Appendix D: Sensor Calibration Accuracies

Understanding what's available:

Uncalibrated—Good

SoftCal™—Better

Calibrated—Best

The accuracy[1] of a sensor relates to how closely the measurement of resistance (or voltage) can be converted to temperature relative to the recognized international temperature scales (ITS-90 and PLTS-2000). Understanding how the accuracy of temperature sensors is specified begins with the definition of the response curve (e.g., voltage vs. temperature, resistance vs. temperature) for a particular sensor.

Temperature sensors either follow a known standard response within a given tolerance, or they must be calibrated against known standards. Details on calibration procedure are defined in this section. More information on the measurement system and uncertainty analysis is found in Appendix E: Temperature Measurement System.

It is convenient to have temperature sensors that match a standard curve and do not need an individual calibration. Such sensors are interchangeable. Interchangeable sensors follow the same response curve to within a given accuracy and can be interchanged routinely with one another.

Some cryogenic temperature sensors exist currently which are interchangeable within several tolerance bands. The Lake Shore DT-670 series silicon diodes are one example. These conform to five defined accuracy bands about a single curve (Curve 670) and can be ordered by simply specifying the tolerance band required for the experimental accuracy required. In this case, individual calibrations are not performed. However, if increased accuracy is required, full calibration over a specified range may be selected. This provides a fully characterized sensor that can be relied upon for much more accurate measurements, at the cost of being considered "interchangeable" with other sensors from that product line.

In addition to diodes, both platinum and ruthenium oxide sensors also follow a standard curve of resistance versus temperature. Platinum sensors follow an industry standard curve (IEC 751). Lake Shore offers platinum available in Class B tolerance band. If greater temperature accuracy is required, these sensors can be individually calibrated or a SoftCal™ can be utilized to increase the accuracy of the temperature measurement.

Ruthenium oxide RTDs are also interchangeable. Like silicon diodes, they are interchangeable within a manufacturer lot. Two tolerance bands for ruthenium oxide are defined by Lake Shore.

Table 1, Table 2, and Table 5 summarize Lake Shore temperature sensor accuracies. They are categorized into Good, Better, and Best for each sensor type. The following pages explain the advantages of investing in SoftCal™ or a full calibration from Lake Shore to obtain improved accuracy.

Good	Uncalibrated	■ Silicon diodes follow standard curve ■ Platinum resistors follow standard curve ■ Ruthenium oxide (Rox™) resistors follow standard curve ■ GaAlAs diode, carbon-glass, Cernox™, germanium, and rhodium-iron sensors can be purchased uncalibrated but must be calibrated by the customer
Better	SoftCal™	■ An abbreviated calibration (2-point: 77 K and 305 K; or 3-point: 77 K, 305 K, and 480 K) which is available for platinum sensors
Best	Calibration	■ All sensors can be calibrated in the various pre-defined temperature ranges. Lake Shore has defined calibration ranges available for each sensor type. The digits represent the lower range in kelvin, and the letter corresponds to high temperature limit, where: A = 6 K B = 40 K D = 100 K L = 325 K M = 420 K H = 500 K J = 800 K For example: The calibration range "1.4L" would result in a sensor characterized from 1.4 K to 325 K

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[1] *The use of the terms accuracy and uncertainty throughout this catalog are used in the more general and conventional sense as opposed to following the strict metrological definitions. For more information, see Appendix B: Accuracy versus Uncertainty.*

Uncalibrated—Good

With the purchase of an uncalibrated sensor you will receive:

Silicon diodes
- Curve 670 data (DT-670)
- Installation instructions

Platinum
- Standard IEC-751 data
- Installation instructions

Ruthenium oxide
- Curve data (102, 103, or 202)
- Installation instructions

Thermocouple
- Reference data

Cernox™, germanium, GaAlAs, carbon-glass, capacitance
- Thermal cycling data—resistance, voltage, or capacitance readings at helium, nitrogen, and room temperature
- Installation instructions

Table 1—Uncalibrated sensors: typical accuracy (interchangeability)

