XVI. *Iron and Steel at Welding Temperatures.*

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Communicated by Professor ROBERTS-AUSTEN, *C.B.*, *F.R.S.*

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[PLATE 17.]

IN 1879–80 I drew attention to a method of measuring the changes of volume taking place in cast iron while passing through the varying temperatures lying between its cold and its molten state.

If a ball of cast iron at atmospheric temperature be immersed in a vessel of molten iron of the same quality, it first sinks. In a few seconds it comes to the surface, owing to the heat penetrating and expanding the ball, which, causing increased displacement of the fluid metal, produces the increased buoyancy observed.

The increase of buoyancy does not stop here, as the ball continues to rise above the surface of the fluid metal to a considerable height, until it arrives at the melting point, when it rapidly melts down and joins the molten iron in the vessel.

An instrument was designed by me* to measure this change in the volume of iron. The principle of the instrument is based on the law of flotation of bodies in liquids, by which an increase of buoyancy in a submerged body is equivalent to an increase in weight of the displaced fluid.

The ball of cast iron to be experimented upon is hung by a chain and rods from a frame, and lowered over a pulley into a ladle of molten iron. The instrument is suspended between the chain and lower rods, and contains a spiral spring similar to that used in a SALTER'S balance; this spring is arranged so that the ball and rods hang with their full weight upon the spring.

If the ball be kept well below the surface of the fluid metal it will, in expanding, and displacing the fluid, relieve the tension on the spring to an extent equivalent to the weight of the displaced metal.

The spring is placed in a brass frame, on which is also mounted a cylinder, which revolves uniformly by clockwork. A pencil attached to the moving end of the spring presses against a sheet of paper wound round the cylinder. This vertical

* 'Journ. Iron and Steel Inst.,' vol. 2, 1879, p. 418.

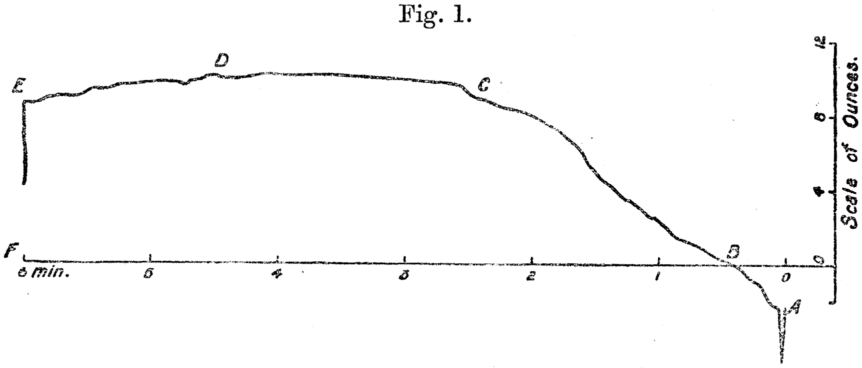
motion of the pencil, when combined with the horizontal motion of the paper on the revolving cylinder, produces the curve of volume.

The first operation is to hang a rod on the spring balance with a piece of wrought iron at the end, which is an exact facsimile of that part of the shank of wrought iron fixed in each ball which will eventually protrude above the molten iron when the ball is submerged. This weight brings down the spring balance to indicate from 1 to 2 lbs. The cylinder is then thrown out of gear and moved round, the pencil making a straight zero line, which represents the position when the cold and molten iron have the same specific gravity. The small piece of iron representing the upper part of the shank is then removed, and the actual ball put in place. This ball has been accurately weighed before, and its specific gravity also taken. Hanging it on the spring balance brings the index below the zero or equilibrium line. The ball is now lowered into the metal, the clockwork having been previously put in action.

A diagram is thus drawn during the heating and melting of the ball, of which the vertical ordinates represent change of volume in ounces of increased displacement, and the horizontal element represents time in minutes.

