Measurement of Viscosity of Molten Light Alloys, Copper Alloys, and Cast Irons at High Temperatures by the Rotating Cylinder Method

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Measurement of Viscosity of Molten Light Alloys, Copper Alloys, and Cast Irons at High Temperatures by the Rotating Cylinder Method.

By

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CONTENTS.

INTRODUCTION.

In casting practice it is very important to have sufficient knowledge of the viscosity of molten metals and alloys. To get a sound casting, one of the most important facts to know is how the viscosity of the casting alloys varies with the temperature and their ingredients.

Nevertheless, up to the present very few investigations into this subject have been made as compared with those of other physical properties. There have been some works on the subject e.g. on the metals and alloys with low melting temperatures, but some of the results are contradictory to each other. In the case of those with high melting temperatures, the researches are very scanty and imperfect. One of the chief reasons why this important subject has been hardly touched until now, is that oxide is formed and disturbs the measurements. All measuring methods were disturbed by this trouble, so the apparatus was kept in a vacuum or in a neutral gas current, and many other possible means were tried, but with rising temperature it is very hard to prevent oxidation completely, and the results obtained are uncertain. Also the difficulty of obtaining materials for the measuring apparatus sufficiently enduring chemically and physically at high temperatures is one of the causes which have prevented the development of this investigation.

After all it seems that there is no suitable apparatus and method for measuring the viscosity of molten metals and alloys.

We adopted the rotating cylinder method which has been applied by different authorities for measuring the viscosity of various liquids i.e. glass, slag, pitch, viscous liquids etc. with good results.

We designed and improved the apparatus to make it suitable for molten metals, and to prevent the oxidation of them their surfaces were covered with carbon powder or a nitrogen gas current, and just before each measurement the oxide scum on the surface was scraped off. Thus we could easily measure the viscosity of molten metals and alloys from base metals to light alloys, copper alloys and cast irons.

PART I. MEASUREMENT OF VISCOSITY OF LIQUIDS.

CHAPTER 1. VISCOSITY OF LIQUID.

1) Definition of Viscosity.

If a portion of a liquid mass is caused to move relatively to the other part, the motion gradually subsides unless it is sustained by some external force; conversely, if a portion of a liquid mass is kept moving, the motion gradually communicates itself to the rest of the liquid. This property of liquids is called viscosity or internal friction.

Newton's fundamental assumption amounts to the following: if two laminae having an area of contact A move with constant velocity v_1 and v_2, the force F required to maintain the constant difference of velocity is

$$F=\eta A\frac{(v_1-v_2)}{(z_1-z_2)}$$

in which z_1 and z_2 are measured in the direction perpendicular to the laminae. Since the velocity in the liquid changes continuously, we may replace the differences by differentials and write:

$$F=\eta A\frac{dv}{dz} \qquad \text{(A)}$$

in which, as experience has shown, η is a characteristic constant for each liquid, which, at ordinary pressure, decreases with temperature, but in all simple liquids and true solutions is independent of $\frac{dv}{dz}$.

By introducing the dimensions in equation (A),

$$[F]=[MLT^{-2}] \qquad [A]=[L^2] \qquad dv=[LT^{-1}] \qquad [dz]=[L]$$

we find the dimensions of η to be

$$[\eta]=[ML^{-1}T^{-1}]$$

η is called the coefficient of viscosity, and its physical meaning becomes clear if the factors on the right hand side of equation (A) are chosen=I. The viscosity coefficient is the force required per unit area to maintain unit gradient of velocity, or the force required per unit area to maintain unit difference of velocity between two parallel planes in the liquid unit distance apart. The coefficient is usually expressed in dynes, centimeters and seconds, and the value $\eta=1{,}000$ in these units is conveniently called a Poise, and its hundredth part a Centipoise; the coefficient of viscosity of water at 20° is approximately a Centipoise.

2) Measurement of Viscosity of Molten Metals and Alloys.

The viscosity of molten metals and alloys has been measured in two ways, the "Capillary tube" method and the "Vibrating body" method. In the former the coefficient of viscosity is determined by the rate of flow through a capillary tube and this method was used by Arpi(1), Plüss(2) and Sauerwald(3). In the latter it is determined by the logarithmic

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(1) Internationale z. Metallog. 5 (1914) 142—68.

(2) Z. anorg. allg. Chem. 93 (1915) 1.

(3) Z. anog. allg. Chem. 157 (1926) 117.

decrement of a vibrating circular disc or cylinder immersed in the molten metal, and this method was used by Fawsitt(4), Oberhoffer and Wimmer(5), Wimmer and Thielman(6), and Majima(7).

3) Measurement of Fluidity of Molten Metals.

The fluidity is the aptitude of a liquid in a given condition to fill a mould prepared under definite conditions. This quality depends on a good many factors, such as temperature, viscosity, specific heat, temperature and nature of the mould, etc. Among these causes the viscosity exerts a great influence upon the fluidity, so we can presume the latter by measuring the former.

No apparatus for measuring the viscosity of molten metals has yet been perfected, but the fluidity has been measured already in many foundry shops. We will relate here its development briefly.

It seems that the first research on the subject must be attributed to Thomas D. West(8), who, in 1898, made experiments as to running qualities by casting a test bar of special shape. This question was studied after West by several persons; A. Ledebur(9) (1904) used a 250 × 25 × 1.5 mm. test bar, and A. H. Sexton and J. G. Primrose(10) (1911) used a thin test bar $1'' \times \frac{1}{16}''$ in section run also on one end. In 1917, Dr. Richard Moldenke(11) used a wedge-shaped test bar pointed at one end of a section of $1'' \times 1\frac{1}{2}''$ at the other. It should be noted that the Shops of Brousseval(12) presented to the first International Foundrymen's Congress in 1923, a similar but very long test bar which was run flat.

All these used straight test bars, but one of the authors and K. Hayashi(13) originated a spiral mould which is adopted in many foreign

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(4) Proc. Roy. Soc. 80 (1908) 290.
(5) St. u. Eisen 25 (1925) 122.
(6) St. u. Eisen 47 (1927) 389.
(7) Bulletin Inst. Phys. and Chem. Research, Japan 3 (1924) 51.
(8) Trans. Amer. Foundrymen's Assoc. 35 (1927) 289.
(9) Das Roheisen (1904) 86.
(10) The Principle of Iron-founding (1911) 289.
(11) The Principle of Iron-founding (1927) 105.
(12) Trans. Amer. Foundrymen's Assoc. 35 (1927) 289.
(13) D. Saito and K. Hayashi Memoirs of College of Eng. Kyoto Imp. Univ. 2 (1919) 83.

countries to-day. A long spiral groove $10 \times 7 \times 5{,}000$ mm. was made in a dry sand mould in which the metal or alloy to be tested was cast, and the length of the bar represents the fluidity at that temperature.

By this method Desh(14) (1921), Remy(15) (1922) and Curry(16) (1927) investigated the question.

CHAPTER 2. MEASUREMENT OF THE VISCOSITY OF A LIQUID BY THE ROTATING CYLINDER METHOD.

1) **History.**

There are two ways of measuring the viscosity of a liquid by the rotating cylinder method.

In one, the space between the two co-axial cylinders is filled with the liquid to be tested, and the coefficient of viscosity is. determined from the torque of the inner cylinder caused by the outer cylinder which is revolving at a constant speed. In the other, the outer cylinder is fixed and the coefficient of viscosity is determined from the rate of revolution of the inner cylinder which is driven by a constant couple.

Margules(17) was the first to use this method, in 1881, and since then the viscosity of water, pitch, viscous liquid, slag and glass etc. has been measured successfully by this method.

The method of rotating the outer cylinder was used in the following works :—

A. L. Feild(18) (1916)—A Method for Measuring the Viscosity of Blast Furnace Slag at High Temperature.

A. L. Feild and P. H. Royster(19) (1918)—Slag Viscosity Tables for Blast Furnace Work, and Temperature-Viscosity Relation in the Ternary System CaO–Al_2O_3–SiO_2.

The method of rotating the inner cylinder was used by

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(14) Foundry Trade Jour. Feb. 2 (1927).
(15) Trans. Amer. Foundrymen's Assoc. 35 (1927) 289.
(16) Trans. Amer. Foundrymen's Assoc. 35 (1927) 289.
(17) Sitzungsber. Akad. Wiss. Wien. 83. 11 (1881).
(18) U. S. Bureau of Mines. Tech. Paper No. 157 (1916).
(19) U. S. Bureau of Mines. Tech. Paper No. 187 and 189.

Hasegawa, Taniguchi and Ueda(20) (1927)—in their "Investigation of the Viscosity of Blast Furnace Slag".

With this method the viscosity of glass was measured by the following persons; Washburn and Shelton(21), English(22), Gehlhoff and Thomas(23), and Proctor and Douglas(24).

2) Theory.

If the space between two co-axial cylinders is filled with liquid, and the inner cylinder rotated with a constant couple, the following relation will be given,

$$\eta=\frac{C}{4\pi h\omega}\left(\frac{1}{r_0^2}-\frac{1}{r^2}\right) \quad \cdots\cdots\cdots \quad (1)$$

where η: Coefficient of viscosity.
C: Couple which rotates the inner cylinder.
h: Depth of the liquid.
ω: Angular velocity.
r_0: Radius of the inner cylinder.
r; Radius of the outer cylinder.

With a fixed depth of liquid in this apparatus formula (1) will be written as follows:

$$\eta=k\frac{W}{S} \quad \cdots\cdots\cdots\cdots \quad (2)$$

where W: Weight of the falling mass.
S: Number of revolutions per minute.
k: Constant of the apparatus.

If T represents the time of one revolution in seconds,

$$S=\frac{60}{T} \quad \cdots\cdots\cdots\cdots \quad (3)$$

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(20) Sei Tetsu Kenkyu. Japan. 97 (1927).

(21) Univ. Illinois Eng. Exper. Stat. Bull. No. 140 Vol. 21. No. 33 (1924).

(22) Jour. Soc. Glass Tech., 8 (1924) 205.

(23) Z. Tech. Phys. 7 (1926) 260.

(24) Proc. Phys. Soc. 41 (1929) 500.

then
$$\eta=\frac{k}{60}TW \quad \ldots\ldots \quad (4)$$

If we keep W constant,

$$\eta=KT$$

If the viscosity of the liquid used for calibrating the viscometer is the same as that being investigated, this is only a substitution.

It is perfect when this apparatus is calibrated with liquids of known different viscosities and the curve of the relationship between the constant K and the coefficients of viscosity of the applied liquid is obtained. Thus the errors caused by the form of the inner cylinder, the friction of the apparatus and others deduced from the defects of the theoretical formula are removed.

The above is the theory of the rotating cylinder method used up to this time.

It is noticeable that the formula has no factor of density of the liquid, which seems to be very convenient, but the true coefficient of viscosity will never be found if the density is neglected. We ascertained by experiments how the density influences the results of the measurement of viscosity by the rotating cylinder method.

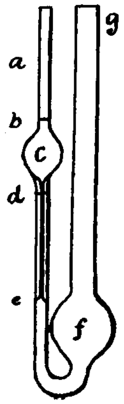
3) Influence of Density of the Liquid.

We prepared some liquids which had the same coefficient of viscosity but different densities and ascertained the influence of density upon this measurement.

Determination of the Coefficient of Viscosity.

The apparatus used was the Ostwald viscometer shown in Fig. 1. de is a fine capillary tube (100 mm. long and 0.7 mm. bore) through which 15 c.c. of a liquid in the bulb *c* is allowed to flow down, and the time required for the surface of the liquid to pass from the mark *b* to *d* is measured by a stop watch. Just 50 c.c. of the liquid is introduced into the large bulb *f* through the tube *g* by means of a pipett,

Fig. 1.



The coefficient of viscosity is calculated from the formula,

$$\frac{\eta}{\eta_w}=\frac{dt}{d_w\,t_w}$$

where, η and η_w, d and d_w, and t and t_w represent the coefficient of viscosity, the density and the time required by the liquid and by water respectively.

For this purpose about 3 liters of a solution was prepared in a wide-mouthed bottle (18 cms. diam. and 24 cms. high), and the concentration of it adjusted many times to get the required viscosity.

During the measurement of the viscosity, the Ostwald viscometer was immersed in the bottle to avoid variation of its temperature.

When we had obtained a solution of the required viscosity, the wide-mouthed bottle was placed at the viscometer and the viscosity of the liquid was measured by the rotating cylinder method.

Table 1.

Kind of Liquid	Temperature °C	Specific Gravity	Coefficient of Viscosity	Measured Results by Rotating Cylinder Method	
				T (A)	T (B)
Petroleum and Volatile Oil	31	0.846	0.01559	1437	1721 1728
Glycerin and Water	32	1.071	0.01596	1502 1478	1809 1828
Copper Sulphate Solution and Gum Arabic	32	1.155	0.01555	1509	1868
Tin	325	6.894	0.01580	3319 3311	5508
		By Sauerwald			
Bismuth	330	9.960	0.01580	4264 4251	7493
		"			

Kinds of Liquids used.

Since the densities of aqueous solutions vary in too narrow limits to be applicable to our investigation of molten metals and alloys, we used molten bismuth and tin, whose densities and coefficients of viscosity have already been measured by different authorities. The results of Sauerwald(25)

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(25) Loc. cit.

obtained by the capillary tube method are the latest and seem to be the most reliable, and so we adopted the coefficients of viscosity and the densities of molten bismuth and tin determined by him. Table I shows the kinds of liquids used, their specific gravity and coefficients of viscosity.

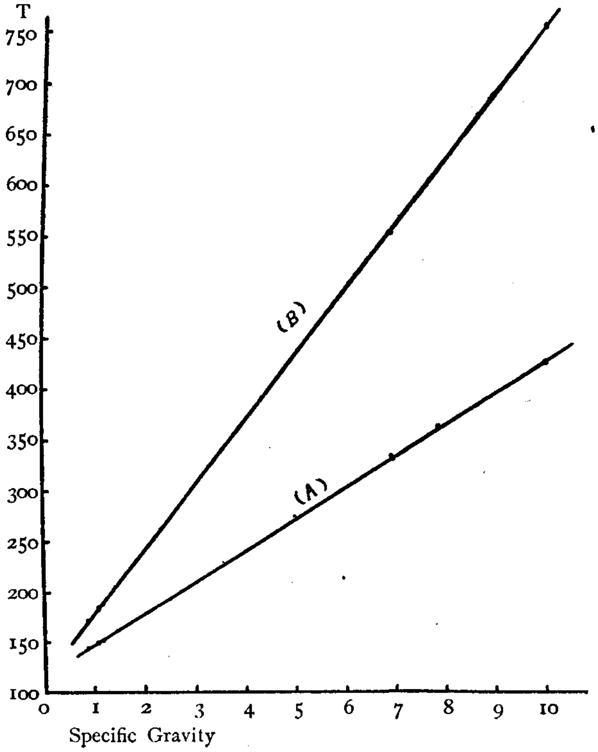
The measurement was made in the same conditions as in light alloys or copper alloys, and (A) corresponds to the former and (B) the latter.

In (A) and (B) the diam. of the pulley fixed at the rotating cylinder and the weight of the falling mass differed. *T* represents the period of one revolution when the rotating cylinder revolves with a constant speed, and 1437 means 0.1437 second.

Measuring by Rotating Cylinder Method.

The rotating cylinders used were of the same size as those used for light alloys and copper alloys.

Fig. 2.



The rotating cylinder was made of wood when the viscosity of an aqueous solution was measured, and a welded steel pipe coated with alundum cement was used for the molten metals. The latter was filled with nickel and lead-shot to balance the bouyancy of the molten metal. About 5 kilograms of electrolytic tin and bismuth were employed in each measurement.

Results obtained.

In Fig. 2, the ordinate represents the measured results and the abscissa the density. They have all the same coefficient of viscosity as in Table 1, but in measuring by the rotating cylinder method, the results obtained are, as shown in this figure, influenced by their density.

So if we wish to compare the viscosity of light alloys or copper alloys accurately, we must first find their density in the molten state, plot this in the abscissa and the (T) in the ordinate, and from these points draw lines parallel to (A) or (B) in order to assume them as having the same density.

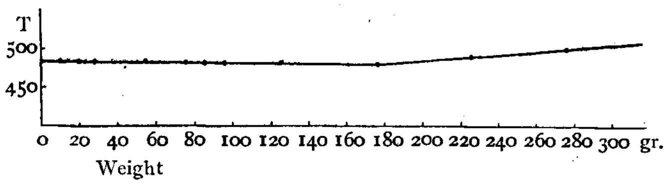
4) Effect of Bouyancy.

When the rotating cylinder is immersed in a molten metal, it is pushed upward remarkably by the bouyancy caused by the difference in their densities, the friction at the ball bearing increase and the results obtained become greater accordingly.

We tried the experiment now to be described to find out the range of bouyancy not disturbing the measurement of viscosity.

It is very difficult to rotate the cylinder when it is being pushed upward with a constant pressure, but it is very easy to press it downward by adding a constant weight to the rotating shaft. The friction on the ball bearing is the same in each case; so we adopted the latter. To make the conditions in dealing with molten metals as similar as possible, we used a wooden rotating cylinder, and immersed this in a glycerin bath in a 500 c.c. beaker. In Fig. 3 the abscissa shows the weight added to the rotating cylinder and the ordinate represents the measured results. We can see from this curve that the bouyancy must be limited within ± 170 grams.

Fig. 3.



5) Effect of Surface of Liquid.

If the rotating cylinder is dipped too deep in the liquid or too near to the surface, the rotation will be prevented. To ascertain the effect of the surface and to get the proper depth, we made measurements changing the depth of the rotating cylinder from the surface of the molten metals.

Fig. 4.

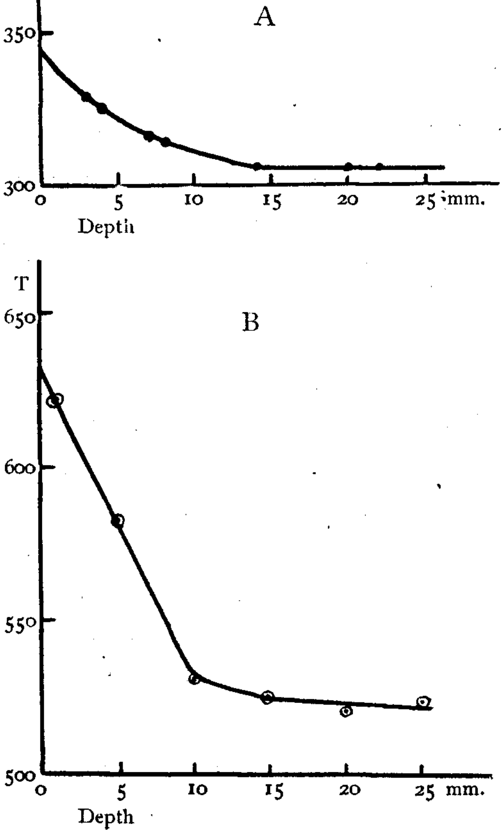


Fig. 5.

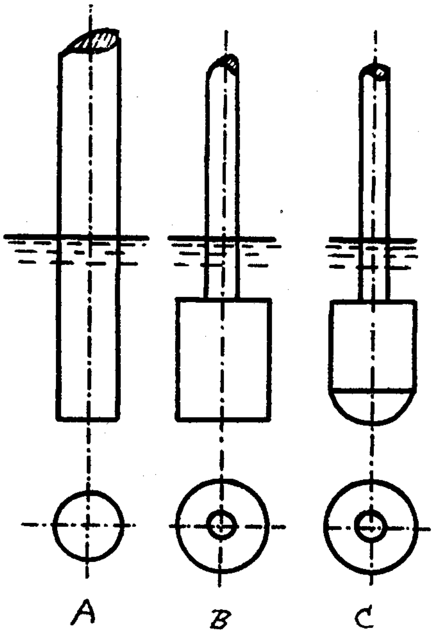


Fig. 4 A shows the case of molten aluminium at 770°C and B represents that of molten bronze at 1052°C. From these curves we can see that 15—20 mm. is the most suitable depth, so we adopted the depth of 20 mm. throughout all the measurements.

