Temperature Scales

Course No: M01-024
Credit: 1 PDH

Robert Steelhammer, P.E.

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

TABLE OF CONTENTS

LIST OF FIGURES

Introduction

When we think of temperature scales, we think either Fahrenheit or Centigrade and not much farther than that. In fact, it is far more complicated than that and there is a history behind how temperature is defined. Not all temperature scales are the same, because they are not defined in the same way. There is more confusion on the usage and origin of temperature units more often than any other variable.

Back when I was growing up in the 1970's, I always saw commercials on television on how we were going into a new ice age. In the 1990's it was global warming. I am not interested in the politics of this. What has definitely changed is the temperature scale. In the 1970's the scale was the IPTS-68 and then in the 1990's the ITS-90, which has been the standard since. So in order to have an accurate comparison with a temperature in the past, we must use the same scale or correct as necessary, regardless of whether the temperature is an atmospheric temperature or a laboratory measurement.

At the Battle of Monmouth, the temperature had exceeded 100 degrees Fahrenheit on June 28, 1778. The average high temperature in July in the present day is about 80.2 degrees Fahrenheit for that area of New Jersey, although temperatures can still reach 100 degrees Fahrenheit in July. Thermodynamic temperature had not been defined at that point where it could be used by General Washington's troops. It had only been first explored the year before. We can only partially understand unless we have a comparison to today's standards.

These scales did not just appear. Each had a range and an instrument used to realize the scale. Some of the early instruments were crude as were the scales. Today's scales may use several instruments to realize them, for example an SPRT (Standard Platinum Resistance Thermometer) up to a certain temperature, and then a Type S thermocouple up to another range of temperature.

The quantity that we define as temperature is defined by the laws of thermodynamics and are termed thermodynamic temperatures. Thermodynamic temperature is based on a physical system created in a laboratory with a temperature related to a set of measurable properties. For example, the freezing point or triple point of a liquid or a metal.

History and Background

Some of the earliest attempts at the gauging of temperature had no fixed scale. Temperature measurement and defining temperature as a standardized measurement took a long time to develop. Some of the early attempts at standardizing were crude. The standardizing became better just as other scientific methods had developed. Even in the twentieth century, the standardized temperature scales changed several times.

The basis of early thermometers was liquids and gases expanding with temperature. The earliest thermometer in documented history was described by a Greek engineer named Philon of Byzantium, who was also known as Philo Mechanicus. He lived from 280-220 BC and is credited with building the first thermoscope (proto-thermometer). The thermoscope consists of a tube connecting a hollow sphere with water in a jug. As the temperature rises, the air in the sphere expands, causing bubbles in the water. When the temperature falls, the air in the sphere contracts causing the water level to rise in the tube. The thermoscope was designed to measure temperature changes or comparing one temperature to another.

Heron of Alexandria made an improved thermoscope design in the first century A.D. He invented the steam engine, which was a rotating ball driven by steam.

As early as 170 A.D., there were early attempts to define a standard. The Roman physician, Claudius Galenus, also known as Aelius Galenus, attempted to create a "neutral" temperature standard, by mixing equal portions of ice and boiling water. He introduced eight degrees of heat and cold, and a neutral temperature on his nine-degree scale to show different levels.

It was in the Renaissance era that instrument development accelerated. In the years 1592-1593, Galileo Galilei built a device known as the thermoscope that showed variation in hotness. It used the contraction of air to draw water up a tube.

In 1612, Santorio Santorio made the first thermometer for medical use. In 1625, he wrote about Heron's thermoscope that he modified. He used it for a different purpose. He modified it to test degrees of fever in man as well as to test the air temperature. He used snow and boiling water to define a scale for his thermometer.

In 1617, Guiseppe Biancani published the first known clear diagram of a thermoscope.

In 1654, the Grand Duke of Tuscany, Ferdinando II de' Medici made the first modern style sealed thermometer. This consisted of sealed tubes that were partially filled with alcohol (wine), with a bulb and stem. It depended on the expansion of liquid and was independent of air pressure.

In 1665, Christiaan Huygens created a clinical thermometer. He set the scale to the freezing and boiling points of water. His idea was an early version of the Celsius temperature scale. Isaac Newton modified Huygens' ideas in 1701. Newton kept the lower value as the freezing point of water. He then put the upper reference as human body temperature, which was equal to 12 degrees on this scale. He then extrapolated the scale to warmer temperatures, giving the boiling point of water as 33 degrees on this scale.