A number of diagrams were taken with 3-inch and 4-inch diameter balls, the specific gravities of which had previously been ascertained. The general character of these is shown on fig. 1, which is one of the numerous diagrams taken, in which B, F represents the liquid volume, and A, B, C, D, E, F the changing volume in passing from the solid to the liquid state.

Fig. 1.



4-inch ball of No. 4 foundry iron (Cleveland); poured from very hot metal; immersed in No. 4 foundry iron.

Weight of ball and immersed part of stalk	132	oz.
Specific gravity of ball, and immersed part of stalk .	6·95	
Maximum sinking effect	2	oz.
Maximum floating effect	11	,,

Specific gravity of fluid iron $= \frac{6 \cdot 95 \times 130 \cdot 0}{132} =$ 6·84

Specific gravity of plastic metal $= \frac{6 \cdot 95 \times 130}{143} =$ 6·32

Between A and B, fig. 1, the average density of the ball changes, until at B it has

become the same as that of the molten iron. It is at this point that a freely floating ball would just appear at the surface. The expansion beyond this corresponds to the gradual rising of a free ball above the surface, the disturbances in the flotation due to the cooling of the emergent part of the ball, and to the interference of the floating scoria in the more crude experiment, are obviated by keeping the ball submerged.

As the ball becomes hotter the curve flattens between C and D, the conduction of the heat into the ball becoming slower, until no further expansion takes place. Several balls, removed at this stage, were found complete in form, but so soft that a steel pin could be pushed right through them. This plastic condition of the mass remains for a short time, when it quickly passes into the liquid condition, the metal of the ball joining the molten iron in the ladle. Of course, so soon as the melting of the ball begins, the pencil no longer registers measurable changes of volume, as a reduction of mass is taking place, but the maximum volume of the ball can be measured in the plastic condition, and the volume when it reaches the liquid condition being known, it can be stated with certainty that it passes rapidly from one condition to the other. The conducting power of iron is so good that little wasting of the surface takes place, until the whole ball from surface to centre is in a plastic condition, and then it very rapidly melts and joins the bath; as shown by the sudden drop of the curve at E.

The mean average of a number of experiments upon grey Cleveland iron led me to conclude that the

Specific gravity of the solid iron at atmospheric temperature was	6·95
That the specific gravity of the molten iron was	6·88
That the specific gravity of the plastic iron was	6·50

In other words, while cast iron passes from the solid to the liquid state its volume is at its minimum when the mass is solid. As the temperature rises the metal first expands 1·02 per cent., and then has the same specific gravity as the liquid metal, viz., 6·88. It then continues expanding until it reaches the plastic condition, when it assumes its maximum volume with a specific gravity of 6·5, the total increase of volume from the solid to the plastic state amounting to 6·92 per cent.

After this, expansion by heat ceases and a quick contraction takes place, until the mass becomes liquid, when its specific gravity is, as before, 6·88. If this is expressed in terms of the volume of liquid iron, taken as 100, the volume of the solid iron at atmospheric temperature is 98·98. That of plastic iron is 105·85, in which condition an increase of heat to the melting point reduces the volume to 100, representing its liquid condition.

These changes of volume were much greater than was expected, and it was thought well to verify them by a converse series of experiments which enabled the changes in a cast iron ball in passing from the liquid to the solid state to be observed. Two

spherical moulds of dried loam were made 15·09 and 15·28 inches diameter respectively. Into these, molten iron was poured, in the former case, Cleveland white iron, and in the latter, Cleveland grey iron. A few minutes after the iron was run, the top of the mould was raised and the diameter of the congealed surface measured with callipers. This was continued at intervals of time, and the diagram, fig. 2, shows the gradual increase of diameter of the grey and white iron balls as they cooled.

Fig. 2.

