# Calibrating Thermometers: The Science Behind Meaningful Temperature Measurement, Part 1: Introduction

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Posted: May 2012

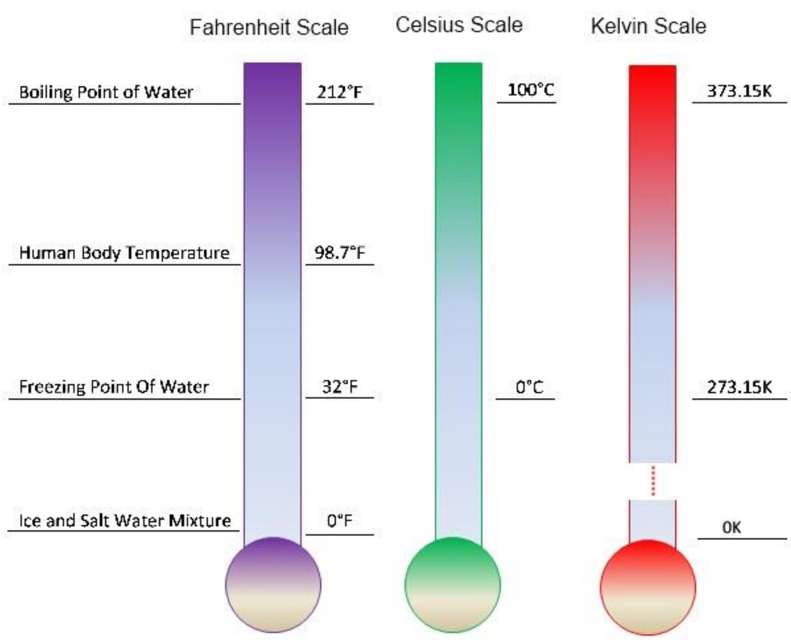
### A Promise is a Promise

I've said it myself: without calibration, we have no confidence in the measurements that we take. And if a measurement isn't meaningful, why even bother? Nevertheless, if you've read my previous articles, "The Anatomy of a Liquid-in-Glass Thermometer" and "Let's Get Digital," you know that, up to this point, I have (intentionally) avoided the subject of thermometer calibration. So, if calibration is such an important subject, why have I been avoiding it for so long? The answer is simple: I've been procrastinating.

As I promised at the end of my last article, it's time to finally talk about thermometer calibration, or what I like to call "the science behind meaningful temperature measurement." If the cornerstone of any good measurement is calibration, then the cornerstone of any good calibration is the method(s) used to complete the calibration. Over my next few posts, I will explain some of the details of thermometer calibration.

### Units of Temperature

Throughout history, many units and scales of temperature measurement have been developed for various applications around the world. In fact, historical accounts claim that over 35 different temperature scales had been developed by the 18th century. One of the most famous scales was developed by Daniel Gabriel Fahrenheit around 1714. Fahrenheit was the first scientist to use mercury in a liquid-in-glass thermometer. He used three fixed points to create his temperature scale. The lowest point was the temperature of an ice and salt water mixture (0 degrees), the midpoint was a mixture of water and ice (32 degrees), and the third was human body temperature. After his death, the human body temperature fixed point was replaced with the boiling point of water (212 degrees). Readily available and easy to use, Fahrenheit's temperature scale quickly gained acceptance and is still in use today, primarily in the United States.




Anders Celsius developed his temperature scale around 1740. Celsius used fixed points that were related to the freezing and boiling points of water to develop his scale. Originally, the boiling point of water was fixed at 0 degrees, and the freezing point at 100 degrees. The scale between the two fixed points was divided into 100 equal increments. The scale was later reversed, and now the boiling point is fixed at 100 degrees, and the freezing point at 0 degrees. The Celsius system rapidly gained popularity for its ease of use with a decimal-based counting system and is still used today all over the world.

