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NEW ZEALAND METEOROLOGICAL SERVICE

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THERMOMETER SCALES

These notes tracing the history of thermometer scales were compiled by I.S. Kerr and are circulated for general information.

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J.F. Gabites
Director

N.Z. Meteorological Service,
P.O. Box 722,
Wellington.

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Introduction

During the last 200 years three temperature scales have been in common use in different countries - Fahrenheit, Réaumur and Centigrade. The first is graduated so that there are 180 scale units, or degrees, between the level of the liquid when the thermometer is at the temperature of melting ice and its level when the thermometer is at the temperature of boiling water at a standard atmospheric pressure; these two reference points are labelled 32 degrees and 212 degrees respectively. The same two reference points on the Réaumur scale are zero and 80 degrees, and on the Centigrade, or Celsius scale as it is now known, they are zero and 100 degrees.

The Réaumur scale has not been in use for many years and the Fahrenheit scale will also disappear, probably long before the end of this century. The Celsius scale has some scientific advantages over the other two scales, and will prevail because it is the scale used in those countries that have long used the metric system which, along with the Celsius temperature scale, is the basis of the International System of units. New Zealand, along with nearly all the nations of the world, has decided to adopt the International System of units and one of the first signs of the change is the appearance in the newspapers, on television and on the air, of air temperatures expressed in degrees Celsius, and of rainfall amounts in millimetres. The Metric Advisory Board in announcing this gave the reason for the international agreement to substitute the name Celsius for the former name, Centigrade. But how strong are the claims of Celsius to have the scale named after him? He did not, in fact, invent the scale in the form we know it today, but neither did Fahrenheit invent the scale that bears his name. Nevertheless their right to the honour is substantial.

The evolution of the thermometer is not as well documented as we would like and it is not surprising that some suppositions have later been repeated many times as facts. The literature and the archives of most of the European centres of learning have been thoroughly searched by W.E.K. Middleton who published his findings in 1966 in "A History of the Thermometer and its Use in Meteorology". The following is largely a summary of part of this exhaustive treatment of the subject.

Until comparatively recent times the quantity "temperature" has always been specified in terms of changes in properties of substances as they are heated or cooled. Throughout the period covered by these notes the property used for the purpose was the volume of substances; the change in volume of a substance as it becomes hotter or colder is the most easily observed. The early history is therefore confined to experiments with different thermometric substances and to the choice of a scale numbering system.

Early thermometers and scales

Philo of Byzantium and Hero of Alexandria in the 2nd and 1st Centuries B.C. respectively both performed experiments which demonstrated the principle which was later used in the thermometer but there is no indication that they thought of using the discovery in this way. The idea of a scale to indicate "degrees of heat and cold" appears to have been first suggested by the Greek physician Galen in the 2nd Century A.D. He proposed a nine-point scale with a neutral point in the middle which would be the temperature of a mixture of equal quantities of ice and boiling water but there is no evidence that he took his idea as far as conceiving a measuring instrument.

The great Galileo is usually credited with the invention of the thermometer some time between 1592 and 1603 but there is no contemporary reference to it and none in Galileo's own writings. The evidence rests on a number of letters written many years later and on a statement in a biography of Galileo written by a pupil in 1654. There is little doubt that he demonstrated a means of "examining the degrees of heat and cold" but whether or not he provided the instrument with a scale is questionable.

The first known drawing of a thermometer is to be found in an unpublished manuscript dated 1611. Unfortunately the description of it given by the author does not tally with the drawing. The author, Bartolomeo Telioux, evidently did not invent the instrument but was trying to describe something that he had seen. The thermometer has a scale of eight degrees each of which is subdivided into "minutes". The scale seems to be quite arbitrary but it is of interest to note that it indicates "degrees of cold", i.e. the scale reading at the highest temperature the instrument was capable of recording would be zero, and at the lowest temperature 8.

In the next few years we have the earliest accounts of thermometers actually used in experiments and in clinical medicine. Giovanfrancesco Sagredo in the Venetian government service and an enthusiastic admirer of Galileo wrote several letters to the latter between 1612 and 1615 in which he described experiments which he had conducted with thermometers he had made. (He credited Galileo with the invention; this is part of the evidence mentioned above.) His letters refer to daily records of air temperature he had kept over a period of several weeks; in fact he must have made observations over several years, but perhaps not daily, because early in 1615 he wrote that the air temperature was at that time 130 degrees higher than it had been in the very rigorous winter two years before. He quotes scale readings but we do not know much about it; from other values given Middleton has deduced that about 7 of Sagredo's degrees would be equal to 1 degree Celsius. He apparently attempted to establish his zero as the temperature of a mixture of snow and salt but says nothing about how he graduated his scale. He does say however that his thermometer had "gone up to 360 degrees in the greatest heat of summer" (in the shade or in the sun?).

