WHITE PAPER

# Thermal Testing, Instrumentation, and Data Acquisition in Academic Institutions

Measuring the temperature of something is easy. Doing so with high precision and accuracy… not so much. For example, the values displayed by a selection of liquid-filled outdoor thermometers at a garden store may quickly diverge by as much as 8°F (4.5°C). Similarly, various bimetallic-coil fridge/freezer thermometers may differ by 4°F/2°C or more. Even a collection of electronic thermostats used to control household HVAC systems may disagree by a couple of degrees.

Why is measuring temperature with precision and accuracy so tricky? Why do we wish to measure temperature at all, and what do we mean by "temperature" in the first place?

The simplest definition of temperature is that it measures how hot or cold something is, but that doesn't help us as much as we wish. One way to view temperature is as the kinetic energy associated with the vibrating and colliding atoms making up a substance. A more sophisticated understanding of temperature involves the intersection of thermodynamics and quantum physics, but that is beyond the scope of this paper.


Different groups require the ability to measure temperature for other purposes and with varying degrees of precision and accuracy. Most people are interested in knowing, measuring, and/or controlling temperature within a couple of degrees for two reasons. The first is cooking; for example, setting and receiving the required temperature in a kitchen oven. The second is personal comfort—specifying and subsequently enjoying the desired temperature in the home and deciding what clothing will be appropriate if going outside.

Chemists need to be able to set and measure the temperature as part of their reactions; scientists need to be able to select and measure the temperature as part of their experiments; industrial engineers need to be able to set and measure the temperature as part of their processes; manufacturers need to be able to set and measure the temperature as part of their component and product testing, and the list goes on.

# Thermal Measurement in Educational and Academic Institutions

Universities have been collaborating with industry for hundreds of years. However, the depth and range of such educational-industrial collaborations have increased dramatically in recent decades.

In addition to performing thermal measurements as part of regular undergraduate and graduate science and engineering courses, such measurements are integral in many educational-industrial partnerships.

A prime example is materials science, a significant domain of cooperation between academia and industry, with benefits accruing to both sides. Companies may gift equipment, fund buildings, or sponsor entire university departments. In return, those companies may guide research directions and gain access to research results while also having access to a potential source of highly trained employees.

# Introducing the Thermocouple

A variety of thermal measurement technologies are available, including Resistance Temperature Detectors (RTDs), which are sensors whose resistance changes as a function of temperature, and semiconductor-based techniques, such as thermistors (a portmanteau of thermal and resistor), whose resistance is strongly dependent on temperature, much more so than in standard resistors.

However, the thermocouple is the most used type of temperature sensor in scientific, engineering, industrial, automotive, and consumer applications, which was introduced to the world in 1821 by the German physicist Thomas Johann Seebeck (1770–1831).

