

Physics as a Calling, Science for Society

Studies in Honour of A.J. Kox

Edited by

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The publication of this book has been made possible by grants from the Institute for Theoretical Physics of the University of Amsterdam, Stichting Pieter Zeemanfonds, Stichting Physica and the Einstein Papers Project at the California Institute of Technology.

Leiden University Press English-language titles are distributed in the US and Canada by the University of Chicago Press.

Cover illustration: Albert Einstein and Hendrik Antoon Lorentz, photographed by Paul Ehrenfest in front of his home in Leiden in 1921. Source: Museum Boerhaave, Leiden.

Cover design: Sander Pinkse Boekproducties
Layout: JAPES, Amsterdam

ISBN 978 90 8728 198 4
e-ISBN 978 94 0060 156 7 (pdf)
e-ISBN 978 94 0060 157 4 (e-pub)
NUR 680

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8 Much ado about cold: Leiden's resistance to the International Temperature Scale of 1927

Dirk van Delft

On 4 October 1927, the 7th *Conférence Générale des Poids et Mesures* (7th General Conference on Weights and Measures), gathered in Sèvres, just outside Paris, implemented the International Temperature Scale. Prior to this decision, prolonged discussions regarding low-temperature research had taken place between the national calibration laboratories of the United States, the United Kingdom and Germany, the *Bureau International des Poids et Mesures* (International Bureau on Weights and Measures) in Sèvres and the Cryogenics Laboratory in Leiden. The research laboratories had diverse interests since they used different temperature scales with their associated problems, while at the calibration laboratories there was a strong desire for practical and simple thermometers that could be read quickly.

The calibration institutes, which had already called for an accurate, usable temperature scale before the First World War, had insisted upon the replacement of the scale that was introduced in 1887 and they were satisfied with the agreement. The platinum resistance thermometer was the basis for the new scale for the region between -190 and 600 °C, a thermocouple determined temperatures between 600 and 1063 °C (the melting point of gold), and for still higher temperatures an optical pyrometer determined temperatures on the basis of radiation laws. An important reason for introducing a new scale was the failure at high temperatures of the gas thermometer, a fundamental instrument of the old temperature scale. Industry presented a strong case for improvements.

In Leiden, the Cryogenics Laboratory was specialized in extremely low temperatures and from that point of view the new scale was open to criticism. The Director of the laboratory, Willem Hendrik Keesom, was loud and clear about this. In the *Comptes Rendus* of the 7th *Conférence Générale* (Proceedings of the 7th General Conference) the text on the International Temperature Scale, including specifications and procedures, was immediately followed by a somewhat grumpy commentary in which the Director of the Cryogenics Laboratory objected to the new scale on a number of technical points. This addition to the official text is striking:

in 1927 the Netherlands was not yet a member of the Metre Convention – quite a separate story – and was therefore notably absent in Paris. What was going on here? How did this exceptional opportunity arise for Leiden to air criticism?

Several authors¹ have described the history of thermometry. However, the long and difficult path to the International Temperature Scale of 1927 is an episode from the history of metrology that science historians have, until now, only explained in a fragmentary or cursory manner. Most of the work so far has been done by employees of the Bureau des Poids et Mesures. J.A. Hall, for example, who began to work at the National Physical Laboratory (the British calibration institute) in 1923, but who was later employed by the Bureau des Poids et Mesures in Sèvres, published several articles in the 1960s detailing the early history of practical international temperature scales.² More recently, in 2006, Terry Quinn, a former Director of the Bureau des Poids et Mesures, published a concise historical overview of thermometry in the broader context of an extensive book review.³

This chapter is an attempt to bridge the observed gaps in knowledge by placing in a broader context the developments that occurred internationally in the area of thermometry between 1880 and 1930. Particular attention is given to aspects of the low temperature region, for which good use was made of the Keesom Archive, which is largely housed in Museum Boerhaave in Leiden.

The most striking aspect of the developments leading up to the International Temperature Scale of 1927 is the long period that elapsed between the emergence of the platinum resistance thermometer as the basis for a temperature scale, in 1886, and the official establishment of such a scale in 1927. Why did it take forty years? This is all the more striking since, at the same time, long-term metrological cooperation developed between the United Kingdom, Germany, the United States and France and quite soon after the First World War the parties were already once again debating metrological issues. Another question that merits further study is the tension in the first quarter of the twentieth century between the increasingly strong, industrially focused national calibration institutes, led by the American Bureau of Standards, and a laboratory for fundamental research such as the Cryogenics Laboratory in Leiden. What fundamental objections were raised in Leiden? Did the calibration institutes still have an eye for science? Did Leiden's criticism of the International Temperature Scale make its mark? Why was the scale introduced provisionally in 1927? And were there possibilities for reconciliation with Leiden?

The international hydrogen scale

The first international temperature scale was the 'normal hydrogen scale', introduced at the *Conférence Générale des Poids et Mesures* of 1889 after thorough preparatory experimental work by Pierre Chappuis of the *Bureau International des Poids et Mesures*. Ten years earlier, in Paris, nineteen countries had signed

the Metre Convention, a series of agreements about units such as the standard metre and the standard kilogram. The Netherlands was not one of the signatories.⁴ A direct outcome of the Convention was the establishment of the Bureau International des Poids et Mesures, housed in the Pavillon de Breteuil in Sèvres. The Bureau International des Poids et Mesures opened its doors in 1884 and carried out high-quality metrological research. It was supervised by the Comité International des Poids et Mesures, which met yearly and whose members were drawn from representatives of the member states of the Metre Convention. One of the first tasks of the Bureau International des Poids et Mesures was the production of an international standard metre, as well as copies for the affiliated member states. Calibrated accurate thermometers were needed to monitor the constant temperature of the metres. These calibrations needed to be performed by using one and the same gas thermometer – for which hydrogen was chosen – after which the participating countries would receive their national standard metre with its calibrated mercury thermometer.