About the same time in Padua a physician, Santorio Santorre, was one of the first to apply quantitative methods in the practice of medicine. Among the instruments he used, and described and illustrated in publications in 1612 and 1625, was the thermometer. He was interested not only in its clinical applications but also discussed its usefulness for studying variations of air temperature. The first of the instruments illustrated by Santorio had no scales. Some of the later ones had graduation marks but no numbers attached to them. He did, however, in 1630 describe his method of determining two "fixed" reference points: for one the bulb was immersed in snow and, for the other, it was held in the flame of a candle.

By the middle of the century thermometers were being made and experimented with in many parts of Europe but there was no hint of a standard scale. Some of the early descriptions were mixed up with ideas of perpetual motion. For example, in a book published in Frankfurt in 1615, Salomon de Caus, an engineer and architect described a thermometer under the heading "To make a machine that will move by itself". The text made it clear, however, that the author understood the cause of the incessant motion of the liquid and the use to which the instrument could be put. He also recognised that to register the temperature of the <u>air</u> it had to be shielded from direct sunlight. It was, incidentally, made to move a pointer over a clock face numbered I to XII.

The Florentine thermometers

All of these early thermometers were air thermometers. Air is trapped in a bulb and tube the lower end of which is immersed in a tank of water. As the bulb is cooled so is the air inside it and as the air contracts the water rises in the tube; on warming the air it expands again and forces the water down the tube. Shortly after the invention of the barometer about 1643 it was realised that the movement of the water surface in the tube of an air thermometer was affected by the variable pressure of the air as well as by its temperature. But even before this there were thermometers that made use of changes in the volume or density of liquids. A small-town French physician, Jean Rey, had an unsealed water thermometer in 1631 but it does not seem to have had a scale.

The invention of the sealed liquid-in-glass thermometer is credited to the Grand Duke of Tuscany, Ferdinand II, one of the famous Medici family. Thermometers of the type familiar to us today were made in Florence no later than 1654. The first meteorological nétwork was established in December 1654 using these thermometers. The "stations" were at Florence, Parma, Milan and Bologna. The series of observations made at Florence from 1654 to 1670 has survived. Northwest-facing and southwest-facing thermometers were read almost every hour of the day; and the state of the sky was also recorded.

The scales on these Florentine thermometers were either 0° to 50°, 0° to 100° or 0° to 300°. It is clear, however, that these scales were not based on fixed points. Comparability depended on the skill of the maker, that is on his ability to make them exactly the same. They were constructed so that the 50 degrees or 100 degrees spanned the range from the extreme cold of winter to the greatest heat of summer. The uniformity of the 50-degree thermometers was astonishing. Over 200 of them were compared in 1830 and their zero was found to correspond to -18¾°C and their 50° mark to 55°C with very little variation.

Approach to standardization

The first attempt to standardize the temperature scale by a method that did not depend on making the thermometers exactly the same was described by Robert Hooke in 1665. He used a single reference point - the freezing point of water. The scale unit or degree corresponded to a change in the volume of the spirit at the reference temperature. This work attracted little attention and Réaumur who, 65 years later, used a somewhat similar method made no reference to Hooke's work.

The superior method of using two fixed points, foreshadowed by Santorio in 1630, was described by at least three workers in the last three decades of the century - Sebastiano Bartolo of Naples in 1672, Francesco Eschinardi, another Italian, in 1680, and Carlo Renaldini of Florence in 1694. Bartolo used snow and, for the first time, boiling water and divided the interval into 18 degrees. Eschinardi used ice and boiling water, and Renaldini used ice cold water and boiling water dividing the interval into 12 degrees.

The next 50 years saw many more attempts to standardize the temperature scale and it was during this period that the three scales that survived into the 19th century - Fahrenheit, Réaumur and centigrade - were developed.

