

Thermometry in Fire Investigation and Analysis

Understanding the Practical Use of Basic Thermometry in Fire and Explosion Investigations and Analyses



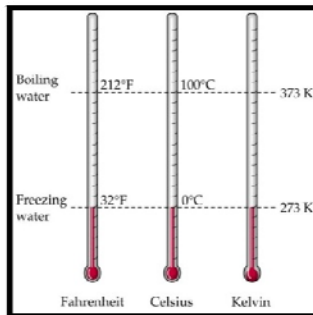
$$V_1 T_2 = V_2 T_1$$

Charles's Law

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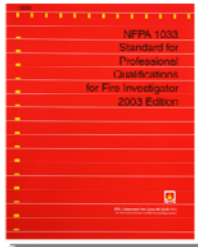
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THERMOMETRY IN FIRE INVESTIGATION AND ANALYSIS **Understanding the Practical Use of Basic Thermometry in Fire and Explosion Investigations and Analyses**

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Thermometry is that branch of fire science/physics which studies the science, methodology, technology, instrumentalities, and practice of temperature measurement.

The days of the fire investigator ill-trained in science are over. The stakes are simply too high to allow to persist, the old-school mentality of considering fire investigation as a “blue collar” occupation. The competent, contemporary fire investigator and fire analyst are required to be educated in, and well conversant with, a myriad of scientific, engineering, and technological subjects. Among these topics is thermometry.



Understanding the basics of thermometry is not only fundamental to competent fire investigation and analysis, but is required by the National Fire Protection Association (NFPA) National Fire Code[©] NFPA 1033-2009 the *Standard for Professional Qualifications for Fire Investigator*, in its section 1.3.8*:

1.3.8* “The investigator shall have and maintain at a minimum an up-to-date basic knowledge of the following topics beyond the high school level at a post-secondary education level:

- (1) Fire science**
 - (2) Fire chemistry**
 - (3) Thermodynamics**
 - (4) Thermometry**
 - (5) Fire dynamics**
 - (6) Explosion dynamics**
 - (7) Computer fire modeling**
 - (8) Fire investigation
 - (9) Fire analysis
 - (10) Fire investigation methodology
 - (11) Fire investigation technology
 - (12) Hazardous materials
 - (13) Failure analysis and analytical tools.”
- [Emphasis added]**

So in order to be in compliance with the *Standard for Professional Qualifications of Fire Investigator*, the individual investigator must be both knowledgeable and up-to-date not only on thermometry itself, but in the basic fields for which a working knowledge of thermometry is required: Fire science; Fire chemistry; Thermodynamics; Fire dynamics, Explosion dynamics, and Computer fire modeling.

The Annex entry for the current edition of NFPA 1033, section A.1.3.8 lists NFPA 921 as the source of information on these required topic areas:

A.1.3.8 “Basic up-to-date information on these topics can be found in the current edition of NFPA 921.”



The NFPA preferred definitions of Heat and Temperature can be found in National Fire Code[©] NFPA 921 the *Guide for Fire and Explosion Investigation*:

3.3.90* Heat. “A form of energy characterized by vibration of molecules and capable of initiating and supporting chemical changes and changes of state.”

A.3.3.90 Heat. “Heat is measured in joules, calories, or BTUs. Heat is not measured in °F or °C. The joule is the preferred unit. A joule/second is a watt.”

3.3.167* Temperature. “The degree of sensible heat of a body as measured by a thermometer or similar instrument.”

A.3.3.167 Temperature. “The lowest possible temperature is absolute zero on the Kelvin temperature scale (-273° on the Celsius scale). At absolute zero it is impossible for a body to release any energy.”

Though the measurement of the temperature of a material does not directly relate to the actual amount of heat energy in a material, it is an indication of the reaction of the subject material to the kinetic heat energy acting upon it. As such, temperature measurement is a fundamental component of the science of thermodynamics. For example: the amount of potential and kinetic heat energy in an iceberg at -40°F . (-40°C ; 419.67 R; 233.15 K) is substantially more than the total heat energy in a burning match flame at 1700°F . (926.67°C ; 2159.67 R; 1199.82 K).