The Newton scale was created in 1701 by Sir Isaac Newton. At that point the term "temperature" was not yet used. This was the first attempt at measuring what would eventually be called temperature. He used the term "gradus caloris" to describe degrees of heat, but did call his device a thermometer. He was attempting to measure rate of heat loss. Newton used linseed oil and measured its change of volume against his reference points. He set his zero point as "the heat of the air in winter at which water begins to freeze." His method lacked a single reference point. He defined the point at which water begins to boils as 33. Human body temperature was 12 on his scale. Conversion of his scale is ambiguous at best. His linseed oil thermometer could be used to the melting point of tin and was likely for practical use for his duties as Master of the Mint.

In 1701-1702, Olaus Roemer, a Danish Astronomer, constructed his own spirit thermometers. He developed a temperature scale for them where the freezing point of water was 7.5 degrees and the boiling point was 60 degrees. His initial scale defined the temperature of freezing brine as zero degrees, but this was changed due to the difficulty of standardizing brine. His temperature scale, along with the Newton scale, were the first calibrated scales. Roemer was visited Copenhagen in 1708 by a young scientist named Daniel Fahrenheit that wanted to learn about his work. He showed Fahrenheit a modified version of his earlier work. In Roemer's modified scale, the upper value was human body temperature (assumed constant). Fahrenheit modified the scale since he did not like the fractional representation that Roemer had in his scale. On Fahrenheit's scale the lower fixed point became 30 degrees and the upper became 90 degrees. On Fahrenheit's scale, the boiling point of water was 205 degrees.

In 1702-1703, Guillaume Amontons published papers that credit him as being the first researcher to discuss the existence of a thermodynamic temperature scale with an absolute zero.

Daniel Fahrenheit used the modified scale that he derived from Roemer until 1717. He then made some changes to the fixed points, that made the freezing point of water 32 degrees and 96 became the human body temperature. We see the beginning of the Fahrenheit scale (^oF). On the modified scale, the boing point of water became 212 ^oF. He later redefined the upper fixed point as the boiling point of water, since body temperature is not constant.

Daniel Fahrenheit is credited with making two major breakthroughs in temperature measurement in the early 18th century. Fahrenheit has been recognized as the first person to develop a commercially available thermometer and developing the first temperature scale with widespread application. He started in 1709 using alcohol in his thermometers and then switched to purified mercury in 1714. Fahrenheit is credited as the first to use mercury in a thermometer. The temperature scale he introduced in 1724 gained widespread use. Presently the freezing point of water on this scale is 32 ^oF and the boiling point of water is 212 ^oF. This puts the temperature of the human body as approximately 98 ^oF.

The French naturalist and scientist, Rene de Reaumur, developed a thermometer based on his study of insect growth with temperature. He made a thermometer where the freezing point of alcohol was zero degrees. Under his scale, the boiling point of alcohol was 80 degrees. His thermometer was known as the Reaumur alcohol thermometer by 1730. His zero to 80 degree temperature scale became known as the Reaumur temperature scale, which was also known as the "octogesimal division". After Reaumur, researchers began using different liquids in their thermometers. They still defined 80 degrees as the boiling point, even after switching to water in the thermometer. This led to confusion and mercury eventually became the standard liquid in thermometers.

Joseph Delisle was a French astronomer. In 1732 he built a mercury thermometer defining the boiling point of water as the zero point. He defined the scale for lower temperatures with the contraction of mercury. His scale was modified in 1738 by a German professor of medicine and anatomy named Josias Weitbrecht. He kept the 0 ^oD (Delisle) as the boiling point of water. He assigned 150 ^oD as the freezing point of water. The Delisle scale was used in Russia for nearly 100 years. It is one of the only scales that is inverted from the amount of thermal energy it measures.

Anders Celsius was a Swedish astronomer and mathematician who proposed a temperature scale in 1742. His original scale had a 100 degree scale between the freezing point of water, which was 100 degrees on his scale and the boiling point of water, which was zero on his scale. It was not until after his death, that the fixed points were inverted, to give us the Celsius scale that we have today, although at that point it was called Centigrade. It was in 1744 that Carl Linnaeus proposed reversing Anders Celsius' temperature scale, where zero represented the freezing point of water and 100 represented the boiling point of water. In 1743, Jean-Pierre Christin, developed independently of Celsius a temperature scale where zero represented the melting point of ice and 100 represented the boiling point of water. His method did not specify a pressure at the boiling point, like Celsius' did.

In 1772, Jean-Andre Deluc studied several substances that were used in thermometers at the time. He concluded that thermometers using mercury were the best for practical use.

