Ensuring the Accuracy and Cost-Effectiveness of Temperature Measurement Systems

APPLICATION NOTE

KEITHLEY
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Temperature is one of the most frequently measured quantities in science and industry, and temperature measurements are made for a variety of reasons. Sensors are the heart of temperature measurements, and, with many varieties from which to choose, it's important to select the proper sensor for the application. In addition, the temperature measurement system used must be matched to the application, as well, for optimal cost-effectiveness. This applications brief will examine how to evaluate the advantages and disadvantages of various sensor types and the instrumentation options available so that sensor outputs result in accurate and reliable measurements.

Temperature Sensor Technologies

A variety of sensor technologies are available, including thermocouples, resistive temperature detectors (RTDs), and thermistors, all of which offer widely different measurement ranges, accuracy levels, prices, and ease of use. However, the best sensor choice often depends largely on the application environment and temperature range required. **Table 1** provides an overview of these sensor types.

Thermocouples

Thermocouples are the most commonly used type of temperature measurement sensor. But, despite their widespread use, thermocouples may be the least understood type of temperature sensors. When compared to some temperature sensors, thermocouples are easy to work with and are based on a simple operating principle. However, there are many different types of thermocouples, and special attention to metallurgy, operating principles, limitations, and treatment of measurement data is required to ensure consistently accurate results.

Thermocouples offer several advantages over other temperature sensor types:

- The basic thermocouple is relatively inexpensive, although protective sheaths, cabling, and connectors can contribute to overall expense.
- Thermocouples are mechanically simple, durable, and reliable. Properties of typical metals used in thermocouples provide predictable output voltages. This allows users to adapt thermocouples to a variety of applications, including those in reactive or caustic environments.
- The physical construction of a basic thermocouple is simple—all that's necessary is twisting together wires of the appropriate alloys. Commercial thermocouples are assembled through welding, crimping, or soldering. All methods produce similar results.
- Thermocouples lend themselves to a variety of packaging techniques that can be adapted to many types of applications.
- Thermocouples offer a wide overall temperature measurement range, spanning about –100°C to higher than 2500°C.

Table 1. Common Temperature Sensor Types

Characteristic	Thermocouples	Resistive Temperature Detectors	Thermistors
Overall	Very broad range; moderate accuracy	High accuracy and repeatability	High resolution
Temperature Range	–100° to +2500°C	–200° to +800°C	–80° to +150°C
Accuracy	±1° to 2°C	±0.1° to 0.2°C	±0.1° to 0.2°C
Type of Output Signal	Very low voltage	Slight resistance change	Wide resistance change
Typical Applications	• Industrial • Food processing • Burn-in • Automotive • Aerospace	• Burn–in • Aerospace • Laboratory monitoring • Pharmaceuticals • Automotive • Paper/pulp • Food processing	• Biological applications • Control systems • Measurement of environmental temps • Consumer devices
Notes	• Several types, each with specific useful temperature range • Non-linear output • Requires cold junction compensation	• Relatively fragile • Non–linear ΔR vs. Δt • Requires a resistive bridge circuit or 4-wire low ohms	• Relatively fragile • Non-linear ΔR vs. Δt • Requires high resolution ohms measurement

- Thermocouple accuracy is typically on the order of ±1–2°C, which is more than adequate for the majority of applications.

Although thermocouples have relatively few disadvantages, these disadvantages affect their usage and the hardware needed to read them significantly. Thermocouple output is on the order of microvolts per degree, and thermocouples are sometimes located at a significant distance from the system used to acquire them. To compensate for these factors, a variety of signal conditioning techniques, including differential measurement mode, high gain, filtering, and increasing measurement integration time is used to maximize the signal and minimize noise. These practices result in relatively slow measurement rates for thermocouples, typically no more than a few hundred readings per second. Furthermore, thermocouple output is non-linear, so linearization routines must be built into the hardware and/or software used to convert thermocouple voltages to a temperature reading. Measuring temperature with thermocouples also requires the use of a reference junction.

A thermocouple is a practical application of the "Seebeck Effect." Almost two centuries ago, physicist Thomas Seebeck discovered that the junction between two dissimilar metals generates a voltage that is a function of temperature. Historically, temperature measurement with thermocouples relied on a second thermocouple element to sense a known temperature as a reference. At one time, the most common way of producing a reference temperature was to immerse the reference junction in an ice bath, which gave it the name "cold junction." Today, however, a growing number of instruments, including Keithley's 3706A System Switch/Multimeter, 2700 Series Multimeter/Data Acquisition/Switch Systems, DAQ6510 Data Acquisition and Logging Multimeter, and the 2750 Multimeter/Switch System, are suitable for temperature measurement and offer one or more reference junction functions.