6) Shape of Rotating Cylinder.

Figs. 5 A and 5 B show the forms of rotating cylinders used in our research; A can be prepared simply but it has large contact area with the surface of the liquid and will be influenced by it, so we took the shape B for measuring the viscosity of light alloys.

But it is easy to understand that when form B is used the oxides on the surface of the metal adhere to the flat bottom of the cylinder when it is immersed in the molten metal; such adhering oxides are very hard to remove by rotation, and disturb the measurement. But by making the bottom of the cylinder semi-spherical, as shown in Fig. 5 C, this disturbance could be completely removed. So we used this form for the measurement of copper alloys and cast iron.

PART II. MEASUREMENT OF VISCOSITY OF MOLTEN METALS AND ALLOYS.

CHAPTER 1. MEASURING APPARATUS.

1) Rotating Cylinder.

For light alloys we used a welded hollow steel cylinder as shown in Fig. 5 B, which was coated with alundum cement. Its dimensions are 40 mm. in diameter, and 50 mm. in length, and the supporting shaft is 15 mm. in diameter and 160 mm. in length. But in measuring the viscosity of light alloys at high temperatures, copper alloys and cast iron, we used a fire-clay rotating cylinder coated with alundum cement. The dimensions of the cylinder used for copper alloys were 50 mm. in diameter, 60 mm. in height, and the supporting shaft was 15 mm. in diameter, 350 mm. in length. For cast iron it was 45 mm. in diameter, and 60 mm. in height.

2) Outer Cylinder. (i.e. Melting Vessel.)

The outer cylinder or vessel which contains the molten metal was a graphite crucible made by the Nihon Crucible Co. For light alloys No. 4 and for copper alloys and cast iron No. 5 crucible was used.

We ascertained previously that the inner wall of the crucibles of these sizes did not affect the measurement of the viscosity.

3) Electric Furnace and its Support.

The electric furnace used was of the vertical type, and for light alloys nichrome resistance and for copper alloys and cast iron where the testing temperatures are very high, carborundum resistance elements (9 in number) were used. The latter furnace consumes about 10 K.V.A., controlled by 6 rheostats. The support for the furnace is made adjustable up and down, right and left, and has levelling screws to adjust its position accurately; and also it is specially designed to move up and down not only the furnace but the crucible independently.

4) The Viscometer.

The arrangement of viscometer and its accessories are shown in Photos. 1 and 2.

In Photo. 1,

(1) Viscometer.
(2) Chronograph.
(3) Chronometer.
(4) Nitrogen Gas Bomb.
(5) Apparatus for Purifying Nitrogen Gas.

The oxygen and moisture included in the gas are absorbed here.

This consists of alkaline pyrogallol solution, conc. sulphuric acid, anhydrous phosphoric acid and copper mesh heated red-hot.

(6) Rheostats.
(7) Pyrometer.

Photo. 2 shows the viscometer in detail.

(1) Regulator of Bouyancy.

This is attached to eliminate the effect of the bouyancy.

For this purpose some circular metallic discs of suitable weight to balance the bouyancy are put on this regulator and the effect of the bouyancy is removed.

(2) Pully for the Falling Mass.

(3) Adjusting Screws.

There are two adjusting screws at side and front normal to each other, by which the rotating cylinder is centered to the graphite crucible containing molten metal.

(4) Protecting Tube Supporter.

By this the protecting tube of the thermocouple is drawn up from the molten metal when the rotating cylinder is being revolved.

(5) *Pt* and *Pt-Rh* Thermo-couple.

(6) Supporting Shaft.

This is made of fire-clay and the rotating cylinder is fixed at its lower end.

(7) A porcelain tube for leading in the nitrogen gas.

(8) Peep Hole.

About a quarter of the crucible cover is made to open; through this opening the state of the molten metal is observed, the hardener is thrown in, and the oxides are taken off.

(9) Water Cooler. } By these the essential parts of the visco-
(10) Cooling Fan. } meter are cooled.

(11) Cobalt Glass.

The state of the molten metal is observed through this.

(12) Carborundum Resistance Electric Furnace.

9 carborundum rods are used.

(13) Electric Furnace Stand.

(14) Rails for Electric Furnace.

(15) Step.

The operator stands on this step when making the measurements. Here also the metal charge is put in or taken out, the steel plate on it being taken off and the electric furnace drawn out.

CHAPTER 2. OPERATION AND MANIPULATION OF THE APPARATUS.

1) Prevention of Oxidation and Removal of Oxide.

As we said in the introduction, the oxide scum on the surface of the metal is the chief obstacle in the measurement of the viscosity of molten metals. Consequently various devices for preventing oxidation have been tried. The surface of the molten metal has been covered with melted resin, salts of zinc and ammonia, or borax, or a current of hydrogen or nitrogen gas has been passed over it, etc. etc.

In the case of light alloys at lower temperatures we took off the oxide scum with an iron spatula coated with alundum cement, but at high temperatures we first covered it with 20 mesh charcoal powder.

In the case of copper alloys we covered it with charcoal powder, and in the case of cast iron, nitrogen gas current was applied. The oxide scums were scraped off before each measurement with a carbon rod. The removal of the oxide just before each measurement has never before been tried.

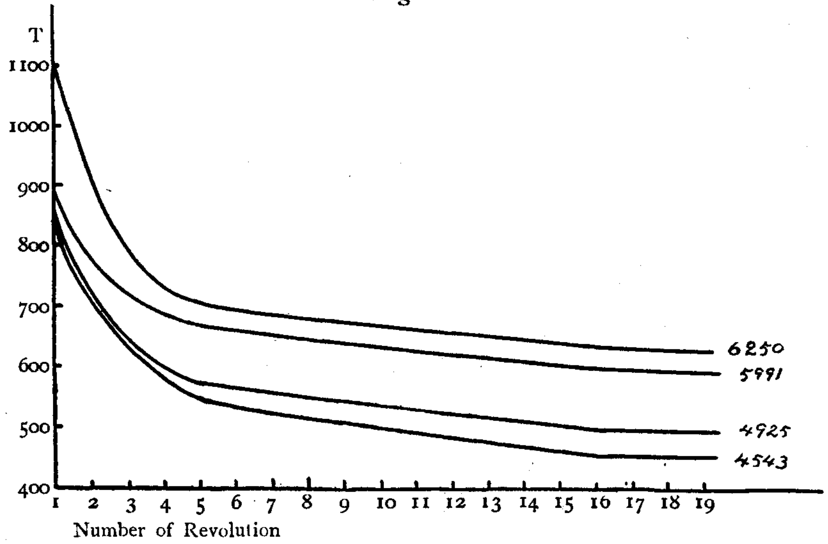
2) Measuring Method.

First a part of the cover of the crucible is opened, and as soon as the oxides are removed, the falling mass is released and the measurement is performed. The temperature at the time is read by means of a pyrometer. At first the speed of rotation is very slow, but it becomes gradually quicker, and then constant, arrested by the viscosity of the molten metal; and the viscosity is represented by the time of one revolution at this time.

Fig. 6 represents the rotation. In it the abscissa represents the number of revolutions and the ordinate shows the time of one revolution. We see that the time for one revolution becomes constant after 17—18 rotations.

The weight of the falling mass used amounts to 16.5 grams for light alloys and copper alloys, and 11 grams for cast iron.

Fig. 6.



CHAPTER 3. VISCOSITY MEASUREMENT OF MOLTEN LIGHT ALLOYS AND COPPER ALLOYS.

1) Results of Measurement of Viscosity of Molten Light Alloys.

The materials employed were as follows: aluminium (99.8% pure), electrolytic copper, electrolytic zinc, ferro-silicon (98% silicon), Mond nickel and commercial magnesium.

The results obtained are shown in Tables 2—13, and Figs. 7—12.

Table 2.

Aluminium.

Temp. °C	T	Temp. °C	T
659	5082	718	3093
”	3965	732	3085
”	3339	744	3080
”	3282	754	3060
664	3249	773	3043
681	3194	779	3033
689	3174	796	3000
701	3155	805	3022
709	3132	823	3011

Table 3.

Aluminium-silicon Alloy.

Si 6.46%.

Temp. °C	T	Temp. °C	T
612	4633	750	3035
613	3356	763	2997
617	3194	770	2997
640	3198	780	3014
670	3142	800	2999
690	3135	820	2985
724	3074		

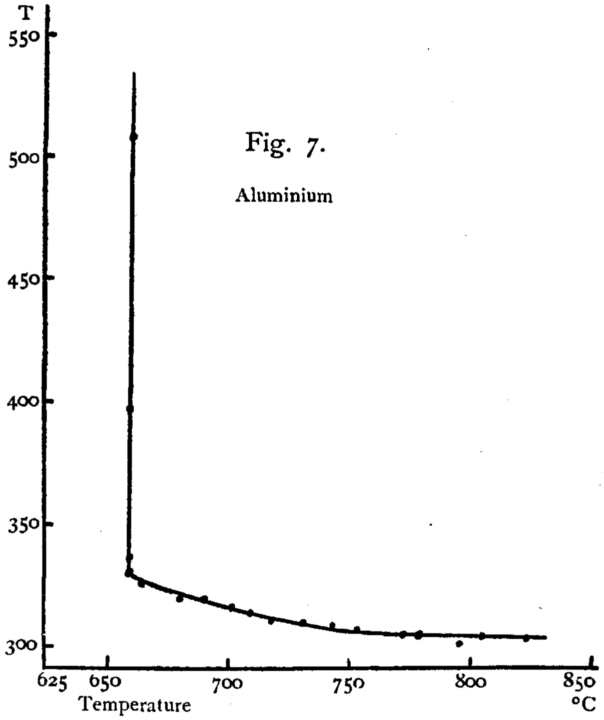


Fig. 7.

Aluminium

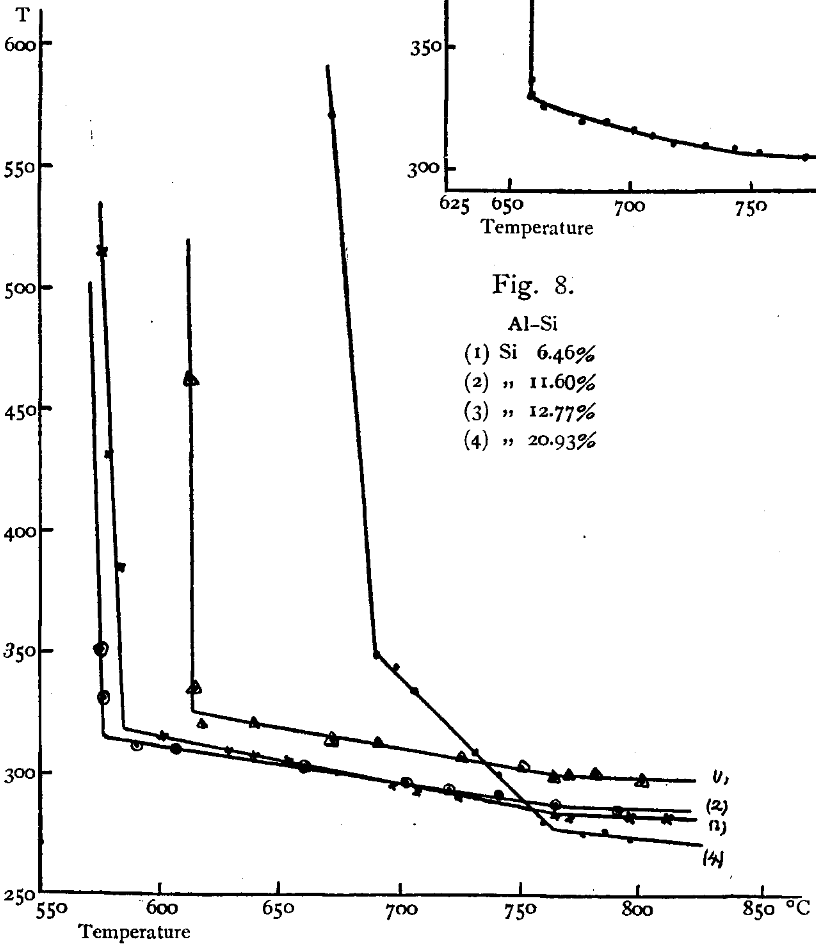


Fig. 8.

Al-Si

(1) Si 6.46%
(2) " 11.60%
(3) " 12.77%
(4) " 20.93%

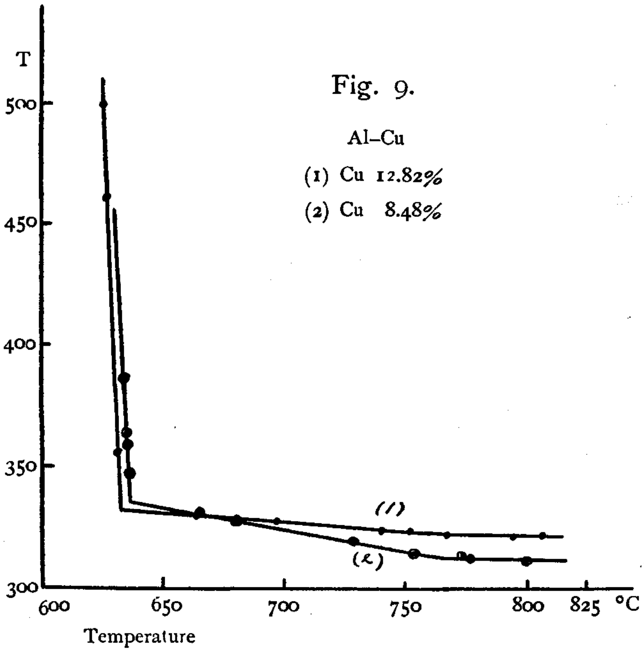


Fig. 9.

Al–Cu

(1) Cu 12.82%

(2) Cu 8.48%

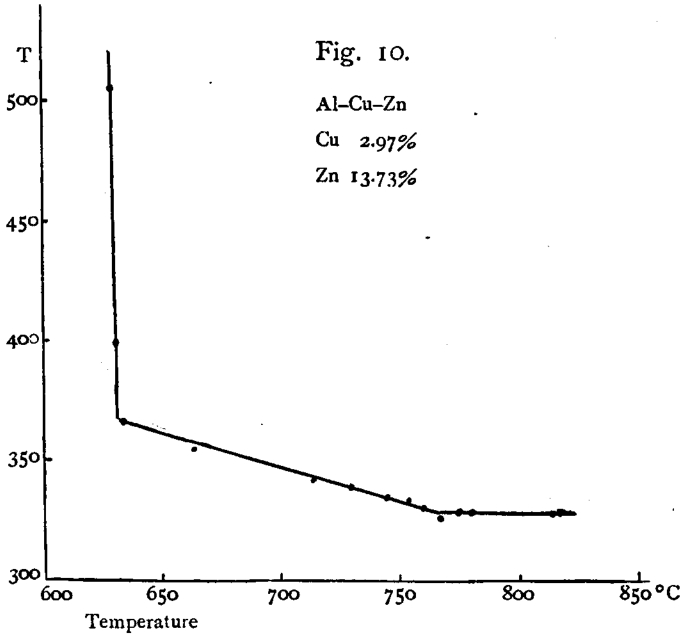


Fig. 10.

Al–Cu–Zn

Cu 2.97%

Zn 13.73%

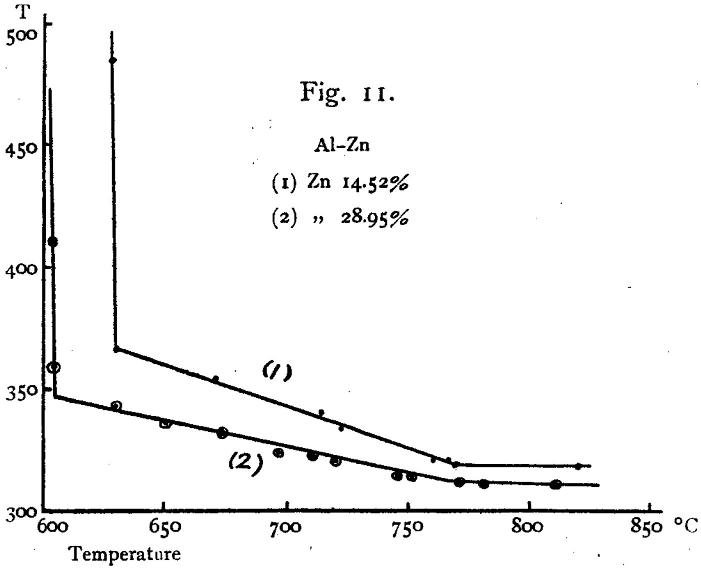


Fig. 11.

Al-Zn

(1) Zn 14.52%

(2) " 28.95%

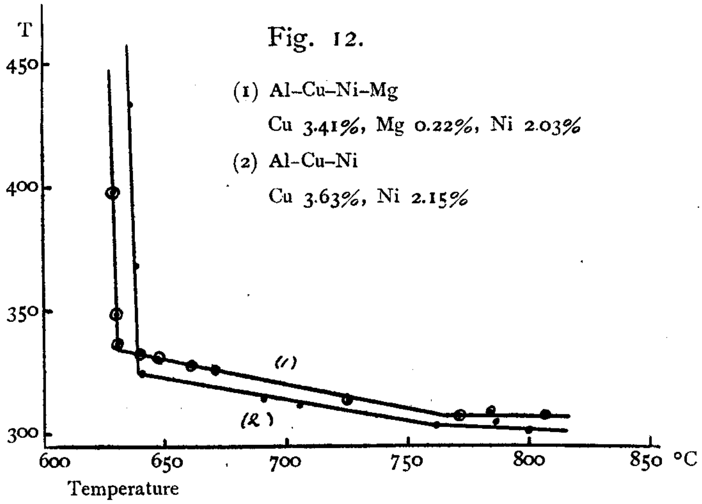


Fig. 12.

(1) Al-Cu-Ni-Mg

Cu 3.41%, Mg 0.22%, Ni 2.03%

(2) Al-Cu-Ni

Cu 3.63%, Ni 2.15%

Table 4.

Aluminium-silicon Alloy.

Si 11.60%.

Temp. °C	T	Temp. °C	T
575	3516	700	2962
577	3304	720	2940
590	3104	740	2920
605	3101	763	2875
660	3030	788	2849

Table 5.

Aluminium-silicon Alloy.

Si 12.77%.

Temp. °C	T	Temp. °C	T
576	5152	696	2959
579	4312	707	2925
583	3860	725	2910
600	3157	765	2837
629	3098	770	2826
640	3074	795	2835
653	3039		

Table 6.

Aluminium-silicon Alloy.

Si 20.93%.

Temp. °C	T	Temp. °C	T
670	5711	750	2920
688	3489	760	2800
697	3439	775	2750
705	3353	785	2756
730	3091	795	2730
740	3012	840	2690

Table 7.

Aluminium-copper Alloy.

Cu 8.48%.

Temp. °C	T	Temp. °C	T
633	3866	728	3190
636	3628	753	3148
”	3595	773	3127
637	3474	777	3118
666	3320	800	3114
680	3291		

Table 8.

Aluminium-copper Alloy.

Cu 12.82%.