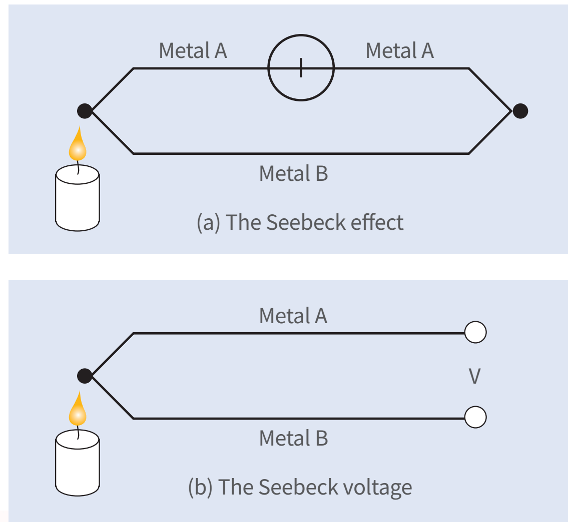
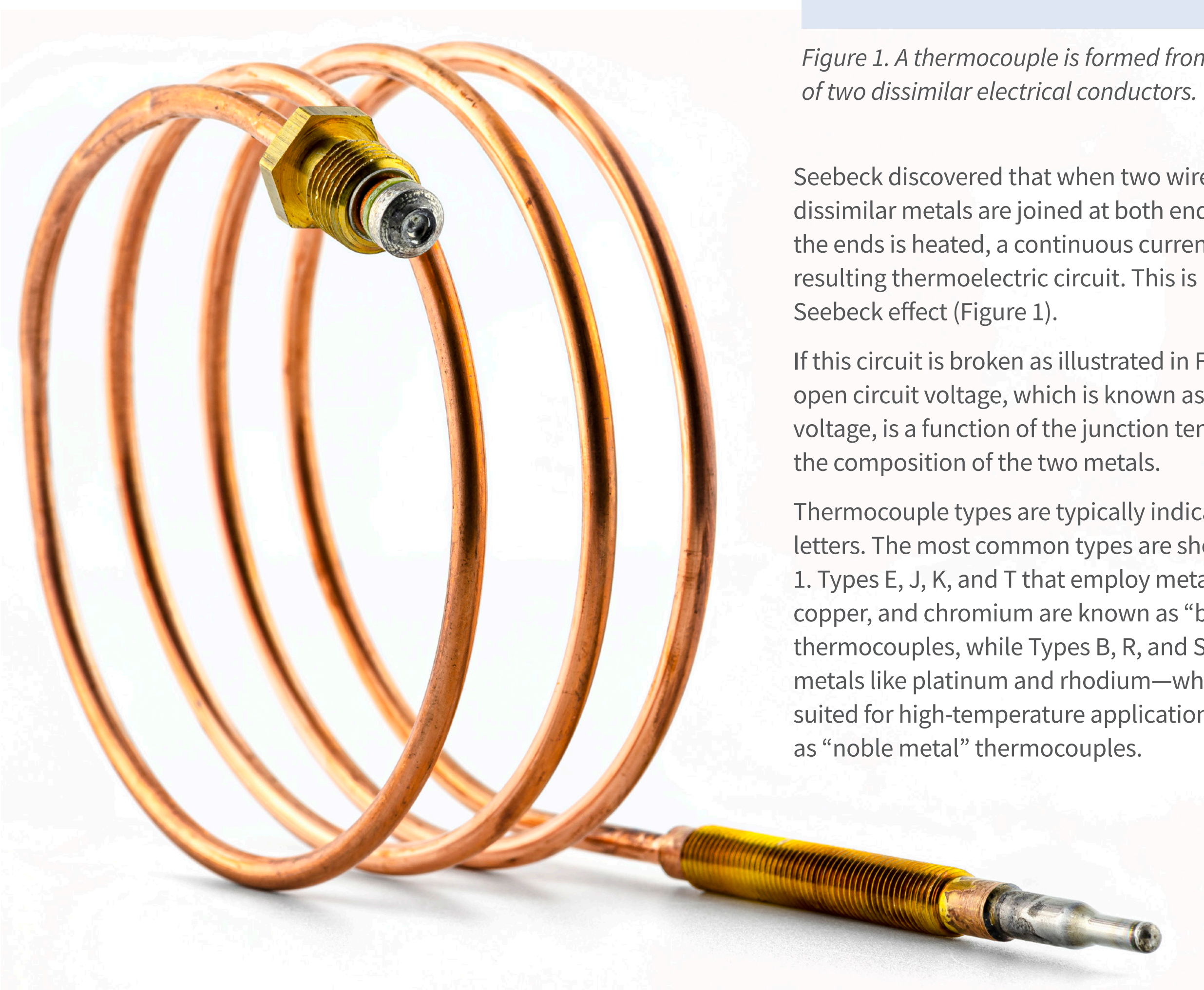



*Figure 1. A thermocouple is formed from the junction of two dissimilar electrical conductors.*



Seebeck discovered that when two wires composed of dissimilar metals are joined at both ends, and one of the ends is heated, a continuous current will flow in the resulting thermoelectric circuit. This is known as the Seebeck effect (Figure 1).

If this circuit is broken as illustrated in Figure 1b, the net open circuit voltage, which is known as the Seebeck voltage, is a function of the junction temperature and the composition of the two metals.