The Fahrenheit scale

The story of the Fahrenheit scale appears to have its beginning in the work of the Danish astronomer, Ole Rømer, who is famous for the discovery that the speed of light is finite. About 1702 Rømer was making thermometers and marking the temperature of boiling water 60 and of melting ice $7\frac{1}{2}$. Why $7\frac{1}{2}$? Presumably he thought that by placing one eighth of the range 0 to 60 below the melting point of ice he would ensure that all meteorological temperatures would be above 0°. About the end of 1708 he had substituted 8 for $7\frac{1}{2}$; it may be presumed that the temperature of boiling water became 64.

This scale bears little obvious resemblance to the Fahrenheit scale as we know it today but the latter scale was in fact derived from Rømer's in a somewhat roundabout way. Daniel Gabriel Fahrenheit, who was born in Danzig in 1686, lived much of his life in Holland and visited Rømer in Copenhagen in 1708. There he saw Rømer calibrating a number of thermometers. They were put in a mixture of water and ice and the spirit level marked $7\frac{1}{2}^{\circ}$. Next they were put into warm water "which was at blood-heat" and this temperature was marked $22\frac{1}{2}^{\circ}$. We know that Rømer's scale had the boiling point of water as the upper fixed point and in view of the impossibility of holding the temperature of the water at blood heat, it is reasonable to assume that one of the thermometers seen by Fahrenheit was a standard being used to calibrate the others in water kept at $22\frac{1}{2}^{\circ}$ which was about blood heat. Fahrenheit apparently did not realise this and in his subsequent work the upper fixed point was determined "when the thermometer is held in the mouth, or under the armpit, of a living man in good health, for long enough to acquire perfectly the heat of the body." This point which he believed corresponded to Rømer's $22\frac{1}{2}^{\circ}$ he labelled 90° ("I divided each degree into 4 smaller ones"). The temperature of a mixture of water and ice he marked 30° (4 times $7\frac{1}{2}$). He also claimed that he used a third fixed point - the temperature of a mixture of ice, water, and salammoniac or sea-salt - which was the zero of his scale. He could hardly have been serious in making this claim - in fact he referred to it as an "experiment (which) succeeds better in winter than in summer" - and obviously the real fixed points were the temperatures of melting ice and of the blood of the healthy human body. About 1717 he modified his scale and used 96 instead of 90 and 32 instead of 30. This follows the change that Rømer himself made, 8° instead of $7\frac{1}{2}^{\circ}$.

Fahrenheit did not use the boiling point of water as a fixed point but he did extrapolate his scale up to 600° and determined the boiling points of a number of liquids on this scale. He apparently had confidence in the uniformity of his thermometer and ignored or knew nothing of the uniformity, or lack of uniformity, of the expansion of the thermometer liquid. At any rate he found, and reported in 1724, that the boiling point of water was 212° on the extrapolated scale. Now, blood heat on the modern Fahrenheit scale is 98.6°. Therefore, if his scale was properly extrapolated and if the boiling point of water was determined at the standard atmospheric pressure, the boiling point should have been about 205° on his scale. Clearly the two conditions did not hold good but by 1740 makers of "Fahrenheit" thermometers were using the boiling point of water instead of blood heat as the upper fixed point and they labelled it 212°. The melting point of ice remained 32°. Hence the modern Fahrenheit scale is not identical with the one he invented but few would deny him the right to have the scale bear his name.

Before Fahrenheit's time the liquid mostly used in thermometers was an alcohol (spirits of wine). Fahrenheit, although not the first to try mercury, did use it in most of his thermometers, and from that time on mercury came to be more and more widely used as the thermometric substance.

The Réaumur scale

As the Réaumur scale has long fallen into disuse little need be said of it. As originally conceived in 1730 the Réaumur method of graduating thermometers harks back to the method described by Hooke in 1665. There was only one fixed, reference point - the temperature at the freezing point of water, 0°. The thermometric liquid was alcohol diluted so that if its volume at 0° was 1000 parts it would expand to 1080 parts when heated to the temperature of boiling water. At least, this is what Réaumur said at the conclusion of a description of his method but the statement is not an accurate summary of the details given earlier which seem to indicate that the liquid expanded from 1000 parts at 0° to 1080 parts at the boiling point of the diluted alcohol itself. Whatever the original method really was makers of "Réaumur" thermometers soon adopted the method of two fixed points - freezing point (or the melting point of ice), 0° and the boiling point of water, 80°. The volume increment of 80 parts was chosen by Réaumur mainly because 80 is "a number convenient to divide into parts."

