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JOSIAH WEDGWOOD (1730-95)—SCIENTIST

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A PAPER published by Robert Schofield in 1959 contains the statement: 'In recent years scholarly attack, aimed primarily at the general picture of the industrial revolution, has directly or indirectly lessened the reputation of Wedgwood . . . and his right to the title of scientist has been denied.'[1] Schofield proceeded in that paper to argue for the re-establishment of Wedgwood's reputation as an industrial chemist, and in his subsequent monograph on the Lunar Society of Birmingham we find him referring to Wedgwood as 'a scientific potter'.[2]

My purpose is to review Wedgwood's work in a field that we now regard as a branch of physics, namely pyrometry or the measurement of high temperatures. In doing so I want to concentrate on one aspect of that work to which Neil McKendrick has drawn attention in an essay, published just over a year ago, dealing with the role of science in the industrial revolution.[3] After stating that 'Wedgwood's pyrometer was certainly industrially useful', McKendrick went on to comment that Wedgwood's 'empirical approach to the problem and his failure to calibrate its scale with that of Fahrenheit raises doubts over the level of scientific achievement involved in its invention'.[4] A detailed examination that I have made of Wedgwood's notebooks and other manuscript material seeking information relating to his pyrometric studies has left me in no doubt that his method of investigation can justly be regarded as scientific, using the term in its modern connotation.

No one was probably more aware of the need for some form of pyrometer for use in pottery kilns than Wedgwood himself, particularly when he was conducting experiments aimed at improving the quality of his own

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I am indebted to the Trustees of the Wedgwood Museum, Barlaston, for permission to reproduce photographs in their collections (Figures 2 and 4); also to the Delegacy of King's College, London, and to the Director of the Science Museum, London, for permission to reproduce a photograph of Wedgwood's pyrometer (Figure 3). I am grateful to Mr Bruce Tattersall, Curator of the Wedgwood Museum, Barlaston, and to Mr Ian H. C. Fraser, Archivist at Keele University Library, for supplying information about documents in the Wedgwood archives.

1 Robert E. Schofield, 'Josiah Wedgwood, industrial chemist', *Chymia*, v (1959), 180–92.

2 Robert E. Schofield, *The Lunar Society of Birmingham: a social history of provincial science and industry in eighteenth century England* (Oxford, 1963), p. 45.

3 Neil McKendrick, 'The rôle of science in the industrial revolution: a study of Josiah Wedgwood as a scientist and industrial chemist', in Mikuláš Teich and Robert Young (eds.), *Changing perspectives in the history of science: essays in honour of Joseph Needham* (London, 1973), pp. 274–319.

4 Ibid., p. 280.

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manufactures. He certainly carried out a great number of trials of ceramic materials, as is shown by entries in one of his experimental notebooks[5] and by the large collection of fired specimens still preserved by the Wedgwood Museum Trust,[6] but it must be recognized that much of this work was empirical rather than scientific.

Wedgwood's recorded interest in the problem of temperature measurement dates from the late 1770s; in his 'Common place book no. 1' we find evidence that he had conducted what might be regarded as a literature search through volumes of the *Philosophical transactions* covering the years from 1693 to 1778, seeking information on thermometers.[7] We know also that he discussed a statement to be found in one of the papers listed, some four years after its publication, when he met the author of that paper, George Fordyce, at the rooms of the Royal Society of London.[8]

Wedgwood's first thoughts were that a pyrometer might be devised to indicate temperature, making use of the phenomenon then well known to potters that the colour-tints of certain clay mixtures change progressively as those mixtures are heated. Although he finally abandoned this proposal late in 1781, the records associated with it are interesting in that they reveal the extent of some of his scientific knowledge at that time.

His proposal for determining the temperature to which test pieces of clay had been subjected in his trials, and for linking the particular colour-tints thereof with relevant firing temperatures, was to use the method of mixtures of thermometric calorimetry. From his notes[9] and from the paper which he communicated through Joseph Priestley and Joseph Banks to the Royal Society late in 1780,[10] it is clear that at that time Wedgwood was not thoroughly familiar with the principle of the method of mixtures, for when making his calculations he omitted to take account of the heat absorbed by the containing vessel—the term calorimeter had not been introduced at that time—and of the immersed portion of the thermometer.[11] He was also apparently under the impression that the distribution of heat within bodies was in direct proportion to their volumes, a view that had been expounded by Boerhaave many years before.[12]

[5] Josiah Wedgwood, J. W. experiments nos. 1–4832, Wedgwood Museum Trust MS. 19117–26.

[6] Located in the Wedgwood Museum at Josiah Wedgwood & Sons Ltd., Barlaston, Stoke-on-Trent, Staffordshire ST12 9ES, England.

[7] Josiah Wedgwood, Common place book no. 1, f. 10, Wedgwood Museum Trust MS. 28408–39.

[8] George Fordyce, 'Of the light produced by inflammation', *Philosophical transactions of the Royal Society of London*, lxvi (1776), 504–8.

[9] Wedgwood, op. cit. (7), ff. 11–20.

[10] Letter from Joseph Priestley to Josiah Wedgwood, 30 November 1780, Royal Society Miscellaneous MSS., vol. v, letter ref. 1; Royal Society Letters and Papers, decade 7, vol. lxvii, no. 178.

[11] The term calorimeter was introduced by Lavoisier in his *Traité élémentaire de chimie* (Paris, 1789), ii. 389–90; English translation by Robert Kerr, *Elements of chemistry* (Edinburgh, 1790), p. 345. Wedgwood referred to his calorimeter as a cistern.

[12] Hermann Boerhaave, *Elementa chemiae* (Leyden, 1732), i. 187–8; English translation by Peter Shaw, *A new method of chemistry* (2nd edn., London, 1741), pp. 245–6.

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Wedgwood read a paper on this subject at a meeting of the Philosophic Society on 29 June 1781, when Adair Crawford was among the few members present.[13] Crawford had begun his own experiments on heat a few years earlier, and his presence on that occasion would have provided an opportunity for him to point out some of the errors that were present in Wedgwood's calculations. If this was the case, then it would explain why, in a subsequent draft prepared by Wedgwood, account was taken of the heat absorption by both the calorimeter and thermometer.[14] A revised version of this paper was read to Sir Joseph Banks and the Hon. Charles Greville at Wedgwood's house in London on 2 December 1781, when Banks praised the idea in general but made some quite critical observations.[15] It may well have been Banks's comments which caused Wedgwood, on reflexion, to abandon his proposal for a colour-tint pyrometer. Soon afterwards he set to work on another type of pyrometer which was intended to operate on an entirely different principle.