Temp. °C	T	Temp. °C	T
626	5000	740	3237
627	4607	752	3237
632	3562	767	3223
665	3277	794	3209
697	3274	806	3223

Table 9.

Aluminium-copper-zinc Alloy.

Cu 2.9%, Zn 13.73%.

Temp. °C	T	Temp. °C	T
628	5059	753	3340
630	3985	760	3310
634	3654	767	3268
663	3549	775	3296
713	3419	780	3296
730	3391	814	3290
745	3352	816	3286

Table 10.

Aluminium-zinc Alloy.
Zn 14.52%.

Temp. °C	T	Temp. °C	T
628	4850	760	3213
630	3652	766	3210
670	3545	768	3196
713	3409	820	3194
722	3333		

Table 11.

Aluminium-zinc Alloy.
Zn 28.95%.

Temp. °C	T	Temp. °C	T
603	4102	720	3204
604	3596	745	3142
630	3434	752	3139
650	3364	771	3117
673	3322	780	3115
696	3235	810	3110
710	3223		

Table 12.

Aluminium-copper-nickel Alloy.
Cu 3.63%, Ni 2.15%.

Temp. °C	T	Temp. °C	T
637	4333	705	3115
638	3677	761	3038
640	3250	786	3062
690	3144	800	3022

Table 13.

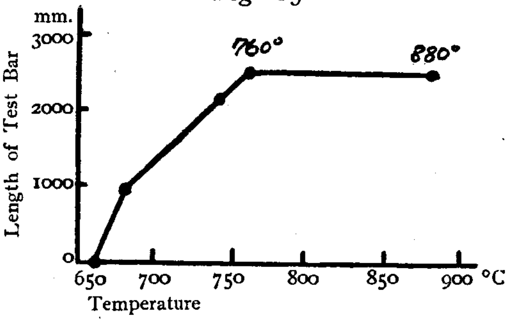
Aluminium-copper-nickel-magnesium Alloy.
Cu 3.41%, Ni 2.03%, Mg 0.22%.

Temp. °C	T	Temp. °C	T
630	3983	670	3252
”	3481	725	3129
631	3372	770	3071
640	3331	784	3089
647	3313	806	3079
660	3275		

2) Viscosity of Molten Light Alloys.

Looking at the results obtained, we see that all the viscosity curves of this category have a change point at 765°C, over which they run nearly horizontal i.e. with the viscosity unchanged, but below this temperature they rise gradually to their solidifying points, and after it they rise up suddenly nearly vertical.

Fig. 13.



Fluidity of Aluminium (Saito and Hayashi)

The results of measurement of fluidity of the metallic aluminium by one of the authors and K. Hayashi(26) are similar to ours, as shown in Fig. 13. The fluidity increases up to 760°C, and between 760° and 880°C it is unchanged.

It is characteritic of aluminium and light alloys to have a change point in viscosity at 765°C, and it does not exist in copper alloys and cast irons.

An examination of the influence of individual ingredients upon the viscosity of aluminium, shows that copper; copper and zinc; copper and nickel, copper, nickel and magnesium, all increase its viscosity.

In the aluminium zinc alloy (Fig. 11 (2)) the result seems to indicate an increase in the viscosity over that of aluminium, but this alloy contains 28.95% Zn and its specific gravity is 3.24, while that of pure aluminium is 2.67; and so by correcting the difference between them from the calibration curve Fig. 2 A, we will see that the viscosity of this alloy will be less than that of aluminium.

Silicon lowers the viscosity.

In this case, the aluminium silicon alloys have smaller density than aluminium, and the viscosity is probably influenced by this. But the difference between the specific gravities is very small, and even if it is calibrated, the viscosity of the aluminium silicon alloys is still smaller than that of aluminium.

3) Results of Measurement of Viscosity of Copper Alloys.

The results are shown in Tables 14—26, and Figs. 14—17.

Table 14.

Aluminium Bronze.
Al 10.90%

Temp. °C	T	Temp. °C	T
1050	10556	1079	6960
,,	8165	1107	6877
,,	7443	1115	6877
,,	7284	1185	6694
1053	7072	1189	6644

Table 15.

Aluminium Bronze.
Al 11.04%, P 0.0067%
(Charge P 0.05%)

Temp. °C	T	Temp. °C	T
1050	11286	1064	6747
,,	7331	1075	6671
,,	7253	1086	6629
,,	7084	1108	6593
1053	6855	1137	6423
1057	6834	1178	6265
1063	6725	1183	6285

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(26) Loc. cit.

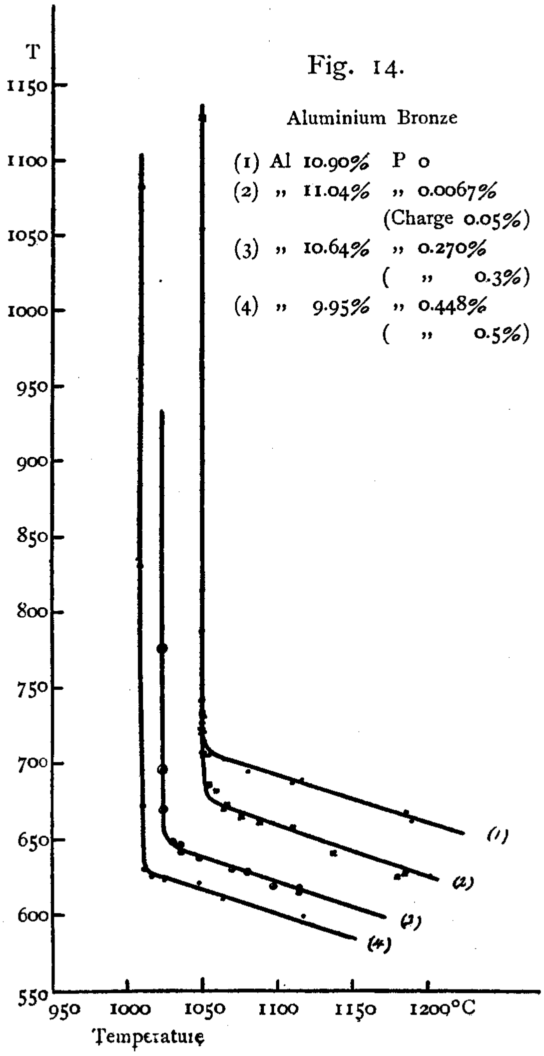

Fig. 14.

Aluminium Bronze

(1) Al 10.90% P 0
(2) „ 11.04% „ 0.0067%
(Charge 0.05%)
(3) „ 10.64% „ 0.270%
(„ 0.3%)
(4) „ 9.95% „ 0.448%
(„ 0.5%)

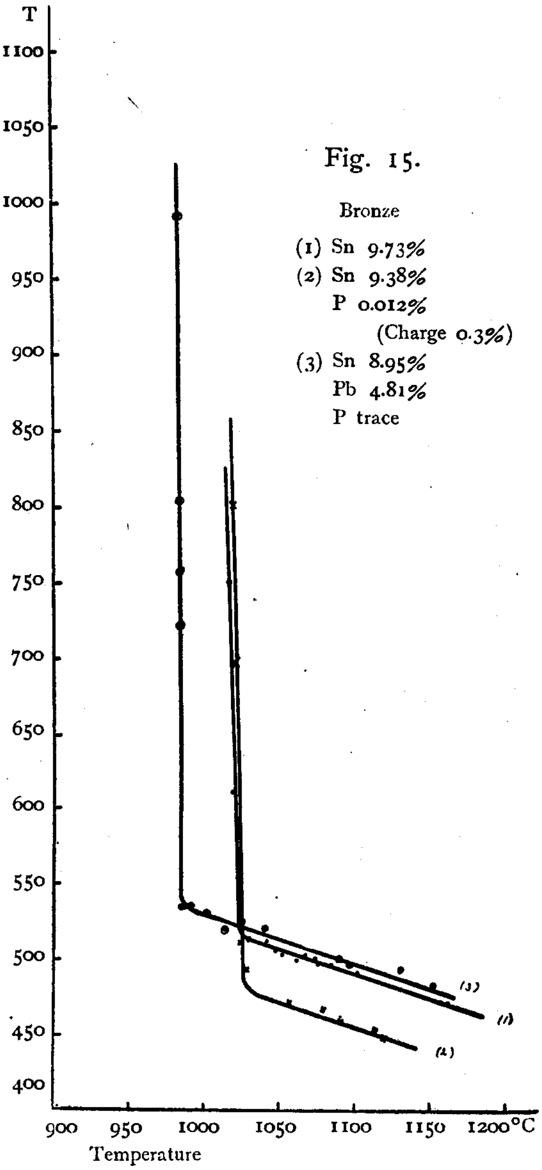

Fig. 15.

Bronze

(1) Sn 9.73%
(2) Sn 9.38%
P 0.012%
(Charge 0.3%)
(3) Sn 8.95%
Pb 4.81%
P trace

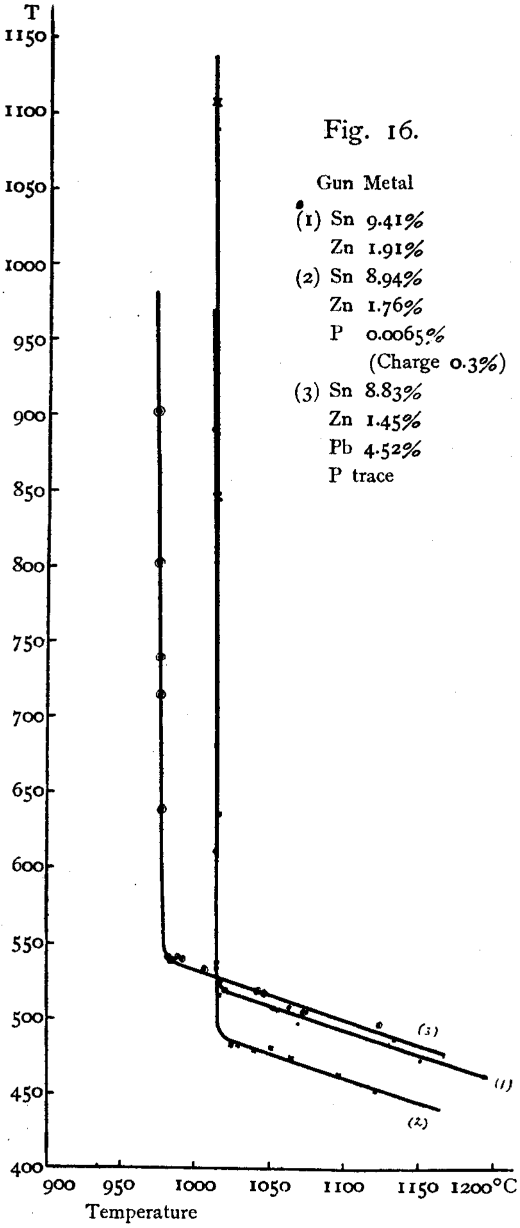
Fig. 16.

Gun Metal
(1) Sn 9.41%
Zn 1.91%
(2) Sn 8.94%
Zn 1.76%
P 0.0065%
(Charge 0.3%)
(3) Sn 8.83%
Zn 1.45%
Pb 4.52%
P trace
T
1150
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
900 950 1000 1050 1100 1150 1200°C
Temperature
(1)
(2)
(3)

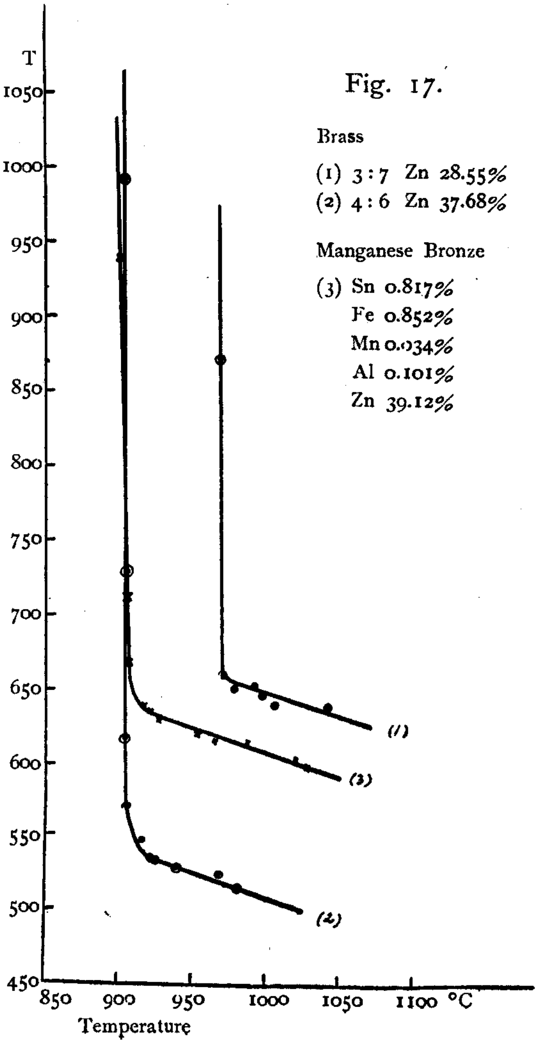
Fig. 17.

Brass
(1) 3 : 7 Zn 28.55%
(2) 4 : 6 Zn 37.68%
Manganese Bronze
(3) Sn 0.817%
Fe 0.852%
Mn 0.034%
Al 0.101%
Zn 39.12%
T
1050
1000
950
900
850
800
750
700
650
600
550
500
450
850 900 950 1000 1050 1100 °C
Temperature
(1)
(2)
(3)

Table 16.

Aluminium Bronze.

Al 10.64%, P 0.270%

(Charge P 0.3%).

Temp. °C	T	Temp. °C	T
1023	7786	1048	6386
"	6983	1070	6311
1024	6721	1079	6296
1030	6485	1097	6204
1035	6475	1114	6196
1036	6426	"	6156

Table 17.

Aluminium Bronze.

Al 9.95%, P 0.448%

(Charge P 0.5%).

Temp. °C	T	Temp. °C	T
1009	10819	1024	6250
1010	8305	1026	6250
1011	6743	1049	6229
1012	6303	1063	6118
1017	6270	1118	6024

Table 18.

Bronze.

Sn 9.73%.

Temp. °C	T	Temp. °C	T
1017	7501	1067	5025
1019	6106	1073	5001
1028	5125	1076	4967
1042	5123	1083	4960
1047	5050	1102	4919
1052	5025	1157	4719
1062	4984	1162	4713

Table 19.

Phosphor Bronze.

Sn 9.38%, P 0.012% (Charge P 0.3%).

Temp. °C	T	Temp. °C	T
1018	8019	1079	4671
1019	6963	1090	4587
1024	5122	1112	4539
1028	4935	1119	4481
1057	4721		

Table 20.

Bronze which contains Lead.

Sn 8.95%, Pb 4.81%, P trace.

Temp. °C	T	Temp. °C	T
983	9918	1002	5311
984	8032	1013	5286
"	7572	1025	5245
985	7213	1040	5204
986	5327	1089	5076
987	5344	1097	5035
991	5345	1128	5003
993	5363	1151	4909
1000	5327		

Table 21.

Gun Metal.

Sn 9.41%, Zn 1.91%.

Temp. °C	T	Temp. °C	T
1012	8900	1063	5084
1013	6123	1068	4975
1014	5373	1074	5057
"	5348	1135	4878
1017	5265	1142	4893
1020	5189	1152	4738
1053	5066	1195	4627

Table 22.

Gun Metal deoxidized with Phosphorus. Sn 8.94%, Zn 1.76%, P 0.0065% (Charge P 0.3%).

Temp. °C	T	Temp. °C	T
1011	11061	1041	4799
1013	8467	1051	4815
1016	6307	1063	4750
1017	5159	1096	4635
1023	4824	1121	4504
1029	4831		

Table 23.

Gun Metal which contains Lead. Sn 8.83%, Zn 1.45%, Pb 4.52%, P trace.

Temp. °C	T	Temp. °C	T
973	9034	992	5409
975	8032	1006	5342
976	7401	1012	5349
977	7154	1042	5230
978	6393	1047	5213
982	5409	1073	5184
985	5392	1124	5008
990	5420		

Table 24.

3 : 7 Brass. Zn 28.55%.

Temp. °C	T	Temp. °C	T
967	15737	989	6530
”	8724	995	6475
968	6617	1003	6414
976	6516	1038	6393

Table 25.

4 : 6 Brass. Zn 37.68%.

Temp. °C	T	Temp. °C	T
903	9934	922	5349
904	7319	925	5344
905	6188	938	5293
906	5737	967	5252
915	5491	978	5162

Table 26.

Manganese Bronze.
Al 0.101%, Sn 0.817%, Mn 0.035%, Zn 39.12%, Fe 0.852%.

Temp. °C	T	Temp. °C	T
902	9388	952	6208
906	7093	963	6172
907	6684	985	6151
915	6396	1018	6043
921	6356	1025	5979
926	6303		

The viscosity of copper alloys decreases with rise of temperature in almost constant ratio irrespective of their ingredients, and this is a distinct difference between them and aluminium and light alloys.

At the primary crystallization temperature, the viscosity increases suddenly and the metal solidifies, giving an almost perpendicular curve.

The results in this chapter may be summarized as follows :—

(1) As is well known aluminium bronze (Fig. 14) is very viscous, but the addition of some phosphorus improves its viscosity considerably, as little as 0.05% P (added with 10% phosphor-copper) producing a remarkable effect.

The influence of phosphorus (0.05%, 0.3% and 0.5%) upon the viscosity of aluminium bronze was examined and it was found that the primary crystallization temperature and the decrease in the viscosity resembles very much what is seen in cast iron. Aluminium bronze has been considered very difficult to cast on account of its great viscosity, but this difficulty can be removed by adding some phosphorus.

It must be noted that when phosphorus is added to bronze or gun-metal, a great part of it is burnt and only a small quantity remains in the alloys, but almost the whole of the charge remains in aluminium bronze (charge 0.3%, 0.27% remained; charge 0.5%, 0.448% remained).

(2) Bronze has very little viscosity.

It is well known that when bronze is deoxidized with phosphorus its casting properties are greatly improved, and our results proved this fact well. Looking at the curve (Fig. 15 (3)) it seems that the viscosity is increased by adding about 5% lead. But the density is increased by this addition, and so the measured results show higher values. The specific gravity of the bronze without lead is 8.43 and that with lead is 8.50. The difference in the density, 0.07, makes the measured results of the viscosity greater by about that amount after the addition of the lead; that is to say, the addition of the lead does not affect the true viscosity of the bronze. The almost equal viscosity and the greater density make the fluidity better, and the descent of the primary crystallization temperature by about 50°C owing to the addition of lead also improves the casting properties.

(3) Gun metal (Fig. 16 (1)) has a slightly greater viscosity than bronze. The addition of 2% of zinc to the bronze does not improve its viscosity. One of the authors and K. Hayashi(27) previously obtained similar results.

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(27) Loc. cit.

Phosphorus decreases the viscosity of gun metal.

Lead seems to increase the viscosity, but, as was mentioned in reference to bronze, it improves its casting properties by increasing the density and causing the primary crystallization temperature to descend.

(4) The viscosity of 3 : 7 brass (Fig. 17) is greater than that of 4 : 6 brass. The manganese bronze (which contains Mn, Sn, Fe and Al) in the latter has greater viscosity and its primary crystallization temperature ascends a little owing to these impurities.

(5) Fig. 18 is the summary of the viscosity-temperature curves of the various molten copper alloys. We see that alminium bronze has the greatest viscosity, phosphor-bronze the smallest, and the other alloys are situated between them.

