EIGHTH REPORT* TO THE
ALLOYS RESEARCH COMMITTEE:
ON THE PROPERTIES OF
ALLOYS OF ALUMINIUM AND COPPER.

BY PROFESSOR H. C. H. CARPENTER, M.A., PH.D.,
AND MR. C. A. EDWARDS,
of the National Physical Laboratory.

GENERAL INTRODUCTION.

The following Research has been carried out by the authors with the co-operation of the Broughton Copper Co., Manchester, and the British Aluminium Co., Milton, who have furnished respectively the best *commercial* copper and aluminium for making the alloys, have undertaken the rolling and drawing of the materials, and have made special castings where necessary.

More than 1000 tests have been made, exclusive of about 200 specimens that have been microscopically examined and photographed. The results are classified in the various sections of this Report, and every care has been taken to render them accessible and clear. A

* For the First, Second, Third, Fourth, Fifth, Sixth, and Seventh Reports, see Proceedings 1891, page 543; 1893, page 102; 1895, page 238; 1897, page 31; 1899, page 35; 1904, pages 7, 859 and 1319; and 1905, page 857.

detailed index is provided on pages 61-63, and where possible summaries are given. But the research is composite in character, and does not lend itself to a general summary. Nevertheless the experimental material is so extensive that it is not easy to grasp the salient points of the research; and accordingly an attempt is made in this introductory section to set these forth briefly:—

(a) The number of alloys that have been found of any industrial and technical promise is small. Such alloys are chiefly those very rich in copper. At this end of the series the limit of serviceable alloys must be placed at 11 per cent. At the other end of the series the limit is even smaller. Among the specifically light alloys rich in aluminium the limit is probably not higher than 4 per cent. of copper. Between 11 and 96 per cent. of aluminium (exclusive) the alloys do not appear to be of any practical promise.

(b) But if the range of serviceable alloys is narrow their quality is certainly high in several instances. This statement holds for certain of the rich copper alloys containing between 7 and 10 per cent. of aluminium. It is not going too far to say that in certain respects the best of them equal and even surpass high quality steels of the same general character.

The following summary refers only to the rich copper alloys:—

(c) Four features of the results of the Tensile-Stress Tests of outstanding interest merit a special comment.

(1) In view of the doubt which exists at the present time as to whether copper and its alloys possess true yield-points, it is important to record that from 0.1 to 9 per cent. of aluminium the alloys possess clearly marked yield-points, Fig. 20 (page 141).

(2) It has been recently shown by Messrs. Stanton and Bairstow * that the primitive yield-point of a rolled or forged steel is usually an artificial figure, and is due to a *stiffening* caused by this mechanical treatment. Such is not the case with these alloys. Their primitive yield-point is the true one.

(3) The ductilities (considered as a product of the percentage elongation and reduction of area) of alloys containing from 0.1 to

* Proceedings, The Institution of Civil Engineers, vol. clxvi, 1906, page 78.

7.35 per cent. of aluminium are very high and practically constant, even although the tenacity increases markedly with rise of aluminium.

(4) The tenacity and ductility of the widely-known "aluminium bronze" or "gold," containing 10 per cent. of aluminium, have been found to be as good in the form of *small chill castings* as in the *rolled bar*, where an 80 per cent. reduction of area of the original ingot has been effected. So far as the authors have been able to learn, this result has no parallel. At their request therefore independent tests were instituted at the Broughton Copper Works, and these have confirmed the above result, which may have important practical consequences.

(d) The research has brought to light several striking instances of the profound influence of a small quantity of aluminium upon copper, notably in the tension tests, but especially in the torsion and electrical conductivity experiments. One tenth of 1 per cent. raises the angle of twist of copper in torsion 90 per cent.; it lowers the electrical conductivity 23 per cent.

(e) The behaviour in torsional stress of the alloys containing from 0.1 to 7.35 per cent. of aluminium is one of the outstanding features of the Report.

(f) The alloys containing from 5 to 10 per cent. of aluminium have come well out of the dynamic-stress tests. The particular merit of alloys Nos. 9 and 13 when tested in alternating stress is the close approximation of the maximum stress under which they will bear an unlimited number of reversals to the stress at the elastic limit as determined in a tensile test. *In this respect they are markedly superior to the iron and steel specimens hitherto investigated.*

Alloys Nos. 6, 9, and 13 stood up well when repeatedly stressed beyond the yield-point in Arnold's test. In fact Professor Arnold has informed the authors that "Alloy No. 9 constitutes a record in its capacity of resisting alternations."

(g) At about 15 per cent. of aluminium the alloys are entitled to rank with quenched steels in *hardness*. Thus the hardness number of No. 17 (15.38 per cent.) in the *cast* state (untreated) is 539, which is about that of a 0.45 per cent. carbon steel quenched in water at

20° C. (68° F.),* and is only slightly lower than that of a 0.66 per cent. carbon steel similarly treated.

(h) In the corrosion tests, which were purposely made as severe as possible, alloys containing from 1 to 10 per cent. of aluminium have shown themselves to be practically incorrodible by sea-water, whether alone or bolted to a plate of mild steel. In these tests they showed themselves superior both to Muntz Metal and Naval Brass, which corroded appreciably. In tap water of medium temporary hardness the positions were exactly reversed.

(k) In view of the discussion in the previous Report as to the trustworthiness of temperatures measured with a protected thermo-junction, the exact influence of the jacket (a fire-clay tube $\frac{1}{8}$ inch in thickness) between temperatures of about 1,100° C. and 550° C. (2,012° F. and 1,022° F.) has been determined (pages 198–203). It has been found to cause a lowering of not more than 3° C. (5.4° F.) at the higher, and 9° C. (16.2° F.) at the lower temperature, and above 800° C. (1,472° F.) comes *within* the experimental errors and uncertainties of the method.

(l) Finally, a special comment must be made on the truly extraordinary similarity in physical and mechanical qualities between Alloy No. 13, which consists of 90.06 per cent. of copper + 9.90 per cent. of aluminium, and Swedish Bessemer rolled steel of about 0.35 per cent. of carbon and 38 tons per square inch ultimate tensile stress (pages 221–224).

* Journal, Iron and Steel Institute, 1901, No. I, page 267.

INDEX OF REPORT.

PART 1.

	PAGE
Historical Introduction	81
Research Scheme	84
Materials used	85
Method of Melting and Casting the Alloys	86
EFFECT OF REMELTING THE ALLOYS—	87
(a) Alloys rich in Copper	87
(b) " " " Aluminium	92
Influence of Casting Temperature	92
CHEMICAL ANALYSES—	96
Methods of Estimation.	96
Composition of the Alloys	99
Colour of the Alloys	104

PART 2. PROPERTIES OF THE RICH COPPER ALLOYS—

Melting and Casting of the Alloys	104
Contraction Experiments	106
Mechanical Treatment of the Alloys	107
Heat " " " "	108
Specific Gravities	109
Tensile-Stress Tests (A)—	113
(a) Sand Castings	113
(b) " " slowly cooled from 800° C. (1,472° F.)	116
(c) " " quenched from 800° C. in water	116
(d) Chill Castings	120
(e) " " slowly cooled from 800° C.	120
(f) " " quenched from 800° C. in water	120
(g) Bars rolled to 1½ inches diameter	123
(h) " " " 1½ inch "	126
(k) " (1½ inch diameter) slowly cooled from 800° C.	127
(l) " " " " quenched from 800° C. in water	131
(m) Cold-drawn Bars (1½ inch diameter)	131
Summary	136
Rolled Bars (1½ inch diameter) of Standard size	139
Stress-Strain Diagrams	140

Tensile-Stress Tests (B)—

Alloy No. 1 (Aluminium 0·10 per cent.)	148
" 2 " 1·06 " 	149
" 3 " 2·10 " 	150
" 4 " 2·99 " 	151
" 5 " 4·05 " 	152
" 6 " 5·07 " 	153
" 7 " 5·76 " 	154
" 8 " 6·73 " 	155
" 9 " 7·35 " 	156
" 10 " 8·12 " 	157
" 11 " 8·67 " 	158
" 12 " 9·38 " 	159
" 13 " 9·90 " 	160
" 14 " 10·78 " 	161
Summary	162
Comparison of Alloys prepared from "Cathode" and "Lake" Copper .	167
Structures of the Alloys	167
Tensile-Stress Tests of Quenched Bars	169
Alloy No. 11	170
" " 12	170
" " 13	172
Experiments on the Recrystallization of the Alloys at High Temperatures .	175
Alloys Nos. 1, 4, 7, and 9	175
Alloy No. 13	181
" " 14	182
" " 15	182
Ball Hardness Tests	183
Torsion Tests	186
Alternating-Stress Tests	190
(a) those carried out in the Engineering Department of the Laboratory	190
(b) those carried out by Professor Arnold in the University of Sheffield	196
Impact Tests	197
Summary of Kinetic-Stress Tests	197
Freezing Ranges and Evolutions of Heat on Cooling	198
Comparison of "bare" and "protected" thermo-junctions	199
Heating and Cooling Curves	206
A general physical interpretation of them	206
Corrosion Tests—	216
A. Sea-water Tests of the Alloys (singly)	217
B. " " " Galvanic Couples of the Alloys and Mild Steel	218
C. Fresh-water " " " " " " " " " "	219
Summary	220

Electrical Conductivities	221
A Comparison of the Properties of Alloy No. 13 with those of Swedish Bessemer Steel of about 0.35 per cent. of Carbon	221

PART 3. ALLOYS OF INTERMEDIATE COMPOSITION—

Tensile-Stress Tests—

Chill Castings	225
Sand Castings	225
Structures	225

PART 4. THE PROPERTIES OF THE RICH ALUMINIUM ALLOYS—

Experiments at Casting under Pressure	226
Mechanical Treatment of the Alloys	227
Specific Gravities	229
Tensile-Stress Tests—	230
(a) Sand Castings	231
(b) " " slowly cooled from 450° C. (842° F.)	231
(c) " " quenched from 450° C. in water	231
(d) Chill Castings	231
(e) Bars rolled to 1½ inches diameter	240
(f) " " " 1½ inch "	240
(g) " drawn (with annealing) to 1½ inch diameter	244
(h) " cold-drawn	244
Summary	245
Tests of the Alloys in Sheet Form—	
Manufacture	246
Tensile-Stress Tests—	
(a) Plates, 0.25 inch thick	247
(b) " 0.10 " "	248
(c) " 0.05 " "	249
Summary	252
Structures	252
Corrosion Tests—	
A. Sea-water Tests	254
B. Fresh-water ¹ ,	255
Summary	256
Experiments to test the suitability of the Alloys for Cooking Utensils	256
General Concluding Summary	257

APPENDIX.

Liquidus Curve	259
Solidus Curve	261
Comparison with Heycock and Neville's Temperature Concentration Diagram	268

SUMMARY OF REPORT,

including statement of more important Results obtained.

The following abstract of the Eighth Report to the Alloys Research Committee has been prepared to enable readers to obtain a general idea of the main conclusions arrived at without having to study the entire text. It is however considerably fuller than the general introduction on pages 57-60. To facilitate reference to any particular portion of the Report, the corresponding pages are given.

Preparation of the Alloys (pages 86-87, and 104-109).

The authors think that the following conclusions may be drawn from the results of their experiments:—

(1.) There is no need to melt the alloys rich in copper in order to obtain thorough mixing, obviate brittleness, and secure the best mechanical properties. With due care the first cast is as likely to be as good as any that may follow it. Such differences in properties as have been found are probably to be ascribed to accidental variations in the conditions of preparation, of which probably the most important are variations in casting temperatures, and small holes in the castings. *This conclusion is not intended to apply to other than small castings.* In large castings the difficulties of securing thorough mixing are much greater. In such cases remelting may always constitute the best *practical* method of ensuring homogeneity of material.

(2.) Copper-rich alloys can be perfectly satisfactorily prepared from the pure metals, and no advantage is gained by using the 50 per cent. alloy instead of aluminium. The alloys described subsequently have been prepared, some of them from the pure metals, others from copper and the 50 per cent. alloy. The continuity of properties that has been found in the various members of a series constitutes additional evidence that the alloys may be satisfactorily prepared by either method.

(3) Alloys rich in aluminium can also be satisfactorily made with only one melting. This conclusion is intended to apply only to small castings. It has been the authors' experience during the Research that it is far more important to cast these alloys at the right temperature than to remelt, in order to get the best mechanical properties.

As will be shown later, it was unnecessary to test the influence of remelting on the properties of alloys of intermediate composition. The Research has thoroughly confirmed Dr. L. Guillet's conclusion that only the alloys at the extreme ends of the series are of any industrial promise.

Accordingly all the alloys subsequently prepared were melted only once. The greatest care was paid to the two important points: (a) casting temperature; (b) thorough stirring.

Measurements of the total linear contraction of castings on cooling from the freezing-point to the ordinary temperature showed—

- (a) That these vary between 1.83 and 2.34 per cent. among the rich-copper alloys (page 107);
- (b) That a uniform value of 1.66 per cent. holds for the rich-aluminium alloys (0 to 3.76 per cent. copper) (page 227).

PROPERTIES OF THE RICH COPPER ALLOYS.

Specific Gravities (pages 109–111).

Attention is directed to the following features of the results:—

(1) The chill castings and rolled bars have the same specific gravity. As is shown later certain of the alloys, viz. Nos. 10, 12, 13, and 15, have practically the same structures in the two conditions, while in Nos. 14 and 16 a similarity exists. In these cases an identity and similarity respectively of specific gravities is natural. But no such structural similarities exist between the chill castings and rolled bars of Alloys Nos. 1 to 9.

(2) With the introduction and addition of aluminium up to 13 per cent. the specific gravity drops regularly, and a smooth curve results, Fig. 5 (page 111). This fact is of importance, because

G

very marked structural changes are caused by the addition of aluminium between 8 and 13 per cent.

(3) The specific-gravity curve of the sand castings exhibits a general similarity to those of the chill castings and rolled bars, but is less regular. Up to 7 per cent. of aluminium the specific gravity values are either equal to or, in most cases, are lower than those of the chill and bars. Within this range the alloys are homogeneous, and appear to consist of a solid solution of aluminium in copper. Beyond and as far as 10·8 per cent. they are higher. In this range the structure is *duplex*, and the alloy consists of at least two structural constituents. Denser alloys are obtained by the slow rather than by the quick cooling of these two constituents. Beyond 11 per cent. there is a further structural change, and the sand castings are no longer sound. This is the principal factor in causing the apparently rapid fall of specific gravity at this point.

(4) 8·90, the specific gravity of the sand and chill castings of the alloy containing 0·1 per cent. of aluminium, is the standard specific gravity for copper conductors adopted by the Sub-Committee on Cables of the Engineering Standards Committee.

Tensile Tests (pages 113-167, and 169-175).

In considering these results as a whole, attention may be directed to the following features :—

(a) The limit of industrially-serviceable alloys must be placed at 11 per cent. of aluminium. For most purposes the limit might be put at 10 per cent., beyond which there is a rapid fall of ductility with no rise of ultimate stress. It will be noticed however, particularly in the castings, that the yield-point is usually decidedly better at 11 than 10 per cent.

(b) Between these limits the alloys fall into two classes.

(1) Those containing from 0 to 7·35 per cent. of aluminium.

(2) " " " 8 to 11 " " "

Class I represents material of apparently low yield-point and moderate ultimate stress, but of very good ductility. The introduction and further addition of aluminium causes a gradual increase of

strength, but hardly affects the ductility. It is true that as regards the steadiness of the ductility this has only been established for the rolled bars. But the sand and chill castings have shown the *same kind of variations* as the rolled bars in all the properties examined, and it appears legitimate to draw this conclusion for them also. This Class is not very sensitive to heat-treatment, but is much improved by mechanical work.

Into Class 2 come alloys of relatively low yield-point, but good ultimate stress. From 8 to 10 per cent. of aluminium, the ductility is also good. Certain alloys in this class are very sensitive to heat-treatment, but one of them is remarkably indifferent to hot rolling (No. 13).

(c) Taken as a whole the chill are superior to the sand castings, and are themselves surpassed by the rolled bars. Alloy No. 13, and to a less extent No. 12, constitute a notable exception to this generalization.

(d) One of the most noteworthy characteristics of the alloys as a whole is their low yield-point, absolutely and relatively. Accordingly the elastic ratio of an alloy of given ultimate stress is low compared with that of a steel of the same ultimate stress. Thus No. 13 (with 10 per cent. of aluminium), with an ultimate stress of 38 tons per square inch, has an elastic ratio of only 0.39, whereas that of a Swedish Bessemer Steel, containing about 0.35 per cent. of carbon of the same ultimate stress, is 0.68. This appears to place these alloys in a position of inferiority. But it has been shown recently by Messrs. Stanton and Bairstow that the primitive yield-point of a steel is usually an artificial figure, and is due to a stiffening caused by mechanical treatment in preparation. Thus they found that the proper yield-point of the Bessemer Steel mentioned was 15.2 tons per square inch. The elastic ratio then became 0.40, which is identical with that of No. 13. As is shown on page 195 these rich copper alloys do not show anything like the same tendency to assume an artificial yield-point. The inferiority of the aluminium bronzes is thus only apparent, not real.

(e) Cold-drawing raises the elastic ratio to a very high figure, and leaves a considerable measure of ductility, but it has not been

successful at about 5 per cent. of aluminium, where a tendency to pipe has been noticed.

(f) Another striking feature of the mechanical qualities of the alloys is the very high ductility which is almost constant between 0 and 7·35 per cent. of aluminium. More especially is this the case with the reduction of area. The values obtained were so much superior to those given in the best results found in the literature that the authors became suspicious of their results. It was accordingly decided to obtain an exact copper blank of the series. At their request a rolled bar $\frac{1\frac{3}{8}}$ inch diameter was prepared at the Broughton Copper Works from the same "cathode" copper as that used in the Research. Analysis showed that it contained 99·96 per cent. of copper. In order to soften it thoroughly, the bar was slowly cooled from 800° C. (1,472° F.). The tensile-stress test gave the following result:—

Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
5·0	14·17	56·0	67·84

These figures may be compared with those obtained from Alloy No. 1, in all respects similar as regards physical treatment and composition, except that it contains 0·10 per cent. of aluminium and 99·86 per cent. of copper—

4·4	14·18	62·0	92·52
-----	-------	------	-------

The tenacities are the same, but the ductility of No. 1 is very much superior. The effect of this small percentage of aluminium is equally well marked in torsion (pages 189 and 190) and electrical-conductivity tests (page 221).

(g) A study of Tables 33 to 44 (pages 148–159) shows that, up to 9·4 per cent. of aluminium, the ultimate stress of the rolled bar $\frac{1\frac{3}{8}}$ inch diameter (untreated) is always higher than that of the chill casting (untreated). (As previously pointed out, the tenacity of the chill is usually superior to that of the sand casting.) The amount varies between 3 and 10 tons per square inch. In Table 45 (page 160),

however (Alloy No. 13), it will be noticed that the chill casting has a tenacity of 37 tons per square inch and an extension of 30.5 per cent. as against the 38 tons and 29 per cent. extension of the rolled bar. These properties are practically identical. Further, the tenacity of the chill is 2 tons higher than that of the rolled bar $1\frac{1}{4}$ inches diameter. This must be regarded as an astonishing result. The authors have searched for a parallel among other known alloys, but without success. So far as they are aware, it is a unique exception to the view generally held that rolled is superior to cast material.

Alloy No. 14 presents a very similar case. The chill casting is 1.73 tons better than the $1\frac{1}{4}$ -inch diameter bar, but it is nearly 2 tons worse than the rolled bar $1\frac{3}{16}$ inch diameter, and its extension is 5 per cent. lower.

That the long-known aluminium-bronze or aluminium-gold, containing 10 per cent. of aluminium, should be as strong and as ductile when cast in chill (1 inch diameter) as when rolled from a 3-inch diameter ingot down to $1\frac{3}{8}$ inch, appeared to the authors to be of such importance, both practically and theoretically, that they have confirmed it by making and testing other casts and bars, and by having the results checked by an independent worker.

Structures (pages 167-169).

The structures revealed by the microscope throw considerable light on the classification of the alloys into two chief classes under the mechanical tests. Up to 7.35 per cent. of aluminium the alloys consist of ductile crystals of a solid solution. Heat treatment affects the size of the crystals to some extent, but does not cause profound structural changes as in the case of alloys containing from 9-11 per cent. of aluminium. Its influence on mechanical properties is not very far-reaching. On the other hand, the crystals are very much broken up by rolling, and are interlocked into a tougher combination than the cast material.

The sudden stiffening of the alloys beyond 8 per cent. of aluminium coincides with the appearance of a dark structural

constituent, which has been shown by microscopic examination to be acicular. Instances of the association of brittleness with an acicular structure are well known. At 11.73 per cent., where the structure is wholly acicular, the alloy has only slight ductility.

Heat-Treatment Tests (pages 175-183).

Alloy No. 13 was the most thoroughly tested of the series on account of its sensitiveness to heat treatment. The results are given in Table 53 (page 178), and are shown graphically in Fig. 29 (page 179). They show that between 300° and 400° C. (572° and 752° F.) this alloy undergoes a profound change. Comparing the results, it will be seen that after treatment at 300° C. the properties are substantially the same as those of the bar as rolled, but that at 400° C. there is a rise of nearly 100 per cent. in the elastic ratio due to an increase in yield-point and decrease in ultimate stress. Most important of all, the ductility has dropped almost to nil. The fracture also is characteristically different. It is somewhat surprising that the microscope reveals no evidences of structural change in the alloy. The etched surface appears identical with that of the untreated bar. From 500° to 700° C. (932° to 1,292° F.) there is a slight return of ductility and the elastic ratio falls, both yield-point and ultimate stress decreasing. At 800° and 900° C. (1,472° and 1,652° F.) there is a further loss of strength, and the fracture becomes coarsely crystalline. The etched surfaces of specimens heated in this range show considerable structural alterations, which are fully represented in Plate 8.

These results show that the properties of the 10 per cent. aluminium-bronze are most injuriously affected by heat treatment at even moderately low as well as high temperatures; 400° C. (752° F.) appears to be particularly fatal. This fact unfortunately limits the usefulness of this otherwise valuable alloy, and prevents its application to any moderate or high-temperature work. Time has not permitted the authors to carry out strength tests on this alloy at varying temperatures.

Ball Hardness Tests, Table 54 (pages 183-186).

The results are of the same kind under the two loads, namely, 1,034 and 3,000 kgs. The values in column 6 represent however "standard" numbers, and only these will be considered. The hardness number 66 was obtained for No. 1, the base of the series. The introduction of aluminium at once hardens the material, but there is no very notable increase in the number up to 7.35 per cent. At 10 per cent. there is a marked rise, and from here up to 15.38 per cent. the increase is rapid. At the last-named percentage the figure 539 was obtained. This is more than eight times that obtained for No. 1, and must be considered a very high figure for an alloy that is not a steel of some kind. The figure for the hardest steel known is about 800, and although this is considerably higher than 539, yet the latter is just about the hardness number of a 0.45 per cent. carbon steel quenched in water at 20° C. (68° F.), and is only slightly lower than that of a 0.66 per cent. carbon steel similarly treated. Accordingly Alloy No. 17 is fully entitled to rank with these hardened steels in this respect.

Torsion Tests, Table 55 (pages 186-190).

Maximum Load (Columns 5 and 6).—The variations of load with rising aluminium are similar to those obtained in the tension tests, except that at 9.90 per cent. there is a slight decrease in torsional stress as compared with a decided increase in tensile stress.

Total Twist.—These figures (columns 7 and 8) must be regarded as very noteworthy. In particular those obtained with Alloys 1 to 3 are far higher than those of either pure copper or any of its alloys of which the authors have found mention in the literature. (The value for No. 3 would have been even higher had the length been 3.0 instead of 2.8 inches.) Professor T. Hudson Beare obtained a mean total twist of 5.41 turns in three closely-agreeing determinations of copper of the same dimensions, and this appears an average figure for good copper. It is the authors' opinion that the particularly high figure

for No. 1 may be attributed chiefly to the presence of one-tenth of a per cent. of aluminium. Rolled copper generally contains more or less dissolved oxide which diminishes its ductility. Accordingly in casting Alloy No. 1 particular care was taken that a slight excess of aluminium should be added in order to remove oxygen, and yield as pure a commercial copper as possible. The authors do not regard No. 1 as a copper-aluminium alloy so much as the base of the series which contains as little aluminium as possible consistent with the absence of oxygen. Viewed as copper it contains only about one-tenth of a per cent. of impurities, as does the "Lake" copper used in this Research.

A direct comparison was obtained by testing the blank of the series, namely, the pure copper referred to on page 138. The values are given in the top horizontal row of Table 55 (page 187). The copper broke after 7.6 complete turns, that is, it showed itself only about half as good as Alloy No. 1. (The calculated maximum stress was 4.6 tons per square inch lower.)

The figures of the alloys immediately succeeding No. 1 show that even up to 4 per cent. of aluminium the total twist is greater than in the copper tested by Professor Beare. There is a steady fall in ductility as far as 7.35 per cent. The sharp drop at 9.90 per cent. brings out the brittleness of the dark structural constituent in alloys of this class. At 11.73 per cent. the alloy breaks after a twist of 51° . Thus the effect of adding this percentage to pure copper is to diminish the angle of twist from $5,184^\circ$ to 51° , that is, to reduce it more than one hundred times.

To sum up.—Alloys containing aluminium up to $7\frac{1}{2}$ per cent. behave extremely well under the torsion test, but beyond this percentage there is a rapid *deterioration of properties*.

Dr. Stanton's Alternating-Stress Test (pages 190–195).

Under this test the 10 per cent. aluminium-bronze (Alloy No. 13) shows itself a most useful material. Its maximum limit of resistance for one million reversals of direct stress at a rate of 800 per

minute and with a ratio of tension to compression of 1.4 is about 28.3 tons per square inch. Comparing this figure with those obtained by Messrs. Stanton and Bairstow for ten varieties of iron and steel (*loc. cit.*) the alloy takes the third place, equal to piston-rod steel, containing 0.446 per cent. of carbon. (The highest figure 31.5 tons was obtained with Swedish Bessemer steel (0.645 per cent. carbon).)

But the particular merit of this alloy (and also the 5 and 7½ per cent. bronzes) is the close approximation of the maximum stress under which it will bear an unlimited number of reversals to the stress at the elastic limit as determined in a tensile test. In this respect it is markedly superior to the iron and steel specimens hitherto investigated. This is shown in Table 58, which contains the values of the ratio of the maximum range of stress to the primitive yield-point of each alloy.

TABLE 58.

Alloy No.	Ratio $\frac{\text{Maximum Range of Stress.}}{\text{Primitive Yield-Point.}}$
1	1.33
4	1.47
6	1.80
9	1.93
13	1.91

The ratio nearly reaches 2 in the case of Nos. 9 and 13, and is high in No. 6. In the case of irons and steels referred to the ratio varied between 1.80 and 1.13 (*loc. cit.*).

Although in the foregoing tests the alloys were sometimes stressed beyond the yield-point, the materials were for the most part in the elastic condition, and the calculated limits of resistance in Table 57 refer to the alloys in this state.

Professor Arnold's Alternating-Stress Test (pages 196-197).

It will be seen from Professor Arnold's report that all the alloys behaved well under this test, but particularly those containing from 5 to 10 per cent. of aluminium. He has informed the authors that "Alloy No. 9 constitutes a record in its capacity of resisting alternations." Thus when the alloys were subjected to alternating stresses beyond the yield-point, the capacity to resist fracture rose with the addition of aluminium to a maximum at about 7.35 per cent., but fell sharply at 10 per cent. This drop coincides with the appearance of the dark brittle structural constituent (*loc. cit.*), and appears only natural. The variations thus found fall more into line with those revealed by the impact tests (in the succeeding section) than with those shown by Dr. Stanton's tests.

Impact Tests (pages 197-198).

These were carried out in the Izod machine on notched bars 2 inches by $\frac{3}{8}$ inch by $\frac{1}{16}$ inch. The results are given in Table 60 (page 198). Except in the case of Alloy No. 4 the values in column 4 are the mean of three tests. Alloys Nos. 1 to 9 did not break under this test, and in these cases the figures in column 4 merely show the energy required to bend the specimens to the same angle, viz., that at which the tup cleared them. The figures bring out the gradual stiffening caused by increasing aluminium up to 7.35 per cent. already shown in the static tests. For Alloys 13, 15 and 16 the mean figures are those required to produce fracture (without deformation).

Summary of Kinetic-Stress Tests.

These tests have yielded one result of particular interest. They have shown that the primitive yield-points of these alloys are very much nearer the proper figure than those of steels, or, in other words, that the alloys show much less tendency to assume an artificial yield-point in their manufacture. Alloys Nos. 9 and 13 are nearly theoretically perfect in this respect (*cf.* Table 58, page 195).

The alloys containing from 0 to 10 per cent. of aluminium behaved very satisfactorily in these tests, but the most valuable range is from 5 to 10 per cent.

Freezing Curves (pages 198-206).

The complete results are given in Table 61 (pages 200-203), and are shown graphically in Fig. 33 (pages 204-205). The circles, dots and crosses represent observed evolutions of heat. The line drawn through the circles represents the "liquidus" curve, that is, the temperatures at which the molten alloys begin to deposit solid crystals on cooling. The curve agrees well with that obtained by Dr. L. Guillet except in one particular, namely, the authors have not found that the curve rises from 44.5 to 50 per cent. of aluminium. Near this percentage it is nearly a horizontal straight line.

The alloys containing from 0 to 13 per cent. of aluminium, whose properties have been investigated in such detail, appear to solidify at one temperature. From 8 to 13 per cent. evolutions of heat take place on cooling at temperatures for the most part between 600° and 500° C. (1,112° and 932° F.). These have been investigated by differential cooling, and are discussed in the succeeding section. Table 61 and Fig. 33 only contain observations of direct cooling. The rise in the liquidus curve from 8 to about 12 per cent. of aluminium coincides with the appearance and growth to a maximum of the dark needles in the alloys after they have cooled to the ordinary temperature. But this must be carefully distinguished from the fact that the alloys solidify to an apparently homogeneous mass from which the dark and yellow structural constituents are ultimately formed.

Heating and Cooling Curves (Fig. 34, pages 206-216).

The complexity of the curves increases with rise of aluminium, and no attempt is made to give a complete physical interpretation of them. This cannot be done without definite and extensive experiments made with this end in view, and time has only permitted

their execution in a preliminary way. The authors think, however, that the following interpretation on broad lines is true as far as it goes.

It will be noted that at 8.12 per cent. of aluminium a very small heat absorption occurs at 563–566° C. (1,045–1,050° F.) (column 2), and that this increases with rising aluminium to a maximum at 12–13 per cent. This coincides with the appearance and growth to a maximum of the dark needle-like structural constituent in the alloys (photo-micrographs, Plates 3 to 5). This thermal change appears to be connected with a change in the properties of the constituent thus characterised. (Experiments have been made with Alloy No. 13, and the authors think their generalization will hold for Alloys Nos. 10, 11, 12, 13, 14 and probably No. 15.)

When Alloy No. 13 was quenched at any temperature not exceeding 560° C. (1,040° F.) no structural change was detected. When quenched at 600° C. (1,112° F.), however, the appearance seen in photo-micrograph Fig. 120, Plate 12, was noted. It will be observed that the dark constituent has become lighter in colour and more striated. The change at 560°–570° C. (1,040°–1,058° F.), which is remarkably constant in temperature throughout the series, appears to correspond to a change in the dark constituent, as a result of which it can dissolve the light yellow constituent.

The heat absorptions between 600° and 800° C. (1,112° F.–1,472° F.), which are more prolonged and variable in position, seem to correspond to the gradual solution of the yellow in the dark constituent. The structures of alloys quenched from 700°, 800° and 900° C. (1,292°, 1,472° and 1,652° F.) are seen in photo-micrographs, Figs. 121, 122 and 123, Plate 12, respectively. They show the gradual disappearance of the yellow constituent which appears complete at 900° C. The alloy then consists of a mass of needles whose colour varies from yellow to dark brown.

This succession of changes was found to be reversed on cooling. Above 800° C. the needles persist to the exclusion of the yellow constituent (photo-micrographs Fig. 124). Below this temperature the latter makes its appearance, Fig. 125, and increases down to about 530° C. (986° F.), Fig. 126. At about this temperature

(column 10), unless the cooling is purposely retarded, the acicular constituent becomes dark and partly loses its acicular character, Fig. 127. (The effect of slow cooling was discussed in pages 181-182.)

The foregoing interpretation has taken no account of the thermal changes between 200° and 400° C. (392°-752° F.). No structural changes corresponding to these have been found by microscopic examination.

Corrosion Tests (pages 216-221).