An entry in Wedgwood's 'Common place book no. 1', dated 19 May 1781, is the first record we have of his idea for making a ceramic pyrometer. This idea was based on his own theory that once an unfired clay body has, as he put it, 'undergone a full red heat', i.e. has been heated to about 600 °C., a linear relation exists between the contraction which the body subsequently undergoes on firing to a higher temperature, and the actual temperature attained by that body in such a firing.[16] From the curve shown in Figure 1, which relates to English china clay but is probably applicable also to the clay mixtures used by Wedgwood in his pyrometric studies, it is clear that the relation between thermal contraction and temperature is non-linear over the temperature range 600 to 1000 °C., the range with which Wedgwood was particularly concerned.[17] However, in the absence of any alternative means of measuring temperatures over that range, there could be no decisive test of the validity of Wedgwood's theory. We should not dismiss Wedgwood's eligibility to be regarded as a scientist on the ground that he propounded and acted upon a theory which it took the scientific advances of more than a further one hundred years to prove was false.

The component parts of Wedgwood's ceramic pyrometer were the gauge, early examples of which were made of brass[18] but later ones of his

[13] Minute book of the Philosophic Society, f. 21, Museum of the History of Science, Oxford, MS. Gunther 4. This meeting was held at the Chapter Coffee House, London. I am indebted to our Honorary Treasurer, Mr G. L'E. Turner, for bringing this record to my notice.

[14] Wedgwood, op. cit. (7), ff. 77–81.

[15] Ibid., ff. 81–2.

[16] Ibid., ff. 19–20.

[17] Based on a curve given by J. F. Hyslop and A. McMurdo in 'The thermal expansion of some clay minerals', *Transactions of the Ceramic Society*, xxxvii (1937–8), 181, fig. 1. The curve relates to tests carried out in an oxidizing atmosphere, the rate of temperature increase being 10°C. per minute.

[18] Brass gauges were made for Wedgwood by Peter Pearson; see Keele University Library, Wedgwood MSS. 9749–11, 9750–11, and 9753–11.

own porcelain or jasper composition,[19] and small clay pieces which underwent burning shrinkage when fired. The gauge consisted of a channel rectangular in cross-section but with the internal width of the channel decreasing uniformly from 0·5 inch at one end to 0·3 inch at the other. Originally the channel was 12 inches long, but a subsequent modification, aimed at reducing the size of the gauge and the quantity of material used in its manufacture, was to have two channels arranged alongside one another, each being 6 inches long; one channel narrowed in width from 0·5 to 0·4 inch over its length, and the other from 0·4 to 0·3 inch. A brass gauge of this type, preserved in the Wedgwood Museum at Barlaston, is illustrated in Figure 2.[20] Wedgwood soon found from experience that he could not get brass gauges made to the requisite degree of accuracy, and in consequence he turned to manufacturing his own gauges in a ceramic material.[21] It then became his practice to make the two sections of the complete gauge as separate units rather than as one composite item. An example of a pyrometer set of this type, made by Wedgwood for George III and now preserved in the Science Museum, London, is illustrated in Figure 3.[22]

After trying out clay pieces of various shapes for pyrometric use Wedgwood found that the most consistent results for burning shrinkage were to be obtained when his pieces were circular in cross-section. Cylindrical clay pieces were therefore manufactured, measuring 0·5 inch across before they were fired. After firing, each piece was allowed to cool and was then inserted in the gauge and pushed gently towards the narrower end of the channel until it could go no farther. The extent of the penetration along the channel was then read off against a scale which was marked at intervals of 0·05 inch along its entire length, each unit division corresponding to one degree of Wedgwood's arbitrary scale of temperature. The zero point was located at the end of the gauge where the width of the channel was 0·5 inch, and the 240-degree mark where the width was 0·3 inch.

A study of Wedgwood's notebooks and correspondence provides a most useful insight to the train of investigations that he carried out during the development of his ceramic pyrometer. These investigations were begun on 1 January 1782.[23] Soon afterwards Wedgwood became aware of a phenomenon now termed thermal expansion hysteresis, when he

[19] Josiah Wedgwood, *Catalogue of cameos, intaglios, medals . . . and other ornamental and useful articles* (6th edn., Etruria, 1787), pp. 69–71. This edition was reprinted with a different pagination as *Wedgwood's catalogue of cameos, intaglios . . . useful articles*, ed. Eliza Meteyard (London, 1873); the relevant entry is on pp. 103–5.

[20] Wedgwood Museum, Barlaston: inventory no. 4549.

[21] Draft of letter from Josiah Wedgwood to Richard L. Edgeworth, 13 February 1786, Keele University Library, Wedgwood MS. 2488–3. The letter as sent is published in Ann Finer and George Savage (eds.), *The selected letters of Josiah Wedgwood* (London, 1965), pp. 291–2.

[22] Science Museum, London: George III collection of scientific instruments: inventory no. 1927–1812.

[23] Josiah Wedgwood, J. W. experiments 1781–1793, f. 47, Wedgwood Museum Trust MS. 19121–29.

observed that a small expansion rather than an expected contraction occurred during the time the clay pyrometric pieces were first heated though not sufficiently to make them red hot.[24] He wondered whether there might be a successive loss of weight by the pieces, in proportion to the temperatures they attained, which could serve to connect the divisions of his gauge with those of the common thermometer, but he found by experiment that this was not the case.[25]

By firing long and short pyrometric pieces together, Wedgwood satisfied himself that the contraction per unit length was the same for both sizes of specimen.[26] In another experiment Wedgwood placed pyrometric pieces in a crucible kept just red hot, adding them one by one at minute intervals over a period of forty minutes, and then removing them all together at the end of a further three minutes; after measuring their individual contractions with the gauge, Wedgwood concluded that only three minutes of heating was sufficient for the pieces to acquire their full burning shrinkage. A similar test, carried out with the crucible at 'full heat', appeared to indicate that a heating time of five minutes was sufficient in that instance for full contraction to occur.[27] There is no doubt that had Wedgwood been able to maintain his pieces at constant temperature over a prolonged period of time, he would have observed a progressive shrinkage taking place. We know now that burning shrinkage depends not only on the temperature involved but also on the duration of the firing; thus prolonged heating of clay at one temperature might result in the same amount of burning shrinkage as a shorter period of heating at a much higher temperature. The shrinkage is a measure of the 'heat work' involved. But this fact was neither appreciated nor could it be demonstrated in Wedgwood's time, the maintenance of such fixed-temperature conditions being beyond the power of anyone to effect either then or for many years thereafter.