In the 19th century, William Thomson (also known as Lord Kelvin) developed the Kelvin temperature scale, which is founded on the theoretical existence of absolute zero. Absolute zero is the point at which a system no longer contains any thermal energy and all molecular movement ceases. This temperature is designated by the fixed point of 0 Kelvin. It is impossible for any temperature to be colder than absolute zero, and therefore negative numbers do not exist on the Kelvin scale. This scale is the only one that is founded on the principals of thermodynamics and not on material behaviors (such as the freezing and boiling of water). For this reason, the Kelvin was chosen as the official unit of temperature by the International System (SI) of Units.

Since most applications do not call for temperature measurement anywhere near absolute zero, the Kelvin scale is somewhat impractical for everyday use. (Can you imagine if your local weather station reported that the temperature would be 298 Kelvin today?) Therefore, for many applications, we still rely on measurements from the Celsius or Fahrenheit temperature scales. It is quite easy to convert between the Celsius and Kelvin scales, as the divisions of each are equal in magnitude. In other words, one Kelvin equals exactly one degree Celsius. To convert temperature from the Kelvin scale to the Celsius scale, simply subtract 273.15.

**I Thought this was Supposed to be an Article about *Calibration*, not *History*!**

Okay, okay, maybe I'm still procrastinating a little. However, the history behind the science is an important element in understanding thermometer calibration. *Seriously*. Bear with me.

**The International Temperature Scale**

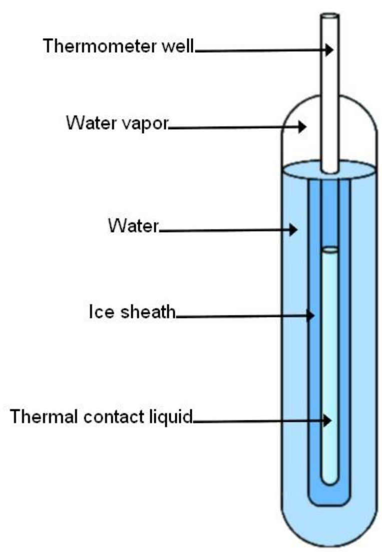
By the turn of the 20th century, scientists began to realize that there was a need to standardize the methods used to define temperature on an international level. In 1927, the first International Temperature Scale was developed by the General Conference of Weights and Measures. This scale is often referred to as the ITS-27. The ITS-27 defined certain fixed points on the Celsius scale. These fixed points were based on the intrinsic physical properties of certain pure materials, such as the boiling point of oxygen. The ITS-27 had six reference points. This scale was refined in 1948, at which time the Kelvin was adopted for use with the international temperature scale. The scale was refined again in 1968, 1976, and finally in 1990. The ITS-90 contains 17 fixed reference points which are used to define the modern-day International Temperature Scale. The scale continues to be refined every twenty years or so, as measurement technology improves. We are likely, therefore, to see another update to the scale sometime within the next few years.

Interestingly, the freezing point of water, or ice point, which is commonly known to be 0.0 degrees Celsius (273.15 Kelvin), is not defined on the ITS-90. Instead, the triple point of water, or 0.1 degrees Celsius (273.25 Kelvin), is used. At this temperature, water can exist in solid, liquid, and gas phases simultaneously. The triple point of water is one of the most valuable fixed points on the ITS-90, with an accuracy of plus 0.0°C or minus 0.00015°C. The ice point of water, typically achieved by use of a water and ice bath, has an accuracy that is greater than plus or minus 0.002°C under the best of circumstances.

**The ITS-90 and Thermometer Calibration**

Primary standards laboratories, such as the National Institute of Standards and Technology (NIST), use fixed-point cells to calibrate thermometers, such as standard platinum resistance thermometers (SPRTs), in accordance with the ITS-90 scale. These fixed-point cells are highly-engineered systems that are stabilized at the desired fixed temperature points by use of thermodynamic principals and known material behaviors.

