Designation: ~~E633 – 21~~ E633 – 21a

Standard Guide for Use of Thermocouples in Elevated-Temperature Mechanical Testing[1]

This standard is issued under the fixed designation E633; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

This guide provides basic information, options, and guidelines to enable the user to apply thermocouples, ~~temperature measurement, and control equipment~~temperature-measuring systems, and temperature-control systems with sufficient accuracy to satisfy the temperature requirements for elevated-temperature mechanical testing of materials.

1. Scope*

1.1 This guide covers the use of ANSI thermocouple Types listed in Specification E230/E230M for elevated-temperature mechanical testing at temperatures typical in testing of metals.

NOTE 1—Typical conditions for mechanical testing are specified temperatures up to 1800 °F (982 °C) in air at one atmosphere of pressure.

1.1.1 This guide focuses on most commonly used base metal and noble metal ANSI type K, N, R, and S thermocouples.

1.1.2 Other ANSI thermocouple types that are listed in Specification E230/E230M may be used if the specific precautions and maximum temperatures for their use are followed.

1.1.3 It does not cover the use of sheathed thermocouples.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

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

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

[1] This guide is under the jurisdiction of ASTM Committee E28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.04 on Uniaxial Testing.
Current edition approved ~~Jan. 1, 2021~~Nov. 1, 2021. Published ~~March 2021~~January 2022. Originally approved in 1987. Last previous edition approved in ~~2013~~2021 as E633–13. DOI: ~~10.1520/E0633-21.~~10.1520/E0633-21A.

***A Summary of Changes section appears at the end of this standard**

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E6 Terminology Relating to Methods of Mechanical Testing
E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E111 Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
E139 Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests of Metallic Materials
E209 Practice for Compression Tests of Metallic Materials at Elevated Temperatures with Conventional or Rapid Heating Rates and Strain Rates
E220 Test Method for Calibration of Thermocouples By Comparison Techniques
E230/E230M Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples
E292 Test Methods for Conducting Time-for-Rupture Notch Tension Tests of Materials
E328 Test Methods for Stress Relaxation for Materials and Structures
E344 Terminology Relating to Thermometry and Hydrometry
E574 Specification for Duplex, Base Metal Thermocouple Wire With Glass Fiber or Silica Fiber Insulation
E1129/E1129M Specification for Thermocouple Connectors
E1684 Specification for Miniature Thermocouple Connectors
E2448 Test Method for Determining the Superplastic Properties of Metallic Sheet Materials

3. Terminology

3.1 ~~*Definitions*—Unless otherwise indicated, the definitions given~~ Definitions of terms common to mechanical testing that appear in Terminology E6 apply to this standard, including accuracy, calibration, indicated temperature, metrological traceability, reduced parallel section, temperature-measuring system, specified temperature, and ~~E344 shall apply.~~ verification.

3.2 Some specific definitions of terms relating to thermometry and hydrometry that appear in Terminology E344 apply to this guide. These terms are compensating extension wire, emf, extension wire, ice point, measuring junction, reference junction, reference temperature, sheathed thermocouple, thermocouple, thermocouple emf, thermoelectric properties, thermoelement, and true value of a temperature.

4. Classification

4.1 The following thermocouple types are identified in Tables E230/E230M:

4.1.1 *Type K*—~~Nickel—10 %~~ Nickel-10 % chromium ~~(+)~~(+) versus ~~nickel—5 %~~ nickel-5 % (aluminum, silicon) (−),

4.1.2 *Type N*—~~Nickel—14 % chromium, 1.5 % silicon (+) versus nickel—4.5 % silicon—0.1 %~~ Nickel-14 % chromium, 1.5 % silicon (+) versus nickel-4.5 % silicon-0.1 % magnesium (−),

4.1.3 *Type R*—~~Platinum—13 %~~ Platinum-13 % rhodium ~~(+)~~(+) versus platinum (−),

4.1.4 *Type S*—~~Platinum—10 %~~ Platinum-10 % rhodium ~~(+)~~(+) versus platinum (−).

5. Summary of Guide

5.1 This guide will help the user to conduct an elevated-temperature mechanical property test with the highest degree of temperature precision available. It provides information on the proper application of thermocouples that are used to measure and control the temperature of the test specimen. It also points out sources of error and suggests methods to eliminate them.

6. Significance and Use

6.1 This guide presents techniques on the use of thermocouples and associated equipment for measuring temperature in elevated-temperature mechanical testing under typical conditions. Test durations range from minutes for tension, compression, Young's modulus, and superplastic property tests to thousands of hours for creep, stress-rupture, creep rupture, notch tension, and stress-relaxation tests.