Within the usable temperature range of any thermocouple, there is a proportional relationship between thermocouple voltage and temperature. However, this relationship is by no means a linear one. In fact, most thermocouples are extremely non-linear over their operating ranges. In order to obtain temperature data from a thermocouple, it is necessary to convert the non-linear thermocouple voltage to temperature units through a process known as linearization.

When thermocouples are connected to the terminals of the datalogger or other measurement instrument, the connections form additional junctions that can generate unwanted thermoelectric voltages. A copper terminal pin plugged into a copper socket will not generate a thermoelectric EMF. However, a constantan pin or socket crimped to a copper wire results in a J-type thermocouple junction that will generate a thermoelectric EMF. Extension wire and connector pins made from thermocouple metals are available to permit connection of like metals. Attention must be paid to every conductor and termination throughout a thermocouple circuit to ensure that unwanted junctions are not introduced into the circuit.

Packaging can affect a thermocouple's suitability for a given application. Although a working thermocouple can be made by twisting the stripped ends of a pair of thermocouple wires together, the most reliable and consistent operation is provided by thermocouples that have been welded. Real-world applications often require that thermocouples be enclosed and protected from the environment or fitted with mounts, probe tips, or other features that best suit a specific application. The sheath (**Figure 1**) is extremely important because it protects the thermocouple element from contamination and physical damage due to caustic materials, liquids, and other environment elements. Common sheath materials include iron, steel, stainless steel, iconel, ceramics, and porcelain.

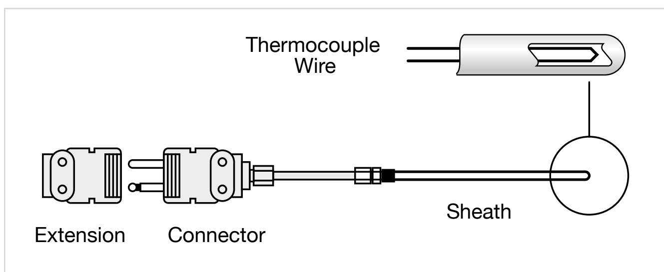

Figure 1. Typical industrial thermocouple

A thermocouple's overall response time depends not only on the tip design but also on the sheath material and diameter, and the surrounding medium. Response times can vary from a tenth of a second to several seconds.

Several different metal alloys are used to construct thermocouples. Each alloy offers characteristics that are advantageous for specific applications. As shown in **Table 2**, these alloys have been assigned a series of standardized letter codes. Each type of thermocouple wire can be identified by a color code for the individual conductors. Several color-coding systems are used around the world, but most indicate the negative thermocouple lead with red. However, the colors of the positive conductor, thermocouple wire jacket, and extension wire jacket can vary. **Table 3** provides an overview of the color code system used in the United States.

Table 2. Thermocouple Types

Type	Gauge	°F Range	°C Range
J (Iron vs. Constantan)	8	–70 to 1400	–57 to 760
	14	–70 to 1100	–57 to 593
	20	–70 to 900	–57 to 482
	24	–70 to 700	–57 to 371
K (Chromel vs. Alumel)	8	–70 to 2300	–57 to 1260
	14	–70 to 2000	–57 to 1093
	20	–70 to 1800	–57 to 982
	24	–70 to 1600	–57 to 870
N (Nicrosil vs. Nisil)	8	–70 to 2300	–57 to 1260
	14	–70 to 2000	–57 to 1093
	20	–70 to 1800	–57 to 982
	24	–70 to 1600	–57 to 870
T (Copper vs. Constantan)	14	–70 to 700	–57 to 371
	20	–70 to 500	–57 to 260
	24	–70 to 400	–57 to 200
E (Chromel vs. Constantan)	8	–70 to 1600	–57 to 871
	14	–70 to 1200	–57 to 649
	20	–70 to 1000	–57 to 538
R, S Platinum vs. Platinum/13% Rhodium	24	–50 to 2650	–46 to 1454
B (Platinum/6% Rhodium vs. Platinum/ 30% Rhodium)	24	32 to 2650	0 to 1454

Table 3. Thermocouple Color Codes, United States

Type	(+) Conductor	(–) Conductor	Thermocouple Jacket	Extension Jacket
J	White	Red	Brown	Black
K	Yellow	Red	Brown	Yellow
N	Orange	Red	Brown	Orange
T	Blue	Red	Brown	Blue
E	Purple	Red	Brown	Purple
R	Black	Red	—	Green
S	Black	Red	—	Green
B	Gray	Red	—	Gray

Base metal thermocouple types J, K, N, E, and T are economical, reliable, and reasonably accurate. They represent more than 90 percent of all thermocouples and are well suited for temperatures ranging from –200° to 1700°C.