	Temperature														
	0.05 K	0.5 K	1.4 K	2 K	4.2 K	10 K	20 K	25 K	40 K	70 K	100 K	305 K	400 K	500 K	670 K
Silicon diode															
DT-470-SD, Band 11	—	—	—	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.5 K	±1.0 K	±1.0 K	—
DT-470-SD, Band 11A	—	—	—	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±1% of temp	±1% of temp	±1% of temp	—
DT-470-SD, Band 12	—	—	—	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±1.0 K	±2.0 K	±2.0 K	—
DT-470-SD, Band 12A	—	—	—	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±1% of temp	±1% of temp	±1% of temp	—
DT-470-SD, Band 13	—	—	—	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1% of temp	±1% of temp	±1% of temp	—
DT-471-SD	—	—	—	—	—	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5% of temp	±1.5% of temp	±1.5% of temp	—
DT-414	—	—	—	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5 K	±1.5% of temp	—	—	—
DT-421	—	—	—	—	—	—	±2.5 K	±2.5 K	±2.5 K	±2.5 K	±2.5 K	±1.5% of temp	—	—	—
DT-670-SD, Band A	—	—	—	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.5 K	±0.5 K	±0.5 K	—
DT-670-SD, Band B	—	—	—	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.5 K	±0.33% of temp	±0.33% of temp	—
DT-670-SD, Band C	—	—	—	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±1.0 K	±0.5% of temp	±0.5% of temp	—
DT-670-SD, Band D	—	—	—	—	—	—	—	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.50 K	±0.2% of temp	±0.2% of temp	—
DT-670-SD, Band E	—	—	—	—	—	—	—	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±0.25% of temp	±0.25% of temp	±0.25% of temp	—
Platinum															
PT-102	—	—	—	—	—	—	—	—	—	±1.3 K	±1.2 K	±0.5 K	±0.9 K	±1.4 K	±2.3 K
PT-103	—	—	—	—	—	—	—	—	—	±1.3 K	±1.2 K	±0.5 K	±0.9 K	±1.4 K	±2.3 K
PT-111	—	—	—	—	—	—	—	—	—	±1.3 K	±1.2 K	±0.5 K	±0.9 K	±1.4 K	±2.3 K
Rox™															
RX-102A-AA	±10 mK	±25 mK	±50 mK	±75 mK	±125 mK	±300 mK	±1.25 K	±1.5 K	±4.0 K	—	—	—	—	—	—
RX-102A-AA-M	±5 mK	±20 mK	±25 mK	±40 mK	±75 mK	±200 mK	±500 mK	±750 mK	±1.5 K	—	—	—	—	—	—
RX-202A-AA	±15 mK	±30 mK	±100 mK	±125 mK	±250 mK	±1 K	±2.5 K	±3 K	±5.0 K	—	—	—	—	—	—
RX-202A-AA-M	±10 mK	±25 mK	±50 mK	±75 mK	±150 mK	±500 mK	±1.0 K	±1.5 K	±2.0 K	—	—	—	—	—	—
RX-103A-AA	—	—	±150 mK	±180 mK	±400 mK	±1 K	±2.0 K	±2.5 K	±4.0 K	—	—	—	—	—	—
RX-103A-AA-M	—	—	±50 mK	±75 mK	±100 mK	±300 mK	±700 mK	±1 K	±1.5 K	—	—	—	—	—	—

SoftCal™—Better

SoftCal™ is only available with platinum resistors.
With the purchase of SoftCal™ you will receive:

- Interpolation table and breakpoint interpolation table
- 2-point calibration report (thermal cycling data at LN_2 and room temperature K) OR
- 3-point calibration report (thermal cycling data at LHe, LN_2, and either 305 K or 480 K)

The temperature characteristics of Lake Shore temperature sensors are extremely predictable, and exhibit excellent uniformity from device to device. The SoftCal™ feature (sensor specific interpolation/extrapolation techniques) allows an abbreviated calibration, based on two or three calibration points, to generate a resistance versus temperature or voltage versus temperature curve over the useful range of selected sensors with remarkable accuracy. In the case of the Lake Shore platinum resistance sensors, the SoftCal™ procedure makes small adjustments to the IEC-751 curve so that the resulting curve matches the resistance versus temperature characteristic of the individual sensor more closely. SoftCal™ provides the means to generate accurate, inexpensive calibrations for selected Lake Shore sensors to use with either Lake Shore temperature controllers and monitors or the customer's own readout electronics.

Table 2—SoftCal™ (2- and 3-point soft calibration sensors): typical accuracy

	70 K	305 K	400 K	475 K	500 K	670 K
Platinum						
PT-102-2S[2]	±0.25 K	±0.25 K	±0.9 K	±1.3 K	±1.4 K	±2.3 K
PT-103-2S[2]	±0.25 K	±0.25 K	±0.9 K	±1.3 K	±1.4 K	±2.3 K
PT-111-2S[2]	±0.25 K	±0.25 K	±0.9 K	±1.3 K	±1.4 K	±2.3 K
PT-102-3S[3]	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±1.4 K	±2.3 K
PT-103-3S[3]	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±1.4 K	±2.3 K
PT-111-3S[3]	±0.25 K	±0.25 K	±0.25 K	±0.25 K	±1.4 K	±2.3 K