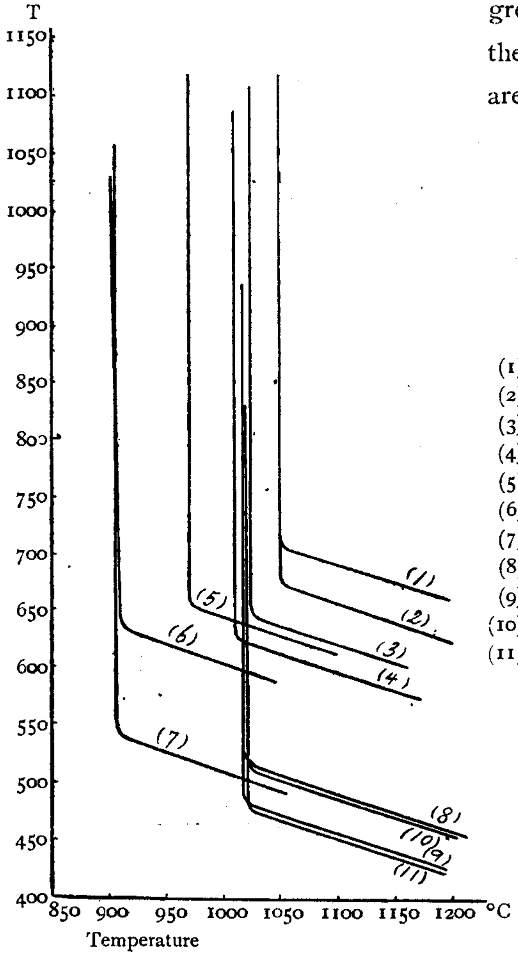

Fig. 18.

(1) Aluminium Bronze.
(2)
(3) „ „ deoxidized with phosphorus.
(4)
(5) 3 : 7 Brass.
(6) Manganese Bronze.
(7) 4 : 6 Brass.
(8) Gun Metal.
(9) „ „ deoxidized with phosphorus.
(10) Bronze.
(11) Phosphor Bronze.

CHAPTER 4. RELATIONS BETWEEN MODIFICATION AND VISCOSITY OF LIGHT ALLOYS.

1) Modification of Silumin.

The results are shown in Table 27, 28 and Fig. 19.

Table 27.

Silumin. Si 12.77%

Modified with (2NaF + NaCl).

Temp. °C	T	Temp. °C	T
578	4666	698	3028
580	4534	710	3008
590	3453	726	3032
605	3256	736	3042
630	3190	756	3052
658	3147	790	3042
670	3114	795	3044
678	3080		

Table 28.

Silumin. Si 12.77%

Modified with (2NaF + NaCl) 2 times.

Temp. °C	T	Temp. °C	T
582	4672	636	3475
585	4221	645	3469
587	4098	663	3401
589	3894	680	3442
590	3688	683	3431
596	3606	693	3442
600	3531	708	3398
603	3524	718	3359
610	3442	722	3442
617	3455	769	3505
625	3442	792	3577

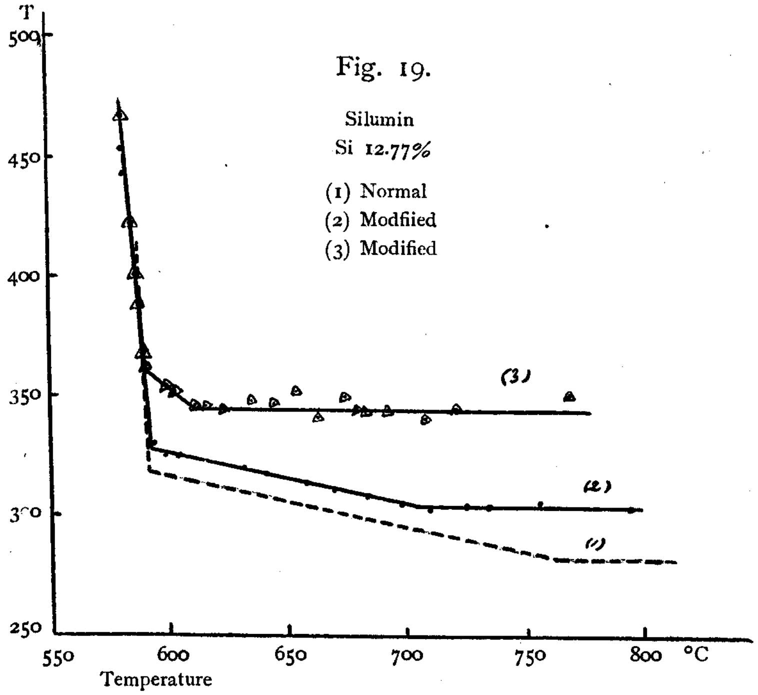

Fig. 19.

In Fig. 19, (1) shows the viscosity curve of aluminium silicon alloy in the normal state, (2) shows that of this alloy modified. The method of modification was as follows: We covered the surface of the molten aluminium silicon alloy with the modifier (2NaF + NaCl by weight) about 5 mm. thick, and maintained it for about 5 minutes at 900°C. When the cover is taken off from the crucible, the modifier solidifies at about 850°C. It is quickly removed entirely, the preheated rotating cylinder is immersed and the viscosity measurement is performed. The furnace is cooled as quickly as possible by cutting off the electric current, but it requires about one hour to reach the solidifing temperature of the alloy.

In the modification of silumin, the modified alloy must not be kept a long time at high temperature, and must not be stirred after modification, for fear of lessening the effect of the modification.

Our conditions are very different from those obtaining in foundry practice, where the alloy is cast within some minutes after modification, but we can understand the relations between the viscosity and the modification. Fig. 19 (2) shows the viscosity curve of modified silumin.

The viscosity increases a little and the change point at 765°C is moved to 705°C.

After solidifying, the alloys was remelted and modified once more, i.e. the alloy was modified more perfectly. Fig. 19 (3) shows the result. The viscosity increases more, and the change point at 705°C is moved to 610°C.

From these experimental results we can infer the following facts: On modification, the change point which is normally at 765°C, moves to a lower temperature, and the more perfect the modification, the more it descends. It seems to us that if the alloy is kept a long time at a high temperature and continuously stirred, the effect of modification (2) at 750°C and (3) at 610°C is lost, and the alloy returns to the normal state. We think that in rapid cooling as in foundry practice the change point will perhaps lag near the primary crystallization point.

2) Modification of Aluminium and Aluminium-copper Alloys.

We measured the viscosity of modified aluminium and aluminium-copper alloys besides silumin. G. Shinoda(28) showed with X-ray analysis that aluminium is modified by sodium, and Gwyer and Phillips(29) reported that aluminium-copper alloys are modifiable.

We measured the viscosity of modified aluminium and aluminium-copper alloys in the same way as in the case of silumin. The results are shown in Tables 29, 30 and Fig. 20, 21. The viscosity of both is increased, but as the temperature descends it decreases and seems at last to return back to the normal state. The transfer of the change point at 765°C does not appear, and from 765°C the viscosity begins to decrease and gradually return to its normal state.

This difference is due to the fact that aluminium-silicon alloys adsorb sodium but aluminium and aluminium-copper alloys have no such property, so the latter soon lose their sodium and return to the normal state on stirring and slow cooling.

Table 29.

Aluminium.

Modified with (2NaF + NaCl).

Temp. °C	T	Temp. °C	T
662	3427	710	3046
663	3118	723	3048
664	2964	740	3032
670	2964	760	3060
680	3015	788	3114
697	3063	800	3114

Table 30.

Aluminium-copper Alloy. Cu 8.48%

Modified with (2NaF + NaCl).

Temp. °C	T	Temp. °C	T
632	6340	702	3032
633	3648	720	3032
635	3278	743	3073
"	3196	766	3073
"	2991	780	3114
640	2950	806	3114
653	3032	820	3114
680	3032		

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(28) Suiyokai Shi, Japan 5 (1928) 422.

(29) Jour. Inst. Metals 2 (1928).

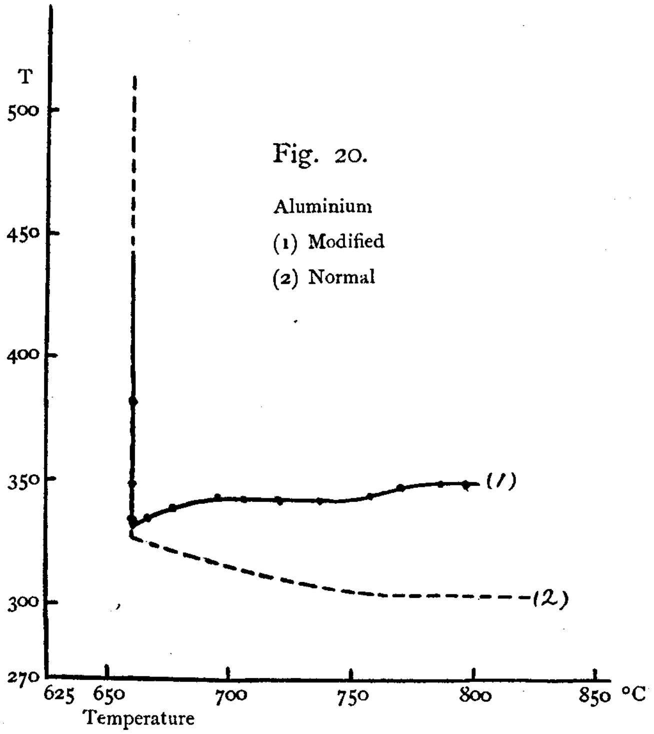
Fig. 20.

Aluminium

(1) Modified

(2) Normal

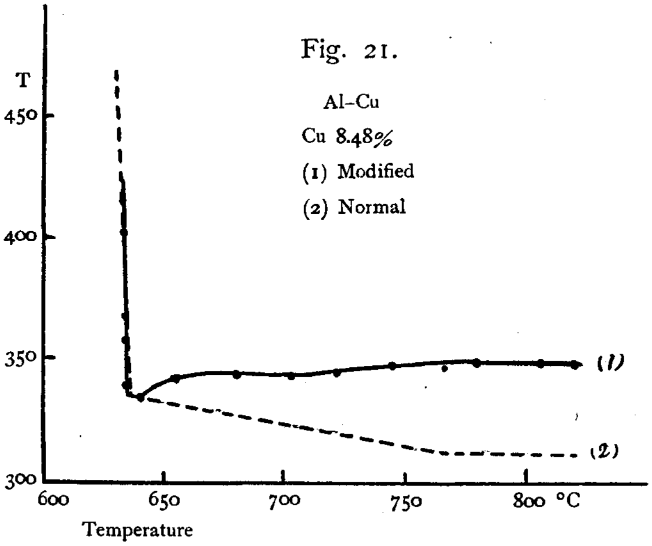
Fig. 21.

Al-Cu

Cu 8.48%

(1) Modified

(2) Normal

3) Relations between Modification of Light Alloys and the Change at 765°C.

There are many theories of modification,—deoxidation (Guillet(30)), ternary eutectic (Curran(31)), ternary monotectic (Otani(32)), super-cooling (Archer and Kempf(33)), protective colloid (Gwyer and Phillips(34)), solid solution (Czochralski(35)) etc. They all ascribe the occurrence of the modification only to the change at the crystallization range, but from our experiments the change at 765°C seems to have some connection with the modification. The temperature selected by Grogan(36), for the modification of the aluminium-silicon alloy by sodium was 760°C, and Archer and Kempf(37) 770°C, but sodium melts at such a low temperature as 97.5°C, and so in order to cause the sodium to diffuse throughout the molten metal these high temperatures, at which the sodium burns immediately, are not be required. As it is said that the modification is less complete when the modifying is done below about 760°C, there must be some relations between the change at 765°C and the modification.

When the modification is performed by the salt method, the best modifying temperature is claimed to be 900°C by Grogan and 927°C by Archer and Kempf. With this method the modification is always done with good results.

If even a slight mistake is made in the operation of modifying by the sodium method, the results are liable to become worse. This is because besides the loss of sodium by burning, the change at 765°C is not completely lagged by the descent of temperature.

In the electric resistance measurement described later, the movement of the change at 765°C is observed too.

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(30) Rev. Met. 19 (1922) 33.
(31) Chem. Met. Eng. 27 (1922) 360.
(32) J. Inst. Metals 37 (1926) 243.
(33) Trans. A. I. M. E. 73 (1926) 597.
(34) Loc. cit.
(35) Z. Metallkunde 15 (1923) 78.
(36) J. Inst. Metals 36 (1926) 269.
(37) Loc. cit.

In the thermal analysis of silumin modified with sodium the amount of the under-cooling of the primary crystallization temperature is 15°C or more. By the modification the change at 765°C is moved to a lower temperature, and accordingly the interval between this change and the primary crystallization point is narrowed remarkably.

The change which takes place between the interval from 765°C to the primary crystallization temperature must come about in this narrow range, and so it seems that the latter is inevitably delayed and under-cooling occurs. As the amount of under-cooling is due to the degree of the modification and the rate of cooling, the facts above mentioned agree well with the theory.

PART III. THE CHANGE AT 765°C AND 855°C OF ALUMINIUM AND LIGHT ALLOYS.

CHAPTER I. THE CHANGE AT 765°C OF ALUMINIUM AND LIGHT ALLOYS.

Aluminium and light alloys have a change point at 765°C which does not occur in copper alloys or cast iron, and this is characteristic of them. We made experiments to ascertain whether the change appears in connection with their other physical properties or not.

1) Measurement of Electric Resistance.

The measurement of the electric resistance of molten metal is easy compared with that of other physical properties of molten metal, and so there have been comparatively many investigations. Chief among those who have dealt with aluminium are E. F. Northrup(38), H. Tsutsumi(39), and Y. Matsuyama(40), but their measuring points were very few and their reading scales so small that it is impossible to make sure of the change point at 765°C. We measured again the electric resistance of molten aluminium and some light alloys.

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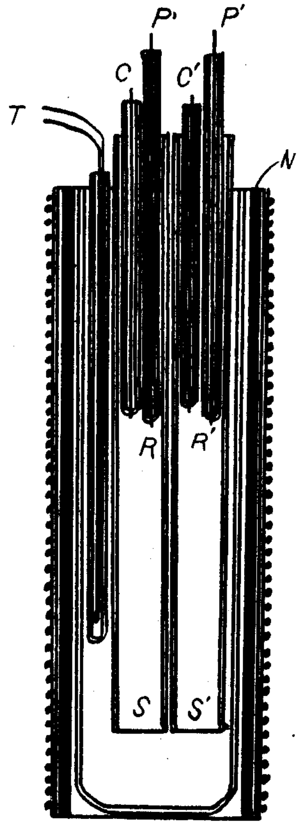
(38) J. Frank. Inst. 177 (1914) 1287.
(39) Scientific Rep. Tohoku Imp. Univ. 7 (1918) 98.
(40) Kinzoku no Kenkyu 3 (1926) 253. 439.

Fig. 22.



The apparatus is illustrated in Fig. 22. In a porcelain Tamman tube (30 mm. in diameter, 120 mm. in length), 2 silica tubes S, S' (8 mm. in inner diameter) are hung and in them there are two leading wires C, C' and P, P' which are insulated by small porcelain tubes. The former is connected to the electric source and the latter to a potentiometer. The leading wires used are platinum wires for light alloys, and piano wires for aluminium, because the former are corroded by molten aluminium. The silica tubes, porcelain tubes and Tamman tube are all coated with alundum cement so as to prevent corrosion.

As the distance between the lower ends of the silica tubes and the bottom of the Tamman tube is about 15 mm., the electric resistance here is very small, and so the electric resistance measured is almost equal to the resistance of the metal included in the silica tubes RS and $R'S'$. The temperature in the electric furnace was kept uniform by putting a rolled nickel plate N in it. T is the *Pt-Pt·Rh* thermocouple.

The materials used were the same as in the measurement of viscosity.

The results are shown in Figs. 23 and 24.

(a) Aluminium. The direction of the curve changes slightly at 765°C. We ascertained this change in six experiments.

(c) Aluminium-copper alloys (Cu 12.82%).

(d) Aluminium-silicon alloy (Si 20.93%)

(e) Aluminium-silicon alloy (Si 13.06%)

In (c), (d), (e) the change at 765°C is clearly observed.

(b) Aluminium modified 2 times with NaF and NaCl.

(f) Aluminium-silicon alloy (Si 14.11%) modified with NaF and NaCl.

(g) Aluminium-silicon alloy (Si 13.06%) modified with NaF and NaCl.

(h) Aluminium-silicon alloy (Si 13.06%) modified twice.

Fig. 23.

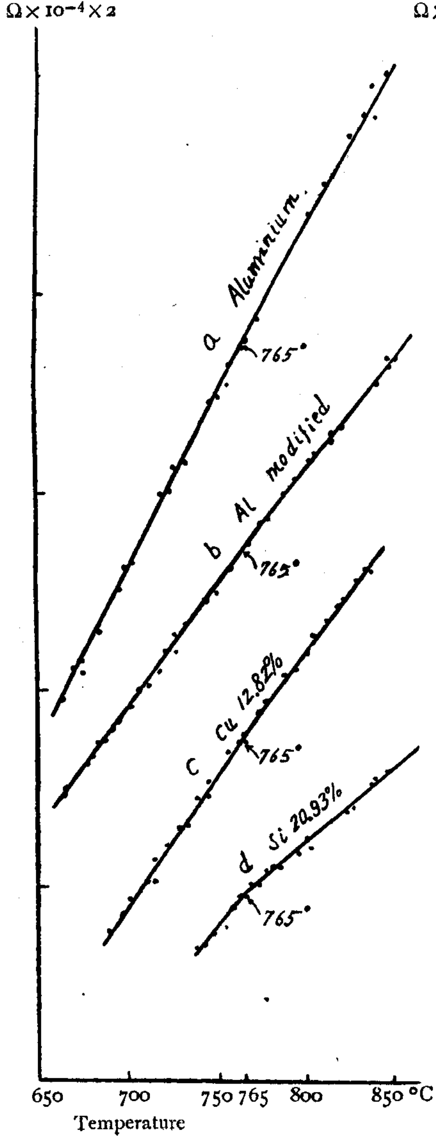
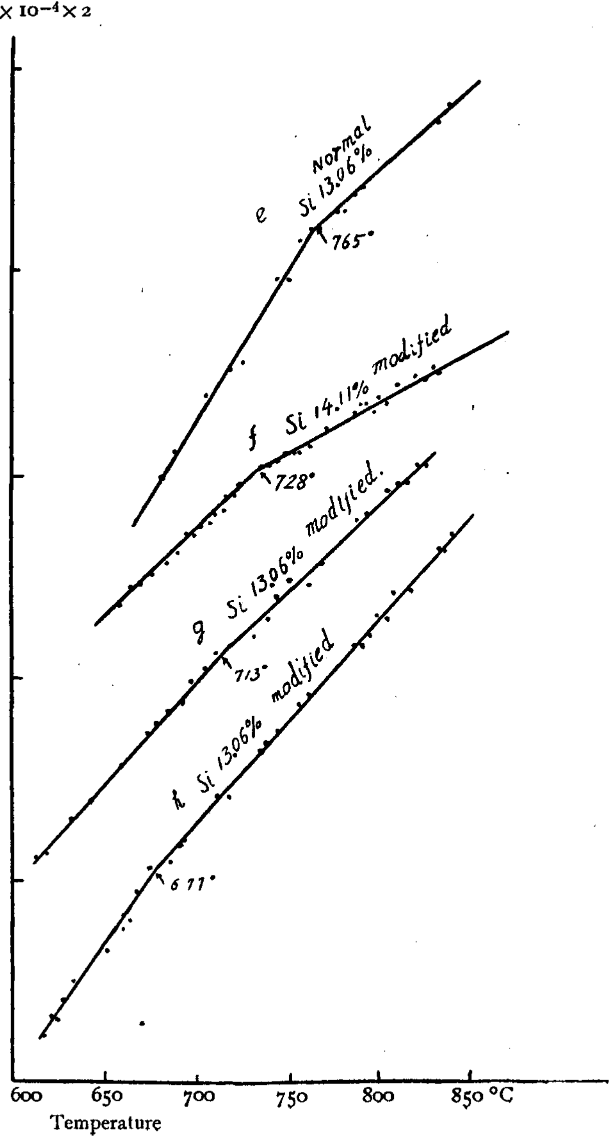


Fig. 24.