Calibration using ITS-90 fixed points is not perfect, however, and a small degree of measurement uncertainty is intrinsic to achievement of one of the fixed points on the ITS-90 scale. For example, it is assumed that the metals and gasses used in the fixed point cells are one hundred percent pure. However, ensuring this level of purity down to every last part per million is impossible. Secondly, the ITS-90 scale is based on the assumption that the gasses used obey the ideal gas laws without exception. This is rarely the case, and adds a small degree of uncertainty to the process. However, calibrations provided by NIST using fixed point cells are incredibly accurate by most standards. For instance, the measurement uncertainty for a NIST calibration on a high-quality SPRT at the triple point of water is 0.00006 degrees Celsius, or 0.06 milikelvins (abbreviated mK).



**Water Triple Point Cell**

Fixed point cells are available commercially, and are used as reference standards by some calibration agencies. These high-dollar items, while not quite as accurate as those maintained by a primary standards laboratory, can still provide a high-end calibration and a low measurement uncertainty that far exceeds what is required in most testing laboratories. ASTM D1502, *Standard Guide for Use of Fixed-Point Cells for Reference Purposes*, provides further guidance on the use of fixed-point cells for thermometer calibration.

**Comparison Methods**

Thermometer calibration by fixed-point cells is not only costly, but it is also excessive for most temperature measurement applications used in construction materials laboratories. More commonly, thermometers are calibrated by use of a comparison method in which the thermometer being calibrated (a.k.a. "test thermometer") is compared to a reference thermometer at certain temperatures within the range of use. In most comparison methods, a stirred liquid bath or isothermal dry block is used as the measuring medium. Measurements are taken with both a reference device and the test thermometer, and the two results are compared.

Comparison methods are based on the *Zeroth Law of Thermodynamics*, which states that "If two systems are in thermal equilibrium with a third system, then they are in equilibrium with each other." By virtue of this law, it can be determined that if a reference thermometer is the same temperature as a measuring medium, then a second thermometer placed in the medium will equilibrate to the same temperature as the reference thermometer. Both stirred liquid baths and dry blocks operate under this simple concept.

*Stirred Liquid Baths*
Stirred liquid baths are by far the most common medium used to perform thermometer calibration. When using this type of device, the reference thermometer and the test thermometer are placed directly into the bath medium or into a fitted test sleeve that is immersed in the test medium. The bath is provided with a stirring apparatus to ensure uniformity of the liquid's temperature. At colder temperatures (below 1 degree Celsius), alcohol (such as ethanol or methanol) is typically used as the bath medium. Water is used at temperatures from 0.5 degrees to around 95 degrees Celsius. Oil baths are typically used from room temperature to around 300 degrees Celsius. For temperatures up to around 600 degrees, salt baths are common.

A stirred liquid bath does an excellent job of providing a constant temperature environment for thermometer calibration. However, even in the best baths, temperature gradients may still exist, and therefore it is important that both the reference and test thermometers be immersed to the same horizontal position during calibration to reduce errors. Liquid baths tend to achieve thermal equilibrium slowly, and it can be time-consuming to calibrate a thermometer at multiple temperature points using a single stirred bath. Nonetheless, these devices are still the preferred method of thermometer calibration for many applications. When used correctly, stirred liquid baths can provide a high-quality calibration at a reasonable cost.

*Dry Blocks*
Dry blocks, also called drywells or temperature block calibrators, did not become commonplace until the 1980s. These devices typically consist of a metal block supplied with a temperature regulator that is used to maintain a constant temperature. The reference thermometer and test thermometer are placed into bored holes in the test block. These devices are usually provided with a protective covering that houses the temperature regulator and the block into one compact unit. While dry blocks are generally considered to provide a calibration that is inferior to that of stirred liquid baths, they do provide a calibration system which is both highly portable and convenient. In addition, dry blocks tend to achieve thermal equilibrium faster than stirred liquid baths, and can therefore expedite the calibration process.

