any documented ramp rate used during production shall be acceptable when performing the TUS.

d. If excess combustion air is used during production, it shall also be used during the TUS.

e. If circulating fans are operated during production, they shall also be operated during the TUS.

3.5.7 Equipment Temperature When TUS Sensors Are Inserted

3.5.7.1 If the normal operation of the equipment when used during production is to load parts or raw material into a hot furnace, it is acceptable to insert the TUS sensors into the furnace with the furnace cold or with the furnace stabilized at or below the TUS temperature.

3.5.7.2 If the normal operation of the equipment when used during production is to load parts or raw material into a cold furnace, pre-heating the furnace prior to the coldest TUS temperature to perform the TUS is not permitted. Ramping from the coldest TUS temperature to a higher test temperature is permitted.

3.5.8 Load Condition and Atmospheres During the TUS

3.5.8.1 A TUS may be performed with a production load, simulated production load, a rack, or empty. Once a method of surveying the equipment is established during the initial TUS, subsequent periodic TUS shall be conducted using the same method. If changes are made to the established method, an initial TUS shall be performed to validate the revised method and the TUS interval shall revert to the normal periodic TUS interval until the required number of consecutive successful periodic TUS are completed.

3.5.8.2 If the TUS is performed empty or with a rack, and if TUS sensors are attached to or inserted into heat sinks, the side-to-side thickness or diameter of the heat sink shall not exceed 0.5 inch or 13 mm and shall not exceed the thickness of the thinnest material being processed in that equipment. Heat sink material shall be the material with the highest room temperature thermal conductivity consistent with the predominant part or raw material processed in the equipment.

3.5.8.3 When the TUS is performed with a load and the TUS sensors are attached to simulated parts or raw material, the load shall represent the thickness of the material normally used during production.

3.5.8.4 The atmosphere used during a TUS shall be the normal atmosphere used during production. Equipment used for processes whose required atmospheres could contaminate the TUS sensors (i.e., carburizing, nitriding, endothermic, and exothermic gases) or atmospheres that could pose a safety hazard (i.e., hydrogen or ammonia containing gases) may be surveyed with an atmosphere of air or inert gas.

3.5.8.5 The furnace vacuum level used during the TUS shall be the lowest vacuum level used during production but need not be less than 1.0 x 10^{-3} mm Hg (1 x 10^{-3} Torr or 1.3 x 10^{-3} millibar).

3.5.8.6 For vacuum furnaces operated in partial pressure (with backfill gas) during production, at least one of the periodic TUSs shall be performed annually at a minimum of one operating temperature and within the partial pressure range used in production. The gas used shall be one of the gases used during production.

3.5.9 TUS Requirements for Batch Furnaces, Salt Baths, Controlled Temperature Liquid Baths, and Fluidized Bed Furnaces (Excluding Controlled Temperature Quench Baths)

3.5.9.1 The number of TUS sensors required during the TUS shall be in accordance with Figure 1 and Tables 17 and 18. An initial TUS of multiple control zone furnaces with Type A or C instrumentation shall be performed with sufficient additional TUS sensors to adequately evaluate the temperature extremes of each control zone to identify hot and cold recording sensor locations.

Table 17 - Minimum number of TUS sensors and required locations

Qualified Work Zone Volume		Minimum Number of TUS Sensors	Qualified Work Zone Shape	Required Location of TUS Sensors
ft^3	m^3			
<3	<0.085	5	Square or rectangular cube	Located at four corners and one located at the approximate center (see Figure 1).
			Cylindrical	Four located at the periphery 180 degrees apart on each end and 90 degrees apart from end to end and one located at the approximate center (see Figure 1).
≥3 and <225	≥0.085 and <6.4	9	Square or rectangular cube	Located at the eight corners of the cube and one located at the approximate center.
			Cylindrical	Three located at the periphery of each end, 120 degrees apart. One located at the approximate center and the other two located to best represent the qualified work zone.
≥225	≥6.4	See Table 18	Square or rectangular cube	Located at the eight corners of the cube and one located at the approximate center. Others uniformly distributed to best represent the qualified work zone.
			Cylindrical	Three located at the periphery of each end, 120 degrees apart. One located at the approximate center and the others located to best represent the qualified work zone.

Table 18 - Number of TUS sensors required for batch furnaces, salt baths, controlled temperature liquid baths, fluidized bed furnaces, or continuous furnaces surveyed using the volumetric method

Furnace Class	Qualified Work Zone Volume Less Than	3 ft^3 0.085 m^3	225 ft^3 6.4 m^3	300 ft^3 8.5 m^3	400 ft^3 11 m^3	600 ft^3 17 m^3	800 ft^3 23 m^3	1000 ft^3 28 m^3	2000 ft^3 57 m^3	3000 ft^3 85 m^3	4000 ft^3 113 m^3
1 and 2	Number of sensors	5	9	14	16	19	21	23	30	35	40
3 to 6	Number of sensors	5	9	12	13	14	15	16	20	23	25
1 and 2	ft^3 per sensor	<1	25	21	25	32	38	43	67	86	100
3 to 6	ft^3 per sensor	<1	25	25	31	43	53	63	100	130	160
1 and 2	m^3 per sensor	<0.03	0.7	0.6	0.7	0.9	1.0	1.2	1.9	2.4	2.8
3 to 6	m^3 per sensor	<0.03	0.7	0.7	0.9	1.2	1.5	1.8	2.8	3.7	4.5

Notes:

(1) For qualified work zone volumes greater than 4000 ft^3 or 113 m^3, the applicable furnace class formula as illustrated in the table below shall be used to determine the number of TUS sensors.

(2) For qualified work zone volumes less than 4000 ft^3 or 113 m^3, it is acceptable to use the appropriate furnace class formula, as illustrated in the table below or interpolation, to determine the number of TUS sensors.

Furnace Class	Formula
1 and 2	9 + 1/2 X √(work zone volume in ft^3 - 225 ft^3) or 9 + 1/2 X √(35.3 X (work zone volume in m^3 - 6.4 m^3))
3 to 6	9 + 1/4 X √(work zone volume in ft^3 - 225 ft^3) or 9 + 1/4 X √(35.3 X (work zone volume in m^3 - 6.4 m^3))