[2] *2S (2-point at 77 K and 305 K)*
[3] *3S (3-point at 77 K, 305 K, and 480 K)*

Calibrated—Best

Lake Shore calibrations include the following:

- Certificate of calibration
- Calibration data plot
- Calibration test data
- Polynominal fit equation and fit comparisons (temperature as a function of resistance or voltage)
- Interpolation table (resistance or voltage as a function of temperature)
- Breakpoint interpolation table
- Instrument breakpoint table

Lake Shore provides precision temperature calibrations for all sensor types, and Lake Shore calibrations are traceable to internationally recognized temperature scales.

Above 0.65 K, calibrations are based on the International Temperature Scale of 1990 (ITS-90). The ITS-90 scale became the official international temperature scale on January 1, 1990; it supersedes the International Practical Temperature Scale of 1968 (IPTS-68) and the 1976 Provisional Temperature Scale (EPT-76). Internally, this scale is maintained on a set of germanium, rhodium-iron, and platinum standards grade secondary thermometers calibrated at the U.S. National Institute of Standards and Technology (NIST) or Great Britain's National Physical Laboratory (NPL), or another recognized national metrology laboratory. Working standard thermometers are calibrated against, and routinely intercompared with, these secondary standards.

For temperatures below 0.65 K, Lake Shore calibrations are based on the Provisional Low Temperature Scale of 2000 (PLTS 2000) adopted by the Comité International des Poids et Mesures in October 2000. Internally, this scale is maintained on a set of germanium and rhodium-iron resistance thermometers calibrated at the U.S. National Institute of Standards and Technology, Great Britain's National Physical Laboratory, or Germany's Physikalisch-Technische Bundesanstalt (PTB). Working standard thermometers are calibrated against, and routinely intercompared with, these secondary standards along with a nuclear orientation thermometer and superconducting fixed points sets.

Calibration method

Lake Shore performs comparison calibrations measuring the resistance or forward voltage of both the sensor under test and the working standard thermometer. All measurements are performed in a four-lead fashion to eliminate lead resistance.

The sensors to be calibrated are mounted, along with appropriate known standards, in a copper block designed to accommodate a variety of sensor styles. This block is enclosed within a quasi-adiabatic copper radiation shield, which, in turn, is thermally isolated within an outer vacuum jacket.

Constant temperature of the block is achieved by an appropriately mounted heater and precision temperature controller. The electrical, mechanical, and thermal designs of the calibration probe provide extremely stable and uniform temperatures within the copper block.

The calibration process above 4.2 K is computer controlled and the calibration data collected automatically. Data points are usually not at integer temperatures since the primary concern is temperature stability near a data point rather than the specific value. The precise temperature for each data point is subsequently determined. The typical number of data points collected is listed in Table 4 (page 192).

Calibration data is provided for each calibration, together with a calibration data plot and polynomial fits to that raw data, along with a computer generated smoothed interpolation table which is listed as a function of temperature. For resistance sensors, the raw data is given as temperature (T) and resistance (R); the interpolation table shows T, R, dR/dT and dimensionless sensitivity d(log R)/d(log T). For diode sensors, the raw data is given as forward voltage (V) and temperature (T), and the interpolation table presents T, V, and dV/dT.

The specific techniques for generating and controlling calibration temperatures vary, depending on the temperature involved.

Calibrations performed over a wide temperature span frequently entail the consecutive use of a variety of procedures and equipment. In these cases, data points are routinely overlapped to assure integrity of the calibration. The sections that follow describe the specific techniques used for the various temperature ranges.

Calibration method—1.2 K to 330 K

Temperatures from 1.2 K to 4.2 K are achieved by filling a He-4 subpot attached to the copper sensor block and pumping on the subpot through a vacuum regulator valve. Temperatures above 4.2 K are achieved by applying controlled power to a heater while the entire probe assembly remains immersed in liquid helium. In either case, the sensors themselves are maintained in a vacuum.

Extreme care is taken to ensure that the sensor block is thermally stable before calibration data is collected. The computer examines successive and interposed measurements of both the known standards and the sensors being calibrated at each data point to verify temperature stability.

Once temperature has stabilized, an appropriate DC excitation current is applied to the thermometer, and the resulting voltage is measured. In the case of resistance sensors, currents from 0.01 mA to 5 mA are selected as required. Sensor voltage is maintained between 1 mV and 3 mV for Cernox™, carbon-glass, germanium, and Rox™ elements up to 300 kΩ. Higher resistances are measured using a fixed current of 0.01 mA. Sensor power is held between 1 mW and 10 mW for platinum and rhodium-iron resistors.