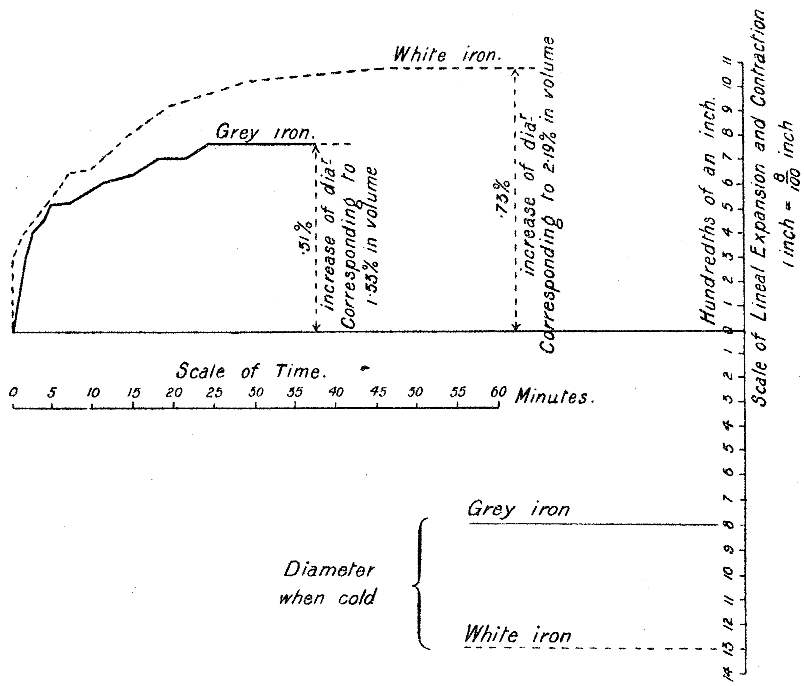


Diagram showing progressive increase of diameter and final contraction of grey and white balls, 15 inches diameter.

The large size of the balls made the cooling a slow process, and the horizontal line representing time could not conveniently be extended in a diagram, but the final diameter, when the balls, after ten or twelve hours, became cold, is shown. The general result is a qualitative confirmation of the previous experiments, although not quantitative, as the early consolidation of the outer layers of metal prevents the free expansion of the interior.

These experiments were made in 1879–80, and proved that grey iron and white iron possessed the property of expanding when cooling, and contracting when heating, within a range of temperature approaching the melting points, and to an extent near that found in the case of water, which in solidifying expands in volume 9·3 per cent., while grey iron expands nearly 6 per cent., and white iron even more; the approximation appearing to indicate that the phenomena were of the same order.

These facts led me to suggest that the phenomena of regelation and welding

might probably prove to be identical. I afterwards found that the same suggestion had been made by LOVE.* As, however, this hypothesis was not based on a knowledge of the properties of wrought iron, which *can* be welded, but upon those of cast iron, which *cannot* be welded, it appeared that the suggestion could only be regarded as speculative, until some method of examining the physical properties of wrought iron within the range of temperature known as the welding heat could be devised.

This brief statement of my earlier researches† will serve to lead to the work embodied in the present paper, which shows that wrought iron at the welding temperature possesses the property of expanding when cooled and contracting when heated, and that the welding property is intimately connected with the critical condition in which this abnormal behaviour is exhibited.

Professor JAMES THOMSON was the first to show that although in the case of normal bodies which expand by heat and contract by cold, the effect of impact or of pressure is to heat them; theoretical considerations rendered it probable that in a material which possessed the physical property of expanding during cooling and contracting during heating, a contrary effect would be produced. The effect of pressure or impact would cool and not heat it. This was subsequently experimentally demonstrated, in the case of freezing water, by Lord KELVIN.‡

These theoretical deductions of Professor JAMES THOMSON, and the well-known confirmatory experiments by Lord KELVIN, led to a theory of regelation now generally accepted, which depends upon the lowering of the solidifying (or freezing) point by pressure.

The condition known as "the welding state" of iron or steel is one which exists only within a very limited range of temperature. If the smith takes his iron bars out of the fire at too low a temperature welding cannot be effected. If, on the other hand, the iron is too hot, a failure is also certain.

The range of temperature during which impact or pressure causes the union known as the welding of two masses of iron or steel, is therefore comprised within narrow limits, and the familiar operation is really a critical one.