(b), (f), (g) and (h) show the electric resistance curves of modified aluminium and its alloys. These metals were melted and modified in a graphite crucible. After modification the metal was poured quickly into the Tamman tube and the electric resistance was measured.

As we could not find any movement of the change at 765°C in the modified aluminium, we modified it once more and again measured the electric resistance, which is shown in Fig. 23 (b).

The change is also recognized at 765°C.

In silumin it is delayed to 728°C in (f), 713°C in (g) and 677°C in (h).

It was ascertained by the measurement of both viscosity and electric resistance that the change at 765°C is moved to the lower temperature by modification.

2) Thermal Analysis.

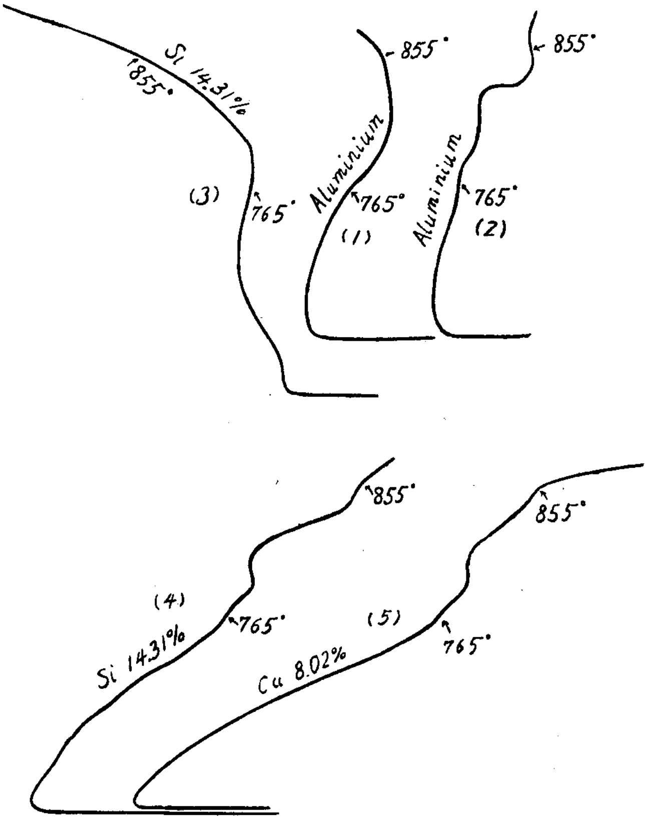
If aluminium and light alloys have a change of state at 765°C, it must be accompanied by some evolution or absorption of heat. To observe these phenomena we tried thermal analysis of them. As the thermal effect, if present, seems to be very small, we adopted the differential method in order to reveal it clearly as possible.

Two Tamman tubes (3 cms. in diameter and 12 cms. in length) were laid in a graphite crucible to maintain the temperature distribution uniform and heated in an electric furnace. One of the tubes was filled with nickel shot as a neutral body, and the other with the molten metal, about 120 grams, to be tested. The differential couple was composed of alumel and chromel, and connected to a mirror galvanometer.

The results are shown in Fig. 25.

(1) Aluminium with ordinary cooling rate.
(2) ,, cooled very slowly 1°C per 3 minutes.
(3) Aluminium-silicon alloy (Si 14.31%) with ordinary cooling rate.
(4) ,, ,, ,, ,, cooled very slowly.
(5) Aluminium-copper alloy (Cu 8.02%) cooled very slowly.

Fig. 25.



Each of these curves shows a slight evolution of heat at 765°C.

In about 20 or more experiments we recognized this thermal change at 765°C. Besides this we found another change at 855°C. At the normal rate of cooling as in (1) and (3) it looks like absorption, but in the very slowly cooled state, as in (2), (4) and (5), there is a slight evolution of heat, and after this the absorption occurs.

CHAPTER 2. ON THE CHANGE AT 855°C IN ALUMINIUM AND LIGHT ALLOYS.

1) Measurement of Viscosity.

We also measured the viscosity of aluminium and light alloys to ascertain whether the change at 855°C which we found in the thermal analysis occurs in this case also.

To prevent oxidation the surface of the molten metal was covered with 20-mesh charcoal powder, and the oxide scum was scraped off before each measurement.

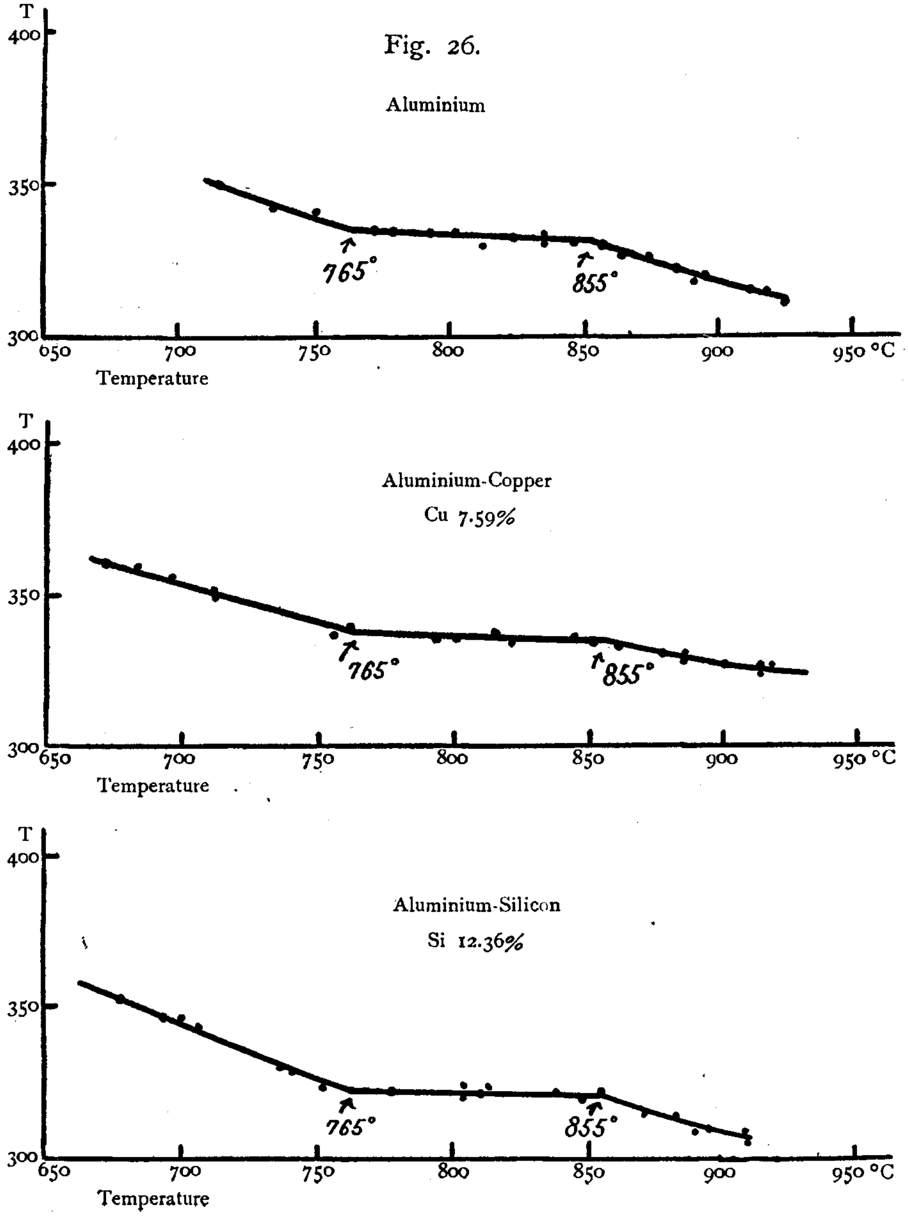


Fig. 26.

Aluminium

Aluminium-Copper
Cu 7.59%

Aluminium-Silicon
Si 12.36%

Fig. 26 shows the results.

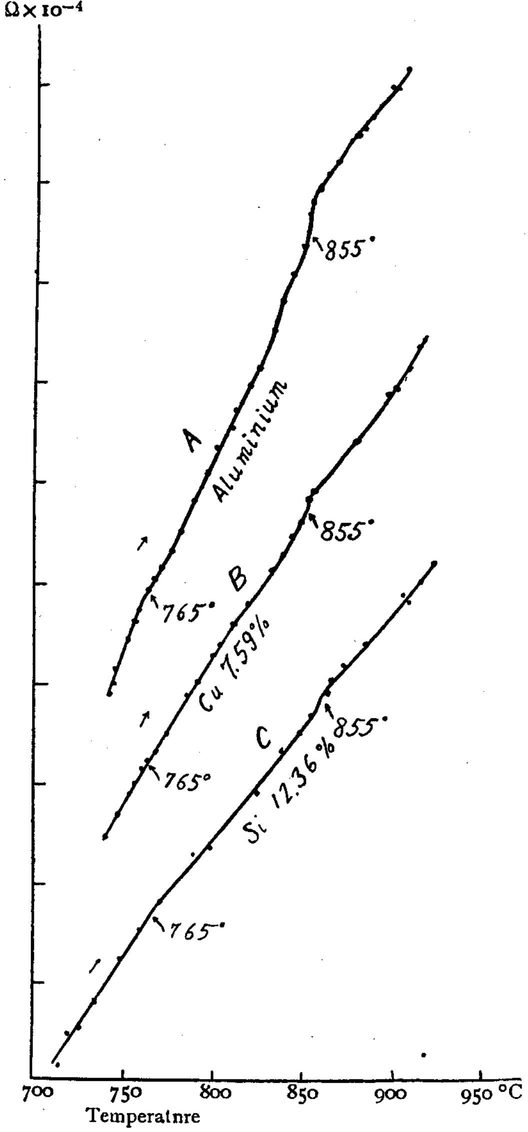
From these experiments we learn that the viscosity of aluminium, aluminium-copper alloy (Cu 7.59%) and aluminium-silicon (Si 12.36%) decreases remarkably from 855°C. The change at 855°C was recognized in the viscosity measurement as well as in the thermal analysis.

2) Measurement of Electric Resistance.

The electric resistance was measured to ascertain whether the change at 855°C is found in this case also. As leading wires we used piano wires, and these were corroded by the molten metal at such high temperatures as about 930°C, so the measurement was performed with ascending temperature, and when the measured results became irregular, the experiments were stopped.

The results are shown in Fig. 27.

Fig. 27.



(A) Aluminium.
(B) Aluminium-copper alloy (Cu 7.59%).
(C) Aluminium-silicon alloy (Si 12.36%).

The change at 765°C and 855°C are recognized clearly in these experiments.

PART VI. MEASUREMENT OF VISCOSITY OF MOLTEN CAST IRONS.

CHAPTER 1. HISTORY.

As cast iron is the metal most generally used in the foundry, the research of its viscosity or fluidity is more important than that of other metals. But as its melting temperature is very high, and severe oxidation and corrosive action upon the measuring apparatus greatly disturb the operation, there have been only a few reports published, notably those from the laboratory of P. Oberhoffer.

The results obtained by P. Oberhoffer and A. Wimmer(41) with the oscillation method show, that carbon and phosphorus increase the viscosity of cast iron, and iron sulphide decreases it, which is the reverse of our results, and with manganese and silicon they did not get good results, being hindered by oxides. A. Wimmer and H. Thielman(42) investigated the influence of carbon upon cast iron with an improved apparatus, and reported that carbon decreases the viscosity of cast iron.

In the oscillatlon method the apparatus is enclosed in a box and when the measurement is being performed, nitrogen gas is passed through it to prevent oxidation, but on account of the great affinity of molten cast iron for oxygen the formation of invisible oxide films which markedly disturb the measurement can not be prevented, and this may have caused the irregular results. After all the oscillation method seems to be unsuitable for the measurement of viscosity of molten metals such as cast irons at high temperature.

CHAPTER 2. EXPERIMENTAL METHOD AND MATERIALS EMPLOYED.

We prevented the oxidation of the molten cast iron by passing a current of nitrogen gas current through the apparatus, and the oxide scum was scraped off just before each measurement as in the case of the

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(41) Loc. cit.

(42) Loc. cit.

light alloys and copper alloys.

The apparatus and the experimental method were the same as described before.

Materials employed.

Pig iron: Wanishi, Kenjiho, Cleveland, Anshan and etc.
Steel Scrap.
Ferro-manganese (76.8% Mn).
Metallic silicon (98% Si).
Phosphorus and Sulphur: Merck.

For the phosphorus-, sulphur-, manganese-, and silicon-series the samples were made as follows: About 35 kilograms of the calculated pig iron and steel scrap were melted together in an oil furnace and made into several lumps of about 3 kilograms each. At the same time phosphorus, sulphur, ferro-manganese or silicon was added to about 10 kilograms of the molten cast iron, and the necessary hardeners were made. A test piece of about 3.5 kilograms was made with one of these hardeners and one of the 3 kilogramlumps.

As to the influence of carbon, a hardener can not be made by adding carbon, so we employed two kinds of pig iron with high and low carbon contents, and adding steel scrap, ferro-manganese, silicon and ferro-phosphorus to each of them made their impurities nearly equal, but their carbon content different. We investigated the influence of carbon upon cast iron with these two kinds of cast iron.

CHAPTER 3. RESULTS OF EXPERIMENTS.

The results are shown in Tables 31—87, and Figs. 28—36.

	C %	Table	Figure
Influence of Phosphorus	3.43	31—38	28
" " "	3.11	39—44	29
" " Sulphur	3.64	45—51	30
" " "	3.00	52—57	31
" " Manganese	3.33	58—63	32
" " "	2.84	64—69	33
" " Carbon		70—75	34
" " Silicon	3.47	76—81	35
" " "	3.07	82—87	36

Table 31.

C 3.43%, Si 1.91%, Mn 0.43%, S 0.02%, P 0.036%.

Temp. °C	T	Temp. °C	T
1220	10864	1252	5679
1223	8512	1263	5662
1225	7233	1284	5606
1229	7111	1296	5596
1231	6551	1301	5596
1232	6239		

Table 34.

P 0.361%.

Temp. °C	T	Temp. °C	T
1195	8852	1221	5245
1200	7950	1225	5147
1204	7664	1236	5122
1205	7295	1270	5041
1207	6578	1283	5020
„	6535	„	4983
1213	5327	1287	4983
1215	5345		

Table 32.

P 0.065%.

Temp. °C	T	Temp. °C	T
1218	7435	1247	5449
1219	6673	1258	5412
1224	6098	1267	5412
1226	5859	1292	5325
1228	5694	1322	5206
1232	5524	1334	5188
1237	5495	1346	5170

Table 35.

P 0.658%.

Temp. °C	T	Temp. °C	T
1193	10521	1273	4800
1196	7596	1285	4752
1198	6284	1291	4732
1202	5677	1296	4688
1207	5159	1223	4611
1219	4939	1328	4635
1232	4901	1336	4622

Table 33.

P 0.301%.

Temp. °C	T	Temp. °C	T
1198	10572	1243	5187
1203	9608	1252	5196
1208	9113	„	5187
1213	6720	1270	5176
1218	6440	1320	4994
1220	5689	1330	4994
1225	5532	1331	4977

Table 36.

P 1.028%.

Temp. °C	T	Temp. °C	T
1164	10154	1246	4760
1170	8113	1253	4707
1171	7401	1278	4653
1182	5153	„	4628
1193	4912	1302	4605
1197	4873	„	4590
1208	4824	1304	4590
1231	4787	1328	4537

Table 37.

P 1.297%.

Temp. °C	T	Temp. °C	T
1153	9958	1196	4708
1155	9338	1228	4646
1160	8000	1325	4375
1169	6661	1352	4312
1171	5578	1382	4229
1187	4732	1385	4238
1192	4725		

Table 38.

P 2.453%.

Temp. °C	T	Temp. °C	T
1092	10197	1171	4462
1098	7041	"	4523
1105	5702	1178	4496
1108	5190	1182	4462
1115	4793	1190	4455
1119	4661	1203	4372
1132	4605	1213	4358
1143	4605	1221	4375
1147	4523	1225	4365
1149	4528	"	4345
1155	4545	1247	4288
1165	4485	1276	4225
1169	4523		

Table 39.

C 3.11%, Si 1.32%, Mn 0.60%,
S 0.039%, P 0.187%.

Temp. °C	T	Temp. °C	T
1245	11683	1280	6702
1250	9125	1300	6642
1260	6879	1325	6525
1270	6759	1380	6302

Table 40.

P 0.373%.

Temp. °C	T	Temp. °C	T
1240	11391	1290	6417
1242	9801	1306	6396
1255	6818	1370	6105
1269	6547	1410	5925
1280	6420		

Table 41.

P 0.868%.

Temp. °C	T	Temp. °C	T
1220	11801	1295	5836
1225	9068	1320	5806
1230	6652	1346	5619
1235	6219	1373	5619
1260	5979	1393	5423

Table 42.

P 1.378%.

Temp. °C	T	Temp. °C	T
1202	10514	1239	5913
1206	8250	1250	5934
1208	7889	1265	5805
1213	6519	1290	5714
1222	6090	1299	5709
1230	6018	1325	5585

Table 43.

P 2.091%.

Temp. °C	T	Temp. °C	T
1169	8366	1247	5693
1170	7865	1266	5573
1180	6186	1288	5477
1193	5910	1309	5442
1230	5780	1360	5174

Table 44.

P 2.706%.

Temp. °C	T	Temp. °C	T
1142	10283	1200	5642
1150	6118	1230	5497
1160	5981	1288	5175
1170	5763	1335	5016
1179	5734	1355	4915

Table 45.

C 3.64%, Si 1.32%, Mn 0.37%, P 0.18%, S 0.019%.

Temp. °C	T	Temp. °C	T
1180	8614	1218	4864
1182	8292	1240	4810
1186	7504	1252	4741
1187	6647	1258	4737
1188	6093	1272	4721
1189	5695	1284	4674
1195	5022	1308	4616
1200	4912	1317	4587
1206	4884	1331	4532

Table 46.

S 0.055%.

Temp. °C	T	Temp. °C	T
1180	8381	1230	4912
1181	7794	1247	4875
1187	6359	1268	4792
1189	6297	1286	4714
1196	5070	1302	4647
1198	4978	1331	4592
1203	4993	1381	4410
1214	4882	1383	4408
1218	4920		

Table 47.

S 0.091%.

Temp. °C	T	Temp. °C	T
1188	6700	1229	4993
1189	6441	1276	4889
1192	5954	1293	4837
1196	5375	1306	4813
1202	5002	1346	4700
1226	4995	1357	4605

Table 48.

S 0.117%.

Temp. °C	T	Temp. °C	T
1192	7868	1237	5067
1193	7504	1247	4986
1196	6565	1258	5010
1200	6390	1287	4952
1201	5673	1305	4886
1203	5276	1326	4809
1206	5151	1331	4820
1220	5118	1345	4726

Table 49.

S 0.151%.

