

Temperature Scales from the early days of thermometry to the 21st century

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1. Early ideas on thermometry

Throughout the whole of recorded history, there exist descriptions of standards of mass, length and time. These are the quantities that are immediately accessible to human evaluation and for which it is easy to make either artefact standards or, in the case of time, to use the natural existing astronomical standards. For the other base quantities of today's SI, namely, temperature, electric current, amount of substance and luminous intensity, standards had to wait until the beginnings of modern science. For electric current and amount of substance, the quantities themselves were unknown while for temperature and luminous intensity, the quantities were readily accessible to human appreciation but any sort of quantitative evaluation was impossible.

At the beginning of the 17th century, very little was known about heat and temperature, most opinions at that time being based upon the writings of the Greek physician Galen (AD 129 – 200). His clinical thermometry was founded on the ideas of Aristotle and he assumed that people differed in their proportions of heat, cold, moisture and dryness. More than a thousand years later in 1578, Hasler of Bern, another physician followed Galen in ascribing various degrees of heat and cold to mixtures of drugs. To assist in their prescription, he set up a temperature scale in which there were Galen's four degrees of heat and four degrees of cold with a zero in the middle. Against this he set a scale of latitude, postulating that inhabitants of the equatorial regions have the fourth degree of heat and those of the polar regions the corresponding fourth degree of cold. Using these scales the appropriate mixtures of drugs could then be calculated depending upon where the patient lived.

At this time, there was no instrument that could be called a thermometer. Admittedly, Philo of Byzantium had made an instrument that demonstrated the expansion of air on heating but it had not been used to give an indication of temperature. The first recorded description of an instrument that could be called a thermometer was that published in 1612 by Santorio of Padua, another physician, in his Commentaries on Galen. The credit for the invention of the thermometer is, however, usually given to Galileo who is thought to have invented the air thermometer in about 1592.

The next major advance, that of using a liquid rather than air as the thermometric fluid was made in 1632 by yet another physician Jean Rey of Lyon, who used an open-ended water-in-glass thermometer. This was not a very practical device and it was Ferdinand II, Grand Duke of Tuscany, who is credited with the invention in 1641 of what we would recognize as the first real thermometer – an alcohol-in-glass thermometer. The stems of his thermometers were marked in equal fractions of the volume of the bulb. By 1654 a number of such thermometers, having 50 “degree” markings had been sent to various observers, in Parma, Milan and Bologna. Soon., such Florentine thermometers began to be made with very long coiled stems and were sensitive enough to respond a warmth breath. In 1657, according to the records of the Accademia del Cimento, experiments were made with mercury-in – glass thermometers but the conclusion was that mercury was less suitable than alcohol as a thermometric fluid. This was a pity, because with their skill in glass blowing the Florentine artisans could have developed the precision thermometer some sixty years before its eventual appearance at the hands of Fahrenheit in about 1713.

Thus, by the middle of the 17th century, sensitive thermometers had been fabricated but no serious attempt had been made to produce a universal scale. In 1661, however, a Florentine thermometer came into the hands of Robert Hooke, at that time curator of experiments of the newly created Royal Society of London for Improving Natural Knowledge – now known as the Royal Society. In 1662 the Society was permitted by Royal Charter to publish and one of the first books it published was Robert Hooke's

Micrographia. Among many other things, *Micrographia* contained a description of Hooke's thermometric scale. This was based upon marking the column of the thermometer with equal increments of volume starting at the freezing point of water. In his scale, each degree represented $1/500^{\text{th}}$ part of the volume of his thermometric liquid. It extended from -7 degrees at extreme cold to +13 degrees for the greatest summer heat. This scale was disseminated by various thermometers calibrated against an original held by the Royal Society which in turn had been calibrated by Hooke's method. This original, described by Hooke to a meeting of the Royal Society in January 1665, became known as the standard of Gresham College (where the first meetings of the Royal Society took place) and was used until 1709. It was this scale that was used in the first systematic meteorological records during the latter part of the seventeenth century. In modern parlance, these meteorological data were traceable to the standard of Gresham College! Examination of some of these records show that a remarkable consistency was obtained, temperatures measured by different people at the same time were on average within the equivalent of $1 \frac{1}{2}^{\circ}\text{C}$ and were never more than 4°C apart. This was before the births of Fahrenheit, Réaumur and Celsius and only some ten years after the first of the Florentine spirit thermometers had been brought to England!.