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

6.2 Since elevated-temperature mechanical properties are highly sensitive to temperature, users should make every effort practicable to make accurate temperature measurements and provide stable control of the test temperature. The goal of this guide is to provide users with good pyrometric practice and techniques for precise temperature control for elevated-temperature mechanical testing.

6.3 Techniques are given in this guide for maintaining a stable temperature throughout the period of test.

6.4 If the techniques of this guide are followed, the difference between indicated temperature and true temperature, as used in Test Methods E21, E111, E139, E292, E328, E2448, and Practice E209 will be reduced to the lowest practical level.

7. Apparatus

7.1 Instrumentation may be individual instruments, a data acquisition system (multipoint recorders or digital type), a computer-based control system, or a combination of these devices.

~~NOTE 2—Since each thermocouple is "grounded" by contacting the specimen, it is necessary that the instrumentation treat each thermocouple as isolated or "floating" from all other thermocouples. Neither leg should be connected to a common ground at the instrumentation end of the system. Also, equipment having a high common mode rejection ratio is necessary because of the proximity of strong electromagnetic fields from the heating elements of the furnace.~~

7.1.1 Since each thermocouple is "grounded" by contacting the specimen, the instrumentation shall treat each thermocouple as isolated or "floating" from all other thermocouples. Neither the extension wire nor thermoelement shall be connected to a common ground at the instrumentation end of the temperature-measuring system.

7.1.2 Instrumentation shall have a high common mode rejection ratio because of the proximity of strong electromagnetic fields from the heating elements of the furnace.

7.2 *Temperature Measurement* ~~*Instrumentation—*~~*System—*The ~~measurement~~ resolution of the temperature-measuring system should be ~~able to resolve the thermocouple signal to ±0.1 °F (0.05 °C). The temperature indication should have~~ ±0.1 °F (0.05 °C) or better. The uncertainty of the indicated temperature should be no more than ±1.0 °F (0.5 °C) ~~uncertainty for the purposes of this test.~~ In addition, where specific corrections for the calibration of individual thermocouples or a thermocouple lot are required, the capability of the ~~instrumentation~~temperature-measuring system to accommodate these data shall be considered.

7.2.1 *Reference Junction Compensation:*

~~7.2.1.1 Thermocouples are usually calibrated to a 32 °F (0 °C) reference temperature. Unless an ice point reference is used, provide some means to compensate for the temperature where the thermoelectric circuit connects to the instrument; refer to MNL-12 on Reference Junctions.[3]~~

7.2.1.1 ~~Reference junction compensation is usually performed within the instrumentation itself. Most devices or electronic data acquisition systems measure the~~ Unless an ice point reference junction is used, provide some means to compensate for the temperature where the ~~thermoelements connect to the input terminals and introduce a compensating emf to simulate the ice point.~~thermoelectric circuit connects to the instrumentation end of the temperature-measuring system.

NOTE 2—Thermocouples are usually calibrated to a 32 °F (0 °C) reference temperature. Refer to MNL-12 on Reference Junctions.[3]

NOTE 3—Reference junction compensation is usually performed within the instrumentation of the temperature-measuring system itself. Most temperature-measuring systems measure the temperature where the thermoelements or extension wires connect to the input terminals and introduce a compensating emf to simulate the ice point reference junction.

7.2.1.2 The input ~~connections~~terminals shall be isothermal and shielded from sudden changes of temperature.

7.2.2 ~~*Recalibration—*~~*Calibration and Verification—*The ~~accuracy of the temperature measurement equipment may be affected by~~

[3] Manual on the Use of Thermocouples in Temperature Measurement, Fourth Edition, 1993. Sponsored by ASTM International Committee E20 on Temperature Measurement. ASTM International MNL-12–4th. DOI: 10.1520/MNL12–4TH-EB.

component aging, environment, handling, or wear. Therefore, a periodic recalibration of the measuring instrumentation with a checking instrument is necessary. The checking instrument should be of higher accuracy than the measurement system, and to ensure conformity to national standards, it should be calibrated with a known primary test standard, traceable to a national metrology institute.temperature-measuring system shall be periodically verified so that the temperature errors are consistent with the specified requirements for the accuracy of the indicated temperature.

7.2.2.1 The accuracy of the verification instrument shall be higher than that of the temperature-measuring system, and its calibration should exhibit metrological traceability to the International System of Units (SI).

7.2.2.2 The period between calibration or verification of the temperature-measuring system should be based on age, use, and the drift exhibited between calibrations.

NOTE 4—The accuracy of the temperature-measuring system can be affected by component aging, environment, handling, or wear. Frequent verifications can help determine the period between calibrations.

