Designation: E 220 – 86 (Reapproved 1996)$^{\epsilon 1}$

Standard Test Method for Calibration of Thermocouples By Comparison Techniques[1]

This standard is issued under the fixed designation E 220; 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.

ϵ^1 NOTE—Keywords were added editorially in November 1996.

1. Scope

1.1 This test method covers the techniques of thermocouple calibration based upon comparisons of thermocouple indications with those of a reference thermometer, different from methods involving the use of fixed points. The precise evaluation of the electromotive force (emf)-temperature relation of a thermocouple is accomplished by determining its emf output at each of a series of measured temperatures. Calibrations are covered over temperature ranges appropriate to the individual types of thermocouples within an over-all range from about − 180 to 1700°C (−290 to 2660°F).

1.2 In general, the test method is applicable to bare wire thermocouples or sheathed thermocouples. The latter may require special care to control thermal conduction losses.

2. Referenced Documents

2.1 *ASTM Standards:*

E 1 Specification for ASTM Thermometers[2]

E 77 Test Method for Inspection and Verification of Thermometers[2]

E 230 Specification for Temperature-Electromotive Force (EMF) Tables for Standardized Thermocouples[2]

E 344 Terminology Relating to Thermometry and Hydrometry[2]

E 563 Practice for Preparation and Use of Freezing Point Reference Baths[2]

2.2 *ANSI Standard:*

C 100.2 Direct-Current Ratio Devices: High Precision Laboratory Potentiometers[3]

2.3 *NIST Publications:*

Circular 590—Methods of Testing Thermocouples and Thermocouple Materials [4]

Monograph 126—Platinum Resistance Thermometry[4]

Monograph 150—Liquid-in-Glass Thermometry[4]

3. Terminology

3.1 *Definitions*—The definitions given in Terminology E 344 shall be considered as applying to the terms used in this method.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *type of thermocouple*—the type of a thermocouple is represented by a letter designation as defined in accordance with Specification E 230.

3.2.2 *reference thermometer*—a thermometer whose calibration is known within a certain specified accuracy.

4. Summary of Test Method

4.1 By this test method a thermocouple is calibrated by comparing its indications with those of a reference thermometer at the same temperature. The reference thermometer may be another thermocouple, a liquid-in-glass thermometer, or a platinum resistance thermometer, depending upon the temperature, the degree of accuracy required, or other considerations.

4.2 Since the success of the test method depends largely upon the ability to bring the thermocouple and the standardized reference thermometer to the same temperature within the required limits of accuracy, considerable care must be taken in choosing the media and conditions under which the comparisons are made. Stirred liquid baths, uniformly heated metal blocks, tube furnaces, and dry fluidized baths, used with proper techniques, are specified for use in their respective temperature ranges.

4.3 Potentiometric instruments, or high-impedance electronic instruments, must be used for the measurement of emf eliminating instrument loading as a significant source of error. The details of the test method, therefore, aim to provide assurance that the emf measured is actually the emf output of the thermocouple at the temperature of test and is not influenced by emf's arising from other sources.

5. Significance and Use

5.1 For users or manufacturers of thermocouples, the test method provides a means of confirming the acceptability of the material in the assembled state. Typically wire producers provide calibration of the individual thermocouple legs.

[1] This method is under the jurisdiction of ASTM Committee E-20 on Temperature Measurement and is the direct responsibility of Subcommittee E20.04 on Thermocouples.

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[2] *Annual Book of ASTM Standards*, Vol 14.03.

[3] Available from American National Standards Institute, 11 W. 42nd St., 13th Floor, New York, NY 10036.

[4] Available from National Institute of Standards and Technology, U.S. Department of Commerce, Washington, DC 20234.

5.2 The test method provides for certifications to temperature tolerances for specifications such as Specification E 230 or other special specifications as required for commercial, military, or research applications.

5.3 The test method assumes that the materials are homogeneous.

6. Apparatus

6.1 The apparatus required for the application of this test method will depend in detail upon the temperature range being covered but in all cases shall be selected from the equipment described below.

6.2 *Comparator Baths and Furnaces*—A controlled comparator bath or furnace shall be used in which the measuring junction of the thermocouple to be calibrated is brought to the same temperature as a reference thermometer.