- Type E: Suitable for –200° to 871°C. Applicable to atmospheres ranging from vacuum to mildly oxidizing and for very low temperatures. Type E provides the highest output of any of the base metal thermocouples.
- Type J: Suitable for lower temperatures (0° to 600°C). Should not be used at temperatures higher than 760°C. Economical and reliable. Popular in the plastics industry but useful as a general-purpose thermocouple within the prescribed temperature range.
- Type K: Industry standard for temperatures up to 1250°C. Can corrode in chemically reducing environments.
- Type N: Similar to Type K but more resistant to oxidation.
- Type T: Suitable for –200° to 350°C. Commonly used in food processing industry.

Thermocouple types R, S, and B are constructed of platinum and rhodium, so they are referred to as *noble metal thermocouples*. As a class, these thermocouples are more accurate and stable than base metal types, but they are also more expensive. They are used for applications up to 1700°C, and as references for testing other types. To prevent contamination at high temperatures from metal vapors, they should be used inside a non-metallic sheath.

- Type R: Industrial standard for high temperature (to 1450°C). Prone to contamination when contacting other metals. Stable in oxidizing atmospheres but degrade rapidly in vacuum or reducing atmospheres.

- Type S: Similar to Type R. Not used extensively as an industrial sensor.
- Type B: Similar to Types R and S, but useful to 1700°C. Best used at temperatures higher than 250°C. A weak, non-linear output at low temperatures and a "dip" in output voltage from 0°C to 50°C make the B type thermocouple unusable at temperatures lower than 50°C.

Resistive Temperature Detectors

Resistive temperature detectors (RTDs) are among the most stable and accurate type of temperature sensors available. They offer a narrower measurement range than thermocouples, covering approximately –200°C to +800°C. The actual range for a particular RTD depends on its composition and construction, but it won't vary appreciably from this range. RTDs are used where high accuracy and repeatability are required, such as in food, laboratory, and pharmaceutical applications. Accuracy is often expressed as a percentage of resistance at a specified temperature.

Several techniques are used to manufacture RTDs. The classic RTD configuration is a length of platinum wire wound on a glass or ceramic bobbin, which is then encapsulated in glass or other protective material (**Figure 2**). Another variety is constructed by depositing a conductive film on a non-conductive substrate, which is then encapsulated or coated to protect the film. RTD assemblies often include connectors, metallic sheaths, and handles that make them resemble thermocouple probes.

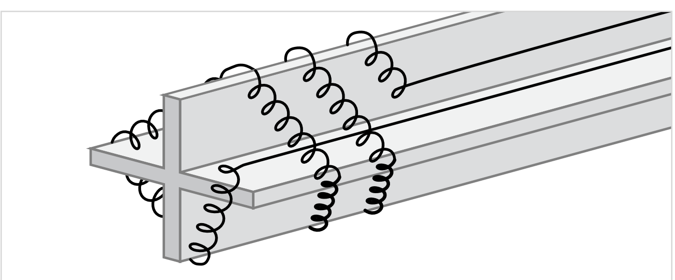

Figure 2. A simple RTD.

RTDs are based on the principle that the resistance of most metals increases with an increase in temperature. Most general-purpose RTDs are made of platinum wire. The resistance of platinum RTDs ranges from tens of ohms to several thousand ohms, but most platinum RTDs have been standardized to a value of 100 Ω at 0°C. Depending on the purity of the platinum used, the temperature coefficient (α) of a platinum RTD is 0.00385 Ω/Ω/°C (the European curve) to 0.00392 Ω/Ω/°C (American curve).

Unlike a thermocouple, an RTD requires no reference junction. It might seem a simple matter to connect a standard DMM to the RTD, measure the resistance of the RTD, then convert to a corresponding temperature. In practice, the resistive properties of the RTD and associated wiring usually require sensitive instrumentation optimized for low resistance measurements. For example, a 100 Ω RTD having α = 0.00385 Ω/Ω/°C produces a resistance change of only 100 Ω × 0.00385 Ω/Ω/°C or 0.385 Ω/°C. The wire leads connecting the RTD to the ohmmeter might have a value of several ohms. With a 100 Ω RTD, 1 Ω amounts to an equivalent temperature error of about 2.5°C.