7.2.2.3 Calibrations and verifications should include multiple points and extend over the intended range of use.

7.3 *Temperature Control Equipment Temperature-Control System Requirements*—A temperature controller or temperature control temperature-control system should be selected on the basis of stability (variations of ±1 °F (0.5 °C) or less), and accuracy (uncertainty of ±1.5 °F (0.7 °C) or less). Generally, a controltemperature-control system with proportional band, automatic reset, and slow approach to final set point features should be used. When employing an automatic feedback control feedback-control system, the tuning constants or control algorithm shall be optimized, not only to maintain the test specimen at the set point without excessive deviations, but to eliminate or limit the amount of overshoot upon initial heating.

NOTE 3—The same precautions regarding reference junction compensation in the control device apply as in 7.2.1.

7.3.1 Follow the requirements of 7.2.1 regarding reference junction compensation in the temperature-control system.

7.3.2 *Configuration*—The control configuration may take one of two forms:configuration of the temperature-control system shall be capable of meeting the indicated temperature variation and configuration requirements of the test method that cites E633.

7.3.1.1 The center thermocouple is connected to a control loop that strives to maintain the temperature of the center of the reduced section at set point. The upper and lower thermocouples are used to measure the temperatures at the ends of the reduced section. Means shall be provided to adjust the heating power above and below the center to equalize the temperatures.

NOTE 5— Many different configurations are used successfully. For example, in one configuration, the center thermocouple is connected to a control loop that strives to maintain the temperature of the center of the reduced parallel section at the set point. The upper and lower thermocouples measure the indicated temperatures at the ends of the reduced parallel section. Independent means are provided to adjust the heating power above and below the center to equalize the temperatures.

In another configuration, the upper and lower thermocouples are connected to control loops that regulate the power to the upper and lower heaters of a two-zone furnace independently. The center thermocouple measures the indicated temperature. Furnaces with three independently controlled zones are also used successfully.

7.3.1.2 The bottom and top thermocouples may be connected to control loops that regulate the power to the upper and lower heaters independently. Thus, the end temperatures are maintained automatically. The center thermocouple is used only as a monitor.

7.3.3 *ControlTemperature-Control System Recalibration Calibration, Verification, and Reliability*—The controltemperature-control system should be subjected to routine recalibration, routinely verified, as circumstances and type of equipment dictate. The checkingverification procedure should include verification, and if necessary, calibration of the controller temperature-control system and a sensitivity check. A calibration circuit, as shown in Appendix X1, should be employed.

7.4 *Heating Equipment*—Furnaces should be well insulated and appropriately sized or adjusted relative to the workload and heat losses to provide a zone of uniform temperature across the specimen. Because elevated-temperature mechanical testing is usually done at constant temperature and with an unchanging furnace load, the main requirement is a well-insulated furnace, capable of achieving the desired temperatures. The top and bottom openings should be closed to limit convection losses, but the furnace should not be sealed airtight.

8. Thermocouples

8.1 The stability of the ~~emf of the thermocouples~~ thermocouple emf and the rapid response of the ~~control~~temperature-control system to any changes of temperature over the period of the test ~~are crucial~~ shall be suitable to maintain the specimen within the ~~allowable~~specified temperature band.

8.2 *Thermocouple ~~Requirements—~~Requirements:* ~~The requirements for thermocouples used for measurement are somewhat different from thermocouples used for control purposes (especially with automatic feedback control systems). Of course, both requirements may be met with one set of thermocouples that is judiciously chosen and placed.~~

8.2.1 *Measurement*—Thermocouples used for measurement ~~are designed to represent~~ shall be capable of representing the temperature of the specimen along its reduced parallel section. Since only two or three thermocouples are used, they shall be located at places on the specimen that represent the average temperature of their respective sections. ~~This can be determined by a test program, where more than the usual number of thermocouples are mounted along the reduced section to establish the temperature profile.~~

NOTE 6—A profile test program, where more than the usual number of thermocouples are mounted along the reduced parallel section can help to establish the temperature profile along the test specimen.

8.2.2 *Control*—Thermocouples used for control ~~are designed~~ shall be selected and placed to be sensitive to changes of or impending changes to the temperature of the specimen. ~~Control thermocouple wire should be as small in diameter as possible. However, the wire should not be so small in diameter that oxidation or strain would cause emf errors or failure during the test period.~~

~~NOTE 4—Locating a control thermocouple next to the heater as a means to limit fluctuations of temperature is not advisable. A controller with a wide proportional band and automatic reset is capable of compensating for the thermal lag of most furnace designs.~~

8.2.2.1 Control thermocouple thermoelements should be as small in diameter as possible. However, the diameter should not be so small that oxidation or strain causes thermocouple emf errors or failure during the test period.