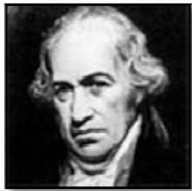
There are several systems for measuring degrees of temperature and the relative hotness and coldness of a substance. These systems can be described in two general categories: Empirical Temperature Scales and Thermodynamic Temperature Scales.

EMPIRICAL TEMPERATURE SCALES

The Fahrenheit and Celsius (Centigrade) scales are the empirical temperature scales most familiar to investigators and consumers of fire investigation reports. Many reference works describing the properties of materials and temperature limits of safety when using products, appliances, equipment, and systems are reported in these colloquial temperature measurement scales, Fahrenheit and Celsius (Centigrade).

The size of a degree of temperature in each empirical system is based upon the relative temperatures at which water boils and freezes and other empirical comparisons.

Fahrenheit: The Fahrenheit scale is based upon a 180 degree difference between the freezing and boiling temperatures of pure water. In the Fahrenheit scale, water freezes at 32 degrees Fahrenheit and boils at 212 degrees Fahrenheit. Absolute zero is -459.67 degrees Fahrenheit.



Fahrenheit

In 1724 German physicist Daniel Gabriel Fahrenheit originally proposed a system of degrees of temperature wherein 0° was determined to represent the freezing/melting point of ice salt water (judged equivalent to sea water); 32° was the freezing/melting point of pure ice water; and 100° the normal temperature of the human body (later, more accurate, measurement showed the actual normal body temperature at 98.6 °F.).¹

Today, the Fahrenheit temperature scale has been replaced by the Celsius scale in most countries, but it remains the official scale of the United States and Belize and is retained as a secondary scale in Canada.²

Celsius (Centigrade): The Celsius or Centigrade scale is based upon the freezing point of pure water being 0 degrees Celsius and the boiling point 100 degrees Celsius. Absolute zero is -273.15 degrees Celsius, a 100 degree difference between the freezing and boiling temperatures of pure water.



Celsius

In 1742 Swedish astronomer Anders Celsius originally created a "reversed" version of the modern Celsius temperature scale whereby zero represented the boiling point of water and one hundred represented the freezing point of water. In 1744, coincident with the death of Anders Celsius, the Swedish botanist Carolus Linnaeus reversed Celsius's scale into the configuration with which we are familiar today, 100°C being the boiling point of water and 0°C the freezing point.³

The system was original known as the Centigrade system recognizing the 100 degree gradients between the freezing and boiling points of water. In 1948, the international standards regulating bodies adopted "degree Celsius" (symbol: °C), though some people still use the old term Centigrade.

¹ Encyclopedia Britannica "Science & Technology: Daniel Gabriel Fahrenheit"

² Excerpt from: wikipedia.org/wiki/Fahrenheit_scale

³ Encyclopedia of World Biography, 2011

The Celsius and Kelvin scales are SI units. They have been adopted by the Systeme Internationale d'Unites (International System of Units) for use by the international scientific community.

OTHER EMPIRICAL TEMPERATURE SCALES (Now Disused)

Delisle Scale: The Delisle scale (°D) is a temperature scale invented in 1732 by the French astronomer Joseph-Nicolas Delisle. The Delisle thermometers usually had 2400 graduations, appropriate to the winter in St. Petersburg. In 1738 Josias Weitbrecht (1702–47) recalibrated the Delisle thermometer with 0 degrees as the boiling point and 150 degrees as the freezing point of water. The Delisle thermometer remained in use for almost 100 years in Russia.⁴

Newton Scale: The Newton scale is a temperature scale devised by Isaac Newton around 1700 (not to be confused with the Newton (unit), the SI unit of force). Newton detailed a qualitative temperature scale, comprising about twenty reference points ranging from "cold air in winter" to "glowing coals in the kitchen fire".⁵

Newton defined the "zeroth degree of heat" as melting snow and "33 degrees of heat" as boiling water. His scale is thus a precursor of the Celsius scale, being defined by similar temperature references. Some scientific historians report that it is likely that Celsius knew about the Newton scale when he invented his. Newton called his instrument a "thermometer".

