

DISCUSSION.

At this point the **Chairman** invited general discussion on the above group of papers.

The Chairman: Had this discussion taken place two years ago, I know whom I should certainly have asked to open it. Dr. Harker has for the last two years been giving his attention to other matters, but I am sure he will retain sufficient interest in the subject of temperature measurement to oblige me by saying something now, especially on the theoretical side of some of the matters that have been mentioned.

Dr. J. A. Harker, F.R.S.: You, sir, have exactly described my position in saying that I have been occupied practically exclusively with other matters, and I came to this discussion to-night intending to have a complete change from my present interests. I regarded myself solely as a visitor and for that reason deliberately did not put my name down as having anything to say, as I have not been thinking about pyrometers for more than a year past. There are one or two matters, however, to which I have listened with very great interest and upon which, now I have been called upon, I should like to say a few words. With regard to the point raised by the last speaker, the people who have been making pyrometers in this country have not by any means neglected the matter; Mr. Whipple will bear me out in this opinion, and there are other makers present who know it quite well. This question of the glass for the eye-pieces is a very important matter indeed in discussing the divergencies from true temperatures obtained with optical pyrometers, particularly on the higher ranges, though it may be useful to point out that at quite low temperatures such as 700° , it makes little or no difference if the red glass be removed altogether. The Cambridge Scientific Instrument Company and a number of other makers, Messrs. Siemens among them, have, I know, devoted considerable trouble to obtaining the right quality of red glass, and in my view the implied slur on the British instrument-maker is undeserved. There are very great differences in the behaviour of different kinds of red glass and even between different samples of what is supposed to be the same glass. Some specimens transmit only a fairly narrow and well-defined band of the spectrum, while others allow transmission through a large range of wave-length. A simple test for identification of a bad quality "copper-ruby" glass is to observe whether there is any transmission of the sodium D lines. If this is the case, matching at high ranges will probably be difficult. The centre of gravity of the wave-length in which the pyrometer is working is quite troublesome to determine; it is important to know whether the dominant wave-length is, say, 65 or 70μ so that the "black-body" correction may be properly calculated. The proper determination of this correction is one of the most awkward things in the whole process of getting true temperatures from readings obtained with a *commercial* optical pyrometer, as distinct from the more refined *laboratory* type. It is, however, not being lost sight of.

There is also another matter which may go a long way toward explaining some of the divergencies which have been spoken of to-night. It is very difficult indeed to make an optical pyrometer which will give readings absolutely independent of the size and distance of the object on which it is focused. In the total-radiation pyrometer there is, with

certain types, a small but perfectly definite variation both with size and with distance which is just as inherent in the instrument as coma or spherical aberration in a lens. The same effect is also found to some degree with most commercial optical pyrometers, especially those of the polarizing type, in which the optical arrangements have been so modified as to render the instrument usable over very low ranges, say from less than 700° upwards. You can partly get rid of it if you have a relatively big object. It is, however, a difficult thing to standardize an instrument on a small object and then to get the same reading up to perhaps $2,000^{\circ}$ C. when the object is large, like a mass of steel in a ladle. This variation of reading with size of object is of course quite apart from the "black-body" question, and is a difficulty which is perhaps not very obvious to people who have not carried out pyrometer standardization, but is a serious one to those who have to imitate in the standardizing laboratory the conditions which obtain in a works. We have not 20 tons or even one ton of molten steel available at the N.P.L. on which to test pyrometers, which you asked Sir Richard Glazebrook to standardize for a fee of 30s. or so. The radiation furnace which serves as the hot object has generally to be of relatively modest dimensions. I think, however, that it is due to the N.P.L. to state that with optical pyrometers every instrument is actually tested right up to the higher ranges, and in those with two scales the upper scale is a *determined* and not merely a *calculated* one as is the practice at the Reichsanstalt.

One speaker asked for the standardization of optical pyrometers to be such as would enable temperatures to be determined within 3° at $1,500^{\circ}$ C. In my opinion, while I do not deny that with carefully trained observers means of groups of observations may, under favourable circumstances, have a *relative* accuracy of this order, it would be quite futile to attempt to give corrections to nearer than perhaps 10° unless a number of other conditions were clearly defined. When the National Physical Laboratory took up the question of the standardization of the high-range pyrometers of all kinds some 15 years ago, one of the first things which came up was that steel-makers of the most progressive type were employing temperature-scales, which differed according to the particular fixed-points taken, by more than 50° at $1,000^{\circ}$ C., and most attempts at measurement of higher temperatures were wild extrapolations. The melting-point of common salt could be taken from current books of tables at anything from 740° to 820° C. To-night we have steel-makers grumbling that the absolute accuracy of their works instruments cannot be guaranteed to 3° C. I think, sir, that shows things have "moved" in the meantime to an extent which few people would realize.

Dr. A. McCance: I did not intend to cast any slur on the manufacturers. I was simply mentioning one or two difficulties that I have been up against during the last three or four years due to the instruments used, and I am glad to have Dr. Harker's assurance that the matter is being investigated.

M. Le Chatelier, writing after the meeting, was glad to see Mr. Cosmo Johns recommend the use of optical pyrometers in metallurgical works. The reasons why they had not been greatly used up to the present were not so much on account of any difficulties or sources of error inherent in such instruments, but because few engineers having had occasion to make photometric measurements they regarded such measurements as difficult and preferred direct-reading apparatus. Optical methods, however, involved less serious errors than electrical methods of measuring high temperatures. Thermoelectric couples were of great service in the laboratory in the hands

of observers familiar with their use. But in the works they easily got out of order, and even skilled observers would allow considerable errors to pass unperceived. Total radiation pyrometers, which received the heat rays on a small thermoelectric junction, were even more dangerous on account of the difficulty of maintaining at a constant temperature the cold junction made by the case of the apparatus.

On the other hand, optical pyrometry depending on monochromatic radiation was subject to no such important errors provided a flame and not an electric lamp was used as the standard. In the hands of almost any operator it would yield almost exact results, the accuracy of which would only vary a little with the experience of the operator. The use of this method necessitated, it was true, a correction on account of differences in emissivity between one body and another, if absolute measurements were required; but in industry the essential purpose of pyrometric measurements was to ensure constancy of temperature in a series of successive operations. Incandescent bodies would always retain the same emissivity, and ignorance of its magnitude would not in any way interfere with the value of comparative measurements.