In these tests the conditions were made as severe as possible. Thus, if the plates had not been freed from deposit each week by brushing, it is probable that the latter would have protected them to some extent from further action. It was considered important, however, to present the alloys in as unfavourable a light as possible, and to publish *maximum* corrosive figures.

The alloys containing from 1 to 10 per cent. of aluminium have shown themselves, under the conditions chosen, to be practically incorrodible by sea-water whether alone or bolted to a plate of mild steel. **This is an important result.** But it must be accepted with this reservation that it does not necessarily hold true in cases where sea-water is exposed to local contamination of particular kinds, for example, town drainage, &c. In the sea-water tests (A) these alloys were undoubtedly superior both to Muntz Metal and Naval Brass, which corroded appreciably.

The fresh-water tests gave an opposite result. Muntz Metal and Naval Brass were unaffected, whereas the copper-aluminium alloys corroded to some extent.

It should be mentioned that *cast* plates of the aluminium-copper alloys, and *rolled* plates of the Muntz Metal and Naval Brass were used. The authors' experience of etching polished surfaces of cast and rolled materials leads them to think that cast specimens are usually more readily attacked by liquids than rolled specimens. If this is so, then the conditions were severer for the copper-aluminium than the other two alloys.

A Comparison of the Properties of Alloy No. 13 with those of Swedish Bessemer Steel of about 0.35 per cent. of Carbon (pages 221-224).

The Research described in Part 2 has brought out a fact of very remarkable interest, namely, that the qualities, both mechanical and physical, of Alloy No. 13 resemble those of a Swedish Bessemer Steel of about 0.35 per cent. of carbon to a truly astonishing degree. When it is remembered that the former is an alloy of copper and aluminium, the latter an alloy principally of iron, carbon, and manganese, the parallelism of qualities appears especially interesting. It is however a matter of surprise that the resemblance between two well-known alloys—for No. 13 is the so-called Aluminium-Bronze or Aluminium-Gold—has not hitherto, so far as the authors are aware, been adequately described.

PROPERTIES OF THE RICH ALUMINIUM ALLOYS.

Specific Gravities (pages 229-230).

As was found for the rich copper alloys, so here the specific gravities of the chill castings and rolled bars are identical. The identity also extends to the drawn bars so far as they have been examined.

With the introduction and addition of copper up to 8 per cent. the specific gravity rises regularly, and a smooth curve results, Fig. 35 (page 229). The specific gravities of the sand castings are lower and vary less uniformly than those of the chill castings and rolled bars.

Tensile Tests of Bars (pages 230-246).

(1) These alloys appear to be unaffected by such heat treatment as quick or slow cooling.

(2) Small chill castings possess superior mechanical qualities to sand castings.

(3) In order to get the full value of the inherent properties of the alloys, a considerable amount of mechanical work, e.g. rolling or

drawing, with or without annealing, should be performed on them. From 0-8 per cent. of copper all the alloys roll well, and from 0 to about 4 per cent. of copper they draw sound. As an illustration of the beneficial effect of mechanical work, Alloy No. 37 is selected. The improvements effected in yield-point and reduction of area are particularly noticeable and important. An alloy whose specific gravity is only 2.79, whose yield-point is 18.5 tons, and whose reduction of area is 20.84, may have an industrial future in cases where a combination of lightness and strength is desired.

(4) The tests of the sand and chill castings, of the rolled and drawn bars, agree in showing that nothing is to be gained by adding more than 4 per cent. of copper to aluminium. The introduction of copper causes a fall of ductility, and a rise of tenacity, which are fairly steady up to 4 per cent. Beyond this there is no increase in tenacity while the ductility continues to diminish.

(5) The elastic ratios of these rich aluminium alloys average much higher than those of the rich copper alloys.

Tensile Tests of Sheets (pages 246-253).

The variations of properties caused by the introduction and addition of copper to aluminium have been found to be very similar in the alloys in the form of sheets to those in the form of rolled and drawn bars. In particular, the conclusion previously drawn that nothing is gained by adding more than 4 per cent. of copper has been confirmed by these experiments.

Corrosion Tests (pages 254-256).

The rich aluminium alloys have proved to be strongly corroded by sea-water, but uncorroded by fresh water of the type used. The rich copper alloys exhibited an opposite behaviour, being uncorroded by sea-water and slightly, but quite appreciably, corroded by fresh-water.

MAIN REPORT.

PART I.

Historical Introduction.—The history of Aluminium and Copper Alloys appears to date back about fifty years. The so-called "aluminium-bronze," or "aluminium-gold," is stated to have been first prepared by the late Dr. Percy, and its useful properties were described by Mons. Debray.* At that time however there was no possibility of applying the alloy to practical purposes on account of the high price of aluminium; and it may be safely concluded that the properties of the aluminium-bronze of that time, prepared from impure aluminium, were different from those of the modern "aluminium-bronze" or "gold," which is a much purer product. At the present time there is a fair demand for this alloy on account of its valuable properties, and there is little doubt but that its application to a great variety of purposes is only retarded by the high price of aluminium and to a less degree of copper.

The Cowles Co., who were among the first to prepare aluminium on an industrial scale, were also among the earliest to place aluminium-copper alloys on the market. The latter gave the following results under tensile stress, Table 1 (page 82).

In recent years alloys containing 2 per cent. of aluminium have been used for tubes, 5 per cent. for rods, and 8 to 9 per cent. for propeller shafts. Alloys containing high percentages of aluminium have hitherto found little application. An alloy containing from 97 to 98 per cent. of aluminium has been found useful in making ornamental silver-coloured castings which are to be chased and engraved. Some years ago an alloy containing 94 per cent. of aluminium was applied to naval construction in France. It was used in the Forban,† a torpedo-boat, in those parts of the vessel

* Comptes Rendus, 43, page 925.

† "Le Yacht." 1893. page 115.

which do not contribute directly to the rigidity of the hull, such as transverse bulkheads, hatchways, skylights, and engine-room floor plates. In 1894 Messrs. Yarrow and Co. built a second-class torpedo-boat for the French Navy,* in which the hull and most of the fittings were composed of an alloy containing 6 per cent. of copper and 94 per cent. of aluminium. The results were highly satisfactory

TABLE 1.

Grade.	Ultimate Stress.	Elongation on 2 inches.
	Tons per sq. inch.	Per cent.
A (11 per cent. Aluminium)	45 to 50	0 to 5
A ₁ (10 " " ")	40 to 45	4 to 8
A ₂ (10 " " ")	34 to 38	8 to 17
A ₃ (10 " " ")	28 to 32	18 to 25
B (7½ " " ")	25 to 28	25 to 30
C ₁ (5½ " " ")	21 to 25	30 to 35
C ₂ (5 " " ")	18 to 21	35 to 40
C ₃ (5 " " ")	15 to 18	40 to 50
D (2½ " " ")	12 to 15	45 to 60
E (1¼ " " ")	9 to 12	20 to 35

so far as speed and lightness were concerned, but the alloy was rapidly corroded by sea-water after a brief period of service.† Alloys containing from 95 to 97 per cent. of aluminium are used in the automobile industry.

Comparatively few researches on the industrial and scientific properties of aluminium copper alloys have been published, and

* "Engineering," 12 April 1895, page 470.

† Proceedings, The Institution of Mechanical Engineers, 1898, Part 3, pages 358 and 369.

these are of quite recent date. An account of a very extended research was published by the late Professor Tetmajer in 1900.* His alloys contained notable quantities of elements other than aluminium and copper. These impurities, principally silicon and iron, ranged from 1 to 4 per cent.; and their influence on the properties of aluminium and copper has since been found to be so considerable that 'his alloys are not comparable with the pure aluminium-copper alloys that can be prepared at the present time.

Freezing-point curves of these alloys have been published by Mons. Gautier† and Mons. A. Le Chatelier,‡ and the latter has examined the alloys microscopically,§ and drawn conclusions with reference to the existence of chemical compounds of the two metals.

Valuable information has been published recently by Dr. L. Guillet in his research, "*Étude théorique et industrielle des alliages de Cuivre et d'Aluminium.*"|| His most important conclusion appears to be that the only alloys which can be used industrially are those which contain less than 11 per cent. and more than 94 per cent. of aluminium, i.e., those which occur at each end of the series. His cooling and heating curves, and his photomicrographs are of great theoretical interest.

Mons. Breuil has obtained interesting results by quenching an alloy, "*Fortior*," which contains principally copper and aluminium, but also small quantities of other elements. He has found that it is susceptible of hardening to a very marked extent by this method.

Thus it will be evident that a research on the properties of pure aluminium-copper alloys has hitherto been lacking. In view of the facts that these can now be prepared commercially, that with the gradual cheapening in the price of aluminium the known valuable properties of the alloy containing 10 per cent. of this metal may be

* Mitteilungen der Materialprüfungsanstalt. ix. Heft. Methoden und Resultate der Untersuchung des Aluminiums und seiner Abkömmlinge.

† Bulletin de la Société d'Encouragement. October 1896.

‡ Revue Générale des Sciences. June 1895.

§ La Technique de la Metallographie Microscopique.

|| Revue de Métallurgie. 1905, page 567.

expected to have a wider industrial application, and that both the commercial and scientific literature contain conflicting statements, it appeared desirable that a research of this kind should be undertaken.

Research Scheme.—The scheme eventually adopted was based on one drafted by Mr. Longmuir (shortly before he resigned his position in connection with the Alloys Research work), which was modified by the authors as a direct result of their visits to the Broughton Copper Works, Manchester, and the British Aluminium Company's Works, Milton. These visits were kindly arranged by Mr. Sumner and Mr. Bonnor, respectively representing these firms on the Alloys Research Committee. By this means the authors were afforded an opportunity of seeing the manufacture of, and themselves carrying out the tests on, the most important aluminium-copper alloys in practical use at the present time. The experience thus gained has been of the greatest service to them throughout the research.

In the scheme as finally approved by the Committee the entire research was to be carried out at the National Physical Laboratory, with the exception of forging and rolling. Mr. Bonnor and Mr. Sumner offered facilities for these operations at their Company's works. The main lines of the scheme were similar to those followed in the Seventh Alloys Research Report, but it was resolved that particular attention should be directed to the following points:—

(1) The mixing of the alloys, and the necessity or otherwise of remelting.

(2) The testing of the alloys containing high percentages of aluminium in the form of sheets.

(3) Corrosion Tests, especially in sea-water.

(4) The effect of prolonged heating at high temperatures on the recrystallization of the alloys.

(5) A comparison of Professor Arnold's Alternating Stress Test as applied to the alloys, with the method in use in the Engineering Department of the National Physical Laboratory.

Furthermore, it was decided that the research should be restricted to the *binary* alloys of copper and aluminium until their properties had been thoroughly investigated.

Materials used.—The copper was furnished by the Broughton Copper Co. Ten cwts. of electrolytic or "cathode" copper of very high purity were supplied.

Two analyses gave the following results :—

Copper, (i) 99·98 per cent. ; (ii) 99·99 per cent.

No impurities were detected.

Three cwts. of "Lake" copper of the following composition were also supplied :—

	Per cent.
Copper	99·90
Iron	0·01
Arsenic	absent
Antimony	0·001
Bismuth	0·001
Lead	absent
Oxygen (by difference)	0·088

The absence of oxygen in the "cathode," and its presence in the "Lake" copper is shown in photo-micrographs, Figs. 48 to 51, Plate 1 (magnification 120 diameters). Figs. 48 and 50 show the polished but unetched surfaces of the "cathode" and "Lake" copper respectively.* There is an entire absence of structure in Fig. 48, whereas the eutectic of copper and copper oxide is visible in Fig. 50. The corresponding etched surfaces are shown in Figs. 49 and 51. The former shows crystal boundaries of very irregular shape quite free from oxide, while the latter shows the eutectic situated between the copper crystals.

4½ cwts. of aluminium were furnished by the British Aluminium Co. This weight was made up of 3-lb. castings of "Notched Bar" metal. Closely-agreeing analyses at the Works Laboratory and the

* It was found difficult to prepare a satisfactorily etched copper surface. The best results have been obtained by dipping the polished specimen in concentrated nitric acid, and immediately chemical action sets in to hold it under a tap discharging a rapid stream of water. In this way a bright clean surface free from oxidation products was obtained.

Chemical Department of the National Physical Laboratory gave the following mean result:—

	Per cent.
Aluminium (by difference).	99·54
Silicon	0·25
Iron	0·14
Sodium	0·07

These figures hold for all the aluminium used in the research except 1 cwt., which was of somewhat higher purity, and contained 99·70 per cent. of aluminium. They represent a great advance in the manufacture of the commercially pure metal upon practice of even three years ago.

Photo-micrographs, Figs. 52 and 53, Plate 1, represent respectively lightly-etched and deeply-etched surfaces of the aluminium at 120 diameters. The surfaces were etched with hot 12 per cent. sodium hydrate solution. They are very uneven and consist of little mounds and hollows (Fig. 54, Plate 2, at 800 diameters). The black lines are shown at 800 diameters, Fig. 55, to consist of deep pits. Cast aluminium seems to be very porous and susceptible to the attack of etching reagents.

Method of Melting and Casting the Alloys.—In order to meet the requirements of the rolling mills of the Broughton Copper Works, and to take advantage of expert opinion there, that in rolling the alloys a considerable reduction of area should be effected if the best results of mechanical work are to be obtained, it was decided to melt and cast 60-lb. charges of the heaviest alloys. This was carried out in the melting-house attached to the Metallurgical Laboratories. In preparing an alloy, (a) sand castings, (b) chill castings, and (c) an ingot for rolling 20 inches by 3 inches diameter, were made.

The metals were melted in a No. 30 Salamander crucible, heated in a Fletcher-Russell petroleum-spray injector furnace, the necessary air-pressure being obtained from a Root's Positive Blower. The time required for melting 60 lbs. of copper was 1½ hours. When needed, the crucible and charge were lifted out of the furnace by

tongs suspended from a chain passing over a travelling pulley-block, and deposited near the moulds.

After the necessary stirring and removal of the dross the charge was teemed. In every cast the temperature of the metal in the sand mould was taken.

The Effect of Remelting the Alloys.—Professor Thurston * states : “The standard aluminium-bronze (10 per cent. aluminium) is brittle after the first fusion, but becomes more ductile as well as stronger after repeated refusion.” The view held in the works to which the authors have had access is that remelting is necessary to produce thorough mixing, and it is customary to remelt castings of aluminium-copper alloys at least twice before rolling. As there does not appear any *a priori* reason for this, and as it adds considerably to the labour of preparing these alloys, this point was thoroughly investigated at the very beginning of the research, both for those alloys rich in copper and for those rich in aluminium. (The latter melt some 500° C. (900° F.) lower than the former.) The alloys were tested in the form of both sand and chill castings. Alloys of well-known properties were chosen.

(a) *The Effect of remelting Alloys rich in Copper.*— $\left\{ \begin{array}{l} 90 \text{ per cent. copper} \\ 10 \text{ ” ” aluminium} \end{array} \right\}$ Alloy.—This alloy was selected as being the best known of those rich in copper. Experiments were made on a 45-lb. charge. The “cathode” copper was first melted down. There was no lid on the crucible, but the metal was melted under pure wood charcoal and by adjustment of the petroleum spray and blast the flame was kept slightly reducing in order to prevent as far as possible the oxidation of the copper. As this metal does not take up carbon the stirrer used was a rod of Acheson graphite (1 inch diameter), [which is an extremely pure form of carbon] fitted with an iron handle. When the copper was thoroughly fluid, the aluminium was stirred in. The view generally held is that under these

* “Materials of Engineering.” Part 3, page 180.

conditions the aluminium and copper combine with a disengagement of so much energy that a "white heat" is attained. This has been found to be very destructive of the crucibles, which are useless after nine or ten heats. The authors have not found that the solution of aluminium in molten copper is attended with this great rise of temperature, provided the copper has been protected from oxidation. Under these conditions mixing occurs with a barely sensible increase of temperature. But it *has* been their experience that, if the copper contains oxygen, a very marked evolution of heat does occur. Accordingly the rise of temperature should be attributed, not, as has sometimes been done, to the combination of aluminium and copper, but to that of aluminium and oxygen, one of the most powerfully exothermic chemical syntheses known.

Particular attention was paid to the thorough stirring of the two metals. After this was finished, the dross and wood charcoal were removed and the molten surface cleared with a gentle air-current from a pair of bellows. It was then teemed into a sand mould for six castings (7 inches by $\frac{5}{8}$ inch), 2 small chill moulds (7 inches by $\frac{3}{4}$ inch), and the remainder into a large chill mould. The sand used was ordinary brass foundry greensand. These castings were designated No. 1. The large chill was then remelted, and a second set of castings made, the excess of metal being again cast into the large chill mould (No. 2 castings). The operation was repeated and gave a third set of castings (No. 3).

The three casts were made at as near $1,100^{\circ}$ C. ($2,012^{\circ}$ F.) as possible, in order to eliminate differences of properties that might arise with varying casting temperatures.

Analyses of each cast were made and the results showed that this alloy can be remelted without sensible alteration of composition.

From each set of six sand castings the three best were selected and machined down to 0.437 inch (2.5 inches parallel). The two chill castings in each set were turned down to 0.564 inch (2.5 inches parallel).

The Tensile-Stress Tests gave the following mean results :—

TABLE 2.
Chill Castings.

No.	Copper.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. in.	Per cent.
1	90.00	37.3	31.5
2	90.09	36.9	30.0
3	89.92	37.0	31.5

These figures show that the mechanical properties of the three sets of chill castings are practically identical. The figures of the first cast are actually the best. Incidentally it may be remarked that they are as good as those obtained from this alloy as ordinarily prepared commercially in the *rolled* state. This very interesting result is discussed in a special section devoted to it (pages 162-164).

TABLE 3.
Sand Castings.

No.	Copper.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. in.	Per cent.
1	90.00	30.2	17.2
2	90.09	28.5	15.0
3	89.92	33.3	24.8

These results are not so regular as those given by the chill castings. The third cast is the best, but the first cast is appreciably superior to the second. The figures for the first cast are only slightly below the mean of those for the second and third casts.

Further light on this question was obtained in another set of experiments which were undertaken primarily to settle another point. A view held by some commercial experts is that, in preparing

the copper-rich alloys, better results are obtained by melting copper and an alloy of aluminium and copper containing 50 per cent. of each metal than by melting and mixing the pure metals. This is merely another aspect of the question of remelting, since in preparing the 50 per cent. alloy the metals undergo one fusion. Three casts of the alloy containing 90 per cent. of copper and 10 per cent. of aluminium were made from copper and the 50 per cent. alloy. The latter is a beautifully crystalline substance with a silvery lustre. Castings of it are so brittle that they break if dropped upon a stone floor. This property makes the alloy extremely convenient for weighing out charges. Fig. 159, Plate 18, is a photograph of a sand casting, half-size. The large interlocking needles and holes render the brittleness of the alloy quite intelligible. It has a very large coefficient of contraction on cooling from the freezing-point (575°C. , $1,067^{\circ}\text{F.}$). On this account the crystals break up, and in so doing give out a clear musical note. The three casts of the 10 per cent. aluminium alloy made in this way were carried out similarly to those previously described. The results of the Tensile-Stress Tests were as follows:—

TABLE 4.
Chill Castings.

No.	Copper.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.
1	90.15	12.4	35.68	30.2
2	90.10	10.8	35.60	34.2
3	90.18	12.9	35.74	34.2

The copper is 0.14 per cent. (mean figure) higher in these castings than in the previous series, and as a result the ultimate stress is a little lower and the ductility a little higher in this series. If due allowance is made for this difference in composition, it is justifiable to conclude that alloys of practically identical properties

in the two series would have been obtained, and therefore that no advantage attaches to the use of the 50 per cent. alloy.

With respect to the influence of remelting, it will be noticed that the ultimate stresses are remarkably constant. The ductility of the first cast is slightly inferior to that of the second, but its yield-point and ultimate stress are superior.

TABLE 5.
Sand Castings.

No.	Copper.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.
1	90·15	11·7	31·90	26·5
2	90·10	10·8	31·92	29·2
3	90·18	13·0	30·77	22·5

These castings agree within themselves better than those of the other series. The ultimate stresses of Nos. 1 and 2 are identical, and are superior to that of No. 3. In yield-point and elongation No. 1 has given results which are almost exactly the mean of those recorded for Nos. 2 and 3.

The authors think that the following conclusions may be drawn from the results of the foregoing experiments:—

(1) There is no need to remelt the alloys rich in copper in order to obtain thorough mixing, obviate brittleness, and secure the best mechanical properties. With due care the first cast is as likely to be as good as any that may follow it. Such differences in properties as have been found are probably to be ascribed to accidental variations in the conditions of preparation, of which probably the most important are variations in casting temperature, and small holes in the castings. *This conclusion is not intended to apply to other than small castings.* In large castings the difficulties of securing thorough mixing are much greater. In such cases remelting may always constitute the best *practical* method of ensuring homogeneity of material.

(2) Copper-rich alloys can be perfectly satisfactorily prepared from the pure metals, and no advantage is gained by using the 50 per cent. alloy instead of aluminium. This conclusion has been substantiated by later experiments. The copper-rich alloys described subsequently have been prepared, some of them from the pure metals, others from copper and the 50 per cent. alloy. The continuity of properties that has been found in the various members of a series constitutes additional evidence that the alloys may be satisfactorily prepared by either method.

(b) *The Effect of remelting Alloys rich in Aluminium.*—In making these alloys it is of great advantage to proceed from pure aluminium and the 50 per cent. alloy. The freezing-points of the two materials lie near together, namely, at 575° C. (1,067° F.) and 657° C. (1,214° F.) respectively, and the working temperature need not be raised above 700° C. (1,292° F.). If the alloys are made from the pure metals, the small quantity of copper must first be melted down and an unnecessarily high temperature has to be reached.

Preliminary experiments were made to determine the best casting temperature of these alloys.

The Influence of Casting Temperature.—Three sets of two chill castings, each of an alloy containing 4·63 per cent. of copper, were made, Nos. 2 and 3 being remelts. The following Table contains the mean results of the tensile tests, together with the chemical composition and casting temperature :—

TABLE 6.

Cast No.	Casting Temperature.	Copper.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.
		Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.
1	650° C. (1,202° F.)	4·63	5·6	9·68	8·5
2	724° C. (1,335° F.)	4·62	5·0	7·04	5·5
3	707° C. (1,304° F.)	4·63	4·5	4·89	3·0

The fracture of the test-pieces of No. 1 cast was close and granular, whereas those of Nos. 2 and 3 were coarsely crystalline. No. 1 was cast at as low a temperature as possible, namely, 650° C., which is only about 10° C. (18° F.) above its freezing-point. Its mechanical properties are decidedly superior all round to those of Nos. 2 and 3, cast at considerably higher temperatures. The casting temperatures in the latter cases were too high. Accordingly in subsequent experiments the alloys were cast at as low a temperature as possible consistent with fluidity. Incidentally this series of tests shows how much more vital to the properties of the resulting alloys casting temperature is than remelting.* It also shows that alloys with higher percentages of aluminium can be remelted without change of composition.

The Effect of remelting the { 95.6 per cent. Aluminium } Alloy.—Three sets of sand and chill castings were obtained in a similar way to that described for the 10 per cent. aluminium alloy. It was considered unsafe to stir with Acheson graphite rods on account of the solubility of carbon in molten aluminium, and accordingly clean iron pokers were used. Subsequent analyses showed that the aluminium did not take up iron. The casts were made at as nearly as possible the same temperature, namely, when the fluid surface, after being skimmed, did not oxidize to a coloured film. This temperature was about 660° C. (1,220° F.)

TABLE 7.
Chill Castings.

Cast No.	Copper.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. inch.	Per cent.
1	3.94	10.0	10.5
2	3.96	9.8	11.0
3	3.95	10.6	13.2

* The authors' results agree with those of Mr. P. Longmuir (Journal of the Iron and Steel Institute, 1903, No. 1, page 457, and 1904, No. 1, page 432) in emphasizing the importance of casting at the correct temperature.

The ultimate stresses of the three casts are nearly constant, but there is a slight improvement in ductility with each successive cast.

TABLE 8.
Sand Castings.

Cast No.	Copper.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. inch.	Per cent.
1	3.94	5.3	4.0
2	3.96	6.2	4.6
3	3.95	7.0	5.3

In this case there is a perceptible improvement in both ultimate stress and ductility after each remelt.

Two sets of three casts each were then made of an alloy containing about 5.25 per cent. copper. The following results were obtained :—

TABLE 9.
Chill Castings.

Cast No.	Copper.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.
A {	1 5.27	5.5	9.15	5.5
	2 5.29	4.5	9.60	7.25
	3 5.27	4.6	8.37	6.0
B {	1 5.23	5.5	8.00	5.5
	2 5.25	5.3	8.63	5.5
	3 5.25	5.5	8.75	6.25

In set A the properties of the first cast are superior to those of the third and only slightly inferior to those of the second.

In set B there is very little to choose between the three casts, the variations being less than sometimes occur among members of the same cast.

TABLE 10.

Sand Castings.

Cast No.	Copper.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.
	Per cent.	Tons per sq.in.	Tons per sq. in	Per cent.
A { 1	5.27	5.1	9.04	4.0
	2	5.5	7.14	3.5
	3	5.4	7.27	3.75
B { 1	5.23	5.1	7.61	4.0
	2	5.5	9.20	4.0
	3	5.6	8.14	4.25

In set A the properties of the first cast are the best of the three. Those of the second and third are practically identical. In set B the properties of the first cast are inferior to those of the second and third which are nearly the same.

If the figures of the three sets of sand and three sets of chill castings are compared with one another it will be found that

The best results were obtained with the first cast in one case.

“ “ “ “ second “ two cases.

“ “ “ “ third “ three cases.

The next best “ “ “ first } casts in two cases each.

“ “ “ “ second }

“ “ “ “ third }

When it is remembered that the differences are not large, and are in some cases less than are found between duplicate members of the same cast, the conclusion appears warranted that alloys rich in

aluminium can be satisfactorily made with only one melting. *This conclusion is intended to apply only to small castings.* It has been the authors' experience during the research that it is far more important to cast these alloys at the right temperature than to remelt, in order to get the best mechanical properties.

As will be shown later it was unnecessary to test the influence of remelting on the properties of alloys of intermediate composition. The research has thoroughly confirmed Dr. L. Guillet's conclusion that only the alloys at the extreme ends of the series are of any industrial promise.

Accordingly all the alloys subsequently prepared were melted only once. The greatest care was paid to the two important points: (a) casting temperature; (b) thorough stirring.

CHEMICAL ANALYSES.

These were carried out on either drillings or turnings of such alloys as permitted of it. The alloys rich in copper oxidise at the ordinary temperature when they are in this form. An analysis of an alloy in the form of thin drillings gave 90.27 per cent. of copper, whereas in the form of coarse turnings the value 90.58 was obtained. Accordingly coarse turnings or drillings were used. In the case of the hard or brittle alloys analyses were made of the powdered material. Although no lack of homogeneity has been found in any of the alloys, care was taken that the samples analysed should be thoroughly average.

Estimation of Copper.—The following method was used for such alloys as contained at least 50 per cent. of copper:—

About one gram of the alloy was dissolved in 10 cm.³ of nitric acid (1.2 specific gravity), diluted to about 150 cm.³ with water, contained in a weighed platinum basin. This solution was electrolysed for about twelve hours with a current of 0.2 ampère. The platinum dish constituted the cathode, while the anode consisted of a platinum spiral just dipping into the liquid. After twelve hours all the copper, except a mere trace, was deposited on the cathode. The copper still dissolved was estimated by making the solution up

to 250 cm.³ and determining it colorimetrically. The cathode copper, after being washed with distilled water and absolute alcohol, was dried at 100° C. (212° F.) in an electrically heated oven, cooled and weighed. To this weight was added that obtained by the colour estimation.

When the aluminium exceeds about 50 per cent., this method cannot be employed. If the nitric acid is kept of the same strength, aluminium comes out of solution as alumina, and some of it is trapped with the copper on the cathode. If the strength of the acid is increased in order to keep the alumina in solution, this has the effect of keeping some of the copper dissolved. Accordingly the following method has been worked out for alloys containing 50 per cent. of aluminium and upwards, and has given satisfactory results.

The alloy is treated with dilute hydrochloric acid and a vigorous action sets in. All the aluminium goes into solution, whereas the copper is brought down in a spongy form. If the copper is filtered off as soon as the evolution of hydrogen ceases, it is usually found that there is not a trace of copper in the filtrate. If the copper is allowed to stand in the acid after effervescence has ceased, a little of it dissolves. This may be precipitated as copper sulphide, filtered, ignited, and added to the copper in the spongy form. The whole of the copper is then dissolved in nitric acid, and electrolysed according to the method previously described.

Estimation of Aluminium.—There does not appear to be a satisfactory method of estimating aluminium, particularly in alloys containing high percentages of this metal. The usual practice in works laboratories is to estimate the other constituents and regard the remainder as aluminium. From a scientific standpoint this is unsatisfactory, and it involves the estimation of all impurities likely to be present. This practice has been followed in the present research except in the case of alloys containing 1 per cent. of aluminium or less, where a direct estimation has been considered to involve less error than the "difference" method, against which the objections become very serious when the absolute amount in question is small.

In the rich aluminium alloys the elements estimated were (a) copper, (b) silicon, (c) iron, (d) sodium, (e) carbon, (f) and nitrogen. The rich copper alloys do not contain determinable quantities of the three last-named impurities, and only the three first-named were estimated.

The direct method by which aluminium was estimated was as follows:—

From 2 to 5 grammes of the alloy (depending on the amount of aluminium present) were dissolved in nitric acid of 1.2 specific gravity. Excess of ammonia was added and the liquid boiled. The precipitate, which contained hydrates of aluminium and iron but was not free from copper, was filtered off, redissolved in nitric acid, and reprecipitated with ammonia. After this treatment it contained no copper. It was washed with warm water dissolved in hydrochloric acid. Two grammes of sodium phosphate were added to the solution, and ammonia added until a small permanent precipitate remained. This was dissolved in a *slight* excess of hydrochloric acid. The solution was then heated to boiling, diluted to 300 cm.³ with hot water, and 10 grammes sodium thiosulphate and 20 cm.³ acetic acid added. After being boiled for 15 minutes the precipitate was filtered off, washed with boiling water, dried, ignited and weighed as aluminium phosphate.

Estimation of Iron.—From 1 to 5 grammes (according to the amount of aluminium present) were dissolved in hydrochloric acid, a few cubic centimètres of redistilled nitric acid added, and the solution heated.

(a) If the alloy was rich in copper, the iron and aluminium were precipitated together as hydrates with ammonia, thus removing the copper. The precipitate was filtered off, redissolved in hydrochloric acid, and the iron reprecipitated with an excess of pure sodium hydrate solution, thus getting rid of the aluminium hydrate.

(b) When the alloy was rich in aluminium the procedure was reversed. The solution was warmed with pure sodium hydrate solution, the precipitated copper and iron hydrates filtered off, redissolved in hydrochloric acid, and reprecipitated with boiling

ammonium hydrate solution. The precipitate, which consisted only of ferrie hydrate, was filtered off and washed in warm water.

In both cases the washed ferrie hydrate precipitate was dissolved in about 5 cm.³ of pure redistilled nitric acid, and the solution made up to 100 cm.³ The iron was estimated colorimetrically by using 5 cm.³ of solution, 10 cm.³ of ether, and 10 cm.³ of a 10 per cent. solution of potassium sulphocyanide.

Estimation of Silicon.—5 grammes of the alloy were dissolved in aqua regia, 20 cm.³ of concentrated sulphuric acid added, and the solution heated till it fumed strongly. Warm water was carefully added, followed by hydrochloric acid, and the whole boiled for some time. The residue was filtered off, washed, ignited, and weighed, and silica estimated by evaporation with hydrofluoric acid.

Estimation of Sodium.—Two grammes of the alloy were dissolved in pure nitric acid diluted with an equal bulk of water. The solution was concentrated in a platinum basin and carefully brought to dryness. The residue was powdered finely with an agate pestle, and then heated for some time below the fusion point of sodium nitrate. At this temperature aluminium nitrate was decomposed, leaving alumina. The sodium nitrate was extracted with warm water and filtered. The filtrate was evaporated to dryness in a weighed platinum basin with sulphuric acid, and strongly ignited. From the weight of sodium sulphate found the percentage of sodium was calculated.

Estimation of Carbon.—Carbon was estimated by the chromic acid wet method used in steel analyses.

Estimation of Nitrogen.—Nitrogen was estimated as ammonia, the method used being that given in Blair's "Chemical Analysis of Iron" (page 201), for the determination of nitrogen in steel.

Composition of the Alloys.—The alloys investigated may be grouped conveniently in three classes. Complete analyses are given in Tables 11-14 (pages 101-103).