6.2.1 *Liquid Baths*—In the range from −160 to 630°C (−250 to 1170°F) the comparator bath shall usually consist of a well stirred, insulated liquid bath provided with controls for maintaining the temperature constant. Suitable types are described in the appendix to Test Method E 77. Laboratory type tube furnaces may be used above ambient temperature but are not recommended for the most accurate work in this temperature range.

6.2.2 *Fluidized Powder Baths*—In the range from −70 to 980°C (−100 to 1800°F) the comparator bath may consist of an air-fluidized [5] bath of aluminum oxide or similar powder. Such a bath should be monitored to ensure consistency and uniformity of temperature.

6.2.3 *Tube Furnaces*—At temperatures above approximately 620°C (1150°F) an electrically heated tube furnace shall usually constitute the comparator bath. Any one of a wide variety of designs may be suitable, but the furnace chosen should have the following capabilities:

6.2.3.1 Means should be provided to control the furnace at a constant temperature for short lengths of time (approximately 10 min) at any temperature in the range over which the furnace is to be used.

6.2.3.2 There should be a zone of uniform temperature into which the thermocouple measuring junctions may be inserted, and the length of the furnace tube must be adequate to permit a depth of immersion sufficient to assure that the measuring junction temperature is not affected by temperature gradients along the thermocouple wires.

NOTE 1—Further discussions of suitable tube furnaces are given in X1.1 and X1.2.

6.2.4 *Other Baths*—The one essential design feature of any bath to be used with this method is that it brings the thermocouple being calibrated to the same temperature as the reference thermometer. Copper blocks immersed in liquid oxygen or some other refrigerant have been used successfully. The blocks are provided with wells for the test thermocouples and the reference thermometer. Similarly, uniformly heated blocks have been used at high temperatures. Such baths are not excluded under this test method, but careful explorations of existing temperature gradients must be made before confidence may be placed in such apparatus.

6.3 *Reference Junction Temperatures*—A controlled temperature bath must be provided in which the temperature of the reference junctions is maintained constant at a chosen value. A commonly used reference temperature is 0°C (32°F), usually realized through use of the ice point, but other temperatures may be used if desired. The reference junction temperature should be controlled to a better accuracy than that expected from the thermocouple calibration to minimize this temperature variation as a source of error. An acceptable method for utilizing the ice point as a reference junction temperature is given in Practice E 563.

6.3.1 For the rapid calibration of large numbers of thermocouples the reference junctions can be made at an isothermal multiterminal strip, whose temperature is determined by a reference thermocouple whose reference junction is in an ice-point bath. This system avoids thermal loading of the ice bath by a large number of thermocouple wires and copper connecting wires.

6.3.2 Minimum error can be achieved only by running the thermocouple wires, without splices, from the measuring junction to the reference junction. Any splice represents an inhomogeneity in the circuit due to the mismatch of nominally similar alloys. The magnitude of the error due to the mismatch will depend on the temperature gradients existing.

6.4 *Emf-Measuring Instruments*—The choice of a specific instrument to use for measuring the thermocouple emf will depend on the accuracy required of the calibration being performed. Generally, the instrument can be chosen from one of three groups of commercially available, laboratory, high-precision types with emf ranges suitable for use with thermometers. The first two groups are manually balanced potentiometers that are not self-contained and that require a more-or-less permanent bench setup with a number of accessories, including a storage battery, high-sensitivity galvanometer or null detector, and a laboratory-type standard cell. All instruments require periodic calibration by the National Institute of Standards and Technology or some other laboratory similarly qualified.

6.4.1 *Group A Potentiometers* shall be used where the highest accuracy is required. Potentiometers of this group have no slide wires, all settings being made by means of dial switches. All design features will be consistent with the attainment of the highest accuracy. Such instruments shall have a limit of error of 0.2 μV at 1000 μV and 5 μV or better at 50 000 μV in accordance with ANSI C100.2.

6.4.2 *Group B Potentiometers* will normally be sufficiently accurate for most work. Such potentiometers may contain a slide wire, but all design features shall be directed toward high accuracy. Instruments of this class shall have limits of error of 1 μV at 1000 μV and 12 μV at 50 000 μV.

6.4.3 *Group C Instruments* include electronic digital voltmeters and analog-to-digital converters of potentiometric or other high-impedance design. Instruments of this class have limits of error similar to those in 6.4.1 and 6.4.2. These instruments permit fast readings of a large number of thermocouples. Such fast readings demand less temperature stability of the bath with time.