For resistors, successive voltage readings taken with the current applied in opposite polarities are averaged together to eliminate thermal EMFs from the data. The resistance of the sensing element is determined and reported to five significant figures at each temperature.

Diode thermometers are normally excited with a 10 µA current (±0.1%) and the resulting forward voltage reported to five significant figures.

Calibration method—below 1.2 K

Calibration temperatures below 1.2 K are produced in a dilution refrigerator. Techniques similar to those for higher temperatures are followed to ensure reliable calibration data. The need for increased care at these lower temperatures, however, requires greater involvement on the part of a skilled system technician and less reliance on automation.

Sensors are measured with a Lake Shore Model 370 AC resistance bridge operated at 13.7 Hz. Germanium and Rox™ sensors are maintained at a nominal excitation voltage of 20 µV RMS (0.05 K to 0.1 K) or 63 µV RMS (0.1 K to 1.2 K). Cernox™ sensors are maintained at a nominal excitation voltage of 20 µV RMS from 0.1 K to 0.5 K and 63 µV RMS from (0.5 K to 1.2 K).

Accuracy considerations

The uncertainty associated with a sensor calibration is the net result of each step in the calibration process. A temperature scale disseminated by national standards laboratories is transferred to secondary thermometers maintained by Lake Shore. Those thermometers are used to calibrate in-house working standard thermometers which are then used to calibrate commercial thermometers. Each step introduces an uncertainty that depends on the instrumentation used in the calibration and the specific temperature dependent characteristics of the sensor type calibrated. Other considerations such as calibration block uniformity and stability must also be accounted for. As a result, the calibration accuracy varies with both temperature range and sensor type. Table 3 summarizes the uncertainties associated with the raw data for Lake Shore calibrations.

Note: The values are the expanded uncertainty based upon a 95% (2 σ) confidence limit with respect to ITS-90.

In practice, however, the uncertainty of subsequent measurements performed with a calibrated sensor should include an additional uncertainty related to the short-term reproducibility of the sensor.

A summary of total calibration uncertainty for selected Lake Shore sensors at specific temperatures is given in Table 5. Errors in each case are expressed in millikelvin deviation from ITS-90 or PLTS-2000. The values in this table reflect the combination of all calibration uncertainties, and the short-term reproductibility upon temperature cycling. It should be noted that at a given temperature, uncertainties are highest for sensors with lowest normalized sensitivity [(1/R)(dR/dT) or (T/R)(dR/dT)] due to the low signal-to-noise ratio.

Lake Shore's calibration facility and procedures for diode and resistance sensor calibrations are traceable to recognized national metrology laboratories and are in compliance with ISO 9001. See page 195 regarding recalibration information.

Table 3—Calibration uncertainty for Lake Shore calibration for selected sensors[4]

	Germanium	Cernox					Platinum		Rox			RF-800	Diode
		1010	1030	1050	1070	1080	100 Ω	25 Ω	102A	103A	202A	27 Ω	
1.4 K	±4 mK	±4 mK	±4 mK	±4 mK	—	—	—	—	±4 mK	±4 mK	±4 mK	±5 mK	±7 mK
4.2 K	±4 mK	±4 mK	±4 mK	±4 mK	±4 mK	—	—	—	±4 mK	±6 mK	±5 mK	±5 mK	±5 mK
10 K	±4 mK	±5 mK	±5 mK	±4 mK	±4 mK	—	—	—	±10 mK	±15 mK	±12 mK	±7 mK	±6 mK
20 K	±8 mK	±10 mK	±9 mK	±8 mK	±8 mK	±8 mK	±9 mK	±10 mK	±35 mK	±35 mK	±28 mK	±13 mK	±9 mK
30 K	±9 mK	±13 mK	±11 mK	±9 mK	±9 mK	±9 mK	±9 mK	±9 mK	±76 mK	±61 mK	±46 mK	±14 mK	±31 mK
50 K	±11 mK	±18 mK	±14 mK	±12 mK	±12 mK	±11 mK	±10 mK	±10 mK	—	—	—	±13 mK	±37 mK
100 K	±20 mK	±29 mK	±22 mK	±17 mK	±16 mK	±14 mK	±11 mK	±12 mK	—	—	—	±12 mK	±32 mK
300 K	—	±78 mK	±60 mK	±46 mK	±45 mK	±36 mK	±24 mK	±24 mK	—	—	—	±25 mK	±35 mK
400 K	—	±124 mK	±94 mK	±74 mK	±72 mK	±60 mK	±45 mK	±45 mK	—	—	—	±45 mK	±49 mK
500 K	—	—	—	—	—	—	±51 mK	±51 mK	—	—	—	—	±54 mK

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[4] *All uncertainties are with respect to ITS-90 and represent an approximate 95% configience interval using a coverage factor k=2.*

Lake Shore calibrations include:

1. Certificate of calibration—This states the traceability of the calibrations performed by Lake Shore to international temperature scales and standards.