The compositions of the alloys rich in copper (100 to 87 per cent.) are contained in Table 11. The purity of these alloys is evident from an examination of column 4, which gives the combined percentages of copper and aluminium. The other elements present do not exceed from 1 to 6 parts in 10,000. These results show that alloys of very high purity can be prepared from the best commercial materials on a scale and by methods approximating to "Works" practice.

Table 12 contains the copper and aluminium percentages of alloys whose composition varies between 84.5 and 10.3 per cent. of copper. These alloys are so brittle that they cannot be regarded as of any practical importance. Accordingly full analyses were not made. Copper was estimated directly by the electrolytic method. The figures in the aluminium column are only approximate. They were obtained by "difference" after making allowance for the gradually increasing amounts of silicon and iron as the alloys became richer in aluminium.

In Table 13 (page 102) will be found the compositions of the alloys in which copper ranged from 8 to 0 per cent. It will be noticed that in Alloys Nos. 33 to 35 the elements other than copper and aluminium aggregate about 47 parts in 10,000, whereas in Nos. 36 to 41 they average about 30 parts in 10,000. The reason of this difference is that the latter alloys were prepared from purer aluminium than the former. The impurities in the rich aluminium alloys thus vary between 0.3 and rather less than 0.5 per cent. In this respect the alloys in Table 13 are inferior to those in Table 11, where the impurities do not exceed 0.01 to 0.06 per cent.

Table 14 (page 103) contains alloys similar to those in Table 13. The analyses are those of alloys especially cast for rolling into sheets. The combined percentages of copper and aluminium correspond to those of Nos. 33 to 35, but the impurities are present in somewhat different proportions. In Table 13 the percentages of silicon and iron are lower, and those of sodium and carbon higher than those in Table 14. In fact no carbon was found in Nos. 42 to 48. In spite of these differences of composition the alloys in Tables 13 and 14 are, broadly speaking, comparable with one another from 0.5 per cent. of copper.

TABLE 11.
Alloys rich in Copper.

Alloy No.	Percentages.				
	Copper.	Aluminium.	Copper and Aluminium.	Silicon.	Iron.
1	99.86	0.10	99.96	0.000	0.000
2	98.95	1.06	100.01	0.010	trace
3	97.88	2.10	99.98	0.018	0.004
4	96.98	2.99	99.97	0.024	0.008
5	95.92	4.05	99.97	0.019	0.011
6	94.90	5.07	99.97	0.018	0.006
7	94.20	5.76	99.96	0.027	0.010
8	93.23	6.73	99.96	0.026	0.016
9	92.61	7.35	99.96	0.027	0.017
10	91.85	8.12	99.97	0.012	0.012
11	91.28	8.67	99.95	0.032	0.021
12	90.58	9.38	99.96	0.021	0.019
13	90.06	9.90	99.96	0.027	0.017
14	89.17	10.78	99.95	0.031	0.015
15	88.23	11.73	99.96	0.028	0.010
16	86.92	13.02	99.94	0.043	0.013
1	2	3	4	5	6

TABLE 12.
Alloys of Intermediate Composition.

Alloy No.	Percentages.	
	Copper.	Aluminium (approximate).
17	84.57	15.38
18	79.22	20.7
19	72.76	27.1
20	70.77	29.1
21	64.70	35.1
22	59.81	40.0
23	54.95	44.9
24	49.90	49.9
25	44.49	55.3
26	39.14	60.6
27	35.52	64.2
28	31.42	68.3
29	28.80	71.0
30	19.58	80.1
31	15.62	84.0
32	10.34	89.3

TABLE 13.

Alloys rich in Aluminium.

Alloy No.	Percentages.							
	Copper.	Aluminium.	Copper and Aluminium.	Silicon.	Iron.	Sodium.	Carbon.	Nitrogen.
33	0·00	99·54	99·54	0·242	0·120	0·08	0·010	0·0055
34	0·86	98·67	99·53	0·273	0·125	0·07	0·000	0·0027
35	1·90	97·63	99·53	0·259	0·125	0·07	0·008	0·0029
36	2·77	96·91	99·68	0·179	0·110	0·03	0·000	0·0000
37	3·76	95·93	99·69	0·162	0·110	0·04	0·000	trace
38	4·97	94·72	99·69	0·151	0·100	0·05	0·004	0·0046
39	6·15	93·52	99·67	0·165	0·120	0·04	0·000	0·0032
40	6·91	92·82	99·73	0·118	0·120	0·03	0·000	0·0054
41	8·08	91·64	99·72	0·116	0·120	0·04	0·000	0·0054

TABLE 14.

Composition of Alloys tested in Sheet Form.

Alloy No.	Percentages.							
	Copper.	Aluminium.	Copper and Aluminium.	Silicon.	Iron.	Sodium.	Carbon.	Nitrogen.
42	0·00	99·53	99·53	0·306	0·141	0·02	nil	0·0028
43	0·93	98·61	99·54	0·302	0·140	0·02	„	0·0012
44	1·57	97·99	99·56	0·270	0·140	0·02	„	0·0073
45	2·36	97·20	99·56	0·283	0·140	0·01	„	0·0043
46	3·74	95·82	99·56	0·277	0·140	0·01	„	0·0093
47	4·74	94·89	99·63	0·216	0·139	0·01	„	0·0024
48	5·34	94·30	99·64	0·215	0·137	0·01	„	0·0023

Colour of the Alloys.—With the addition of aluminium to copper the latter quickly loses its characteristic colour, which is gradually “diluted” and disappears at about 3·5 per cent. aluminium. From 3·5 to about 8 per cent. there is a continuous change from deep to pale gold. After this percentage is passed there is a gradual darkening of the pale gold through various reddish-coloured bronzes up to about 18 per cent. This alloy has an extremely fine lustre. From here the colour changes successively to lead grey and light grey, until at 25 per cent. it is silvery white. From 25 to 100 per cent. of aluminium the colour is the same. A good deal of light on the colour changes from 0 to 25 per cent. of aluminium has been thrown by microscopic investigation. Thus, in the matter of colour, aluminium is the more influential of the two metals.

PART 2.

THE PROPERTIES OF THE RICH COPPER ALLOYS.

These alloys have proved to be the most important of those investigated, and accordingly they have been the most thoroughly examined.

Melting and Casting of the Alloys.—The main features of the methods used have been described (pages 86–88). Certain details, however, have still to be mentioned.

The authors had been warned that they might expect difficulties in casting some of the alloys. They were led to expect that the alloy containing 5 per cent. of aluminium was very difficult to pour successfully, on account of the tendency to separation of a difficultly fusible constituent. An instance of this kind was witnessed in one of their Works' visits. No examples of difficulties of this kind have been met with in the present research. *All the alloys prepared were teemed to the last drop of metal.* Two casts of the 5 per cent. alloy were made to test this material in particular. Both were successful. Care was always taken that the alloys were thoroughly fluid and well stirred before pouring.

The view that it is difficult to obtain sound sand-castings is well founded. Mons. A. Le Chatelier has gone so far as to say that the difficulties are so great that the alloys present little interest from a practical point of view.* The authors have made numerous experiments designed to overcome these difficulties, and have succeeded, by simple methods and ordinary precautions, in obtaining perfectly clean and sound castings of alloys containing from 0 to 11 per cent. aluminium. These are the limits of serviceable alloys.

The difficulties caused by the shrinkage of the alloys on

FIG. 1.—*Moulding Box used for the Sand Castings.*

solidification were met by ensuring a wide gate and a good "head" of metal in the moulding box. By this means the fluid metal in the gate follows up the quickly contracting alloy in the mould, and enables the latter to be completely filled. A vertical section of the box with the gate and mould is shown in Fig. 1. The tongue of sand (A) was made to project prominently in order to trap any dross that enters the gate, and prevent it entering the mould proper. This device has been found of great service. The thermojunction (protected with a fine fireclay sheath) for measuring the temperature at which the alloy was cast is shown at B. Six sand castings (C) were poured from each heat.

* Contribution à l'étude de la Fragilité dans des Fers et les Aciers, page 134.

The following was the order of casting:—

- (1) Six sand-castings.
- (2) Three small chill-castings.
- (3) One large ingot.

The pouring was under the charge of two operators, while a third read the casting temperature and took the cooling curve.

The small chill-castings were 7 inches by 1 inch. A vertical section, two-thirds size of the mould into which the large ingot was cast, is shown in Fig. 2. The plan is shown in Fig. 3. That of the ring which held the two halves of the mould together is in Fig. 4. The ingot was 3 inches diameter and on an average 20 inches long. The pipe, which would otherwise result from shrinkage, was as far as possible avoided by "following it up" with fluid metal from the pot.

Large C.I. Chill used for casting the Ingots for Rolling.

FIG. 3.
Plan.

FIG. 2.

FIG. 4.
Clamping Ring.

Unless this is done, a large part of the ingot is useless and has to be "cropped."

In every case the alloys were cast as quickly as possible to minimise oxidation. Should any oxide get into the castings it renders the turning of the specimens very difficult, as the edge of the tool is soon blunted.

If the foregoing precautions are observed, the melting and casting of rich copper alloys can be most satisfactorily carried out. Moreover, it has been found that (a) with the clean method of heating and (b) the care taken to prevent oxidation the life of the crucibles can be made much longer than has been supposed. Crucibles were still perfectly sound after twenty heats.

Measurements of the total Linear Contraction of certain Alloys on cooling from the freezing-point to the ordinary temperature.—The

method consisted in making a sand mould 13 inches long by $\frac{1}{2}$ inch square—

Two very thin needles were embedded in the mould exactly twelve inches apart, with the help of a gauge. The sand round the needles was embedded very loosely, so that it would offer as little resistance as possible to the movement of the needles during the contraction of the casting. When the alloy had cooled to the ordinary temperature the distance between the needles was measured by a rule divided into 100ths of an inch. The results are given below:—

Alloy No.	Aluminium.	Linear Contraction.
	Per cent.	Per cent.
1	0·10	2·00
5	4·05	2·08
8	6·73	2·00
10	8·12	2·33
11	8·67	2·34
13	9·90	1·83
—	12·4	1·83

They show that (a) the introduction and addition of aluminium up to 6·73 per cent. has no effect on the contraction; (b) at 8 per cent. there is a marked rise of contraction followed by a drop at 10 per cent.

Mechanical Treatment of the Alloys.—The ingots were rolled at the Broughton Copper Works, under the active supervision of Mr. L. Sumner and Mr. F. Tomlinson, and in the presence of one of the authors. The treatment was as follows:—They were first surfaced in a lathe and the diameter thus reduced to about $2\frac{1}{8}$ inches. They were then heated to about 800° C. (1,472° F.) and rolled down to $1\frac{1}{4}$ inches diameter. At this stage about one-third

was cut off in the shears and reserved for tests. The remainder was rolled down to $\frac{1}{8}$ inch. The reason for reserving some of the $\frac{1}{4}$ -inch bar for test was in order to see what reduction of area is really necessary in order to get the full value from mechanical work of this kind. In all cases the top end of the ingot was not rolled farther than to $\frac{1}{4}$ inches diameter, as it was desired to keep the material least likely to contain pipe for the tests at $\frac{1}{8}$ inch diameter. The alloys rolled perfectly well.

Five of the alloys, containing about 1, 3, 5, $7\frac{1}{2}$ and 10 per cent. of aluminium respectively, were also "hard-drawn." The treatment was as follows:—The bars were rolled hot from $\frac{1}{4}$ inches to $\frac{1}{8}$ inch full, drawn cold to $\frac{7}{8}$ inch, annealed at 750°C . ($1,382^{\circ}\text{F}$.), and finally drawn cold to $\frac{1}{8}$ inch. The only alloy that cracked under this treatment was that containing 5 per cent. of aluminium. As a result of this treatment the following lengths of material were at the author's disposal for their tests:—

- (a) From 3–4 feet of bar $\frac{1}{4}$ inches diameter.
- (b) About 12 feet of bar $\frac{1}{8}$ inch diameter.

Tests were carried out not only on sand and chill castings, on rolled and drawn bars, but on these materials "heat-treated" in various ways. In the great majority of such tests the alloys were (a) slowly cooled, (b) quickly cooled from 800°C . ($1,472^{\circ}\text{F}$.). This temperature was chosen because it clears the various critical ranges on heating found by Dr. L. Guillet.

Heat Treatment.—(a) *Slow Cooling from 800°C . ($1,472^{\circ}\text{F}$.)*—The specimens were heated in a large muffle gas-furnace. They were firmly bedded in bone-ash to avoid buckling, and were lightly covered with the same material. As a large number of specimens were thus treated, (a) the quantity of bone ash, (b) the number of specimens, (c) the conditions of heating and cooling, were kept as nearly as possible the same in the various sets thus treated in order to get comparable materials. As soon as 800°C . was reached the gas was turned out, the dampers closed and the muffle thus slowly allowed to cool. The temperature was given by a bare thermojunction in direct contact with the alloys.

(b) *Water-quenching from 800° C. (1,472° F.)*—The heating was done in the same furnace, with the bone ash removed. The sand castings were placed vertically in order to avoid buckling. The chills and rods were laid on the floor of the muffle. The heating was slowed up as 800° C. was approached. The specimens were quenched outright in a large tank filled with water at the ordinary temperature, as soon as possible one after the other.

In special cases other temperatures were used, but the methods were similar. Under the conditions described only a thin skin-oxidation of the alloys occurs.

Specific Gravities.—These were determined at the ordinary temperatures on (a) the sand castings, (b) the chill castings, and (c) the bars rolled to $\frac{1}{8}$ inch. The results have been expressed in two ways:—

(1) As grammes per cubic centimetre in Table 15 (*below*).

(2) As pounds per cubic foot in Table 16 (page 110).

The values calculated in (1) are also shown graphically in Fig. 5 (page 111).

TABLE 15.

Specific Gravities (expressed as grammes per cubic centimetre).

Alloy No.	Aluminium. Per cent.	Sand Castings.	Chill Castings.	Rolled Bars $\frac{1}{8}$ inch diameter.
1	0.10	8.90	8.90	8.92
2	1.06	8.79	8.77	8.78
3	2.10	8.54	8.61	8.62
4	2.99	8.44	8.47	8.47
5	4.05	8.29	8.31	8.31
6	5.07	8.16	8.18	8.18
7	5.76	8.04	8.07	8.07
8	6.73	7.94	7.96	7.95
9	7.35	7.85	7.86	7.85
10	8.12	7.79	7.78	7.78
11	8.67	7.73	7.69	7.69
12	9.38	7.64	7.61	7.61
13	9.90	7.60	7.56	7.56
14	10.78	7.45	7.45	7.45
15	11.73	7.19	7.34	7.35
16	13.02	6.98	7.23	7.23

TABLE 16.

Specific Gravities (expressed as pounds per cubic foot).

Alloy No.	Aluminium. Per cent.	Sand Castings.	Chill Castings.	Rolled Bars $\frac{1}{8}$ inch diameter.
1	0.10	555	555	556
2	1.06	548	547	548
3	2.10	533	537	537
4	2.99	526	528	528
5	4.05	517	518	518
6	5.07	509	510	510
7	5.76	501	503	503
8	6.73	497	498	499
9	7.35	492	492	492
10	8.12	488	487	487
11	8.67	484	482	482
12	9.38	479	477	477
13	9.90	475	473	473
14	10.78	466	466	466
15	11.73	450	460	460
16	13.02	435	451	451

Attention is directed to the following features of the results :—

(1) The chill castings and rolled bars have the same specific gravity. As will be shown later, certain of the alloys, namely, Nos. 10, 12, 13, and 15, have practically the same structures in the two conditions, while in Nos. 14 and 16 a similarity exists. In these cases an identity and similarity respectively of specific gravities is natural. But no such structural similarities exist between the chill castings and rolled bars of Alloys Nos. 1 to 9.

(2) With the introduction and addition of aluminium up to 13 per cent. the specific gravity drops regularly, and a smooth curve results, Fig. 5. This fact is of importance, because very marked structural changes are caused by the addition of aluminium between 8 and 13 per cent.

(3) The specific gravity curve of the sand castings exhibits a general similarity to those of the chill castings and rolled bars, but is less regular. Up to 7 per cent. of aluminium the specific gravity values are either equal to or, in most cases, are lower than those of the chill and bars. Within this range the alloys are homogeneous,

and appear to consist of a solid solution of aluminium in copper. Beyond and as far as 10·8 per cent. they are higher. In this range the structure is *duplex*, and the alloy consists of at least two structural constituents. Denser alloys are obtained by the slow rather than the quick cooling of these two constituents. Beyond 11 per cent. there is a further structural change, and the sand castings are no longer sound. This is the principal factor in causing the apparently rapid fall of specific gravity at this point.

(4) 8·90, the specific gravity of the sand and chill castings of the alloy containing 0·1 per cent. of aluminium, is the standard specific gravity for copper conductors adopted by the Sub-Committee on Cables of the Engineering Standards Committee.

Tensile-Stress Tests.—A very large number of these tests have been carried out, more than 300 in all. These have been performed as far as possible in accordance with the specifications laid down by

the Engineering Standards Committee. For castings the dimensions specified are:—

Diameter 0.564 inch.

Gauge length 2 inches.

Parallel portion at least $2\frac{1}{2}$ inches.

The form of the ends is left open.

These dimensions have been adhered to. Fig. 6 shows the form of the sand castings, and Fig. 7 that of the chill castings.

It is provided for rods that "these may be tested either full size or turned down when the diameter is considerable. In both cases the gauge length on which the extension is to be measured shall not be less than eight times the diameter of the test-piece, and where enlarged ends are used the parallel portion shall be not less than nine times the diameter of the test-piece." These conditions have also been adhered to. But in order that the precise influence of

FIG. 6.—*Sand Castings.*

FIG. 7.—*Chill Castings.*

mechanical work on the castings may be rendered evident, tensile-stress tests have also been carried out on 2-inch gauge lengths, diameter 0.564 inch, Fig. 7.

Tetmajer (page 83) found that the yield-point determinations of his alloys were uncertain and sometimes impossible, because, after the limit of proportionality had been passed, no sudden change of condition occurs as in the case of most iron alloys. The authors' experience with their alloys does not confirm this. Stress-strain diagrams of the rolled bars, Fig. 20 (page 141), show that at any rate from 0.1 to 9 per cent. of aluminium the alloys possess well-marked yield-points. Moreover a comparison of yield-points as measured, (1) by reading the stress-strain diagrams of 8-inch lengths, and (2) by noting the first permanent set on a 2-inch length by means of dividers, gave figures which, with one exception out of thirteen, differed from one another on an average, by not more than

0.9 of a ton. Accordingly in each tensile-stress test of 2-inch gauge length the first permanent set was noted by means of dividers. The load at which this occurred is included in the Tables and diagrams as the yield-point. As far as possible a uniform rate of loading was used throughout the tests.

The two principal variables in the following series are :—

- (a) The percentages of aluminium and copper.
- (b) The physical condition of the alloys.

In presenting and discussing the results it has been found convenient to group them under these two heads. Certain relationships and contrasts are rendered more evident by the one, others by the other, grouping.

FIG. 8.
Tensile Tests on Sand Castings.

(Reduction of Area of the Castings could not be measured, see text.)

Tensile-Stress Tests—(A.)—In this section chief prominence is given to the variations caused by the introduction of aluminium into copper and its gradual rise to 13 per cent.

(a) *Sand Castings.*—The results are tabulated in Table 17 (page 114) and shown graphically in Fig. 8.

K

TABLE 17.

Sand Castings.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.		
1	0·10	3·8	11·50	0·33	46·0	Sound, salmon-coloured, silky	Wavy.
2	1·06	3·0	13·4	0·22	52·0	Sound, pale salmon, silky	Wavy, with slip-lines.
3	2·10	3·4	13·5	0·25	53·5	Sound, reddish gold, silky	Wavy, with slip-lines.
4	2·99	3·8	14·5	0·26	60·0	Sound, pale gold, silky	Wavy.
5	4·05	3·5	16·7	0·21	83·0	Sound, pale gold, silky	Very wavy.
6	5·07	4·3	18·1	0·24	75·0	Small holes, pale gold, silky	Wavy.
7	5·76	4·8	17·8	0·27	67·0	Sound, pale gold, silky	Wavy.
8	6·73	4·8	18·65	0·26	{ could not be measured; }	{ Small hole, pale gold, slightly crystalline }	Wavy.
9	7·35	6·6	21·30	0·31	71·0	Slight dross, pale gold, silky	Wavy.
10	8·12	7·7	24·91	0·31	58·0	Sound, pale gold, silky	Wavy.
11	8·67	9·8	28·1	0·35	48·0	Sound, pale gold, silky	Slightly wavy.
12	9·38	9·7	30·38	0·32	36·2	Sound, pale gold, silky	Wavy.
13	9·90	11·3	31·70	0·36	21·7	Sound, dark gold, slightly silky	Slightly wavy.
14	10·78	14·1	29·52	0·48	9·0	Sound, greyish brown, crystalline	Smooth and bright.
15	11·73	14·0	25·43	0·55	5·0	{ Radial slits, light brown, crystalline }	Smooth and bright.
16	13·02	{ coincident with fracture }	19·75	—	1·0	{ Radial slits, lustrous grey brown, crystalline }	Smooth and bright.

These figures are the mean of two tests in which the *average* difference in ultimate stress was 0·7 of a ton per square inch, and the *greatest* difference 1·3 tons. (Alloys 1 to 14.)

Yield-Point.—Up to about 7 per cent. of aluminium the values are low, and differ only slightly from one another. Beyond this they rise steadily until at 13 per cent. the yield-points and ultimate stresses coincide.

Ultimate Stress.—Up to about 7 per cent. the stress rises steadily. From 7 to 10 per cent. the rise is steady and more rapid. Beyond this there is a steady fall.

FIG. 9.
Tensile Tests on Sand Castings.
Slowly cooled from 800° C. (1,472° F.)

The *Elastic Ratio* is very low. Up to 7 per cent. of aluminium it averages only 0.25. From 7.35 to 9.90 it is approximately steady at 0.33. Beyond here where the yield-point continues to rise but the ultimate stress falls, the elastic ratio gradually rises to 1. The change of properties which occurs between 7 and 8 per cent. of aluminium corresponds to an important structural alteration of the alloys. As far as 7.35 per cent. the alloys appear to be homogeneous. Beyond this a second structural constituent appears, which is hard and brittle. This fact is also brought out by the figures representing the ductility of the alloys. The percentage

elongation is quickly raised by the addition of aluminium up to 4 per cent.; from here to 7.35 per cent. there is a slight fall and the figures are rather irregular. Beyond this point there is a rapid and almost uniform fall, until at 13 per cent. the alloy fractures with only 1 per cent. extension.

The cross-section of the fractured surfaces of both sand and chill castings was found to be so irregular that the measurements of reduction of area were uncertain. Accordingly these figures have not been given. Occasionally the test-pieces pulled out so irregularly that the gauge-marks could not be detected.

(b) *Sand Castings, slowly cooled from 800° C. (1,472° F.)*—The results are given in Table 18 (page 118), and are shown graphically in Fig. 9 (page 115). If they are compared with those obtained from the untreated sand castings, the following features will be noticed:—

(1) Up to 7.35 per cent. of aluminium this heat treatment has practically no influence on the properties of the castings. The yield-points and ultimate stresses are the same in the two series. The only difference is that in the heat-treated alloys the ductility reaches a maximum at 7.35 per cent. as compared with 4 per cent. in the untreated alloys.

(2) From 8 to 13 per cent. of aluminium the properties of the alloys *deteriorate* under this treatment. This is particularly noticeable in the case of the alloy containing 9.9 per cent. of aluminium. In both tests made on this material it broke in the head shortly after the yield-point had been passed, and the fracture was found to be coarsely crystalline. The reason for this change of behaviour is that the two structural constituents of alloys in this class themselves change under this treatment. Thus it will be seen that nothing is gained by subjecting the alloys to a slow cooling from 800° C. after they have been cast.

(c) *Sand Castings, quenched from 800° C. (1,472° F.) in Water.*—The results are given in Table 19 (page 119) and are shown graphically in Fig. 10 (page 117). In this case also the alloys containing not more than 7.35 per cent. of aluminium are indifferent to the heat

TENSILE TESTS.

FIG. 10.—Sand Castings.

Quenched from 800° C. (1,472° F.) in Water.

FIG. 11.—Chill Castings.

TABLE 18.

Sand Castings, slowly cooled from 800° C. (1,472° F.).

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.		
1	0.10	4.2	11.34	0.37	40.0	Sound, salmon coloured, silky	{ Wavy, slip-bands well marked.
2	1.06	3.2	12.9	0.25	46.0	Sound, pale salmon, silky	Wavy, with slip-bands.
3	2.10	3.5	14.0	0.25	46.5	Sound, reddish gold, silky	Wavy, with slip-bands.
4	2.99	3.7	14.8	0.25	60.5	Sound, pale gold, silky	Wavy, with slip-bands.
5	4.05	3.9	17.0	0.23	68.5	Sound, pale gold, silky	{ Very wavy, with slip-bands.
6	5.07	3.6	18.8	0.19	65.5	Small hole, pale gold, silky	Wavy.
7	5.76	3.8	19.4	0.20	65.0	Sound, pale gold, silky	Wavy.
8	6.73	4.8	18.82	0.26	64.0	{ Small hole, pale gold, slightly crystalline	Wavy.
9	7.35	5.9	20.1	0.29	81.0	Slight dross, pale gold, silky	Wavy, with slip-bands.
10	8.12	6.9	22.15	0.31	69.0	Sound, pale gold, silky	Wavy.
11	8.67	8.8	23.5	0.37	48.0	Sound, pale gold, granular	Slightly wavy.
12	9.38	10.7	23.41	0.46	17.2	Sound, pale gold, silky	Wavy.
13*	9.90	13.3	—	—	—	{ Sound, greyish brown, coarsely crystalline	Smooth.
14	10.78	27.0	29.21	0.92	2.0	Sound, greyish brown, granular	Smooth and bright.
15	11.73	{ coincident with fracture }	19.37	—	1.0	{ Radial slits, greyish-brown, granular }	Smooth and bright.
16	13.02	„	15.83	—	2.0	{ Small slits, lustrous greyish brown, granular }	Smooth.

These figures are the mean of two tests in which the average difference in ultimate stress was 1.1 tons, and the greatest difference 3.4 tons per square inch. (Alloys 1-14.)

* Both of these specimens broke in the head; they were found to be coarsely crystalline.

TABLE 19.

Sand Castings, quenched from 800° C. (1,472° F.) in Water.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons persq.in.	Tons persq.in.		Per cent.		
1	0.10	2.9	10.67	0.27	40.0	Sound, salmon coloured, silky	Wavy, with well-marked slip-bands.
2	1.06	—	—	—	—	—	—
3	2.10	4.3	14.0	0.31	47.0	Sound, reddish gold, silky	Wavy, with slip-bands.
4	2.99	4.9	14.8	0.33	58.5	Sound, pale gold, silky	Wavy, with slip-bands.
5	4.05	5.0	16.5	0.30	60.0	Minute holes, pale gold, silky	Very wavy, with slip-bands.
6	5.07	5.0	18.6	0.27	66.5	Small holes, pale gold, silky	Wavy.
7	5.76	5.4	18.1	0.30	52.5	Sound, pale gold, silky	Wavy.
8	6.73	6.3	19.9	0.32	51.0	{ Sound, pale gold, slightly crystalline }	Wavy.
9	7.35	6.7	20.0	0.33	70.0	Sound, pale gold, silky	Wavy.
10	8.12	7.9	26.0	0.30	62.5	Sound, pale gold, silky	Wavy.
11	8.67	11.7	30.7	0.38	35.0	Sound, pale gold, silky	Slightly wavy.
12	9.38	20.8	38.16	0.55	9.5	Sound, pale gold, silky	Wavy.
13	9.90	22.4	50.0	0.45	3.0	{ Sound, pale gold, silky, crystalline }	Smooth.
14	10.78	29.7	35.45	0.84	2.5	Sound, pale gold, platey fracture	Smooth and bright.
15	11.73	16.8	24.79	0.68	5.0	{ Radial slits, greyish brown, platey fracture }	Smooth and bright.
16	13.02	14.0	23.18	0.60	4.5	{ Small slits, lustrous light-brown, crystalline }	Smooth.

These figures are the mean of two tests in which the average difference in ultimate stress was 0.8 ton and the greatest difference 2.7 tons per square inch. (Alloys 1-14.)

treatment. The yield-points, and therefore the elastic ratio, are slightly higher (the ultimate stresses are hardly affected); the ductilities are slightly less as compared with the untreated specimens. From 8 to 11 per cent., however, the alloys are considerably stiffened by this treatment. The ultimate stress rises sharply to a maximum of 50 tons per square inch at 9.90 per cent., while the maximum yield-point, namely, 29.7 tons per square inch, occurs at 10.78 per cent. Corresponding to this there is a very rapid fall in ductility, a 3-per-cent. extension being obtained at 9.90 per cent.

(d) *Chill Castings.*—The results are given in Table 20 (page 122) and are shown graphically in Fig. 11 (page 117). The character of these results is very similar to that shown by the sand castings, but the materials are rather better. The yield-points and ultimate stresses average higher, particularly the former, so that the elastic ratio is also higher. It averages about 0.38 among Alloys Nos. 11 to 15; in No. 16 it approaches unity. There is a steady rise in ductility up to 4 per cent. of aluminium, where the high figure of 82 per cent. is reached. As in sand castings there is a drop from here, followed by a rise up to 7.35 per cent. of aluminium where the percentage elongation is 84. From here onwards there is a rapid fall in ductility.

(e) *Chill Castings, slowly cooled from 800° C. (1,472° F.).*—The results are given in Table 21 (page 124), and are graphically shown in Fig. 12 (page 121). Just as in the case of the sand castings, up to 7.35 per cent. the alloys are indifferent to this treatment, and beyond this they are deteriorated by it. Alloy No. 5, containing 4 per cent. of aluminium, gave an extension of 89 per cent. on 2 inches.

(f) *Chill Castings, quenched from 800° C. (1,472° F.) in Water.*—The results are given in Table 22 (page 125), and are graphically shown on Fig. 13 (page 121). Beyond 7.35 per cent. of aluminium the alloys are less stiffened by this treatment than were the corresponding sand castings. The reason for this is that in the

TENSILE TESTS.

FIG. 12.—Chill Castings.

Slowly cooled from 800° C. (1,472° F.).

FIG. 13.—Chill Castings.

Quenched from 800° C. (1,472° F.) in Water.

TABLE 20.

Chill Castings.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.		
1	0.10	4.1	11.53	0.36	46.0	Sound, salmon coloured, silky	Wavy.
2	1.06	5.2	11.8	0.44	53.0	Sound, pale salmon, silky	Wavy, with slip-bands.
3	2.10	4.5	13.7	0.33	54.5	Small hole, reddish gold, silky	Wavy, with slip-bands.
4	2.99	6.8	13.8	0.49	60.0	Sound, pale gold, silky	Wavy.
5	4.05	4.9	17.1	0.29	82.0	Sound, pale gold, silky	Very wavy.
6	5.07	7.1	18.1	0.39	60.5	Sound, pale gold, silky	Wavy.
7	5.76	6.0	18.8	0.32	61.0	Slight dross, pale gold, silky	Wavy.
8	6.73	not taken	19.96	—	69.0	{ Sound, pale gold, radially crystalline }	Wavy.
9	7.35	not taken	21.58	—	84.0	Sound, pale gold, silky	Wavy.
10	8.12	9.7	27.47	0.35	62.0	Sound, pale gold, silky	Wavy.
11	8.67	not taken	30.8	—	55.0	Sound, pale gold, granular	Wavy.
12	9.38	10.5	33.98	0.31	43.5	Sound, pale gold, silky	Wavy.
13	9.90	12.4	36.93	0.34	30.5	Sound, pale gold, silky	Slightly wavy.
14	10.78	16.9	36.73	0.46	9.0	{ Sound, greyish brown, large radially-placed crystals }	Smooth and bright.
15	11.73	14.8	30.63	0.48	6.0	Sound, light brown, crystalline	Smooth and bright.
16	13.02	{ coincident with fracture }	25.06	—	nil.	{ Sound, lustrous grey - brown, large radially-placed crystals }	Smooth.

former case the volume quenched was 5.5 cubic inches, in the latter 2.4 cubic inches. The surface of the sand castings was also relatively greater. The rate of cooling of the chill was therefore less than that of the sand castings. A special section devoted to this point will be found on pages 172-175.

(g) *Bars rolled to $1\frac{1}{4}$ inches diameter.*—The results are given in Table 23 (page 128), and are graphically shown in Fig. 14. With

FIG. 14.—*Tensile Tests on Bars rolled to $1\frac{1}{4}$ inches diameter. Untreated.*

the introduction of aluminium and its gradual rise to 13 per cent. the properties vary in a manner similar to those of the sand and chill castings. Up to 7.35 per cent. of aluminium the properties are on an average decidedly superior to those of the castings. The yield-points and ultimate stresses are higher than those of the chill castings, but the elastic ratio is the same, namely, 0.39 as compared with 0.38. The ductility reaches a very high value. Regarding the product of the percentage elongation and reduction

TABLE 21.