Fahrenheit and Amontons were the next people to make significant advances in thermometry. Fahrenheit seems to have been the first person to have learnt how to make reliable mercury-in-glass thermometers. In addition, he developed between 1708 and 1724, after discussions with the Danish astronomer Römer, the method of making a scale by taking two fixed points and dividing the interval between them into a convenient number of degrees. His scale was based on the temperature of the human body, to which he assigned a value of 96 degrees, and the freezing point of water at 32 degrees. Using this scale, published in 1724 he made measurements of the boiling points of fluids up to 600 degrees. At about the same time, the French scientist Amontons developed the constant volume gas thermometer. He used air as the thermometric fluid and found that the ratio of the greatest summer heat to greatest winter cold in Paris was approximately six is to five. He then concluded that the lowest temperature possible would be that corresponding to a zero gas pressure. He suggested that a temperature scale could be established on the basis of just one fixed point and that temperatures would be simply proportional to gas pressure.

Thus by mid eighteenth century the two aspects of thermometry that we know today had been established. On the one hand we had the development of ever more refined practical scales based on arbitrary fixed points (Fahrenheit, Celsius, Réaumur and in due course the IPTS's of the 20th century) and on the other, the parallel development of gas thermometry (Gay-Lussac, Regnault and Chappuis) and, more generally, primary thermometry upon which the practical scales came to be based.

The need today for a practical scale remains the same as it was at the time of Fahrenheit and Amontons, namely, that gas thermometry (and other primary thermometers) are complex and time consuming as well as being less precise than the practical thermometers used in everyday life, despite their measurements being more fundamental. The day that a primary thermometer is developed that is as precise as a platinum resistance thermometer and as easy to operate, there will be no further need for an International Temperature Scale. It is interesting to note that the first temperature range in which this is close to happening is the very high temperature range where absolute radiometry can match both the precision and, nearly, the ease of operation of the ITS-90 optical pyrometers.

2. The first internationally agreed temperature scale: the normal hydrogen scale of 1887.

The first task of the BIPM, created by the Metre Convention in 1875, was to acquire new international prototypes of the metre and the kilogram and a set of national prototypes of the same for distribution to Member States of the Convention. It had already been decided by the International Commission on the Metre in 1872 (the body that recommended the establishment of the BIPM) that each national prototype of the metre would be accompanied by a calibrated thermometer so that the length and temperature coefficient of the prototype metre bars could be specified and that this thermometer should be calibrated against a gas thermometer using air as the thermometric fluid. In the years

following the opening of the laboratories of the BIPM in 1884, Pierre Chappuis constructed a constant volume gas thermometer using a bulb made of Pt-Ir and studied its behaviour with nitrogen, carbon dioxide and hydrogen (but not air). He also acquired a number of high-precision mercury-in-glass thermometers. The best of these were made by Tonnelot in Paris and could be read to a few thousandths of a degree. The hydrogen gas thermometer scale that resulted from Chappuis' work was adopted by the CIPM on 15 October 1887. It was intended not only for calibrating the thermometers accompanying prototype metres but was proclaimed as the thermometric scale for general use by the "International Service of Weights and Measures". The formal definition of the scale was:

"The CIPM adopts as the standard thermometric scale for the International Service of Weights and Measures the centigrade hydrogen scale having as fixed points the temperature of pure melting ice (0 °C) and that of the vapour of distilled water (100 °C) under a standard atmospheric pressure the hydrogen being taken at an initial pressure of 1 metre, i.e., at $1000/750 = 1.3156$ of the standard atmospheric pressure.

The standard atmospheric pressure was then defined as *that represented by the weight of a column of mercury of height 760 mm having a density of 13.59593 and under a standard acceleration due to gravity itself defined as the acceleration due to gravity at the Pavillon de Breteuil divided by 1.0003322 such as to make it equivalent to the acceleration due to gravity at a latitude of 45° at sea level.*

In this way, the CIPM defined all the essential parameters necessary to realize the normal hydrogen scale to a few thousandths of a degree. It is interesting to note that the corrections to be made to the readings of the best Tonnelot thermometers amounted to about 0.11 degrees at 50 °C. The scale was valid between -25 °C and 100°C.

At the end of this session of the CIPM, a special allowance was voted to the senior scientific staff of the BIPM for the excellent work that had been carried out! Chappuis was encouraged to continue his gas thermometry to improve certain aspects of the work.