We may infer that before the end of March 1782 Wedgwood's investigations of the burning shrinkage of clay had progressed sufficiently for him to believe that he could make use of this particular property of clay to obtain a reliable measure of high temperature. Certainly he was confident enough by then to speak and write on the subject to friends. We know that Matthew Boulton had already learnt something of Wedgwood's work on the pyrometer, possibly at a meeting of the Lunar Society of Birmingham, and had mentioned it to Joseph Priestley, who later visited Wedgwood and approved of the instrument.[28] Richard Watson, professor

[24] Ibid., f. 48.
[25] Wedgwood, op. cit. (7), ff. 88–9.
[26] Wedgwood, op. cit. (23), f. 56.
[27] Ibid., f. 58.
[28] Letter from Joseph Priestley to Josiah Wedgwood, 21 March 1782, Royal Society Miscellaneous MSS., vol. v, letter ref. 8. Published versions of this letter are to be found in: Henry Carrington Bolton (ed.), *Scientific correspondence of Joseph Priestley* (New York, 1892), pp. 35–6, and Robert E. Schofield, *A scientific autobiography of Joseph Priestley* (Cambridge, Mass., 1966), pp. 206–7.

of chemistry at Cambridge University from 1764 to 1771, also went to inspect the pyrometer,[29] and Wedgwood later reported that several other chemists and philosophers had examined it and given it their approbation.[30]

Wedgwood's first paper on the ceramic pyrometer, read at the Royal Society on 9 May 1782, included values on his arbitrary scale of temperature for the melting points of brass (21), copper (27), silver (28), gold (32), and cast iron (130).[31] His own determination of the melting point of copper caused Wedgwood some concern, on account of the range of values that he had obtained in various trials; the particular trial that he thought was the most reliable yielded a value of '32 or 33' on the Wedgwood scale.[32] Wedgwood sought the assistance of Stanesby Alchorne at the Tower,[33] in order to carry out trials with the pure metals available at the London Mint, the values quoted above for copper, silver and gold being those obtained either by or with Alchorne.[34] In fact, the melting point of copper (1086°C.) is appreciably higher than that of silver (962°C.) and even a little above that of gold (1064°C.). It is likely that had Wedgwood adopted his own experimental value of 32 or 33°W for the melting point of copper, rather than the value of 27°W determined at the Tower, there would have been no occasion for later observers to question his scientific ability once it became widely recognized that silver melts at a lower temperature than does copper.

I wish to turn now to consider Wedgwood's method of relating his own temperature scale to that of Fahrenheit. The procedure he adopted was first to determine by experiment the apparent expansion of a rectangular block of silver when the temperature of the block was raised from that of spring water (50°F.) to that of boiling water (212°F.) and also to that of boiling mercury, then generally assumed to be 600°F but now accepted as 675°F.[35] Wedgwood did this by using what he termed an 'intermediate' gauge; this was of ceramic construction, similar in design to the pyrometric gauge but with different dimensions and having its own set of graduations. To one side of the channel in this intermediate gauge there was a cup-shaped receptacle intended to hold a small quantity of mercury. Wedgwood noted the readings on this intermediate gauge beyond which a silver block could not be made to pass easily when both block and gauge

[29] Letter from Josiah Wedgwood to Matthew Boulton, 8 April 1782, Birmingham Public Library, Boulton and Watt Collection, box 36, bundle 1781–1835.

[30] Letter from Josiah Wedgwood to James Watt, 15 May 1782, Keele University Library, Wedgwood MS. 18956–26. Published in Finer and Savage, op. cit. (21), pp. 265–6.

[31] Josiah Wedgwood, 'An attempt to make a thermometer for measuring the higher degrees of heat, from a red heat up to the strongest that vessels made of clay can support', *Philosophical transactions*, lxxii (1782), 305–26.

[32] Wedgwood, op. cit. (23), f. 65. Degrees on the Wedgwood scale are cited hereafter as °W.

[33] Alchorne was then master's assay master and later king's assay master at the London Mint. See Sir John Craig, *The Mint* (Cambridge, 1953), p. 231.

[34] Wedgwood, op. cit. (23), f. 66.

[35] Josiah Wedgwood, 'An attempt to compare and connect the thermometer for strong fire . . . with the common mercurial ones', *Philosophical transactions*, lxxiv (1784), 358–84.

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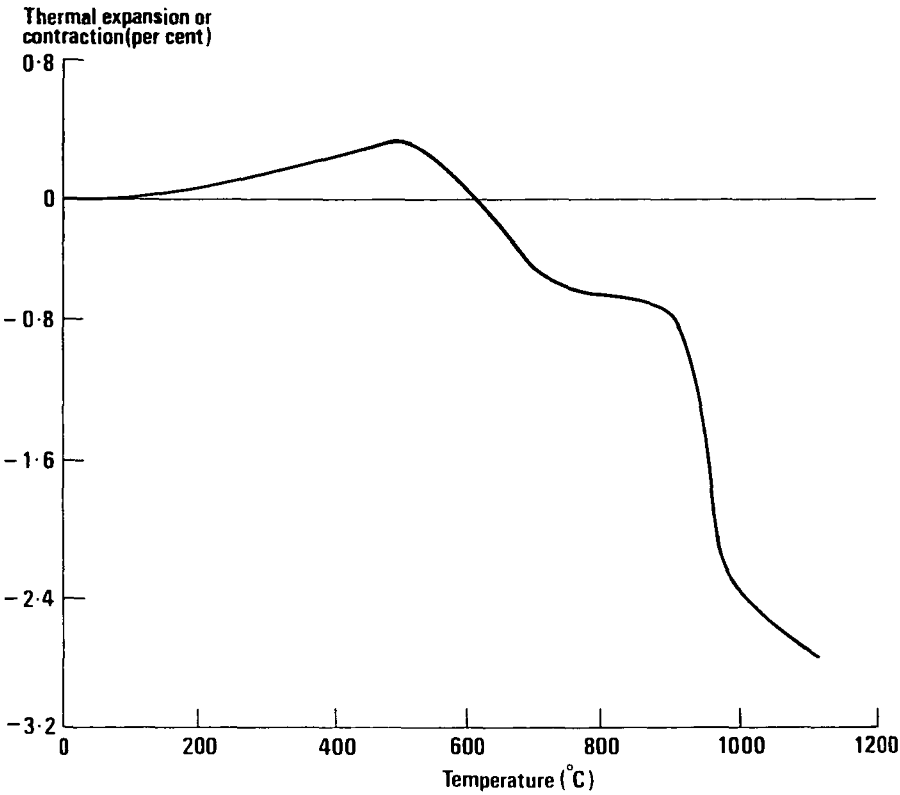