Réaumur scale: The Réaumur scale (°Ré, °Re, °R), also known as the "octogesimal division," is a temperature scale in which the freezing and boiling points of water are set to 0 and 80 degrees respectively. The scale is named after, René de Réaumur, who first proposed something similar in 1730.⁶

The Réaumur scale saw widespread use in Europe, particularly in France and Germany as well as Russia. But by the 1790s, France chose the Celsius scale for the metric system over the Réaumur measurements. Its only modern use is in the measuring of milk temperature in cheese production.

Rømer scale: Rømer is a temperature scale named after the Danish astronomer Ole Christensen Rømer, who proposed it in 1701. In this scale, the zero was initially set using freezing brine. The boiling point of water was defined as 60 degrees. Rømer then saw that the freezing point of pure water was roughly one eighth of the way (about 7.5 degrees) between these two points, so he redefined the lower fixed point to be the freezing point of water at precisely 7.5 degrees.⁷

A plausible story of how the Fahrenheit scale was invented is that Fahrenheit learned of Rømer's work and visited him in 1708; he improved on the scale, increasing the number of divisions by a factor of four and eventually establishing what is now known as the Fahrenheit scale, in 1724.⁸

⁴ Ibid.wikipedia Delisle_scale

⁵ Ibid.Newton_scale

⁶ Ibid. Réaumur_scale

⁷ Ibid.Rømer_scale

⁸ Ibid.

THERMODYNAMIC (ABSOLUTE) TEMPERATURE SCALES

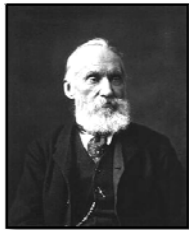
The thermodynamic temperature scales are based upon the lowest possible temperature of absolute zero, and therefore are called the absolute temperature scales. The NFPA preferred definition of Absolute Temperature can be found in NFPA 921 and is based (somewhat circumlocutiously) upon the two thermodynamic scales:

3.3.1* “Absolute Temperature. A temperature measured in Kelvins (K) or Rankines (R).”

A.3.3.1 Absolute Temperature. The Celsius and Fahrenheit scales are relative scales that use “degrees.” The Kelvin and Rankine scales are absolute scales that do not utilize the term *degree*. Absolute zero is the lowest possible temperature, with 0 K being equal to $-273\text{ }^{\circ}\text{C}$, and 0 R equal to $-460\text{ }^{\circ}\text{F}$; 273 K corresponds to $0\text{ }^{\circ}\text{C}$, and 460 R corresponds to $0\text{ }^{\circ}\text{F}$.

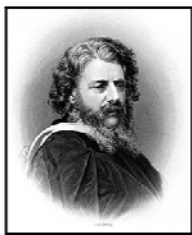
The simplified definition of absolute zero is: a theoretical lowest feasible temperature characterized by complete absence of heat and molecular motion.

Thermodynamic temperature scales differ from empirical scales in that they are based on the fundamental laws of thermodynamics or statistical mechanics instead of some scaling of properties arbitrarily chosen working material.



Lord Kelvin

In 1848, William Thomson, 1st Baron Kelvin (1824 – 1907), and his collaborators (including Rankine) devised a scale of absolute temperature which was independent of the properties of any particular substance and was based solely on the fundamental laws of thermodynamics.⁹ In the Kelvin scale a degree is the same size as a degree Centigrade (Celsius).



Rankine

In 1859 William John Macquorn Rankine (1820 – 1872), a collaborator with Kelvin in the creation of the science of thermodynamics, proposed the Rankine scale of temperature, an absolute or thermodynamic scale whose degrees were equal in size to a Fahrenheit degree.¹⁰

Throughout the scientific world where measurements are made in SI units, thermodynamic temperature is measured in Kelvins (symbol: K). Many engineering fields in the U.S. however, measure thermodynamic temperature using the Rankine scale (symbol: R).