At the Bureau International des Poids et Mesures, Pierre Chappuis was responsible for this wide ranging and meticulous task.⁵ He calibrated the *verre dur* (hard glass) high-precision mercury thermometers – produced by the Paris instrument maker Tonnelot – against a constant-volume gas thermometer with a one-litre tubular reservoir made of platinum-iridium, 1.10 metres in length and with an outer diameter of 3.6 cm. This gas thermometer was filled first with nitrogen, then with carbon dioxide, and finally with hydrogen. These measurement series resulted in the so-called ‘normal hydrogen scale’ with melting ice (0 °C) and boiling water (100 °C) as its two fixed points.⁶ The range remained limited to the interval between -24 and 100 °C and the reproducibility was 0.01 °C. The normal hydrogen scale gave rise to corrections to the Tonnelot mercury thermometers up to a maximum of 0.11 °C at 50 °C. On 15 October 1887 the normal hydrogen scale was adopted as the first international temperature scale at the annual meeting of the Comité International in Sèvres, and two years later it was officially implemented at the 1st Conference Internationale des Poids et Mesures.

After the departure of Chappuis in 1902, Charles-Édouard Guillaume became Deputy Director of the Bureau International des Poids et Mesures and in 1915 he was appointed Director.

Resistance thermometers

The gas thermometer is an accurate and reliable – though laborious – instrument if it is used correctly. Its use has certain disadvantages, though, particularly at high temperatures. Above 500 °C, the expansion of the reservoir creates problems and the purity of the gas that is used also suffers under these conditions. For this reason, alternatives were welcome. One of these alternatives is the resistance thermometer, which makes use of the fact that in metals the electrical resistance is

dependent on temperature. This effect that had already been discovered in 1821 by Humphrey Davy, who was, at the time, the Director of the Royal Institution in London. Wilhelm (William) Siemens, who had moved to London as a boy of nineteen and had made a considerable name for himself in the field of electrical engineering – transatlantic cables for telegraphy – subsequently launched the idea for a resistance thermometer in 1861. In a letter to John Tyndall, entitled ‘On a New Resistance Thermometer’ published in the *Philosophical Magazine*, Siemens describes how he had best resort ‘to an instrument based upon the well-ascertained fact that the conductivity of copper wire increases in a simple ratio inversely with its temperature’.⁷ Siemens had thought of a rod, around which a copper wire was coiled, connected to a battery in series with a galvanometer. He returned to this idea in 1871, in his Bakerian Lecture for the Royal Society, where he presented the case for the platinum thermometer.⁸ Siemens stated that the advantages of this thermometer were its wide temperature range and the possibility to accurately determine temperatures in difficult locations, such as ovens, which until that time had in effect remained out of reach.

The British Association Scale

It was not until 1885, two years after Siemens’ death, that the platinum thermometer came on the scene again. Hugh Longbourne Callendar, who had just started as a student at the Cavendish Laboratory in Cambridge, was given the temperature dependence of platinum as a research project by his Director J.J. Thomson. The experimentally gifted Callendar enthusiastically went to work and concluded that there was nothing wrong with the principle of the platinum thermometer, although its experimental realization required considerable accuracy. In particular, the presence of contaminants in the metal and mechanical forces on the wire quickly put a spanner in the works. In June 1886, Callendar presented his findings at a meeting of the Royal Society, and a year later he published an extensive article – which was also his dissertation – in the *Transactions*.⁹ In this publication, he presented a case for the platinum thermometer as an international standard for temperatures up to 1200 °C, or even higher. In the opening sentence of his paper Callendar comes straight to the point: ‘In view of the enormous discrepancies at present in estimates of high temperatures, it is exceedingly desirable that strictly comparable thermometric standards should be issued by some recognized authority’.

In 1899, as a member of the Electrical Standards Committee of the British Association, Callendar wrote a proposal for a new temperature scale based on the platinum thermometer. The document, which was circulated in advance, was discussed at the annual meeting in Dover.¹⁰ After an explanation by Callendar about the ‘British Association Scale’, as he had named his standard, the discussion was initiated by J.A. Harker of Kew Observatory, who had recently been appointed as

assistant at the National Physical Laboratory that had opened its doors in 1900, and Pierre Chappuis the man of the normal hydrogen scale of the Bureau International des Poids et Mesures. Harker and Chappuis had compared the platinum resistance thermometer with the hydrogen gas thermometer of the Bureau International des Poids et Mesures and had found no difference in its temperature readings within the set limits of accuracy. They had also shown that a platinum thermometer could be repeatedly heated to 1000 °C over a period of three months without the resistance showing any noticeable deviation.¹¹

Callendar considered the platinum thermometer to be a superb replacement of a gas thermometer, as its resistance can be accurately measured and is quadratically dependent on the temperature. Any possible slight difference with Kelvin's theoretical thermodynamic scale could always be dealt with in the future by means of corrections. Callendar stated that for platinum it was desirable to choose a certain type of wire of very high purity, coiled around a mica plate. As a third calibration point, in addition to melting ice and boiling water, he proposed the boiling point of sulphur, for which he had measured a temperature of 444.53 °C.¹² The Electrical Standards Committee of the British Association considered Callendar's proposal in the spring of 1900. The outcome of that deliberation was that Callendar was commissioned to produce a series of platinum thermometers for the new standard.

National calibration institutes

During the last decades of the nineteenth Century – a time of rapid internationalization of science and technology and increasing ties between scientific research and industrial enterprise – the need for standardization became urgent.¹³ Under the influence of a growing demand by industry and government for reliable units and well-calibrated instruments, Germany, the United Kingdom and United States decided to set up national calibration institutes at the end of the nineteenth century. Although the focus was on practical applications, there was – certainly in the early days – clearly room for fundamental research. In 1887, three years after the opening of the Bureau International des Poids et Mesures in Sèvres, the Germans start the ball rolling with their *Physikalisch-Technische Reichsanstalt* (Physical Technical Imperial Institute) in the Berlin suburb of Charlottenburg. The founding fathers were Werner von Siemens, who had made his name in the electrical engineering industry, and Hermann von Helmholtz, a physicist at the University of Berlin and the first director of the *Physikalisch-Technische Reichsanstalt*. They clearly also wanted to use the new institute for 'pure research'.¹⁴ In 1899, the British founded their National Physical Laboratory, which opened its doors in Teddington in 1902.¹⁵ Finally, the American National Bureau of Standards was founded in 1901 and was set up in Washington.¹⁶ Most of the research into the

applicability of the platinum thermometer took place in Charlottenburg, so it was the Physikalisch-Technische Reichsanstalt that took the lead in 1911.