The Centigrade and Celsius scales

We now come to the development of the centigrade scale. As we have seen some of the Florentine thermometers of the seventeenth century were graduated from 0 to 100 degrees but the zero and 100° were certainly not fixed points and comparability depended on the maker's skill. The first 100-degree thermometers that purported to be standardised in the modern sense were four made by Joseph Nicholas Delisle, a French astronomer, and his brother for the purpose of measuring the air temperature during the total solar eclipse of 22 May, 1724. They indicated 0° in boiling water and 100° in the cellars of the Paris Observatory. While the temperature in these cellars undoubtedly varied little it can hardly be regarded as a satisfactory reference temperature. No more of these thermometers were made but in 1725 Joseph Delisle went to St. Petersburg where he made more thermometers. There were no cellars of sufficient depth so he turned to the freezing point of water as his lower fixed point. A colleague, Josias Weitbrecht, determined that the contraction of mercury between the boiling point and the freezing point of water was very close to 150/10,000 of the volume at the boiling point. They therefore made their scale run from 0° at the boiling point to 150° at the freezing point.

The Delisle 150-degree thermometers, although well constructed and used in Russia for more than 50 years, are of little interest in their own right but they almost certainly had a direct influence on the work of Anders Celsius, a Swedish astronomer at the University of Uppsala. At the end of 1737 Delisle sent two of his thermometers to Celsius and one of these still survives in the Meteorological Institute at Uppsala. The most interesting thing about it is the fact that the original Celsius scale has been marked on it alongside the Delisle scale. The two zeros coincide but freezing point is marked 100° Celsius opposite 151.8° Delisle (not 150°, probably because the instrument was re-calibrated).

Celsius' account of his original scale was published in 1742. The upper fixed point, marked 0°, was determined by the temperature of boiling water when the barometer stands at 25$\frac{1}{4}$ Swedish inches; and the lower fixed point, 100° was the temperature of melting snow. The standard pressure used now is slightly different so that on the present day definition Celsius' upper fixed point was at 99.67°C. The original Celsius scale was therefore very close to the modern scale in reverse.

The recording of temperatures at Uppsala using the original Celsius scale began in December, 1741, and continued until April, 1750. Who was responsible for reversing the scale remains one of the mysteries of the story. Certainly not long after Celsius' death a Stockholm instrument maker, Ekstrom, and Celsius' successor, Stromer, had both constructed thermometers with the ice point at 0° and the boiling point at 100°. Readings of thermometers bearing their names were recorded along with those of the original Celsius thermometer from 1747. There is evidence that the famous botanist, Linnaeus, who also worked at Uppsala and was a friend of Celsius, had ordered a centigrade thermometer with the ice point at 0° from Ekstrom in 1745. This has often been taken as proof that Linnaeus instigated the reversal and, indeed, he claimed, in 1758, that he had done so. Whether it was Ekstrom, Stromer, Linnaeus or someone else may never be known.

There is, in fact, one other who may lay claim to the honour of having invented the centigrade scale as we know it today. This was Jean Pierre Christin of Lyon. He described his thermometer to the Lyon Academy of Science, Literature and Art in May, 1743. It was a mercury thermometer with 0° marking the freezing point and 100° the boiling point of water. His thermometers were made by Pierre Casati, became known as the thermomètres de Lyon, and were used fairly extensively in southern France for a time but they did not win the day against the Réaumur thermometers backed by the prestige of the Paris Academy.

The centigrade scale was well established in Sweden by 1750 and gradually ousted all others on the Continent - it replaced the Réaumur scale in France officially in 1794 - and will soon replace the Fahrenheit scale wherever it is still used. The name "Celsius" replacing "centigrade" was adopted officially in 1948 by the ninth General Conference on Weights and Measures - a body constituted following an international Convention in Paris in 1875 which was responsible for all international matters concerning the metric system. The World Meteorological Organization agreed in 1953 that the Celsius scale should be used for reporting upper air temperatures. In 1959 the Organization passed a more general Resolution - "To adopt the Celsius degree and metric system of units for the evaluation of meteorological elements included in reports for international exchange", and requested Members who do not use the Celsius scale to adopt it for use in meteorological messages for international exchanges by the end of 1963. The New Zealand Meteorological Service responded to this request, as did most other countries, and is now taking the final steps in the changeover.