3. The period 1887 to 1927 and the origins of ITS-27

After the adoption by the CIPM in 1887 of the normal hydrogen scale, there followed a period of forty years (interrupted by the First World War for nearly ten years) during which various proposals were discussed for an internationally agreed scale for general scientific and industrial use covering a much wider range. It was well understood by the CIPM in 1887 that the normal hydrogen scale was not the thermodynamic scale but it was considered to be the closest practical approach. It was always intended that ultimately what was required would be the thermodynamic scale.

Only twelve years later, Callendar made a proposal to the British Association for the Advancement of Science at its meeting in Liverpool in 1889 for an international temperature scale extending up to the freezing point of aluminium, which he gave as 645.5 °C (cf the modern value of 660.32 °C). Callendar's scale was based on the use of a platinum resistance thermometer calibrated at the freezing point of water and the boiling points of water and sulphur which he gave as 444.5 °C (cf 444.64 °C today). He also proposed that a particular batch of platinum wire be selected from which the thermometers maintaining the scale would be made. His proposal was that this scale be called the British Association Scale. It was based on the quadratic difference formula between so-called platinum temperatures and gas thermometer temperature previously obtained at the BIPM by Chappuis and Harker (the latter from the Kew Observatory). Callendar also presented a list of secondary fixed points, the values of which mostly differed by only a few tenths of a degree from the present day values on ITS-90. It is not clear why his proposal was not taken up. Maybe because at the time the NPL had not yet been founded and the Kew observatory was busy with other things. In any event, it was not until 1911 that the next move was made.

In 1911 the Presidents of the Physikalisch Technische Reichenstalt (founded in 1887) addressed a circular letter to the Directors of the BIPM, the NPL (founded in 1901) and the Bureau of Standards (founded in 1900) suggesting that the thermodynamic scale be adopted as the international temperature scale and that its practical realization be the 1899 proposal of Callendar. Both the NPL and the NBS agreed with this proposal and went further, specifying the constants of the platinum to be used and further proposing that above the upper limit of the platinum resistance thermometer a scale be set using the optical pyrometer. At the 5th CGPM held in Paris in 1913, this initiative was strongly encouraged. The CIPM was asked to organize a meeting at the BIPM of the Directors of the national laboratories interested in this proposal to formulate a plan of work. A meeting was subsequently arranged to take place at the BIPM in November 1914 - but this was not a time when such meetings could take place. It was not until 1921 at the first meeting of the CIPM to be held after the War, that the matter was taken up again. At that time Stratton, Director of the Bureau of Standards asked the Director of the BIPM to take up the matter without delay and once again organize a meeting of interested Directors. This was agreed but the Director of the BIPM said that for the time being the BIPM would be unable to participate in future experimental work owing to the death in 1915 of Pierre Chappuis who had previously retired from the BIPM but that the BIPM would use its good offices to advance the international programme in thermometry. Unfortunately, it appears that the Director of the BIPM became too busy with other things to carry out the wishes of the CIPM and no meeting was organized despite further requests by the CIPM and at subsequent CGPMs. By 1923, when further discussions took place between the three major laboratories, they had each put into operation a scale from -38 °C to +444.5 °C. During these 1923 discussions the form of the future scale was agreed. It would comprise the platinum resistance thermometer from -38.81 °C up to the freezing point of aluminium at 650 °C and from this temperature up to 1100 °C a Pt-Rh thermocouple would be used and above 1063 °C, the freezing point of gold, an optical pyrometer using the Wien equation for extrapolation. The introduction of the thermocouple was at the request of the BS where it was felt that the upper limit of the platinum resistance thermometer should not exceed 650 °C. This was resisted at first by the NPL which preferred the original proposal of Callendar. The decision to use the thermocouple was finally overturned only some seventy years later!

The informal agreement between the three major laboratories was followed by wider discussions bringing in the BIPM and the University of Leiden, at that time the leading laboratory in low-temperature thermometry. A new draft was put to the CIPM in 1927 (still accompanied by a request for a Conference on thermometry!). This draft extended the range down to -193 °C.

The proposal put to the 7th CGPM in 1927 was essentially that agreed by the CIPM just before but it was accompanied by a clear statement that the new scale was considered to be provisional and that a Conference on thermometry should be held without delay. In fact it was planned to hold the Conference in 1928 but it did not in fact take place.