The cryogenics laboratory of Heike Kamerlingh Onnes

Heike Kamerlingh Onnes, the first Director of the Leiden Physical Laboratory, together with his successor Keesom and Guillaume from the Bureau International des Poids et Mesures, led the camp of the 'objectors' in the period preceding the establishment of the International Temperature scale of 1927. Kamerlingh Onnes, appointed in Leiden in 1882, had set himself the ambitious goal of subjecting the molecular theories of his compatriot J.D. van der Waals to accurate experimental tests.¹⁷ As substances with a simple atomic structure only become liquid at extremely low temperatures, Kamerlingh Onnes felt the need to build a cryogenics laboratory in Leiden. He became the first person to produce liquid helium at four degrees from absolute zero, in 1908. In 1925, Walther Meissner from the Physikalisch-Technische Reichsanstalt also managed to 'conquer' the 'last of the permanent gases', and in 1931, the Bureau of Standards became the first institution in the United States to produce liquid helium.

Thermometry received considerable attention in Leiden: the goal was to reach an accuracy of 0.01 °C. In his in-house journal *Communications from the Physical Laboratory at the University of Leiden*, Kamerlingh Onnes published a series of 32 articles under the collective title 'On the measurement of very low temperatures' between 1896 and 1925. Article number 1 in the series was published in 1896 and discussed the two hydrogen gas thermometers that were built in Leiden.¹⁸ The necessary corrections included the shrinkage of the glass upon cooling.¹⁹ In practice, hydrogen and helium gas were not ideal for the purpose. Extra corrections were required, which were dictated by the position of the hydrogen and helium isotherms.

Meanwhile in Leiden considerable expertise had been developed with thermometers constructed from metal wire. The first results date from 1902, when B. Meilink tested a platinum thermometer for continuity.²⁰ In a subsequent publication, Meilink established that, down to -180 °C, Callendar's measuring points could be captured with a second degree function of the resistance against the temperature, but the accuracy then remained limited to 0.2 °C.²¹ According to Meilink, an accuracy of 0.05 °C required six, and not three, fixed calibration points. In the period 1906-1908 Jacob Clay and Kamerlingh Onnes extended the measurements on gold and platinum down to the liquid hydrogen range. They also tested other metals and alloys for theoretical reasons.²² The only problem with platinum or gold thermometers was their sensitivity to contaminants. The necessary wires were drawn by Heraeus from Hanau and eventually it transpired that this German instrument company introduced contaminants into the metal while producing the wires.

Association Internationale du Froid

The final actor in this international thermometry story was the Association Internationale du Froid.²³ It was founded in Paris on 25 January 1909, in the presence of delegates from 35 countries. Kamerlingh Onnes was elected to the Central Committee and also became chair of the 'First Committee', which would concern itself with scientific matters. One of the first problems that the First Committee considered was the lack of uniformity of units in the cold industry. Guillaume, the driving force behind the report, and Kamerlingh Onnes called for cold technology on the basis of thermodynamics. They called upon the industry to make sure that cold technology did not become isolated from its scientific roots.²⁴

Initiative for a new temperature scale

When, in November 1911, President Emil Warburg of the Physikalisch-Technische Reichsanstalt wrote to his colleagues, Richard Glazebrook of the British National Physical Laboratory, Samuel Stratton of the American Bureau of Standards, and Charles-Édouard Guillaume of the Bureau International du Poids et Mesures, to reach an agreement about a new temperature scale. Twelve years had passed since Hugh Callendar's 1899 proposal for a British Association Scale on the basis of the platinum thermometer. Nobody disputed the fact that the only correct scale was Kelvin's absolute temperature scale. However, the question was how that thermodynamic scale, in which the melting point of water was set at 0 °C and the boiling point of water at 100 °C, could best be approached in practice: by means of the gas thermometer or the platinum thermometer? Later it transpired that there were fundamental differences of opinion about this issue and that the three calibration institutes favoured the resistance thermometer, whereas the Bureau International des Poids et Mesures, the Association Internationale du Froid and Leiden preferred the gas thermometer.

There was an overwhelming need for a new temperature scale. The normal hydrogen scale of 1887, with its link to mercury thermometers, was only valid from -24 to 100 °C, and industry in particular was desperate for a temperature scale that could also adequately measure the higher and lower temperature ranges. Only then would the measured value of the boiling point of liquid oxygen or the melting point of gold in the United States not differ from that in France or the Netherlands. The conditions for an international initiative were favourable. The contacts between the national calibration institutes were good, the interests ran parallel, for the most part, and the cooperation was fruitful.²⁵ The problem lay in the mixing of fundamental scientific with technical-industrial interests, which had won considerable ground since the founding of the calibration institutes. Within the calibration institutes, this shift in emphasis also played a role. In the early years of the twentieth century, the academic departments of these insti-

tutions – which had been established at their founding – came under considerable pressure, as a result of the increasing number of practical commissions the staff had to deal with. For that reason, a pragmatic view was expedient under the circumstances.

The dissatisfaction with the situation is strikingly apparent in an internal memorandum from the Bureau of Standards of February 1911, written by researcher George K. Burgess to his Director, Samuel Stratton.