Thermocouple types are typically indicated using letters. The most common types are shown in Table 1. Types E, J, K, and T that employ metals like nickel, copper, and chromium are known as “base metal” thermocouples, while Types B, R, and S that employ metals like platinum and rhodium—which are better suited for high-temperature applications—are known as “noble metal” thermocouples.

| Type | Material | | | | NIST-Specified Range (˚C) |
|---|---|---|---|---|---|
| | – | | + | | |
| S | 90% Platinum | 10% Rhodium | Platinum | | -50 to 1,768 |
| R | 87% Platinum | 13% Rhodium | Platinum | | -50 to 1,768 |
| B | 90% Platinum | 30% Rhodium | 94% Platinum | 6% Rhodium | 0 to 1,820 |
| K | 90% Nickel | 10% Chromium | Alumel* | | -270 to 1,372 |
| E | 90% Nickel | 10% Chromium | Constantan | | -270 to 1,000 |
| J | Iron | | Constantan | | -210 to 1,200 |
| T | Copper | | Constantan | | -270 to 400 |
| N | Nicrosil | | Nisil | | -270 to 1,300 |

**Alumel is a registered trademark of Concept Alloys, Inc.*

*Table 1. Overview of common thermocouple types.*

Alumel is an alloy of approximately 95% nickel, 2% aluminum, 2% manganese, and 1% silicon. Constantan is a copper-nickel alloy (also known as Eureka, Advance, and Ferry) consisting of 55% copper and 45% nickel. Nicrosil is an alloy containing 84.1% nickel, 14.4% chromium, 1.4% silicon, and 0.1% magnesium. Nisil is an alloy containing 95.5% nickel, 4.4% silicon, and 0.1% magnesium.

Not surprisingly, the end of the thermocouple being used to sense the temperature is known as the "hot junction." The other end, known as the "cold junction," is terminated at the measuring instrument, which typically has copper input terminals (Figure 2).

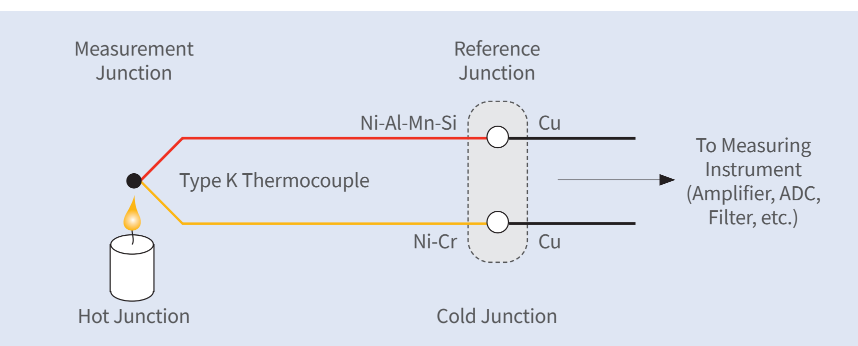



*Figure 2. Type K thermocouple connected to input terminals of measuring instrument.*

Since the voltage produced by the thermocouple is small (in the order of microvolts), it must be amplified before being fed to an analog-to-digital converter (ADC). Another problem with the small signal from the thermocouple is its susceptibility to electromagnetic noise. This can be addressed by analog filtering before the ADC and/or digital signal processing (DSP) after the ADC.

Another consideration is that the junctions between the primary thermocouple wires and the copper input terminals are themselves thermocouples (excluding the negative terminal of the Type T thermocouple, which is itself formed from copper).

To make a proper measurement from the primary thermocouple, it's necessary to accurately measure the temperature at the cold junction point where the dissimilar thermocouple metals meet the copper measurement terminals. This point is called the Reference Junction, and accounting for the temperature at this point is commonly referred to as Cold Junction Compensation (CJC).

Obtaining accurate CJC measurements is often the biggest hurdle that must be overcome to get temperature measurements precisely and accurately from the primary thermocouple.

# Instrumentation Options (What to Look For)

In general, universities are on a tight budget. They are looking for cost-effective, high-accuracy test instrumentation products that are easy to install and use. Based on this, there may be a temptation to opt for low-channel-count devices, such as 4-channel or 8-channel thermal measurement instruments. However, it's invariably the case that more channels are required over time. It's also worth noting that an 8-channel instrument will be more cost-effective than purchasing two 4-channel devices. Similarly, a 16-channel instrument is more cost-effective than purchasing two 8-channel devices.