Mr. Cosmo Johns in his study has otherwise made all the corrections necessitated by the low emissivity of steel. He has perhaps taken unnecessary precautions in extending them to measurements made in the interior of a furnace. If the temperature there was absolutely uniform there would be no necessity to allow for emissivity at all; every point in the enclosure would radiate like a "black body," that is to say, would have an emissivity equal to unity. In reality there were small differences of temperature between one point and another necessitating a small correction impossible otherwise to determine. In approximating to 25° only instead of 100° or more one came very near the truth. In this manner one arrived at a temperature of 1,700° for the hottest part of a steel furnace. This temperature could hardly be exceeded, since silica bricks softened at about 1,750°. It was difficult to admit that the surface of the bath heated principally by radiation from the roof could attain a temperature higher than this latter figure.

Mr. S. A. Main, B.Sc. (Sheffield) (*partly communicated*): I think the Faraday Society is to be congratulated on the success of this meeting, as shown by the excellent set of papers it has brought forth, the number of exhibits, large attendance, and vigorous discussion. It is apparent that even more time might profitably have been devoted to the meeting. The last occasion on which a Symposium on Pyrometers took place was as long ago as 1904, under the auspices of the Iron and Steel Institute, through the instrumentality of Dr. Stead, Sir Robert Hadfield, and the late Mr. Brough. The subject has since been discussed in a rather fragmentary manner in individual papers, but the progress made is rendered strikingly apparent by the papers presented to this meeting. In this progress British instrument-makers have taken a large share, having spared no efforts in ascertaining the conditions under which pyrometers are employed and the various features influencing their accuracy. The success of Mr. Whipple and the Cambridge Scientific Instrument Company in producing an optical pyrometer which replaces, and in some respects improves upon, the German instruments, should be recorded. A large amount of work has to be done under the control of optical pyrometers, and serious difficulties would have arisen in connection with the output of munitions if this instrument had not been forthcoming.

The following remarks, which are based on several years' experience

with pyrometers in the works of Hadfields, Ltd., Sheffield, may be of interest:—

Pyrometers in General.—Various speakers have pointed out the necessity for considerable intelligence in the use of pyrometers. I think this point cannot be too strongly emphasized. A pyrometer is not, for example, like an ammeter or voltmeter, which, if made by a reliable firm, may be used with little expert knowledge to obtain accurate readings, and with little attention to the instrument itself. A pyrometer may vary, not only in itself, but according to the manner of usage. It requires constant supervision. An ordinary workman may be trained to use and take readings with the instrument, according to specific instructions, but the care and responsibility must be placed in the hands of one of the staff, with a proper knowledge of the principles involved. In other words, it is not sufficient merely to buy a pyrometer, but also to have an acquaintance with the science of pyrometry. With knowledge of the principles, the most suitable pyrometer may be chosen, kept in calibration, and applied in the proper manner to obtain accurate results.

Thermoelectric Pyrometers.—The question of a satisfactory base-metal couple still remains to be solved. While it is quite true there are a good many base-metal couples on the market which are suited for the comparatively low temperatures up to 800° and 900° C., for temperatures above 1 000° C. there is still nothing to compare with Le Chatelier's original platinum and platinum-rhodium element. While supplies of these metals are available, there is nothing serious about this: even at present prices this couple pays for itself in the regularity of the heat-treated products. The fact is, however, that platinum is becoming more and more scarce, the price continually rises, and it is within the bounds of possibility that there may not be enough of these metals available for pyrometry—a serious prospect, having in view the large amounts which are being used for this purpose. Dr. Burgess, of the Bureau of Standards, has told me that base-metal couples are being successfully applied in America, but this being the case I do not think the same accuracy can be looked for, or obtained, in American works as in this country.

There are a number of quite excellent pyrometers on the market described as portable pyrometers. My advice with regard to these instruments is, take as little advantage of their portability as possible; have an instrument for each furnace or group of furnaces. Moving these delicate instruments about the works, to say the least, does them no good, and, further, the calibration varies with the surroundings and the levelling.

Optical and Radiation Pyrometers.—Our experience with radiation pyrometers has not been particularly favourable to their use, largely, perhaps, due to the conditions in a steel works being hardly suitable for their employment. There is a certain inherent time-lag in taking readings. It is true this may be minimized by proper manipulation, but, as a previous speaker has pointed out, the conditions are often such that only a matter of two or three seconds is available for the reading. Another trouble we have found is due to the unequal heating of the instrument itself by radiation from the furnace, which affects the zero. This type of instrument has, however, the advantage of being direct-reading, that is, it does not require setting by the operator for each reading.

As between the two principal types of optical pyrometer, namely, the polarizing type, represented by the Wanner, Leskole, and Cam-

bridge Scientific Instrument Company's instruments, and the disappearing filament type, we have tried these side by side, and our experience is in favour of the former. With the same amount of care both types of instrument give equally accurate results. The polarizing type, however, has no inherent lag, a reading being obtained as soon as the operator can make the adjustment. The disappearing filament type requires a certain interval of time for the lamp filament to acquire the temperature corresponding to the current which is put through. The polarizing type also has the great advantage of possessing a definite physical law, which may be expressed mathematically. This facilitates and checks the calibration, especially if one of the calibration charts shown among the exhibits of Messrs. Hadfield (see p. 360) is made use of. A resulting advantage is, the extrapolation to higher temperatures is more accurately carried out by following the same law.

The following figures regarding the wave-length of the coloured glass used in optical pyrometers may be interesting, as supplementing those given by Mr. Griffiths. The figures have been obtained by calculation from the calibration curves of a number of instruments. The average of a number of instruments made by the Cambridge Scientific Instrument Company is 0.650μ , with a mean variation of ± 0.009 . The average of the German-made Leskole instrument is 0.653μ , with a mean variation of ± 0.0075 . These figures show that the glass used in the English instruments is of the same average colour as that in the German instruments, but is rather more variable.

The principal trouble experienced, however, is in connection with the "neutral" glass which is interposed for the higher temperature measurements, such as those on molten steels. This glass we have found very much increases the effective wave-length, the average of several instruments made by the Cambridge Scientific Instrument Company with the neutral glass interposed being 0.689μ , with also a mean variation of ± 0.025 . Not only, therefore, is the glass not so neutral as required, but it has also shown considerable variation. As the question of emissivity corrections is mostly connected with these higher temperatures, this is a point which should be seen to. One or two instruments show a satisfactory wave-length both for the low-reading scale and also for the high-temperature scale with the neutral glass interposed. We have found in some instruments a departure at the lower ends of the scale from the proper law, the angular motion of the analyser for a given temperature being lower than indicated by the law, the remainder of the scale being quite satisfactory.

I should like to point out that there is need for a good recording optical pyrometer. Such instruments, of the radiation type, are already available, but, as mentioned above, these do not, in their present form, quite meet the conditions in a steelworks.