2. Calibration data—The measured test data (resistance or forward voltage) is plotted as a function of the temperature. A straight-line interpolation is shown between the data points as a visual aid to the behavior of the sensor.

3. Calibration data plot—This table contains the actual calibration data recorded during the calibration of the temperature sensor. The indicated temperatures are those measured using the standard thermometers maintained by Lake Shore, while the voltage or resistance values are the measurements recorded on the device being calibrated.

Table 4—Number of calibration data points

Range (K)	Typical number of data points	Interpolation calibration printout interval
0.050–0.100	6	0.005
0.100–0.300	9	0.010
0.300–0.500	5	0.020
0.500–1.00	7	0.050
1.00–2.00	18	0.10
2.00–5.00		0.20
5.00–10.0	40	0.50
10.0–30.0		1.0
30.0–40.0		2.0
40–100		5.0
100–300	28	5.0
300–380		5.0
340–480 (silicon diodes)	10	5.0
340–480 platinum and rhodium-iron resistors (400 K upper limit)	15	5.0
480–800 platinum sensors only	2	5

4. Curve fit—A curve fit is given for each sensor, allowing temperature to be calculated from the measurement of the forward voltage (diodes) or the resistance. One of two curve fit types are used: the first curve fit type is a polynomial equation based on the Chebychev polynomials; the second curve fit type is based on a cubic spline routine. Cubic spline routines are preferred when fitting a rapidly varying function or when smoothing is not desired. In general, the differences between the spline technique and the polynomial fits will be considerably less than the measurement uncertainties.

Chebychev polynomial fits

A polynomial equation based on the Chebychev polynomials has the form

$$T(X) = \Sigma\, a_n t_n(X) \qquad \text{Eqn. 1}$$

where $T(X)$ represents the temperature in kelvin, $t_n(X)$ is a Chebychev polynomial, a_n represents the Chebychev coefficient, and the summation is performed from 0 to the order of the fit. The parameter X is a normalized variable given by

$$X = ((Z-Z_L)-(Z_U-Z))/(Z_U-Z_L). \qquad \text{Eqn. 2}$$

For diodes, Z is simply the voltage V. For resistors, Z is either the resistance R or $Z = \log_{10}(R)$ depending on the behavior of the resistance with temperature. Z_L and Z_U designate the lower and upper limit of the variable Z over the fit range.

The Chebychev polynomials can be generated from the recursion relation

$$t_{n+1}(X) = 2Xt_n(X) - t_{n-1}(X) \qquad \text{Eqn. 3}$$

$$\text{where } t_0(X) = 1,\ t_1(X) = X$$

Alternately, these polynomials are given by

$$t_n(X) = \cos\,[n \cdot \arccos(X)]. \qquad \text{Eqn. 4}$$

All the necessary parameters for using equations 1 through 4 to calculate temperatures from either resistance or voltage are given in the calibration report. This includes the Chebychev coefficients, Z_L and Z_U, and also the definition of Z. Depending on the sensor being calibrated and the calibration range, several different fit ranges may be required to span the full temperature range adequately.

The use of Chebychev polynomials is no more complicated than the use of the regular power series, and they offer significant advantages in the actual fitting process. The first step is to transform the measured variable, either R or V, into the normalized variable using equation 2. Equation 1 is then used in combination with equation 3 or 4 to calculate the temperature.

An interesting and useful property of the Chebychev fits is evident in the form of the Chebychev polynomial given in equation 4. The cosine function requires that $[t_n(X)] \le 1$, so no term in equation 1 will be greater than the absolute value of the coefficient. This property makes it easy to determine the contribution of each term to the temperature calculation and where to truncate the series if the full accuracy of the fit is not required.