Another consideration is that many cheaper thermal measurement instruments support only one thermocouple type, requiring more instruments to be purchased as additional thermocouple types are brought into play. What some low-cost instrumentation providers do is move the CJC to the PCB by using a specific connector type. While this does maintain relatively good accuracy, it limits the flexibility of the instrument and only allows using one type of thermocouple. This means buying instruments that can work with multiple thermocouple types can be significantly more cost-effective.

Yet another consideration is that many thermal measurement instruments require the user to connect the thermocouples to the instrument's input terminals using an external terminal block. In this case, it's common to take a single CJC temperature measurement on the terminal block and use this for all the channels. Far greater accuracy can be obtained by connecting the thermocouple directly to the measuring instrument's inputs, performing the CJC temperature measurement as close to the junction as possible, and having dedicated CJC temperature sensors for each channel.

Many university science and engineering departments start with standalone test instruments sitting on a desk or workbench. As the test environment increases in sophistication, with additional instrumentation, power supplies, and servers added to the setup, mounting everything in a rack may become necessary. Thus, purchasing test instruments that can stand alone on a desk and be mounted on a rack is a good idea.

One final piece of advice is to avoid instruments that require unique, proprietary (expensive) connectors. Instead, opt for instrumentation that employs common, low-cost, easy-to-use solutions.

# Data Acquisition Capabilities (What to Look For)

Many test instruments require special data acquisition software to make them function. While this does provide a turn-key solution, it may prove to be an expensive option in the long run, especially for software requiring an annual license fee.

Other options are available. LAN eXtensions for Instrumentation (LXI) is a standard developed by the LXI Consortium,[1] which maintains the LXI specification and promotes the LXI Standard. This standard defines the communication protocols for instrumentation and data acquisition systems using Ethernet.

The LXI standard also embraces the concept of Interchangeable Virtual Instrument (IVI) drivers as defined by the IVI Foundation.[2] IVI drivers define an I/O abstraction layer that provides an interface-independent communication channel for test and measurement instruments. Furthermore, IVI drivers encapsulate Standard Commands for Programmable Instruments (SCPI) commands, which are ASCII-based commands for reading and writing instrument settings and measurement data. The IVI standard allows an abstract way to program remote-control applications using various programming languages.

Some test instruments are accompanied by a free web-based utility that allows the instruments to be monitored and controlled over Ethernet. Others are accompanied by software drivers enabling users to create their own data acquisition applications. Some allow users to create driverless applications in Python, C/C++, and Java programming languages.

In the case of data logging, some test instruments allow the test data to be stored in internal memory, others will enable it to be stored on a plug-in USB Flash Drive (a.k.a. a memory stick), and some allow the data to be streamed to a server over Ethernet. It's recommended to purchase test instrumentation that supports all three of these options because each may be advantageous in different situations.

It's also a good idea to ensure that the test instruments store and manipulate data in a standard CSV (comma-separated value) format that can be accessed by any application, as opposed to some weird and wonderful proprietary format that will end up having to be translated somewhere down the line.

If you wish to write your own software, look for instruments backed by free-of-charge IVI-compatible drivers and/or driverless solutions, along with documentation on creating your own applications. If using drivers, ensure these are (a) free and (b) available for both the Linux and Windows operating systems. Last but certainly not least, whether you create driver-based or driverless applications, ensure your test instrumentation solution supports popular programming languages like Python, C/C++, and Java.

# VTI’s Instrumentation and Data Acquisition Solutions

VTI Instruments provides a wide range of products and systems to monitor and record the data that characterizes the physical integrity and performance of everything from materials to large structures like engines, aircraft, and wind turbines.

In the case of thermal testing, one particularly relevant device is the EX1401 16-channel isolated thermocouple and voltage measurement instrument. The EX1401 delivers accurate and highly repeatable thermocouple (±0.2°C) and voltage measurements by implementing fully integrated signal conditioning, providing 24-bit analog-to-digital converters (ADCs), and by offering independent cold junction compensation on a per-channel basis.

The EX1401 supports all the standard thermocouple types listed in Table 1. Users can use any mix of thermocouples and attach any thermocouple type to any input. Although thermocouples may exhibit linear characteristics over a limited temperature swing, they are all non-linear over their complete temperature range. For this reason, the EX1401’s firmware supports up to a 12th order polynomial and uses the ITS-90 linerization for each respected thermocouple type.