Brown Control Pyrometer.—It may be interesting to members to have the results of our experience with this apparatus, shown among the exhibits, which we believe to be the only one in this country. The electrical arrangements we have found to work very well—that is, the instrument quite reliably actuates the main switch controlling the current, according as the pyrometer is reading above or below the control temperature. We have found some difficulty, however, owing to the fact that the thermocouple is of base metal, and rather heavily lagged, so that the furnace itself may fluctuate in temperature between fairly wide limits without producing corresponding fluctuations in the temperature of the couple itself, which latter, of course, is what actuates

the control pyrometer. If a similar pyrometer could be devised, but making use of a platinum-platinum-rhodium couple, the latter having less heat capacity and requiring less protection, improved results would be obtained. This point would apply, however, to a less extent with larger furnaces, where the couple is better able to follow the more sluggish temperature changes of the furnace.

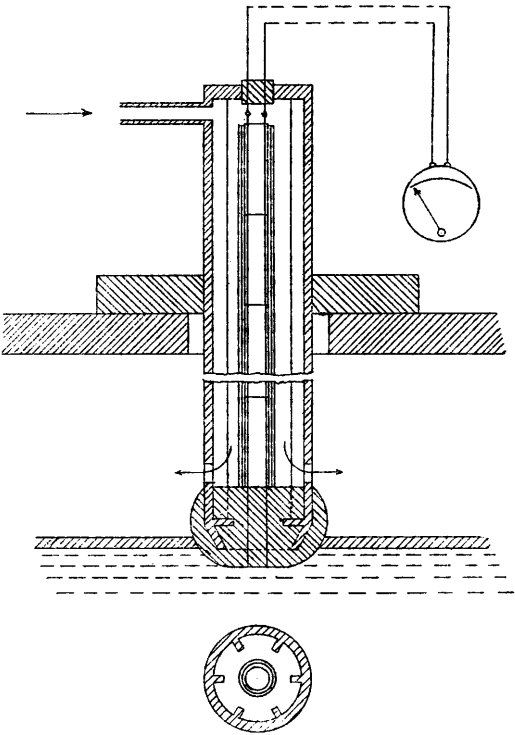
Mr. John Rhodin: With regard to optical instruments which are dependent upon colour, they are so subject to the personal equation that I do not think the optical comparison of temperatures will ever replace the radiation type or the thermocouple. We have an example before us. I remember before the penumbral apparatus was brought out that when adjusting the polarimeter the variations covered 15 deg., and now the penumbral instrument has practically replaced all the original polarimeters which depended upon specific colour. Hence, to call an optical pyrometer an instrument for measuring temperature I do not think is quite correct, because, after all, the intensity of the temperature is actually the radiation, and the temperature is the fourth power of the radiation. We were unfortunate in beginning our temperature system at a time when physics was not so developed as it is now. We started with the expansion of mercury or water, but we found afterwards that this gave not an intensity scale but an energy quantity scale, and that the very latest development in pyrometers, the thermocouple, is independent of its dimensions and hence measures intensity. Our best way now would be to reason and go back to defining temperature as a function of the radiation; but that is a wider subject. I do not think the optical pyrometer is the thing.

Dr. F. Rogers (Sheffield) said he was not satisfied with radiation or optical pyrometers for work upon molten metals. He had for long sought to use thermocouples without success, but recently he had had success with the method which he described (see Fig., p. 317). The ends of the thermocouple wires have refractory material (clay or moulder's compo, etc.), moulded about them and firmly into contact with, and even over the end of, the sheath. The ends of the wires are not united to form a thermocouple, but they are placed in contact with the molten metal. A perfectly steady reading is instantly obtained, and in the majority of applications the pyrometer can then at once be withdrawn before the stem becomes heated sufficiently to damage it, although in actual tests of several minutes' duration the pyrometers had not failed. Merely the tip is heated to the temperature to be measured, and possibly the wires melt or alloy with the molten metal for a very short length, perhaps $\frac{1}{16}$ -in. but the electric circuit remains continuous, and the net effect corresponds to what would be given by a thermocouple of the two wires simply, under otherwise similar conditions. When the stem of the pyrometer is exposed to flame, as in the open hearth furnace, it may be air cooled. The air enters the sheath near the head, and blows out through holes a little above the end. All trouble with the cold junction is very conveniently avoided in this type by simply placing the cold junction inside the sheath near the air blast inlet.

He had not yet made a thorough calibration of a pyrometer of this type, but gave the following examples of readings obtained in trials. In each case a galvanometer was used whose readings when used in the ordinary way with the thermocouple were approximately correct, and for the trial the resistance stated was used in series. In the final column is given the temperature calculated from the ratio of the resistances, but this does not give necessarily a very accurate idea of the temperature.

In each of these trials the end of the pyrometer was actually immersed in

No.	Trial.	Resistance of Galvanometer and Ordinary Thermocouple Circuit.	Additional Resistance in Series.	Steady Reading.	Temperature Calculated from Relative Resistance.
1	Solidification of cobalt-chrome high-speed steel, in crucible ...	132 ohms	100 ohms	863	1,530
	Solidification of copper (in open furnace) ...	Ditto	Ditto	600	1,062
3	Temperature in 70-ton acid open hearth steel furnace, during melting down ...	54	24	850	1,450



the molten metal for several minutes ($3\frac{1}{2}$ minutes in trial 3), as they were intended to be of the nature of endurance tests, *inter alia*. In trials 1 and 2, air cooling was not used. In trial 1 the wires were in one outer sheath; in trial 2 they were in two separate sheaths. In trial 3 the stem was air-cooled, and was about 9 ft. long, massive, and was clad with heavy clay sleeves.

He felt every confidence that they now had a really practical and sensitive method of obtaining the temperature of the molten metal, in the bath or in the crucible. This was essential for really complete control, for so

long as the temperature in making open hearth steel could only be effectually taken after tapping the furnace, practically they had burned their boats—there were very few means of control remaining at that late stage. This was particularly important, not only in regard to teeming temperature, but as regards “condition”—that was, deoxidation—of the metal. The first developments of the open-end couple were made in conjunction with Mr. P. R. Kuehnrich and Mr. J. F. Kayser in experiments in the crucible at the Spartan Steel Company's works, Sheffield. The experiments on the acid Siemens furnace were made at Messrs. Taylor Bros. & Co.'s Works, Leeds. He thanked both firms for permission to publish the respective results.

(*Communicated later* :) Although Mr. Darling's suggestion (see further, p. 346) did not go all the way, yet in one respect it resembled the pyrometer which he (Dr. Rogers) had described, in that the thermocouple metals were not directly joined to form a couple, and they might even be in the fused state. As it appeared to him, however, Mr. Darling's suggestion would not lessen the difficulties with sheaths, especially if one attempted to use it in molten ferrous metals, which would alloy with the graphite contact block, unless it were enclosed in a suitable sheathing; but the point was that it would doubtless extend the usable range for given thermocouple metals, as in fact the method which he (Dr. Rogers) had described above had certainly done.