Finally, it appears that the idea of a Conference on thermometry, originating in 1913 and current throughout the 1920s was replaced towards the end of the 1930s by the idea of creating a permanent Consultative Committee for thermometry. In 1933, however, the 8th CGPM still requested that such a Conference take place by a formal Resolution (Resolution 7). The purpose of the Conference, that would be held under the auspices of the CGPM, was to ratify and make definitive the provisional ITS-27. The success of the first Consultative Committees, those for Electricity (1927) and Photometry (1933) probably led people to think that such a permanent body would be better suited to address the continuing problems of thermometry rather than a single Conference. The CIPM, in creating the CCT in 1937, gave as its mission simply the task of advising the CIPM on matters related to precision thermometry. This is of course the basic mission of every Consultative Committee in its own field.

The ITS-27 was slightly modified at the 8th CGPM in 1933, but since the modifications were considered editorial it remained the ITS-27. The next significant change did not take place until 1948.

3. The IPTS-48

The first revision of the ITS-27 took place in 1948. In this revision the only change below 0 °C was the disappearance of the extrapolation below the oxygen point to -190 °C as it had been found to be unreliable. The much more significant changes in this range did not take place until the next revision in 1968. The lower limit of the IPTS-48 was thus set at -182.97 °C. At higher temperatures, the junction between the resistance thermometer and the thermocouple was changed from 660 °C to the freezing point of antimony, 630.5 °C. This was done to rectify the strange situation in which the freezing point of aluminium had become inaccessible on ITS-27! This had arisen due to the lower calibration point of the thermocouple, the freezing point of antimony at 630.5 °C being below the lower limit of the range defined by the thermocouple. It so happened that a temperature measured with a thermocouple and found to be just below 660 °C and thus not in the thermocouple range was, when measured with a platinum resistance thermometer calibrated at 0 °C, 100 °C and 444.5 °C, found to be just above 660 °C and therefore not in the platinum resistance thermometer range either! Improvements in the manufacturing of aluminium had resulted in a small change in melting point that had shifted it into this small inaccessible range of temperature. Another change that took place in 1948 was a small increase in the temperature assigned to the silver point designed to reduce the discontinuity between the resistance thermometer and the thermocouple. In the optical pyrometer range Wien's equation was replaced by the Planck equation and the value of the second radiation constant c_2 was increased to 1.438 cm K. It was also decided to drop the name "degree centigrade" and replace it by "degree Celsius" so that all common temperature scales would have their units named after someone closely associated with them., namely, Kelvin, Celsius, Fahrenheit, Réaumur and Rankine.

The IPTS-48 became very widely used in science and industry all over the world and indeed even after it was replaced by the IPTS-68 twenty years later it took many more years before references to IPTS-48 disappeared from various texts and manuals. In some areas this was perhaps no bad thing because as we now know, in some temperature ranges IPTS-48 was a better representation of thermodynamic temperature than was IPTS-68!

4. The definition of the unit of thermodynamic temperature: the kelvin

In the twenty years following the adoption of IPTS-48, a great deal of new work in thermometry was carried out, reflecting the growth of science in general in this period. Much of it was concentrated in the low-temperature range, stimulated by the flourishing of low-temperature physics. In the high-temperature range, up to the gold point, new gas thermometry was carried out and all of this led to the need to change IPTS-48. Before this happened, however, an important change was made in 1960 to the definition of the unit of thermodynamic temperature. The 1854 proposal of Kelvin, following upon that of Amontons, was finally adopted, namely, that the unit of thermodynamic temperature should be defined in terms of the interval between the absolute zero and one fixed point. The single point chosen was the triple point of water which was assigned the temperature of exactly 0.01 degrees Kelvin above the freezing point of water, which in turn was fixed at 273.15 degrees Kelvin. This proposal had already been made in 1948 but at that time there was differences of opinion as to the temperature to be assigned to the absolute zero, whether it should be -273.15 °C or -273.16 °C. Remember that the temperature of the absolute zero had been deduced from gas thermometry mostly carried out in the 1930s based upon an interval of exactly 100 °C between the freezing and boiling points of water.