Chill Castings, slowly cooled from 800° C. (1,472° F.).

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.		
1	0.10	4.9	11.07	0.44	44.0	Sound, salmon coloured, silky	Wavy.
2	1.06	4.5	12.9	0.35	57.0	Sound, pale salmon, silky	Wavy, with slip-bands.
3	2.10	4.8	13.9	0.35	56.0	Sound, reddish gold, silky	Wavy, with slip-bands.
4	2.99	4.4	14.6	0.30	73.0	Sound, pale gold, silky	Wavy.
5	4.05	4.3	16.4	0.26	89.0	Sound, pale gold, silky	Very wavy.
6	5.07	5.1	18.0	0.28	61.0	Small hole, pale gold, silky	Wavy.
7	5.76	5.6	19.5	0.29	74.0	Traces of dross, pale gold, silky	Wavy.
8	6.73	—	—	—	—	—	—
9	7.35	6.0	20.2	0.30	80.0	Small hole, pale gold, silky	Wavy.
10	8.12	7.3	22.23	0.33	59.0	Sound, pale gold, silky	Wavy.
11	8.67	8.8	27.1	0.32	63.0	Sound, pale gold, granular	Wavy.
12	9.38	11.3	27.46	0.41	27.0	Sound, dry grey brown	Wavy.
13	9.90	16.5	26.4	0.62	5.0	{ Sound, dull gold, coarsely } crystalline	Smooth.
14	10.78	23.6	28.72	0.82	nil	Sound, greyish brown, granular	Smooth and bright.
15	11.73	—	—	—	—	—	—
16	13.02	{ coincident with fracture }	16.51	—	nil	{ Sound, lustrous grey brown, } coarsely crystalline	Smooth.

TABLE 22.

Chill Castings, quenched from 800° C. (1,472° F.) in Water.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.		
1	0.10	4.0	11.30	0.35	47.5	{ Small hole, salmon coloured, silky }	Wavy.
2	1.06	—	12.60	—	53.5	Sound, pale salmon, silky	{ Wavy, with slip-bands. }
3	2.10	4.3	13.90	0.31	55.0	Sound, reddish gold, silky	{ Wavy, with slip-bands. }
4	2.99	4.7	14.9	0.32	53.0	Small hole, pale gold, silky	Wavy.
5	4.05	5.1	17.7	0.29	81.0	Sound, pale gold, silky	Very wavy.
6	5.07	5.7	19.1	0.30	80.0	Sound, pale gold, silky	Wavy.
7	5.76	8.2	20.5	0.40	49.0	Traces of dross, pale gold, silky	Wavy.
8	6.73	5.2	18.9	0.27	42.0	Sound, pale gold, crystalline	Wavy.
9	7.35	7.3	19.8	0.37	79.0	Sound, pale gold, silky	Wavy.
10	8.12	8.4	24.94	0.34	61.0	Sound, pale gold, silky	Wavy.
11	8.67	9.7	29.8	0.33	54.0	Sound, pale gold, granular	Wavy.
12	9.38	18.7	35.59	0.53	28.0	Sound, pale gold, silky	Wavy.
13	9.90	17.7	38.57	0.46	22.0	Sound, pale gold, silky	Slightly wavy.
14	10.78	26.7	32.36	0.83	3.0	{ Sound, yellowish brown, silky } crystalline	Smooth and bright.
15	11.73	12.5	25.04	0.50	5.0	Sound, light brown, crystalline	Smooth and bright.
16	13.02	11.8	25.97	0.45	4.0	{ Sound, lustrous grey brown, } coarsely crystalline	Smooth.

of area as a measure of this, it will be noticed that the ductility is practically constant from 1 to 7.35 per cent. of aluminium. (The figures for No. 1, containing 0.10 per cent. of aluminium, are not available.)

From about 9.38 to 11.73 per cent. of aluminium the properties of the rolled bars are very little, if at all, superior to those of the chill castings. In the case of Alloy No. 13, the so-called "aluminium gold" or "bronze," with 9.90 per cent. of aluminium, the figures for the chill castings are actually superior to those obtained with the rolled bar. A special section is devoted to this very interesting result (pages 162-164).

Fractures.—Up to 3 per cent. of aluminium, double cup fractures were obtained; beyond this, cup and cone fractures as far as 5 per cent. After this point was passed the fractures were irregular. Up to 10 per cent. of aluminium the fractures were silky, beyond this markedly crystalline.

Surface.—The rolled bars pulled out regularly and the cross-section of the fractured test-piece was as a rule uniform, thus enabling the reduction of area to be calculated. Up to 7.35 per cent. of aluminium the surface of the bars which had undergone "general extension" was uniformly frosted, whereas in the chill and sand castings it was irregularly wavy.

(h) *Bars rolled to $\frac{1}{8}$ inch diameter.*—The results are given in Table 24 (page 129), and are shown graphically in Fig. 15. The further reduction of area has brought about a slight stiffening of the alloys. Both the yield-points and ultimate stresses are higher, and as the rise is more marked in the yield-points, the elastic ratio averages out at 0.42 as compared with 0.39 for the $\frac{1}{4}$ -inch bars. The ductilities have been somewhat reduced, but the general character of the curves is very similar in the two series.

The best mechanical properties are reached at 9.38 per cent. of aluminium in both series. The further addition of aluminium causes

a diminution of ductility without increasing the tenacity. Beyond 11 per cent. the ultimate stress also drops.

Fig. 161, Plate 19, is a photograph of the fractured test-pieces of the (a) sand castings; (b) chill castings; (c) $\frac{1}{8}$ -inch-diameter bars. These have been mounted in such a way that the variations of ductility caused by the introduction and addition of aluminium can be readily seen. The surface irregularities of the castings are also evident.

FIG. 15.—Tensile Tests on Bars rolled to $\frac{1}{8}$ inch diameter.
2½ inches parallel.

(k) Bars ($\frac{1}{8}$ inch diameter) cooled slowly from 800° C. (1,472° F.). —The results are given in Table 25 (page 132), and are shown graphically in Fig. 16 (page 130). While this treatment improves the ductility of alloys containing aluminium up to 8.67 per cent., it ruins the alloys beyond this percentage (*cf.* No. 13). Moreover it causes a loss of strength throughout the series, and the average elastic ratio drops to 0.33. This treatment is not to be recommended for any of the bars.

TABLE 23.
Bars rolled to $1\frac{1}{4}$ inches diameter.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
1	0.10	—	—	—	—	—	—	—
2	1.06	6.7	15.65	0.43	59.0	90.85	{ Sound, pale salmon, double-cup	Dull frosted.
3	2.10	6.4	17.22	0.37	61.0	90.03	{ Sound, reddish gold, double-cup	Frosted.
4	2.99	7.9	18.98	0.42	67.0	88.81	{ Sound, pale gold, silky, double cup	Dull frosted.
5*	4.05	7.3	21.93	0.33	71.0	81.83	{ Sound, pale gold, silky, cup and cone	Slightly frosted.
6	5.07	6.8	24.54	0.28	79.0	77.00	{ Sound, pale gold, silky, cup and cone	Frosted.
7	5.76	—	—	—	—	—	—	—
8	6.73	7.5	26.17	0.29	82.0	75.37	Sound, pale gold, silky	Frosted.
9	7.35	9.3	27.42	0.34	80.0	75.27	Sound, pale gold, silky	Frosted.
10	8.12	9.8	30.88	0.32	70.0	64.47	{ Sound, pale gold, silky, granular	Slightly frosted.
11	8.67	—	—	—	—	—	—	—
12	9.38	14.8	37.34	0.40	40.0	41.37	Sound, pale gold, silky	Wavy streaks.
13	9.90	13.6	35.03	0.39	31.5	30.52	{ Sound, pale gold, silky, crystalline	Smooth.
14	10.78	18.0	35.00	0.51	12.5	12.07	Sound, pale gold, crystalline	Smooth and bright.
15	11.73	19.0	32.11	0.59	5.5	4.19	{ Sound, pale gold, coarsely crystalline	Smooth and bright.
16	13.02	—	—	—	—	—	—	—

* The diameter of this bar was $1\frac{7}{16}$ inches.

TABLE 24.—Bars rolled to $\frac{1\frac{1}{8}}$ inch diameter.

JAN. 1907.

ALLOYS RESEARCH.

129

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
1	0.10	6.9	14.50	0.48	65.5	90.71	{Sound, salmon coloured, silky, double cup	Dull, frosted.
2	1.06	6.9	15.88	0.43	61.0	88.63	{Sound, pale salmon, double-cup	Dull, frosted.
3	2.10	8.6	17.46	0.49	56.5	89.65	{Sound, reddish gold, silky, double cup	Frosted.
4	2.99	11.6	19.79	0.59	57.2	86.11	{Sound, pale gold, silky, double cup	Slightly dulled.
5	4.05	11.3	23.80	0.47	67.0	83.27	{Sound, pale gold, silky, cup and cone	Slightly frosted.
6	5.07	11.4	26.41	0.43	69.2	77.80	{Sound, pale gold, silky, cup and cone	Frosted.
7	5.76	11.8	28.40	0.41	74.2	76.93	{Sound, pale gold, silky, cup and cone	Frosted.
8	6.73	10.4	28.85	0.36	71.0	75.02	{Sound, pale gold, silky	Slightly frosted.
9	7.35	10.6	29.68	0.36	72.5	74.34	{Sound, pale gold, silky, cup and cone	Frosted.
10	8.12	13.0	33.22	0.40	51.5	60.40	{Sound, pale gold, silky, cup and cone	Slightly frosted.
11	8.67	11.1	36.67	0.30	38.0	50.66	{Sound, pale gold, granular, cup and cone	Almost smooth.
12	9.38	17.7	38.00	0.47	34.0	33.60	{Sound, pale gold, silky	Wavy streaks.
13	9.90	14.8	38.10	0.39	28.8	30.80	{Sound, pale gold, silky, granular	Smooth.
14	10.78	15.4	38.62	0.40	14.0	18.60	{Sound, pale gold, coarsely crystalline	Smooth and bright.
15	11.73	12.6	33.85	0.37	8.5	15.37	{Sound, pale gold, coarsely crystalline	Smooth and bright.
16	13.02	—	37.14	—	2.0	1.87	{Sound, lustrous grey brown, granular	Smooth.

These figures are the mean of two tests in which the average difference in ultimate stress was 0.18 of a ton, and the greatest difference 0.5 of a ton per square inch. (Alloys 1 to 14.)

TENSILE TESTS.

FIG. 16.—Bars rolled to $\frac{1}{8}$ inch.
Slowly cooled from 800° C. (1,472° F.).

FIG. 17.—Bars rolled to $\frac{1}{8}$ inch.
Quenched from 800° C. (1,472° F.) in Water.

(l) Bars ($\frac{1\frac{3}{8}}$ inch diameter) quenched from 800° C. ($1,472^{\circ}$ F.) in Water.—The specimens quenched were 5 inches by $\frac{1\frac{3}{8}}$ inch. The results are given in Table 26 (page 133), and are shown graphically in Fig. 17 (page 130). They are very similar to those of the preceding section, except in regard to the alloys containing from 9 to 11 per cent. of aluminium. There is a very high average ductility up to

FIG. 18.—Tensile Tests on Rolled Bars cold-drawn from $\frac{7}{8}$ inch to $\frac{1\frac{3}{8}}$ inch.

7.35 per cent. of aluminium. From 8 to 11 per cent. the alloys are stiffened, $45\frac{1}{2}$ tons per square inch ultimate stress being obtained at 9.90 per cent. This figure, however, is $4\frac{1}{2}$ tons less than was obtained with the sand castings. The average elastic ratio of the series is 0.34.

(m) Cold-drawn bars ($\frac{1\frac{3}{8}}$ inch diameter).—The results are given in Table 27 (page 134), and are shown graphically in Fig. 18. It will be observed that at 5 per cent. of aluminium, the

TABLE 25.—Bars ($\frac{1}{8}$ inch diameter) slowly cooled from 800° C. (1,472° F.)

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
.	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
1	0.10	4.4	14.18	0.31	62.0	92.52	{ Sound, salmon coloured, silky, double cup	Dull frosted.
2	1.06	4.4	15.22	0.29	67.0	91.87	{ Sound, pale salmon, double cup	Wavy.
3	2.10	4.4	16.60	0.26	66.0	90.00	{ Sound, reddish gold, silky, double cup	Frosted.
4	2.99	4.8	18.00	0.27	73.0	90.00	{ Sound, pale gold, silky, double cup	{ Frosted, and slightly wavy in streaks.
5	4.05	6.1	21.50	0.28	73.0	85.65	{ Sound, pale gold, silky, cup and cone	{ Frosted, and wavy streaks.
6	5.07	5.2	23.65	0.22	79.0	82.00	Sound, pale gold, silky	{ Frosted, and slightly wavy.
7	5.76	7.9	26.60	0.30	77.5	70.95	Sound, pale gold, silky	Frosted.
8	6.73	7.1	26.50	0.27	82.5	73.50	Sound, pale gold, silky	{ Frosted, and slightly wavy.
9	7.35	7.4	25.41	0.29	80.5	74.83	{ Sound, pale gold, silky, cup and cone	Wavy.
10	8.12	8.1	27.30	0.30	80.0	70.00	Sound, pale gold, silky	Slightly wavy.
11	8.67	11.4	30.04	0.38	65.0	64.90	{ Sound, pale gold, slightly silky	Slightly frosted.
12	9.38	—	—	—	—	—	—	—
13	9.90	15.5	28.51	0.54	6.5	10.20	{ Sound, greyish brown, granular	Smooth.
14	10.78	18.5	30.37	0.60	1.5	4.00	{ Sound, greyish brown, granular	Smooth and bright.
15	11.73	—	24.44	—	1.0	2.68	{ Sound, greyish brown, granular	Smooth and bright.
16	13.02	—	—	—	—	—	—	—

These figures are the mean of two tests.

TABLE 26.

Bars ($\frac{1}{8}$ inch diameter) quenched from 800° C. (1,472° F.) in Water.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
1	0.10	4.4	14.05	0.31	65.0	91.80	{Sound, salmon coloured, silky, double cup	Dull frosted.
2	1.06	4.3	15.39	0.28	63.5	90.76	{Sound, pale salmon, double cup	Dull frosted.
3	2.10	4.3	16.77	0.26	63.5	88.80	{Sound, reddish gold, silky, double cup	Frosted.
4	2.99	5.5	18.11	0.30	69.0	88.80	{Sound, pale gold, silky, double cup	{Frosted and slightly wavy.
5	4.05	6.4	21.29	0.30	79.0	84.80	{Sound, pale gold, silky, cup and cone	{Frosted and wavy streaks.
6	5.07	6.2	23.57	0.26	83.0	78.80	Sound, pale gold, silky	Frosted, slightly wavy.
7	5.76	6.9	24.94	0.28	84.5	75.60	Sound, pale gold, silky	Rather wavy.
8	6.73	7.4	25.46	0.29	83.0	72.00	Sound, pale gold, silky	Wavy.
9	7.35	8.0	25.51	0.31	82.0	74.80	{Sound, pale gold, silky, cup and cone	Wavy.
10	8.12	7.5	28.41	0.26	74.0	69.26	{Sound, pale gold, silky, cup and cone	Frosted.
11	8.67	12.6	34.94	0.36	51.0	59.60	{Sound, pale gold, silky, cup and cone	Smooth.
12	9.38	19.1	30.01	0.50	32.0	42.66	Sound, pale gold, silky	Wavy streaks.
13	9.90	26.2	45.48	0.58	11.0	16.78	{Sound, pale gold, silky, crystalline	Smooth.
14	10.78	12.0	36.11	0.33	5.0	13.32	Sound, pale gold, platey	Smooth and bright.
15	11.73	12.0	25.44	0.43	6.0	10.57	Sound, pale gold, platey	Smooth and bright.
16	13.02	—	—	—	—	—	—	—

These figures are the mean of two tests.

TABLE 27.

Cold-drawn Bars, $\frac{1}{8}$ inch diameter.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
2	1.06	17.3	18.10	0.96	42.0	88.75	{ Sound, pale salmon, silky, double cup }	Dull frosted.
4	2.99	21.0	22.26	0.94	44.0	86.05	{ Sound, pale gold, silky, double cup }	Frosted.
6	5.07	23.8	30.43	0.78	—	—	Pipe, pale gold, silky	Frosted.
9	7.35	24.6	31.42	0.78	48.0	58.79	Slight pipe, pale gold, silky	Frosted and wavy.
12	9.38	29.0	38.83	0.75	32.0	46.31	Sound, pale gold, silky	Slightly wavy.
13	9.90	40.4	43.94	0.92	13.0	22.19	{ Sound, pale gold, silky, crystalline }	Slightly wavy.

These figures are the mean of two tests.

alloy does not draw sound, and that there is a slight tendency to draw hollow at 7.35 per cent., without, however, a serious impairment of properties. The remaining alloys drew well. As in the other series there is an abrupt change of properties beyond 7.35 per cent. of aluminium. The most important result is the rise of yield-point, both absolutely and relatively to the ultimate stress throughout the series. Up to 3 per cent. of aluminium it averages 0.95, from 5 to 9.4 per cent. it averages 0.77, and at 9.9 per cent. it rises to 0.92. Even in this stiffened condition the alloys preserve a very appreciable ductility. No. 13 with 40 tons yield-point reduces 22 per cent. on fracture with an elongation of 13 per cent.

As is customary the stresses have been calculated on the *original* area of the specimen. Had it been possible they would also have been calculated on the reduced area after the bar had undergone its "general" extension. This method of calculation is fairer to the ductile alloys. It was found, however, that the diameter was not constant, but that the bar gradually increased in width from the fracture to the screwed ends. Consequently the results could not be presented in this way. With the view, however, of bringing out the toughness of the softer alloys, the ultimate stresses of the rolled bars have been calculated on the original area, and also on the *area at fracture*, and may be compared in Table 28 (page 136). The length of the bars under test was 8 inches.

In column 4 the properties of the alloys are presented in a new aspect. From 0.1 to 4 per cent. of aluminium the ultimate stresses come out very near one another and are astonishingly high. Alloy No. 1 withstood up to 178 tons per square inch at the moment of fracture. At 5 per cent. there is a drop to 133 tons. Similar figures are obtained up to 7.35 per cent. At 8 per cent. there is a sharp drop to 66 tons. This corresponds to the appearance of a brittle structural constituent in the material. At 10 per cent. there is a further drop, and this alloy broke at 47.6 tons.

TABLE 28.

Bars rolled to $\frac{1}{8}$ inch diameter.

Parallel portion . . . 10.5 inches.

Diameter . . . 0.564 inch.

Alloy No.	Aluminium. Per cent.	Ultimate Stress. Tons per square inch.	
		Calculated on original area.	Calculated on area at fracture.
1	0.10	14.01	178.0
2	1.06	15.25	154.4
3	2.10	16.86	172.0
4	2.99	19.25	157.7
5	4.05	22.97	154.2
6	5.07	25.56	133.1
7	5.76	27.78	132.6
8	6.73	28.45	116.1
9	7.35	29.00	127.2
10	8.12	32.87	66.2
11	8.67	35.72	71.7
12	9.38	36.86	69.0
13	9.90	37.34	47.6
1	2	3	4

SUMMARY.

In considering these results as a whole, attention may be directed to the following features:—

(a) The limit of industrially-serviceable alloys must be placed at 11 per cent. of aluminium. For most purposes the limit might be

put at 10 per cent., beyond which there is a rapid fall of ductility with no rise of ultimate stress. It will be noticed however, particularly in the castings, that the yield-point is usually decidedly better at 11 than 10 per cent.

(b) Between these limits the alloys fall into two classes:—

(1) Those containing from 0 to 7.35 per cent. of aluminium.

(2) " " " 8.12 to 11 " " "

Class 1 represents material of apparently low yield-point and moderate ultimate stress, but of very good ductility. The introduction and further addition of aluminium causes a gradual increase of strength, but hardly affects the ductility. It is true that as regards the steadiness of the ductility this has only been established for the rolled bars. But the sand and chill castings have shown the *same kind* of variations as the rolled bars in all the properties examined, and it appears legitimate to draw this conclusion for them also. This class is not very sensitive to heat treatment, but is much improved by mechanical work.

Into Class 2 come alloys of relatively-low yield-point, but good ultimate stress. From 8 to 10 per cent. of aluminium, the ductility is also good. Certain alloys in this class are very sensitive to heat-treatment, but one of them is remarkably indifferent to hot rolling (No. 13).

(c) Taken as a whole the chill are superior to the sand castings, and are themselves surpassed by the rolled bars. Alloy No. 13, and to a less extent No. 12, constitutes a notable exception to this generalization. This exception is discussed on pages 162-164.

(d) One of the most noteworthy characteristics of the alloys as a whole is their low yield-point, absolutely and relatively. Accordingly the elastic ratio of an alloy of given ultimate stress is low compared with that of a steel of the same ultimate stress. Thus No. 13 (with 10 per cent. of aluminium), with an ultimate stress of 38 tons per square inch, has an elastic ratio of only 0.39, whereas that of a Swedish Bessemer Steel, containing about 0.35 per cent. of carbon of the same ultimate stress, is 0.68. This appears to place these alloys in a position of inferiority. But it has been

shown recently by Messrs. Stanton and Bairstow * that the primitive yield-point of a steel is usually an artificial figure, and is due to a stiffening caused by mechanical treatment in preparation. Thus they found that the proper yield-point of the Bessemer Steel mentioned was 15.2 tons per square inch. The elastic ratio then became 0.40, which is identical with that of No. 13. As is shown on page 195 these rich copper alloys do not show anything like the same tendency to assume an artificial yield-point. The inferiority of the aluminium-bronzes is thus only apparent, not real.

(e) As has been shown (page 135), cold-drawing raises the elastic ratio to a very high figure, and leaves a considerable measure of ductility, but it has not been successful at about 5 per cent. of aluminium, where a tendency to pipe has been noticed.

(f) Another striking feature of the mechanical qualities of the alloys is the very high ductility which is almost constant between 0 and 7.35 per cent. of aluminium. More especially is this the case with the reduction of area. The values obtained were so much superior to those given in the best results found in the literature, that the authors became suspicious of their results. It was accordingly decided to obtain an exact copper blank of the series. At their request a rolled bar $\frac{1\frac{3}{8}}$ inch diameter was prepared at the Broughton Copper Works from the same cathode copper as that used in the research. Analysis showed that it contained 99.96 per cent. of copper. In order to thoroughly soften it, the bar was slowly cooled from 800° C. (1,472° F.). The tensile-stress test gave the following result :—

Yield-Point.	Ultimate Stress.	Elongation	Reduction
Tons per	Tons per	2 inches.	of Area.
sq. in.	sq. in.	Per cent.	Per cent.
5.0	14.17	56.0	67.84

These figures may be compared with those obtained from Alloy No. 1, in all respects similar as regards physical treatment and

* Proceedings, The Institution of Civil Engineers, vol. clxvi., 1906, page 78.

composition, except that it contains 0.10 per cent. of aluminium and 99.86 per cent. of copper—

4.4

14.18

62.0

92.52

The tenacities are the same, but the ductility of No. 1 is very much superior. The effect of this small percentage of aluminium is equally well marked in torsion (pages 189-190) and electrical-conductivity tests (page 221).

TABLE 29.

Bars rolled to $\frac{13}{16}$ inch diameter.

Diameter . . .	0.564 inch.	} (Standard size.)
Gauge length . . .	4.5 inches.	
Parallel portion	5.0 inches.	

Alloy No.	Aluminium.	Ultimate Stress.	Elongation.	Reduction of Area.
	Per cent.	Tons per sq. in.	Per cent.	Per cent.
1	0.10	14.24	55.55	90.81
2	1.06	15.70	51.11	88.66
3	2.10	17.38	48.00	88.61
4	2.99	19.33	53.78	87.48
5	4.05	23.47	62.22	83.51
6	5.07	26.17	61.78	78.76
7	5.76	28.15	61.33	77.82
8	6.73	28.93	60.90	75.46
9	7.35	29.44	60.00	75.46
10	8.12	33.00	46.66	58.62
11	8.67	35.88	30.66	50.00
12	9.38	37.90	24.88	31.44
13	9.90	37.85	20.22	28.17

The tensile tests of bars of standard dimensions are given in Table 29 (page 139), and are shown graphically in Fig. 19.

STRESS-STRAIN DIAGRAMS.

These were taken chiefly on account of the uncertainty which has hitherto prevailed with reference to the question whether

FIG. 19.

*Tensile Tests on Bars rolled to $\frac{1}{8}$ inch diameter. Turned to 0.564 diameter.
5.0 inches parallel.
(Length 9 times the diameter.)*

aluminium - copper alloys possess a true yield - point. The dimensions of the bars tested were the following:—

Diameter	.	.	.	.	0.564 inch.
Parallel portion	.	.	.	.	10.5 inches.
Gauge length	.	.	.	.	8.0 inches.

FIG. 20.—*Stress-Strain Diagrams, Rolled Bars $\frac{1}{8}$ inch diameter.*

The dotted line shows the yield-points.

The 8-inch gauge length was divided into inches, and the extensions on these were subsequently measured. The stress-strain diagrams are reproduced in Fig. 20 (page 141). Increasing aluminium has been plotted from right to left as the curves overlap one another only slightly and are clearly seen in this way. The dotted line

FIG. 21.

Tensile Tests on Bars rolled to $\frac{1}{8}$ inch diameter.

10.5 inches parallel.

(Length 9 times the diameter.)

shows the yield-points. Up to 9 per cent. of aluminium the yield-points are clearly seen. They are less clear in the case of the harder alloys between 9 and 10 per cent. The yield-points read from these diagrams are included in Table 30 and Fig. 21. Some difficulty was experienced with the harder alloys Nos. 11 to 13, which showed a tendency to break outside the gauge-length where a change of section occurred.

TABLE 30.

Bars $\frac{13}{16}$ inch diameter.

Diameter . . .	0.564 inch.
Parallel portion . .	10.5 inches.
Gauge length . . .	8.0 inches.

Alloy No.	Aluminium.	Yield-Point.	Ultimate Stress.	Elongation.	Reduction of Area.
	Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
1	0.10	6.0	14.01	48.25	92.00
2	1.06	5.5	15.25	44.00	90.00
3	2.10	8.0	16.86	43.00	90.00
4	2.99	11.5	19.25	44.75	87.60
5	4.05	11.5	22.97	53.12	84.86
6	5.07	9.8	25.56	59.62	80.48
7	5.76	11.4	27.78	55.25	78.71
8	6.73	10.0	28.45	55.37	75.10
9	7.35	10.4	29.00	60.75	76.83
10	8.12	15.5	32.87	42.00	52.52
11	8.67	20.0	35.72	23.75	49.40
12	9.38	16.2	36.86	23.00	47.20
13*	9.90	14.0	37.34	14.50	20.32

* This specimen broke near the head, and the values are slightly low.

Photograph Fig. 162, Plate 20, shows the fractured bars with the gauge-marks. The marked drop of local contraction at 8 per cent. is well seen; also the variations in elongation caused by the addition of aluminium up to 10 per cent. Fig. 22 (pages 144-145) shows the percentage elongations on each of the 8 inches. The local

FIG. 22.—*Rich Copper Alloys.*
Percentage Elongations on each of the 8 inches. (See Plate 20.)

FIG. 22.—*Rich Copper Alloys.*
Percentage Elongation on each of the 8 inches. (See Plate 20.)

contractions at fracture have been brought into the same space except for Nos. 12 and 13 where they are very slight.

TABLE 31.

Alloy No.	Yield-Points. Tons per square inch.		Difference. $b-a$
	(a) Diagrams.	(b) Dividers.	
1	6.0	6.9	+ 0.9
2	5.5	6.9	+ 1.4
3	8.0	8.6	+ 0.6
4	11.5	11.6	+ 0.1
5	11.5	11.3	- 0.2
6	9.8	11.4	+ 1.6
7	11.4	11.8	+ 0.4
8	10.0	10.4	+ 0.4
9	10.4	10.6	+ 0.2
10	15.5	13.0	- 2.5
11	20.0	11.1	- 8.9
12	16.2	17.7	+ 1.5
13	14.0	14.8	+ 0.8

Table 31 enables a comparison of the yield-stresses of bars Nos. 1 to 13 to be made as measured.

(a) By reading the stress-strain diagrams of 8-inch lengths.

(b) By noting the first permanent set on a 2-inch length by means of dividers.

It was to be expected that the values in column (a) would be lower than those in (b), as the diagram method was the more delicate. This is the case in ten out of the thirteen alloys. The agreement is sufficiently good in all cases except Alloys Nos. 10 and 11, especially the latter.

The uniformity of the bars used in this research is well shown in Table 32, which gives the ultimate stresses obtained by testing $2\frac{1}{4}$, 5 and $10\frac{1}{2}$ -inch lengths.

TABLE 32.

Alloy No.	Ultimate Stresses. Tons per square inch.		
	$2\frac{1}{4}$ -inch length.	5-inch length.	$10\frac{1}{2}$ -inch length.
1	14.50	14.24	14.01
2	15.88	15.70	15.25
3	17.46	17.38	16.86
4	19.79	19.33	19.25
5	23.80	23.47	22.97
6	26.41	26.17	25.56
7	28.40	28.15	27.78
8	28.85	28.93	28.45
9	29.68	29.44	29.00
10	33.22	33.00	32.87
11	36.67	35.88	35.72
12	38.00	37.90	36.86
13	38.10	37.85	37.34

As was to be expected, the tenacities decrease as the lengths tested increase. The 5-inch length of Alloy No. 8 is the only exception. Its tenacity is very slightly higher than that of the $2\frac{1}{4}$ -inch length. In all other cases the variations are remarkably uniform.

Tensile-Stress Tests. (B.)—In this section the influences of the kind of casting, of mechanical work, and of thermal treatment on the properties of each particular alloy, are rendered evident.

TABLE 33.

Alloy No. 1. (Aluminium 0·10 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	3·8	11·50	46·0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	4·2	11·34	40·0	—
Sand casting, quenched from 800° C.	2·9	10·67	40·0	—
Chill casting	4·1	11·53	46·0	—
Chill casting, slowly cooled from 800° C.	4·9	11·07	44·0	—
Chill casting, quenched from 800° C.	4·0	11·30	47·5	—
Rolled bar $\frac{1}{8}$ inch diameter	6·9	14·50	65·5	90·71
Rolled bar $\frac{1}{8}$ inch diameter, slowly cooled from 800° C.	4·4	14·19	62·0	92·52
Rolled bar, quenched from 800° C.	4·4	14·05	65·0	91·80

TABLE 34.

Alloy No. 2. (Aluminium 1.06 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	3.0	13.4	52.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3.2	12.9	46.0	—
Chill casting	5.2	11.8	53.0	—
Chill casting, slowly cooled from 800° C.	4.5	12.9	57.0	—
Chill casting, quenched from 800° C.	—	12.6	53.5	—
Rolled bar 1½ inches diameter	6.7	15.65	59.0	90.85
Rolled bar 1⅜ inch diameter	6.9	15.88	61.0	88.63
Rolled bar 1⅜ inch diameter, slowly cooled from 800° C.	4.4	15.22	67.0	91.87
Rolled bar 1⅜ inch diameter, quenched from 800° C. .	4.3	15.39	63.5	90.76
Cold drawn bar 1⅜ inch diameter	17.3	18.1	42.0	88.75

TABLE 35.

Alloy No. 3. (Aluminium 2·10 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	3·4	13·5	53·5	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3·5	14·0	46·5	—
Sand casting, quenched from 800° C.	4·3	14·0	47·0	—
Chill casting	4·5	13·7	54·5	—
Chill casting, slowly cooled from 800° C.	4·8	13·9	56·0	—
Chill casting, quenched from 800° C.	4·3	13·9	55·0	—
Rolled bar $1\frac{1}{4}$ inches diameter	6·4	17·22	61·0	90·03
Rolled bar $1\frac{3}{8}$ inch diameter	8·6	17·46	56·5	89·65
Rolled bar $1\frac{3}{8}$ inch diameter, slowly cooled from 800° C.	4·4	16·60	66·0	90·00
Rolled bar $1\frac{3}{8}$ inch diameter, quenched from 800 C.	4·3	16·77	63·5	88·80

TABLE 36.