[5] Callahan, J. T., "Heat Transfer Characteristics in Air Fluidized Solids up to 900°F," ASME Paper 70W A/Temp 3, *Journal of Basic Engineering*, 1971.

6.5 *Connecting Wire Assembly*—Connecting wires from the reference junction to the potentiometer are of insulated copper and should be run in a grounded conduit or braided cable if they are subject to electrical pickup.

6.5.1 Selector switches may be used to switch between different thermocouples being calibrated and the standard thermocouple. Such switches should be of rugged construction and designed so that both connecting wires are switched when switching from one thermocouple to the next, leaving thermocouples not in use entirely disconnected from the potentiometer. The switches should be constructed with copper contacts, connections, and terminals and must be located in the copper portion of the circuit to preserve the all-copper circuit from the reference junction to the potentiometer. Precautions should be taken to protect the switches from temperature fluctuations due to air currents or radiation from hot sources.

6.5.2 Terminal blocks may be used in the connecting circuit, if convenient, but should be provided with copper binding posts and should be protected against the development of temperature gradients in the blocks.

6.6 *Thermocouple Insulation and Protection Tubes*—Two-hole ceramic tubing may be used to support and electrically insulate the immersed portion of the two bare conductors of a thermocouple. Only suitable ceramic should be used, chosen of a material which will not contaminate the thermocouple and which will provide the necessary electrical insulation at the highest temperature of the calibration. To avoid unnecessary mass and to minimize axial heat conduction in the region of the measuring junction, the tubing should be relatively thin walled and should have bore diameters that provide a loose fit for the thermocouple wires without binding. During the test, the thermocouples may be inserted in a protection tube which should be resistant to thermal shock, noncontaminating to the thermocouple materials, and gastight.

6.6.1 Sheathed thermocouples may be tested without further protection or support in liquid or dry fluidized baths, provided that the bath medium is compatible with the sheath material. Care must be taken to keep thermal conduction losses within the limits of experimental error. The sheathed wire should extend, without splicing, to the reference junction for minimum error (see 6.3.2).

7. Reference Thermometers

7.1 The reference thermometer to be used for the comparison calibration of thermocouples will depend upon the temperature range covered, whether a laboratory furnace or stirred liquid bath is used, the accuracy desired of the calibration, or in cases where more than one type of thermometer will suffice, the convenience or preference of the calibrating laboratory.

7.2 *Platinum Resistance Thermometers*—The standard platinum resistance thermometer is the most accurate reference thermometer for use in stirred liquid baths at temperatures from approximately − 180 to 630°C (−300 to 1170°F). In cases where accuracy approaching 0.1°C (0.2°F) is required at temperatures below about − 60°C (−70°F) or above 200°C (400°F), there are few alternatives to the use of resistance thermometers as references. Standard resistance thermometers are described in X2.1 and X2.2.

7.3 *Liquid-in-Glass Thermometers*—This type of thermometer may be used from − 180°C (−300°F), or lower, to 400°C (750°F), or even higher with special types. Generally, the accuracy of these thermometers is less below − 60°C, where organic thermometric fluids are used, and above 400°C where dimensional changes in the bulb glass may be relatively rapid, requiring frequent calibration. The uncertainties of different types of liquid-in-glass thermometers are given in X2.3. Specifications for ASTM thermometers are given in Specification E 1.

7.4 *Types R and S Thermocouples (Platinum-Rhodium/Platinum)*—The platinum-10 % rhodium/platinum (Type S), or the platinum-13 % rhodium/platinum thermocouple (Type R) of 24-gage (0.51-mm) wire is recommended as the reference thermometer for temperatures from 630°C (1170°F) to 1200°C (2190°F). Their use may also be extended down to room temperature. Accuracies attainable with careful use are given in Table 1. Group A and B potentiometers (6.4.1 and 6.4.2) and Group C instruments (6.4.3) can be used with these thermocouples.