Mr. P. Peakman (Manchester) : Technically, accurate high temperature measurement experiments are exceedingly interesting and useful, but for the man in the shops, i.e. on the steel furnace, in the ironfoundry, or the hardening shop, they mean little or nothing, and hence their practical value is very small.

For all who are in touch with the works find such terms as “bright red” and “dazzling white,” etc., in common use, and intelligent use, and the good results met with in practice almost warrant the disuse of pyrometric control.

However, my experience in temperature control, both in heat treatment shops and foundries, is that as long as the man on the furnace has some means of checking his judgment by eyesight, even without knowing the actual temperature of the work, that is all he needs, and this type of control lies easily within the reach or scope of the simple thermocouple.

For example, in the hardening of high-speed steel, the couple can be inserted into the bottom or side of the furnace, but not entering into the high temperature zone.

The actual furnace temperature is then found by means of salts or metals, or by means of an optical or radiation pyrometer; the temperature of the couple is then noted, and checks are taken to correct periodically the temperature gradient, e.g. :

Actual Furnace Temperature.
1,350° C.

Couple Temperature.
920° C.

Even supposing, however, that one has no means of taking the actual temperature, after one or two hardening experiments, the best result for a certain steel are obtained, the couple temperature is then noted, and all the subsequent hardenings are made at this temperature, as shown by the couple.

By this means a recording instrument can be fitted, so that records of the running of the furnace can be made and kept for reference.

The weakness of this method is of course “time lag,” but for all practical purposes this can be ignored, especially where the furnace is in use for long periods of time.

The great advantage of this method of control is that a permanent record can be made automatically for each furnace. It can be adapted to all classes of furnaces and ladles, etc.

At any rate, this method of control is better than that used in South Wales, where a board is painted a special tone of red, and when the furnace is the colour of the paint, then it is supposed to be correct; or even still better than using a particular tint of orange peel, for the best temperature at which certain components for cycles may be carburized.

For calibration of thermocouples I have found that an excellent method is to use a piece of steel of known carbon transformation point, for by this means there is no danger of interaction between the metal of the couple and the material in which it is placed for calibration. It is, however, important to drill a fresh hole for each calibration, otherwise the film of oxide may interfere with the test or change point, and entirely to prevent oxidation at temperatures of about 950°C . means a costly outfit.

Mr. C. J. Peddle (Derby) spoke on "Pyrometry as applied to the Manufacture of Glass."

It may be of interest to the meeting to have the experience of a worker in a sphere other than that of iron and steel. My field of labour lies in the manufacture of glass, in which industry pyrometry has been neglected in the past. Recently, however, the glass manufacturer has begun to appreciate the pyrometer and value it at its true worth.

In glass manufacture it is necessary to control the temperature (1) of the furnace, (2) of the molten glass in the furnace, (3) of the annealing of the finished article. The control of the temperature of annealing is the simplest of these three problems, because it is a low temperature, probably never more than 500°C ., which is being dealt with. This can be accomplished quite satisfactorily by means of base-metal thermocouples placed in the annealing chamber and reading automatically or at sight on a recorder.

The control of furnace temperature is a somewhat difficult problem in our industry, particularly where glass is melted in tanks or open pots. Although the furnace temperatures are considerably less than those in the iron and steel industry, being some 400°C . lower, yet the atmosphere of the furnace, where the glass is in actual contact with the furnace gases, is such that any thermocouple inserted through the roof or sides of the furnace has, as a rule, a very short life. The envelope of the couple is rapidly attacked, and the couple itself soon deteriorates. Where closed melting-pots are used, and vapours from the glass do not actually pass into the furnace, the thermocouple has a longer life and is more satisfactory.

More important than the furnace temperature is the actual temperature of the molten glass, and here the problem is widely different from that of the iron and steel industry. Direct insertion pyrometers are useless, owing to the attack of the molten glass on the envelope of the thermocouple. A fireclay envelope would quickly dissolve, and a metal envelope would tend to discolour the glass. Recourse therefore must be had to either the radiation or optical type of pyrometer. The former has the advantage in so far as it may be made automatically recording, but since this is not necessary when taking actual glass temperatures, and indeed cannot be done except over the short interval of time the glass surface is exposed for working, there seems little to choose as to the availability of the two types. My own personal preference is for an optical pyrometer of the Cambridge type. In a glass-pot there are almost ideal conditions for working an optical pyrometer. The

whole of the glass is enclosed except at the small sighting opening, and so an almost complete "black body" condition exists. To my mind it is a proof of the accuracy of a pyrometer when known glass conditions result at different times with the pyrometer registering the same temperature. An optical pyrometer responds to this test quite faithfully.

Radiation pyrometers of the Foster type tend to deteriorate badly after a comparatively short working life, due to the "peeling" of the mirror. This may be due to the somewhat rough usage so hard to eliminate from works practice.

Professor Arnold's remarks on the Mesuré and Nouel pyrometer were very interesting to me, because I have had considerable experience of that extremely useful instrument. It is small and does not require "setting." I most heartily agree with Professor Arnold that the personal equation with this instrument is considerable. Only in the hands of an experienced worker is it reliable. In working the instrument the analyser is rotated until the "sensitive" or "midway between red and green" colour is obtained, and the angular rotation is read. This angular rotation is transformed into centigrade temperature, using Pouillet's scale. On this scale a rotation of 40° corresponds with 900°C. , a rotation of 57° with $1,200^\circ$, and so on. In practice I find that different persons read a different "sensitive" colour when sighted on the same incandescent mass, and so Pouillet's scale is useless. To work the instrument properly each person using it must draw up his own scale of temperatures corresponding to different sensitive points, using a Cambridge optical pyrometer say, to standardize by. Then readings by two different observers will agree. As an example, I read 65° on the Mesuré and Nouel, and my colleague 67° ; but our actual temperature record was the same, say $1,250^\circ\text{C.}$, because my scale reading 65° is equivalent to $1,250^\circ\text{C.}$, whilst in his scale 67° is its equivalent. One bad fault with the instrument is its tendency to read high when it gets warm.

Being in the glass industry, I was interested in what Dr. Harker and Dr. McCance said about glass for optical pyrometers. There appears to be a want of glass of definite refractive index for lenses, etc., and also a demand for red glass which will only pass monochromatic light. Probably if instrument makers would specify exactly the glasses they require, work could be done and the glasses discovered. One melting would supply glass enough to last the optical pyrometer manufacturer for a very long time.