The desirability of inaugurating international agreement and co-operation in establishing and maintaining a well-defined, sufficiently exact, reproducible and common temperature scale and other thermal constants, merits the systematic attention of the several national standardizing laboratories. Such agreement among the several countries as now exists as to thermal scales and constants is largely accidental and haphazard, and the resulting condition of affairs in certain realms of the domain of heat is far from satisfactory.²⁶

Similar feelings were prevalent elsewhere and in November of that same year, the Physikalisch-Technische Reichsanstalt took the initiative Burgess had hoped for. In his letter, Warburg proposed the selection of Kelvin's thermodynamic scale as the fundamental temperature scale. He noted that the differences in the range of 0 to 100 °C fell within the measurement errors for the normal hydrogen scale and were therefore not a point of concern. Warburg suggested establishing a scale for the broader range of 0 to 450 °C, by means of a platinum thermometer in combination with a series of fixed calibration points and further a formula for interpolation – exactly as Callendar had previously proposed in 1899.²⁷ The idea fell on fertile ground at the Bureau of Standards and the National Physical Laboratory, while the Americans came with additional ideas and with proposals for specifications of the platinum wire in March 1913.²⁸ The platinum thermometer, according to Burgess, was 'the most satisfactory secondary standard for the calibration of all other types of thermometers between -200 and +1100 °C. In fact, if the International Bureau were destroyed and all the existing copies of its thermometer standards as well, the international scale would be perpetuated with entire satisfaction by means of the platinum thermometer which may be constructed and calibrated independently anywhere it may be desired.' He further commented that 'Both at low temperatures and high, there have been almost as many scales as observers, and some of the outstanding differences were relatively very large.' Upon reading this last comment, Charles-Édouard Guillaume – who became Deputy Director of the Bureau International des Poids et Mesures after Chappuis' departure in 1902 and later (in 1915) its Director – probably raised his eyebrows.

The amendments to the Physikalisch-Technische Reichsanstalt initiative proposed by the Americans included the extension of the platinum scale to -100 °C on the cold side and to +1100 °C on the hot side. Above that temperature, radia-

tion methods (optical pyrometers) would have to take over, by means of which the melting point of gold would be set as the calibration point at 1063 °C. After consultations with the calibration laboratories in London and the Cryogenics Laboratory in Leiden with respect to the cold side of the scale, the Reichsanstalt came up with a modified proposal in April 1913. It covered the range from 0 to 1100 °C, keeping what fell outside that range for a later consultation and leaving the method of interpolation between the jointly agreed series of fixed calibration points and the choice of the formulas to be applied up to the individual laboratories: a weak position from an international standpoint.²⁹ For the values of the calibration points, an international mean was chosen, based on the most accurate determinations.

The next step was a meeting between the directors of the three calibration laboratories planned for 25 September 1914 in Berlin. That meeting did not take place because of the outbreak of the First World War, but in preparation for it the Bureau of Standards proposed to limit the platinum thermometer to a range between -38.88 °C (the freezing point of mercury) and 444.5 °C (the boiling point of sulphur), and to slightly relax the requirements for the purity of the platinum wire.³⁰ The proposal also contained a new series of calibration points, from the boiling point of oxygen to the melting point of copper.

The attitude of the Bureau

How did the Bureau International du Poids et Mesures respond to Emile Warburg's letter? The contact person in Sèvres was Deputy Director Guillaume. In the period preceding the 5th Conférence Générale, in October 1913, he produced a progress report entitled *Les récents progrès du système métrique*³¹ (Recent progress in the metric system). Guillaume observed that there was still no adequate solution for the area of thermometry. First an agreement should be reached about an unequivocal correction table to convert the various types of gas thermometers to the absolute scale. According to Guillaume, the majority of the physicists who had worked with the platinum thermometer recognized that the melting point of ice and the boiling point of water, together with the boiling point of sulphur, completed the formula required for temperature determinations. However, for very low temperatures another formula was needed. The platinum thermometer could certainly be interesting for the future but, for the time being, efforts should be devoted to improving gas thermometers, especially the helium thermometer.

In the proceedings of the Conférence Générale Guillaume made two recommendations. The first one was for research into the various gas thermometers and their conversion to the absolute scale. The second was an international partnership for setting up a series of calibration points, spread across the entire experimentally accessible range of the temperature scale. At the initiative of Stratton, the Director of the American Bureau of Standards, who was one of the

delegates, the meeting in Paris accepted a resolution to set a series of calibration points. The Bureau International des Poids et Mesures was commissioned to organize an international meeting with the Directors of the national laboratories in the near future.³² The results of this conference, to be held in Sèvres, would be discussed at the meeting of the Comité International in November 1914. However, things never got that far: the First World War put a temporary hold on things.

Leiden and the Association

Within the Association Internationale du Froid there were also discussions about the temperature scale. At the 3rd International Cold Congress, held in the autumn of 1913 in Washington and Chicago, the First Committee presented a preliminary study (*avant-projet*) about low-temperature thermometry, which gave the gas thermometer centre stage. An excerpt of the report appeared in the *Travaux et Mémoires* (Studies and Memoirs) of the Bureau International des Poids et Mesures.³³ According to this report, the fundamental starting point of science and industry was Kelvin's thermodynamic scale, which was based on the ideal Carnot cycle. Previously, Guillaume had called for this scale to be used in an Association report about cold units. Kamerlingh Onnes, the Director of the Leiden Cryogenic Laboratory, and Guillaume, the prospective Director of the BIPM, maintained close contact via the Association and with respect to thermometry they were of one mind.

The report gave a detailed resume of the use of the gas thermometer and stated that helium was the best choice at low temperatures. Much attention was given to corrections on the gas thermometer. At the end of the report, which mainly described the situation in Leiden, the fixed calibration points and the platinum thermometer were also considered. Regarding the formula of the platinum thermometer for the low-temperature area, Kamerlingh Onnes noted that this was 'complex' and that a simple polynomial did not provide the required accuracy. According to him, resistance thermometers deserved full attention but then within the context of accurately determining the size of the corrections on the gas thermometer.

The war and the postwar years

The outbreak of the First World War put a stop to all international consultations and long after the Versailles Treaty (1919) official meetings in the presence of Germans were still very sensitive. For the International Temperature Scale, the war was an annoying break: the hostilities started little more than a month before the decisive conference in Sèvres. In practice, the Bureau of Standards, the National Physical Laboratory and the Physikalisch-Technische Reichsanstalt implemented the latest proposal of the Americans in anticipation of better times: a

platinum thermometer for the region between -40 and 450 °C, and, above that, calibration points up to the freezing point of copper (1083 °C) in combination with some form of interpolation.³⁴ The Germans were the first to implement a temperature scale based on these new ideas. In December 1915, its Director Warburg officially announced that the Physikalisch-Technische Reichsanstalt would switch to a new temperature scale for its calibrations.