7.5 *Type B Thermocouples (Platinum-Rhodium/Rhodium-Platinum)*—The platinum-30 % rhodium/platinum6 % rhodium (Type B) thermocouple, formed from 24-gage (0.51-mm) or larger size wire, is recommended as the reference thermometer for temperatures above 1200°C (2190°F). The uncertainties of temperature measurements with this type of thermometer are given in Table 1. Group A and B potentiometers (6.4.1 and 6.4.2) and Group C instruments (6.4.3) are suitable for use with this type of thermocouple.

7.6 *Type T Thermocouples (Copper-Constantan)*—This type of thermocouple may serve as a useful reference thermometer in the range of − 180 to 370°C (−300 to 700°F) in some instances, although its accuracy is, in general, limited by the stability of the wire at temperatures above approximately 200°C (400°F), and by the accuracy of the emf measurements and the inhomogeneity of the wire below 200°C. Twenty-four gage (0.51-mm) wire is a useful compromise between the lesser stability of smaller wire and the greater heat leakage of large wire. The uncertainties of temperature measurements with this thermocouple are given in Table 1. If measurements approaching an uncertainty of 0.1°C are to be made, a Group A potentiometer (6.4.1) must be used.

7.7 *Similar Thermocouples*—When Procedure C (9.4) is used, the reference thermometer shall be a previously calibrated thermocouple having the same composition as the test thermocouples.

8. Sampling

8.1 Sampling is normally specified in the ASTM material specification that calls for the calibration. As a guideline for compliance testing, a minimum of three samples are often taken for calibration compliance of a lot of wire or of thermocouples. In the case of wire, the samples should preferably be widely separated within the lot, for example, both ends and the middle of a coil. Users should be aware that in some instances compliance testing will cause changes to occur in the thermoelectric properties of the thermocouple wire.

9. General Procedures

9.1 The calibration procedure consists of measuring the emf

TABLE 1 Calibration Uncertainties in Calibrating Thermocouples by the Comparison Method—Temperatures in Degrees Celsius[A]

Thermocouple Type[B]	Temperature Range	Calibration Points[C]	Uncertainty[D]	
			At Observed Points	Of Interpolated Values[E]
E	0 to 870[F]	every 100	0.5	1
	0 to 870[F]	300, 600, and 870	0.5	2
	0 to 350[G]	every 100	0.1	0.5
	−160 to 0[G]	every 50	0.1	0.5
J	0 to 760[F]	100, 300, 500, and 750	0.5	1
	0 to 350[G]	every 100	0.1	0.5
K	0 to 1250[F]	every 100	0.5	1
	0 to 1250[F]	300, 600, 900, and 1200	0.5	2
	0 to 350[G]	every 100	0.1	0.5
	−160 to 0[G]	every 50	0.1	0.5
R and *S*	0 to 1450[F]	every 100	0.3	0.5 to 1100 and 2 at 1450
	0 to 1450[F]	600 and 1200	0.3	1 to 1100 and 3 at 1450
B	0 to 1700[F]	every 100	0.3	0.5 to 1100 and 3 at 1700
		600 and 1200	0.3	1 to 1100 and 5 at 1700
T	0 to 370[G]	every 100	0.1	0.2
	0 to 100[G]	50 and 100	0.05	0.1
	−160 to 0[G]	every 60	0.1	0.2

[A] Values given in this table are extracted from National Bureau of Standards Circular 590.
[B] See 3.2.
[C] Approximate calibration points.
[D] With homogeneous thermocouples and reasonable experimental care.
[E] Using difference curve from reference table.
[F] In tube furnaces, by comparison with a calibrated Type S thermocouple.
[G] In stirred liquid baths, by comparison with a standard platinum resistance thermometer.

of the thermocouple being calibrated at selected calibration points, the temperature of each point being measured with a standard thermocouple or other thermometer standard. The number and choice of test points will depend upon the type of thermocouple, the temperature range to be covered, and the accuracy required. Table 1 or Table 2 will serve as a guide to the selection. One of the following three general methods may be used in the calibration procedure.