In order that the phenomenon of the welding of iron may be identified with the regelation of ice, it must be experimentally proved that the surfaces of the iron, at the moment of welding, are in that peculiar and critical condition in which an increase of heat will cause contraction and a diminution of heat will be followed by the expansion of the mass. On the other hand the identification of regelation and welding will be equally satisfactory if the collateral property of the cooling of the hot iron by pressure or impact can be demonstrated.

The first method of demonstration is impracticable, as the welding state is transient

* 'Proceedings of Civil and Mechanical Engineering Society,' February 19th, 1880.

† 'Proc. Iron and Steel Institute,' 1879-80.

‡ 'Proc. Roy. Soc. Edin.,' January, 1850.

and only affects a portion of the mass, so that methods which are available for measuring changes of volume in cast iron are inapplicable.

The only method of proof left open was to show that pressing the welding masses is attended by a fall in their temperature.

Unfortunately, fourteen years ago, when I made my earlier experiments, the investigation could not be continued as there was no suitable pyrometer with which such a delicate experiment could be carried out.

The recent successful application to metallurgical research, by Professor ROBERTS-AUSTEN, of a recording pyrometer,* led me to resume the investigation of the question.

This pyrometer, which depends upon the use of a thermo-junction, consisting of a platinum wire twisted with another wire of platinum alloyed with 10 per cent. of rhodium, had been of service in the investigation of critical temperatures in various metals and alloys, and as Professor ROBERTS-AUSTEN offered to place his laboratory and appliances at my disposal, and to aid me by advice, the opportunity for conducting the new experiments was gladly accepted.

The first experiments were made by placing the thermo-couple between the two welding faces of bars heated in an ordinary smith's fire. The wires of the thermo-couple were carried from the smith's shop to the pyrometer in the laboratory, but signalling was necessary to ensure the taking of the photographic record of the temperature at the exact moment the smith applied pressure, and it soon became evident that the arrangement was awkward. The results were far from being uniform, although on several occasions a distinct fall of temperature was apparent when welding was effected, which encouraged the expectation that with a more perfect system of work the true facts of the case would be revealed.

After full consideration it was decided that the only satisfactory way to proceed would be to use the electric welding apparatus of THOMPSON HOUSTON with alternating currents. The Electric Welding Company readily put one of their admirable appliances and a suitable dynamo at my disposal; the manager, Mr. ARMSTRONG, and the electrician, Mr. RELF, assisted in installing it at the Mint, and helped in every way to make the arrangement effective. By the kindness of Mr. R. A. HILL, Superintendent of the Operative Department, the composite alternating dynamo was driven from the Mint engines, and the conductors from the dynamo were carried over the intervening buildings to Professor ROBERTS-AUSTEN's laboratory, where they were connected to the electric welder.

The wires of the thermo-junction, which was placed in contact with the surfaces to be welded, were carried from the welder, round the walls of the laboratory to the galvanometer placed inside the camera of the recording pyrometer.

It may be well to point out that the deflection of the galvanometer mirror causes a

* 'Proc. Roy. Soc.,' vol. 49, 1891, p. 347, and 'Proc. Inst. Civil Engineers,' vol. 10, 1891-2, Part 4, where a full description of the pyrometer is given.

spot of light to move horizontally across the plate in the photographic slide, which slide moves vertically upwards at a uniform speed controlled by clockwork. The spot of light thus describes a curve, the ordinates of which represent respectively temperature and time. By this means a photographic record is produced. A base line (also produced by photography) represents the zero of temperature. When the indications of the thermo-junction are calibrated the diagram affords a complete record of the changes of temperature in the material in contact with the thermo-junction.