Table 5—Calibrated sensors: typical accuracy[5]

	Temperature												
	0.05 K	0.1 K	0.3 K	0.5 K	1 K	1.4 K	4.2 K	10 K	20 K	77 K	300 K	400 K	500 K
Silicon diode													
DT-670-SD/CO	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	±45 mK	±50 mK
DT-670-CU/CO/LR/CY/ET/BO	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
DT-414	—	—	—	—	—	—	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
DT-421	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
DT-470-SD/CO	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	±45 mK	±50 mK
DT-470-BO/BR/CU/CY/ET/LR/MT	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
DT-471-SD/CO	—	—	—	—	—	—	—	±12 mK	±14 mK	±22 mK	±32 mK	±45 mK	±50 mK
DT-471-BO/BR/CU/CY/ET/LR/MT	—	—	—	—	—	—	—	±12 mK	±14 mK	±22 mK	±32 mK	—	—
GaAlAs diode													
TG-120-P	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
TG-120-PL	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
TG-120-SD/CO	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	±45 mK	±50 mK
TG-120-CU	—	—	—	—	—	±12 mK	±12 mK	±12 mK	±14 mK	±22 mK	±32 mK	—	—
Cernox™													
CX-1010-AA/CD/CO/CU/LR/ET/MT/SD	—	±3 mK	±3.5 mK	±4.5 mK	±5 mK	±5 mK	±5 mK	±6 mK	±9 mK	±25 mK	±75 mK	—	—
CX-1010-BC	—	—	—	—	—	±5 mK	±5 mK	±6 mK	±9 mK	±25 mK	±75 mK	—	—
CX-1030-AA/CD/CO/CU/LR/ET/MT/SD	—	—	±3 mK	±4 mK	±5 mK	±5 mK	±5 mK	±6 mK	±9 mK	±25 mK	±75 mK	—	—
CX-1030-BC	—	—	—	—	—	±5 mK	±5 mK	±6 mK	±9 mK	±25 mK	±75 mK	—	—
CX-1050-AA/BC/CD/CO/CU/LR/ET/MT/SD	—	—	—	—	—	±5 mK	±5 mK	±6 mK	±9 mK	±16 mK	±40 mK	—	—
CX-1070-AA/BC/CD/CO/CU/LR/ET/MT/SD	—	—	—	—	—	—	±5 mK	±6 mK	±9 mK	±16 mK	±40 mK	—	—
CX-1080-AA/BC/CD/CO/CU/LR/ET/MT/SD	—	—	—	—	—	—	—	—	±9 mK	±16 mK	±40 mK	—	—
CX-1030-CO/SD-HT	—	—	±3 mK	±4 mK	±5 mK	±5 mK	±5 mK	±6 mK	±9 mK	±16 mK	±40 mK	±65 mK	—
CX-1050-CO/SD-HT	—	—	—	—	—	±5 mK	±5 mK	±6 mK	±9 mK	±16 mK	±40 mK	±65 mK	—
CX-1070-CO/SD-HT	—	—	—	—	—	—	±5 mK	±6 mK	±9 mK	±16 mK	±40 mK	±65 mK	—
CX-1080-CO/SD-HT	—	—	—	—	—	—	—	—	±9 mK	±16 mK	±40 mK	±65 mK	—
Carbon-glass													
CGR-1-500, CGR-1-500-CD	—	—	—	—	—	±4 mK	±4 mK	±5 mK	±8 mK	±25 mK	±105 mK	—	—
CGR-1-1000, CGR-1-1000-CD	—	—	—	—	—	±4 mK	±4 mK	±5 mK	±8 mK	±25 mK	±105 mK	—	—
CGR-1-2000, CGR-1-2000-CD	—	—	—	—	—	±4 mK	±4 mK	±5 mK	±8 mK	±25 mK	±105 mK	—	—
Rox™													
RX-102A-AA/CD	±3 mK	±3.5 mK	±4 mK	±4.5 mK	±5.5 mK	±5 mK	±16 mK	±18 mK	±37 mK	—	—	—	—
RX-103A-AA/CD	—	—	—	—	—	±5 mK	±17 mK	±22 mK	±38 mK	—	—	—	—
RX-202A-AA/CD	±3 mK	±3.5 mK	±4 mK	±4.5 mK	±5.5 mK	±5 mK	±16 mK	±18 mK	±37 mK	—	—	—	—
Rhodium-iron													
RF-100T-AA/CD/BC/MC	—	—	—	—	—	±11 mK	±11 mK	±12 mK	±14 mK	±15 mK	±25 mK	—	—
RF-100U-AA/CD/BC	—	—	—	—	—	±11 mK	±11 mK	±12 mK	±14 mK	±15 mK	±25 mK	—	—
RF-800-4	—	—	—	—	—	±7 mK	±7 mK	±8 mK	±10 mK	±13 mK	±23 mK	±41 mK	±46 mK
Platinum													
PT-102	—	—	—	—	—	—	—	—	±10 mK	±12 mK	±23 mK	±40 mK	±46 mK
PT-103	—	—	—	—	—	—	—	—	±10 mK	±12 mK	±23 mK	±40 mK	±46 mK
PT-111	—	—	—	—	—	—	—	—	±10 mK	±12 mK	±23 mK	±40 mK	±46 mK
Germanium													
GR-50-AA/CD	±5 mK	±5 mK	±5 mK	±5 mK	±6 mK	±6 mK	±6 mK	—	—	—	—	—	—
GR-300-AA/CD	—	—	±4 mK	±4 mK	±4 mK	±4 mK	±4 mK	±4 mK	±8 mK	±25 mK	—	—	—
GR-1400-AA/CD	—	—	—	—	—	±4 mK	±4 mK	±4 mK	±7 mK	±15 mK	—	—	—