This led to the interesting situation that the degree Kelvin, unit of thermodynamic temperature, would only be identical to the International Practical Kelvin, unit of International Practical Temperature defined by IPTS-48, if the gas thermometry had been exactly right in assigning at temperature of -273.15 °C to the absolute zero. Since, formally, this could not be the case it was recognised that the definition of the unit of International Practical Temperature needed also to be changed. This took place in 1968 with the IPTS-68 in which the units of practical and thermodynamic temperatures were defined to be identical and equal to 1/273.16 of the thermodynamic temperature of

the triple point of water.. The unit itself was re-named “the Kelvin” in place of degree Kelvin and the symbol was given as K rather than °K.

There is sometimes confusion as to how thermodynamic temperatures can have the same unit as International Practical Temperatures when we know that the two temperatures cannot be identical. This is, however, perfectly consistent with quantity calculus in which we define a quantity as a number multiplied by a unit. In the case of thermodynamic temperature the quantity is thermodynamic temperature, symbol T , which is different from International Practical Temperature, symbol T_{90} but both have the same unit. In this way we can write, for example: $T - T_{90} = 5 \text{ mK}$. If T and T_{90} had different units such a relation could not be written as it would be like trying to find the difference between the distance between two points when one distance is measured in metres and the other in feet. In defining the International Temperature Scale of 1990, what we are really doing is giving the definition of a new quantity T_{90} that can be used for all practical purposes and is a close representation of thermodynamic temperature.

5. The IPTS-68 and EPT-76

The IPTS-68 was originally conceived as a modification to IPTS-48 that would deal with the problem of the units and extend the range of the scale down to the boiling point of hydrogen, near 20 K. On the basis of gas thermometry, the CCT in 1964 published a “Provisional Reference Table CCT-64 of W against T for platinum resistance thermometers in the range 12 K to 273.15 K”, known as CCT-64 for short. However, once discussions began in earnest it became clear that modifications were needed in the higher temperature ranges as well and in the end the whole scale was replaced. The new scale was in four parts: from 13.81 K, the triple point of hydrogen, to 273.15 K; from 0 °C to 630.74 °C, freezing point of antimony; from 630.74 °C to 1064.43 °C, freezing point of gold and above 1064.43 °C. The interpolation instruments were the platinum resistance thermometer up to the freezing point of antimony, then the Pt-10%Rh thermocouple up to the gold point and the optical pyrometer above the gold point.

Almost before the IPTS-68 had been adopted, studies had begun on how to improve it! During the twenty years that followed, more thermometric work was carried out than ever before. Some of these were related to measurements of thermodynamic temperature over almost the whole range of the scale some were related to the development of new fixed point cells and some were related to a particular property of scales, namely their “uniqueness”. The word uniqueness is used to indicate how well different realizations of the scale agree using different examples of the defining interpolation instruments. For example, two platinum resistance thermometers correctly calibrated at the specified fixed points according to the prescriptions of the scale will, at temperature between the fixed points give slightly different readings for the same temperature. These differences arise because no sample of platinum is exactly the same as another and thus a given interpolation equation will give slightly different results for different thermometers. The magnitude of these differences is a measure of the uniqueness of the definition of the scale.

In IPTS-68, the apparent uniqueness differences observed in a well known study at NPL carried out by Compton and Ward were as much as 10 mK in the range below 250 K. This was not considered satisfactory. It was soon realized, however, that these differences were in fact due mostly to differences in the realization of the low-temperature fixed points of IPTS-68 and that the non-uniqueness of the scale itself did not exceed about 1.5 mK in any part of the range. The introduction of sealed triple point cells for the realization of the low temperature points much improved the situation.

There was a need for an internationally agreed scale below the lower limit of IPTS-68. To meet this, a provisional scale was adopted in 1976 known as the 1976 Provisional 0.5 to 30 K temperature Scale, EPT-76. This was based on a set of specified pre-existing gas, acoustic, vapour pressure, magnetic temperature scales that had been developed over a number of years, as well as on IPTS-68 in the part where it overlapped IPTS-68, plus a set of fixed points having defined temperatures. It was recognized that EPT-76 was a preparatory scale to what was hoped at the time would be a new International

temperature Scale that would be adopted in the about 1980. In fact the huge amount of work that finally went into the preparation of the next scale delayed its adoption by another ten years.