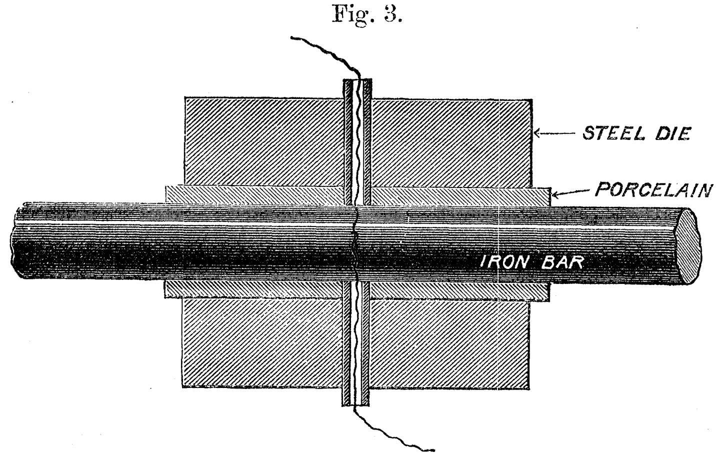
Plate 1, figs. 1 and 2, were the first taken, and some transient surprise was caused by finding that on the pressure being applied, by a hand lever acting on a pinion and rack, there was a rise instead of a fall of temperature. On reflection it appeared that this would certainly be due to the distortion and crushing up of the soft heated iron when the bars were pressed together at the welding temperature. Work was thus done, and the heat evolved masked any true fall of temperature.

To get rid of this heat of distortion it was necessary to confine the bar when pressed in some rigid envelope, which, from the conditions of the experiment, must, because of the electric current used for the heating, be a non-conductor of electricity.

After many attempts and failures the plan was adopted of placing the bar inside a close-fitting cylinder of porcelain, outside of which was closely fitted a strong steel die.

Both porcelain cylinder and steel die were cut through the centre in a plane transverse to the axis. This plan enabled the wires of the thermo-junction to be led to the centre of the bar, where the maximum heat was evolved. The bar was perforated by a minute hole, into which the wires forming the thermo-junction passed from each side.

Fig. 3.



Pipe-clay insulators encircled the wires and rested in grooves between the faces of the transverse cut, through the die, so as to prevent contact between the die and the wire.

After the temperature of welding had been noted on a series of photographic plates, there was no object in severing the bar so as to make a welded junction for each experiment.

All that was necessary was to heat by electricity in the electric welder a continuous bar until the position of the spot of light on the scale made it certain that the temperature was within the welding limits in the neighbourhood of the thermo-junction. The pressure was then applied.

When the bar was raised to welding heat inside the cylinder of porcelain, the pressure was applied. The time of its application is marked P on the photographic curve in each case. The position of this point was indicated by a signal made by momentarily obscuring the light which fell on the galvanometer mirror, thereby producing a brief interruption to the continuity of the curve.

These signals could be varied at will and proved to be of great service (see Plate 1, figs. 3, 4, 4*a*, 5, 6 and 7).

The current which heated the bar was not entirely cut off. This was done to avoid any fall of temperature before the pressure was put on, and in some of the diagrams it will be seen that it has not always been possible to avoid a slight and uniform rise, which merely means that the current of the electric welder did something more than counterbalance the loss of heat by radiation.

The pressure was applied when the temperature of the bar was 1347° C. (see Plate 1, fig. 3). A sudden rise of 27° C. showed itself, but a rise in temperature might be expected to take place, until all interstices between the outside of the bar and the envelope were filled by the plastic iron. The porcelain of course cracked, and the minute cracks had also to be filled before the effect of pressure in producing a fall in temperature could be demonstrated.

The second time the bar was heated to 1371° C., and on pressing a rise of temperature equal to 8° C. was shown (see Plate 1, fig. 4).

This small rise appeared to indicate that the interstices were nearly, or quite filled.

The third time the same bar was heated to 1420° C. and pressed, a distinct fall of 27° C. was indicated by the diagram, thus for the first time realizing the anticipation with which I began the investigation (see Plate 1, fig. 5).

The fourth time the bar was heated to 1400° C., when a pressure of about 1200 pounds per square inch of the area of the bar, or 80 atmospheres, gave the remarkable fall of 57° C. (see Plate 1 fig. 6).