FIG. 1

Thermal expansion of English china clay, as determined by J. F. Hyslop and A. McMurdo.[17]

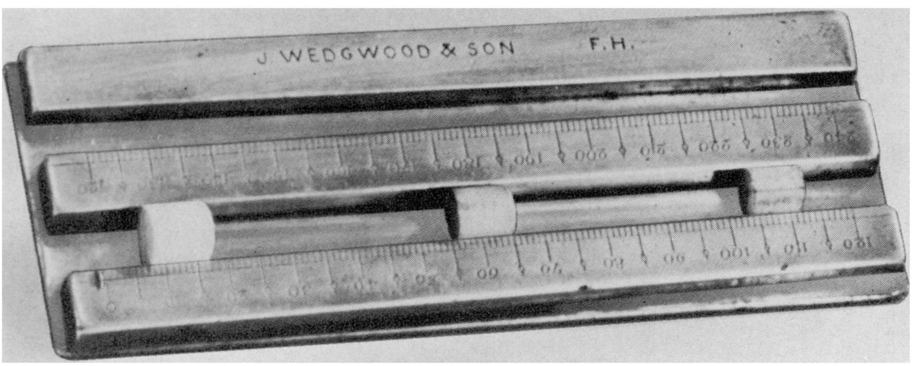

FIG. 2

Brass double-channel pyrometer gauge.[20] (Copyright Trustees of the Wedgwood Museum, Barlaston)

[Face page 6

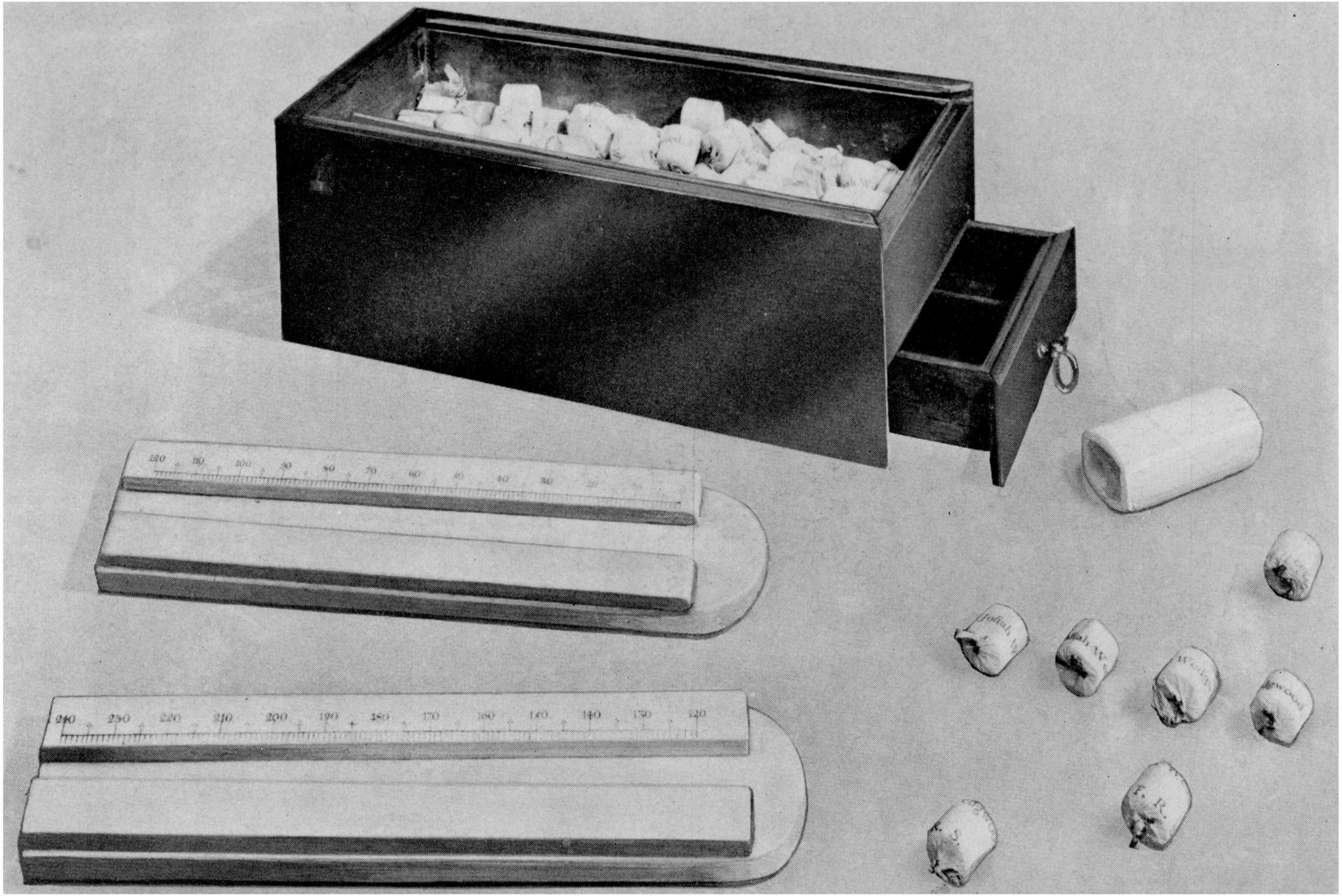

Fig. 3

Pyrometer set with earthenware gauges, supplied by Wedgwood to George III.[22] (Crown copyright, Science Museum, London)