⁹ Excerpt from: Hellemans, Alexander; Bryan Bunch (1988). *The Timetables of Science*. New York, New York: Simon and Schuster.

¹⁰ Excerpt from: Chisholm, Hugh, ed (1911). "Rankine, William John Macquorn". *Encyclopædia Britannica* (11th ed.). Cambridge University Press.

Kelvin: A Kelvin of temperature is the same size as a degree Celsius. But the scale begins at absolute zero (0 Kelvin) and water freezes at 273.15 Kelvin.

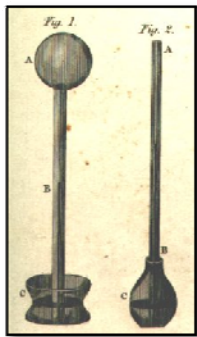
Rankine: The Rankine scale uses increments of the same relative size as the Fahrenheit degrees scale. But, like the Kelvin scale, the Rankine scale begins at absolute zero (0 Rankine) and in the Rankine scale water freezes at 491.67 Rankine.

The size of a degree Fahrenheit or Rankine is smaller than that of a degree Celsius or Kelvin by a ratio of 9:5.

Conversely, the size of a degree Celsius or Kelvin is larger than that of a degree Fahrenheit or Rankine by a ratio of 5:9.

TEMPERATURE MEASURING DEVICES

Of equal importance to the competent, contemporary fire investigator or fire analyst is an understanding of the instrumentalities of temperature measurement and how to properly select and use them. Knowledge of the capabilities and limitations of those devices which the fire investigator/analyst may be using to acquire temperature data is essential. These capabilities and limitations may include: temperature scales of the individual devices, sensitivity; accuracy ranges; reaction times; appropriate physical phases of the subject materials being measured; ease of use and cost compared to the needed accuracy for the analysis being contemplated; calibration of the device; analog, digital, computer, printed or direct-read output; and changes in the accuracy of the results depending upon the heat transfer mechanisms actually being employed.



1832 Edinburgh Encyclopedia

Galileo's Thermoscope and the Florentine Thermometer. The practical scientific measurement of temperature began in 1592 in Padua, Italy with Galileo's invention of the thermoscope (*Fig. 1*) and the translation of his work in to the Florentine Thermometer (*Fig. 2*) in about 1655.

Galileo's original thermoscope measured the thermal expansion and compression of air over expanding and contracting water sealed in a bulbous glass tube.

Six decades later, the Florentine Thermometer measured temperature changes by the changing height (volume) of distilled wine similarly to the glass mercury or alcohol thermometers of today.¹¹



Glass Thermometer

Glass Thermometer. This consists of a glass tube filled with mercury or some other liquid, which acts as the working fluid. Temperature increases cause the fluid to expand, so the temperature can be determined by measuring the volume of the fluid. Such thermometers are usually calibrated so that one can read the temperature simply by observing the level of the fluid in the thermometer.

¹¹ W. E. Knowles Middleton, *The History of the Thermometer and its Use in Meteorology* (Baltimore: Johns Hopkins University Press, 1966).



**Bi-Metal
Thermometer**

Bi-Metal Thermometer. A direct indicating dial thermometer (such as a patio thermometer or a meat thermometer) uses a bimetallic strip wrapped into a coil. The two dissimilar metal strips which form the coil expand and contract at different rates when exposed to changes in temperature. One end of the coil is fixed to the housing of the device and the other drives an indicating needle. Tiny movement of the bimetallic strip causes much larger movement of the free end of the lever and the indicator.



**Welded Bead
Thermocouple**

Thermocouple. A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. Thermocouples are a widely used type of temperature sensor for temperature measurement and control of temperature sensitive apparatus and can also be used to convert heat into electric power. Certain combinations of alloys have become popular as industry standards. Selection of the combination is driven by cost, availability, convenience, melting point, chemical properties, stability, and output. Different types are best suited for different applications. They are usually selected based on the temperature range and sensitivity needed.