Dr. Walter Rosenhain, F.R.S.: There is a great number of very interesting questions raised by these papers. Perhaps the most important thing that has been said to-night is one which has been a little neglected in the discussion, and that is the importance of not only obtaining a correct temperature, but of finding the temperature of the object wanted, and not of something else. The use of pyrometers is becoming fashionable at the present time. They are used extensively, and in many places they are employed in a manner which is worse than useless. It is absolutely necessary to realize that putting a pyrometer into a furnace will not necessarily give the temperature of the articles, metal or otherwise, which are heated in the furnace. Dr. Hatfield draws attention to this, and gives an example from the practice of his own works, which is typical of the best way, or one of the best ways, in which the thing can be done. One can carry it a step further still, and not only make a preliminary trial run in order to discover the rate at which a given mass in a furnace acquires heat, but one can actually in some cases introduce with the working charge a dummy article with a thermocouple in its interior. In the case of a charge of 20 or 30 small things, one or possibly two are put in with holes in them with thermocouples in the

holes. If the temperature of these couples is taken, that gives a result which is quite different from the ordinary temperature of the furnace. That is not everywhere possible, and consequently it is no doubt very desirable, as Dr. Hatfield mentioned, to be able to calculate from the known physical constants of the material the time it will take thoroughly to heat up a given mass, but I am afraid there are difficulties in the way. There are a good many factors, some of which Dr. Hatfield mentions himself; but so far as the thermal conductivity is concerned I warn him that it is not sufficient even approximately to take the thermal conductivity of the metal at the ordinary temperature from 100° down to 0° , but that it is necessary to determine the thermal conductivity and the specific heats also at the high temperatures involved in the work. At Teddington we have come across the problem in quite a different connection in regard to aluminium alloys, and my colleague, Dr. Griffiths, has developed a method of determining the thermal conductivities at temperatures up to 900°C. , and he could possibly go to considerably higher temperatures. With regard to conductivities, I am not surprised that Dr. Hatfield has found large differences in thermal conductivities between various alloy steels. Sir Robert Hadfield has mentioned that manganese in steels acts as a bad thermal conductor. Curiously enough manganese carries that property into other alloys. One per cent. of manganese produces a large effect in depressing the thermal conductivity of several alloys. Nickel is not so bad, although with 25 per cent. the thermal conductivity of nickel steel is very much lowered; but it is evident that these differences are large and will have to be considered in the treatment of alloy steels.

With regard to the question of pyrometry of non-ferrous metals by means of optical instruments, I would raise the point that although the figures Professor Donnan has given are very interesting, their interest is, perhaps, more theoretical than practical. Any one who has used both types of instrument, however, in this connection will think that the thermocouple is the more useful. Dr. Rogers, in putting his platinum iridium wires in fireclay, or some other substance, is not risking the wires but condemning them. These wires will not stand that treatment, and they will become seriously damaged by silicon and be very rapidly destroyed. The saving grace of the method is that the exposure is only for a few minutes, but I am quite sure that the consumption of platinum wire by that method will be extremely large, and the risks of error also very large indeed. I think the future, after all, with these very high temperatures must lie with some form of pyrometer the sensitive members of which are outside the furnace. If you have to put things into the furnace at the temperatures of melting steel, I am inclined to think that their life must be short, although it may be merry.

Dr. F. Rogers later wrote that Dr. Rosenhain's criticism was not found to apply materially in the actual and reasonable use of the pyrometers. Probably Dr. Rosenhain was under the misconception that the pyrometers must be immersed for a long time in the molten metal, which was generally not the case. The plan of the trials recorded included the fairly long immersion in order to test the durability and reliability of the pyrometers, and he would emphasize the fact that in practice in the majority of cases it was sufficient to immerse the tip of the pyrometer for from 2 to 10 seconds only at a time. There was no lag with the naked wires in contact with the molten metal. It was possible to grind a layer off the tip of the pyrometer if ever one felt a doubt that it had been affected by use, and so get back to fresh material in a moment. He would repeat that this had already proved a valuable practical method, although its exact standardization yet remained

to be carried out, and he hoped that the N.P.L. might have the means of co-operating in that aspect of its development.

Mr. Walter Carter: I think that pyrometers are generally sold too cheaply, with the result that the maker is not able to give the assistance to the user that is sometimes necessary.

It cannot be expected that all users of pyrometers can be well acquainted with the upkeep of these instruments, and if the margin of profit were greater, it would then be possible for pyrometer makers to enable their representatives to pay more frequent visits to users.

One of the undesirable features of many pyrometers is that they are not made sufficiently robust. They are doubtless quite proper for laboratory use and practice, but in many cases are lacking in essential details and robustness for works practice.

It should not be overlooked that pyrometers are frequently used under dirty and other arduous conditions. It is also difficult at times and under certain conditions to read the scales, and it might be worth while considering an attachment to a pyrometer which would enable the dial to be easily and continuously illuminated from a source of light not visible to the operator. This would not be a difficult matter should a pyrometer maker really give his mind to the problem.

The next point is that there is room for two totally different kinds of pyrometers. For many purposes it does not matter how much a pyrometer may be registering incorrectly so long as it is permanent and not variable in its readings, and as to whether it is 20° or 50° wrong is really of no practical moment. The essential feature of a pyrometer of this kind is that it must not vary. The views of the pyrometer makers as to whether this feature is possible would be much appreciated.

I realize, of course, that for other purposes it is necessary to have a pyrometer registering as accurately as possible, as such pyrometers can be calibrated regularly. It is not, however, always possible or even sometimes desirable to have pyrometers registering accurately, but, to repeat, it is very desirable that such pyrometers shall be very constant.

The **Chairman** thought the meeting would like to hear the point of view of the pyrometer maker on some of the criticisms that had been made by Mr. Carter and others. He asked Mr. Whipple to reply briefly.

Mr. R. S. Whipple: About three months ago I spent a pleasant afternoon with Mr. Carter going through his hardening shop and other works, and in a very friendly way he offered suggestions for making pyrometers more suitable for the rough treatment meted out to some of them in practice. We are trying to take advantage of that advice.

I do not think the users of pyrometers realize all the difficulties of the pyrometer maker. In some cases he is asked to make the scale on which the instrument reads as open as possible, and to obtain this result a sensitive instrument has to be constructed, and this, unless very special precautions are taken, involves difficulties with the stability of the zero, creep, etc. The majority of users do not realize how much the accuracy of their work depends upon the position in which the pyrometer is placed in the furnace. I remember very well going into a large works in Birmingham where complaints were made that the instruments were not reading as high as they should have done. I examined one of the pyrometers and found that it was mounted through the

top of the furnace, the head being practically on the top of the brickwork. I suggested that it would be advisable to place the pyrometer horizontally, and the result was that the apparent temperature on the indicator rose by 105° C. It was obvious that when the pyrometer was mounted vertically the cold junction was roughly 100° hotter than in the horizontal position.