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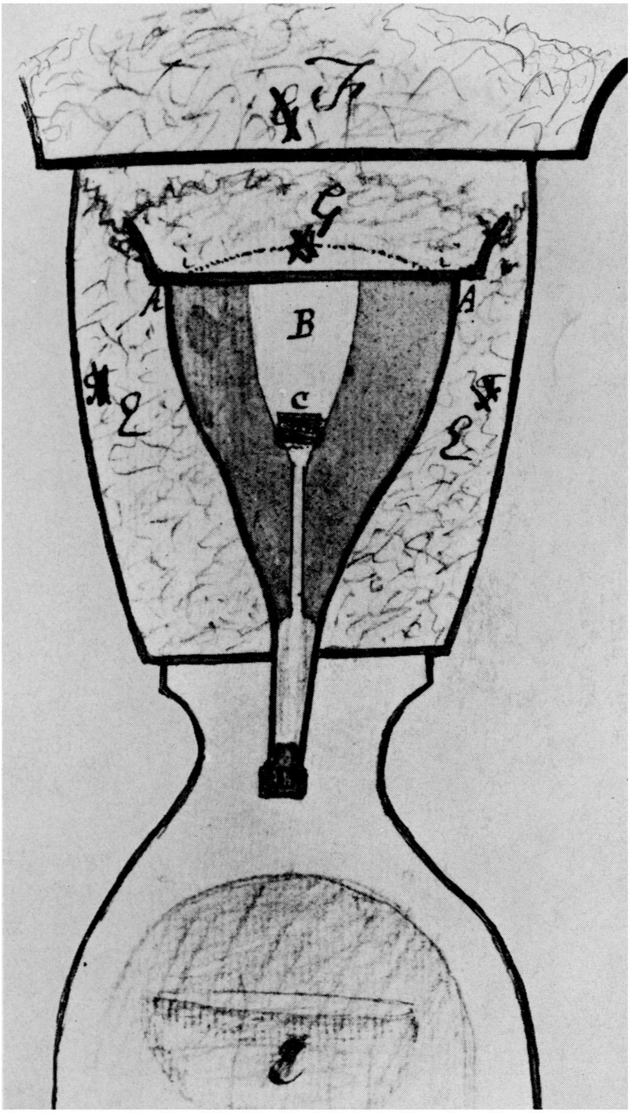

FIG. 4

Wedgwood's sketch for an ice-calorimeter made in earthenware. From J. W. Experiments 1781–1793, facing f. 204, Wedgwood Museum Trust MS. 19121–29. (Copyright Trustees of the Wedgwood Museum, Barlaston)

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were immersed for some time, first in spring water (the zero-point on the intermediate gauge) and then in boiling water (the 8-division on that gauge). This gave by calculation that one division of the intermediate gauge was indicative of the apparent expansion of the silver block caused when its temperature was raised by 20·25°F.

For measurements at the boiling point of mercury, the intermediate gauge with some mercury in the cup was laid on a smooth and level bed of sand on the bottom of an iron muffle kept open at one end. The fire was increased gradually until the mercury was seen to be boiling, after which the fire was kept steady for a considerable time; the silver block, which had rested on the base of the gauge and was located around the middle range of the scale, was then pushed gently as far as it would go towards the narrower end of the channel, by means of a flat strip of iron which had been subjected to the same heating conditions. The gauge reading was found to be 27·5 divisions, so that over the range from 50 to 600°F., the average apparent expansion of the silver block, corresponding to one intermediate gauge division, occurred when the rise in temperature of the block was 20°F. This value was sufficiently close to the one derived in the earlier determination (20·25) for Wedgwood to adopt a factor of twenty in his subsequent calculations. One can only wonder what his reaction would have been had he used the true figure of 675°F. for the boiling point of mercury and thereby obtained a factor of just over twenty-two!

Wedgwood's next step was to place the intermediate gauge and silver block in the middle of one of his ovens used for the burning-on of enamel colours upon earthenware. Some of his pyrometric pieces were set on end on the silver block, care being taken to ensure that the ends of the pieces in contact with the block were those that would later go foremost in the channel of the pyrometric gauge. The muffle was observed through a small door in the side of the oven; when the muffle appeared to be of a 'low red heat' such as was judged to come fully within the range of the Wedgwood pyrometer, it was drawn towards the oven door, the muffle quickly opened, and the silver block pushed along the intermediate gauge as far as it would go. The muffle was then lifted out of the oven carefully and, when it was sufficiently cool to be examined, Wedgwood found that the silver block had been moved as far as the 66-division of the intermediate gauge. The pyrometric pieces were then measured in the Wedgwood pyrometer gauge, a mean value of 2·25°W being obtained. The whole arrangement was then returned to the oven and subjected to a stronger heat than before; the corresponding readings taken in this second instance being 92 divisions on the intermediate gauge, and 6·25°W on the pyrometric gauge.

From these observations, made over several trials which gave almost identical results, Wedgwood deduced that one degree on his own temperature scale was equivalent to 130 Fahrenheit degrees, and that 0°W corresponded to 1077·5°F. On that basis Wedgwood obtained figures for the melting points of silver, copper, and gold that are very much higher than those we accept today (see Table 1). I presume it is the magnitude of

TABLE 1

MELTING-POINT TEMPERATURES (in °F.)

	Silver	Copper	Gold
Wedgwood and Alchorne	4717	4587	5237
Modern value	1763	1984	1948

these differences which McKendrick regards as evidence of Wedgwood's so-called failure to calibrate his own thermometric scale with that of Fahrenheit. But does this really justify, as McKendrick suggests, the raising of 'doubts over the level of scientific achievement involved' in the invention of Wedgwood's pyrometer? Might such differences be indicative rather of a poor level of achievement not in the invention but in the calibration of the instrument. How does Wedgwood measure up in that respect? Was a higher level of achievement possible in Wedgwood's time?

I have already referred to the fact that Wedgwood's calibration was based on the then generally accepted, but in reality far too low, value for the boiling point of mercury (600 instead of 675°F.). I have also drawn attention to the non-linearity of the contraction/temperature relationship for china clay, as shown by the curve in Figure 1. We can deduce that Wedgwood's trials carried out in the muffle involved temperatures in the range immediately above 1200°F. (650°C. say), where departure from a linear relationship is most noticeable.

We can identify other factors that would contribute in part towards the derivation of a faulty calibration of Wedgwood's scale. For example, it was not known in Wedgwood's time that the linear coefficient of expansion of silver was greater at higher temperatures; Wedgwood's calibration was made in the belief that this coefficient remained constant, whereas it is quite likely that the coefficient increased by some twelve per cent or more over the entire range of temperature involved. Furthermore, we know that the heating of the pyrometric pieces inside the muffle went on for some hours,[36] and, in consequence, the contraction shown by those pieces was more than would have been the case had they been left in the muffle for no longer than the five minutes which Wedgwood considered sufficient for full burning shrinkage to occur. There is also the possibility that instead of using fresh pieces for the calibration test at the higher temperature, the pieces selected were those which had already been used in the test at the

[36] Ibid., p. 367.

lower temperature. If this was so, then an even larger contraction would have been measured than would have been the case had fresh pieces been used. But again I would point out that at that time there was no way of determining whether prolonged heating of a pyrometric piece at a constant temperature did in fact result in progressive shrinkage.

As Wedgwood's calibration experiments involved measurement of the apparent thermal expansion of the silver block, that is to say of the difference between the thermal expansions of the silver block and of the material of which the intermediate gauge was made, any variation in the linear coefficient of expansion of the gauge material over the temperature range involved in the calibration experiments would necessarily have caused an error in the results calculated from such readings.