Alloy No. 4. (Aluminium 2.99 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	3.8	14.5	60.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3.7	14.8	60.5	—
Sand casting, quenched from 800° C.	4.9	14.8	58.5	—
Chill casting	6.8	13.8	60.0	—
Chill casting, slowly cooled from 800° C.	4.4	14.6	73.0	—
Chill casting, quenched from 800° C.	4.7	14.9	53.0	—
Rolled bar 1½ inches diameter	7.9	18.98	67.0	88.81
Rolled bar 1⅜ inch diameter	11.6	19.79	57.25	86.11
Rolled bar 1⅜ inch diameter, slowly cooled from 800° C.	4.8	18.00	73.0	90.0
Rolled bar 1⅜ inch diameter, quenched from 800° C. .	5.5	18.11	69.0	88.8
Cold-drawn bar 1⅜ inch diameter	21.0	22.26	44.0	86.05

TABLE 37.

Alloy No. 5. (Aluminium 4.05 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	3.5	16.7	83.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3.9	17.0	68.5	—
Sand casting, quenched from 800° C.	5.0	16.5	60.0	—
Chill casting	4.9	17.1	82.0	—
Chill casting, slowly cooled from 800° C.	4.3	16.4	89.0	—
Chill casting, quenched from 800° C.	5.1	17.7	81.0	—
Rolled bar $1\frac{1}{2}$ inches diameter	7.3	21.93	71.0	81.83
Rolled bar $1\frac{3}{8}$ inch diameter	11.3	23.80	67.0	83.27
Rolled bar $1\frac{3}{8}$ inch diameter, slowly cooled from 800° C.	6.1	21.50	73.0	85.65
Rolled bar $1\frac{3}{8}$ inch diameter, quenched from 800° C. .	6.4	21.29	79.0	84.80

TABLE 38.
Alloy No. 6. (*Aluminium 5.07 per cent.*)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	4.3	18.1	75.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3.6	18.8	65.5	—
Sand casting, quenched from 800° C.	5.0	18.6	66.5	—
Chill casting	7.1	18.1	60.5	—
Chill casting, slowly cooled from 800° C.	5.1	18.0	61.0	—
Chill casting, quenched from 800° C.	5.7	19.1	80.0	—
Rolled bar 1½ inches diameter	6.8	24.54	79.0	77.0
Rolled bar 1⅝ inch diameter	11.4	26.41	69.2	77.8
Rolled bar 1⅝ inch diameter, slowly cooled from 800° C.	5.2	23.65	79.0	82.0
Rolled bar 1⅝ inch diameter, quenched from 800° C. .	6.2	23.57	83.0	78.8
Cold drawn bar 1⅝ inch diameter *	23.8	30.43	—	—

* This specimen split owing to its containing pipe.

TABLE 39.

Alloy No. 7. (Aluminium 5.76 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	4.8	17.8	67.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	3.8	19.4	65.0	—
Sand casting, quenched from 800° C.	5.4	18.1	52.5	—
Chill casting	6.0	18.8	61.0	—
Chill casting, slowly cooled from 800° C.	5.6	19.5	74.0	—
Chill casting, quenched from 800° C.	8.2	20.5	49.0	—
Rolled bar $\frac{1}{8}$ inch diameter	11.8	28.40	74.2	76.93
Rolled bar $\frac{1}{8}$ inch diameter, slowly cooled from 800° C.	7.9	26.60	77.5	70.95
Rolled bar $\frac{1}{8}$ inch diameter, quenched from 800° C. .	6.9	24.94	84.5	75.60

TABLE 40.

Alloy No. 8. (Aluminium 6.73 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	4.8	18.65	—	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	4.8	18.82	64.0	—
Sand casting, quenched from 800° C.	6.3	19.90	51.0	—
Chill casting	—	19.96	69.0	—
Chill casting, quenched from 800° C.	5.2	18.90	42.0	—
Rolled bar $1\frac{1}{4}$ inches diameter	7.5	26.17	82.0	75.37
Rolled bar $1\frac{3}{8}$ inch diameter	10.4	28.85	71.0	75.02
Rolled bar $1\frac{3}{8}$ inch diameter, slowly cooled from 800° C.	7.1	26.50	82.5	73.5
Rolled bar $1\frac{3}{8}$ inch diameter, quenched from 800° C. .	7.4	25.46	83.0	72.0

TABLE 41.

Alloy No. 9. (Aluminium 7·35 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	6·6	21·30	71·0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	5·9	20·1	81·0	—
Sand casting, quenched from 800° C.	6·7	20·0	70·0	—
Chill casting	—	21·58	84·0	—
Chill casting, slowly cooled from 800° C.	6·0	20·2	80·0	—
Chill casting, quenched from 800° C.	7·3	19·8	79·0	—
Rolled bar $1\frac{1}{2}$ inches diameter	9·3	27·42	80·0	75·27
Rolled bar $\frac{1}{4}$ inch diameter	10·6	29·68	72·5	74·34
Rolled bar $\frac{1}{4}$ inch diameter, slowly cooled from 800° C.	7·4	25·41	80·5	74·83
Rolled bar $\frac{1}{4}$ inch diameter, quenched from 800° C. .	8·0	25·51	82·0	74·80
Cold-drawn bar $\frac{1}{4}$ inch diameter	24·6	31·42	48·0	58·79

TABLE 42.

Alloy No. 10. (Aluminium 8·12 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	7·7	24·91	58·0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	6·9	22·15	69·0	—
Sand casting, quenched from 800° C.	7·9	26·00	62·5	—
Chill casting	9·7	27·47	62·0	—
Chill casting, slowly cooled from 800° C.	7·3	22·23	59·0	—
Chill casting, quenched from 800° C.	8·4	24·94	61·0	—
Rolled bar 1½ inches diameter	9·8	30·88	70·0	64·47
Rolled bar 1⅜ inch diameter	13·0	33·22	51·5	60·40
Rolled bar 1⅜ inch diameter, slowly cooled from 800° C.	8·1	27·30	80·0	70·00
Rolled bar 1⅜ inch diameter, quenched from 800° C. .	7·5	28·41	74·0	69·26

TABLE 43.

Alloy No. 11. (Aluminium 8.67 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	9.8	28.1	48.0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	8.8	23.5	48.0	—
Sand casting, quenched from 800° C.	11.7	30.7	35.0	—
Chill casting	—	30.80	55.0	—
Chill casting, slowly cooled from 800° C.	8.8	27.10	63.0	—
Chill casting, quenched from 800° C.	9.7	29.80	54.0	—
Rolled bar $\frac{1\frac{1}{8}}$ inch diameter	11.1	36.67	38.0	50.66
Rolled bar $\frac{1\frac{1}{8}}$ inch diameter, slowly cooled from 800° C.	11.4	30.04	65.0	64.90
Rolled bar $\frac{1\frac{1}{8}}$ inch diameter, quenched from 800° C. .	12.6	34.94	51.0	59.60

TABLE 44.

Alloy No. 12. (Aluminium 9·38 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	9·7	30·38	36·25	47·20
Sand casting, slowly cooled from 900° C. (1,652° F.) .	10·7	23·41	17·25	31·92
Sand casting, quenched from 800° C. (1,472° F.) . .	20·8	38·16	9·50	20·00
Chill casting	10·5	33·98	43·50	50·00
Chill casting, slowly cooled from 800° C.	11·3	27·46	27·00	30·52
Chill casting, quenched from 800° C.	18·7	35·59	28·00	46·31
Rolled bar 1½ inches diameter	14·8	37·34	40·00	41·37
Rolled bar 1⅜ inch diameter	17·7	38·00	34·00	33·60
Rolled bar 1⅜ inch diameter, quenched from 800° C. .	19·1	39·01	32·00	42·66
Cold-drawn bar 1⅜ inch diameter	29·0	38·83	32·00	46·31

TABLE 45.

Alloy No. 13. (Aluminium 9·90 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	11·3	31·70	21·7	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	13·3	Not obtainable. The bar broke in the head.		
Sand casting, quenched from 800° C.	22·4	50·00	3·0	—
Chill casting	12·4	36·93	30·5	—
Chill casting, slowly cooled from 800° C.	16·5	26·40	5·0	—
Chill casting, quenched from 800° C.	17·7	38·57	22·0	—
Rolled bar 1½ inches diameter	13·6	35·03	31·5	30·52
Rolled bar 1⅝ inch diameter	14·8	38·10	28·8	30·80
Rolled bar 1⅞ inch diameter, slowly cooled from 800° C.	15·7	28·51	6·5	10·20
Rolled bar 1⅞ inch diameter, quenched from 800° C. .	26·2	45·48	11·0	16·78
Cold-drawn bar 1⅞ inch diameter	40·4	43·94	13·0	22·19

TABLE 46.

Alloy No. 14. (Aluminium 10·78 per cent.)

Condition.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Sand casting	14·1	29·52	9·0	—
Sand casting, slowly cooled from 800° C. (1,472° F.) .	27·0	29·21	2·0	—
Sand casting, quenched from 800° C.	29·7	35·45	2·5	—
Chill casting	16·9	36·73	9·0	—
Chill casting, slowly cooled from 800° C.	23·6	28·72	0·0	—
Chill casting, quenched from 800° C.	26·7	32·36	3·0	—
Rolled bar 1½ inches diameter	18·0	35·00	12·5	12·07
Rolled bar 1⅜ inch diameter	15·4	38·62	14·0	18·6
Rolled bar 1⅜ inch diameter, slowly cooled from 800° C.	18·5	30·87	1·5	4·0
Rolled bar 1⅜ inch diameter, quenched from 800° C. .	12·0	36·11	5·0	13·32

Tables of Alloys Nos. 15 and 16 have been omitted, as their properties do not appear to indicate any possibility of industrial application. A feature of the greatest interest is brought out by the preceding method of presenting the results of the mechanical tests. A study of Tables 33 to 44 shows that, up to 9.4 per cent. of aluminium, the ultimate stress of the rolled bar $\frac{1\frac{3}{8}}$ inch diameter (untreated) is always higher than that of the chill casting (untreated). (As previously pointed out, the tenacity of the chill is usually superior to that of the sand casting.) The amount varies between 3 and 10 tons per square inch. In Table 45 (page 160), however (Alloy No. 13), it will be noticed that the chill casting has a tenacity of 37 tons per square inch and an extension of 30.5 per cent. as against the 38 tons and 29 per cent. extension of the rolled bar. These properties are practically identical. Further, the tenacity of the chill is 2 tons higher than that of the rolled bar $1\frac{1}{4}$ inches diameter. This must be regarded as an astonishing result. The authors have searched for a parallel among other known alloys, but without success. So far as they are aware, it is a unique exception to the view generally held that rolled is superior to cast material.

Alloy No. 14 presents a very similar case. The chill casting is 1.73 tons better than the $1\frac{1}{4}$ -inch diameter bar, but it is nearly 2 tons worse than the rolled bar $\frac{1\frac{3}{8}}$ inch diameter, and its extension is 5 per cent. lower.

That the long-known aluminium-bronze or aluminium-gold, containing 10 per cent. of aluminium, should be as strong and as ductile when cast in chill (1 inch diameter) as when rolled from a 3-inch diameter billet down to $\frac{1\frac{3}{8}}$ inch, appeared to the authors to be of such importance, both practically and theoretically, that they have confirmed it by making and testing other casts and bars, and by having the results checked by an independent worker. Their own results are given in Table 47 (page 163).

Nos. 2 and 5 are from the same cast. The remainder represent different melts. Nos. 1-5 were made from electrolytic, No. 6 from Lake copper.

At the authors' request Mr. L. Sumner undertook to repeat the experiments at the Broughton Copper Works. Two castings in

TABLE 47.

Condition.	Aluminium.	Ultimate Stress.	Elongation on 2 inches.	No.
	Per cent.	Tons per sq. in.	Per cent.	
Cast Chill . .	9.87	36.9	30.0	1
„ . .	9.90	36.9	30.5	2
„ . .	9.96	37.3	31.5	3
„ . .	10.04	37.0	31.5	4
Rolled Bar $\frac{1}{8}$ in.	9.90	38.1	28.8	5
„ „	9.95	37.3	31.0	6

chill moulds were made. They were 12 inches long and $1\frac{3}{4}$ inches diameter. The castings were thus somewhat larger than those made by the authors. The results obtained were:—

No.	Ultimate Stress.	Elongation on 2 inches.
	Tons per square inch.	Per cent.
1	35.48	30.0
2	34.46	40.0

These figures do not agree with one another as closely as those obtained by the authors. The mean is about 35 tons and 35 per cent. elongation. The material has rather less tenacity but more ductility. This is not surprising in view of the fact that the casting represented 29 cubic inches of metal as against the authors' 5.5, and therefore cooled more slowly. These results constitute a satisfactory check on those of the authors, *but the identity of mechanical properties of the $\frac{1}{8}$ -inch bar and the chill casting only holds strictly for a small casting.*

In seeking for an explanation of this result, it was found that the structures of the chill casting and $\frac{1}{8}$ -inch rolled bar were very similar. These are shown in photo-micrographs, Figs 70 and 71,

Plate 4 (magnified 120 diameters). Each alloy consists of a light and dark structural constituent. These are well mixed, and the crystals average about the same size in each. This fact suggested the following explanation:—The effect of casting in a chill mould is to preserve the two structural constituents in that degree of intermixture which is also brought about by the rolling of an ingot 3 inches diameter down to $\frac{1}{8}$ inch. Consequently, it is only natural that the two materials should give the same results on testing. That this view does not constitute an explanation was however shown by the following observations:—The structures of three sand castings were examined which had given very closely-agreeing ultimate stresses during the preliminary experiments on the effect of remelting this alloy (page 91). These are shown in photo-micrographs, Figs. 81–83, Plate 6. It will be noticed that with each successive cast the size of the crystals increases. Thus the tenacity in these cases seems to be, within those limits, independent of the size and degree of intermixture of the crystals.

The observation that after each remelt the size of the crystals increases is, they think, new. (The rate of cooling was approximately the same in the three cases.) The following view as to the crystal growth is put forward tentatively. After the first cast the crystals attain a certain size on cooling. When the alloy is remelted it is exposed to temperatures of the order of $1,000^{\circ}$ C. ($1,832^{\circ}$ F.) for some time previously to its actually becoming fluid. During this period recrystallization takes place and the crystals grow. This is a conclusion that might have been drawn from the known behaviour of metals and alloys under these conditions, but it has been shown to be true in this particular case (photo-micrographs, Figs. 81–83, Plate 6). When the alloy finally melts, these crystals *persist* as “liquid crystals” during the range of temperature reached in these experiments. After the alloy has been poured a second time these solidify and continue to grow on cooling. The same cycle occurs during the second reheat, remelt, and recast, and thus the crystal growth would be accounted for.

The conception of “liquid crystals” and “crystalline liquids,” although novel in its application to metals, is by no means new. In

1888 the German chemist, Herr Reinitzer, noticed that Cholesterine benzoate melted at 145.5° C., yielding a turbid liquid. This clarified sharply at 178.5° C. Herr Reinitzer, thinking that it was a case of isomerism, entrusted the microscopic study to Herr Lehmann, who made the following unexpected discovery, namely, that the turbid liquid was doubly refracting, and that this disappeared at the moment of clarification. Since then other chemical compounds have been shown to possess similar properties, and numerous researches have been carried out, more particularly by Messrs. Lehmann and Schenck. The former has used the microscope as his chief weapon of experimental attack; the latter has made numerous measurements of physical constants.

That the new conceptions which have arisen from these researches have an important bearing on certain unexplained phenomena exhibited by metals is shown by the fact that Mons. A. Le Chatelier has included, both an editorial note on and an abstract of recent literature in this field by Mons. Etienne, in the "*Revue de Métallurgie*," March 1906. The following is a free translation of the editorial note:—

"The discovery of crystalline liquids made by Messrs. Lehmann and Schenck about ten years ago has aroused a lively interest among chemists, and their discussions are not yet closed. The facts observed are as follows: Certain organic chemical compounds liquefy at a well-defined temperature but preserve a certain opalescence; then, at a higher temperature equally well defined, the liquid clarifies. These two transformations are accompanied by calorific phenomena just as in changes of state. The opalescent liquids no longer present a crystalline outline; a drop suspended in a liquid of the same density takes an exactly spherical form, but when examined by polarised light it is strongly doubly-refracting, thus leaving no doubt as to the existence of a systematic orientation of its material, i.e. of that which is called the crystalline state.

"More recently a class of crystalline substances has been discovered intermediate between liquid crystals and solid crystals, *e.g.* among the alkaline oleates, especially that of ammonium. The phenomena observed are of extreme interest from the point of view of the study

of metals, by reason of certain analogies which would not have been suspected *a priori*.

"The crystals of ammonium oleate have well-defined geometrical forms. They are however very soft, the least pressure of the finger breaks them; the contact with a gas-bubble in the liquid where they are formed suffices to deform them completely; they surround it and take its shape, forming a veritable envelope. If two similarly oriented crystals touch one another they gradually coalesce to form a larger crystal, in which the orientation is the same at all points. Even deformed crystals are shown by examination in polarised light to preserve a constant orientation.

"These are exactly the same phenomena as have long been recognised as occurring among metals, but the precise observation of which is less easy on account of the impossibility of employing polarised light. Each metal annealed at a particular temperature, zinc at about 150° C., copper and silver at about 700° , iron at about $1,200^{\circ}$ C., shows a considerable growth of crystalline grain, *i.e.* several grains of different orientations coalesce to a single grain of the same orientation, exactly like the small crystals of ammonium oleate. Moreover, according to the experiments of Ewing and Rosenhain, where a metal is deformed, each of the crystalline grains elongates, but the orientation from one point to another of the same grain remains identical; all that is necessary to produce this deformation is a greater stress than in the case of ammonium oleate."

The authors venture to think that their observations as to the growth of the crystals of Alloy No. 13, with successive remeltings, may constitute evidence that when crystalline metals and alloys pass from the solid into the liquid state they do not forthwith lose their crystalline character; that although the chief external attribute of the crystal, namely, form, is lost, yet the essence remains in the shape of a systematic orientation of its material; that the crystal units persist in what is probably a very mobile condition, at any rate for a certain range of temperature above the melting-point. It is hardly necessary to point out that the weapons of experimental attack will have to be different from those employed in the investigation of organic chemical compounds of low melting-point and high

transparency. The authors have not developed this side of the work in the present Report, but they hope to take it up in the near future.

Comparison of Alloys prepared from "Cathode" and "Lake" Copper.—This has been made for one alloy in each class, namely, No. 9 in class 1 and No. 13 in class 2.

Tensile-stress tests have been carried out on bars both of $1\frac{1}{4}$ inches and $\frac{1}{8}$ inch diameter.

TABLE 48.

Quality.	Aluminium.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
	Per cent.	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.
Cathode $1\frac{1}{4}$ -inch bar	7.35	9.3	27.42	80.0	75.27
Lake $1\frac{1}{4}$ -inch bar	7.35	10.0	28.74	79.0	70.42
Cathode $\frac{1}{8}$ -inch bar	7.35	10.6	29.68	72.5	74.34
Lake $\frac{1}{8}$ -inch bar	7.35	12.0	28.36	75.0	77.10
Cathode $1\frac{1}{4}$ -inch bar	9.90	13.6	35.03	31.5	30.52
Lake $1\frac{1}{4}$ -inch bar	9.95	13.3	36.30	27.0	24.0
Cathode $\frac{1}{8}$ -inch bar	9.90	14.8	38.10	28.8	30.80
Lake $\frac{1}{8}$ -inch bar	9.95	14.5	37.14	25.5	28.79

The tenacities of corresponding bars are seen to be almost identical, but the ductilities of the alloys made from cathode copper are slightly superior. Broadly speaking, there is nothing to choose between alloys made from the two kinds of copper.

The Structures of the Alloys.—Although the results of further tensile-stress tests have still to be described, they cannot be adequately treated without reference to the structures of the alloys.

The technique of the preparation of the specimens does not call

for special mention, except that the following reagent has been found to give the best services for microscopic examination:—

4 parts of a solution of ferric chloride in water (1 to 12).
1 part concentrated hydrochloric acid.

A magnification of 120 diameters has been found convenient for the majority of the photo-micrographs. Unless otherwise stated the illumination is vertical and the enlargement 120 diameters.

Photo-micrographs of each alloy in the form of (a) a sand casting, (b) a chill casting, and (c) a rolled bar $\frac{1}{8}$ inch diameter have been taken. The crystals are largest in the sand casting (which has cooled the slowest of the three). In certain cases there is remarkable similarity between the structures of the chill casting and rolled bar.

Up to certainly 7.35 per cent. the addition of aluminium to copper does not cause the separation of a second structural constituent. The two metals form a solid solution; it is therefore unnecessary to reproduce more than one set of typical structures. These are shown in Figs. 56, 57 and 58, Plate 2. Fig. 56 shows part of a large crystal in the sand casting on which a rectangular pattern has been etched out. Fig. 57 shows a crystal of the chill casting, while Fig. 58 shows how rolling breaks up the crystals. In this class the crystals of the sand casting are the largest, those of the rolled bar much the smallest of the three types. With the gradual addition of aluminium up to 7.35 per cent. the colour of the crystals changes from red to pale gold.

At 8.12 per cent. of aluminium a dark structural constituent makes its appearance, Figs. 60, 61 and 62, Plate 3. In the slowly cooled sand casting this coalesces to a few comparatively large dark patches here and there; in the chill casting and rolled bar it is more profusely distributed, but in very small patches. The further addition of aluminium causes an increase in the dark constituent until, at 10.78 per cent., it predominates, Figs. 63 to 74, Plates 3 to 5. At 11.73 per cent. the pale gold crystals disappear completely and the structure is wholly acicular, Figs. 75-77, Plate 5. This is well seen in all three conditions at 120 diameters, but is particularly well developed in the sand casting. The acicular

structure does not make its appearance suddenly at this percentage. It can be seen in Fig. 74 (10.78 per cent. rolled bar). It is also present in Alloy No. 13 with 9.9 per cent. of aluminium, but is much less clear. A higher magnification than 120 diameters is required to resolve the dark patches. Fig. 59, Plate 2, shows that at 800 diameters they are viewed as an indistinct dark acicular mass. At 13 per cent. of aluminium there is another change, and a duplex structure is seen, Figs. 78 to 80, Plate 6.

These structures throw considerable light on the classification of the alloys into two chief classes under the mechanical tests. Up to 7.35 per cent. of aluminium the alloys consist of ductile crystals of a solid solution. Heat treatment affects the size of the crystals to some extent, but does not cause profound structural changes as in the case of alloys containing from 9-11 per cent. of aluminium. Its influence on mechanical properties is not very far-reaching. On the other hand, the crystals are very much broken up by rolling, and are interlocked into a tougher combination than the cast material.

The sudden stiffening of the alloys beyond 8 per cent. of aluminium coincides with the appearance of the dark structural constituent, which has been shown by microscopic examination to be acicular. Instances of the association of brittleness with an acicular structure are well known. At 11.73 per cent., where the structure is wholly acicular, the alloy has only slight ductility.

Tensile-Stress Tests of Quenched Bars.—The experiments detailed on page 131, etc., show that up to 8 per cent. of aluminium the alloys, although not strictly indifferent to heat treatment, are not improved but in most cases somewhat deteriorated by it. On the other hand, from 8.67 to 10 per cent. the alloys are very sensitive to heat treatment, and as their mechanical properties present possibilities of usefulness, further experiments were decided upon.

The tests with the castings of Alloy No. 13 showed how important it is that the size of the specimens should be alike in the comparative tests. Thus the sand casting quenched from 800° C. (1,472° F.) gave 50 tons per square inch ultimate stress and 3 per cent. extension, whereas the chill casting gave 38.5 tons and 22 per

cent. extension. The volume of the latter was about four times that of the former, and it exposed relatively less surface to the quenching bath. Consequently the rate of chilling was much less.

Table 49 contains the results obtained with rolled bars ($\frac{1\frac{3}{8}}$ inch) of Alloy No. 11. They are shown graphically in Fig. 23.

TABLE 49.

Alloy No. 11. (Aluminium 8.67 per cent.)

Shape of Specimen quenched { Bar $4\frac{1}{2}$ inches long; diameter $\frac{3}{8}$ inch, turned
down to $\frac{1}{2}$ inch over $2\frac{1}{4}$ inches in the centre.
Volume of Specimen quenched . . . 1.43 cubic inches.

Quenching Temperature.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.
600° C. (1,112° F.)	Tons per sq. in. 37.82	Per cent. 48.0	Per cent. 61.22
700° C. (1,292° F.)	35.14	54.0	66.66
800° C. (1,472° F.)	34.94	51.0	59.60
900° C. (1,652° F.)	39.22	40.0	51.70

This alloy was only slightly affected by this treatment.

Table 50 and Fig. 24 (page 171) give the results obtained with Alloy No. 12.

TABLE 50.

Alloy No. 12. (Aluminium 9.38 per cent.)

Shape of Specimen quenched . Bar $4\frac{1}{2}$ inches long; $\frac{1\frac{3}{8}}$ inch diameter.
Volume of Specimen quenched . . . 2.33 cubic inches.

Quenching Temperature.	Yield-Point.	Ultimate Stress.	Elongation on 2 inches.	Reduction of Area.	Elastic Ratio.
	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.	
600° C. (1,112° F.)	15.9	38.97	38.5	50.79	0.41
700° C. (1,292° F.)	16.6	38.51	35.5	42.86	0.43
800° C. (1,472° F.)	19.1	39.01	32.0	42.66	0.49
900° C. (1,652° F.)	18.5	42.38	25.5	39.33	0.44

QUENCHING EXPERIMENTS ON BARS.

FIG. 23.—Alloy No. 11.

(Cu 91.28%, Al 8.67%.)

Volume of specimens quenched 1.43 cubic ins.

FIG. 24.—Alloy No. 12.

(Cu 90.58%, Al 9.38%.)

Volume = 2.33 cubic inches.

FIG. 25.—Alloy No. 13.

(Cu 90.06%, Al 9.90%.)

Volume = 5.5 cubic inches.

This alloy shows a slight progressive stiffening the higher the quenching temperature. The elastic ratio comes out at the fair average of 0.44. The structures of specimens quenched at 600° C. (1,112° F.) and 700° C. (1,292° F.), cut from the end of the bars tested, were found to be unaffected. Fig. 68, Plate 4, is typical of them. At 800° C. (1,472° F.), however, the light-coloured has begun to be absorbed by the dark-coloured constituent, Fig. 84, Plate 7, while at 900° C. (1,652° F.) solution has proceeded still further, and the structure is markedly acicular in parts, Fig. 85

Quenching Experiments with Alloy No. 13 (Aluminium 9.90 per cent.).—Three sets of tests were carried out at temperatures varying from 600°–900° C.

Set A. Chill castings 7 inches by 1 inch were used. The volume was 5.5 cubic inches and the weight about 1.49 lb.

Set B. Rolled bars, 5½ inches by ½ inch were used. The volume was 2.85 cubic inches, and the weight about 0.77 lb.

Set C. Rolled bars were used 4½ inches long, of diameter ¾ inch, turned down to ½ inch over 2¼ inches in the centre. The volume was 1.43 cubic inches, and the weight 0.39 lb.

Thus the volumes were in the following proportions :—

$$C : B : A :: 1 : 2 : 4.$$

As the properties of the chill castings and rolled bars are the same, the results are directly comparable, and show the influence of mass on quenching this alloy.

The results are given in Table 51 (page 173), and are shown graphically in Figs. 25 to 28 (pages 171 and 174).

It will be observed that, when the volume of the specimen quenched was 5.5 cubic inches, its properties were hardly affected by quenching from temperatures up to 800° C. (1,472° F.), but that quenching from 900° C. (1,652° F.) stiffened it very considerably, the elastic ratio reaching 0.81.

When the volume was either 2.85 or 1.43 cubic inches there was very little stiffening below 800° C. At this temperature there

TABLE 51.
Alloy No. 13.

Quenching Temperature.	Set.	Volume.	Yield- Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.
		Cubic inches.	Tons per square inch.	Tons per square inch.		Per cent.	Per cent.
700° C. (1,292° F.)	A	5.5	12.7	38.13	0.33	25.0	32.0
800° C. (1,472° F.)	A	5.5	13.8	38.50	0.36	22.0	28.5
900° C. (1,652° F.)	A	5.5	36.6	45.00	0.81	3.0	10.81
600° C. (1,112° F.)	B	2.85	17.0	38.59	0.44	29.0	35.70
700° C.	B	2.85	15.6	37.14	0.42	20.5	27.01
800° C.	B	2.85	26.2	45.48	0.58	11.0	16.78
900° C.	B	2.85	41.8	54.20	0.77	2.5	7.00
600° C.	C	1.43	17.0	38.18	0.45	22.2	30.00
700° C.	C	1.43	18.1	39.76	0.46	15.4	20.60
800° C.	C	1.43	32.4	43.57	0.75	7.0	14.29
900° C.	C	1.43	39.8	51.51	0.77	3.0	4.83

QUENCHING EXPERIMENTS ON BARS.

FIG. 26.—Alloy No. 13.
(Cu 90.06%, Al 9.90%)
Volume of specimen quenched
= 2.85 cubic inches.

FIG. 27.—Alloy No. 13.
(Cu 90.06%, Al 9.90%)
Volume = 1.43 cubic inches.

FIG. 28.—Three Experiments
with Alloy No. 13.
Vol. of Specimens = 1.43,
2.85, and 5.5 cub. ins.

was a marked rise of tenacity and of elastic ratio. Except that at 800° C. the value of the elastic ratio was somewhat higher in set C than B, these two series have given very similar results. Attention may be drawn to set B at 900° C., where a yield-point of 42, an ultimate stress of 54 tons per square inch (elastic ratio 0.77), and a reduction of area of 7 per cent. were obtained.

An examination of specimens cut from the quenched bars in set C (before stressing) showed that up to 800° C. the light and dark structural constituents persisted (typical photo-micrograph, Fig. 71, Plate 4), but that at 900° C. the structure was wholly acicular, Fig. 111, Plate 10. (When small specimens are quenched at these temperatures structural changes begin to be manifested at 600° C. (1,112° F.) (page 213 and Plate 12).)

Experiments on the Recrystallization of the Alloys at High Temperatures.—These experiments were undertaken in order to test the extent of the recrystallization of the alloys at various temperatures and of changes of mechanical properties ensuing therefrom. Mons. A. Le Chatelier states * that the 9 per cent. aluminium bronze has,

at 15° C. (59° F.),	an ultimate stress of 25.4 tons per square inch.
117° C. (243° F.),	" " " " 20.3 " " "
180° C. (356° F.),	" " " " 10.8 " " "

and that the aluminium-bronzes cannot be used with safety at high temperatures. It has already been shown in the present research that a slow cooling of the 10 per cent. aluminium-bronze from 800° C. (1,472° F.) ruins both the chill and sand castings and the rolled bar (Table 45), the effect on the ductility being particularly fatal. It appeared from the quality of the fractures that these results were connected with recrystallization.

The alloys have been heated for one hour at the temperatures specified, cooled in a quickly cooling furnace, and afterwards tested at the ordinary temperature.

The following results, Table 52, have been obtained with Nos. 1 4, 7 and 9, which have been selected from Class 1 of the alloys.

* "Contribution à l'étude de la Fragilité dans les Fers et les Aciers," page 134.

TABLE 52.

Alloy No.	Aluminium.	Condition.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.
	Per cent.		Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.
1	0·10	Rolled, untreated	6·9	14·50	0·48	65·5	90·71
		Rolled, one hour at 600° C. (1,112° F.)	5·0	14·11	0·35	65·0	91·60
		Rolled, one hour at 900° C. (1,652° F.)	5·8	13·26	0·44	56·0	87·65
4	2·99	Rolled, untreated	11·6	19·79	0·59	57·25	86·11
		Rolled, one hour at 600° C. . . .	6·9	18·54	0·37	66·00	89·84
		Rolled, one hour at 900° C. . . .	5·8	19·76	0·30	82·5	83·60
7	5·76	Rolled, untreated	11·8	28·40	0·42	74·2	76·93
		Rolled, one hour at 600° C. . . .	9·4	27·20	0·33	77·0	75·00
		Rolled, one hour at 900° C. . . .	6·0	23·65	0·25	86·0	70·00
9	7·35	Rolled, untreated	10·6	29·68	0·36	72·5	74·34
		Rolled, one hour at 900° C. . . .	7·1	23·89	0·30	92·0	72·00

The values in Table 52 show that under this treatment the alloys are softened. The yield-points fall more rapidly than the ultimate stresses, and consequently the elastic ratio is lowered. The ductilities increase except in the case of No. 1, the rise being particularly marked in Nos. 4 and 9. No. 9 has an elongation of 92 per cent. after one hour's treatment at 900°C . ($1,652^{\circ}\text{F}$.).

Thus the alloys in this Class preserve good mechanical qualities, even after exposure for some time at high temperatures.

It is otherwise with the alloys in Class 2.