Two options for converting resistance to temperature are available. One is simply to consult a look-up table and find the temperature corresponding to a specific resistance. This method is workable in software programs where an event will be triggered at a certain temperature (the corresponding resistance or voltage can be used as a trigger level), but it is not suitable for real-time readout of temperature based on RTD resistance values. A second method of converting resistance to temperature is by means of an equation. The most commonly cited equation for this purpose is a polynomial that uses a set of constants called the Callendar-Van Dusen coefficients.

Table 4. Callendar-Van Dusen coefficients for common RTD alphas

Standard	RTD Temperature Coefficient (α)	A	B	C*
DIN 43760	0.003850	3.9080×10^{-3}	-5.8019×10^{-7}	-4.2735×10^{-12}
American	0.003911	3.9692×10^{-3}	-5.8495×10^{-7}	-4.2325×10^{-12}
ITS-90	0.003926	3.9848×10^{-3}	-5.8700×10^{-7}	-4.0000×10^{-12}

* Used for temperatures less than 0°C only. For temperatures higher than 0°C, C = 0.

The general equation for the relationship between RTD resistance and temperature is:

$$RTD = R_0[1 + At + Bt^2 + C(t-100)^3]$$

where: RTD is the resistance of the RTD at temperature t, R_0 is the resistance of the RTD at 0°C, and A, B, and C are the Callendar-Van Dusen coefficients shown in **Table 4**. For temperatures higher than 0°C, the “C” coefficient is 0, and the equation becomes:

$$RTD = R_0[1 + At + Bt^2]$$

One aspect of using RTDs and most other resistive sensors is resistive (“joule”) heating that results from excitation current passing through the sensor (power = excitation current^2 × RTD resistance). Although the amount of heat energy may be slight, it can affect measurement accuracy nonetheless. Self-heating is typically specified as the amount of power that will raise the RTD temperature by 1°C. Its typical value is about 1 mW/°C.

Inaccuracy caused by joule heating is aggravated by higher excitation currents and stagnant surrounding media of low specific heat. These effects can be minimized if the surrounding medium is in motion or is agitated to carry heat away from the RTD.

Thermistors

Thermistors (thermally sensitive resistors) are another variety of commonly used resistive temperature detector. Although RTDs and thermistors are both resistive devices, they differ substantially in operation and usage.

Thermistors (**Figure 3**) are passive semiconductor devices. Both negative temperature coefficient (NTC) and positive temperature coefficient (PTC) thermistors are available. The resistance of an NTC thermistor decreases as its temperature increases, while the resistance of a PTC thermistor increases as its temperature increases. For temperature measurement applications, NTC types are used more commonly than PTC thermistors.

Figure 3. A thermistor.

Very small thermistors can be manufactured and this small size allows them to respond quickly to slight temperature changes. However, they can be prone to self-heating errors. Thermistors are also relatively fragile, so they must be handled and mounted carefully to avoid damage.

Thermistors offer a significantly broader range of base resistance values than RTDs do, with base resistance values of kilo-ohms to mega-ohms readily available. Compared to RTDs, the temperature coefficient of a typical thermistor is relatively large—on the order of several percent or more per degree Celsius. This high temperature coefficient results in a resistance change of up to several thousand ohms per degree Celsius. Therefore, the resistance of the wires connecting the instrumentation to the thermistor is insignificant, so special techniques such as high gain instrument inputs and three- or four-wire measurement configurations are unnecessary to achieve high accuracy.

Although thermistors have relatively few drawbacks associated with them, it’s important to be aware of these limitations in order to achieve accurate, reliable measurements. For example, thermistors are relatively low temperature devices, with a typical measurement range of –50°C to 150°C, although some thermistors can be used at temperatures up to 300°C. This range is significantly narrower than that of thermocouples and RTDs. Exposure to higher temperatures can decalibrate a thermistor permanently, producing measurement inaccuracies. Thermistors are highly non-linear in their response, and are not as standardized as thermocouples and RTDs. They tend to be more appropriate for applications that require sensitive measurements over a relatively restricted temperature range, rather than for general-purpose temperature measurements.

Given that thermistors have a higher base resistance value and a higher temperature coefficient of resistance than RTDs, techniques such as four-wire configurations and sensitive measurement capability are required only in more critical thermistor applications, because any resistance in the test leads is relatively insignificant when compared to the resistance of the thermistor itself.