After Versailles, the Germans were no longer permitted to take the lead and the Bureau of Standards took on the final leading role. During the second postwar meeting of the Comité International, in October 1921, Stratton returned to the resolutions adopted in 1913, including the call by Guillaume and his Bureau International des Poids et Mesures for the organization of an international thermometry conference. The Comité commissioned the Bureau to contact the national institutes. However, Guillaume did not make much progress with the coordination,³⁵ so the Americans took the initiative themselves. At the end of September 1923, Hobert C. Dickinson, who had just been appointed as Head of the Heat and Power Department of the Bureau of Standards, came to Europe for consultations with all parties concerned. The endgame of the development of the International Temperature Scale had begun.

Dickinson started his tour in Leiden. Kamerlingh Onnes established immediately that research in that area fell under the auspices of the First Committee of the *Association Internationale du Froid* (International Association on Cold).³⁶ The gentlemen discussed the fine details of gas thermometry in relation to the thermodynamic scale, after which Dickinson brought up the subject of platinum thermometers. According to the American, these 'could be used with greater accuracy than gas thermometers' and gave results that were 'far more easily reproduced', whereas only a few calibration points were needed.

Dickinson then made a brief visit to the Physikalisch-Technische Reichsanstalt for a meeting with Director Walther Nernst – who had succeeded Emil Warburg in 1922 – and with Friedrich Henning, one of the most important researchers within the Physikalisch-Technische Reichsanstalt in the area of thermometry. At the meeting they discussed a new proposal for the international temperature scale. The following division was agreed upon:

- I. From -38.88 to 650 °C: based on the platinum thermometer with the Callendar formula, calibrated using the melting point of ice, the boiling point of water and the boiling point of sulphur (444.60 °C was taken as the value).
- II. From 650 to 1100 °C: based on a platinum/platinum-rhodium thermocouple, calibrated by using the melting points of zinc, antimony, silver and gold.
- III. Above 1100 °C: radiometric basis using Wien's Law. The starting point was the brightness of black bodies at the melting point of gold. The brightness was measured by using an optical pyrometer.³⁷

The only remaining region was the one below $-40\text{ }^{\circ}\text{C}$. On 28 September, Dickinson was back in Leiden. He agreed with Kamerlingh Onnes to hold a small international conference in Leiden, starting on 5 October, about how to cover the low temperature scale, to which Henning would also be invited.³⁸ Guillaume agreed to the American-Dutch proposal and, in his role as coordinator, he promised Dickinson that he would contact the calibration institutes. The mini-conference in Leiden mainly discussed the use of the platinum thermometer. Henning and Kamerlingh Onnes doubted whether a limited number of calibration points, as proposed by Dickinson, would be sufficient.³⁹

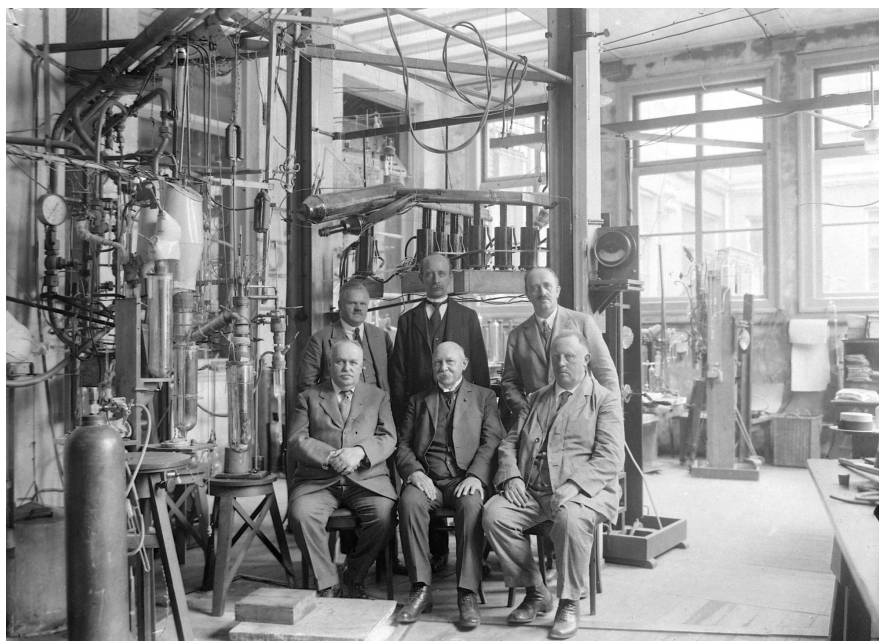


Fig.1 – Kamerlingh Onnes, sitting in the middle, and Keesom next to him on the right in the Leiden laboratory. Source: Leiden Institute of Physics

Meanwhile, Leiden and the Physikalisch-Technische Reichsanstalt were using different temperature scales. In 1914, at a time when Nernst and his staff in Berlin were acclaimed for their groundbreaking specific heat measurements, Keesom – who had been trumped by Berlin – contested the accuracy of the platinum thermometer used by the Germans.⁴⁰ Nernst tersely rejected this claim,⁴¹ but the observation in Leiden that the Leiden and Berlin scales differed by 0.06 degrees at a temperature of about $-50\text{ }^{\circ}\text{C}$, whereas the accuracy of the Leiden platinum thermometer was at least 0.02 degrees, did of course require further investigation. Such further investigation did indeed confirm the correctness of the Leiden scale. Kamerlingh Onnes did not want to put relations with Germany under pressure, so

he did not officially publish the difference with the results of the Physikalisch-Technische Reichsanstalt.⁴²

Two questions from Guillaume

At the end of 1923, Guillaume finally put some energy into the coordinating task he had been assigned two years earlier by the Comité International. He sent a letter to the four institutes that were directly involved in the temperature scale: the Bureau of Standards, the Physikalisch-Technische Reichsanstalt, the National Physical Laboratory and the Cryogenics Laboratory in Leiden. According to Guillaume, the time was not yet ripe for an international thermometry conference. Meanwhile, he had two questions. First, ‘What are the most reliable data we have available that we can use to derive the absolute scale from the scale related to the rarefied, real gases?’ and second, ‘Which calibration points, determined very precisely, and ranging from the lowest achievable temperatures to the very highest, can serve as thermometric beacons?’⁴³