Alloy No. 13 was the most thoroughly tested of the series, on account of its sensitiveness to heat treatment. The results are given in Table 53 (page 178), and are shown graphically in Fig. 29, (page 179). They show that between 300° and 400°C . (572° and 752°F .) this alloy undergoes a profound change. Comparing the results, it will be seen that after treatment at 300°C . the properties are substantially the same as those of the bar as rolled, but that at 400°C . there is a rise of nearly 100 per cent. in the elastic ratio due to an increase in yield-point and decrease in ultimate stress. Most important of all, the ductility has dropped almost to nil. The fracture also is characteristically different. It is somewhat surprising that the microscope reveals no evidences of structural change in the alloy. The etched surface appears identical with that of the untreated bar. From 500° to 700° (932° to $1,292^{\circ}\text{F}$.) there is a slight return of ductility and the elastic ratio falls, both yield-points and ultimate stresses decreasing. At 800° and 900°C . ($1,472^{\circ}$ and $1,652^{\circ}\text{F}$.) there is a further loss of strength, and the fracture becomes coarsely crystalline. The etched surfaces of specimens heated in this range show considerable structural alterations, which are fully represented in Plate 8.

These results show that the properties of the 10 per cent. aluminium-bronze are most injuriously affected by heat treatment at even moderately low as well as high temperatures; 400°C . (752°F .) appears to be particularly fatal. This fact unfortunately limits the usefulness of this otherwise valuable alloy, and prevents its application to any moderate or high-temperature work. Time has not permitted the authors to carry out strength tests on this alloy at varying temperatures

TABLE 53.

Alloy No. 13. (9.90 per cent. of Aluminium.)

Treatment.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
Bar as rolled	14.8	38.10	0.39	28.8	30.80	{ Sound, pale gold, silky granular }	Slightly wavy.
Bar after being heated 1 hour at 300° C. (572° F.) }	14.6	38.04	0.38	27.0	33.06	{ Sound, pale gold, silky granular }	Slightly wavy.
Bar after being heated 1 hour at 400° C. (752° F.) }	23.4	31.69	0.74	2.5	2.86	{ Sound, dry - grey brown }	Smooth, no cracks.
Bar after being heated 1 hour at 500° C. (932° F.) }	20.5	31.08	0.60	9.5	13.11	{ Sound, dry - grey brown }	Smooth, no cracks.
Bar after being heated 1 hour at 600° C. (1,112° F.) }	15.7	31.74	0.50	9.0	14.50	{ Sound, dry - grey brown }	Smooth, no cracks.
Bar after being heated 1 hour at 700° C. (1,292° F.) }	15.1	31.85	0.48	9.0	11.25	{ Sound, dry - grey brown }	Smooth, no cracks.
Bar after being heated 1 hour at 800° C. (1,472° F.) }	12.7	26.23	0.48	13.5	21.60	{ Sound, pale gold, crystalline plates }	Slightly wavy, surface cracks.
Bar after being heated 1 hour at 900° C. (1,652° F.)	13.3	21.95	0.61	6.0	8.76	{ Sound, pale gold, very large plates }	Slightly wavy, surface cracks.

MECHANICAL PROPERTIES.

FIG. 29.—*Alloy No. 13.*
(Cu 90·06 per cent., Al 9·90 per cent.) after being heated for 1 hour at various temperatures.

The recrystallization experiments have mainly centred round the alloys containing from 8 to 13 per cent. of aluminium, more particularly those containing the dark structural constituent which appears beyond 8 per cent. Dr. L. Guillet* has investigated this material, and has come to the conclusion that it is either Cu_3Al or a solid solution. He found that on annealing an alloy containing about 8.1 per cent. of aluminium (and therefore only a small quantity of the dark constituent) for 4 hours at 800°C . ($1,472^\circ \text{F}$.), the light crystals grouped themselves in "polyhedra," while the dark crystals formed black lines across the specimen. The authors repeated this experiment with Alloy No. 10, containing exactly the same percentage of aluminium, and found that the dark constituent had almost disappeared. For the most part the etched surface appeared homogeneous, and consisted of irregularly shaped yellow polyhedra. Here and there traces of the dark constituent remained, and also evidences of a transition stage before its absorption by the yellow polyhedra. The untreated and treated bars are shown in Figs. 86 and 87, Plate 7. The two granular patches in Fig. 87 appear to be transition material.

The same experiment was made with No. 11 (aluminium 8.67 per cent.), containing more of the dark constituent. Structures of the untreated and treated specimens are shown in Figs. 88 and 89 respectively. It will be observed that the dark constituent has *entirely* disappeared. (The two parallel bars in the large light coloured crystal in Fig. 89 are not remnants of the dark constituent.)

The experiments with No. 12 showed that the dark constituent very nearly disappears under this treatment at 900°C . ($1,652^\circ \text{F}$.). Thus it appears that when the rate of cooling of these alloys is comparatively rapid, as in ordinary manufacture, a second structural constituent separates at about 8 per cent. of aluminium; but that if the alloys are kept for a few hours at 800° – 900°C . ($1,472^\circ$ – $1,652^\circ \text{F}$.) and cooled slowly, the second constituent does not separate until about 9.4 per cent. In all the cases examined the heat treatment at 900°C . causes a considerable increase in the size of the crystals.

* Revue de Métallurgie, 1905, pages 573, 574.

Thus, as ordinarily prepared, the commercial alloys at about 8 per cent. of aluminium are metastable substances. The slowly cooled alloys, which represent more nearly the stable condition, have no industrial value.

Alloys Nos. 13 and 14, which contain more of the dark than can be absorbed by the yellow constituent under the foregoing treatment, have been very exhaustively studied. Here also the alloys, as ordinarily prepared, are metastable substances. The authors think that, at any rate in the case of No. 14, they have obtained the material in the stable condition of chemical equilibrium. The plan adopted has been to maintain specimens at 900° C. (1,652° F.) for various periods, followed by *slow* cooling and finally by microscopic examination. Unless the same rate of cooling in all cases is adopted, the results lack uniformity.

*Experiments with Alloy No. 13 (Photo-micrographs, Plate 8).—*The structure of the rolled untreated bar is shown in Fig. 90. After 1–3 hours treatment the structure of the dark constituent becomes clearer. The patch in Fig. 91 is not typical, being considerably larger than the average, but is reproduced on account of the detail it presents. Part of it is acicular, part banded, and part honeycomb. The yellow constituent has not changed except to become larger. After 7 hours, Fig. 92, the acicular structure has disappeared. The banded and honeycomb structures remain. After 14 hours, Fig. 93, the honeycomb structure preponderates, and the yellow constituent has grown still larger. After 20 hours, Fig. 94, the relative growth of the yellow at the expense of the other constituent is very manifest. After 28 hours, Fig. 95, a stage is reached which, interpreted in the light of still more exhaustive tests with Alloy No. 14, seems to be the penultimate, and contains evidence of the final stage. In the centre of the photo-micrograph there is a brown (but not black) structureless patch, surrounded by a partly banded and partly honeycomb structure, which in its turn is surrounded by the yellow constituent (also structureless). The yellow and brown structureless constituents represent the final stage, while the banded and honeycomb structures represent transition material, which is being absorbed by the constituents referred to.

High magnification photographs of this series have been taken, but are omitted because those of No. 14 are sufficiently typical of them, and the number of photographs necessarily reproduced is very large.

Experiments with Alloy No. 14 (Photo-micrographs, Plate 9, at 100 diameters).—The sequence of changes is similar to that described for No. 13. The yellow constituent naturally occupies relatively less of the field than in No. 13. The photographs represent the structures of the bar as rolled, and after 1, 3, 7, 14, 20, 30 and 50 hours at 900° C. (1,652° F.). Special attention is directed to the final stage shown in Fig. 103 (after 50 hours). Here the yellow and brown structureless constituents occupy practically the whole of the field, only the merest traces of the banded structure remaining. This final stage is reached in parts of the alloy after even 1 hour's treatment (*cf.* Fig. 97).

High-power magnification throws a very interesting light on the sequence of changes from the black or dark acicular into the final brown structureless constituent. (Figs. 104–110, Plate 10, at 700 diameters.) Fig. 104 shows the original acicular structure, and Fig. 105 the honeycomb structure formed at a very early stage of the heat treatment. Fig. 106 shows the first indications of the banded structure which, as first observed, is fine, but becomes coarser after prolonged heat treatment, Figs. 107 and 108, and gradually disappears, Figs. 109 and 110, until after 50 hours' treatment practically none is left.

Experiments with Alloy No. 15.—In view of the thermal instability of the acicular constituent of these alloys as ordinarily prepared, and more especially having regard to Dr. Guillet's view that at 11.8 per cent. of aluminium the acicular structure may correspond to a definite compound, Cu_3Al (*loc. cit.*), experiments were made on Alloy No. 15 (11.73 per cent. of aluminium), which corresponds almost exactly to the percentage named. Fig. 112, Plate 11, shows the structure of the untreated material. It appears homogeneous and consists of a mass of needles. After 8 hours' treatment at 900° C. (1,652° F.) structures corresponding to Figs. 113 and 114

were obtained. These are very complex. In Fig. 114 certain evidences of acicular structure remain, but all signs of it have disappeared in Fig. 113. Part of the alloy is structureless, part presents an extremely well-banded structure (visible at 100 diameters, but best seen in Fig. 115 at 700 diameters), and part presents irregular crosses dotted here and there. It is obvious, therefore, that this alloy as ordinarily prepared is as thermally unstable as its predecessors, and if the acicular structure corresponds to a chemical compound, the latter must be classed as unstable. Dr. L. Guillet appears to have made a slight numerical error in stating that a compound Cu_3Al corresponds to 11.8 per cent. of aluminium. Such a compound corresponds to 12.44 per cent. In order to test this point, an alloy was cast in chill in which this percentage was aimed at. The analysis showed that this very percentage had been attained. Photo-micrograph Fig. 116, Plate 11, shows the structure at 100 diameters. It is duplex, and consists of dark crystals bedded in a light mass which is resolved at 700 diameters into an acicular texture, Fig. 117. Thus the cast alloy contains at least two structural constituents. When heated for 8 hours at 900°C . ($1,652^\circ \text{F}$.) and slowly cooled, the structures seen in Figs. 118 and 119 (100 and 700 diameters respectively) are obtained. Here also at least two structural constituents are present, and the acicular has given way to the banded structure, as in the other alloys examined.

The authors' results are in harmony with the view that, provided the conditions are favourable for the attainment of stable chemical equilibrium, aluminium is held in solution by copper to the extent of about 9.4 per cent. This figure is near that required for a compound Cu_4Al (9.6 per cent. of aluminium).

Ball Hardness Tests.—The Ball Hardness Test, introduced by Brinell, has been made, as this appears to be the method in most general use at the present time. The specimens tested were cylinders 20 mm. (0.79 inch) high, and 21 mm. (0.83 inch) diameter. The diameter of the hardened steel ball was 9.516 mm. (0.381 inch). This ball was measured both before and after the tests, and was found to be almost perfectly spherical, the greatest difference in

diameters being 0.0025 mm. (0.0001 inch). The alloys had polished surfaces, and were tested under loads of (a) 1 ton (1,034 kilograms), and (b) 3,000 kilograms, the latter being the standard load for this

BALL HARDNESS TESTS.

FIG. 30.

$$\text{Hardness Number} = \frac{\text{Load (Kilograms)}}{\text{Superficies of Concavity (mm}^2\text{)}} \times \sqrt[5]{\rho}$$

(Where ρ = radius of hardened ball.)

test. As is well known, with the same-sized ball, the hardness number is increased when the load is increased. Therefore an empirical standard has to be adopted. Further, with uniform loading, the hardness number increases as the diameter of the ball

decreases. Benedicks has found, however, that the hardness number becomes independent of the diameter of the hardened ball when it is multiplied by $\sqrt[5]{\rho}$, where ρ is the radius of the ball. Accordingly, in order to obtain standard values for comparison the figures in Table 54 have been calculated as follows:—

$$\frac{\text{Load (in kilograms)}}{\text{Superficies of cavity in square millimetres}} \times \sqrt[5]{\rho}$$

The superficies rather than the projection of the cavity has been chosen as it gives more uniform numbers. The diameters quoted are the mean of two at right angles measured in a travelling microscope capable of reading to $\frac{1}{1000}$ th of a millimetre.

The results are given in Table 54 and are shown graphically in Fig. 30.

TABLE 54.

Alloy No.	Aluminium. Per cent.	Load of 1 Ton (1,034 kgs.).		Load of 3,000 kgs.	
		Diam. of Indentation in mm.	Hardness number.	Diam. of Indentation in mm.	Hardness number.
1	0.10	4.66	78	7.91	66
4	2.99	3.97	109	6.61	102
6	5.07	3.89	113	6.09	124
9	7.35	3.74	123	5.90	134
13	9.90	3.10	180	4.81	210
15	11.73	2.86	213	4.28	269
16	13.02	2.31	332	3.79	349
—	13.50	2.18	372	3.36	437
17	15.38	2.08	411	3.07	539
1	2	3	4	5	6

(These tests were done on the rolled bars ($1\frac{3}{8}$ inch) of all alloys, except those containing 13.50 and 15.38 per cent. of aluminium, where sand castings were used.)

The results are of the same kind under the two loads. The values in column 6 represent however "standard" numbers, and only these will be considered. The hardness number 66 was obtained for No. 1, the base of the series. The introduction of aluminium at once hardens the material, but there is no very notable increase in the number up to 7.35 per cent. At 10 per cent. there is a marked rise, and from here up to 15.38 per cent. the increase is rapid. At the last-named percentage the figure 539 was obtained. This is more than eight times that obtained for No. 1, and must be considered a very high figure for an alloy that is not a steel of some kind. The figure for the hardest steel known is about 800, and although this is considerably higher than 539, yet the latter is just about the hardness number of a 0.45 per cent. carbon steel quenched in water at 20° C. (68° F.),* and is only slightly lower than that of a 0.66 per cent. carbon steel similarly treated. Accordingly Alloy No. 17 is fully entitled to rank with these hardened steels in this respect.

Torsion Tests of Bars rolled to $1\frac{1}{4}$ inches Diameter.—The results are given in Table 55 (page 187) and are shown graphically in Fig. 31 (page 188).

Maximum Load (Columns 5 and 6).—The variations of load with rising aluminium are similar to those obtained in the tension tests, except that at 9.90 per cent. there is a slight decrease in torsional stress as compared with a decided increase in tensile stress. Table 56 (page 189) shows the ratio of ultimate stresses in tension and torsion ($1\frac{1}{4}$ -inch bars).

* Journal, Iron and Steel Institute, 1901, No. 1, page 267.

TABLE 55.

Alloy No.	Aluminium.	Diameter.	Length.	Maximum Load.		Total Twist on whole length.	
				Twisting Moment.	Calculated Maximum Stress.	No. of Turns.	Angle of Twist.
	Per cent.	Inch.	Inches.	Inch-lbs.	Tons per sq. inch.		Degrees.
Pure copper } 99.96 p.c. }	0.00	0.624	3.0	1,792	16.74	7.60	2,736
1	0.10	"	"	2,293	21.41	14.40	5,184
2	1.06	"	"	2,359	22.03	12.07	4,345
3	2.10	"	2.8	2,464	23.01	10.00	3,600
5	4.05	"	3.0	2,813	26.28	6.43	2,316
8	6.73	"	"	3,306	30.88	4.51	1,623
9	7.35	"	"	3,373	31.51	3.82	1,374
13	9.90	"	"	3,351	31.30	0.65	234
15	11.73	"	"	3,584	33.47	0.14	51
1	2	3	4	5	6	7	8

TABLE 56.

Alloy No.	Aluminium.	Maximum Stress.		Ratio $\frac{\text{Torsion}}{\text{Tension}}$.
		Tension.	Torsion.	
	Per cent.	Tons per sq. in.	Tons per sq. in.	
1	0.10	14.20	21.41	1.51
2	1.06	15.65	22.03	1.41
3	2.10	17.22	23.01	1.34
5	4.05	21.93	26.28	1.20
8	6.73	26.17	30.88	1.18
9	7.35	27.42	31.51	1.15
13	9.90	35.03	31.30	0.89
15	11.73	32.11	33.47	1.04

It will be seen from this Table that all the alloys except No. 13 have greater tenacity in torsion than in tension; the ratio diminishing with rising aluminium.

Total Twist.—These figures (columns 7 and 8) must be regarded as very noteworthy. In particular those obtained with Alloys 1 to 3 are far higher than those of either pure copper or any of its alloys of which the authors have found mention in the literature. (The value for No. 3 would have been even higher had the length been 3.0 instead of 2.8 inches.) Professor T. Hudson Beare * obtained a mean total twist of 5.41 turns in three closely-agreeing determinations of copper of the same dimensions, and this appears an average figure for good copper. It is the authors' opinion that the particularly high figure for No. 1 may be attributed chiefly to the presence of one-tenth of one

* "Industries," 4 Dec. 1891.

per cent. of aluminium. Rolled copper generally contains more or less dissolved oxide which diminishes its ductility. Accordingly in casting Alloy No. 1 particular care was taken that a slight excess of aluminium should be added in order to remove oxygen, and yield as pure a commercial copper as possible. The authors do not regard No. 1 as a copper-aluminium alloy so much as the base of the series which contains as little aluminium as possible consistent with the absence of oxygen. Viewed as copper it contains only about one-tenth of one per cent. of impurities, as does the "Lake" copper used in this research.

A direct comparison was obtained by testing the blank of the series, namely, the pure copper referred to on page 138. The values are given in the top horizontal row of Table 55. The copper broke after 7.6 complete turns, that is, it showed itself only about half as good as Alloy No. 1. (The calculated maximum stress was 4.6 tons per square inch lower.)

The figures of the alloys immediately succeeding No. 1 show that even up to 4 per cent. of aluminium the total twist is greater than in the copper tested by Professor Beare. There is a steady fall in ductility as far as 7.35 per cent. The sharp drop at 9.90 per cent. brings out the brittleness of the dark structural constituent in alloys of this class. At 11.73 per cent. the alloy breaks after a twist of 51° . Thus the effect of adding this percentage to pure copper is to diminish the angle of twist from $5,184^\circ$ to 51° , that is, to reduce it more than one hundred times.

To sum up.—Alloys containing aluminium up to $7\frac{1}{2}$ per cent. behave extremely well under the torsion test, but beyond this percentage there is a rapid *deterioration of properties*.

Alternating-Stress Tests of Rolled Bars $\frac{1}{8}$ inch diameter.—These have been carried out on duplicate sets of bars:—

- (a) In the Engineering Department of the Laboratory.
- (b) In the University of Sheffield (by Professor J. O. Arnold).
- (a) These tests were under the charge of Dr. Stanton, who has furnished the following report:—

"The tests were carried out in the Alternating-Stress Testing Machine of the Engineering Department. The rate of reversals was 800 per minute, and the ratio of maximum tensile to compression stress was 1.4. The limiting value of the resistance given in Table 57 is the maximum range of stress for fracture after one million reversals. This resistance is estimated from plotting the actual results obtained, the ranges of stress being the ordinates and the corresponding number of reversals the abscissæ. In this way a curve can be drawn from which the required limit can be obtained.* In the present experiments the number of specimens tested is not sufficient to enable the limits of resistance to be obtained with great accuracy, but the approximations are quite sufficient to indicate the relative resistance of the different alloys to alternating stresses."

"The specimens 5 inches long were turned down to $\frac{3}{4}$ inch diameter, screw-cut the whole length to gauge, and finally turned down to $\frac{1}{4}$ inch diameter in the centre, the length of the parallel part being $\frac{1}{2}$ inch and the radius of the fillet $\frac{3}{8}$ inch."

No. 1 (Aluminium 0.10 per cent.).

No.	Total Reversals.	Range of Stress.	Maximum Tensile Stress.
		Tons per sq. in.	Tons per sq. in.
1	120,000	12.02	7.01
2	272,400	10.83	6.32
3	470,800	9.85	5.74

(Yield-point in tension 6.9 tons per sq. in.)

It will be noticed that in test 1 the alloy was stressed practically at the yield-point, and endured 120,000 reversals. In tests 2 and 3 it was stressed below the yield-point.

* Proceedings, The Institution of Civil Engineers, vol. clxvi, 1906, page 78.

No. 4 (Aluminium 2.99 per cent.).

No.	Total Reversals.	Range of Stress.	Maximum Tensile Stress.
		Tons per sq. in.	Tons per sq. in.
1	10,600	19.23	11.20
2	118,000	17.76	10.34
3	485,000	17.10	9.96

(Yield-point in tension 11.6 tons per sq. in.)

The same remarks apply to these tests as to No. 1 (page 191).

No. 6 (Aluminium 5.07 per cent.).

No.	Total Reversals.	Range of Stress.	Maximum Tensile Stress.
		Tons per sq. in.	Tons per sq. in.
1	25,000	22.44	13.07
2	654,000	20.99	12.22
3	44,700	20.06	11.99
4	1,032,500	19.01 (unbroken)	11.06

(Yield-point in tension 11.4 tons per sq. in.)

Tests 1 and 2 were carried out above the yield-point. The latter test is abnormal. Test 3 was carried out just above, test 4 just below, the yield-point.

No. 9 (Aluminium 7.35 per cent.).

No.	Total Reversals.	Range of Stress.	Maximum Tensile Stress.
		Tons per sq. in.	Tons per sq. in.
1	147,400	22.36	13.02
2	260,100	20.74	12.07
3	1,039,800	18.82 (unbroken)	10.96

(Yield-point in tension 10.6 tons per sq. in.)

All three tests were carried out above the yield-point, but only just above in No. 3.

No. 13 (*Aluminium 9.90 per cent.*).

No.	Total Reversals.	Range of Stress.	Maximum Tensile Stress.
		Tons per sq. in.	Tons per sq. in.
1	415,700	28.62	16.66
2	1,001,000	26.60 (unbroken)	15.48
3	1,097,000	22.48 (unbroken)	13.08

Yield-point in tension 14.8 tons per sq. in.

Tests 1 and 2 were above, test 3 below the yield-point.

It is most remarkable that the alloys containing from 5 to 10 per cent. of aluminium (Nos. 6, 9 and 13) should withstand so many stress repetitions at and indeed just above the yield-point. The facts seem to suggest that the yield-points found in tension have not the same meaning for these alloys as for iron-carbon alloys.

Table 57 contains the range of stress calculated from the above results at which these specimens will break after one million reversals. The results are shown graphically in Fig. 32 (page 194).

TABLE 57.

Alloy No.	Aluminium.	Range of Stress.
	Per cent.	Tons per sq. in.
1	0.10	9.2
4	2.99	17.0
6	5.07	20.5
9	7.35	20.5
13	9.90	28.3

P

As stated above these figures are only approximate. Considering that this is so, their relation to the yield-points in tension is

FIG. 32.

Alternating-Stress Tests (Stanton).

Maximum limit of resistance (for 1 million reversals of direct stress at a rate of 800 per minute) compared with Yield-Point in Simple Tension.

uniform. The variations in both cases are of the same kind. A sharp rise to 3 to 5 per cent. of aluminium, followed by only slight variations up to 7.35 per cent. and this succeeded by another rise.

Under this test the 10 per cent. aluminium-bronze (Alloy No. 13) shows itself a most useful material. Its maximum limit of resistance for one million reversals of direct stress at a rate of 800 per minute, and with a ratio of tension to compression of 1.4, is about 28.3 tons per square inch. Comparing this figure with those obtained by Messrs. Stanton and Bairstow for ten varieties of iron and steel (*loc. cit.*) the alloy takes the third place, equal to piston-rod steel, containing 0.446 per cent. of carbon. (The highest figure, 31.5 tons, was obtained with Swedish Bessemer steel (0.645 per cent. carbon).)

But the particular merit of this alloy (and also the 5 and 7½ per cent. bronzes) is the close approximation of the maximum stress, under which it will bear an unlimited number of reversals, to the stress at the elastic limit as determined in a tensile test. In this respect it is markedly superior to the iron and steel specimens hitherto investigated. This is shown in Table 58, which contains the values of the ratio of the maximum range of stress to the primitive yield-point of each alloy.

TABLE 58.

Alloy No.	Ratio <u>Maximum Range of Stress.</u> <u>Primitive Yield-Point.</u>
1	1.33
4	1.47
6	1.80
9	1.93
13	1.91

The ratio nearly reaches 2 in the case of Nos. 9 and 13, and is high in No. 6. In the case of irons and steels referred to, the ratio varied between 1.80 and 1.13 (*loc. cit.*).

Although in the foregoing tests the alloys were sometimes stressed beyond the yield-point, the materials were for the most part in the elastic condition, and the calculated limits of resistance in Table 57 refer to the alloys in this state.

(b) *Duplicate Alloys as tested at Sheffield by Professor Arnold* were stressed beyond the yield-point. In these tests the rate of alternation was 650 per minute. The distance of the striking line on the radius of the plunger from the face of the die was 3 inches. The deflection of the test-piece 3 inches above the face of the die was $\frac{3}{8}$ inch each way.

Professor Arnold has furnished the authors with the following Table of results:—

TABLE 59.

Alloy No.	Aluminium. Per cent.	Shape and Size of Test-piece.	Alternations endured under Standard Conditions.			Remarks on the quality of the Alloy.
			First Test.	Second Test.	Mean.	
1	0·10	$\frac{3}{8}$ in. round, $5\frac{1}{2}$ ins. long	308	266	287	Fair.
4	2·99	„ „	330	334	332	Good.
6	5·07	„ „	658	606	632	Very good.
9	7·35	„ „	1,530	1,260	1,395	Excellent.
13	9·90	„ „	707	607	657	Very good.
1	0·10	$\frac{3}{8}$ in. square, $5\frac{1}{2}$ ins. long	430	456	443	Good.
4	2·99	„ „	432	480	456	Good.
6	5·07	„ „	894	734	814	Very good.
9	7·35	„ „	1,280	1,466	1,373	Excellent.
13	9·90	„ „	810	756	783	Very good.

Except in the case of No. 9, where the round and square bars gave almost the same mean value, the square bars gave the better results. It will be seen from Professor Arnold's report that all the alloys behaved well under this test, but particularly those containing from 5 to 10 per cent. of aluminium. He has informed the authors that "Alloy No. 9 constitutes a record in its capacity of

resisting alternations." Thus when the alloys were subjected to alternating stresses beyond the yield-point, the capacity to resist fracture rose with the addition of aluminium to a maximum at about 7.35 per cent., but fell sharply at 10 per cent. This drop coincides with the appearance of the dark *brittle* structural constituent (*loc. cit.*), and appears only natural. The variations thus found fall more into line with those revealed by the impact tests (in the succeeding section) than with those shown by Dr. Stanton's tests.

Impact Tests on Bars rolled to $\frac{1\frac{3}{8}}$ inch diameter.—These were carried out in the Izod machine on notched bars 2 inches by $\frac{3}{8}$ inch by $\frac{3}{16}$ inch. The results are given in Table 60 (page 198). Except in the case of Alloy No. 4 the values in column 4 are the mean of three tests. Alloys Nos. 1 to 9 did not break under this test, and in these cases the figures in column 4 merely show the energy required to bend the specimens to the same angle, namely, that at which the tup cleared them. The figures bring out the gradual stiffening caused by increasing aluminium up to 7.35 per cent. already shown in the static tests. For Alloys 13, 15 and 16 the mean figures are those required to produce fracture (without deformation). It has been already pointed out (page 137) that, in ultimate tensile stress, Alloy No. 13 resembles a Swedish Bessemer steel of about 0.35 per cent. of carbon. The energy absorbed on fracture by impact is also about the same. Alloy No. 15 gave results more nearly approximating to those of No. 13 than might have been anticipated from the static tests.

Summary of Kinetic-Stress Tests.—These tests have yielded one result of particular interest. They have shown that the primitive yield stresses of these alloys are very much nearer the proper figure than those of steels, or, in other words, that the alloys show much less tendency to assume an artificial yield-point in their manufacture. Alloys Nos. 9 and 13 are nearly theoretically perfect in this respect (*see* Table 58, page 195).

The alloys containing from 0 to 10 per cent. of aluminium behaved very satisfactorily in these tests, but the most valuable range is from 5 to 10 per cent.

TABLE 60.

Alloy No.	Aluminium.	Foot-Pounds Absorbed.	Mean.	Condition after Test.
	Per cent.			
1	0.10	8.9	8.9	Unbroken
	"	9.0		
	"	8.9		
4	2.99	12.4	12.3	"
	"	12.3		
6	5.07	14.5	14.2	"
	"	13.7		
	"	14.3		
9	7.35	15.7	15.4	"
	"	15.9		
	"	14.7		
13	9.90	4.4	4.5	Broken
	"	4.9		
	"	4.3		
15	11.73	3.6	3.9	"
	"	3.8		
	"	4.2		
16	13.02	0.9	0.9	"
	"	0.8		
	"	1.1		
1	2	3	4	5

Freezing Ranges and Evolutions of Heat on Cooling.—These have been determined for 37 alloys ranging over the entire series from 0–100 per cent. of aluminium, and will be described in their entirety here. As previously stated, the temperature of each cast was taken and the cooling followed by time and temperature observations with a direct-reading pyrometer. This method, however, was not sufficiently sensitive for the detection of small heat evolutions. Accordingly sufficient of each alloy was re-melted in a covered crucible (in which, as has been shown, hardly any change of composition occurs), and the cooling followed by a thermo-junction

and potentiometer and time observations exactly as was described by one of the authors in the Seventh Report to the Alloys Research Committee.* In several instances it was necessary to prepare an alloy of special composition—for example, one containing about 67 per cent. of aluminium—in order to complete the curve.

In view of the discussion on the errors likely to arise from the use of "protected" thermo-junctions, which took place on the Seventh Report, the exact influence was determined in this research. The temperatures range over more than 500° C. (900° F.), namely, from $1,084^{\circ}$ – 544° C. ($1,983^{\circ}$ – $1,011^{\circ}$ F.). Accordingly, alloys freezing near each limit were tested.

(a) With protected junction Alloy No. 17 froze at $1,035^{\circ}$ C. ($1,895^{\circ}$ F.). A bare junction was ultimately attacked by the alloy and ceased to record, but previous to this the steady point was $1,038^{\circ}$ C. ($1,900^{\circ}$ F.). Accepting this figure as trustworthy, it shows that at $1,000^{\circ}$ C. ($1,832^{\circ}$ F.) the loss due to protection was extremely small.

(b) With protected junction an alloy containing about 5.6 per cent. of copper began to freeze at 604° C. ($1,119^{\circ}$ F.); with bare junction the temperature recorded was 612° C. ($1,133^{\circ}$ F.). These figures were confirmed in another experiment. Thus at about 600° C. ($1,112^{\circ}$ F.) the error due to protection is larger than at $1,000^{\circ}$ C. ($1,832^{\circ}$ F.), but still is not more than 8° C. (14° F.).

Accordingly, the determinations have been made with protected junctions, and the following corrections applied. (The protection was a fire-clay sheath $\frac{1}{16}$ inch in thickness.)

It may be pointed out, however, that above 800° C. ($1,472^{\circ}$ F.) these corrections come within the experimental errors and uncertainties of the method.

Temperature.	Correction.
$1,050^{\circ}$ C. ($1,922^{\circ}$ F.)	+ 3° C.
950° C. ($1,742^{\circ}$ F.)	+ 4° C.
850° C. ($1,562^{\circ}$ F.)	+ 5° C.
750° C. ($1,382^{\circ}$ F.)	+ 6° C.
650° C. ($1,202^{\circ}$ F.)	+ 8° C.
550° C. ($1,022^{\circ}$ F.)	+ 9° C.

* Proceedings, 1905, Part 4, page 910-912.

TABLE 61—(continued on opposite page).

Evolutions of Heat on Cooling.

Aluminium. Per cent.	1,100°-1,000° C. (2,012°- 1,832° F.)	1,000°-900° C. (1,832°- 1,652° F.)	900°-800° C. (1,652°- 1,472° F.)	800°-700° C. (1,472°- 1,292° F.)	700°-600° C. (1,292°- 1,112° F.)	600°-500° C. (1,112°-932° F.)
0.00	1,085° C. (1,985° F.) (very large)	—	—	—	—	—
2.99	1,070° C. (1,958° F.) (very large)	—	—	—	—	—
5.76	1,051° C. (1,923° F.) (very large)	—	—	—	—	—
7.35	1,035° C. (1,895° F.) (very large)	—	—	—	—	—
8.12	1,032° C. (1,889° F.) (very large)	—	—	—	—	—
8.67	1,034° C. (1,893° F.) (very large)	—	—	—	—	—
9.90	1,041° C. (1,906° F.) (very large)	—	—	—	—	—
10.78	1,043° C. (1,909° F.) (very large)	—	—	—	—	—

11.73	1,044° C. (1,911° F.) (very large)	—	—	—	—	—	—
13.02	1,042° C. (1,908° F.) (very large)	—	—	—	—	—	—
15.38	1,038° C. (1,900° F.) (very large)	959° C. (1,758° F.) (medium)	—	—	—	—	—
18.0	1,019° C. (1,866° F.) (large)	—	860° C. (1,582° F.) (small)	—	—	—	—
20.7	—	990° C. (1,814° F.) (large)	860° C. (1,582° F.) (small)	—	—	—	—
22.5	—	951° C. (1,744° F.) (large)	850° C. (1,562° F.) (small)	—	682° C. (1,259° F.) (very small)	—	—
25.0	—	903° C. (1,658° F.) (medium)	850° C. (1,562° F.) (small)	—	608° C. (1,126° F.) (small)	—	—
27.1	—	—	857° C. (1,575° F.) (medium)	—	625° C. (1,157° F.) (small)	590° C. (1,094° F.) (small)	555° C. (1,031° F.) (small)
29.1	—	—	801° C. (1,474° F.) (medium)	—	619° C. (1,146° F.) (medium)	591° C. (1,096° F.) (medium)	559° C. (1,038° F.) (small)
32.1	—	—	—	755° C. (1,391° F.) (medium)	620° C. (1,148° F.) (medium)	580° C. (1,076° F.) (large)	552° C. (1,026° F.) (small)
35.1	—	—	—	708° C. (1,306° F.) (medium)	619° C. (1,146° F.) (medium)	584° F. (1,083° F.) (large)	555° C. (1,031° F.) (small)

NOTE: The terms "very large," "large," "medium," "small," and "very small," qualify the evolutions of heat.