The output of most thermistors is highly non-linear, and their response has been standardized much less than for thermocouples or RTDs. Therefore, manufacturers frequently supply resistance-temperature curves, tables, or constants for their specific products. Typical thermistor alphas (α) range from –2% to –8% per °C, and are generally larger at the lower end of the temperature range. Linearized thermistors also exist, although the use of computerized data acquisition systems and software make them unnecessary unless the readout hardware must be used with a linearized type.

For computerized applications, relatively accurate thermistor curves can be approximated with the Steinhart-Hart equation:

$$T = \frac{1}{A + B \times \ln(R_T) + C\left[\ln(R_T)\right]^3}$$

T is the temperature in degrees Kelvin, which is equal to the Celsius temperature plus 273.15. R_T is the resistance of the thermistor. The thermistor manufacturer should provide the constants A, B, and C for a given thermistor.

Measurement Instrumentation Options

The performance of a temperature measurement system depends just as much on the measurement hardware used as on the sensors. If multiple sensors must be monitored, selecting appropriate switching hardware is also critical. To ensure the completed system meets the application's requirements fully, it's helpful to consider a few critical questions before beginning the selection process.

- What kinds of temperature transducers must the system be able to handle?
- How many temperature channels must the system be able to accommodate?
- Does the application require measuring/monitoring temperatures in remote locations?
- Does the application require incorporating electrical measurements other than temperature into the system?
- What type of traceability is required for my measurements?

Although thermocouples, RTDs, and thermistors are compatible with many types of measurement instruments, digital multimeters (DMMs) are among the most common choices. A growing number of DMMs are capable of measuring the very low voltages or resistances that temperature sensors produce. Their inherently low noise design and traceable accuracy specifications make them well suited for temperature measurement applications. For applications that require monitoring temperature at multiple points, DMMs with integrated switching hardware are often the most economical solution in terms of flexibility, measurement accuracy, and test throughput. For example, Keithley's 3706A System Switch/Multimeter (**Figure 4**) combines scalable, instrument-grade switching and multi-channel measurement into a single instrument.

Figure 4. The 3706A System Switch/Multimeter supports up to 360 thermocouple channels in a single 2U chassis.

For the temperature monitoring system builder, this all-in-one-box combination of high-speed switching and high integrity measurements greatly simplifies the system integration process and helps control system hardware costs. The 3706A incorporates multiple features that make it suitable for a variety of temperature monitoring and control applications:

- Up to 360 thermocouple channels with standard terminal block connections in a single 2U chassis.
- Automatic cold junction compensation (CJC) on the compatible 3720, 3721, and 3724 Multiplexer Cards with a screw terminal accessory for thermocouple-type temperature measurements.
- Built-in support for measuring temperature with three thermistor types: 2.2 kΩ, 5 kΩ, and 10 kΩ.
- LXI/Ethernet connection for simplified temperature monitoring in remote locations.
- Option to expand to additional temperature monitoring channels in additional 3700A Series chassis via the built-in TSP-Link™ interface.
- 14 programmable digital I/O lines allow controlling external devices, such as component handlers or other instruments, or sending alarm indications if a critical temperature parameter exceeds tolerance.
- An embedded graphing toolkit that supports real-time data trending and analysis, which can be invaluable for temperature monitoring tasks. This toolkit gives users a quick, easy, flexible way to observe data as it's acquired – they can check the progress of long-duration tests in just seconds, then make adjustments if the results are not as anticipated. There's no need to install special software on the PC or the instrument itself or to write code to extract data from the instrument's reading buffer and import the data into a third-party package or a spreadsheet for analysis.
- In applications like burn-in, which typically involve monitoring multiple temperature, voltage, and resistance measurements, the 3706A's plotting capabilities simplify spotting trends over the course of the test. Users can view up to 40 channels of acquired data in a line or scatter plot in either real-time mode or in user-defined increments. The 3706A makes it simple to compare and contrast readings on a per-channel basis so users can spot potential problems early.

Similarly, the Keithley DAQ6510 Data Acquisition and Logging Multimeter and the 2750 Multimeter/Switch System (**Figures 5 and 6**) are well suited for monitoring and logging temperature. Both instruments support thermocouples, RTDs, and thermistors with built-in signal conditioning and 300V isolation. To begin using a temperature sensor, the system builder simply plugs in one of the nine 7700 Series switch/control modules that support temperature measurements, connects the sensor, and the instrument does the rest. If a thermocouple is broken or disconnected, the instrument will alert the operator.