9.2 *Procedure A* is applicable when a standard thermocouple and two potentiometers can be employed. The method is particularly adapted to the calibration of the thermocouples at any number of selected points when the same furnace is to be used over a wide temperature range, its temperature being changed for each point. Through the use of two potentiometers it is possible to make simultaneous readings of a standard thermocouple and a thermocouple being calibrated without waiting for the furnace or bath to stabilize at each temperature. The standard thermocouple is connected to one potentiometer and the thermocouple being calibrated to the other, as shown in Fig. 1. Each potentiometer is provided with a reflecting

TABLE 2 Calibration Uncertainties in Calibrating Thermocouples by the Comparison Method—Temperatures in Degrees Fahrenheit[A]

Thermocouple Type[B]	Temperature Range	Calibration Points[C]	Uncertainty[D]	
			At Observed Points	Of Interpolated Values[E]
E	32 to 1600[F]	every 200	1	2
	32 to 1600[F]	600, 1100, and 1600	1	4
	32 to 650[G]	every 200	0.2	1
	−256 to + 32[G]	every 100	0.2	1
J	32 to 1400[F]	300, 600, 1000, and 1400	1	2
	32 to 650[G]	every 200	0.2	1
K	32 to 2300[F]	every 200	1	2
	32 to 2300[F]	600, 1200, 1800, and 2300	1	4
	32 to 650[G]	every 200	0.2	1
	−256 to + 32[G]	every 100	0.2	1
R and *S*	32 to 2700[F]	every 200	0.5	1 to 2000 and 4 at 2700
	32 to 2700[F]	1100 and 2200	0.5	2 to 2000 and 5 at 2700
B	0 to 3100[F]	every 200	0.5	1 to 2000 and 5 at 3100
		1100 and 2200	0.5	2 to 2000 and 9 at 3100
T	32 to 700[G]	every 200	0.2	0.4
	32 to 200[G]	110 and 200	0.1	0.2
	−256 to + 32[G]	every 100	0.2	0.4

[A] This table is based upon the values in Table 1, but Fahrenheit temperatures are given in round numbers rather than exact equivalents of the Celsius temperature.
[B] See 3.2.
[C] Approximate calibration points.
[D] With homogeneous thermocouples and reasonable experimental care.
[E] Using difference curve from reference table.
[F] In tube furnaces, by comparison with a calibrated Type S thermocouple.
[G] In stirred liquid baths, by comparison with a standard platinum resistance thermometer.

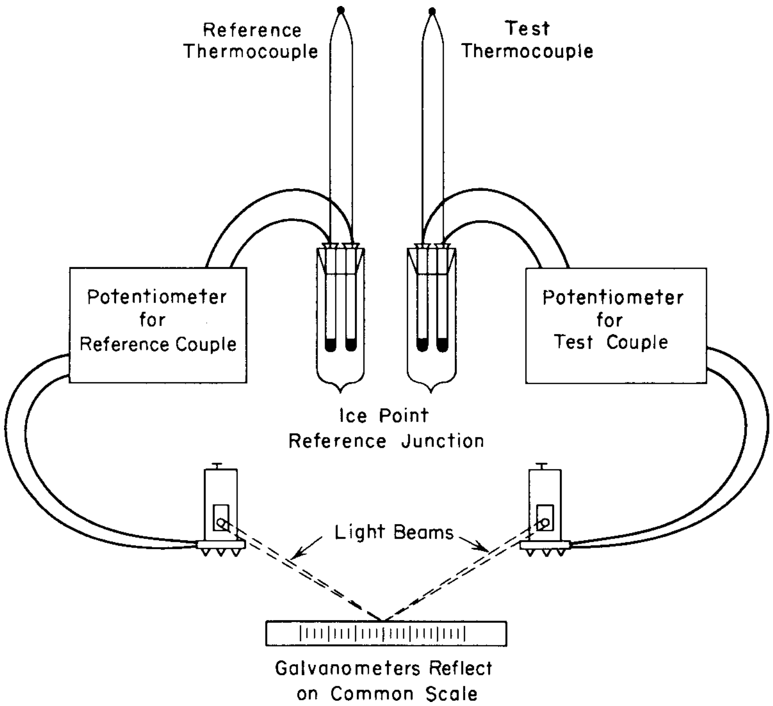

FIG. 1 Schematic Arrangement for Two-Potentiometer Method

galvanometer. The spots of light are reflected from the two galvanometers onto a single scale, the galvanometers being adjusted so that the spots coincide at the zero of the scale when the circuits are open and, therefore, also when the potentiometers are set to balance the emf of each thermocouple. When more than one thermocouple is to be calibrated, a selector switch is introduced between the reference junctions of the thermocouples being calibrated and the associated potentiometer. The above procedure for taking data is then repeated for each thermocouple in turn.