The first submission came from the Bureau of Standards. On 26 April 1924, its Director, Burgess, sent a new specification for an international temperature scale, following the American proposal of 1914 and incorporating the results of the meeting between Dickinson and Henning. According to Burgess, the experimental evidence that served as the basis for the International Scale was overwhelming.⁴⁴ A new aspect was the range between -195 and -40 °C. A platinum thermometer was used for this purpose, calibrated at the boiling point of oxygen, the sublimation point of carbon dioxide, the freezing point of mercury and the melting point of ice. The selected formula was $R = R_0 (1 + at + bt^2 + ct^4)$, which was identical to the proposal that Henning and Heuse had published in 1924 as a communication from the Physikalisch-Technische Reichsanstalt.⁴⁵

One month later, Burgess sent some additional comments regarding his proposal.⁴⁶ He also proposed an amendment for the low temperature range. It now covered -195 to 0 °C, so the sublimation point of carbon dioxide and the freezing point of mercury as primary calibration points were dropped. The Henning and Heuse’s interpolation formula, which was apparently difficult to use, was exchanged for a new formula that was just as accurate and was, in effect, the Callendar formula with an extra term.⁴⁷

The second response to Guillaume’s questions came from the National Physical Laboratory in Teddington. Joseph Petavel, who had succeeded Glazebrook as Director in 1919, had little to add to the American proposal.⁴⁸ The Physikalisch-Technische Reichsanstalt submitted its proposal at the end of July 1924.⁴⁹ Compared to the proposals from the Bureau of Standards the interpolation formulas took the form of a simple polynomial. An important aspect for the future discussion was the German value for the boiling point of oxygen: -183.00 °C, which was too low, according to Leiden.

Meanwhile, Keesom had informed Guillaume that the Leiden submission had temporarily been put on hold due to high work pressure and also because the contribution would be discussed with Dickinson and Henning before it was sent to Sèvres. However, Keesom did not consider the platinum thermometer 'suitable as a fundamental scale in any case'.⁵⁰ The feeling of dissatisfaction in Leiden was fuelled by Burgess's observation that the differences between the proposals by the three calibration institutes were so insignificant that the remaining differences could also be easily resolved by correspondence, thus making an international conference unnecessary.⁵¹ Guillaume sent a letter to Washington in which he noted that before any further steps could be taken, the exact relationship between the gas thermometer and the thermodynamic scale should be made clear. This was a matter of waiting for the report from Leiden, which was to arrive shortly.⁵²

Burgess wanted to push ahead and was not interested in any further delays. The adoption of an International Scale had, in his view, the objective of unifying and stabilizing the art of temperature measurement.

The national standardizing laboratories are daily confronted with the necessity of standardizing temperatures measuring instruments, and the establishment of a uniform and stable basis of reference is a matter of great and immediate concern. [...] The propositions submitted by the Reichsanstalt and the Bureau of Standards contemplate standardizing the best representation of the thermodynamic scale now available. [...] Agreement upon the essential features of such a scale had practically been reached in 1914, and the general agreement now existing in the views of the several laboratories, as to the values to be assigned to the temperatures of the fixed points and the instruments and formulas to be used for interpolation, would indicate that no amount of further study of existing data could lead to important modifications in the conclusions.⁵³

Meanwhile, the Germans had enshrined their prevailing temperature scale in a law that was announced on 7 August 1924.⁵⁴

Response

Under this barrage of memoranda from the three national calibration laboratories, memoranda that quickly converged towards a joint proposal for an international temperature scale, the response by Guillaume, Kamerlingh Onnes and Keesom took a long time. At the end of November 1924, Keesom finally sent the printer's proof of his report to Guillaume, with copies for the three directors of the calibration institutes: Holborn, Burgess and Petavel.⁵⁵ The Leiden report concentrated solely on the gas thermometer. Based on the gas thermometer an 'international provisional Celsius scale' could be constructed, usable for the range -200

till 450 °C. Apart from this primary scale, there was room for a secondary temperature scale based on calibration points and interpolation formulas and intended for practical use. However, the accurate definition of this secondary scale required agreement about the primary fundamental scale. In that context, the difference in the boiling point of oxygen on the Leiden temperature scale and that of the Physikalisch-Technische Reichsanstalt, -182.95 versus -183.00 °C, was cause for concern.⁵⁶

Two camps

Guillaume continued to proceed at a slow pace. On 17 July, eight months after he had been the last to submit his report, Keesom enquired as to whether any progress could be reported concerning the International Temperature Scale.⁵⁷ Burgess had also become impatient and on 20 July a new American proposal with specifications and a draft treaty text was sent to Sèvres.⁵⁸ The message from Washington was that the implementation of a practical and clear international temperature scale could simply no longer be delayed. The American proposal received a warm welcome from the Reichsanstalt.⁵⁹ Keesom was also positive but could not agree with Burgess's -183.00 °C for the boiling point of oxygen.⁶⁰ In the event of precise measurements, Keesom wanted to be able to deviate from the temperature scale and did not want to accept the fact that the American proposal did not grant him this freedom.⁶¹

Endgame

In a final effort to turn the tide, Keesom sent Guillaume the first part of the manuscript about the gas thermometer in the summer of 1926. This was a review study that he had carried out, together with Tuyn, on behalf of the Bureau International des Poids et Mesures.⁶² The rest was to follow soon. Yet, Leiden once again opted for a detailed study, and it was not until 2 August 1927 that the Memoir was ready to be sent. It presented a case for the helium gas thermometer as the fundamental basis for an international temperature scale and a procedure for establishing this scale, supported by a considerable mass of experimental data. Guillaume would collect comments and distribute these at the end of 1927.⁶³

Yet this counteroffensive had no effect. In August, Burgess had already distributed a new version of his proposal. The amendments were few. The idea was to reach a final proposal at the international conference planned in September 1927 in London, which would be a cosy meeting between the three calibration institutes, since the Netherlands was still not a member of the Metre Convention. Afterwards, the Conférence Général des Poids et Mesures to be held in October in Sèvres could eventually take action after so many years of waiting.