Temp. °C	T	Temp. °C	T
1180	10614	1254	5031
1187	8762	1268	5031
1189	8268	1281	4940
1192	7034	1292	4924
1195	6079	1307	4898
1203	5204	1318	4854
1225	5163	1357	4756
1242	5089	1368	4728

Table 50.

S 0.202%.

Temp. °C	T	Temp. °C	T
1172	9871	1222	5230
1175	9210	1235	5160
1181	7809	1254	5124
1186	6689	1281	5028
1192	5552	1293	4996
1193	5474	1313	4896
1195	5305	1352	4830
1203	5243		

Table 51.

S 0.640%.

Temp. °C	T	Temp. °C	T
1177	6930	1214	5673
1179	6483	1262	5553
1181	6093	1271	5542
1184	5913	1281	5482
1185	6206	1313	5400
1187	5862	1341	5323
1198	5772	1344	5308
1208	5727	1351	5277

Table 52.

C 3.00%, Si 1.32%, Mn 0.51%,
P 0.55%, S 0.032%.

Temp. °C	T	Temp. °C	T
1238	10071	1278	5664
1240	7575	1298	5622
1243	6386	1320	5525
1250	5801	1341	5427
1260	5741		

Table 53.

S 0.063%.

Temp. °C	T	Temp. °C	T
1236	9199	1300	5652
1238	8116	1307	5585
1240	6167	1339	5465
1246	5941	1373	5360
1262	5783	1390	5285
1272	5744	1400	5207

Table 54.

S 0.096%.

Temp. °C	T	Temp. °C	T
1230	10046	1291	5861
1234	9834	1340	5601
1243	6875	1388	5440
1248	6274	1398	5360
1260	5970		

Table 55.

S 0.106%.

Temp. °C	T	Temp. °C	T
1243	8665	1330	5686
1246	8234	1343	5656
1250	7080	1370	5526
1269	5960	1379	5496

Table 56.

S 0.140%.

Temp. °C	T	Temp. °C	T
1240	8009	1315	5840
1246	7025	1320	5760
1254	6124	1350	5710
1263	6049	1380	5578
1273	5995		

Table 57.

S 0.208%.

Temp. °C	T	Temp. °C	T
1240	10108	1302	5919
1241	8322	1320	5852
1254	6197	1338	5809
1262	6129	1370	5673
1273	6108	1383	5605
1284	6098	1397	5548

Table 58.

C 3.33%, Si 1.92%, P 0.189%,
S 0.029%, Mn 0.22%.

Temp. °C	T	Temp. °C	T
1239	6293	1358	5071
1243	5568	1370	4983
1258	5434	1381	4990
1301	5315	1390	4948
1340	5144	1397	4873

Table 59.

Mn 0.41%.

Temp. °C	T	Temp. °C	T
1235	5769	1318	5052
1240	5489	1327	5073
1249	5412	1342	5025
1272	5308	1364	4926
1308	5135	1378	4884

Table 60.

Mn 0.86%.

Temp. °C	T	Temp. °C	T
1237	5511	1293	5109
1250	5313	1322	4988
1269	5200	1340	4941

Table 61.

Mn 1.03%.

Temp. °C	T	Temp. °C	T
1233	5928	1288	5114
1241	5405	1292	5091
1246	5298	1322	4948
1268	5165	1337	4929
1270	5207		

Table 62.

Mn 1.63%.

Temp. °C	T	Temp. °C	T
1222	8420	1316	4921
1226	6903	1331	4837
1230	5361	1350	4741
1243	5167	1362	4682
1250	5169	1400	4569

Table 63.

Mn 1.97%.

Temp. °C	T	Temp. °C	T
1231	5419	1290	4870
1233	5110	1300	4870
1244	5045	1335	4717
1261	4989	1350	4652
1271	4938	1375	4550

Table 64.

C 2.84%, Si 1.52%, P 0.17%,
S 0.10%, Mn 0.58%.

Temp. °C	T	Temp. °C	T
1243	10645	1255	6154
1245	7925	1310	5909
1248	6654	1330	5855

Table 65.

Mn 1.06%.

Temp. °C	T	Temp. °C	T
1240	10206	1262	5956
1241	9272	1286	5863
1242	7457	1300	5816
1245	6129	1320	5770
1252	6016	1336	5656

Table 66.

Mn 1.17%.

Temp. °C	T	Temp. °C	T
1240	8235	1290	5805
1245	6855	1297	5760
1253	5959	1331	5600
1262	5885		

Table 67.

Mn 1.65%.

Temp. °C	T	Temp. °C	T
1234	10359	1277	5765
1239	7989	1287	5729
1245	6053	1306	5670
1252	5903	1317	5603
1267	5865		

Table 68.

Mn 1.82%.

Temp. °C	T	Temp. °C	T
1233	6840	1297	5648
1237	5998	1326	5518
1253	5828	1347	5426
1272	5740	1363	5390
1287	5690		

Table 69.

Mn 2.44%.

Temp. °C	T	Temp. °C	T
1228	7966	1272	5603
1238	5900	1287	5597
1258	5696	1310	5501
1269	5657	1321	5429

Table 70.

C 1.95%, Si 0.91%, Mn 0.53%,
P 0.17%, S 0.16%.

Temp. °C	T	Temp. °C	T
1277	6869	1321	5704
1279	6609	1350	5528
1287	5861	1368	5523
1302	5788	1379	5478

Table 71.

C 2.36%, Si 0.96%, Mn 0.55%,
P 0.15%, S 0.13%.

Temp. °C	T	Temp. °C	T
1239	8871	1270	5724
1242	7865	1281	5658
1244	7007	1290	5656
1248	6132	1316	5498
1252	5842		

Table 72.

C 2.85%, Si 1.09%, Mn 0.52%,
P 0.20%, S 0.17%.

Temp. °C	T	Temp. °C	T
1240	7809	1266	5690
1244	7365	1300	5573
1250	5918	1320	5497
1257	5789	1350	5400

Table 73.

C 3.13%, Si 1.10%, Mn 0.51%, P 0.26%, S 0.16%.

Temp. °C	T	Temp. °C	T
1229	8061	1303	5469
1232	7825	1333	5355
1243	5730	1340	5364
1276	5565	1352	5281
1290	5537		

Table 74.

C 3.42%, Si 1.15%, Mn 0.53%, P 0.21%, S 0.12%.

Temp. °C	T	Temp. °C	T
1210	11578	1266	5470
1213	8023	1300	5325
1218	6292	1330	5215
1238	5607	1340	5188

Table 75.

C 3.69%, Si 1.33%, Mn 0.51%, P 0.22%, S 0.14%.

Temp. °C	T	Temp. °C	T
1170	7003	1238	5275
1175	5921	1258	5226
1185	5592	1283	5115
1193	5472	1314	5010
1222	5360	1345	4907
1224	5350		

Table 76.

C 3.47%, Mn 0.55%, P 0.226%, S 0.027%, Si 0.19%.

Temp. °C	T	Temp. °C	T
1247	9082	1311	5882
1252	6224	1329	5841
1270	6099	1369	5685
1273	6025		

Table 77.

Si 0.55%.

Temp. °C	T	Temp. °C	T
1239	9544	1304	5590
1243	7607	1308	5558
1250	5950	1348	5370
1271	5687	1361	5339
1285	5650	1380	5298
1291	5629	1390	5247

Table 78.

Si 0.94%.

Temp. °C	T	Temp. °C	T
1243	8421	1340	5326
1245	6095	1358	5273
1250	5879	1371	5211
1278	5634	1398	5123
1308	5511	1407	5090

Table 79.

Si 1.33%.

Temp. °C	T	Temp. °C	T
1241	7847	1289	5460
1243	6821	1307	5397
1251	5622	1339	5240
1267	5512	1378	5098
1268	5535		

Table 80.

Si 1.95%.

Temp. °C	T	Temp. °C	T
1224	9365	1313	5287
1233	6394	1329	5253
1239	5627	1346	5166
1259	5549	1400	4952
1298	5351	1406	4896

Table 81.

Si 2.23%.

Temp. °C	T	Temp. °C	T
1247	7802	1309	5739
1249	6771	1346	5609
1251	6135	1385	5409
1267	5926	1393	5368

Table 82.

C 3.07%, Mn 0.17%, P 0.19%,
S 0.025%, Si 0.42%.

Temp. °C	T	Temp. °C	T
1270	8434	1354	5879
1274	6570	1393	5662
1292	6091	1404	5634
1324	5967		

Table 83.

Si 0.81%.

Temp. °C	T	Temp. °C	T
1270	8583	1332	5803
1278	6118	1348	5761
1282	6079	1368	5652
1302	5979	1379	5631
1303	5973	1396	5591

Table 84.

Si 1.12%.

Temp. °C	T	Temp. °C	T
1269	8866	1354	5574
1272	7369	1377	5461
1290	5884	1389	5403
1309	5790	1400	5408

Table 85.

Si 1.47%.

Temp. °C	T	Temp. °C	T
1268	7543	1351	5567
1274	6050	1365	5454
1291	5831	1378	5414
1312	5712	1392	5351
1333	5611	1402	5349
1340	5589		

Table 86.

Si 1.98%.

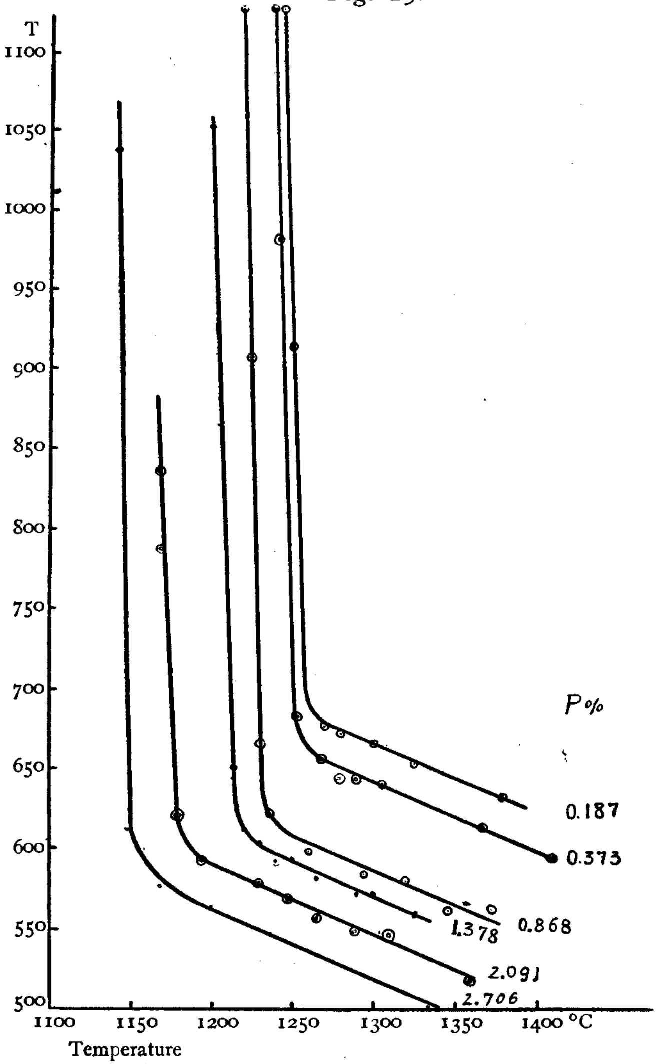
Temp. °C	T	Temp. °C	T
1264	8291	1329	5526
1269	6432	1361	5375
1286	5755	1370	5404
1300	5634	1390	5274
1314	5578		

Table 87.

Si 2.40%.

Temp. °C	T	Temp. °C	T
1262	7718	1330	5433
1263	6740	1353	5345
1269	5756	1370	5283
1277	5637	1389	5203
1298	5573	1406	5130

Fig. 29.

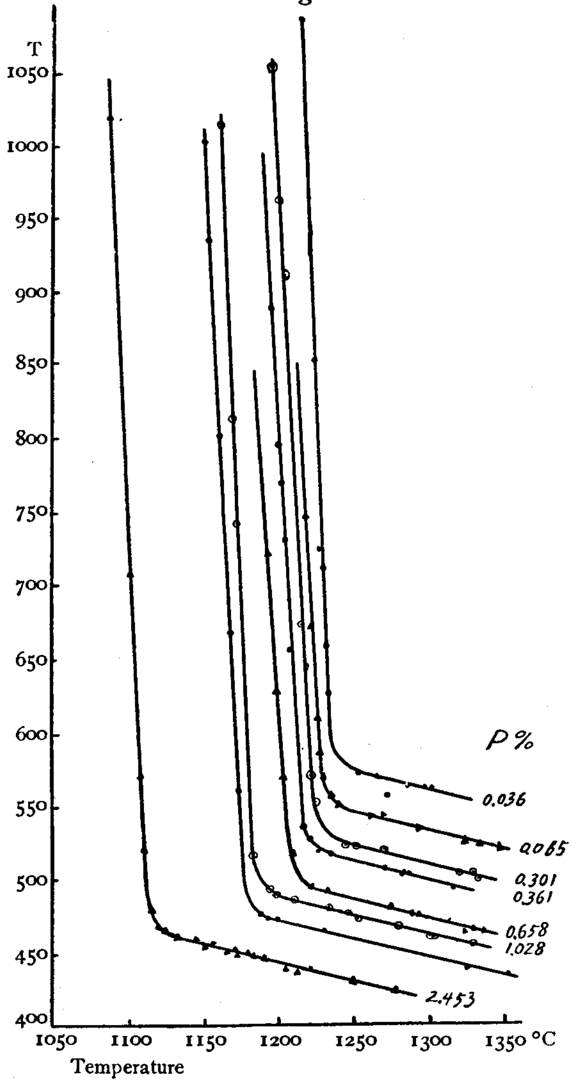


Influence of Phosphorus.

Carbon 3.11% Silicon 1.32%

Manganese 0.60% Sulphur 0.038%

Fig. 28.

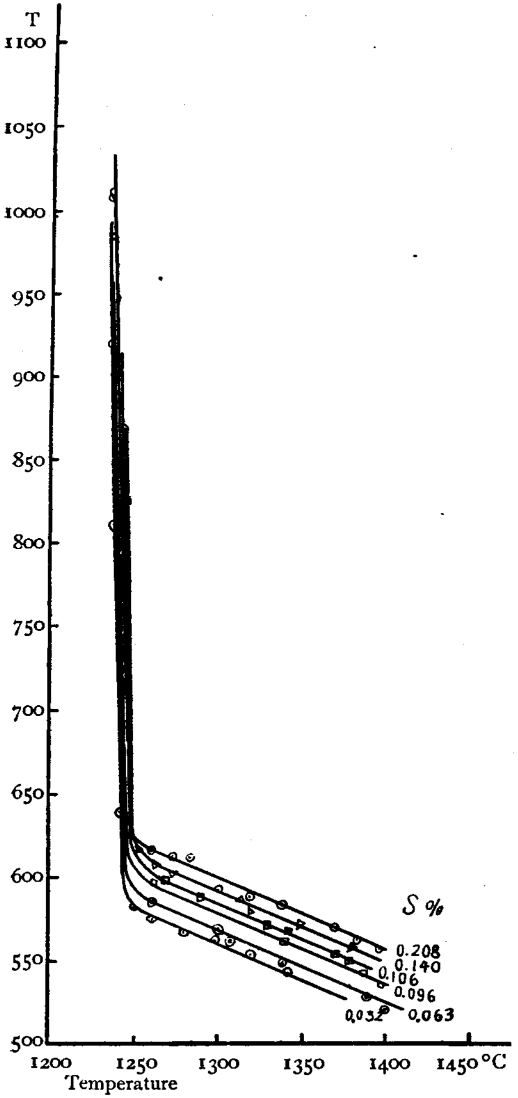


Influence of Phosphorus.

Carbon 3.43% Silicon 1.91%

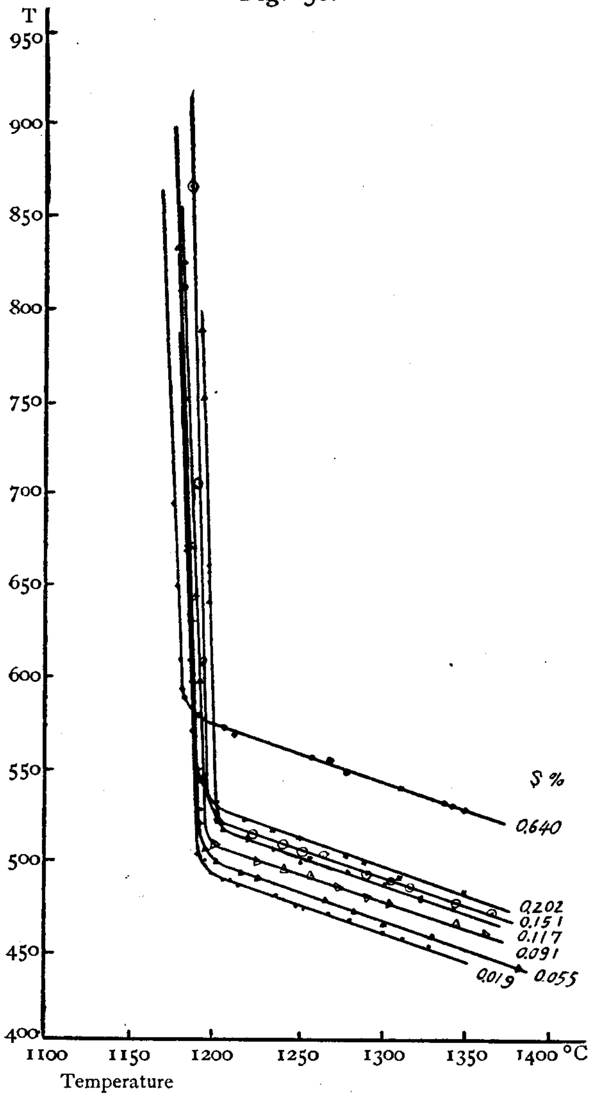
Manganese 0.43% Sulphur 0.02%

Fig. 31.



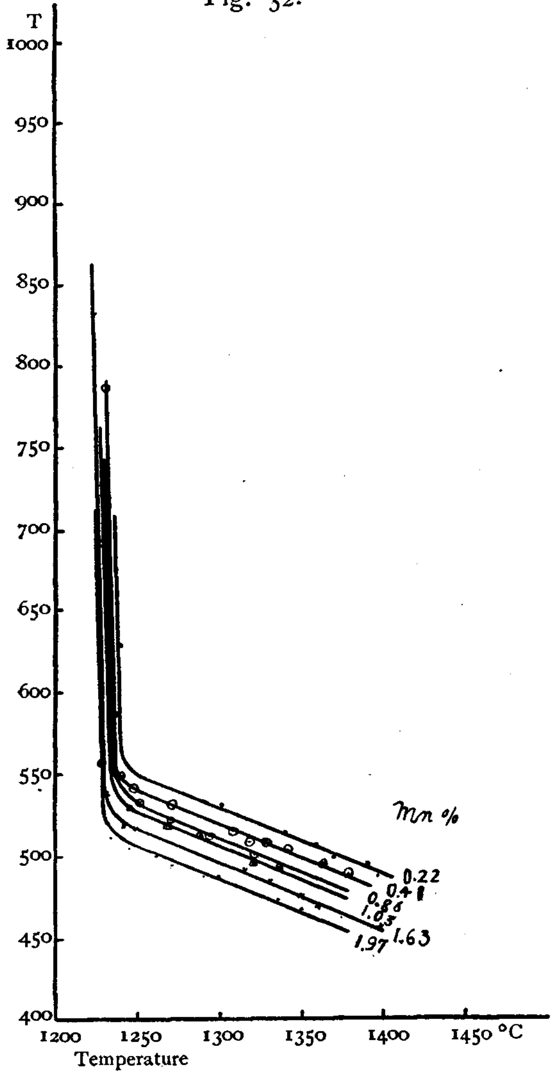
Influence of Sulphur.
Carbon 3.00% Silicon 1.32%
Manganese 0.51% Phosphorus 0.55%

Fig. 30.