During the preparation of the new scale in the 1980s, the thermometry community had become quite large. Meetings of the CCT were taking place annually and the demands for rigour in setting up a temperature scale were growing. In addition, measurements made by gas, acoustic and total radiation thermometry confirmed that there were significant differences between T_{68} and T even in the room temperature range. It had become clear that the temperature that had been assigned to the absolute zero of $-273.15\text{ }^{\circ}\text{C}$ had been in error and that to be consistent with the fundamental interval of $100\text{ }^{\circ}\text{C}$ exactly between the freezing and boiling points of water a value of $-273.22\text{ }^{\circ}\text{C}$ would have been required. It was too late to change the definition of the Kelvin (although this possibility was briefly discussed at a meeting of the CCT) so the consequence was that the temperature of the boiling point of water would have to be changed from $100\text{ }^{\circ}\text{C}$ to something like $99.975\text{ }^{\circ}\text{C}$. In fact, the boiling point of water would no longer be a defining point of the scale but its value and that of the fixed points above and below would have to be changed to reflect these differences between T_{68} and T .

In addition to the work on IPTS-68 itself, a great deal of work was also done to bring up to date compendia of thermocouple tables as well as thermophysical data, and many of these were published in the 1970s and 80s.

6. ITS-90 and PLTS-2000

The ITS-90 came into effect on 1 January 1990 and was the fifth international temperature scale to be adopted by the CIPM. It replaced IPTS-68 and EPT-76. It included the differences between ITS-90 and EPT-76 and between ITS-90 and IPTS-68 given as Tables of the differences $T_{90}-T_{76}$ and $T_{90}-T_{68}$ and $t_{90}-t_{68}$.

The ITS-90 differs in a number of important respects from IPTS-68 and previous scales:

- it extends to lower temperatures, 0.65 K instead of 13.81 K, and hence replaces EPT-76;
- it is in closer agreement with thermodynamic temperatures;
- it has improved continuity and precision;
- it has a number of overlapping ranges and sub-ranges;
- in certain ranges it has alternative but substantially equivalent definitions;
- it includes the 1958 ^4He and 1962 ^3He helium vapour pressure scales;
- it includes an interpolating gas thermometer as one of the defining instruments;
- the range of the platinum resistance thermometer as defining instrument has been extended from $630\text{ }^{\circ}\text{C}$ up to the silver point;
- the Pt-10%Rh thermocouple is no longer a defining instrument of the scale;
- the range based on the Planck radiation law begins at the silver point instead of the gold point but options exist for using any one of the silver, gold or copper points as reference points for this part of the scale.

One of the guiding principles adopted by the CCT, under its President Hugh Preston-Thomas, in drawing up ITS-90 was that it should allow the user as much choice in its realization as was compatible with an accurate and reproducible scale. For this reason, the scale includes many sub-ranges; all except one of these can be realized without requiring a fixed point outside the sub-range. For example, room temperatures can be covered by a sub-range that requires calibration of a platinum resistance thermometer only at the triple point of water and at the melting point of gallium $29.7646\text{ }^{\circ}\text{C}$. To cover temperatures just below $0\text{ }^{\circ}\text{C}$ there is a range from the triple point of mercury at $-38.834\text{ }^{\circ}\text{C}$ to the gallium point where calibration at just these three fixed points is required. This is much more convenient than in previous scales.

The CCT also prepared two supporting documents: The *Supplementary Information for the ITS-90* and “*Techniques for Approximating the ITS-90*”. These documents were published by the BIPM shortly

after the adoption of the new scale. It is planned that they be periodically updated and work is underway in this respect at the present time.

The process of preparing and finalizing the text of the ITS-90 was undertaken by four Working Groups of the CCT:

Working Group 1: Preparation of the text of the ITS-90 and revision of the *Supplementary Information for the ITS-90* (Chairman, the President of the CCT);

Working Group 2: Completion of the document *Techniques for Approximating the ITS-90* (Chairman Ron Bedford, NRC Ottawa)

Working Group 3: Platinum resistance thermometer range of the ITS-90 (Chairman Luigi Crovini, IMGC Turin);

Working Group 4: Values of $T_{90} - T_{68}$ and the gas thermometer range of the ITS-90 (chairman Ralph Hudson, formerly NIST Washington).

In the months before the meeting of the CCT in September 1989, an additional, *ad-hoc* Working Group made up of the Chairmen of the four Working groups plus a small number of other people, was formed to produce the final drafts of the text of the scale. During the meeting itself this Working Group continued to meet outside the sessions for the same purpose. This 17th meeting of the CCT was undoubtedly the most productive meeting of the Committee that had ever taken place. The whole text of the new scale was reviewed line by line, important scientific discussions took place on many facets of the scale including values to be adopted of the fixed points, ranges and sub-ranges of the scale and interpolation equations. Between sessions on successive days, calculations or simulations were made overnight at the NRC Ottawa and communicated by fax (these were in the days before e-mail!).