TABLE 61—(concluded on opposite page).

Evolutions of Heat on Cooling.

Aluminium. Per cent.	1,100°-1,000° C. (2,012°- 1,832° F.)	1,000°-900° C. (1,832°- 1,652° F.)	900°-800° C. (1,652°- 1,472° F.)	800°-700° C. (1,472°- 1,292° F.)	700°-600° C. (1,292°- 1,112° F.)	600°-500° C. (1,112°-932° F.)	
40.0	—	—	—	—	653° C. (1,208° F.) (medium)	590° C. (1,094° F.) (very large)	538° C. (1,000° F.) (very small)
42.5	—	—	—	—	618° C. (1,144° F.) (medium)	590° C. (1,094° F.) (very large)	537° C. (999° F.) (very small)
44.9	—	—	—	—	—	590° C. (1,094° F.) (very large)	530° C. (986° F.) (very small)
47.4	—	—	—	—	—	585° C. (1,085° F.) (very large)	530° C. (986° F.) (small)
49.9	—	—	—	—	—	575° C. (1,067° F.) (very large)	523° C. (973° F.) (small)
55.3	—	—	—	—	—	574° C. (1,065° F.) (large)	540° C. (1,004° F.) (large)
60.6	—	—	—	—	—	562° C. (1,044° F.) (medium)	541° C. (1,006° F.) (large)
64.2	—	—	—	—	—	549° C. (1,020° F.) (medium)	542° C. (1,008° F.) (large)

66.5	—	—	—	—	—	—	544° C. (1,011° F.) (very large)
68.3	—	—	—	—	—	547° C. (1,017° F.) (small)	543° C. (1,009° F.) (very large)
71.0	—	—	—	—	—	559° C. (1,038° F.) (medium)	542° C. (1,008° F.) (very large)
75.0	—	—	—	—	—	576° C. (1,069° F.) (medium)	538° C. (1,000° F.) (large)
80.1	—	—	—	—	600° C. (1,112° F.) (medium)	—	542° C. (1,008° F.) (large)
84.0	—	—	—	—	611° C. (1,131° F.) (large)	—	538° C. (1,000° F.) (large)
89.3	—	—	—	—	625° C. (1,157° F.) (large)	—	536° C. (999° F.) (medium)
94.7	—	—	—	—	639° C. (1,182° F.) (large)	—	534° C. (993° F.) (small)
96.9	—	—	—	—	646° C. (1,195° F.) (large)	—	—
100.0	—	—	—	—	657° C. (1,215° F.) (large)	—	—

NOTE: The terms "very large," "large," "medium," "small," and "very small" qualify the evolutions of heat.

FIG. 33 (continued on next page).
Equilibrium Curves of the Copper-Aluminium Alloys.

FIG. 33 (continued from opposite page).
Equilibrium Curves of the Copper-Aluminium Alloys.

The complete results are given in Table 61 (pages 200–203), and are shown graphically in Fig. 33 (pages 204–205).^{*} The circles, dots and crosses represent observed evolutions of heat. The line drawn through the circles represents the “liquidus” curve, that is, the temperatures at which the molten alloys begin to deposit solid crystals on cooling. The curve agrees well with that obtained by Dr. L. Guillet† except in one particular, namely, the authors have not found that the curve rises from 44.5 to 50 per cent. of aluminium. Near this percentage it is nearly a horizontal straight line.

It will be observed that the alloys containing from 0 to 13 per cent. of aluminium, whose properties have been investigated in such detail, appear to solidify at one temperature. From 8 to 13 per cent. evolutions of heat take place on cooling at temperatures for the most part between 600° and 500° C. (1,112° and 932° F.). These have been investigated by differential cooling, and are discussed in the succeeding section. Table 61 and Fig. 33 only contain observations of direct cooling. The rise in the liquidus curve from 8 to about 12 per cent. of aluminium coincides with the appearance and growth to a maximum of the dark needles in the alloys, after they have cooled to the ordinary temperature. But this must be carefully distinguished from the fact that the alloys solidify to an apparently homogeneous mass, from which the dark and yellow structural constituents are ultimately formed. A complete discussion of the equilibrium-curves of copper-aluminium alloys will be found in the Appendix (page 259).

Heating and Cooling Curves.‡—Dr. L. Guillet obtained some noteworthy results from experiments of this type.§ He found (a) that the only alloys which showed “transformation points” were

* The final form of the diagram is given on Fig. 204 (page 370).

† Revue de Métallurgie, 1905, page 568.

‡ The Committee are of opinion that further discussion is required to determine the relative value of the differential method and the direct method of observing evolutions of heat during cooling, and absorptions of heat during heating, of metals, alloys, &c. Several experimenters are making further investigations by the various methods, with a view to full discussion before another Society.

§ Revue de Métallurgie, 1905, pages 569–571.

those containing from 8 to 14 per cent. of aluminium; (b) that the transformations on heating took place in several stages; (c) that the transformation on cooling was "plus nette," but took place at a higher temperature than on heating. Commenting upon this last result, which is very remarkable, he says (*loc. cit.*):—"Ceci semble, *a priori*, tout à fait contraire à la logique. On peut toutefois expliquer ce phénomène par ce fait que le métal, préalablement constitué d'une solution α et du constituant β , se transforme en une solution γ , quand il passe par le point de transformation et qu'au refroidissement cette solution γ ne donne pas les constituents α et β , mais bien une solution α' différente de α et de la solution β ." *

Dr. Guillet's interpretation of his own curves shows the improbability of the correctness of this explanation. If the change from γ to α' is associated with a "transformation point," it is very probable that the same holds for the change from α' to α . It is therefore to be expected that there will be at least *two* thermal evolutions on cooling. Dr. Guillet's Table (page 570) only contains one in all five cases examined.

It appeared to the authors that only one of the curves (No. 4) bore the interpretation put upon them by Dr. Guillet, and that Nos. 2 and 3 were normal in the sense that the transformations on cooling did not take place at a higher temperature than on heating. But it seemed desirable to make a definite attempt to settle the question by fresh experiments, and accordingly heating and cooling curves have been taken of Alloys Nos. 9 to 16 inclusive. With the exception of No. 9, these come within the percentages quoted by Dr. Guillet. No. 9 was also examined in order to get the "blank" curve of the series.

The method employed was that described in the Seventh Alloys Research Report (pages 916-922), and is the same in principle as

* Translation. "This seems, *a priori*, quite illogical. But the phenomenon can be explained by supposing that the metal, consisting originally of a solution α and a solution β , is transformed into a solution γ when it has passed through the critical point, and that on cooling this solution γ does not yield the constituents α and β , but a solution α' different from α and the solution β ."

that used by Dr. Guillet. The curves are reproduced in Fig. 34 (pages 209-212). The vertical ordinate represents absolute temperatures of the alloy during cooling. The horizontal ordinate represents differences of temperature between the alloy and a cylinder of platinum cooling under the same conditions as registered by the movements of the differential galvanometer. The distance between two vertical lines represents about 16° C. A summary of the temperatures over which the critical ranges extend is given in Table 62 (pages 214-215).

These results are quite conclusive in regard to the point in question. On the whole the curves form a very uniform series. They show that the "transformation points" or "critical ranges," as the authors prefer to style them, are not abnormal in the sense suggested by Dr. Guillet. They are not higher, but *lower* on cooling than on heating. Accordingly there is no need for any such explanation as that attempted by him.

The curves of Alloy No. 9, Fig. 34 (page 209), represent the blanks of the series, that is, the forms in the absence of changes of internal energy in the alloys.

The complexity of the curves increases with rise of aluminium, and no attempt will be made to give a complete physical interpretation of them. This cannot be done without definite and extensive experiments made with this end in view, and time has only permitted their execution in a preliminary way. The authors think, however, that the following interpretation on broad lines is true as far as it goes.

It will be noted that at 8.12 per cent. of aluminium a very small heat absorption occurs at $563-566^{\circ}$ C. ($1,045^{\circ}-1,050^{\circ}$ F.) (col. 2, page 214), and that this increases with rising aluminium to a maximum at 12-13 per cent. This coincides with the appearance and growth to a maximum of the dark needle-like structural constituent in the alloys (photo-micrographs, Plates 3 to 5). This thermal change appears to be connected with a change in the properties of the constituent thus characterised. (Experiments have been made with Alloy No. 13, and the authors think their generalization will hold for Alloys Nos. 10, 11, 12, 13, 14 and probably No. 15.)

FIG. 34 (continued to page 212).

Heating and Cooling Curves of Alloys Nos. 9 and 10.

FIG. 34 (continued on next page).

Heating and Cooling Curves of Alloys Nos. 11 and 12.

FIG. 34 (continued on next page).

Heating and Cooling Curves of Alloys Nos. 13 and 14.

FIG. 34 (concluded from page 209).

Heating and Cooling Curves of Alloys Nos. 15 and 16.

With a view to stereotyping the structure existing at a particular temperature, the customary method of quenching small specimens as rapidly as possible in water was adopted. It seems to have been clearly established by Mons. A. Le Chatelier * that this method does not cause instantaneous cooling, but that at any rate in the case of steels several seconds elapse in cooling from about 700° – 100° C. ($1,292^{\circ}$ – 212° F.). Accordingly, the structures of alloys thus quenched cannot be regarded as necessarily the same as those existing at the particular temperature in question, although in certain cases they may be so. The method however remains in general use.

When Alloy No. 13 was quenched at any temperature not exceeding 560° C. ($1,040^{\circ}$ F.), no structural change was detected. When quenched at 600° C. ($1,112^{\circ}$ F.) however, the appearance seen in photo-micrograph Fig. 120, Plate 12, was noted. It will be observed that the dark constituent has become lighter in colour and more striated. The change at 560° – 570° C. ($1,040^{\circ}$ – $1,058^{\circ}$ F.), which is remarkably constant in temperature throughout the series, appears to correspond to a change in the dark constituent, as a result of which it can dissolve the light yellow constituent.

The heat absorptions between 600° and 800° C. ($1,112^{\circ}$ F.– $1,472^{\circ}$ F.), which are more prolonged and variable in position, seem to correspond to the gradual solution of the yellow in the dark constituent. The structures of alloys quenched from 700° , 800° and 900° C. ($1,292^{\circ}$, $1,472^{\circ}$ and $1,652^{\circ}$ F.) are seen in photo-micrographs, Figs. 121, 122 and 123, Plate 12, respectively. They show the gradual disappearance of the yellow constituent which appears complete at 900° C. The alloy then consists of a mass of needles whose colour varies from yellow to dark brown.

This succession of changes was found to be reversed on cooling. Above 800° C. the needles persist to the exclusion of the yellow constituent (photo-micrograph Fig. 124). Below this temperature the latter makes its appearance, Fig. 125, and increases down to about 530° C. (986° F.), Fig. 126. At about this temperature (col. 10, page 215), unless the cooling is purposely retarded, the

* *Revue de Métallurgie*, 1904, page 473.

TABLE 62 (continued on opposite page.)

Heating Curves (from 200°-900° C. (392°-1652° F.)).					Alloy No.
400° C. (752° F.)	500° C. (932° F.)	600° C. (1112° F.)	700° C. (1292° F.)	800° C. (1472° F.)	
—	—	{ 610°-718° C. (1130° F.-1324° F.) very small }		—	9
—	{ 563°-566° C. (1045°-1050° F.) very small }	—	741°-? C. (1366° F.)	}	10
—	{ 563°-568° C. (1045°-1054° F.) small }	658°-718° C. (1216°-1324° F.) small	735°-813° C. (1355°-1495° F.) small	}	11
—	{ 563°-568° C. (1045°-1054° F.) medium }	658°-718° C. (1216°-1324° F.) small	735°-789° C. (1355°-1452° F.) small	}	12
—	{ 563°-574° C. (1045°-1065° F.) large }	610°-622° C. (1130°-1151° F.) small	700°-824° C. (1292°-1515° F.) small	}	13
427°-452° C. (801°-846° F.) small	562°-574° C. (1043°-1065° F.) very large	688°-712° C. (1270°-1313° F.) very small	}	—	14
403°-440° C. (757°-824° F.) large	562°-570° C. (1043°-1058° F.) very large	688°-706° C. (1270°-1303° F.) very small	762°-789° C. (1403°-1452° F.) very small	}	15
361°-397° C. (681°-747° F.) medium	560°-566° C. (1040°-1050° F.) very large	670°-706° C. (1238°-1303° F.) medium	}	—	16
1	2	3	4	5	6

(concluded from opposite page) TABLE 62.

Alloy No.	Aluminium.	Cooling Curves (from 900°-200° C. (1652°-392° F.)).			
		700° C. (1292° F.)	600° C. (1112° F.)	500° C. (932° F.)	400°-200° C. (752°-392° F.)
9	Per cent. 7.35	—	—	{ 574°-537° C. (1065°-998° F.) very small	—
10	8.12	—	—	{ 580°-525° C. (1076°-977° F.) very small	—
11	8.67	—	—	{ 580°-522° C. (1076°-971° F.) small	—
12	9.38	—	—	{ 533°-513° C. (991°-955° F.) medium	349°-267° C. (660°-513° F.) small
13	9.90	{ 789°-753° C. (1452°-1387° F.) large	—	527°-513° C. (980°-955° F.) medium	397°-274° C. (747°-525° F.) small
14	10.78	—	{ 628°-600° C. (1162°-1112° F.) small	530°-507° C. (986°-945° F.) large	361°-267° C. (682°-513° F.) small
15	11.73	—	—	{ 537°-509° C. (999°-948° F.) large	350°-286° C. (622°-536° F.) medium
16	13.02	{ 706°-692° C. (1303°-1277° F.) small	658°-644° C. (1216°-1191° F.) medium	513°-490° C. (955°-914° F.) large	293°-254° C. (559°-489° F.) medium
6	7	8	9	10	11

acicular constituent becomes dark and partly loses its acicular character, Fig. 127. (The effect of slow cooling was discussed in pages 181-182.)

The foregoing interpretation has taken no account of the thermal changes between 200° and 400° C. (392°-752° F.). No structural changes corresponding to these have been found by microscopic examination.

Corrosion Tests.—These have been carried out on the lines indicated in the discussion on the Seventh Alloys Report as being most likely to yield useful information. At the outset the authors submitted their scheme of tests to the Chairman of the Committee, Sir William H. White, and are much indebted for his helpful suggestions. The tests have been performed on Alloys Nos. 2, 4, 6, 9, and 13. Special castings of each were made, 3 inches square by $\frac{3}{8}$ inch. These were machined accurately to $2\frac{3}{4}$ inches square by $\frac{1}{4}$ inch. The alloys have been subjected to corrosion both by sea-water and fresh- (but not distilled) water.

The sea-water tests have been of two kinds :—

(1) That in which the alloy alone was immersed.

(2) That in which a galvanic couple of the alloy and mild steel (acid Siemens-Martin, of carbon percentage 0.19) was immersed. Half-inch diameter holes were drilled in plates of the alloy and the mild steel, which were the same size, Fig. 163, Plate 20. These were afterwards bolted together to make a firm lap-joint, Fig. 164. The total surface exposed was 0.093 square foot, and the total surface in contact was 0.017 square foot.

By these tests it was hoped to get a measure of the protective influence of the electropositive element of the couple, namely, the mild steel, on the aluminium-copper alloy.

Moreover, in order to contrast the behaviour of these alloys with that of other copper alloys which are habitually exposed to sea-water, similar couples of Muntz Metal and Naval Brass were prepared and tested in the same way.

Although, doubtless, the most trustworthy practical results would have been obtained if the corrosion tests had been carried out *in the*

sea, it was felt that it was most important to have the plates under frequent observation, and that a close approximation to practical conditions would be realised if the alloys were continually exposed to fresh sea-water. Accordingly, during the four months over which the tests have extended, fresh sea-water has been supplied each week, and further, the water has been frequently kept in agitation so as to aerate it thoroughly.

The seven couples were separately suspended in about 3 gallons of sea-water (contained in a large glass trough) by string, which did not touch either plate of the couple, but passed under the head of the bolt on one side and the nut on the other. Care was taken that the circulation of the water round each plate was as free as possible.

Each metal plate was weighed before and after the complete test.

(A) *Sea-water Corrosion Tests of the Alloys (singly).*—These plates were suspended by string, which passed through a small hole drilled in one corner. The duration of the test was 104 days and the surface exposed was 0·123 to 0·124 square foot. The action that took place was very slight. The appearances of the surfaces at the end of the test were as follows:—

No. 2 (1·06 per cent. of aluminium) . . .	{ A slight green deposit in parts, the surface fairly smooth, crystalline structure well de- veloped.
No. 4 (2·99 „ „ „) . . .	{ Surface bright and smooth, no deposit, colour somewhat darkened.
No. 6 (5·07 „ „ „) . . .	Ditto.
No. 9 (7·35 „ „ „) . . .	Ditto.
No. 13 (9·90 „ „ „) . . .	{ Patches of aluminium adhering in places, the surface slightly roughened.
Muntz Metal	{ The surface uniformly dimmed and covered with small brown excrescences.
Naval Brass	{ Slight green deposit in parts, but the polished surface fairly well maintained.

In Table 63 the corrosion is expressed in the form of the alteration in lbs. per square foot per month.

TABLE 63.

Alloy No.	Change in lbs. per square foot per month (30 days).
2	0·0028 lb. loss.
4	0·0001 lb. loss.
6	0·0000
9	0·0000
13	0·0001 lb. gain.
Muntz Metal	0·0014 lb. loss.
Naval Bras	0·0018 lb. loss.

Thus of the five copper-aluminium alloys tested, three showed no signs of corrosion, namely, 6, 9 and 13. The gain in weight of No. 13 is probably due to a slight conversion of the aluminium at the surface into alumina which adheres to the alloy. The corrosion of No. 4 is extremely slight. That of No. 2 is rather more than Muntz Metal and Naval Brass show under similar conditions. Thus copper-aluminium alloys containing from 3 to 10 per cent. of aluminium come well out of this test, and are decidedly superior to Muntz Metal and Naval Brass. It is rather surprising that the Naval Brass corroded more than the Muntz Metal.

(B) *Sea-water Corrosion Tests of Galvanic Couples of the Alloys and Mild Steel.*—The specimens were weighed and measured before and after the test. They were immersed for 123 days, with the exception of the Muntz Metal and Naval Brass couples, which were immersed for 112 days. The surface exposed was 0·093 square foot. In every case the mild-steel plates began to corrode rapidly. The brown hydrated oxide of iron thus formed for the most part did not adhere to the plate, but passed into the liquid. Any

adherent precipitate was removed by lightly brushing the plates when the water was changed weekly. The corrosion of the mild-steel plates was extremely uniform, and continued during the whole test.

For several weeks no change in the copper-aluminium plates occurred. By degrees, however, a coloured surface film formed, and as time went on the surface became slightly dulled. At the end of the test, however, this could be removed by rubbing, except in the case of Naval Brass, which appeared uniformly dulled, and, to a less extent, Muntz Metal. None of the copper alloys showed any appreciable alteration either in weight or dimensions, and were thus perfectly protected by the mild-steel plates. The latter corroded at the rate of about 0.008 lb. per square foot per month.

(C) *Fresh-water Corrosion Tests of Galvanic Couples of the Alloys and Mild Steel.*—These couples were duplicates of those used in the sea-water corrosion tests, and the method of suspension was the same. The tap-water was kept in gentle movement through and out of the vessel during the test, which lasted 126 days. The surface exposed was 0.093 square foot. The chemical composition of the water was as follows :—

Constituent.	Grains per gallon.
Free ammonia	nil
Albuminoid ammonia	nil
Organic carbon	0.016
Calcium carbonate	12.54
Calcium sulphate	0.03
Magnesium sulphate	1.32
Sodium nitrate	0.42
Sodium chloride	2.82
Alumina, phosphates, &c.	0.12

These figures characterise the water as "temporarily hard."

The mild-steel plates corroded rapidly, but the products of corrosion adhered somewhat firmly to the plates, and the action was much less uniform than in the sea-water corrosion tests. The plates were in some parts very much, and in others only slightly, affected. Each week the deposit was removed as completely as possible by brushing. Nevertheless the diminution of thickness amounted in no instance to as much as $\frac{1}{1000}$ th of an inch. The loss of weight averaged about 0.012 lb. per square foot per month, which is rather higher than in sea-water. The copper-aluminium plates also began to corrode after a few days, and as time went on they became roughened and pitted to a slight extent, but no difference in thickness was detected at the end of the test, and the diminution in weight was small, as is shown by the following results:—

TABLE 64.

Alloy No.	Aluminium.	Loss in Weight.
	Per cent.	Lb. per square foot per month.
2	1.06	0.0008
4	2.99	0.0008
6	5.07	0.0008
9	7.35	0.0010
13	9.90	0.0010
Muntz Metal	—	0.0000
Naval Brass	—	0.0000

Thus, in fresh-water of this kind, the copper-aluminium alloys are slightly corrodible to about the same extent, from 1 to 10 per cent. of aluminium, whereas Muntz Metal and Naval Brass withstand corrosive action.

Summary of Corrosion Tests.—In the foregoing tests the conditions were made as severe as possible. Thus, if the plates had not been freed from deposit each week by brushing, it is probable that the

latter would have protected them to some extent from further action. It was considered important, however, to present the alloys in as unfavourable a light as possible, and to publish *maximum* corrosive figures.

The alloys containing from 1 to 10 per cent. of aluminium have shown themselves, under the conditions chosen, to be practically incorrodible by sea-water whether alone or bolted to a plate of mild steel. This is an important result. But it must be accepted with this reservation, that it does not necessarily hold true in cases where sea-water is exposed to local contamination of particular kinds, for example, town drainage, &c. In the sea-water tests (A) these alloys were undoubtedly superior both to Muntz Metal and Naval Brass, which corroded appreciably.

The fresh-water tests gave an opposite result. Muntz Metal and Naval Brass were unaffected, whereas the copper-aluminium alloys corroded to some extent.

It should be mentioned that *cast* plates of the aluminium-copper alloys and *rolled* plates of the Muntz Metal and Naval Brass were used. The authors' experience of etching polished surfaces of cast and rolled materials leads them to think that cast specimens are usually more readily attacked by liquids than rolled specimens. If this is so, then the conditions were severer for the copper-aluminium than the other two alloys.

Electrical Conductivities.—These were not determined for the whole series. The conductivity of Alloy No. 1, containing 0.10 per cent. of aluminium, was measured because it was thought that a high value might be obtained. Such was not the case; the very low value, 76.5 (at 15.6° C. (60° F.)), referred to standard copper at the same temperature being obtained. There is no doubt that this surprising diminution is caused by the $\frac{1}{10}$ th per cent. of aluminium, since the value 99.5 was obtained for the pure copper blank (99.96 per cent.) of the series.

A Comparison of the Properties of Alloy No. 13 with those of Swedish Bessemer Steel of about 0.35 per cent. of Carbon.—The

research described in Part 2 has brought out a fact of very remarkable interest, namely, *that the qualities, both mechanical and physical, of Alloy No. 13 resemble those of a Swedish Bessemer Steel of about 0·35 per cent. of carbon to a truly astonishing degree.* When it is remembered that the former is an alloy of copper and aluminium, the latter an alloy principally of iron, carbon, and manganese, the parallelism of qualities appears especially interesting. It is however a matter of surprise that the resemblance between two well-known alloys—for No. 13 is the so-called Aluminium-Bronze or Aluminium-Gold—has not hitherto, so far as the authors are aware, been adequately described.

(A) *Similarity of Mechanical Properties.* (Rolled Materials.)

Tension Test.

	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.
	Tons per sq. in. *	Tons per sq. in.		Per cent.
Steel (0·35 per cent. carbon) .	15·2	38·0	0·40	26·0
Alloy No. 13	14·8	38·1	0·39	28·8

* This is the true, not the primitive, yield-point (*cf.* page 138).

Although no figures are available for an exact comparison of the quenched alloys, there is an undoubted resemblance between the two. The tenacity is raised and the ductility lowered.

Alternating-Stress Test.

	Maximum Limit of Resistance for one million reversals at 800 per minute, with a ratio of tension to compression of 1·4.
Steel (0·35 per cent. carbon) .	29·5
No. 13	28·3

Impact Test. (Izod Machine.)

	Foot-lbs. absorbed on fracture (without deformation).
Steel (0.35 per cent. carbon) .	4.3
No. 13	4.5

*(B) Similarity of Physical Properties.**Hardness and Hardening Capacity Tests.*

	Hardness Numbers.		Hardening Capacity.
	Annealed.	Quenched in water at 20° C. (68° F.)	
Steel (0.35 per cent. carbon) .	156	402	2.58
No. 13	210	349	1.66

The similarity is probably closer than the above Table represents. The hardness number (210) of No. 13 is that of the unannealed alloy. A lower value would probably be obtained for the annealed alloy. Thus the hardening capacity figure would be raised and brought nearer that of the steel.

Structures. (Plate 13.)

(a) *Rolled Bars.* In both cases the structure is duplex.

	Structural Constituents.	
Steel (0.35 per cent. carbon) .	Ferrite (white) (soft)	Pearlite (dark) (harder).
Alloy No. 13 *	Yellow crystals (soft)	Dark crystals (harder).

* Photo-micrograph Fig. 128, Plate 13.

(b) Bars annealed for a short time.

The structure remains duplex. In both cases a banded structure is developed in the harder of the two constituents. Fig. 129 is typical.

(c) Bars annealed for a long time.

The pearlitic structure eventually disappears. In both cases the resulting duplex structure is almost featureless.

	Structural Constituents.	
Steel (0.35 per cent. carbon)	Ferrite (white)	Massive cementite (white).
Alloy No. 13* . . .	Yellow crystals	Light brown crystals.

* Photo-micrograph Fig. 130.

(d) Bars quenched from a high temperature in water.

The structure becomes markedly acicular in both cases. Fig. 131 is typical of the aluminium-bronze thus treated. The similarity of the so-called martensitic structure of steels to this is very close.

PART 3.

ALLOYS OF INTERMEDIATE COMPOSITION.

This section includes alloys whose composition ranges between 15 and 90 per cent. of aluminium. The analyses have been given in Table 12 (page 101). These alloys do not appear to be of any technical promise. From 15 to 18 per cent. they are very hard, but very brittle. From about 20 to 65 per cent. they diminish in hardness and are so brittle that they can be powdered with ease in a mortar. Most of them break if dropped on a hard floor. This excessive brittleness ceases at about 67 per cent. of aluminium.

Tensile-Stress Tests.—From this percentage up to 90 the alloys possess some tenacity, but no ductility whatever, as the following Tables show :—

TABLE 65.
Chill Castings.

Alloy No.	Aluminium.	Ultimate Stress.	Elongation on 2 inches.	Fracture.
	Per cent.	Tons per sq. inch.	Per cent.	
28	68.3	9.06	0.0	Clean, fine.
29	71.0	9.44	0.0	Clean, fine.
30	80.1	6.76	0.0	Granular, slightly dirty.
31	84.0	6.26	0.0	Clean, granular.
32	89.3	8.69	0.0	Clean, granular, crumbly.

These figures are the mean of two tests.

TABLE 66.
Sand Castings.

Alloy No.	Aluminium.	Ultimate Stress.	Elongation on 2 inches.	Fracture.
	Per cent.	Tons per sq. inch.	Per cent.	
28	68.3	6.00	0.0	These were similar to those of the chill castings.
29	71.0	6.30	0.0	
30	80.1	6.74	0.0	
31	84.0	7.00	0.0	
32	89.3	6.68	0.0	

Structures.—The structures (120 diameters) of sand castings of the sixteen alloys in this class are represented in photo-micrographs, Plates 14 to 16. Broadly speaking these agree well with those shown in Dr. L. Guillet's Paper (*loc. cit.*), but form a more complete series. The structures of Figs. 142 to 144, Plates 15 and 16, which are the lowest freezing alloys of the series, are those of typical eutectics.

PART 4.

THE PROPERTIES OF THE RICH ALUMINIUM ALLOYS.

The percentages of aluminium in these alloys varied from 91.64 to 99.54. These alloys have been studied in considerable detail, but less attention has been given to them than to the rich copper alloys whose technical promise appeared greater.

The general operations of melting and casting alloys of this type under ordinary pressure have been described already (pages 92-93). It was eventually decided to follow the same procedure as in the case of the rich copper alloys, but only after experiments had been made to see whether the properties of the alloys were improved by casting them under pressure. It was hoped that by this means materials of higher tenacity might be obtained without any large increase in density. The attempt to make sand castings under pressure was carried out as follows:—

Casting under Pressure.—The moulding-box was enclosed top and bottom by iron plates well screwed down. In the top plate a hole of $1\frac{1}{2}$ inches diameter was drilled which served as a gate through which the fluid alloy could be poured, and into which an iron plunger fitted. This plunger could be actuated by a hand lever, and served to put pressure on the metal during solidification. The arrangement is shown in photograph, Fig. 165, Plate 20. The results of the experiments, although not unpromising, were rather irregular. The properties of some casts were superior, of others inferior to those cast under ordinary pressure. The authors think that this was a direct consequence of the fact that they were working with only a small quantity of metal. It was necessary to pour at a higher temperature than would have been desirable had the cast been made under ordinary pressure, in order to have time to adjust the plunger in position and apply pressure before the metal in the gate had solidified. This was in itself a drawback, since it had been shown that a high casting temperature militated against good tenacity and ductility. Thus with small castings any

advantages due to pressure are neutralised by the disadvantages due to the temperature at which the metal must be poured. The authors think, however, that in the case of large castings which could be made at a lower temperature, it would be worth experimenting with the material under pressure.

Nine alloys, whose copper varied from 0 to 8 per cent., were prepared. As in the case of the rich copper alloys, six sand and three chill castings, and an ingot for rolling, etc., were made.

Measurements of the *total linear contraction* of castings of Alloys Nos. 33, 35, and 37 on cooling from the freezing-point to the ordinary temperature gave a uniform result, namely, 1.66 per cent. Thus the introduction and addition of copper up to 3.76 per cent. has no effect on the contraction.

Mechanical Treatment.—The ingots were sent to the Milton Works (Staffs) of the British Aluminium Co., and were treated as follows:—

The ingots, 20 inches long and 3 inches diameter, were heated to about 400° C. (752° F.) and rolled in round grooves to 1½ inches diameter. From this a piece about 18 inches long was cut. All the bars were found to be in good condition.

The remainder was divided into three lengths:—

(a) One piece was at once rolled to $\frac{1\frac{3}{8}}{8}$ inch diameter, first through square and finally through round grooves; 4-foot lengths were then available, and they were all in good condition.

(b) Another piece was annealed, drawn down to 1 inch diameter, reannealed, and finally drawn to $\frac{1\frac{3}{8}}{8}$ inch diameter. The drawing was by sixteenths. Bars 38 to 41 inclusive were annealed more frequently, as their behaviour on drawing showed it to be necessary. Even thus, either hollowness or breakage occurred. Of the good bars, about 5-foot lengths were available. Details are given in Table 67:—

TABLE 67.

Bars Drawn to $\frac{13}{16}$ inch diameter with Annealing.

Alloy No.	Copper.	Final Diameter.	Remarks.
	Per cent.		
33	0.00	$\frac{13}{16}$ inch	Bar in good condition.
34	0.86	"	Bar in good condition.
35	1.90	"	Bar in good condition.
36	2.77	"	Bar in good condition.
37	3.76	"	Bar in good condition.
38	4.97	"	Bar drew hollow at the last pass ($\frac{13}{16}$ in.).
39	6.15	"	Bar also annealed at $\frac{7}{8}$ inch. In spite
40	6.91	1 inch	of this part it drew hollow.
41	8.08	$\frac{13}{16}$ inch	Bar drew hollow at 1 inch.
			A piece broke off at $1\frac{1}{8}$ inches. Bar
			annealed after every pass, but drew
			hollow at $\frac{13}{16}$ inch.