Influence of Sulphur.
Carbon 3.64% Silicon 1.32%
Manganese 0.37% Phosphorus 0.18%

Fig. 32.

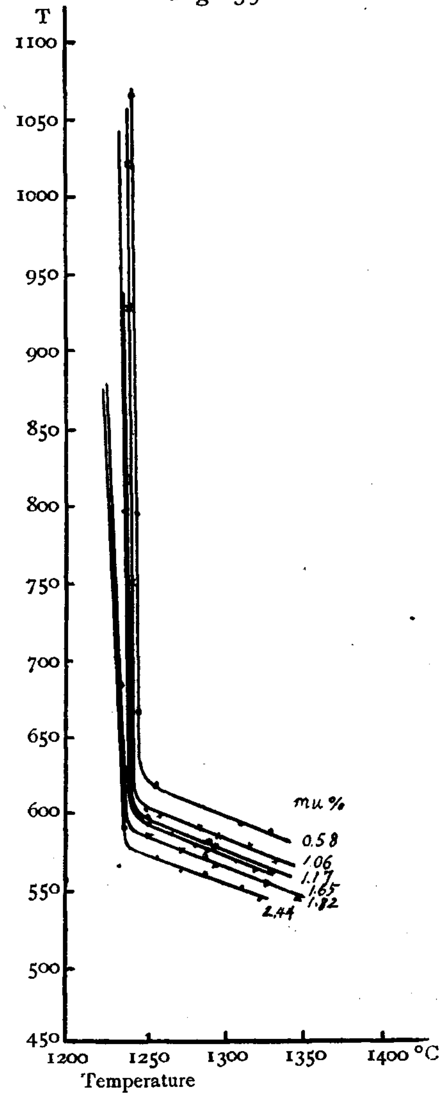


Influence of Manganese.

Carbon 3.33% Silicon 1.92%

Phosphorus 0.19% Sulphur 0.029%

Fig. 33.

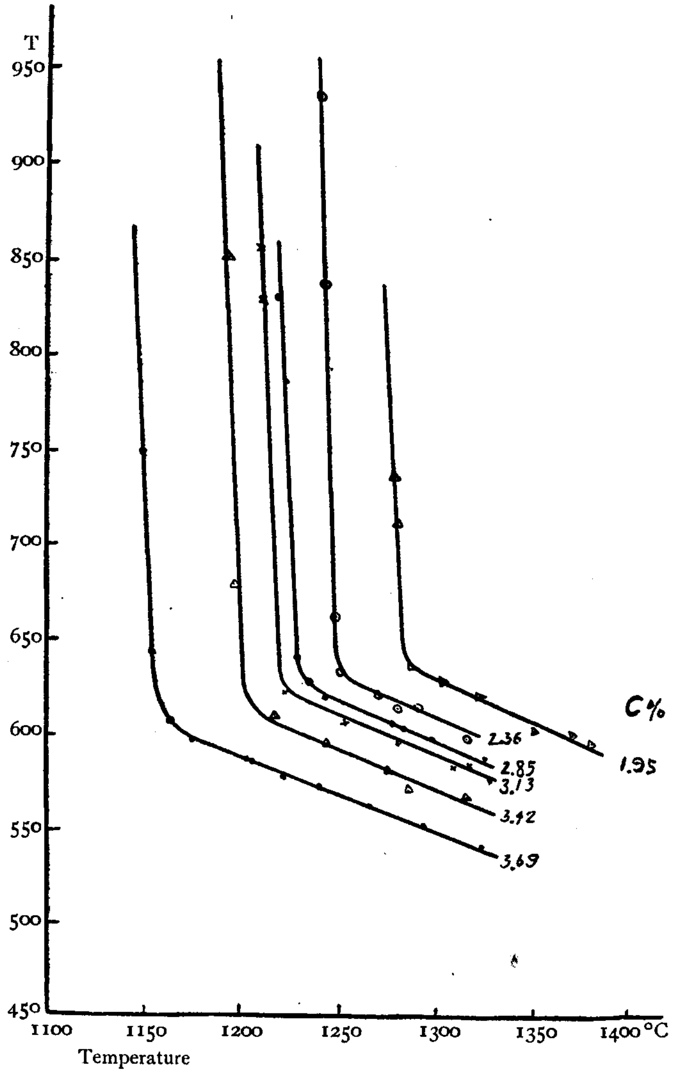


Influence of Manganese.

Carbon 2.84% Silicon 1.52%

Phosphorus 0.17% Sulphur 0.10%

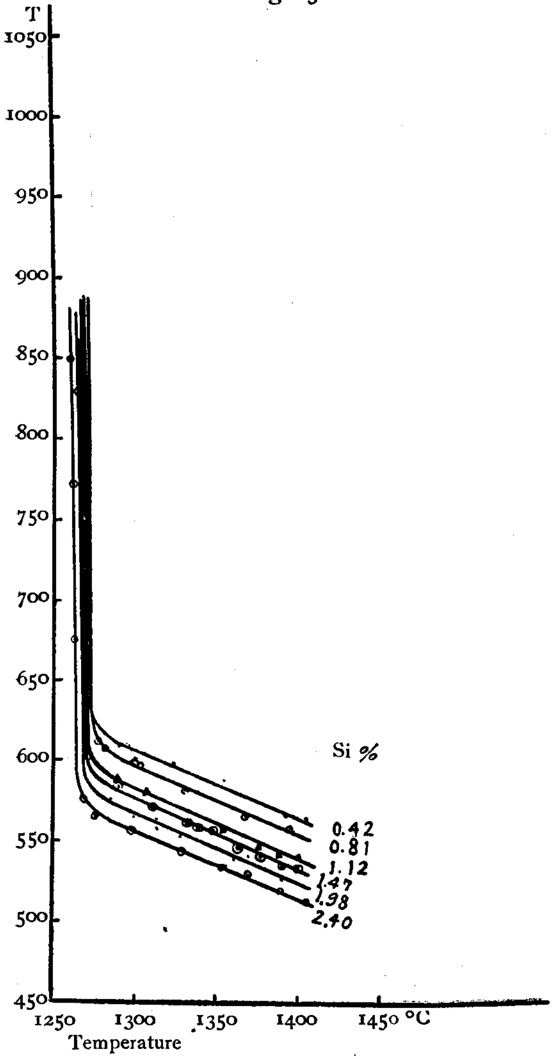
Fig. 34.



Influence of Carbon.

Carbon %	Silicon %	Manganese %	Phosphorus %	Sulphur %
1.95	0.91	0.53	0.17	0.16
2.36	0.96	0.55	0.15	0.13
2.85	1.09	0.52	0.20	0.17
3.13	1.10	0.51	0.26	0.16
3.42	1.15	0.53	0.21	0.12
3.69	1.33	0.51	0.22	0.14

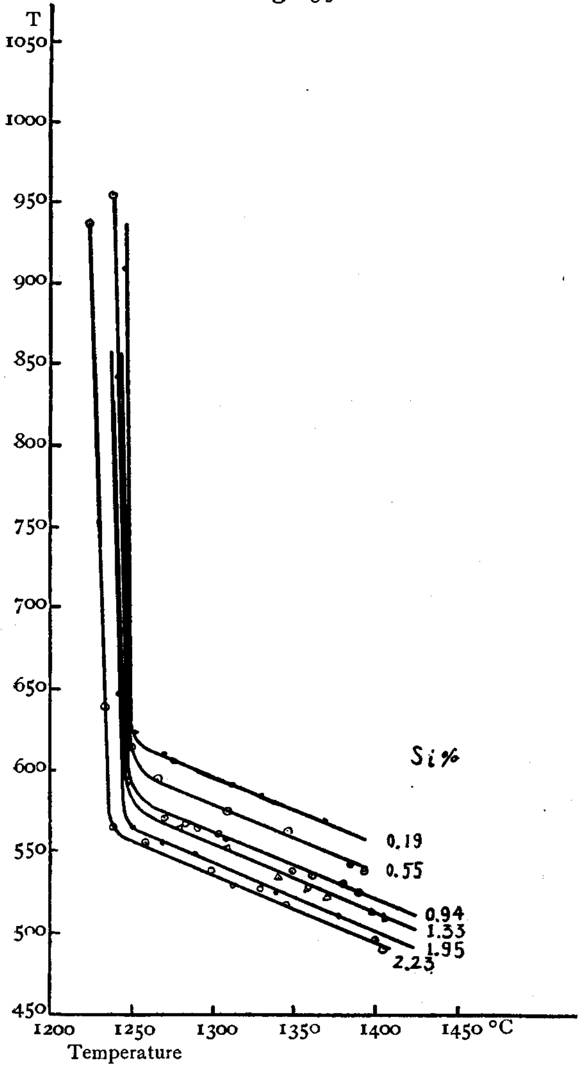
Fig. 36.



Influence of Silicon.

Carbon 3.07% Manganese 0.17%
Phosphorus 0.19% Sulphur 0.025%

Fig. 35.



Influence of Silicon.

Carbon 3.47% Manganese 0.55%
Phosphorus 0.23% Sulphur 0.027%

1) Influence of Impurities upon the Viscosity of Cast Iron at the Primary Crystallization Temperature.

The rate of the decrease of viscosity of cast iron in ascending temperature is independent of the quality and quantity of the impurities contained, as is shown in Figs. 28—36.

In practice, the casting temperature selected is 50° or 70°C higher than the melting temperature, so the viscosity of the molten cast iron at that time will be deduced from that at the crystallization temperature. Figs. 37—43 show the relations between the amount of impurities and the viscosity at the primary crystallization temperature.

Fig. 37.

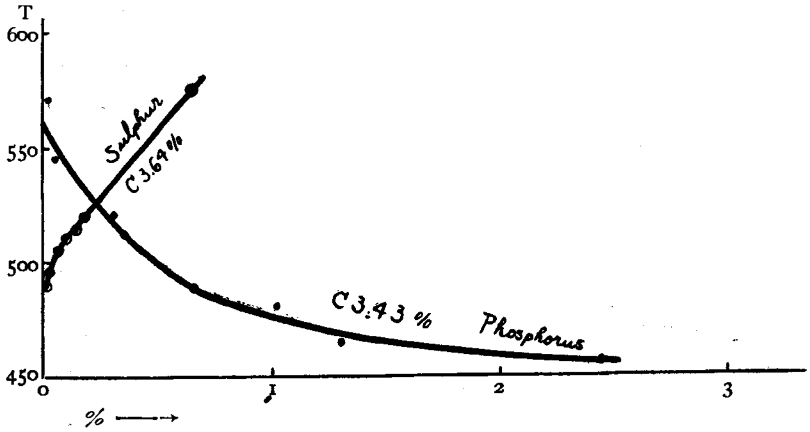


Fig. 38.

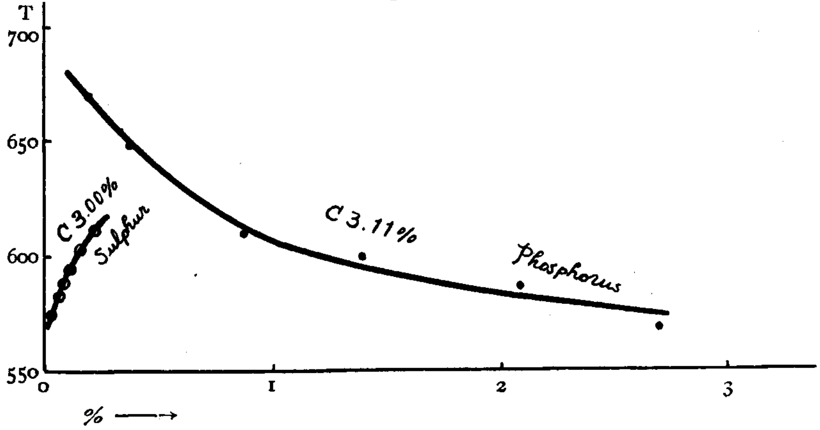


Fig. 39.

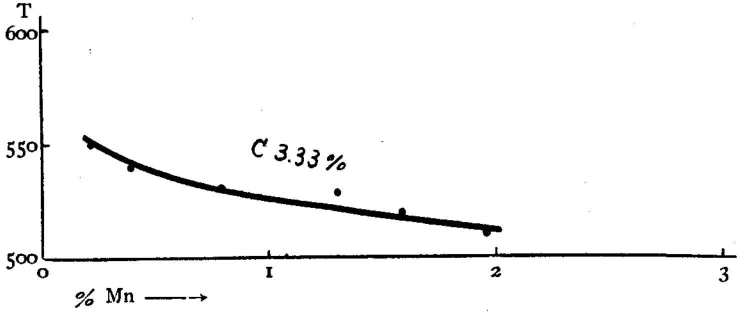


Fig. 40.

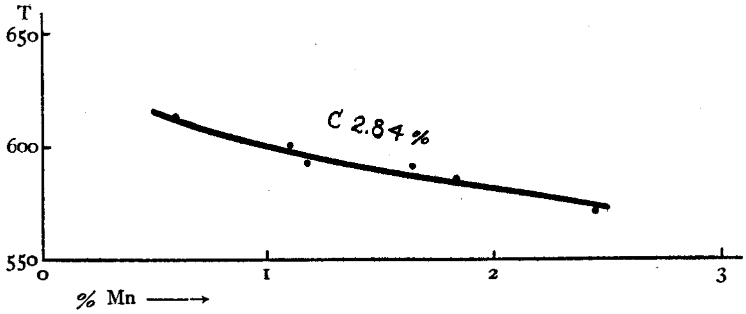


Fig. 41.

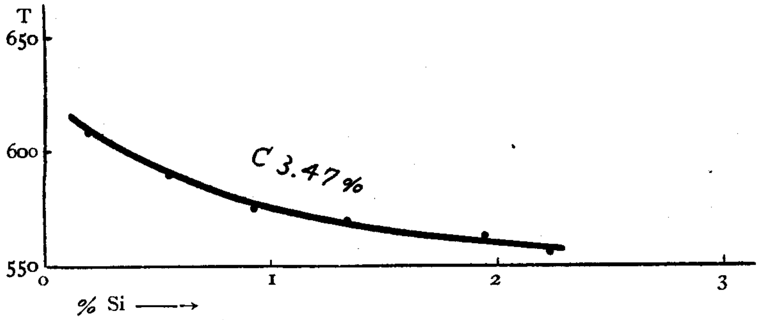


Fig. 42.

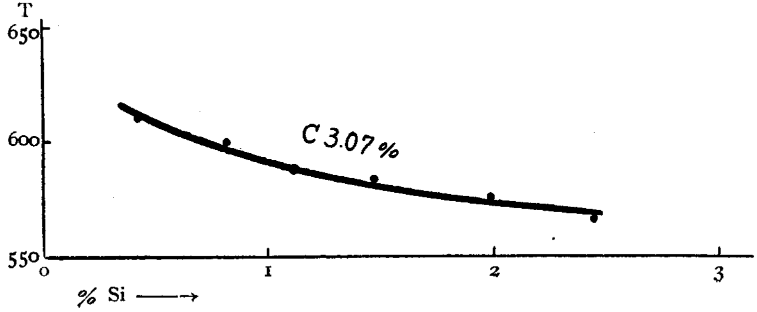
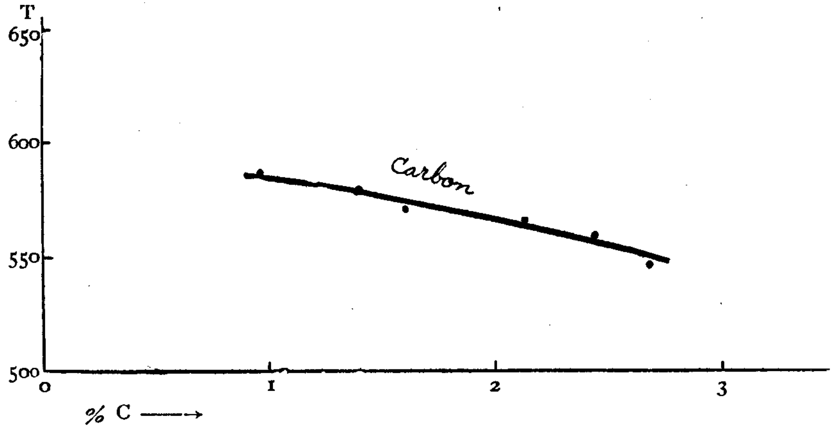


Fig. 43.



The above results can be summarized as follows:

Phosphorus.	This element decreases the viscosity of cast iron and up to about 0.7% the decrease is marked.
Sulphur.	This element increases the viscosity greatly, especially the effect being especially marked up to about 0.1%.
Manganese.	This element decreases the viscosity and the greater the amount of it the greater the decrease.
Silicon.	This element also decreases the viscosity.

We got similar results in the 3% and 3.5% carbon series in the measurements of the influence of the above substances upon the viscosity of cast iron.

Carbon.	This element decreases the viscosity also.

2) Influence of Impurities upon the Viscosity of Cast Iron at a Constant Temperature.

Figs. 44—52 show the relationship between the quantity of the impurities and the viscosity at 1250°C or 1300°C. When the casting temperature is made constant, these curves will serve well.

As it is very interesting and important to know how a certain fixed quantity, say 0.1%, of impurities influences the viscosity of cast iron, we show them in Table 88 and Fig. 53.

Fig. 44.

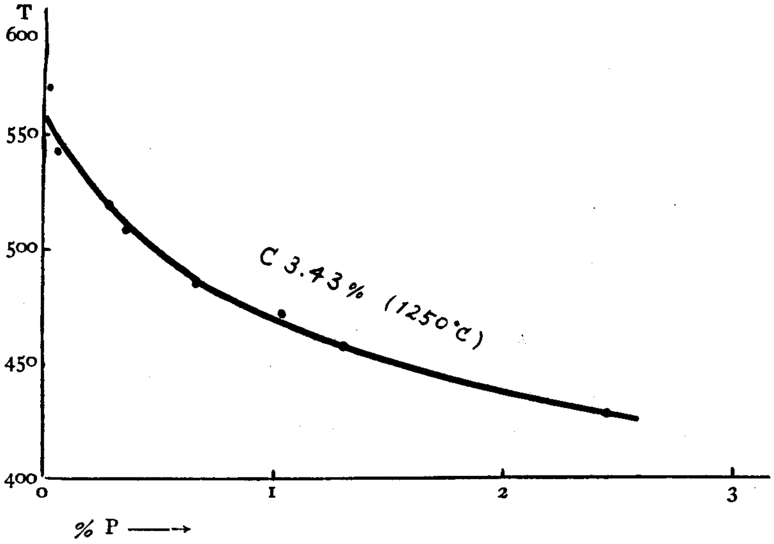

T
600
550
500
450
400
0
1
2
3
% P ⟶
C 3.43% (1250°C)

Fig. 45.