Because they are still fairly new to the metrology world, the design, stability, and accuracy of dry blocks is not well regulated. Furthermore, the impact of design variability on the quality of these instruments is not universally understood. The purity of the materials used, dimensions, and other engineering elements can greatly influence the quality of dry block calibrators. Dry block devices should be scrutinized closely before use to ensure that they are of the proper dimensions and design. A calibration guide published by the European Association of National Metrology Institutes (EURAMET) entitled "Calibration of Temperature Block Calibrators" (Guide 13) provides additional guidance on the makeup and dimensional requirements of dry blocks, and it is recommended that this guide be utilized to ensure the quality of dry blocks used for thermometer calibration.

*Other Comparison Methods*
While uncommon in construction materials applications, a host of other devices besides stirred liquid baths and dry blocks are sometimes used for thermometer calibration by comparison. One such device is the *wet well*, which is a hybrid device consisting of a portable block containing a small amount of liquid. Another somewhat rare calibration instrument, the *fluidized powder bath*, contains a powered material such as aluminum oxide. A uniform flow of gas is blown through the powder bath to maintain temperature equilibrium. In addition, *tube furnaces* are sometimes used at very high temperatures where other comparison methods are not suitable. The common theme with any thermometer comparison device that is used is that it must provide a method for the reference thermometer and test thermometer to be maintained at the same temperature.

**What's Next?**
Now that we've explored the history, background, and two basic techniques of thermometer calibration, it's time to *really* dig into the details of the subject. In my the next few posts I will continue to explore the science behind meaningful temperature measurement. Some of the topics that will be covered include:

- Commonly used calibration procedures and methodologies
- Thermometer calibration "dos and don'ts"
- Ice point and steam point verification

- What to look for on a calibration record
- Hysteresis (what is it and why should you care?)
- Uncertainty and traceability
- Water triple-point cells
- Visual inspection of liquid-in-glass thermometers
- Replacing mercury thermometers with safer alternatives
- Choosing a reference thermometer

Sure, we could talk about all of this now, but I think I'd like to procrastinate just a little bit longer. I promise that it will be worth the wait.

**References**


- ASTM International, "ASTM E1502, Standard Guide for Use of Fixed Point Cells for Reference Temperatures," *Book of Standards*, Volume 14.03, 2010.
- ASTM International, "ASTM E220, Standard Test Method for Calibration of Thermocouples by Comparison Techniques," *Book of Standards*, Volume 14.03, 2007(a).
- Calibration of Temperature Block Calibrators (EURAMET/cg-13/v.01)," *European Association of National Metrology Institutes*, July 2007.
- Dedikov, Yu A., "International Temperature Scale," Thermopedia, February 2, 2011, <http://www.thermopedia.com/content/882>(March 16, 2012).
- "History of Temperature," Capgo, November 4, 2010, <http://www.capgo.com/Resources/InterestStories/TempHistory/TempHistory.html>(March 16, 2012)
- "Temperature Calibration with Isotech Block Baths," *Isothermal Technology Limited*, Pine Grove, Southport, Merseyside, England, 1999.
- Preston-Thomas, H., "The International Temperature Scale of 1990 (ITS-90)," *Metrologia*, Springer-Verlag, Volume 27, 1990.
- Ruhf, Robert J., "A Lesson on the Arbitrary Nature of Thermometer Scales Using the Historical Case of the Creation of the Fahrenheit Temperature Scale," *Dr. Bob Ruhf's Personal Home Page*, <http://www.x98ruhf.net/temperature_lesson.pdf >(March 16, 2012).
- Strouse, G.F., "Standard Platinum Resistance Thermometer Calibrations from the Ar TP to the Ag FP," Special Publication 819, National Institute of Standards and Technology, Gaithersburg, Maryland, January 2008.
- Sostmann, Henry E., "Fundamentals of Thermometry Part I: The Absolute, or Thermometeric Kelvin, Temperature Scale," *The Encyclopedia of Thermometry* [also known as *Isotech Journal of Thermometry*], Vol. 1, No. 1, 1st Quarter, 1990, p. 1.