Keesom formulated all of the Leiden objections to the American proposal of August 1927. His conclusion:

[I]t seems impossible that the Laboratories concerned may unite in proposing [...] a temperature scale which they can trust for the low temperatures till -193°C to be correct to a hundredth of a degree or so. The Leiden laboratory is waiting for a proposal of the International Bureau of Weights and Measures as to a special thermometric conference.⁶⁴

Keesom's objections were all in vain. On 4 October, the joint proposal by the three calibration institutes, submitted by the Americans, was on the table in Sèvres at the 7th General Conference on Weights and Measures. As a compromise for Leiden, the boiling point of oxygen had been set at -182.97°C . Leiden was not impressed. Nevertheless, the proposals were unanimously accepted. The treaty text in the *Comptes Rendus* (Proceedings) was followed by a Memoir containing Keesom's objections.⁶⁵

Sequel

In his comments on the Leiden Memoir of August 1927 Burgess stated that the International Temperature Scale offered 'a standardization of practice, and as such [it] will prove to be of the greatest utility.' But, he then continued:

The gas thermometer is, however, almost solely an instrument of research, and the standardization of research as proposed in the Memoir cannot in our opinion lead to any useful result. We would prefer to leave the widest possible latitude in the field of research and then, as the results of research become available, to use them in the more perfect standardization of practice.⁶⁶

Burgess's closing praise for the collection of so much data could not hide the fact that the Bureau of Standards had issued a devastating judgement on Leiden's gas thermometry.

In July 1929, Keesom finally struck back.⁶⁷ It was 'a pleasure,' he wrote, to send to Guillaume his rebuttal to the criticisms from the Reichsanstalt and the Bureau of Standards, adding a French translation of a devastating article he had just published in the Dutch journal *Physica*: 'Concerning the experimental basis for the International Temperature Scale, with respect to low temperatures'.⁶⁸ The article's English translation was sent to Washington one month later.⁶⁹ He also sent the corrections to the last printer's proof of his Memoir: a never-ending lament. The article was published in *Travaux et Mémoires* of 1944.⁷⁰ According to Keesom, the International Temperature Scale for low temperatures was based on only a single study. The accuracy of the concurrence of the international temperature

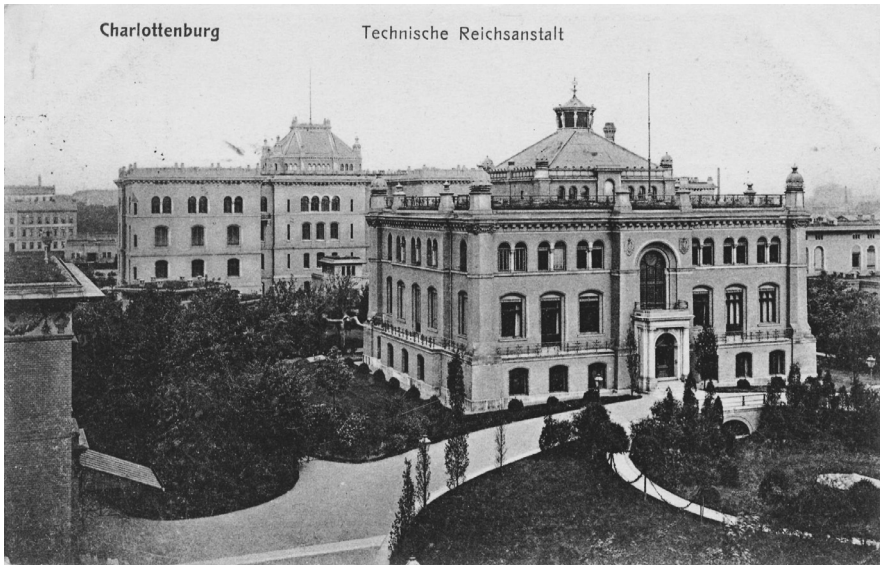


Fig. 2 – The Physikalisch-Technische Reichsanstalt in Charlottenburg, Berlin

scale with the thermodynamic scale was about $0.04\text{ }^{\circ}\text{C}$, and that was far less than the $0.01\text{ }^{\circ}\text{C}$ that had been achieved in Leiden with a platinum thermometer. As Keesom puts it: ‘with this state of affairs [...] we do not yet consider that there is any justification for adopting the international temperature scale’.⁷¹

Conclusion

The discussions that took place in the period preceding the establishment of the International Temperature Scale of 1927 and the events following that decision all revolved around an argument about temperature margins in the order of no more than several hundredths of a degree. However, the essential characteristic of the Cryogenic Laboratory of Leiden lies in its precision measurements and those did revolve around hundredths of a degree. From that point of view, it is hardly surprising that Kamerlingh Onnes and Keesom adhered to the gas thermometer as the basis for an international temperature scale as a matter of principle. After all, the numerical values of the fixed points of the platinum thermometers were established on the basis of gas thermometers.

The decisive factor in the outcome of the ‘battle’ between the proponents of precision (Bureau International des Poids et Mesures, Leiden) and the more flexible parties (Bureau of Standards, Reichsanstalt, Physical Laboratory) was the growing demand in industry for an unequivocal and practically convenient approach to measuring temperatures. The calibration institutes had to meet this demand. It was no longer possible to accommodate the time-consuming and me-

ticulous approach of Leiden, focusing on the scientific basis for gas thermometry for years and years, without a clear end point.

Another decisive factor was that Keesom did not enjoy the same status as his illustrious predecessor. Whereas Kamerlingh Onnes could deliver a report on behalf of the First Committee of the Association Internationale du Froid, in which the calibration institutes were strongly represented, with recommendations that were contrary to the views of these institutes, Keesom lacked the authority to be so influential. In his objections to the International Temperature Scale of 1927 Keesom undoubtedly had a point. Unfortunately, being right is sometimes not enough.