Furthermore, some applications require the development of special thermocouples, for example, thermocouples capable of withstanding extreme temperatures or tiny thermocouples with extremely low thermal mass and inertia. For this reason, the EX1401 allows users to define two custom 12-point polynomial representations.

Although thermocouples are reasonably rugged, they can be damaged or become disconnected. For this reason, each channel on the EX1401 has an associated light-emitting diode (LED) that will show green or red to indicate the status of its associated channel.

The EX1401 is equipped with a rubber protection sleeve allowing it to be used standalone on a desk or work bench. This sleeve can quickly and easily be removed to allow the EX1401 to be mounted in a rack.

The EX1401 supports sample rates up to 20,000 samples per second. This may seem “overly enthusiastic” when we consider that most thermal measurement tests require samples to be taken once a minute, once every ten minutes, or with an even greater temporal separation. However, some applications require samples to be taken 100 times a second. In contrast, others—like monitoring the response of a microprocessor to different software workloads—may require 1,000 samples a second or more.

Remembering that the amplitude of the thermocouple signal, which is in the order of millivolts, is susceptible to electromagnetic noise, the ability to sample at a much higher rate allows the use of oversampling to improve the overall signal-to-noise ratio (SNR) dramatically.

In addition to supporting Power over Ethernet, the EX1401 is fully LXI-compliant, including support for IVI drivers. Also, it can be controlled by an external device in the test environment (e.g., to start and stop capturing data) via a standard digital interface. The EX1401 allows test data to be stored internally on a plug-in memory stick or streamed to a server over Ethernet.

Complete remote control of the EX1401 is supported by its firmware, allowing it to be used “out-of-the-box” with a free web-based Software Front Panel (SPF). In the same way an Ethernet-connected printer can be queried to determine its ink-level status, the EX1401 can be set up and monitored using a web browser.

Associated data acquisition software, such as general-purpose, and high-speed data acquisition packages are available. However, free IVI drivers are available for Linux and Windows, along with documentation allowing users to create their applications. These drivers can be accessed from within MATLAB from MathWorks, and free drivers are also available for use with LabVIEW from National Instruments.

Of particular interest for university settings, the EX1401 supports a driverless interface, allowing custom test data acquisition software to be created in any programming language (Python, C, C++, C#, Java, …) and run under any operating system.

# Conclusion

In addition to performing thermal measurements as part of regular undergraduate and graduate science and engineering courses, such measurements form an integral element in many educational-industrial collaborations, which have increased dramatically in recent decades. A prime example is materials science, a major domain of cooperation between academia and industry, with benefits accruing to both sides.

Over several decades, VTI Instruments has built an enviable reputation in test and instrumentation circles. VTI's instrumentation and data acquisition solutions are used around the globe to characterize the physical integrity and performance of everything from materials to large structures like engines, aircraft, and wind turbines.

Regarding thermal measurements, VTI's EX1401 16-channel isolated thermocouple and voltage measurement instrument are particularly interesting to university science and engineering departments. In addition to being cost-effective and highly accurate and offering support for every common thermocouple type, this test instrumentation product is easy to install and use. It can be used out-of-the-box with a free web-based interface. Off-the-shelf data acquisition software is available, but users can also employ free drivers and documentation to create their own applications. Users can also create driverless applications using their chosen programming languages and operating systems.

You can find out more about the EX1401 or any of the other EX14xx instruments at: https://www.vtiinstruments.com/products/data-acquisition/ex1400-series

## The EX1401 is part of the VTI Instruments family of Data Acquisition instruments.

*Each is specialized for specific measurements, but all are designed to work together.*

**EX1401**

Isolated Precision Temperature and Voltage data acquisition

**EX1402**

Isolated High voltage data acquisition

**EX1403A**

Precision Bridge/Strain, Voltage and Resistance data acquisition


**References**

1 https://www.lxistandard.org/

2 https://www.ivifoundation.org/

VTI Instruments
9250 Brown Deer Road
San Diego, CA 92121, USA
+1 858-450-0085
vti.sales@ametek.com
www.VTIInstruments.com