8.2.2.2 A control thermocouple should not be located next to the heater as a means to limit fluctuations of temperature.

NOTE 7— A temperature-control system with a wide proportional band and automatic reset is capable of compensating for the thermal lag of most furnace designs

8.2.3 If permitted by the test method standard that cites E633, the measurement and control requirements may be met with one set of thermocouples that is judiciously chosen and placed.

8.3 *Basic Information*—~~Information on basic thermocouple characteristics and performance is available from ASTM publications such as MNL-12.~~Atmosphere, temperature ~~Stability of the emf over the period of test is the most crucial requirement for a control thermocouple, whereas accuracy of the measurement thermocouple is paramount for successful correlation of test results.~~of exposure, duration of testing, and response time shall be considered to determine type (K, N, R, or S), thermoelement size, insulation, and installation methods.

~~8.3.1 Factors affecting thermocouple selection are: atmosphere, temperature of exposure, duration of testing, and response time. These factors should be considered to determine type (K, N, R, or S), wire size, insulation, and installation methods.~~

NOTE 8—Information on basic thermocouple characteristics and performance is available from ASTM publications such as MNL-12.[3] Stability of the emf over the period of test is the most crucial requirement for a control thermocouple, whereas accuracy of the measurement thermocouple is paramount for successful correlation of test results.

8.4 *Precautions*—~~The emf output of a thermocouple is affected by inhomogeneities in the region of a temperature gradient. Inhomogeneities are produced by cold work, contamination, or metallurgical changes produced by temperature itself. Therefore, thermocouples~~ Thermocouples should be handled carefully without unnecessary stretching, bending, or twisting the wires. Bending around small radii should be avoided entirely, especially where the wires may lie in a temperature gradient. Where ~~necessary, a minimum amount of bending may be performed carefully around bend radii~~bending is necessary, the bend radius should be at least 20 times the diameter of the wire.

NOTE 9—The thermocouple emf is affected by inhomogeneities in the region of a temperature gradient. Inhomogeneities are produced by cold work, contamination, or metallurgical changes produced by temperature itself.

8.5 *Types K and N Thermocouples:*

8.5.1 ~~*Suitability*—~~*Suitability:* ~~Types K and N thermocouples are useful for elevated-temperature mechanical testing because they provide a relatively high emf and are relatively stable over the low and middle temperatures of the testing range.~~

NOTE 10—Types K and N thermocouples are useful for elevated-temperature mechanical testing because they provide a relatively high emf and are relatively stable over the low and middle temperatures of the testing range.

8.5.2 *Limitations*—~~Conventional Type K, and to a lesser extent, Type N thermocouples undergo emf drift as the result of metallurgical changes during use. Therefore, that portion of wire that~~ Any portion of Type K or Type N thermoelement that has been exposed to temperatures above 500 °F (260 °C) or 1600 °F (870 °C) for Types K and N thermocouples, respectively, should be discarded after one use.

NOTE 11—Conventional Type K, and to a lesser extent, Type N thermocouples undergo emf drift as the result of metallurgical changes during use.

8.5.3 *Assessment*—Type K or N thermocouples should be reused only after their suitability for a particular test program is proven by a body of test data. Stability ~~tests are advised,~~ tests, using Type R or S thermocouples as ~~references.~~references should be conducted to establish their suitability.

8.6 *Types R and S Thermocouples:*

8.6.1 *Suitability*—~~Types R and S are highly resistant to oxidation and are therefore stable for these tests at the higher temperatures of the range. They provide the highest reproducibility and repeatability of the several thermocouple types but are initially more costly.~~ Because they do not deteriorate during normal use, ~~it is possible to reuse them. When Types R and S wires are no longer suitable for service, they still retain a significant portion of their initial cost in salvage value.~~Type R and Type S thermocouples may be reused.

NOTE 12—Types R and S are highly resistant to oxidation and are therefore stable for these tests at the higher temperatures of the range. They provide the highest reproducibility and repeatability of the several thermocouple types but are initially more costly. When Types R and S wires are no longer suitable for service, they still retain a significant portion of their initial cost in salvage value.

8.6.1.1 The calibration of Type R or Type S thermocouples that have been exposed to or in contact with chromium-containing alloys should be verified before they are reused.

NOTE 13—Type R and Type S thermocouples degrade significantly at temperatures above 1650 °F (900 °C) when attached to chromium-containing alloys because the chromium vaporizes and contaminates the thermocouple. The net result at 2200 °F (1200 °C) can be an error of up to 14 °F (8 °C).