In the majority of cases sufficient care is not taken in selecting the position in which the pyrometer should be placed in the furnace. Pyrometers are generally broken mechanically and are not burnt out.

With regard to the optical pyrometer, I think it must be admitted that the subject has advanced a great deal during the last few years when a gentleman of Mr. Cosmo Johns' position can demand an accuracy of 2° when working at $1,500^{\circ}$ C. He would not do this if it were not for the fact that he believes it may be possible to obtain the desired accuracy.*

The Cambridge optical pyrometer is, after all, the old Abney colour box as modified by Koenig and improved by Wanner, and is capable of work of high precision.

The question arose as to whether it would be an improvement to fit a vernier to the temperature scale on the instrument so that the scale could be subdivided. After consideration we came to the conclusion that no higher accuracy would be obtained if such a vernier were fitted. With a little practice one can subdivide a division such as a millimetre to an accuracy of $\frac{1}{10}$ th mm. with precision, and a vernier in such a case appears to be an unnecessary complication.

As Dr. Harker stated, the obtaining of monochromatic red glass has been a great difficulty. The glass we are now using is supplied by the Corning Glass Company of Rochester, New York. This firm has devoted a great deal of time to the production of monochromatic glasses.

I think that in future we shall have to ask Sir Richard Glazebrook to add a statement on his certificates of test as to the limits of wave lengths of the light passed by the coloured glass on the instruments. This could readily be determined for every pyrometer, and would, I believe, add considerably to the value of the standardization.

Mr. C. R. Darling (*communicated*): Dr. Hatfield in his Paper draws attention to the important practical problem of the heating of masses of steel in furnaces in relation to the time required for heat to penetrate to the interior. Some figures bearing on this question were first published in my book, *Heat for Engineers*, 1st edition, 1908, and refer to mild steel billets of circular section. The results were obtained by inserting a thermal couple in the centre of the mass, and noting the time required for the centre to attain $1,900^{\circ}$ F., the temperature of the furnace being maintained at approximately $2,000^{\circ}$ F. The diameters of the billets ranged from 18 in. to 45 in., and the time required from $3\frac{1}{4}$ hours in the first case to $19\frac{1}{2}$ hours in the last. An examination of the figures shows that the time required varied nearly as the square of the diameter; that is, directly as the area of section. Experiments of this kind on test ingots, of the same dimensions and composition as those operated on in practice, would furnish the necessary data in all cases, and a reliable set of figures relating to various sizes and shapes of different kinds of steel would be of great value. Such figures would be far more reliable than those

* *Note added December 5th.*—In the present state of our knowledge it is admittedly impossible for any one to measure a temperature of $1,500^{\circ}$ C. by an optical pyrometer to an accuracy of 2° . The gas scale temperatures are not known to this accuracy at this temperature, and the black body conditions under which any observation of such temperatures is being made must be considered most carefully. Given satisfactory black body conditions it may perhaps be possible to measure a temperature of $1,500^{\circ}$ C. to an accuracy of $\pm 5^{\circ}$ C.

deduced from determinations of conductivity and specific heat, both of which, as Dr. Hatfield points out, vary to such an extent with the temperature as to render calculations uncertain. With reference to Dr. Northrup's pyrometer based on the expansion of molten tin, it may be mentioned that Dufour, in 1900, suggested molten tin in a quartz envelope for measuring high temperatures. The objection to this in practice would be the devitrification which quartz undergoes at elevated temperatures, and the graphite enclosure used by Dr. Northrup would appear to give promise of a serviceable instrument. In some recent experiments in which artificial graphite was used, I found that prolonged heating rendered the graphite very friable; and if this be a general property of graphite, Dr. Northrup's instrument would require careful handling. Possibly, however, the graphite I have used has not been of the best type.

Mr. W. J. Rees (*communicated*): A lengthy experience of the use of radiation pyrometers of the Féry type in a glassworks has shown the absolute necessity for protecting the mirror from the tarnishing action of sulphurous gases, more particularly when the instrument used is in proximity to a glass furnace melting a salt-cake batch. Very slight tarnishing causes the reading to be appreciably low. The best protection is afforded by fitting a thin plate-glass window to the Féry telescope; the instrument then needs calibrating with this in place. The earlier type of Féry telescope, in which a quartz or fluorite lens was used instead of a plated concave mirror to focus the radiation on the thermopile, had advantages for works use, as it was completely enclosed.

The Wanner optical pyrometer was also found of great value after an observer had obtained sufficient experience in its use. The observations of a trained observer were dependable within $\pm 5^\circ \text{C}$. at temperatures from $1,100^\circ$ to $1,300^\circ \text{C}$.

Reference was made to the difficulty of obtaining in this country monochromatic ruby glass for use with optical pyrometers of the Cambridge type. Tentative experiments have shown that there is no insuperable difficulty in the manufacture of this ruby glass, in which colloidal copper is the colouring ingredient, and as the required quantities are so small, manufacture on the laboratory scale would probably be sufficient. It is obviously desirable that the monochromatic glass should be made in this country, and it is to be hoped that one of the glass research laboratories will produce the necessary supply. A paper on "The Effective Wave-length of Transmission of Red Pyrometer Glasses" * was read before the American Physical Society in April, 1915, by Messrs. Hyde, Cady, and Forsythe, of the Vela Research Laboratory, and reference is made to the use of Jena "Kupferrubin" glass, No. F. 2745, and Jena "Rotfilter," No. F. 4512. Waidner and Burgess, Pirano, and others had recognized that, owing to the breadth of the transmission band, the effective wave-length of monochromatic light is subject to change with change in spectral distribution of the incident radiation, as occasioned by changes in temperature of the radiating source, and the authors determined the effective wave-length between two definite temperatures of a black body and the change in this effective wave-length with changes in the temperature interval.

Mr. Alleyne Reynolds (Hove) (*communicated*): It is now twenty years since I have had daily to measure temperatures reliably and quickly when hardening fire tubes, armour plates, etc., and I was much disappointed at the absence of any practical advance indicated in regard to enabling the

* The *Physical Review*, vi. 1, July 1915.

heat treatment of large thin forgings to be better conducted. I will go further and even say that my general impression is that a pyrometer, as apparently generally employed or even capable of employment, is from the manufacturer's point of view about as dangerous a weapon as an automatic pistol in the hands of a schoolboy. There was no attempt at any specification of demands to be fulfilled by a pyrometer or of precautions required to be observed in using one.