In 1777, Johann Heinrich Lambert proposed an absolute temperature scale based on the pressure/temperature relationship of a fixed volume of a gas. This was the beginning of the exploration of the thermodynamic scale. Lambert defined absolute zero as -270 ^oC.

In 1782, the maximum minimum thermometer was invented by James Six. This records the maximum and minimum temperatures reached over a time period.

The 19th century began to change the way that temperature scales were defined. Before that time, the temperature scales were based on the expansion or contraction of a material such as alcohol or mercury. After the development of thermodynamic theory, the way temperature was defined was linked to other physical properties. Joseph Louis Gay-Lussac studied the behavior of gases presented in 1802 what is now known as Charles's Law, from the unpublished work of Jacques Charles from the 1780's. The concept expressed was that a volume of gas at constant pressure is proportional to the temperature. The volume of an ideal gas under this would theoretically reach zero at -273 ^oC.

In 1794, the thermoelectric effect was first discovered by Italian scientist Alessandro Volta. In 1821, the thermocouple was invented by Thomas Johann Seebeck. He discovered that an electric potential difference (voltage) between different conductive materials (usually metals) at different temperatures.

The concepts in Charles's Law were further developed by William Thomson (Scottish physicist and engineer). In 1848, Thomson proposed a temperature scale based on the fundamental laws of thermodynamics. This was in his paper "On an Absolute Thermometric Scale". His scale had a zero point where no caloric heat could be transferred (now Kelvin scale with absolute zero as the zero point). It is now known as absolute zero and Robert Boyle had discussed it in 1665. Thomson was given the Title First Baron Kelvin (after a river near his laboratory) in 1892. He became known as Lord Kelvin and his temperature scale as the kelvin scale. Today 0 K is equal to -273.16 ^{o}C (1 K change is equal to 1 ^{o}C change).

William Thomson began to develop the science of thermoelectricity in 1851. He described the heating and cooling of a current carrying conductor that has a temperature gradient. This became known as the Thomson effect.

In 1859, William Rankine (Scottish engineer) proposed a temperature scale that was also an absolute temperature scale, like the kelvin scale. The Rankine scale uses the change equal to Fahrenheit (1 ^{o}R is equal to 1 ^{o}F change). Under this scale the freezing point of water is 491.688 ^{o}R.

In 1871, William Siemens described the resistance thermometer at the Bakerian lecture. A few years later, in 1885, the platinum resistance temperature device (RTD) was invented.

The constant volume hydrogen gas temperature scale was made available in 1887 through mercury thermometers. It is commonly referred to as Normal Hydrogen Scale (NHS).

The Austrian physicist, Ludwig Eduard Boltzmann, is credited with developing statistical mechanics and the statistical explanation concerning the second law of thermodynamics. He linked the collective behavior of molecules and atoms to macroscopic qualities. These qualities included heat capacity and viscosity allowing temperature to be understood as a measure of the mean kinetic energy of atoms and molecules.

Figure 1 shows the temperature scales discussed so far. Specific temperatures are chosen for comparison.