All these are valid criticisms that we can make in the light of our present-day knowledge, but they certainly could not have been substantiated in Wedgwood's time.

We might question whether Wedgwood should not have adopted other methods in order to calibrate his scale. But what methods were then available to him? Thermometric calorimetry had scarcely developed, and certainly not to the point where it was known that the specific heat of a metal was not constant over all temperature ranges. Latent heat calorimetry became a possibility only at that very time, and Wedgwood deserves great credit for recognizing that it might provide him with a means of calibrating his own temperature scale. The idea occurred to him after he had read in the latest issue of a publication called *The monthly review*[37] an abstract of a memoir by Lavoisier and Laplace concerning a method of measuring heat.[38] This method involved the use of an ice calorimeter, a description of which was given in the abstract but without any illustration. Wedgwood immediately set about making for himself a similar piece of equipment in earthenware. It so happened that a thaw had set in only the previous day at Etruria following a prolonged spell of continuous frost, and this made it possible for Wedgwood to collect a quantity of ice from the nearby canal, to beat it into pieces and to store it for future use. Wedgwood was apprehensive that water resulting from ice melting inside the calorimeter would be retained by the surrounding powdered ice owing to capillary attraction, and this fear was confirmed by his own experiments. Accordingly, he decided to form a solid cake of ice round the

[37] 'Abstract of a memoir upon heat by Messrs. Lavoisier and De La Place, Members of the Royal Academy of Sciences of Paris, read at the said Academy June 28, 1783', *The monthly review; or, literary journal*, lxix (1783), 568–79. See footnote 38 regarding the confusion which arises over the date quoted in the above title.

[38] A. L. Lavoisier and P. S. Laplace, 'Mémoire sur la chaleur', *Mémoires de l'Académie Royale des Sciences, Paris* (1780; read 18 June 1783; published 1784), 355–408; reprinted in *Oeuvres de Lavoisier* (Paris, 1862), ii. 283–333. Their memoir was printed in 1783 as a brochure for private distribution, but with the date incorrectly given as 28 June. The abstract in the *Monthly review* (see footnote 37) must have been based on a copy of that brochure. For details of other reprints, abstracts, and translations of this memoir, see Denis I. Duveen and Herbert S. Klickstein, *A bibliography of the works of Antoine Laurent Lavoisier* (London, 1954), pp. 54–6, 248–9.

inside of the funnel A (see Figure 4) by means of a freezing mixture; a cavity B was made in the middle of this cake of ice to receive a heated body C, and an outlet was made below C for running off any water formed by melting ice. Tests carried out with bodies heated in boiling water did not yield consistent results; the mass of water resulting from ice melted by the heat given up by the hot body was found to be less when a longer interval of time elapsed between dropping the body into the calorimeter and running off the water produced by melting. When Wedgwood used a body heated to 6°W, the water formed inside the cavity B was run off after half an hour; but after a further seven hours, Wedgwood observed that a considerable quantity of water had collected in the funnel-shaped portion of the apparatus. However, when the cork stopper D was removed, this water ran out only very slowly and it was discovered that the passage through the ice below C was almost closed by ice crystals.[39] Wedgwood was astonished that the water inside the apparatus should have frozen again; clearly he did not realize that the temperature of the solid cake of ice prepared by means of a freezing mixture would for some time be below 0°C., and that the ice cake would thus be able to re-freeze some of the water produced by melting when the hot body was dropped into the calorimeter. Lavoisier and Laplace had been aware of this danger and had pointed out that it was essential for the ice not to be below 0°C.; but unfortunately for Wedgwood this part of their memoir was not included in the *Monthly review* abstract. Is it surprising, in view of the anomalous results Wedgwood obtained in experiments using his own ice calorimeter, that he should lose confidence in the method as a means of calibrating his own pyrometer scale and therefore pursue it no further?

In 1782, when Wedgwood's first paper on the ceramic pyrometer was read to the Royal Society, there was no intention on his part to manufacture pyrometer gauges and pyrometric pieces for sale to the public. It was then his hope that interested persons would find sufficient information in his paper to enable them to make their own equipment. In a pamphlet that Wedgwood published two years later, however, he revealed that he would after all be prepared to meet requests for the supply of pyrometer sets. This change of mind was occasioned by a fear that if manufacture was left to others, the pyrometer might be brought into disrepute before its general utility was established.[40] Wedgwood felt that the formation of pyrometric pieces could only be carried out satisfactorily by someone with experience in the working of clay; furthermore, the uniformity of burning shrinkage was influenced very much, as he said, 'by minute and seemingly insignificant circumstances, which a tedious course of very perplexing

[39] Wedgwood, op. cit. (23), ff. 203–5; op. cit. (35), 371–84. For an evaluation of Wedgwood's criticism of the ice calorimeter and of his influence on British writers, see T. H. Lodwig and W. A. Smeaton, 'The ice calorimeter of Lavoisier and Laplace and some of its critics', *Annals of science*, xxxi (1974), 1–18 (4–9).

[40] Josiah Wedgwood, *Description and use of a thermometer for measuring the higher degrees of heat, from a red heat up to the strongest that vessels made of clay can support* (London, 1784), pp. 22–3.

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experiments has been necessary for ascertaining'. With this in mind, Wedgwood thereupon supervised the manufacture of several thousand pieces, a quantity which was not exhausted until a few years after his death.

We do not know to what extent Wedgwood's offer of supply was taken up. One of his ledger-books has a record of the sale of forty pyrometer sets between June 1786 and February 1787, of which seven sets were charged against Wedgwood's name, some perhaps for use at the factory at Etruria, some for use in London, and the remainder perhaps as gifts to friends.[41] My researches so far have revealed a further thirty persons who used a Wedgwood pyrometer, or who requested or had one in their possession; included in this list are such notables as Bergman, Black, Guyton de Morveau, Sir James Hall, Hope, Lavoisier, Pictet, Priestley, Rumford, and Wollaston.