9.3 *Procedure B* is applicable when only one potentiometer is used. The arrangement when several thermocouples are being calibrated using a thermocouple thermometer as a reference is shown in Fig. 2. This method requires that the bath or furnace including the thermocouple be stabilized at the desired temperature before readings are taken. Each thermocouple is connected to the potentiometer in sequence by means of the selector switch, as shown. The reference thermocouple should be read just before and just after the reading of the emf of each thermocouple. After measuring the emf of each thermocouple once, the whole sequence should be repeated at least once at the same temperature to give check readings of emf. When a large volume of work is involved, or when for some other reason it is inconvenient to use only one furnace or bath for all of the calibration temperatures, a series of furnaces or baths may be used, each being maintained at the different temperatures corresponding to the desired calibration temperatures. After insertion in each furnace or bath, time must be allowed for steady state conditions to be reached before readings are taken. Variations of this method would include the use of a platinum resistance thermometer or liquid-in-glass thermometer as reference in a stirred liquid bath.

9.4 *Procedure C*

9.4.1 When the thermocouple being calibrated is of the same type as the reference, as, for example, a Type S thermocouple being calibrated against a Type S reference thermocouple, a convenient variation of the two potentiometer methods may be employed. With this technique, the emf of the reference thermocouple is measured with one potentiometer, as in Procedure A, but in this case the second potentiometer is used to measure simultaneously the relatively small emf difference between the reference thermocouple and the thermocouple being calibrated. At least two distinct advantages may be realized through the use of this technique. First, since the emf differences are a small fraction of the emf, they can be

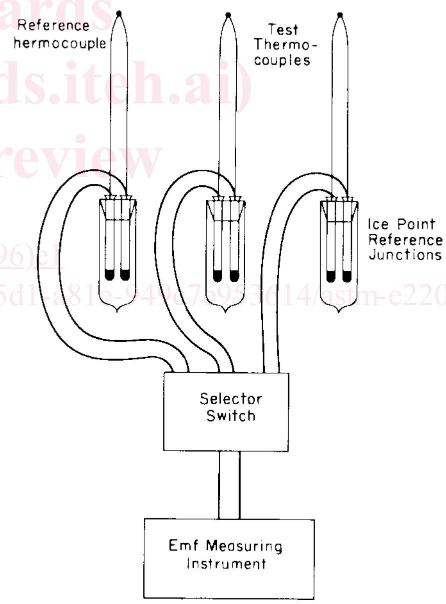

FIG. 2 Schematic Arrangement with a Selector Switch and a Single Measuring Instrument

measured to a higher degree of absolute accuracy (microvolts). Secondly, if the emf differences vary relatively slowly with change in temperature, the actual temperature at the time of a measurement need not be known accurately, and a higher rate of change of furnace temperature can be used than that tolerated when using Procedure A. Because of these two circumstances the method may be readily automated .