Kelvin	Rankine	Celsius	Fahrenheit	Delisle	Reaumur	Newton	Romer	Real world item measured
0	0	-273.15	-459.67	559.725	-218.52	-90.1395	-135.9038	Absolute zero
13.8033	24.84594	-259.3467	-434.82406	539.0201	-207.47736	-85.5844	-128.657	Triple point of H (Hydrogen) *
54.3584	97.84512	-218.7916	-361.82488	478.1874	-175.03328	-72.2012	-107.3656	Triple point of O (Oxygen) *
184	331.2	-89.15	-128.47	283.725	-71.32	-29.4195	-39.30375	Lowest recorded on Earth 7/21/1983 in Vostok, Antartica
233.15	419.67	-40	-40	210	-32	-13.2	-13.5	Crossover temperature Celsius, Fahrenheit (point they are the same)
234.3156	421.7681	-38.8344	-37.90192	208.2516	-31.06752	-	-12.88806	Triple point of Hg (Mercury) *
255.27	459.486	-17.88	-0.184	176.82	-14.304	-5.9004	-1.887	Fahrenheit's brine mixture
273.15	491.67	0	32	150	0	0	7.5	Freezing point of water
273.16	491.688	0.01	32.018	149.985	0.008	0.0033	7.50525	Triple point of water *
287	516.6	13.85	56.93	129.225	11.08	4.5705	14.77125	Average Earth surface temperature
302.9146	545.2463	29.7646	85.57628	105.3531	23.81168	-	23.12642	Melting point of Ga (Gallium) *
310	558	36.85	98.33	94.725	29.48	12.1605	26.84625	Average person's body temperature
329.8	593.64	56.65	133.97	65.025	45.32	18.7275	37.24125	Highest recorded on Earth 7/10/1913 in Furnace Creek, California (Death Valley)
373.15	671.67	100	212	0	80	33	60	Boiling point of water
429.7485	773.5473	156.5985	313.8773	-84.89775	125.2788	51.67751	89.71421	Freezing point of In (Indium) *
505.078	909.1404	231.928	449.4704	-197.892	185.5424	76.53624	129.2622	Freezing point of Sn (Tin) *
692.677	1246.819	419.527	787.1486	-479.2905	335.6216	138.4439	227.7517	Freezing point of Zn (Zinc) *
933.473	1680.251	660.323	1220.5814	-840.4845	528.2584	217.9066	354.1696	Freezing point of Al (Aluminum) *
1234.93	2222.874	961.78	1763.204	-1292.67	769.424	317.3874	512.4345	Freezing point of Ag (Silver) *
1337.33	2407.194	1064.18	1947.524	-1446.27	851.344	351.1794	566.1945	Freezing point of Au (Gold) *
1357.77	2443.986	1084.62	1984.316	-1476.93	867.696	357.9246	576.9255	Freezing point of Cu (Copper) *
1941	3493.8	1667.85	3034.13	-2351.775	1334.28	550.3905	883.1213	Melting point of Ti (Titanium)
5800	10440	5526.85	9980.33	-8140.275	4421.48	1823.861	2909.096	Surface of the Sun

** Fixed point in the ITS-90 Scale*

Figure 1. A comparison of temperature scales

In 1911, the directors of the national laboratories of the United States, Great Britain, and Germany agreed to undertake unification of temperature scales used. The first International Temperature Scale (ITS) was adopted in 1927 by the Seventh General Conference on Weights and Measures. It was known as the International Temperature Scale of 1927 (ITS-27) and developed to measure temperature based on the thermodynamic scale. The area of determination covered the normal boiling point of oxygen (-182.97 ^{o}C) up to the solidifying point of gold (1063 ^{o}C). There were six reference points. These reference points were combined with interpolation to ensure unity of temperature measurements using the scale. The suggested interpolation instruments were the platinum resistance thermometer and the platinum-rhodium thermocouple.

The General Conference on Weights and Measures is the international body representing nations that subscribe to the Treaty of the Meter, and it has six advisory committees. The Advisory Committee on Thermometry first met in 1939.

In 1948, the Ninth General Conference on Weights and Measures changed the reference from degrees centigrade to degrees Celsius. The made refinements to the values of the reference points in the ITS-27. They also adopted the ^{o}C symbol to represent degrees Celsius. They also added the adjective “Practical” to the name. The International Practical Temperature Scale of 1948 (IPTS-48) was created from refinements in the values of the ITS-27 reference point values. The

IPTS-48 had 6 defining fixed points. The procedures to realize the scale and interpolate between the values required dividing the scale into four parts. Realizing the scale required the use of a standard resistance thermometer or a standard thermocouple, depending on the division of the scale.

The kelvin has been the preferred temperature scale used by scientists since 1954, when the General Conference on Weights and Measures adopted it as the basic unit of thermodynamic temperature. Kelvin was first defined as a unit of temperature in the IPTS-68 standard. The degree symbol was eliminated from the kelvin. It was released in October 1968 and adopted eight major changes to the international temperature scale. This can be used for the low temperature range to the triple point of hydrogen (-253.34 ºC). The number of reference points went to thirteen. The error was estimated to be 0.01 K at the low temperature range, up to 0.2 K at the freezing point of gold. There were a total of eight major changes made to the international temperature scale.

In 1954, the Advisory Committee proposed a resolution that would redefine the Kelvin temperature scale by assigning a value to the triple point of water. The proposal was adopted and it became necessary to revise the introduction of the text of the ITS-48.

The IPTS-68 standard was amended in 1976. This was for the temperature range of 0.5 K to 30 K. The modified scale was known as the EPT-76.

Thermodynamic temperature satisfies all of the laws of thermodynamics. Even the ITS-90, the most current, approximates the thermodynamic temperature scale. The reasons are that we have to come up with a practical approximation that we can realistically use. The ITS-90 replaces the earlier temperature scales ITS-27, ITS-48, and IPTS-68.