The fifth time the bar was heated to 1300° C., a much lower temperature than the last, when, on being pressed, the fall in temperature was recorded as 19° C. (see Plate 1, fig. 7).

If the bar experimented on be examined, a number of vein-like protuberances will be seen, showing that the plastic iron had to fill the crevices in the cracked porcelain, before the pressure could cause a fall of temperature.

It appears from the series of experiments on this bar, that the limits of temperature within which the thermal expansion is negative, certainly include a range between 1300° C. and 1420° C., and they may extend both above and below these limits, although, the fall being only 19° C. at the lower temperature as compared with 57° C. at the higher, it looks as if the lower temperature were approaching the limit.

No doubt a series of experiments to determine the exact limits of the critical state would be full of interest.

Between the temperature of 1400° and that of melting wrought iron (stated to be 1600°) there are doubtless increasing degrees of mobility in the material. When pressure is put on the bar, say at 1400°, it not only lowers the temperature of the melting point, but increases the mobility at lower temperatures, so that if before pressure the temperature be 1400°, after pressure there may be a condition of mobility between the molecules which corresponds to a temperature without pressure of 1500°, although the temperature has been reduced by pressure to 1343°.

If two pieces of iron, or almost any metal, be raised to the melting point, union can no doubt be effected, but this is by melting together and not by welding. The process of welding appears to be that by which complete union can be effected by hammering or pressure, at a temperature considerably below that required to melt the material. The heat of the fire having raised the bars within the critical range of temperature above described, the smith in striking with his hammer is assisted by the special properties of this welding material in producing an increased mobility of the molecules, which approach though never arrive at liquidity. This condition is favourable to the interpenetration of the molecules, and consequent adhesion of the surfaces on hammering.

Since I made this experiment in Professor ROBERTS-AUSTEN's laboratory, I have had the opportunity of experimenting in steel works upon the behaviour of solid masses of soft weldable rolled steel when lowered into molten steel of the same quality. The mass at first sinks, and then quickly floats to the surface, where it remains until melted, showing that weldable low carbon steel follows the same law as cast iron, and therefore possesses that property which it is contended is essential to bodies which can be united by the process of regelation or welding. The increase of carbon in steel appears to prevent welding just as it does in the case of the more highly carbonized form of iron known as cast iron.

In conclusion I would observe that if I have been able to demonstrate this remarkable property in wrought iron of being cooled by pressure when at the welding temperature, it would not have been possible to attain this result without the aid of Professor ROBERTS-AUSTEN's admirable pyrometer, and without the help which he and his able assistants, Mr. STANSFIELD and Mr. REGINALD ROBERTS, have contributed.

EXPLANATION OF PLATE.

Effect of Pressure on an Iron Bar.

Fig. 1.—Current cut off before pressure.
Fig. 2.— „ „ at a lower temperature.

In each experiment pressure applied at point marked *P*.

Effect of Pressure in a series of Five Experiments on an Iron Bar ½″ in diameter, enclosed in a Porcelain and Steel Cylinder.

1st Experiment.—Fig. 3 at a temperature of 1347° C. gave a *rise* of 27° C.
2nd ,, —Fig. 4 ,, ,, 1371° C. ,, ,, 8° C.

Fig. 4A is a diagram produced at the same time as fig. 2, but from a more sensitive galvanometer. The same scale of temperature is not applicable.

In each experiment pressure applied at time marked *P*.

Fig. 5.—3rd Experiment at 1420° C. pressure gave a *fall* of 27° C.
Fig. 6.—4th ,, at 1400° C. ,, ,, ,, 57° C.
Fig. 7.—5th ,, at 1300° C. ,, ,, ,, 19° C.

In each experiment pressure applied at time marked *P* between first two signals, and relieved between last two signals. The current was cut off immediately after the fourth signal.