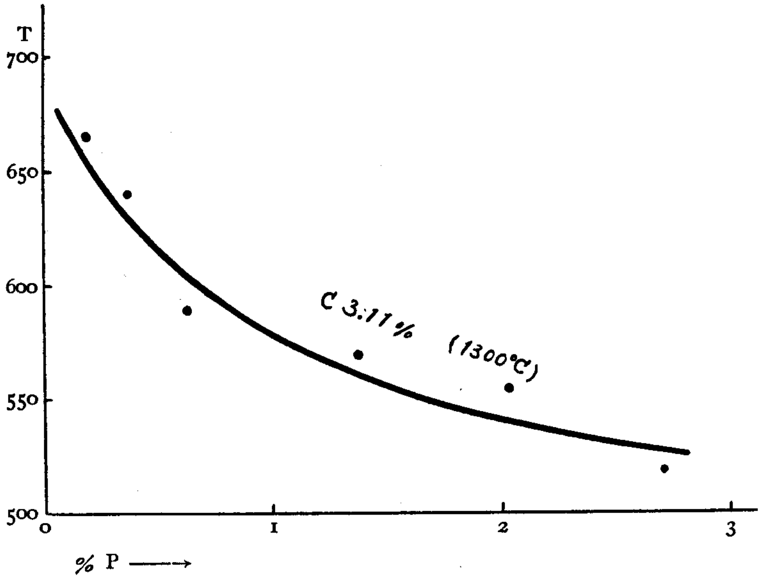

T
700
650
600
550
500
0
1
2
3
% P ⟶
C 3.11% (1300°C)

Fig. 46.

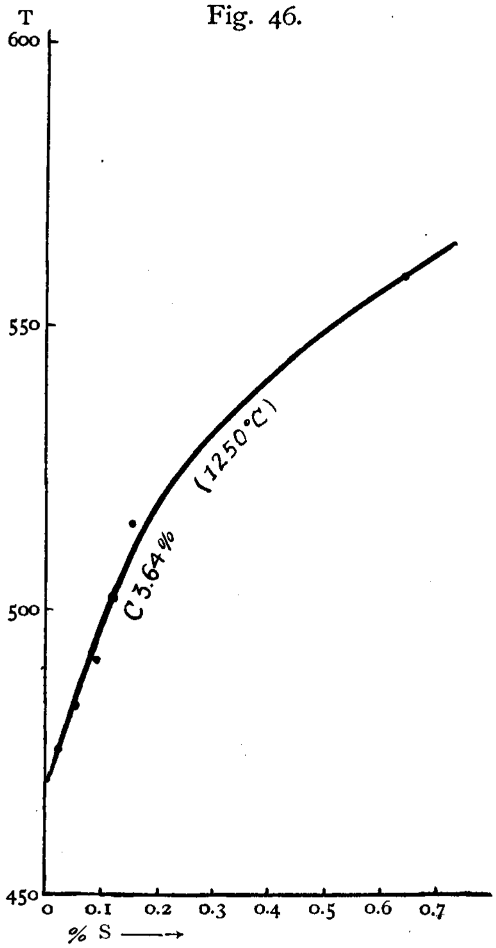


Fig. 47.

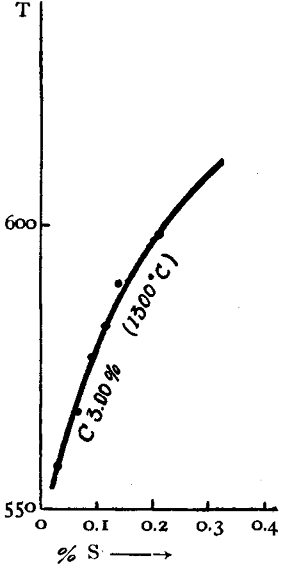


Fig. 48.

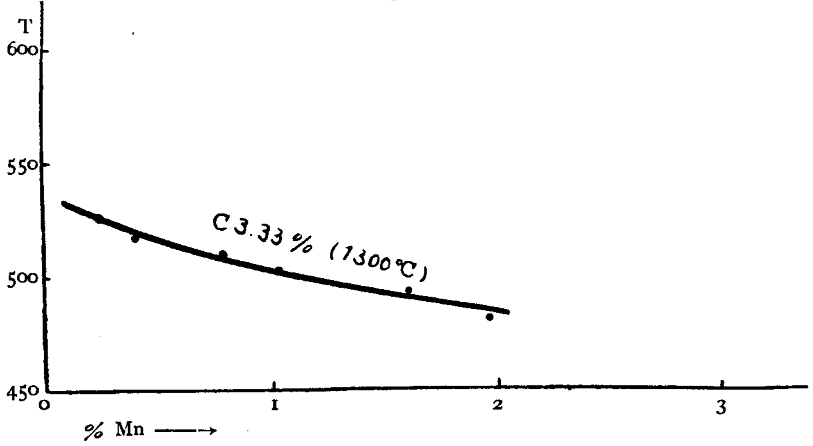


Fig. 49.

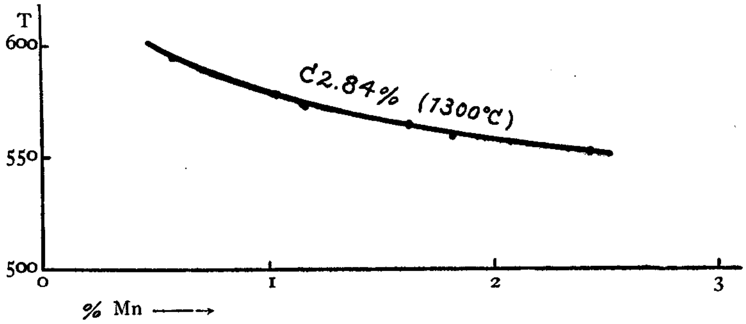


Fig. 50.

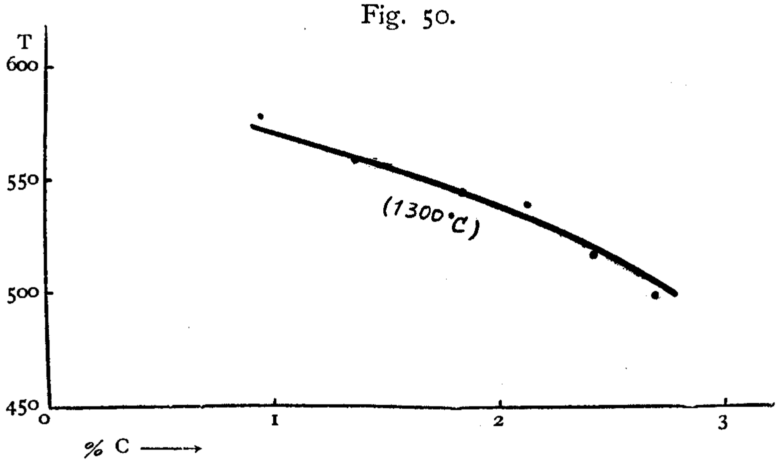


Fig. 51.

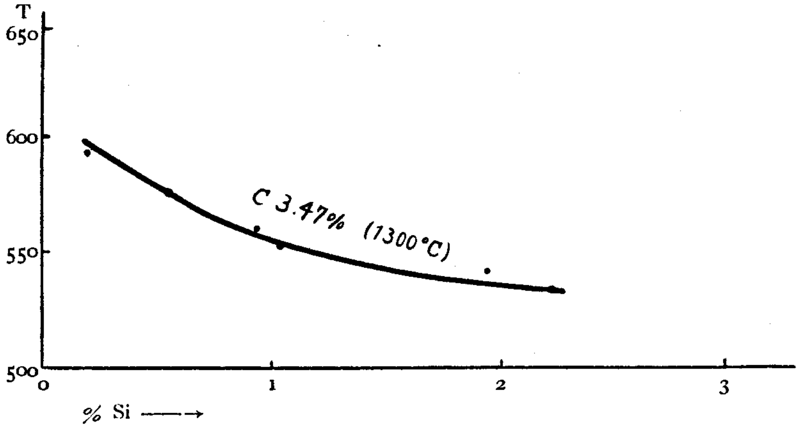


Fig. 52.

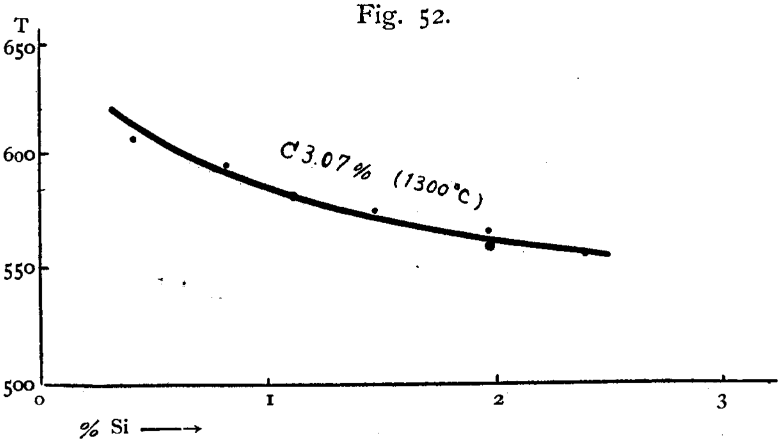


Table 88.

Influence of 0.1% Impurity upon the Viscosity of Cast Iron.

	C 3.5% Series (1)			C 3.0% Series (2)		
	C %	Average range	Ratio	C %	Average range	Ratio
Phosphorus	3.43	P 0.036—2.453%	− 5.8	3.11	P 0.187—2.706%	− 5.7
Sulphur	3.64	S 0.019—0.202 "	+20.5	3.00	S 0.032—0.208 "	+21.3
Silicon	3.47	Si 0.19 —2.23 "	− 2.9	3.07	Si 0.42 —2.40 "	− 2.5
Manganese	3.33	Mn 0.22 —1.97 "	− 2.5	2.84	Mn 0.58 —2.44 "	− 2.2
Carbon	—	C 1.95 —3.69 "	− 4.7			

Where (−) decrease of viscosity, (+) inciease of viscosity.

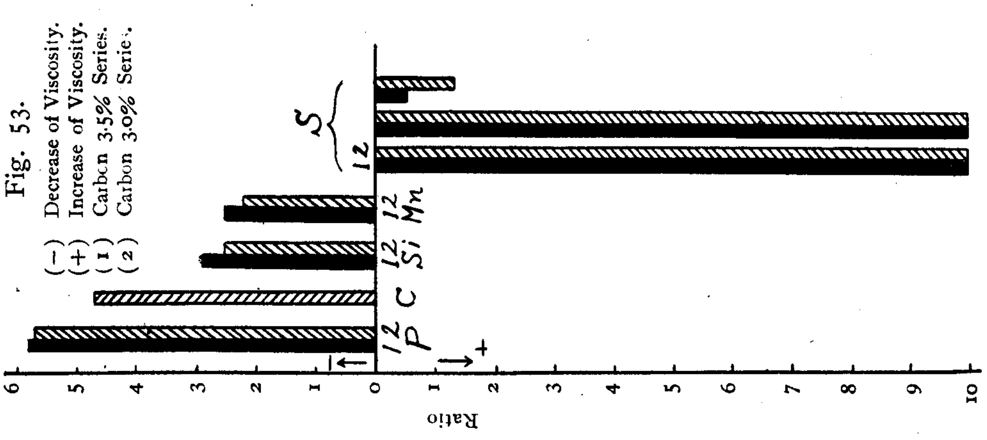


Fig. 53.

(−) Decrease of Viscosity.
(+) Increase of Viscosity.
(1) Carbon 3.5% Series.
(2) Carbon 3.0% Series.

These cast irons have different quantities of the ingredients, so the results are not perhaps strictly to be compared, but we can know the general tendency. Since they represent the effect of 0.1%, if the cast iron have 3.2% carbon, it must be multiplied by 32, and if the content of sulphur 0.06%, it must be multiplied by 0.6.

3) Relationship between the Primary Crystallization Temperature and the Amounts of Impurities in Cast Iron.

The primary crystallization temperatures in the equilibrium diagram are generally determined by thermal analysis. When the primary crystals begin to separate out, the viscosity of the molten metal suddenly increases, and, in consequence, we get the primary crystallization temperature easily from the viscosity-temperature curves.

If the amount of the primary crystals is very small, and the determination of the primary crystallization temperature by thermal analysis is very difficult, it can be obtained from the viscosity curve without difficulty.

Figs. 54—56 show the curves of primary crystallization temperature given by this method.

Fig. 54.

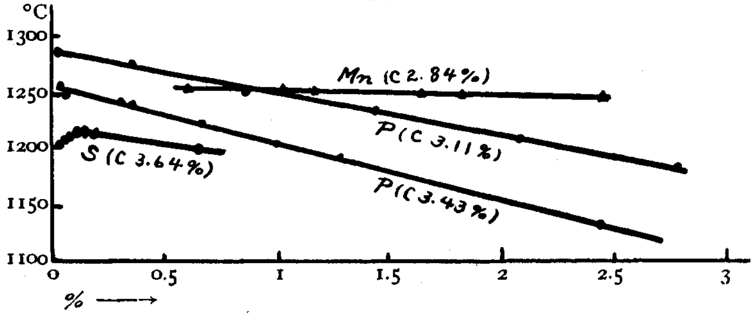


Fig. 55.

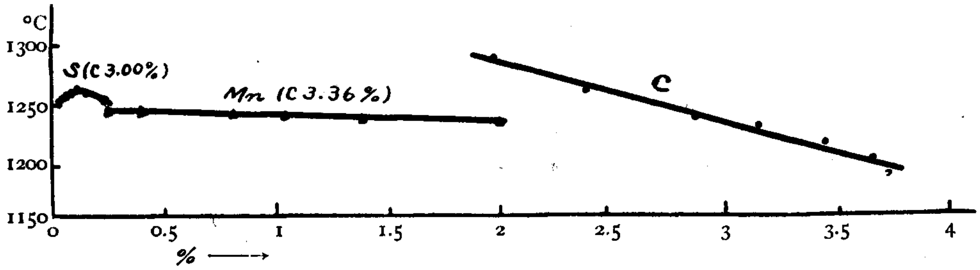
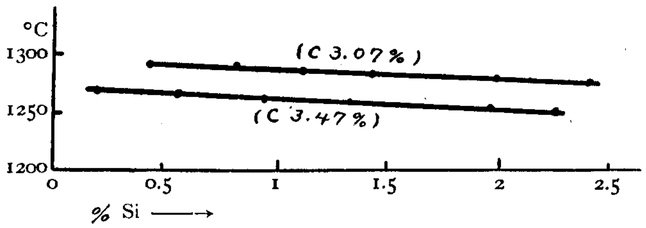


Fig. 56.



Among the elements which decrease this temperature when the amount of them is increased, carbon is most marked, and phosphorus comes next.

In the case of sulphur, with up to 0.1% of it the primary crystallization temperature ascends, and over this temperature descends.

The peak on the curve is perhaps due to the crystallization of the double compound of iron- and manganese-sulphide, and the further temperature decrease is probably due to the increase of the amount of iron-sulphide.

PART V. SUMMARY.

1. The rotating cylinder method was adopted with success for the measurement of the viscosity of various molten metals and alloys.

2. The measuring apparatus is fully described.

3. The viscosity of molten aluminium and a number of casting light alloys (Al–Cu, Al–Zn, Al–Cu–Zn, Al–Si, Al–Cu–Ni, Al–Cu–Ni–Mg, and silumin) was measured.

4. The viscosity of various casting copper alloys (aluminium-bronze, bronze, phosphor-bronze, brass, gun metal and manganese-bronze) was measured.

5. The authors found two change points at 765°C and 855°C in molten aluminium and light alloys during the measurement of viscosity, and their existence was further verified by thermal analysis and measurement of the electric resistance.

6. The modification of silumin seems to have some connection with the change at 765°C. By modification the change point is moved to a lower temperature.

7. The influence of various impurities upon the viscosity of cast iron have been ascertained. Phosphorus, carbon, silicon and manganese improve the viscosity of cast iron in different degrees but sulphur has a marked injurious effect on it.

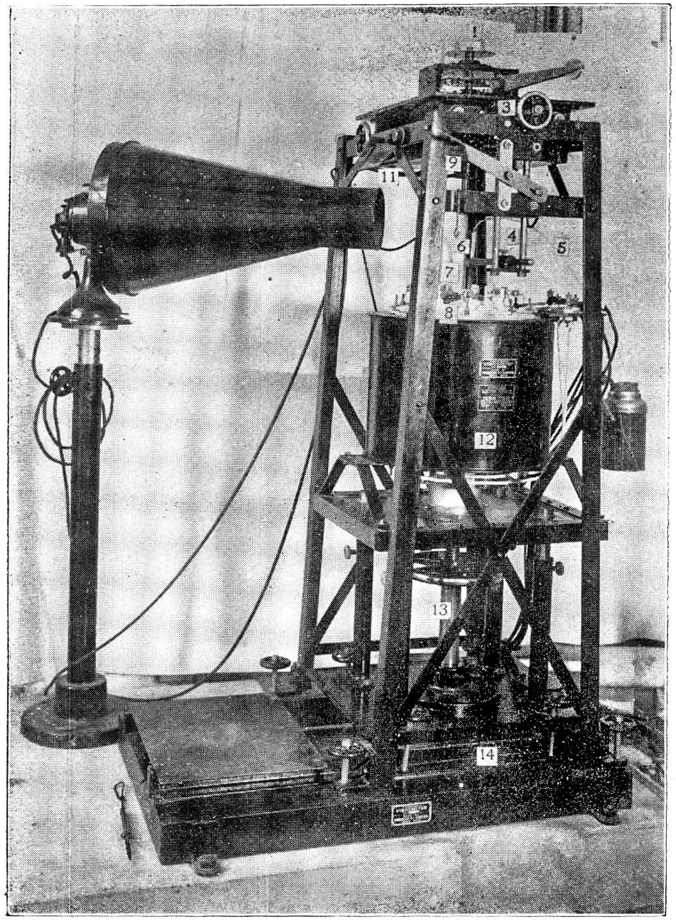


Photo. 2.

Apparatus for Measuring Viscosity of Molten Metals.

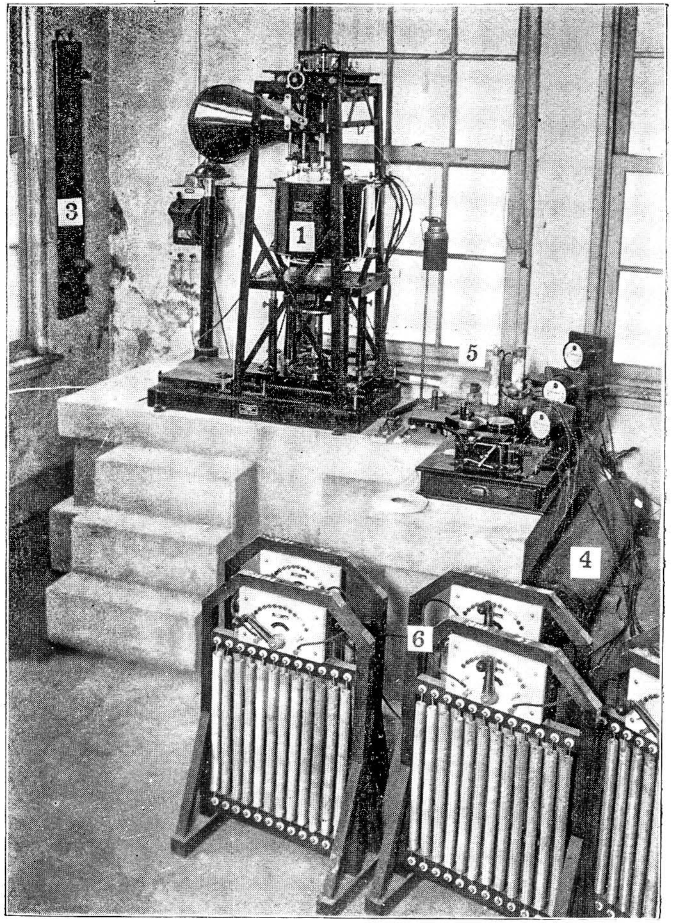


Photo. 1.

Arrangement of Apparatus and its Accessories.