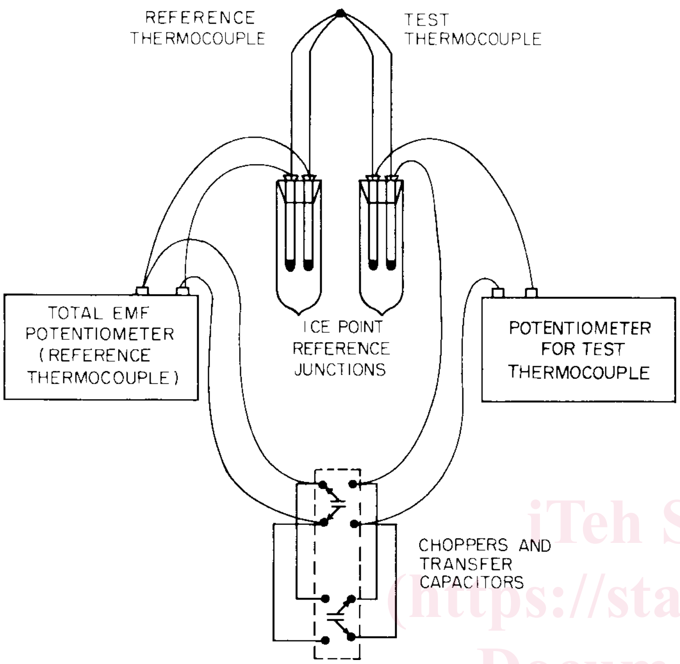

FIG. 3 Schematic Arrangement Showing Basic Isolating Potential Circuit

9.4.2 When comparison measurements are being made by direct subtraction in this manner, there can be no electrical circuit between the various thermocouples except at the point where the difference voltage is measured. In liquid and dry fluidized baths with common media, this requirement presents no problem, provided that the thermocouples do not touch each other. In tube furnaces it may be difficult to keep the various junctions at the same temperature without electric contact. In this situation the electrical isolation can be achieved at the reference end by use of an isolating potential comparator circuit.[6] The basic circuit is shown in Fig. 3. The isolating potential device is a double-pole, double-throw chopper (vibrating switch) and a capacitor which is first charged to the potential of the reference thermocouple and then is moved into series opposition with the emf of the test thermocouple so that the difference potentiometer indicates the difference in emf between the two. The total emf of the reference thermocouple is continuously monitored by the other potentiometer. To obtain the highest sensitivity, two chopper and condenser units are used at 180-deg phase difference, as shown in Fig. 3. The potentiometers may be of the manually balanced type, or if self-balancing potentiometers are used, the results may be presented on a recorder chart or other automatic data systems. With appropriate switching, automatic or manual operation, the number of thermocouples that may be calibrated together will depend principally on the size of the furnace used.

10. Preparation of Thermocouples for Test

10.1 In preparation for test, a suitable thermocouple protection tube shall be chosen that is long enough to provide sufficient immersion and to extend out from the furnace or bath for 50 to 75 mm (2 to 3 in.). A two-hole ceramic insulating tube, somewhat longer than the protection tube, shall be selected for each thermocouple. Except when using Procedure C (9.4), the wires of each thermocouple are threaded through the holes in its respective tube, and the group of thermocouple tubes loosely bundled together. The measuring junctions of all of the thermocouples may be welded together into a common bead to provide good thermal contact between the junctions of the different thermocouples.[7] If it is not convenient to weld the junctions together, the junction of each thermocouple must be welded separately and the junctions brought into good contact by wrapping them with platinum wire or foil. Slip the insulating tubes down on the thermocouple wires as close to the measuring junctions as possible without stressing the wires. Insert the bundle of thermocouples to the bottom of the protection tube; then place the tube at the proper depth in the furnace or bath. Such an assembly is shown schematically in Fig. 4. In this process take care not to stress or cold work the wires. Special care must also be taken during handling of the thermocouple wires to avoid contaminating them.

10.2 *Procedures for Types B, R, and S Thermocouples (Platinum-Rhodium/Platinum)*—This procedure for annealing is adapted to the calibration of bare wire platinum-10 % rhodium/platinum (Type S) or platinum-13 % rhodium/platinum (Type R) thermocouples in the temperature range from 0 to 1480°C (32 to 2700°F) and to the calibration of platinum-30 % rhodium/platinum-6 % rhodium (Type B) thermocouples in the range from 0 to 1700°C (32 to 3100°F). Suspend the thermocouple freely in air from two binding posts, which should be close together so that the tension in the wires and stretching while hot are kept to a minimum. Shield the thermocouple from drafts. Electrically anneal the thermocouple in air for a period of 45 min at approximately 1450°C (2650°F). Then cool it slowly (over a period of approximately 1 min) to 750°C (1380°F) and hold it at that temperature approximately 30 min. Following this anneal, allow the thermocouple to cool to room temperature within a few minutes. Alternating current from a variable transformer is a convenient source of controlled power for heating the thermocouple wires, about 12 A being required for 24-gage (0.51-mm) wire. The temperature is most readily determined by sighting on the platinum leg of the thermocouple with an optical pyrometer. A pyrometer reading of 1300°C (2380°F) will correspond to a wire temperature of about 1450°C. This correction is necessary to account for the emissivity of the wire.

10.2.1 Following the anneal, thread the thermocouple through its insulating tube and mount, together with a reference

[6] Dauphinne, T. M., "An Apparatus for Comparison of Thermocouples," *Canadian Journal of Physics*, Vol 33, 1955, p. 275.

[7] For information on welding of measuring junctions, see *Manual on the Use of Thermocouples in Temperature Measurement*, *ASTM STP 470 B*, 1981.