Experience since 1990 has fully justified the work that went into preparing the scale, both at the 17th meeting and in the months and years before. It stands as a tribute to all those who contributed and to Hugh Preston-Thomas under whose firm guidance a Scale was finally produced. Very few changes would be made today to the 1990 text and it is a fine example of the best in international cooperation and a high point in thermometry. When the time comes to revise ITS-90, it is most unlikely that any significant changes will be made other than to extend it to lower temperatures by incorporating the provisional low temperature extension adopted by the CIPM in 2000, PLTS-2000 (see below). Other changes might be corrections to values of the temperatures assigned to the fixed points as determinations of thermodynamic temperature improve. Here there are already indications that in the temperature range just below room temperature corrections may have to be made. A further possibility is the abandonment of the optical pyrometer range altogether because absolute radiometry can now do an equivalent or even better job in this range (see below) but this would in no way be a correction to made to the 1989 decisions of the CCT.

While ITS-90 extends to significantly lower temperatures than previous scales, it still did not extend to the millikelvin range. Considerable work had been done to establish a temperature scale down to below 10 mK using helium melting point thermometry and magnetic and nuclear orientation thermometry. The melting pressure of ³He was chosen as the property on which the extension of ITS-90 should be based because (here I quote the text of the scale) “.. of the sensitivity and reliability with which it may be measured over a wide range (covering more than three decades of temperature) apart from a narrow region around the pressure minimum at 1315.24 mK. The pressure minimum itself has the compensating advantage of providing a convenient pressure fixed point for calibrating the pressure transducer (the pressure must be measured using a transducer in-situ because for temperatures below the minimum a sensing line will be blocked with solid ³He and the cell is therefore isolated)..”

Among other features of the scale are the fixed points which, in addition to the pressure minimum, are the transition to the superfluid A phase, the A to B transition in the superfluid and the Néel transition in the solid. The scale extends from 0.9 mK to 1 K. It is estimated that the uncertainty in terms of

thermodynamic temperature is 0.5 mK down to 500 mK and then decreases linearly to 0.2 mK at 100 mK. It decrease further with falling temperature but in percentage terms it increase to about 0.3% of T at 25 mK and 2% of T at 0.9 mK. The scale is designed to be of use primarily to the low-temperature physics community.

7. Final remarks.

The story of temperature scales will never end but it will change. New discoveries in physics and new technologies will lead to novel ways of measuring temperature. We have already seen that the introduction of absolute radiometry based on the cryogenic radiometer has opened the way to direct radiometric ways of measuring high temperatures. In the 1990s a joint CCT/CCPR working group was established to examine the question. This has now been replaced by Working Group 5 of the CCT which has already produced extensive discussion documents on the subject. It is clear that direct measurements of thermodynamic temperature can now be made by absolute radiometry having a lower uncertainty than those that can be obtained using ITS-90. At the highest levels of accuracy neither method is particularly simple but the direct absolute radiometry has equivalent or better precision than the ITS-90 method and this is the key to a future abandonment of the International Scale in this range.

The practical realization of ITS-90 is not a simple process, it is time consuming and requires a high degree of skill to reach the smallest uncertainties. This will always be the case, since measurements of the highest accuracy by their very nature require high expertise and the most modern equipment. The existence of commercially available fixed-point cells is of great help, not only to national metrology institutes but also to users as they allow easy check measurements to be carried out. They do not, however, absolve users from the need to have calibrations from a national metrology institute or properly accredited calibration laboratory to provide formal traceability to ITS-90 and the world's measurement system. No NMI purely by itself these days would be recognized if it was not part of the CIPM MRA and did not take part in appropriate key comparisons. In the same way, a demanding user of thermometry cannot expect to have its measurements recognized without appropriate calibrations or, in the case of some fixed points, comparisons that link it to the national and international traceability chain.

The recent emphasis on traceability of measurement results will reinforce the need for international comparisons of temperature measurements. The recent difficulties encountered by the CCT in reaching satisfactory conclusions in this area must be overcome otherwise the users of thermometry will not be well served.

The decision of the CIPM in 1937 to create the CCT has turned out to be fully justified and over many years it has served the thermometry community well. It is important that this continue.