Interest in Wedgwood's pyrometer may have been stimulated in the closing years of the eighteenth century by the republication of his pyrometer papers which had appeared in the *Philosophical transactions*,[42] and by the appearance of an article about the instrument written by Scherer for the benefit of German chemists.[43] The war between France and England, begun in 1793, probably made it difficult, if not virtually impossible, for the French to obtain further stocks of pyrometric pieces from Wedgwood's factory, and in the absence of any other means of measuring high temperatures the French were obliged to investigate the possibility of making their own pieces from such materials as were available to them within their own country.[44]

The results of two gravimetric analyses of Wedgwood pyrometric pieces, one furnished by Guyton[44] and the other attributed to Vauquelin,[45] were both published in 1799. These differed so much from one another that Guyton invited Vauquelin to carry out a fresh analysis using pieces supplied by Wedgwood to Guyton some years earlier. Vauquelin agreed, and in due course he provided Guyton with a new set of figures that were very different from those already attributed to him (see Table 2). Vauquelin was unable to account for the publication of the erroneous figures, for on examining the notes of his earlier analysis he found that the values actually obtained were not those which had appeared in print; furthermore, the figures obtained in his first analysis were very nearly the same as those in the later work carried out at Guyton's request. Unfortunately,

41 Josiah Wedgwood, Private ledger 1786–1890, f. 52a, Wedgwood Museum Trust MSS.

42 *The repertory of arts and manufactures*, vi (1797), 255–68, 324–43; vii (1797), 173–95, 239–59.

43 Alexander N. Scherer, 'Wedgwood's pyrometer', *Allgemeines Journal der Chemie (Scherer)*, ii (1799), 50–62.

44 L. B. Guyton de Morveau, 'Extraits d'une lettre de M. A. N. Scherer au cit. Guyton', *Annales de chimie*, xxxi (1799), 171 n., 172 n.

45 L. N. Vauquelin, 'Réflexions sur la qualité des poteries, et résultats de quelques analyses de terres et de poteries communes', *Bulletin des sciences, par la Société Philomathique de Paris*, ii, no. 26 (1799), 10–12.

TABLE 2

GRAVIMETRIC ANALYSIS OF WEDGWOOD'S PYROMETER PIECES

Constituent	Name of analyst and publication date		
	Guyton	Vauquelin	
	1799	1799	1810
Silica	43·764	64·2	47·35
Alumina	54·705	25	44·29
Magnesia	Slight trace		
Iron oxide	Slight trace	0·2	
Lime		6	
Water		6·2	8·36
Loss	1·531		
	100·000	101·6	100·00

the analysis figures falsely attributed to Vauquelin had already received wide publicity, having been copied in a German and in a British journal, both of which enjoyed a wide circulation, and later in a French book on pottery manufacture.[46] It was not until 1810 that Vauquelin's true analysis figures were published.[47] In the meantime, French workers attempting to make pyrometric pieces according to the composition denoted by those erroneous figures, and most likely not using the correct manufacturing techniques as Wedgwood had done, found that they did not get satisfactory results when measuring high temperatures with pieces of their own manufacture. Little wonder that the French lost confidence in the reliability of Wedgwood's pyrometer.

Confidence was revived to some extent in France as a result of Guyton's further investigations. In 1810 he read to the Class of Physical and Mathematical Sciences of the French Institut the third part of his 'Essai de pyrométrie',[48] in which he gave details of his own comparison of temperature readings obtained using a Wedgwood pyrometer with

[46] 'Chemische Betrachtungen über die irdenen Geschirre', *Allgemeines Journal der Chemie (Scherer)*, iii (1799), 734–7; L. N. Vauquelin, 'Reflections on the qualities of pottery, with the result of some analysis of earths, and of common pottery', *A journal of natural philosophy, chemistry, and the arts*, ed. W. Nicholson, iii (1800), 264–5; O*** [Oppenheim], *L'art de fabriquer la poterie, façon anglaise* (Paris, 1807), p. 160.

[47] L. B. Guyton de Morveau, 'Examen des faits sur lesquels sont fondées les objections contre la régularité de la marche du pyromètre de Wedgwood', *Annales de chimie*, lxxiv (1810), 129–52 (130–1).

[48] L. B. Guyton de Morveau, 'Correction de la table de Wedgwood; valeurs réelles des degrés de son pyromètre; et leur concordance avec les differentes échelles thermométriques et pyrométriques', *Mémoires de la Classe des Sciences Mathématiques et Physiques de l'Institut de France*, xii, part 2 (1811, published 1814), 89–120; a slightly edited version appears in *Annales de chimie*, xc (1814), 113–37, 225–38.

those derived from a platinum pyrometer of Guyton's own design.[49] He considered that the most important error Wedgwood had made in his calibration of the ceramic pyrometer was in respect of the melting point of silver (28°W), and that an amended value of 22°W, as had been suggested by Robert Kennedy in 1798, was more appropriate.[50] From the results of his own trials, Guyton concluded that the Fahrenheit temperatures assigned to corresponding points on the Wedgwood scale were far too high; he preferred a value of 517°F. for the zero on Wedgwood's scale (not 1077·5°F.) and reckoned that one Wedgwood degree was equivalent to 62·5 (not 130) deg F. Provided this new relation was adopted, Guyton saw no reason why the Wedgwood pyrometer should not continue to be used in chemical works and in industry, but he counselled the use of his own platinum pyrometer for research work.

Unfortunately, Guyton's platinum pyrometer was not a particularly accurate instrument. There is no indication in Guyton's published work of the highest temperatures actually recorded with his platinum pyrometer; it seems unlikely, however, that the instrument could have been applied successfully to the determination of temperatures higher than about 600 °C., in consequence of the softening which platinum undergoes at red heat.[51]

I feel that we are in grave danger of depreciating Wedgwood's pyrometric achievements on account of the wide gaps which exist between

TABLE 3

MELTING-POINT TEMPERATURES FOR SILVER, COPPER, AND GOLD (in °F.)

Year	Authority	Silver	Copper	Gold
1782	Wedgwood and Alchorne	4717	4587	5237
1798	Kennedy	3937		
1810	Guyton	1893	2205	2518
1821	Daniell	2233	2548	2590
1827	Prinsep	1830		
1830	Daniell	1873	1996	2016
1836	Pouillet	1832		2192
1857	Salvétat	1985		<2129
1879	Violle	1749	1929	1895
1968	International Practical Temperature Scale	1763	1984	1948

[49] For details of this instrument, see John A. Chaldecott, 'The platinum pyrometers of Louis Bernard Guyton de Morveau, F.R.S. (1737–1816)', *Annals of science*, xxviii (1972), 347–68.

[50] Sir James Hall, 'Experiments on the effects of heat modified by compression', *A journal of natural philosophy, chemistry, and the arts*, ix (1804), 98–107 (99 n.). A translation appeared in *Bibliothèque britannique* (Sciences et arts), xxvii (1804), 289–309.