The International Temperature Scale of 1990

It was soon after the adoption of the IPTS-68 that it was realized that it had many limitations as well as deficiencies. A given thermodynamic temperature defined in the ITS-90 scale is different from that on the IPTS-68 scale. The exception to these are at absolute zero (0 K), at the triple point of water (273.16 K), and a few other points.

The International Temperature Scale (ITS-90) was adopted in September of 1989 (placed in service at the National Institute of Standards and Technology January 1, 1990) during the meeting of the International Committee for Weights and Measures. The ITS-90 superseded all previous thermodynamic scales. The ITS-90 defined the unit of kelvin as 1/273.16 part of the thermodynamic temperature of the triple point of water.

In November 2018, the definition of the kelvin was changed by the 26th General Conference on Weights and Measures as part of changes made to SI unit definitions.

The ITS-90 is based on seventeen reference points. In terms of the ITS-90 the melting point of ice is slightly below 0 ^oC and the boiling point of water at normal atmospheric pressure is approximately 99.974 ^oC.

A difference in temperature on the ITS-90 scale can be expressed in degrees Celcius or in kelvins. Figure 2 shows the comparison of the ITS-90 scale with the thermodynamic scales coming before it. The size of the kelvin is defined as 1/273.16 of the thermodynamic temperature of the triple point of water.

NHS	ITS-27	ITS-48	IPTS 48	IPTS-68	IPTS-68(75)	EPT-76	ITS-90	Point
-	1336.15	1336.15	1336.15	1337.58	1337.58	-	1337.73	Au Freezing Point
-	1233.65	1233.95	1233.95	1235.08	1235.08	-	1234.93	Ag Freezing Point
-	-	-	-	-	-	-	933,473	Al Freezing Point
-	717.75	717.75	717.75	-	-	-	-	S Boiling Point
-	-	-	692.655	692.73	692.73	-	692.677	Zn Freezing Point
-	-	-	-	505.1181	505.1181	-	505.078	Sn Freezing Point
-	-	-	-	-	-	-	429.7485	In Freezing Point
373	373.15	373.15	373.15	373.15	373.15	-	-	H_2O Boiling Point
-	-	-	-	-	-	-	302.9146	Ga Triple Point
-	-	-	273.16	273.16	273.16	-	273.16	H_2O Triple Point
273	273.15	273.15	-	-	-	-	-	H_2O Freezing Point
-	-	-	-	-	-	-	234.3156	Hg Triple Point
-	90.18	90.18	90.18	90.188	90.188	-	-	O_2 Boiling Point
-	-	-	-	-	83.798	-	83.8058	Ar Triple Point
-	-	-	-	54.361	54.361	-	54.3584	O_2 Triple Point
-	-	-	-	27.102	27.102	27.102	-	Ne Boiling Point
-	-	-	-	-	-	24.5591	24.5561	Ne Triple Point
-	-	-	-	20.28	20.28	20.2734	20.3	H_2 Boiling Point
-	-	-	-	17.042	17,042	17.0373	17	H_2 Boiling Point (reduced
-	-	-	-	13.81	13.81	13.8044	13.8033	H_2 Triple Point
-	-	-	-	-	-	7.1999	-	Pb Superconductive Transition
-	-	-	-	-	-	4.2221	4.2	He Boiling Point
-	-	-	-	-	-	3.4145	-	In Superconductive Transition
-	-	-	-	-	-	-	3.2	'He Boiling Point
-	-	-	-	-	-	1.1796	-	Al Superconductive Transition
-	-	-	-	-	-	0.851	-	Zn Superconductive Transition
-	-	-	-	-	-	0.519	-	Cd Superconductive Transition

Figure 2. NIST comparison of the thermodynamic temperature scales

In Figure 2, the boiling point of Sulphur is taken at 14.69595 psi. The ITS-90 scale replaced thermocouple thermometry with platinum resistance thermometry in the range of 630 ^oC to the freezing point of silver. It also replaced thermocouple thermometry with radiation thermometry from the freezing point of silver to 1337.73 K (freezing point of gold).

The key elements of the ITS-90 scale are the way it is defined and the way it is realized. The ITS-90 is defined between 13.8033 K (triple point of H) and 1234.93 K (freezing point of Ag). Looking back at Figure 2, that those points and the points between them in the ITS-90 column.