[5] *All accuracies are: 2 ▯ figures; [(calibration uncertainty)^2 + (reproducibility)^2]$^{0.5}$; for additional information, please see Appendix D.*

The Chebychev polynomial fit is a smoothing fit and often yields a better representation of the calibration, as it can eliminate some random errors. Along with each set of Chebychev coefficients, a deviation table is given to show how well the polynomial fits the measured test data. This table gives the measured resistance or voltage, the measured temperature, and the temperature calculated from the fit equation. The last column gives the difference in millikelvin (0.001 K) between the measured value and the calculated value. A root mean square (RMS) deviation is given as an indication of the overall quality of the fit and as an indication of the accuracy with which the equation represents the calibration data. Chebychev polynomial fits are provided for all resistance temperature sensor calibrations.

Cubic spline fit

Some device types (e.g., GaAlAs diode thermometers) have either a fine structure that is undesirably smoothed by a Chebycheb polynomial fit or else a rapidly varying response with temperature. For these devices, a cubic spline fit is provided. A cubic spline fit creates a cubic equation for each interval between calibration points. At each calibration point, the method requires that the cubic equations on either side of the calibration point match in value, first derivative (slope), and second derivative (curvature) at the calibration point. For this fit method, a table is provided listing temperature (T), forward voltage (V), and curvature (C) for each calibration point. In use, the voltage V is measured at the unknown temperature T. Using the provided table, the bracketing calibration points V(k) and V(k+1) are determined and the following quantities are defined:

$$dV=V(k+1)-V(k),\ dT=T(k+1)-T(k),\ dx=V-V(k), \qquad \text{Eqn. 5}$$

$$\text{from which } S(0)=T(k), \qquad \text{Eqn. 6}$$

$$S(1)=(dT/dV)-dV\cdot(2\cdot C(k)+C(k+1))/6, \qquad \text{Eqn. 7}$$

$$S(2)=C(k)/2, \text{ and} \qquad \text{Eqn. 8}$$

$$S(3)=(C(k+1)-C(k))/(6\cdot dV) \text{ are derived.} \qquad \text{Eqn. 9}$$

Finally, the temperature is calculated as

$$T=S(0)+S(1)\cdot dx+S(2)\cdot dx^2+S(3)\cdot dx^3. \qquad \text{Eqn. 10}$$

A major difference between the Chebychev polynomial fit and the cubic spline fit is that the cubic spline fit provides no smoothing. The curve fit produced by this method passes through each calibration point exactly, so there are no error terms to report.

5. Interpolation table—A complete interpolation table is provided over the calibration range of the sensor. This table lists the temperature, the resistance (resistance sensors) or voltage (diode sensors), the sensitivity (dR/dT or dV/dT), and, in the case of resistors, a normalized dimensionless sensitivity [d(log R)/d(logT) = (T/R)·(dR/dT)]. The interpolation table lists resistance or voltage as a function of temperature, which is the reverse of the curve fit, which gives temperature as a function of sensor units. A cubic spline routine is used to calculate the resistance or voltage at a predetermined set of temperatures. For resistors, the interpolation table is calculated from the smoothed data produced by the Chebychev curve fit. For diodes, however, the interpolation table is calculated from the raw data in order to maintain the fine structure of the sensors' temperature response. Consequently, slight differences between the polynomial equations and the interpolation table are expected. These differences may be on the order of the RMS deviations for the polynomial fits. For resistors, these differences are typically about one tenth the calibration uncertainty. For diodes, the differences may be on the order of the calibration uncertainty in the regions of high curvature and one tenth the calibration uncertainty in the linear regions.