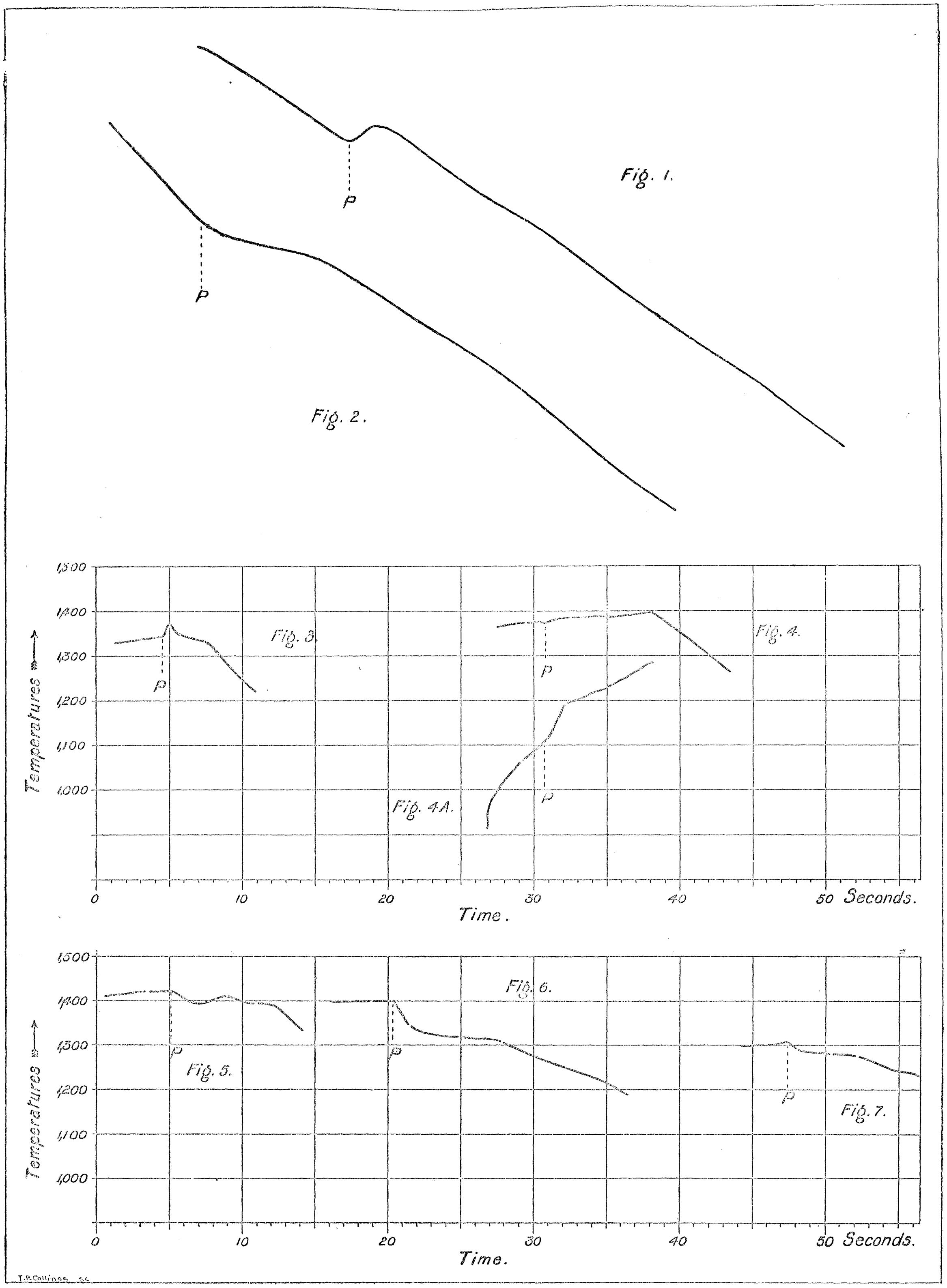


Fig. 1.
P
P
Fig. 2.
Fig. 3.
Fig. 4.
Fig. 4A.
1,500
1,400
1,300
1,200
1,100
1,000
Temperatures
0
10
20
30
40
50 Seconds.
Time.
Fig. 5.
Fig. 6.
Fig. 7.
T.R.Collings sc.