[51] This fact was pointed out in John Frederic Daniell, 'On a new register-pyrometer, for measuring the expansions of solids, and determining the higher degrees of temperature upon the common thermometric scale', *Philosophical transactions*, cxx (1830), 257–86 (259).

his melting-point temperatures for silver, copper, and gold on the Fahrenheit scale and those we accept today. What I suggest we should do is to see how Wedgwood's figures compare with those obtained by later workers (see Table 3); there were no earlier determinations, for, as I have shown elsewhere, figures given by Spielmann in 1766 were meaningless, having been based on a misreading of a diagram published in 1747 relating to Mortimer's metallic thermometer.[52]

The values that appear in Table 3 opposite the names of Wedgwood and Alchorne, Kennedy, Guyton, and Salvétat, all relate to determinations carried out with Wedgwood's pyrometers. Kennedy's revision arose from a number of observations that silver melted at 22°W,[50] and Hall suggested that this difference from Wedgwood's figure of 28°W was probably accounted for by Wedgwood's use of one particular clay for the pyrometric pieces used in the measurements carried out at the Tower, and of a slightly different clay for the manufacture of the large quantity of pieces which he made available to chemists and others some two or more years later.[53]

The values shown in Table 3 against the names of Guyton[48] and of Salvétat[54] arose from fresh ideas of the Fahrenheit temperature corresponding to 0°W, and of the number of Fahrenheit degrees equivalent to one Wedgwood degree. It is interesting to note that it was almost forty years before anyone devised a different method of measuring these melting points.

Daniell used a pyrometer in which temperature was determined by measuring the difference in thermal expansion of a platinum bar and of a black-lead earthenware tube, the original design of 1821[55] being modified for use in his determination reported in 1830.[51] Prinsep made use of a series of silver-gold and gold-platinum alloys whose melting points were evaluated using an air thermometer.[56] Pouillet used an iron-platinum thermocouple calibrated against an air thermometer,[57] and Violle used a calorimetric method.[58]

[52] Jacob Reinbold Spielmann, *Institutiones chemiae* (2nd edn., Strasburg, 1766), pp. 118–20; *Instituts de chymie* (Paris, 1770), i. 260, 263. For an examination of the source of Spielmann's information, see John A. Chaldecott, 'Cromwell Mortimer, F.R.S. (*c.* 1698–1752), and the invention of the metalline thermometer for measuring high temperatures', *Notes and records of the Royal Society of London*, xxiv (1969), 113–35 (125–6).

[53] The small quantity of pyrometric clay dug out in 1779 was almost exhausted by the end of 1782; a fresh supply was obtained early in 1783 from the same location but it was found to have somewhat different burning-shrinkage characteristics. See Wedgwood, op. cit. (23), ff. 106, 117, 120.

[54] Alphonse Salvétat, *Leçons de céramique professées à l'École Centrale des Arts et Manufactures, ou téchnologie céramique* (Paris, 1857), ii. 258–61.

[55] John Frederic Daniell, 'On a new pyrometer', *The quarterly journal of science, literature, and the arts*, xi (1821), 309–20; also Daniell, op. cit. (51), 257–86.

[56] James Prinsep, 'On the measurement of high temperatures', *Philosophical transactions*, cxviii (1827), 79–95.

[57] Claude S. M. Pouillet, 'Recherches sur les hautes températures et sur plusieurs phénomènes qui en dépendent', *Comptes rendus hebdomadaires des séances de l'Académie des Sciences*, iii (1836), 782–90; cited hereafter as *Comptes rendus*.

[58] Jules L. G. Violle, 'Chaleurs spécifiques et points de fusion de divers métaux réfractaires', *Comptes rendus*, lxxxix (1879), 702–3.

In case one is tempted to criticize Wedgwood for failing to observe that the melting point of copper is higher than that of gold, then I would point out that a period of almost one hundred years elapsed after the invention of Wedgwood's pyrometer before anyone else was able to establish this fact by experiment.

Wedgwood certainly deserves credit for carrying out a thorough investigation of the conditions affecting burning shrinkage, and for developing a simple and cheap method whereby it was possible to determine temperatures within a range extending from 600 to 1100°C. That the method proved not to be so successful when practised by others should in no sense be taken as an indication that it was unsatisfactory, or that Wedgwood had failed to appreciate the technical difficulties involved. Rather is it indicative of Wedgwood's wider experience in matters relating to the handling of clays, and of the extreme care and attention to detail which he himself gave to the manufacture of his own pyrometric pieces.

Time has not permitted me to say anything about the many investigations that Wedgwood carried out on clay bodies, first in order to select one suitable for pyrometric use and then to try to ensure that pieces made from that body would yield readings when heated which were consistent one with another. However, I should like to draw attention to a paper published early in the present century, in which are listed the main criticisms of the Wedgwood pyrometer made during the nineteenth century.[59] These were that the burning shrinkage of the pyrometric pieces varies according to: (a) the nature of the body used, (b) the conditions under which the pieces are prepared, and (c) the conditions of firing. The nature of the body is dependent on its chemical composition, the grain size, the compactness of the wet body, and the amount of water present. As regards the conditions of manufacture, the relevant features are the amount of pressure applied in forming the pieces and the nature of the mechanical operations involved.

It is true that Wedgwood did not investigate the effect on burning shrinkage of varying the grain size, but by using the same lawn material for sifting the clay particles intended for the manufacture of his pyrometric pieces, he did in fact ensure that the grain size did not exceed a certain limit.[60] Apart from that one feature, it is clear from an examination of his notebooks that he did investigate the effects of varying all the other factors enumerated above.[61] And having investigated them, he took care to arrange his manufacturing processes so that all his pyrometric pieces would conform to a uniform standard. Surely this is good evidence of Wedgwood's scientific acumen. Add to this the many activities in Wedg-

59 Henry Watkin, 'The principle of contraction of clays as a pyrometer for pottery purposes', *Transactions of the North Staffordshire Ceramic Society*, ii (1902–3), 72–92 (75).

60 Wedgwood, op. cit. (7), f. 82.

61 For a survey of these investigations, see John A. Chaldecott, 'Studies in the history of pyrometry' (University of London Ph.D. thesis, 1972), pp. 39–56, 62–82.

wood's career to which McKendrick has already drawn attention: his unquestioned belief in experiment and his adoption of scientific techniques; his purchase of scientific publications and his familiarity with a wide range of scientific literature; his friendship with scientists and his discussion with them of scientific problems of mutual interest; his apparent familiarity with theory; his membership of scientific societies; his correspondence with scientists at home and abroad, and his willingness to give them the benefit of his experience; and his own published work in the scientific field.[62] I suggest that, taking all these attributes into account, we have sufficient evidence to justify regarding Wedgwood as a true scientist of his age.

[62] McKendrick, op. cit. (3), p. 279.