6. Breakpoint table—Lake Shore temperature instruments provide a seamless solution for measuring temperature sensors and converting the measurement into temperature units. The conversion from sensor units to temperature units requires the entry of the temperature response curve into the instrument. For calibrated sensors, this is accomplished through the use of a breakpoint table. With each calibration, Lake Shore provides breakpoint table formats to optimize the performance of the sensor when used with a Lake Shore instrument. The formats provided are compatible with any Lake Shore instrument produced over the last twenty years that accepts user curves. Software is also provided to install the breakpoint table file into most instruments using USB, Ethernet, IEEE-488, or RS-232 interfaces (instrument dependent).

In addition to the breakpoint table and software mentioned above, the CalCurve™ service provides the user with additional alternatives for installing a temperature response curve into a Lake Shore instrument. When the sensor and instrument are ordered together, a factory installed CalCurve service can be provided. A CalCurve can be done in the field when additional or replacement sensors are installed. In this case, curve data is loaded into a non-volatile memory that can be installed into the instrument by the user.

If the sensor is used with customer provided equipment (e.g., voltmeter, current source, and computer) then the curve fit (Chebychev or cubic spline) described in number 4 above should be used. The breakpoint tables are not necessary in this case.

Caution: Proper calculation of a breakpoint table is based upon the interpolation method utilized by the specific instrument for which it is intended. The use of the breakpoint table in an instrument that uses a different interpolation method can cause significant conversion errors.

Lake Shore calibration services

- Recalibration
- CalCurve™
- Calibration report
- Certificate of conformance
- Expanded interpolation table
- Second copy of calibration report

Recalibration

The stability of a temperature sensor over time is dependent on both its operating environment and history of use. These environmental effects contribute to the degradation of calibration over time:

- Ionizing radiation
- Thermal shock
- Thermal stress from continuous exposure to high temperatures (relative to the sensor materials)
- Mechanical shock
- Improper use
- Corrosion (a serious problem for systems of dissimilar metallurgies in the presence of moisture and chemical agents such as salts—this includes integrated circuits and other electronics)
- Electrical stress/electromagnetic interference (EMI)/electrostatic discharge (ESD)

There are no specific published regulations or guidelines that establish requirements for the frequency of recalibration of cryogenic temperature sensors. There are certainly military standards for the recalibration of measuring devices. However, these standards only require that a recalibration program be established and then adhered to in order to fulfill the requirements.

Many highly regarded manufacturers of more complex measuring devices such as voltmeters recommend that such instruments be recalibrated every six months.

Temperature sensors are complex assemblies of wires, welds, electrical connections, dissimilar metallurgies, electronic packages, seals, etc., and hence have the potential for drift in calibration. Like a voltmeter, where components degrade or vary with time and use, all of the “components” of a temperature sensor may also vary, especially where they are joined together at material interfaces. Degradation in a sensor materials system is less apparent than deterioration in performance of a voltmeter.

Lake Shore sensor calibrations are certified for one year. Depending upon the sensor type and how it is used, it is recommended that sensors be recalibrated in the Lake Shore Calibration Service Department periodically. Certainly, recalibration before important experiments would be advisable.

Model 8000 CalCurve™

The Model 8000 CalCurve™ is provided free of charge at the time of order to any customer who orders a calibrated sensor. The Model 8000 is the calibration breakpoint interpolation data. Also included is an executable program to load the data into a Lake Shore instrument. Once the data is loaded into the instrument, the user can calculate and display temperature with the data. The following information is included with the Model 8000 CalCurve™:

- Raw data
- Coefficients
- Interpolation table
- Instrument breakpoints
- A program for installing curves into instrument
- Instructions describing all file formats and contents

There is a charge to load previously stored calibration curves.

Model 8001, 8002 CalCurve™

A Lake Shore CalCurve™ provides users with a convenient method of storing sensor calibrations within Lake Shore instruments. Calibration data (breakpoint interpolation table) for a specific sensor is stored into a nonvolatile memory. The breakpoint data improves combined sensor/instrument accuracy to within ±0.1 K or better over the calibrated temperature range of the sensor.

Lake Shore-installed Model 8001—breakpoint table from a calibrated sensor stored in the instrument

Field-installed Model 8002-05—breakpoint table from a calibrated sensor loaded into a nonvolatile memory

Also available with Lake Shore calibrations

Model ECRIT (expanded calibration report interpolation table)—Lake Shore calibrations are provided with a standard number of points in the interpolation table. If a customer requires more points within a specific range, the ECRIT can be ordered.

Model SCR (second calibration report)—A calibration report is supplied with every calibrated sensor that is shipped to the customer. An SCR is needed only when the customer requires a second copy. Specify sensor model and serial numbers when ordering. Calibration data is kept on file for two years only.

Model COC-SEN (certificate of conformance)—Sensors

Model COC-INS (certificate of conformance)—Instruments