8.6.2 *Limitations*—~~The limiting factor for reuse of Type R or S thermocouples is error introduced by strain or contamination. Wires of Types R and S are mechanically weaker than Types K and N, so they must~~ Type R and Type S thermocouples shall be adequately supported to avoid straining them. Sufficient slack should be provided so that the wires do not strain or tear when the specimen elongates. ~~Contamination of the wire~~Care should be exercised to avoid contaminating the thermocouple[4] ~~may be caused~~ by oils, grease, or other chemicals, and from metallic vapors from the test specimen during heating.

NOTE 14—The limiting factor for reuse of Type R or S thermocouples is error introduced by strain or contamination. Wires of Types R and S are mechanically weaker than Types K and N.

[4] "*Creep and Rupture Test Pyrometry*," Charles R. Wilks, ASTM Special Technical Publication No. 178—Panel Discussion on Pyrometric Practices, Presented at the 58th Annual Meeting, June 30, 1955 http://dx.doi.org/10.1520/STP178-EB.

TABLE 1 Thermocouple and Extension Wire Tolerances and Calibration Uncertainties

Type	Temperature Range	Tolerance Standard[B]	Tolerance Special	Typical Calibration Uncertainty[A]
Thermocouples, °F				
K, N	32 to 2000	4 or 0.75 %	2 or 0.4 %	1.8 to 2.2
S, R	32 to 2000	2.7 or 0.25 %	1 or 0.1 %	1.1 to 1.2
Extension Wire, °F[C]				
KX, NX	32 to 400	4	D	0.5 to 2
Compensating Extension Wire				
RX, SX	32 to 400	9	D	2 to 4
Thermocouples, °C				
K, N	0 to 1100	2.2 or 0.75 %	1.1 or 0.4 %	1 to 1.2
R, S	0 to 1100	1.5 or 0.25 %	0.6 or 0.1 %	0.6 to 0.7
Extension Wire, °C[C]				
KX, NX	0 to + 200	2	D	0.3 to 1
Compensating Extension Wire				
RX, SX	0 to + 200	5	D	1 to 2

[A] Calibration uncertainty in an actual test depends on number of test points, media, and reference standard used during the calibration (see Test Method E220).

[B] Tolerances and uncertainties are plus or minus the indicated values expressed in degrees Fahrenheit or degrees Celsius or as a percentage of the value of the measured temperature, whichever is greater (see Tables 1, 2, and 3 in Specification E230/E230M).

[C] Worst case, where the temperature of the transition point ~~differs~~ is 400 °F (differs from the instrument's reference junction by 360 °F ~~(200 °C).~~(200 °C)).

[D] No special tolerance limits have been established, but it is possible that materials with tolerances closer than the standard limits ~~may be~~ are available.

8.6.3 *Assessment*—A Type R or S thermocouple should not be used indefinitely.

NOTE 15—One way to determine the end of its useful life is to place a new thermocouple from the same lot beside the old one and compare outputs. Replace the older thermocouple when the change exceeds the uncertainty indicated on Table 1.~~One way to determine the end of its useful life is to place a new thermocouple from the same lot beside the old one and compare outputs. Replace the older thermocouple when the change exceeds the uncertainty indicated on Table 1. Special precaution is advised to avoid errors arising from the use of compensating extension wires. See Table 1.~~

8.6.3.1 Special precaution should be taken to avoid errors arising from the use of compensating extension wires. See Table 1.

8.7 *Stability*—~~Studies have been made to determine emf stability with time of the thermocouple types covered by this guide. Results of those investigations show that the Types R and S thermocouples may be expected to have greater stability under favorable conditions than either Type K or N. Other work indicates Type N is more stable than Type K.~~For measurements where thermocouple emf stability is critical, Type K and Type N thermocouples should not be used.~~ Relative stabilities are summarized in Table 2.~~

NOTE 16—Studies of the thermocouple emf stability show that the thermocouple emf of Types R and S thermocouples is more stable under favorable conditions than the thermocouple emf of either Type K or N. Other work indicates Type N thermocouple emf is more stable than Type K thermocouple emf.[5] Relative stabilities are summarized in Table 2.

8.8 *Calibration:*

8.8.1 *Method*—Calibration of thermocouples should be done on representative lot samples with Test Method E220. ~~Recalibration~~

[5] "The Nicrosil versus Nisil Thermocouple: Properties and Thermoelectric Reference Data," NBS Monograph 161, April 1978, U.S. Dept. of Commerce, NIST, Gaithersburg, MD. Also see RR:E20-1001, available from ASTM.