Notes

1. Knowles Middleton (1966); Fox (1971); Chang (2004).
2. Hall (1966), pp. 541-547; Hall (1967), pp. 25-28.
3. Quinn (2006), pp. 203-214.
4. Johannes Bosscha, the Netherlands representative in the international preparation committee to the Metre Convention, advised against membership. According to Bosscha, the Metre Convention was too centralistic, with too little power for the national committees. See Van Lunteren (2004) pp. 61-65.
5. Chappuis (1888).
6. The 100 degrees fixed point was specified as the boiling point of distilled water at a pressure of one standard atmosphere. A standard atmosphere corresponded to a mercury column of 760 mm, with a mercury density of $13,58593 \text{ g/cm}^3$, while the value of the constant g at Breteuil was divided by a factor 1,0003322 to reach the sea level value at 45 degrees NB.
7. Siemens (1861), p. 73.
8. Siemens (1871), p. 351.
9. Callendar (1887), pp. 161-230.
10. Callendar (1899), pp. 519-547.
11. Harker & Chappuis (1900), pp. 37-134.
12. Callendar & Griffith (1891), pp. 119-157.
13. For the historiography of precise measurements in science see, for example Gooday (2004), Galison (2003), Darrigol (2003) and Bartky (2000).
14. Cahen (1989).
15. Pyatt (1983).
16. Cochrane (1966).
17. For detailed information about Kamerlingh Onnes see Van Delft (2007 B).
18. Kamerlingh Onnes (1896).
19. Kamerlingh Onnes & Heuse (1905), pp. 674-684; Kamerlingh Onnes & Clay (1906), pp. 199-207.
20. Meilink (1902), pp. 495-500; Meilink (1905), pp. 290-299.
21. Meilink (1904).
22. For an overview see Crommelin (1922), pp. 383-400.

23. Van Delft (2007 A), pp. 227-245.
24. Bulletin Mensuel (1910) pp. 18-33; Bulletin Mensuel (1911) pp. 38-72.
25. Examples of such cooperation can be found in the 'Annual Reports' of the Bureau of Standards. See Cochrane (1966), p. 246, note 76.
26. As cited in Hall (1967), pp. 25-26.
27. Hall (1966), pp. 541-547.
28. $\delta = 1.49 \pm 0.01$; R_{100}/R_0 not less than 1.389.
29. See Hall (1967), pp. 25-26.
30. R_{100}/R_0 not smaller than 1.388 and δ not greater than 1,52.
31. Guillaume (1913).
32. Travaux et mémoires (1917), pp. 42-47.
33. Kamerlingh Onnes (1913).
34. Hall (1967), pp. 25-26.
35. Guillaume to Kamerlingh Onnes, 1 June 1922, Museum Boerhaave, Keesom Archive, 93M.
36. Museum Boerhaave, Keesom Archive, 93E.
37. Museum Boerhaave, Keesom Archive, 93M.
38. Nernst to Kamerlingh Onnes, 1 October 1923, Museum Boerhaave, Keesom Archive, 93E.
39. Museum Boerhaave, Keesom Archive, 93E.
40. Keesom & Kamerlingh Onnes (1915).
41. W. Nernst (1969), p. 52.
42. Museum Boerhaave, Keesom Archive, 93F.
43. Guillaume to Kamerlingh Onnes, 29 December 1923, Museum Boerhaave, Keesom Archive, 93F.
44. Copy Burgess to Guillaume, 26 April 1924, Museum Boerhaave, Keesom Archive, 93F, file Thermometrie II.
45. Henning & Heuse (1924), pp. 95-104.
46. Burgess to Kamerlingh Onnes, 23 May 1924, Museum Boerhaave, Keesom Archive, 93F, file Thermometrie II.
47. Dusen (1925), pp. 326-332.
48. Petavel to Kamerlingh Onnes, 5 June 1924, Museum Boerhaave, Keesom Archive, 93F.
49. Holborn to Kamerlingh Onnes, 28 July 1924, Museum Boerhaave, Keesom Archive, file Thermometrie II.
50. Keesom, internal report, Museum Boerhaave, Keesom Archive, 93F. Machey and Heraeus were British c.q. German manufacturers of platinum wire.
51. Burgess to Guillaume, 15 August 1924, Museum Boerhaave, Keesom Archive, file Thermometrie II.
52. Guillaume to Burgess, 10 September 1924, Museum Boerhaave, Keesom Archive, 93F.
53. Burgess to Guillaume, 10 October 1924, Museum Boerhaave, Keesom Archive, 93F.
54. Gesetz über die Temperaturskale und die Wärmeeinheit, Reichsgesetzblatt, Teil I, 1924, Nr. 52.
55. Keesom to Guillaume, 25 November 1924, Museum Boerhaave, Keesom Archive, file Thermometry II.

56. Keesom to Paschen, 27 November 1924, Museum Boerhaave, Keesom Archive, file Thermometry II.
57. Keesom to Guillaume, 17 July 1925, Museum Boerhaave, Keesom Archive, file Thermometry II.
58. Burgess to Guillaume, 20 July 1925, Museum Boerhaave, Keesom Archive, file Thermometry II.
59. Paschen to Guillaume, 22 September 1925. According to the PTR the boiling points of palladium and platinum lacked the accuracy to put them on the fixed points list.
60. Keesom to Paschen, 6 October 1925, Museum Boerhaave, Keesom Archive, 93F.
61. Keesom to Henning, 11 November 1925, Museum Boerhaave, Keesom Archive, 93F.
62. Keesom to Guillaume, 25 July 1926, Museum Boerhaave, Keesom Archive, 93F.
63. Guillaume to Keesom, 2 Augustus 1927, Museum Boerhaave, Keesom Archive, 93M.
64. Keesom to Burgess, Oktober 1927, Museum Boerhaave, Keesom archive, 93M.
65. *Comptes Rendu 7e Conférence Général des Poids et Mésures*, 1927.
66. Burgess to Guillaume, 16 January 1928. Museum Boerhaave, Keesom Archive, 93G.
67. Keesom to Guillaume, 16 July 1929. Museum Boerhaave, Keesom Archive, 93M.
68. Keesom (1929), pp. 385-410.
69. Keesom to Burgess, 26 August 1929. Museum Boerhaave, Keesom Archive, 93M.
70. Keesom & Tuyn (1944).
71. Keesom (1929), p. 409.

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