Thermistors

Thermistor. A thermistor is a type of resistor whose electrical resistance varies significantly with temperature, more so than in standard resistors. Thermistors are widely used as temperature sensors, self-resetting over current protectors, and self-regulating heating elements. Thermistors differ from resistance thermometers in that the material used in a thermistor is generally a ceramic or polymer, while resistance thermometers use pure metals. The temperature response is also different; resistance thermometers are useful over larger temperature ranges, while thermistors typically achieve a higher precision within a limited temperature range [usually $-90\text{ }^{\circ}\text{C}$ to $130\text{ }^{\circ}\text{C}$].



**Resistance
Thermometers**

Resistance thermometers. Resistance thermometers, also called resistance temperature detectors or resistive thermal devices (RTDs), are temperature sensors that exploit the predictable change in electrical resistance of some materials with changing temperature. As they are almost invariably made of platinum, they are often called platinum resistance thermometers (PRTs). They are slowly replacing the use of thermocouples in many industrial applications below $600\text{ }^{\circ}\text{C}$, due to higher accuracy and repeatability.



Analog Pyrometer

Pyrometer. A pyrometer is a non-contacting device that intercepts and measures thermal radiation, a process known as pyrometry. This device can be used to determine the temperature of an object's surface. The word pyrometer comes from the Greek word for fire, " $\pi\rho$ " (*pyro*), and *meter*, meaning to measure. Pyrometer was originally coined to denote a device capable of measuring temperatures of objects above incandescence (i.e. objects bright to the human eye).



**Infrared
Thermometer**

Infrared Thermometer. Infrared (IR) light is electromagnetic radiation with a wavelength longer than that of visible light, starting from the nominal edge of visible red light at 0.7 micrometers, and extending conventionally to 300 micrometers. These wavelengths correspond to a frequency range of approximately 430 to 1 THz, and include most of the thermal radiation emitted by objects near room temperature. Microscopically, IR light is typically emitted or absorbed by molecules when they change their rotational-vibration movements. Infrared radiation can be used to remotely determine the temperature of objects (if the emissivity is known). The amount of radiation emitted by an object increases with temperature, (hence the name).

FIRE INVESTIGATION AND THE ANALYTICAL USE OF THERMOMETRY

Though thermometry is seldom if ever needed at the fire scene, it is frequently used during the post-scene analysis, or in cases of fire safety or code compliance, in which the various physics or thermodynamic formulae present themselves.

Many aspects of fire investigation and analysis require an understanding of the principles and subtleties of temperature and temperature measurement. In fire investigation¹² determining ignition sequence¹³ requires that the investigator establish the competence of both the hypothesized ignition source¹⁴ and first fuel ignited. Minimum ignition temperatures must be compared to “effective fire temperatures.”¹⁵ The ignitability of substances is dependent upon their physical phases, flash and fire points of liquids, pyrolysis temperatures of solids. Calculating these temperatures or converting physical testing results to workable temperature scales is frequently fundamental.

In fire analysis¹⁶, particularly dealing with establishing of the responsibility for a fire event scientific evaluation of the flammability properties or reactions to heat of substances and products can provide useful data.

Most fire science considerations involving temperature and their mathematical expressions and formulae require that they be used in absolute degrees of temperature.

Using these techniques, such as the Ideal Gas Law, Charles’s Law; Flash Point comparisons of various ignitable liquids; comparison of materials’ ignition temperatures and responses to heat; thermal expansion of materials; etc., when the temperature input

¹² **NFPA 921-2011 3.3.62 Fire Investigation.** The process of determining the origin, cause, and development of a fire or explosion.

¹³ **NFPA 921-2011 18.4.4 Ignition Sequence. 18.4.4.1** The ignition sequence of a fire event is defined as the succession of events and conditions that allow the source of ignition, the fuel, and the oxidant to interact in the appropriate quantities and circumstance for combustion to begin.