I only found two pyrometers of any real use in the "nineties," viz. the Mesuré and Nouel optical pyrometer and a piece of fairly dry pine lath. I had started elaborating others when I ceased to require them, owing to change in my occupations. All attempts to employ refined pyrometers for deciding the moment when to quench large forgings must result in greater error than that of a practised eye, unless quick and reliable readings are securable. So far back as over twenty years, aided by a grand crane and simple tackling and other devices of my own, I thought nothing of cutting down the time from full heating of the forging to its immersion in the oil tank to occupy only five minutes. That is to say a large "A" tube 40 to 50 feet long was so handled that pyrometer readings top, bottom, and middle were taken, it was attached to the crane, lifed out of the furnace and fully immersed in the quenching tank within five minutes of first interfering with its heating. This depended on simple but good devices being employed. The lifting tackle seized the tube safely without exercising side pressure on it, and in spite of pendulum swing engaged it quickly and safely.

Pyrometer readings were taken through a 2-in. gas pipe passed through sight holes up to the surface of the forging, and the flame could be cut off and restored full bore in one second of time. I should now employ more refined gas-valve operating devices, and the inspiration for these may be taken from many old devices for operating the reversing gear of locomotives. An excellent device for the purpose would be one I saw over twenty-five years ago on some North-Eastern locomotives. This was a combined screw and hand lever reversing device. The pawl on the hand lever, in lieu of engaging in a sector plate, engaged in a coarse screw thread cut in a barrel of the same curvature as a sector plate would be. Thus the driver could extremely quickly release the pawl and let the engine into full gear, and equally quickly pull the lever back and let the pawl fall into the same portion of groove as it had been when finely adjusted by means of using the screw to operate it.

I found that my assistants and myself varied hardly at all in our readings with the same or different Mesuré and Nouel pyrometers, but we found the scale furnished by the makers unreliable, our readings varying some 40° to 50° C. therefrom. Now, the proper quenching temperatures were ascertained by the laboratory staff using a refined thermocouple pyrometer for the purpose, and therefore, whether that were correct or not as to the actual temperatures, the important thing was to heat the forgings to the temperature which the laboratory pyrometer had demonstrated to be required. I therefore trained myself and my assistants in using simple pyrometers *to take reliable readings of the laboratory pyrometer.*

For this purpose I used a 2-in. gas pipe with a closed end immersed in a lead bath in which the end of the refined pyrometer was also immersed, and further, the reading of the latter was only able to be made in an ante-room, so that when making my readings I did not even know the electrical pyrometer readings. A system of signals was arranged, and I and my assistants and the laboratory staff took readings and noted them simul-

taneously, and only compared them when the tests were completed. By these means human errors and obsessions were reduced to a minimum.

Also, using a pipe of the same length and diameter as the closed-ended one for taking readings of the forgings, errors due to varying fields of vision were eliminated.

I found the optical pyrometer only reliable over a range of some 150°C. , but repeated tests in varying states of health showed it reliable within that range.

For lower temperatures I found only one pyrometer reliable, and reliable to a most astonishing extent, that is to say, within 10° over a range of some 200°C. The pyrometer in question was a wooden lath some $\frac{3}{4}$ -in. \times $\frac{3}{8}$ -in. section, cut to a knife edge. Differences of dryness had within reasonable limits very little effect. Varying degrees of fuming with or without friction, sparking, free sparking, flaming only when rubbed, just igniting, etc., gave a sensitive and reliable scale.

This was established on similar lines to the scaling of the optical pyrometer. A 2-in. diameter solid bar of iron was heated in the lead pot, and the laths were tested on this.

I had commenced investigations on various graduated wax, fusible metal and other bars pressed in contact by means of springs in tubes for a given unit of time, when, as before stated, I had to drop the work. I think something may be elaborated on these lines.

Using double tubes, outer ones of fused silica or plumbago, sufficient insulation for quick reading may be secured.

Again, by means of graduated screens so that the point at which a mark ceases to be visible is read, a field for development of a rapid reading pyrometer is indicated, and for final record a photograph through a chessboard type graded negative at constant distance and pin-hole with constant spring shutter is again a promising line to follow up.

I would emphasize that the work will be better done by an eye trained at reading in a closed ended tube as indicated, than by any pyrometer which takes above 15 seconds to give a reading of the work treated.

A misused or inapplicable highly scientific instrument is a most dangerous tool to introduce into the actual factory.

Mr. W. Bowen (Leeds) (*communicated*): Referring to the paper by Mr. Cosmo Johns, I take it that his object as a metallurgist is to control the temperature of the steel before pouring; in which case, I would suggest that the proper place to measure his temperature is when the steel is inside the furnace, and that temperatures taken subsequent to tapping the furnace serve to control the final pouring temperatures only.

Mr. Cosmo Johns appeared to place too great confidence in the accuracy of his readings within $\pm 5^{\circ}\text{C.}$ at the pouring temperatures of steel. In the light of the paper by Dr. Griffiths, his appeal to the pyrometer makers to construct an instrument accurate to within $\pm 2^{\circ}\text{C.}$ at these high ranges would seem to be unnecessary at the present stage. Dr. Griffiths states (p. 223): "The practical difficulties of gas thermometer work at high temperatures are very considerable. . . . Consequently the results obtained by different investigators often show divergencies of serious magnitude." Also, an experiment described by Dr. Griffiths shows that taking the melting-point his results compared within 3°C. under very favourable conditions. These remarks clearly indicate that as yet the scale of temperatures in the region of $1,600^{\circ}\text{C.}$ is an almost unexplored field even under laboratory conditions, and that readings comparable within 3°C. are considered remarkably good. Hence I suggest that the demand made by Mr. Cosmo

Johns for a pyrometer accurate within $\pm 2^{\circ}\text{C.}$ under works conditions of a very unfavourable nature is an ideal one impossible in the present stage of development to fulfil. Any readings obtained for molten steel under works conditions such as Mr. Cosmo Johns describes should be considered very good if they can be relied upon to within 10 or even 20 degrees.

Mr. Cosmo Johns described the careful precautions taken by him in reading the temperatures of molten steel by means of an optical pyrometer. May I suggest that now that he has realized the necessity for such precautions, he would probably secure equally comparable readings by the use of the simpler radiation pyrometer by adopting the same precautions.

Mr. Cosmo Johns uses an emissivity factor of 0.50 in correcting the temperatures of Table I of his paper, and a factor of 0.40 in Table II. I fail to see how he arrives at these emissivity factors in the two cases. It appears to me a very difficult matter to ascertain an emissivity factor to correctly fit the case, seeing that he acknowledges a difference between the apparent temperatures at the top, middle, and bottom of the same stream; also that he probably experiences occasional flashes of light at times, and possible haze at other times, momentary though they may be.

Mr. Carter in the discussion has apparently no recent experience of at least one firm manufacturing pyrometers, when he states that the manufacturers neglect to advise and visit their customers when trouble arises. This is not the case in general.