Figure 5: The DAQ6510 Data Acquisition and Logging Multimeter System is well suited for temperature measurement with support for thermocouples, RTDs, and thermistors.

Figure 6: The 2750 Multimeter/Switch System can switch and measure up to 200 thermocouples and 100 4-wire RTDs and thermistors.

Like the 3706A, these mainframes support three methods for cold-junction compensation (CJC): automatic (built-in), external, and simulated. A built-in channel monitor feature allows monitoring any specific input channel on the front panel display during a scan. This feature can also serve as an analog trigger to initiate a scan sequence based on some external factor, such as a temperature rising above a pre-set limit. Only the data of interest is acquired, so there's no need to spend hours searching through reams of normal readings to find anomalous data.

The two-slot DAQ6510 is optimized for applications like temperature logging, precision measurement and control, and mixed signal data acquisition for product development, ATE, component testing, and process monitoring.

The DAQ6510 has a touchscreen graphical user interface which greatly simplifies the setup, execution, monitoring, and analysis of a multichannel temperature measurement system. A temperature scan can be set up from a single menu. The status of the test is monitored and critical channels can be viewed with the display status screen. Trends from up to 20 channels can be viewed in graphical or tabular form. All of these tasks can be performed without the need for a PC. Thus tests can be set up quickly and easily, and researchers, designers, and test engineers can get test results as soon as possible.

With five module slots, the 2750 simplifies configuring solutions for measurement and control applications with hundreds of channels. It's especially useful for applications such as power supply burn-in testing.

Temperature measurements are made for a variety of reasons. Though there are many sensors, thermocouples, resistive temperature detectors, and thermistors are the three main types. Temperature measurement system performance is as dependent on the measurement hardware used as on the sensor type selected. **Table 5** offers an overview of Keithley's temperature measurement options. For additional information on specific switching cards optimized for particular transducers, consult the on-line data sheets for the 3706A, the DAQ6510, and the 2700 Series data acquisition systems.

Table 5. Keithley Multi-channel Temperature Measurement Solutions

Model	Compatible Transducers	Maximum Channels	Relay Types	Special Features
3706A 6-slot, 2U full-rack-width mainframe with integrated digital multimeter	Thermocouple J, K, N, T, E, R, S, B types	360	• Electromechanical relay • Solid state relay	• Fast scanning with low noise Multimeter • Open thermocouple detection • Screw terminal accessory for thermocouple connections and cold junction compensation (Internal CJC) • Selectable temperature reference • Long-life solid state card (3724) • Selectable temperature units (°C, °F, K) • Offset compensated ohms for improved low resistance accuracy • Screw terminal accessory for RTD and thermistor connections
	RTD, 3- or 4-wire PT100, D100, F100, PT385, PT3916, Custom RTD	180	• Electromechanical relay • Reed relay • Solid state relay	
	Thermistor 2.2kΩ, 5kΩ, 10kΩ	360	• Electromechanical relay • Reed relay • Solid state relay	
DAQ6510 2-slot, 2U half-rack-width mainframe with integrated digital multimeter	Thermocouple J, K, N, T, E, R, S, B types	80	• Electromechanical relay • Solid state relay	• Open thermocouple detection • Card-enabled cold junction compensation (internal CJC) • Selectable temperature reference • Long-life solid state card (7710) • Selectable temperature units (°C, °F, K) • Offset compensated ohms for improved low resistance accuracy • Screw terminal for RTD and thermistor connections
	RTD, 4-wire PT100, D100, F100, PT385, PT3916, Custom RTD	40	• Electromechanical relay • Reed relay • Solid state relay	
	Thermistor 2.2kΩ, 5kΩ, 10kΩ	40	• Electromechanical relay • Reed relay • Solid state relay	
2750 5-slot, 2U full-rack-width mainframe with integrated digital multimeter	Thermocouple J, K, N, T, E, R, S, B types	200	• Electromechanical relay • Solid state relay	• Open thermocouple detection • Card-enabled cold junction compensation (internal CJC) • Selectable temperature reference • Long-life solid state card (7710) • Selectable temperature units (°C, °F, K) • Offset compensated ohms for improved low resistance accuracy • Screw terminal for RTD and thermistor connections
	RTD, 4-wire PT100, D100, F100, PT385, PT3916, Custom RTD	100	• Electromechanical relay • Reed relay • Solid state relay	
	Thermistor 2.2kΩ, 5kΩ, 10kΩ	100	• Electromechanical relay • Reed relay • Solid state relay	

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Rev. 090617

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