¹⁴ **NFPA 921-2011 3.3.33 Competent Ignition Source.** An ignition source that has sufficient energy and is capable of transferring that energy to the fuel long enough to raise the fuel to its ignition temperature.

¹⁵ **NFPA 921-2011 3.3.46 Effective Fire Temperatures.** Temperatures reached in fires that produce physical effects that can be related to specific temperature ranges.

¹⁶ **NFPA 921-2011 3.3.59 Fire Analysis.** The process of determining the origin, cause, development, responsibility, and, when required, a failure analysis of a fire or explosion.

data must be either determined in the laboratory or from references. These are consideration mostly used in fire analysis rather than mere fire scene investigation.

If one uses empirical temperature scales instead of absolute temperature scales in a thermal radiation heat transfer calculation, doing so can result in an incorrect answer. In radiation equations the temperature component is raised to the fourth power is $[T^4]$. Any error is significantly amplified to the fourth power. This is not true of the temperature difference associated with the concept of net heat flux as opposed to incident heat flux.¹⁷

The best example of the need for a basic understanding of thermometry, and how and when to use it, is the individual who thinks that 100 degrees Fahrenheit is twice as hot as 50 degrees Fahrenheit (because 100 is double 50). But in order for the actual relationship between the temperatures and the “hotness” of the material to be accurately assessed, conversions must be made to one of the thermodynamic scales. The actual relationship between 100 degrees Fahrenheit (559.67 R) and 50 degrees Fahrenheit (509.67 R) is the ratio of their absolute temperatures 559.67 R to 509.67 R or 1.1, not 2.0. 100 degrees Fahrenheit is only 10% “hotter” than 50 degrees Fahrenheit.

CONVERSIONS BETWEEN THE VARIOUS TEMPERATURE SCALES.

To convert between the Fahrenheit, Celsius, Rankine, and Kelvin temperature scales, the following formulae are used:

To convert from Fahrenheit to Celsius:	$^{\circ}\text{C} = \frac{5}{9} (^{\circ}\text{F} - 32)$
To convert from Celsius to Fahrenheit:	$^{\circ}\text{F} = \left(\frac{9}{5} ^{\circ}\text{C} \right) + 32$
To convert from Fahrenheit to Rankine:	$\text{R} = ^{\circ}\text{F} + 459.69$
To convert from Rankine to Fahrenheit:	$^{\circ}\text{F} = \text{R} - 459.69$
To convert from Fahrenheit to Kelvin:	$\text{K} = \frac{5}{9} (^{\circ}\text{F} - 32) - 273.15$
To convert from Kelvin to Fahrenheit:	$^{\circ}\text{F} = \frac{9}{5} (\text{K} - 273.15) + 32$
To convert from Celsius to Kelvin:	$\text{K} = ^{\circ}\text{C} - 273.15$
To convert from Kelvin to Celsius:	$^{\circ}\text{C} = \text{K} - 273.15$
To convert from Celsius to Rankine:	$\text{R} = \frac{9}{5} ^{\circ}\text{C} + 491.69$
To convert from Rankine to Celsius:	$^{\circ}\text{C} = \frac{5}{9} (\text{R} - 491.69)$
To convert from Rankine to Kelvin	$\text{K} = \frac{5}{9} \text{R}$
To convert from Kelvin to Rankine	$\text{R} = \frac{9}{5} \text{K}$

¹⁷ Added to the original paper as a result of a communication from Douglas J. Carpenter, MScFPE, CFEL, PE, Vice President & Principal Engineer, Combustion Science & Engineering, Inc. Columbia, MD, 2011

About the Author

A summa cum laude Fire Science graduate of the University of Cincinnati College of Engineering and Applied Science, Patrick Kennedy has been a practicing professional fire and explosion investigator and analyst, in both the public and private sectors for more than five decades. He is the world's senior-most practicing fire investigator and analyst. He is the principal fire and explosion analyst of John A. Kennedy and Associates, Inc., the world's oldest established fire and explosion investigation firm.

†Photos acquired from Google® Images

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