Professor J. O. Arnold, in responding to the Chairman's invitation to reply, said: I have only one remark to make in reply, and that is this. Dr. Hatfield said he would present to us the facts with regard to pyrometry of the Siemens furnace. These facts he could have obtained from the University records from 1910 onwards. The practical point about the Siemens furnace that we have arrived at to-night is this, and with it I quite agree: that the flame temperature inside the Siemens furnace is from $1,700^{\circ}$ to $1,750^{\circ}\text{C.}$, and that of the molten metal varies from perhaps $1,575^{\circ}$ to $1,525^{\circ}$. These figures, which Dr. Hatfield has confirmed with a thermocouple, are extremely interesting, and I think we may take it that we have by this discussion arrived at these two solid facts.

Mr. Cosmo Johns, in reply to the discussion on his paper and the communications received after the meeting, writes that he is pleased that so much interest has been aroused in the subject. Unfortunately, many of those who discussed the paper failed to notice that all the observations on liquid steel recorded were made to determine its "apparent" temperature, and that the accuracy claimed only referred to comparative readings obtained with the particular type of instrument employed by trained observers with long experience under the conditions described in the paper. No suggestion was made that the readings employed could be corrected to give real temperatures on any of the accepted scales to the degree of accuracy mentioned. What was claimed, and the claim is now repeated, is that under the most favourable conditions the "apparent" temperature of "clean" surfaces of liquid steel can be read to $3^{\circ} \pm$ on the scale of the instrument employed, and under ordinary works conditions to something less than $5^{\circ} \pm$.

The degree of accuracy obtained depends on several factors, and it might serve some useful purpose if these are briefly referred to. If the instrument employed uses monochromatic light, readings can be reproduced with greater accuracy than when rays of more than one wave-length are transmitted. In the best type of instrument, the line dividing the two

halves of the field entirely disappears when correct adjustment has been made by the observer. Accuracy in this case depends on the skill of the observer and the quality of his eyesight. As a rule, not less than three months' training is required for an observer to acquire sufficient skill in the use of an optical pyrometer for the work described in the paper. The records given were made by an observer who has been engaged for three years in regular practice. Three observers have been tried with the same instrument on the same clean surface of liquid steel, and the readings they obtained always varied less than 10° from each other, and on several occasions the total variation was only 5° . As a rigorous test of the degree of accuracy with which readings might be reproduced, a trial was arranged with three observers, using the same instrument. The object selected was the interior face of a furnace wall kept as nearly constant in temperature as possible. The scale of the instrument was covered with a paper shield, and after the observation had been made the screen was removed and the reading noted by the present writer and one other observer, who was waiting his turn to use the instrument. When the reading had been noted the pointer was displaced and the paper shield placed over the scale before the instrument was handed back to the original observer to reproduce the reading. The scale was read by estimating fractions of the divisions to the nearest quarter with a pocket lens. The results were as follows:—

Observer.	Readings.	Observer.	Readings.
Y	1,360	W	1,357.5
W	1,360	X	1,362.5
W	1,360	Y	1,360
Y	1,360	Y	1,362.5

The apparent temperatures given in Table III of the paper were made under similar rigorous conditions. The conditions were favourable in that the steel was at a lower temperature than when it issued from the tap-hole. The lower the temperature of the liquid steel, the greater is the accuracy with which observations can be made and repeated. As the effect of distance, angle of view, and curvature of surface of the liquid steel has not been completely investigated, it was decided to adopt a standard position for recording purposes. In deciding on the particular position to be adopted and the surface to be observed, the theoretical considerations came under review and many experiments made before a decision was arrived at. The suggestion made by both Mr. Bowen and Mr. Greenwood, that the temperature should be determined within the furnace and not when the steel has been tapped, amounts to a counsel of perfection. There does not appear to be any method available by which the temperature of the steel in the furnace can be determined with the rapidity and accuracy required. Control can, however, be effected by determining the "apparent" temperature of the surface of the slag in the furnace. This is being done daily in more than one works. The remarks of Mr. Greenwood, that he found that light emitted from liquid steel was polarized, and that the variations with different angles of view were of the order found with platinum, are of great interest. Dr. Burgess* found that polarization effects with liquid steel were nearly negligible, and such is the experience of the present writer.

It is to be hoped that Mr. Greenwood will be able to find an opportunity of repeating and extending his investigations on this point.

* Technologic Paper 91, Bureau of Standards.

It might interest Mr. Greenwood, and possibly other workers in the same field, to know that the present writer discarded the tripod for use with optical pyrometers. The instrument is held in the hands of the observer. For routine works readings a single observer can use the instrument and also keep the rheostat adjusted to give a constant current, but for the apparent temperatures given in the paper one observer used the instrument while the other looked after the accumulator box and adjusted the rheostat when necessary. With skilled observers it is possible to take a reading of the surface of the bath in the interval when gas is off the furnace during the periodical reversal. Inexperienced observers would naturally take more time to adjust the instrument for a correct reading, and in their case it might be necessary to put the furnace "on centre" for half a minute or even more.

Enough has been written to make it clear that optical pyrometers of the correct type can be employed to give readings of the "apparent" temperature of liquid steel of a high order of accuracy. These readings are comparable among themselves. The real temperature of the steel observed cannot be determined with anything approaching the same degree of accuracy.

More observations of the highest possible degree of accuracy are required on the effect of variations in the method of observing plane and curved clean surfaces of steel under various conditions. Instruments capable of being read with the accuracy suggested in the paper are required for such work. It is very desirable that the emissivity of a "clean" surface of liquid steel should be determined again. The value quoted by Mr. Greenwood is certainly too high. That found by Dr. Burgess, viz. 40, is probably a little high for an optically clean surface, though probably correct under most conditions in works practice. The remarks of M. le Chatelier are of special interest. The writer agrees that the corrections applied for the brickwork in Table I are probably too high and possibly nearer that suggested by M. le Chatelier than those given in the paper. The problem bristles with difficulties and much more research is required. The corrected temperatures given for the surface of the bath are, however, in the opinion of the writer very nearly correct. Any criticism must not overlook the fact quoted in the paper, that it has been found possible to fuse into liquid state the purest quartz sand when floated on the surface of the bath. This could hardly be achieved if the real temperature did not exceed $1,750^{\circ}\text{C}$.

The Chairman : I have listened with very great interest to what has been said, and I feel I have learned a great deal. We have done a great deal of standardization of pyrometers at the National Physical Laboratory with what I thought was high accuracy, but I confess I never realized that in these instruments the demand of industry was anything approaching two degrees; and it is quite clear that there is ample scope for careful collaboration between the makers, ourselves at the Laboratory, and those who are using these instruments. I will now ask Mr. Watkin to give a brief account of his paper, dealing with quite another branch of our subject.