Realizing the ITS-90 scale is typically done in one of four different ways, depending on the range from 0.65 K upward. In the temperature range of 0.65 K to 5 K, the ITS-90 is realized using the vapor pressure to temperature relationships of the helium isotopes ^3He and ^4He, known as ^3He and ^4He vapor pressure thermometry. In the temperature range from 3 K to 24.5561 K (triple point of Ne) the ITS-90 scale is realized by a constant volume helium gas thermometer calibrated at three points (including triple point of neon and triple point of equilibrium hydrogen). This is ^3He and ^4He constant volume gas thermometry. In the temperature range of 13.0833 K to 1234.93 K (freezing point of Ag), the ITS-90 scale is realized using platinum resistance thermometry. Above 1234.93 K, Planck's radiation law is used. Notice that there is overlap in most cases.

Conclusion

The temperature scales that we use today developed over many centuries. A historical development of instruments and scales has been shown. Once we have an understanding of how we arrived to using the International Temperature Scale of 1990 (ITS-90), we can then begin to show how to realize it in the various ranges. These ranges have different methods to realize them. They have been mentioned, but not discussed in detail in this course.

References

1. Hillger, Don and Toth, Garry. *Temperature Scales and their Inventors*. Philatelia Chimica Et Physica, Vol. 37, No. 2, Spring 2016.
2. Stimson, H.F. International Practical Temperature Scale of 1948, Texas Revision of 1960. Journal of Research of the National Bureau of Standards. June 1961.
3. National Institute of Standards and Technology. NIST Monograph 175. United States Department of Commerce.
4. Fisher, David. Legends and Lies The Patriots. Henry Holt and Company. New York. 2016.
5. Ripple, Dean. NIST Thermocouple Workshop. National Institute of Standards and Technology. September 19, 2000.
6. ASTM. Manual on the Use of thermocouples in Temperature Measurement, Fourth Edition. ASTM. 1993
7. ISA and Beamex. Calibration Essentials: Temperature. ISA and Beamex as accessed 08/19/2022.
8. Mangum, B. W. and G. T. Furukawa. *NIST Technical Note 1265: Guidelines for Realizing the International Temperature Scale of 1990 (ITS-90)*. National Institute of Standards and Technology. August 1990.
9. https://en.wikipedia.org/api/rest_v1/page/pdf/Temperature_measurement as accessed on 06/21/2022.
10. https://www.stephan-matthiesen.de/en/texts-blog/49-texts-blog/138-a-short-history-of-temperature-measurements-and-temperature-scales.html as accessed on 06/21/2022.
11. https://www.teos-10.org/pubs/gsw/pdf/t90_from_t48.pdf as accessed 06/22/2022.
12. https://thermopedia.com/content/882/ as accessed on 06/23/2022.
13. https://en.wikipedia.org/wiki/Christiaan_Huygens as accessed 07/06/2022.
14. https://en.wikipedia.org/wiki/Medical_thermometer as accessed 07/06/2022.
15. https://en.wikipedia.org/api/rest_v1/page/pdf/Timeline_of_temperature_and_pressure_measurement_technology as accessed 07/08/2022.
16. https://en.wikipedia.org/api/rest_v1/page/pdf/Thermodynamic_temperature as accessed 07/08/2022.
17. https://en.wikipedia.org/wiki/Hero_of_Alexandria#Inventions as accessed 07/11/2022.
18. https://en.wikipedia.org/wiki/Charles%27s_law#History as accessed 07/15/2022.

19. https://en.wikipedia.org/wiki/Ludwig_Boltzmann as accessed 07/18/2022.
20. https://www.weather-atlas.com/en/new-jersey-usa/monmouth-beach-weather-july as accessed 07/31/2022.
21. https://en.wikipedia.org/wiki/R%C3%B8mer_scale as accessed 07/31/2022.
22. https://en.wikipedia.org/wiki/R%C3%A9aumur_scale as accessed 07/31/2022.
23. https://en.wikipedia.org/wiki/Newton_scale as accessed 07/31/2022.
24. https://en.wikipedia.org/wiki/Delisle_scale as accessed 07/31/2022.
25. https://www.convertunits.com/from/newton/to/kelvin as accessed 07/31/2022.
26. https://en.wikipedia.org/wiki/Thermodynamic_temperature#History as accessed 08/01/2022.
27. https://www.britannica.com/biography/Thomas-Johann-Seebeck as accessed 08/02/2022.
28. https://en.wikipedia.org/wiki/Thermoelectric_effect as accessed 08/02/2022.
29. https://en.wikipedia.org/wiki/Hugh_Longbourne_Callendar as accessed 08/18/2022.