(c) The remaining third was drawn without annealing. Bars 33 to 35 were the only ones that could be reduced to $\frac{13}{16}$ inch diameter.

TABLE 68.

Bars Drawn without Annealing.

Alloy No.	Copper.	Final Diameter.	Remarks.
	Per cent.		
33	0.00	$\frac{13}{16}$ inch	Bar in good condition.
34	0.86	"	Bar in good condition.
35	1.90	"	Bar in good condition.
36	2.77	"	Bar drew hollow at the last pass.
37	3.76	$\frac{3}{8}$ inch	Bar broke at last pass.
38	4.97	$1\frac{1}{16}$ inches	Bar drew hollow at 1 inch.
39	6.15	"	Bar drew hollow at 1 inch.
40	6.91	$1\frac{1}{8}$ inches	Bar drew hollow at $1\frac{1}{8}$ inches.
41	8.08	"	Bar drew hollow at $1\frac{1}{8}$ inches.

Five-foot lengths of bars 33 to 35 were available after this treatment.

Specific Gravities.—These were determined at the ordinary temperature on (a) the sand castings; (b) the chill castings; (c) the bars rolled to $\frac{1\frac{3}{8}}$ inch diameter; (d) the bars drawn with annealing to $\frac{1\frac{3}{8}}$ inch. The results have been expressed in two ways:—

- (1) As grammes per cubic centimetre in Table 69.
- (2) As pounds per cubic foot in Table 70 (page 230).

The values calculated in (1) are also shown graphically in Fig. 35.

FIG. 35.

Specific Gravities.

TABLE 69.

Specific Gravities (expressed as grammes per cubic centimetre).					
Alloy No.	Copper.	Sand Castings.	Chill Castings.	Roller Bars $\frac{1\frac{3}{8}}$ inch diameter.	Drawn Bars $\frac{1\frac{3}{8}}$ inch diameter.
	Per cent.				
33	0.00	2.69	2.71	2.71	2.71
34	0.86	2.72	2.73	2.73	2.73
35	1.90	2.73	2.75	2.75	2.75
36	2.77	2.75	2.77	2.77	2.77
37	3.76	2.77	2.79	2.79	2.79
38	4.97	2.78	2.81	2.81	—
39	6.15	2.81	2.83	2.83	—
40	6.91	2.82	2.85	2.85	—
41	8.08	2.85	2.88	2.88	—

TABLE 70.

Specific Gravities (expressed as pounds per cubic foot).					
Alloy No.	Copper.	Sand Castings.	Chill Castings.	Rolled Bars $\frac{1\frac{1}{8}}$ inch diameter.	Drawn Bars $\frac{1\frac{1}{8}}$ inch diameter.
	Per cent.				
33	0.00	168	169	169	169
34	0.86	170	170	170	170
35	1.90	171	172	172	172
36	2.77	172	173	173	173
37	3.76	173	174	174	174
38	4.97	173	175	175	—
39	6.15	175	177	177	—
40	6.97	176	178	178	—
41	8.08	178	180	180	—

As was found for the rich copper alloys, so here the specific gravities of the chill castings and rolled bars are identical. The identity also extends to the drawn bars so far as they have been examined.

With the introduction and addition of copper up to 8 per cent. the specific gravity rises regularly, and a smooth curve results, Fig. 35. The specific gravities of the sand castings are lower and vary less uniformly than those of the chill castings and rolled bars.

TENSILE TESTS.

These tests to the number of about 300 have been carried out on specimens of 0.564 inch diameter and 2-inch gauge length (*cf.* Figs. 6 and 7, page 112).

(a) *Sand Castings*.—The results are given in Table 71 (page 232), and are shown graphically in Fig. 36 (page 233). With the introduction and addition of copper up to 8 per cent. the yield-point rises fairly steadily from 2.5 to 6.5 tons per square inch, whereas there is no *notable* increase in ultimate stress above 3.76 per cent. of copper. Accordingly the elastic ratio rises with fair uniformity from 0.65 to 0.88 as the copper rises from 4 to 8 per cent.

The ductility is quickly lowered by the addition of copper up to 2 and 3 per cent. After this the diminution is less rapid, but above 6 per cent. copper the ductility is almost nil.

(b) *Sand Castings, slowly cooled from 450° C. (842° F.)*.—The results are given in Table 72 (page 234), and are shown graphically in Fig. 37 (page 233). They show that this treatment does not improve the properties of the castings.

(c) *Sand Castings quenched from 450° C. (842° F.) in Water*.—The results are given in Table 73 (page 235), and are shown graphically in Fig. 38 (page 233). This treatment has very little effect on the properties of the castings.

(d) *Chill Castings*.—The results are given in Table 74 (page 236) and are shown graphically in Fig. 39 (page 237). They show that the properties of the chill are superior to those of the sand castings, both in strength and ductility. The absolute values of yield and ultimate stress are higher with only two exceptions. The elastic ratio varies somewhat irregularly, but shows a general rise from 0.44 to 0.68 as the copper increases from 0 to 8 per cent. The alloys containing upwards of 4 per cent. of copper possess satisfactory ductility. At 8 per cent. of copper, however, the ductility is practically nil. The values of the percentage elongation and reduction of area of Alloy No. 34 are probably lower than the true ones, for the character of the fractures and surfaces of the broken test-pieces, both of the sand and chill castings, indicates that this alloy was cast at too high a temperature.

TABLE 71.
Sand Castings.

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	0.00	2.5	4.90	0.51	24.0	39.42	Small holes, bright silky	Wavy cracks.
34	0.86	2.6	5.12	0.51	12.5	12.11	Grossly crystalline	Smooth.
35	1.90	3.3	4.57	0.72	5.5	18.44	Grossly crystalline	Smooth.
36	2.77	3.7	5.22	0.71	4.5	10.96	Grossly crystalline	Smooth.
37	3.76	4.9	7.49	0.65	5.0	7.23	Finely crystalline	Smooth.
38	4.97	5.2	6.73	0.77	4.0	5.00	Granular	Smooth.
39	6.15	6.1	7.72	0.79	*	3.50	Granular	Smooth.
40	6.91	5.2	6.14	0.81	2.0	1.60	Grossly crystalline	Slight cracks.
41	8.08	6.5	7.40	0.88	*	1.99	Coarsely granular	Smooth.

* Broke outside the gauge marks.

The above figures are the mean of two tests in which the average difference in ultimate stress was 0.31 ton, and the greatest difference 0.5 ton per square inch.

TENSILE TESTS.

FIG. 36.—Sand Castings.

FIG. 37.—Sand Castings, slowly cooled from 450° C. (842° F.).

FIG. 38.—Sand Castings, quenched from 450° C. (842° F.) in Water.

TABLE 72.

Sand Castings, slowly cooled from 450° C. (842° F.).

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	0.00	1.9	4.58	0.41	19.0	27.35	Small holes, bright silky	Wavy cracks.
34	0.86	2.5	5.23	0.48	10.5	11.76	Grossly crystalline	Surface cracks.
35	1.90	3.3	4.65	0.71	6.0	22.73	Grossly crystalline	Slight cracks.
36	2.77	4.3	5.56	0.77	5.0	7.30	Grossly crystalline	Slight cracks.
37	3.76	4.9	7.52	0.65	4.0	12.00	Granular	Smooth.
38	4.97	5.5	7.85	0.70	4.0	1.20	Granular	Smooth
39	6.15	6.5	7.28	0.90	3.0	5.00	Granular	Smooth.
40	6.91	5.8	5.83	0.99	*	1.20	Grossly crystalline	Smooth.
41	8.08	5.9	7.08	0.83	*	1.60	Coarsely granular	Smooth.

* Broke outside the gauge marks.

These figures are the mean of two tests in which the average difference in ultimate stress was 0.60 ton, and the greatest difference 1.1 ton per square inch.

TABLE 73.

Sand Castings, quenched from 450° C. (842° F.) in Water.

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	0.00	2.4	5.05	0.47	22.0	33.82	Small holes, bright silky	Wavy cracks.
34	0.86	2.8	5.68	0.49	13.0	21.48	Coarsely crystalline	Surface cracks.
35	1.90	3.6	5.01	0.72	7.0	9.12	Coarsely crystalline	Smooth.
36	2.77	4.6	5.34	0.86	5.0	8.00	Coarsely crystalline	Smooth.
37	3.76	5.7	7.05	0.81	4.0	12.16	Granular	Smooth.
38	4.97	6.2	7.31	0.85	4.0	1.08	Granular	Smooth.
39	6.15	7.0	8.11	0.86	3.5	1.48	Granular	Smooth.
40	6.91	6.1	7.71	0.79	3.0	1.60	Coarsely crystalline	Smooth.
41	8.08	7.6	8.03	0.95	3.0	1.66	Coarsely crystalline	Smooth.

These figures are the mean of two tests in which the average difference in ultimate stress was 0.4 ton, and the greatest difference 0.9 ton per square inch.

TABLE 74.

Chill Castings.

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	0.00	2.3	5.22	0.44	37.0	60.70	Sound, bright silky	Wavy.
34	0.86	3.1	6.12	0.51	15.5	33.25	Sound, crystalline	Wavy.
35	1.90	3.9	8.18	0.48	17.0	26.44	Granular	Wavy.
36	2.77	4.9	8.60	0.57	10.5	24.57	Granular	Wavy.
37	3.76	5.4	9.60	0.56	10.5	21.46	Granular	Wavy.
38	4.97	5.9	9.62	0.61	6.0	9.66	Granular	Slightly wavy.
39	6.15	5.3	9.92	0.54	5.0	10.60	Granular	Slightly wavy.
40	6.91	6.1	9.42	0.65	4.0	4.62	Finely crystalline	Smooth.
41	8.08	7.2	10.65	0.68	*	1.60	Finely granular	Smooth.

* Broke outside the gauge marks.

FIG. 39.—Tensile Tests on Chill Castings.

FIG. 40.—Tensile Tests on Bars rolled down to $1\frac{1}{2}$ inches diameter.

TABLE 75.—*Bars rolled to $1\frac{1}{4}$ inches diameter.*

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. inch.	Tons per sq. inch.		Per cent.	Per cent.		
33	0.00	4.4	6.50	0.68	35.5	79.35	{A few holes, bright silky}	{Longitudinal streaks, wavy, well-marked transverse slip-bands.
34	0.86	5.5	9.35	0.59	30.0	72.93	Sound, bright silky	{Longitudinal streaks, wavy, well-marked transverse slip-bands.
35	1.90	6.4	10.90	0.59	27.5	61.67	Sound, bright silky	Wavy streaks.
36	2.77	6.7	13.89	0.48	26.5	52.24	{Irregular cup and cone, silky}	Slightly wavy.
37	3.76	9.0	16.83	0.54	20.0	38.21	Sound, silky	Frosted.
38	4.97	8.9	14.66	0.61	19.5	36.90	Sound, dull silky	Frosted.
39	6.15	9.1	16.37	0.55	18.0	33.75	Sound, dull silky	Slightly frosted.
40	6.91	9.0	15.38	0.59	13.5	11.54	Sound, dull silky	Slightly dulled.
41	8.08	8.4	14.65	0.57	17.5	23.26	Sound, dull silky	Slightly frosted.

TABLE 76.—Bars rolled to $\frac{1}{16}$ inch diameter.

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. inch.	Tons per sq. inch.		Per cent.	Per cent.		
33	0.00	6.5	7.20	0.90	30.5	81.20	{Double cup, bright silky}	{Longitudinal streaks, wavy, well-marked transverse slip-bands.
34	0.86	7.6	10.47	0.72	28.5	73.33	{Double cup, bright silky}	{Longitudinal streaks, wavy, well-marked transverse slip-bands.
35	1.90	12.8	14.36	0.88	19.0	58.16	{Irregular cup and cone, bright silky}	{Longitudinal streaks, wavy.
36	2.77	12.5	16.57	0.75	16.0	44.60	{Cup and cone, bright silky}	Slight streaks, frosted.
37	3.76	11.6	17.00	0.68	21.0	49.76	Bright silky	Frosted.
38	4.97	10.4	15.15	0.69	19.5	36.40	Dull silky	Frosted.
39	6.15	13.1	17.27	0.76	15.5	33.60	Dull silky	Slightly frosted.
40	6.91	12.2	16.05	0.76	14.5	27.60	Dull silky	Slightly frosted.
41	8.08	11.0	15.31	0.72	17.5	27.60	Dull silky	Slightly frosted.

(e) *Bars rolled to $1\frac{1}{4}$ inches diameter.*—The results are given in Table 75 (page 238), and are shown graphically in Fig. 40 (page 237). The properties of these bars represent in their turn a marked advance upon those of the chill castings, and show the beneficial effect of

FIG. 41.—*Tensile Tests on Bars rolled to $1\frac{3}{8}$ inch diameter.*

mechanical work upon these alloys. The effect is particularly noticeable in regard to ductility, which is well maintained even in the range from 4 to 8 per cent. of copper. At the same time the results show that there is no increase in either yield or ultimate stress above 4 per cent. of copper.

(f) *Bars rolled to $1\frac{3}{8}$ inch diameter.*—The results are given in Table 76 (page 239), and are shown graphically in Fig. 41. They

show that the improvement conferred by mechanical work did not reach a maximum in the previous section (e), but that rolling can be advantageously continued until a reduction of at least 80 per cent. of the original area has been effected, if greater tenacity and a higher

FIG. 42.—Tensile Tests on Bars drawn (with annealing) to $\frac{1}{16}$ inch diameter.

elastic ratio be desired at only a slight expense of ductility. The yield-point and ultimate stress of No. 39 are very similar to those given by Messrs. Yarrow and Co. for their 6 per cent. copper alloy * rolled to a medium extent of hardness.

* "Engineering," 12 April 1895, page 470.

TABLE 77.

Bars drawn (with annealing) to $\frac{13}{16}$ inch diameter.

Alloy No.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	0.00	7.0	7.42	0.94	23.0	82.05	{Cup and cone, bright silky}	{Longitudinal streaks, wavy.
34	0.86	10.2	10.74	0.95	19.0	71.72	{Cup and cone, bright silky}	{Longitudinal streaks, wavy.
35	1.90	12.9	13.80	0.94	16.5	59.44	{Cup and cone, bright silky}	{Longitudinal streaks, wavy.
36	2.77	Drew hollow		—	—	—	—	—
37	3.76	15.5	16.90	0.92	8.0	21.79	{Cup and cone, bright silky}	Frosted.

(The remainder of the alloys drew hollow.)

TABLE 78.

Cold-drawn Bars.

Alloy No.	Diameter.	Copper.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.	Fracture.	Surface.
	Inches.	Per cent.	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.		
33	$1\frac{3}{8}$	0.00	8.5	8.70	0.98	19.5	73.28	{ Cup and cone, bright silky }	{ Longitudinal streaks, wavy. }
34	$1\frac{3}{8}$	0.86	12.2	12.87	0.95	14.5	63.28	{ Cup and cone, bright silky }	{ Longitudinal streaks, wavy. }
35	$1\frac{3}{8}$	1.90	14.0	15.00	0.93	13.0	46.51	{ Cup and cone, dull silky }	{ Longitudinal streaks, wavy. }
36	$1\frac{3}{8}$	2.77	16.4	17.78	0.92	9.5	27.64	{ Cup and cone, bright silky }	{ Frosted, and slightly wavy. }
37	$\frac{3}{8}$	3.76	18.5	20.00	0.92	7.5	20.84	{ Cup and cone, bright silky }	Frosted.
38	$1\frac{1}{8}$	4.97	15.9	17.73	0.90	6.0	20.84	Silky	Slightly frosted.
41	$1\frac{1}{8}$	8.08	15.4	16.45	0.94	5.5	15.04	Dull silky	Slightly frosted.

(g) *Bars drawn (with annealing) to $\frac{1}{8}$ inch diameter.*—The results are given in Table 77 (page 242), and are shown graphically in Fig. 42. As was to be expected, the elastic ratios are uniformly higher than those in Table 76, but these are only gained at the expense of ductility. No tests were carried out on bars Nos. 36, 38, 39, 40 and 41, which were found to have drawn hollow.

(h) *Bars cold-drawn.*—The results are given in Table 78 (page 243), and are shown graphically in Fig. 43. This treatment produces the stiffest forms of the alloys examined, but in every case a considerable measure of ductility is retained, particularly as evidenced by the reduction of area.

Summary of Tensile Tests.

The broken test-pieces are shown in photograph, Fig. 160, Plate 19.

(1) These alloys appear to be unaffected by such heat treatment as quick or slow cooling.

(2) Small chill castings possess superior mechanical qualities to sand castings.

(3) In order to get the full value of the inherent properties of the alloys, a *considerable* amount of mechanical work, *e.g.* rolling or drawing, with or without annealing, should be performed on them. From 0-8 per cent. of copper all the alloys roll well, and from 0 to about 4 per cent. of copper they draw sound. As an illustration of the beneficial effect of mechanical work, Alloy No. 37 is selected. The facts are summarised in the following Table :—

TABLE 79.

Condition.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 2 inches.	Reduction of Area.
	Tons per sq. in.	Tons per sq. in.		Per cent.	Per cent.
Chill casting	5.4	9.60	0.56	10.5	21.46
1½-inch rolled bar	9.0	16.83	0.54	20.0	38.21
1½-inch rolled bar	11.6	17.00	0.68	21.0	49.76
1½-inch bar drawn } with annealing . }	15.5	16.90	0.92	8.0	21.79
3½-inch bar drawn } without annealing }	18.5	20.00	0.92	7.5	20.84

The improvements effected in yield-point and reduction of area are particularly noticeable, and important. An alloy whose specific gravity is only 2.79, whose yield-point is 18.5 tons, and whose reduction of area is 20.84, may have an industrial future in cases where a combination of lightness and strength is desired.

(4) The tests of the sand and chill castings, of the rolled and drawn bars, agree in showing that nothing is to be gained by adding more than 4 per cent. of copper to aluminium. The introduction of copper causes a fall of ductility, and a rise of tenacity, which are fairly steady up to 4 per cent. Beyond this there is no increase in tenacity while the ductility continues to diminish.

(5) The elastic ratios of these rich aluminium alloys average much higher than those of the rich copper alloys.

Tensile Tests of the Alloys in the form of Sheets.—Special castings were made for these tests at the Milton Works of the British Aluminium Co., under the superintendence of Dr. Seligman and one of the authors. About 12·5 lbs. of each alloy were made by melting down suitable mixtures of pure aluminium and the 50 per cent. alloy in a plumbago crucible heated in a coke-fired furnace. After being stirred and cleaned with an iron rod, the alloy was allowed to cool until, on skimming, the surface kept silvery white. It was then cast into an ingot $6\frac{3}{4}$ inches by $9\frac{3}{4}$ inches by $\frac{5}{8}$ inch. This was rolled hot to $\frac{3}{8}$ inch, allowed to cool, and then rolled cold to $\frac{1}{4}$ inch. The slab was then cut into five pieces as shown in the following sketch.

A. L.	A. T.	U. T.	
U. L.			

The slabs marked U. L. (*i.e.* unannealed longitudinal) and U. T. (*i.e.* unannealed transverse) were reserved for test. Those marked A. L. and A. T. were annealed at about 500° C. (932° F.) and also reserved for test. The remaining large piece was annealed at 500° C. and then rolled down to $\frac{1}{10}$ inch. No. 47 cracked at 0·133 inch, and No. 48 at 0·178 inch. These had to be reannealed before further rolling. The slab was then cut up, and the pieces marked and treated as before. After being annealed, the large piece was rolled down to $\frac{1}{20}$ inch. Nos. 47 and 48 required an extra

annealing when the thickness was 0.07 inch.²⁵ The sheet was then cut up as before. Thus of the seven alloys prepared, twelve pieces of each were available for test, namely, four pieces each, A. L., U. L., A. T., and U. T., in thicknesses of 0.25, 0.1, and 0.05 inch.*

The full analyses of the alloys are given in Table 14 (page 103). The form of the test-piece is shown in Fig. 44, the large diameter being 1 inch and the distance between the gauge-marks 3 inches. The total parallel length was $3\frac{1}{2}$ inches.

Of the eighty specimens broken in tension, forty were longitudinal and forty transverse. On comparing the results it was found that in twenty-eight cases the difference between the tenacities of

corresponding longitudinal and transverse specimens was less than 1 ton per square inch. Of the remaining twelve, in which the differences ranged between 1 and 3 tons per square inch, higher values were obtained in the transverse specimens in nine cases. Thus, although there is a slight balance in favour of the transverse specimens, it is hardly sufficient to warrant the conclusion that they are superior to the longitudinal ones. Accordingly the values given in the following Tables are the mean of those obtained from specimens cut longitudinally and transversely.

Tensile-Stress Tests.—(a) *Plates 0.25 inch thick.*—The results are given in Table 80 (page 250), and are shown graphically in Fig. 45 (page 248).

* Nos. 47 A. L. and A. T., 48 A. L. and A. T., of thickness 0.25 inch, were missing.

Unannealed Specimens.—The values are similar to those obtained with the cold-drawn bars, Table 78 (page 243), but are rather inferior both in tenacity and ductility. The elastic ratio is steady between 0.91 and 0.96. Alloy No. 48 is brittle.

FIG. 45.—Tensile Tests on Plates 0.25 inch thick.

Annealed Specimens.—The elastic ratio is about half that of the unannealed alloys, and varies between 0.40 and 0.51. Ductility is well maintained throughout the series.

(b) *Plates 0.10 inch thick.*—The results are given in Table 81 (page 251), and are shown graphically in Fig. 46 (page 249). The tenacity of the unannealed alloys is slightly higher than in the

previous series (0.25 inch), but the properties do not exhibit the same uniformity. Thus the elastic ratio varies between 0.78 and 0.96. The ductility is lower than in the previous series.

Annealed alloys, Nos. 42 to 46, are very similar to those of the previous series. But Nos. 47 and 48 are obviously unannealed,

the values agreeing with those obtained with the unannealed specimens.

(c) Plates 0.05 inch thick.—The results are given in Table 82 (page 253), and are shown graphically in Fig. 47 (page 252). They are very similar to those of the previous series. There is a slight increase in the tenacity and a decrease in the ductility of the unhardened alloys.

TABLE 80.

Plates 0.25 inch thick.

Alloy No.	Copper.	Condition.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 3 inches.
	Per cent.		Tons per sq. in.	Tons per sq. in.		Per cent.
42	0.00	U	7.9	8.36	0.95	10.6
43	0.93	U	11.0	11.94	0.92	7.0
44	1.57	U	13.0	13.80	0.93	5.3
45	2.36	U	13.4	14.13	0.95	4.3
46	3.74	U	14.9	15.60	0.96	4.0
47	4.74	U	14.8	16.20	0.91	2.0
48	5.34	U	12.5	13.56	0.92	*
42	0.00	A	2.7	5.91	0.46	41.0
43	0.93	A	3.7	8.18	0.45	28.7
44	1.57	A	4.5	10.02	0.45	24.7
45	2.36	A	5.0	9.69	0.51	28.6
46	3.74	A	4.3	10.76	0.40	24.0

* Broke outside gauge-marks.

U (unannealed).

A (annealed at about 500° C. (932° F.)).

TABLE 81.

Plates 0.10 inch thick.

Alloy No.	Copper.	Condition.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 3 inches.
	Per cent.		Tons per sq. in.	Tons per sq. in.		Per cent.
42	0.00	U	8.6	9.18	0.94	6.3
43	0.93	U	11.5	12.96	0.88	4.7
44	1.57	U	12.7	16.20	0.78	5.3
45	2.36	U	11.6	14.84	0.78	5.3
46	3.74	U	16.8	17.58	0.96	4.0
47	4.74	U	14.3	15.16	0.94	4.7
48	5.34	U	12.3	13.26	0.93	*
42	0.00	A	3.0	5.90	0.51	31.0
43	0.93	A	3.8	8.09	0.47	31.7
44	1.57	A	4.6	10.43	0.44	25.3
45	2.36	A	4.8	11.60	0.41	25.3
46	3.74	A	5.1	11.00	0.46	21.0
47	4.74	A?	13.8	15.82	0.87	4.6
48	5.34	A?	12.4	13.48	0.92	2.0

* Broke outside gauge-marks.

U (unannealed).

A (annealed at about 500° C. (932° F.)).

Summary of Tensile Tests.—The variations of properties caused by the introduction and addition of copper to aluminium have been found to be very similar in the alloys in the form of sheets to those in the form of rolled and drawn bars. In particular, the conclusion previously drawn that nothing is gained by adding more than 4 per cent. of copper has been confirmed by these experiments.

FIG. 47.—*Tensile Tests on Plates 0.05 inch thick.*

Structures.—The rich aluminium alloys are difficult to grind and polish. Up to a certain point they can be ground on emery papers. The authors have found, however, that the emery of the fine papers (00 and beyond) tends to work into the aluminium, and leave a deposit which cannot be removed on the wet cloth polishing block. If ordinary blotting-paper be substituted for 00 emery, the film can

TABLE 82.

Plates 0.05 inch thick.

Alloy No.	Copper.	Condition.	Yield-Point.	Ultimate Stress.	Elastic Ratio.	Elongation on 3 inches.
	Per cent.		Tons per sq. in.	Tons per sq. in.		Per cent.
42	0.00	U	8.4	9.34	0.90	3.7
43	0.93	U	11.7	12.16	0.96	3.3
44	1.57	U	13.8	15.16	0.91	3.3
45	2.36	U	15.3	16.85	0.91	4.0
46	3.74	U	15.9	18.56	0.85	4.0
47	4.74	U	14.7	16.77	0.88	4.0
48	5.34	U	14.3	16.52	0.87	*
42	0.00	A	3.2	5.83	0.55	36.3
43	0.93	A	3.4	8.46	0.40	29.2
44	1.57	A	4.1	10.61	0.39	25.7
45	2.36	A	4.5	11.76	0.38	24.7
46	3.74	A	4.9	11.66	0.42	24.7
47	4.74	A	4.8	11.93	0.40	18.7
48	5.34	A	5.6	12.16	0.46	21.7

* Broke outside the gauge-marks.

U (unannealed).

A (annealed at about 500° C. (932° F.)).

be removed, and a clear polished surface is afterwards obtained on the wet block. Only the lightest pressure is required.

The most suitable etching reagent has been found to be a 10 per cent. cold aqueous solution of sodium hydrate. The average time required is from 3 to 5 minutes. The castings etch more readily than the rolled bars.

Dr. L. Guillet's microscopic work in this field has been confirmed and extended by the authors. Photo-micrographs, Figs. 149 and 150, Plate 17, are typical of the structure of a sand and chill casting respectively of Alloy No. 33, containing 99.54 per cent. of aluminium, small quantities of silicon, iron and sodium, but no copper. The chill casting shows no eutectic. That observed in the sand casting is probably caused by the impurities above mentioned. The introduction of copper (according to Guillet above 0.05 per cent.) causes the separation of what is probably a copper-aluminium eutectic, which increases with each further addition of copper. This fact is shown by photo-micrographs, Figs. 151 to 156, Plates 17 and 18, which typifies the structures of Alloys Nos. 35, 37, and 41, containing 1.90, 3.76 and 8.08 per cent. of copper respectively.

The effect of slow cooling is to distribute this eutectic as a cement round the crystals, which are probably nearly pure aluminium. Photo-micrographs, Figs. 157 and 158, Plate 18, represent at magnifications of 120 and 800 diameters respectively the structure of Alloy No. 38 containing 4.97 per cent. of copper.

Corrosion Tests.—These were carried out in sea-water and fresh-water. The general conditions observed were the same as in the tests of the rich copper alloys. The materials were tested singly, and not with mild steel plates. Tests were made on Alloys Nos. 42 to 48 containing from 0.6 per cent. of copper. Plates about 3 inches square were cut from the rolled sheets, 0.05 inch thick, and the edges polished. The surface exposed was 0.129 square foot. The duration of the test was 62 days.

(A) *Sea-Water Tests.*—The corrosion of the plates took place steadily throughout the test. In each case there was a regular

stream of hydrogen given off in minute bubbles, due to the decomposition of the water probably by the sodium and aluminium present. The aluminium hydrate formed in white tufts, which were however dislodged from the plates by slight shaking. At the end of the test the plates were found to be markedly pitted. With increasing copper the pitting was more uniformly distributed. The results of the test are given in Table 83.

TABLE 83.

Alloy No.	Copper.	Loss of Weight.
	Per cent.	Lbs. per square foot per month (30 days).
42	0.00	0.008
43	0.93	0.008
44	1.57	0.008
45	2.36	0.007
46	3.74	0.005
47	4.74	0.004
48	5.34	0.003

These losses of weight must be regarded as considerable when it is remembered that the alloys are light. They diminish with rising copper after 2 per cent. is passed, but even in the case of No. 48, which corroded least, the loss of weight is large. The corrosion of Alloys 42 to 44 was about $3\frac{1}{2}$ times that which would have been experienced by mild steel. The results show that these alloys cannot be used for shipbuilding in cases where lightness of material is desired, except when protected from the action of sea-water by a suitable "coating composition."

(B) *Fresh-Water Tests.*—The behaviour of the alloys was quite different in fresh-water, of which the analysis has been already given (page 219). So far from losing weight, they all gained it slightly,

except Alloy No. 42 (containing no copper), whose weight remained constant. This alloy was unattacked, except to a minute extent. The remaining six were corroded, giving off small quantities of hydrogen, but the aluminium hydrate formed remained as an adherent deposit on the plate and protected it from further action. The small gain in weight was very nearly the same in all cases.

Summary of Corrosion Tests.—Thus the rich aluminium alloys have proved to be strongly corroded by sea-water, but uncorroded by fresh-water of the type used. The rich copper alloys exhibited an opposite behaviour, being uncorroded by sea-water and slightly, but quite appreciably, corroded by fresh-water.

Experiments to test the Suitability of the Alloys for Cooking Utensils.—Plates similar to those used in the corrosion tests were exposed for six hours continuously to the action of—

- (a) boiling tap water.
- (b) boiling 1 per cent. aqueous oxalic acid.
- (c) „ 1 „ „ acetic „
- (d) „ 2 „ „ citric „

The concentrations of solutions *b* to *d* represent the maxima likely to be met with in ordinary cooking operations. The results are given in Table 84.

TABLE 84. *

Alloy No.	Copper. Per cent.	Loss in lbs. per square foot per hour in boiling.			
		Water.	1 per cent. Aqueous Oxalic Acid.	1 per cent. Aqueous Acetic Acid.	2 per cent. Aqueous Citric Acid.
42	0.00	Nil.	0.0010	0.0002	0.0001
44	1.57	„	0.0019	0.0002	0.0002
45	2.36	„	0.0020	0.0001	0.0002
46	3.74	„	0.0021	0.0002	0.0002
47	4.74	„	0.0022	0.0002	0.0002
48	5.34	„	0.0023	0.0003	0.0003
		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>

The plates exposed to boiling tap water were found to have gained slightly in weight, due to a deposit of carbonate precipitated from the water by the process. The loss of weight caused by oxalic acid was about 10 times that caused by either acetic or citric acid, but even in this case the absolute loss was small. Broadly speaking, the more copper the alloys contained the greater was their corrosion by these reagents.

An important fact noticed was that no copper was removed from any of the alloys in any of the tests. The loss of weight was due to the withdrawal of aluminium, which is not poisonous. The tests show, however, that *pure* aluminium is the most suitable material for cooking utensils.

Concluding Summary.—Except in regard to a few points, the properties of aluminium-copper alloys have been fairly thoroughly elucidated by this research. An important omission is that of hydraulic tests of castings. These tests have actually been made, but the results were unsatisfactory because the original castings were too thin to allow of sufficient machining to give smooth sound surfaces. This omission would have been made good, but for the necessity of winding up the research caused by one of the authors having to relinquish the work. Broadly speaking, however, the limits of these binary alloys are now set, and the way is clear for investigating the influence of a third metal.

The foregoing research would have been impossible of execution without the co-operation of the Broughton Copper Co. and the British Aluminium Co., and the authors have the greatest pleasure in thanking Mr. Leonard Sumner and Mr. F. Tomlinson of the former, and Mr. Bonner, Mr. Harvey, and Dr. Seligman of the latter works for their cordial help whenever asked for. They desire to thank Dr. Glazebrook, the Director of the Laboratory, for having arranged for the testing resources of the various departments to be at their disposal, thus rendering possible the large number of tests that have been made. To various members of the staff they are much indebted: to Dr. Stanton, Mr. Jakeman and Mr. Bairstow of

T

the Engineering Department, and Messrs. Naylor and Gemmell of the Chemical Department, upon whom the brunt of the co-operation has fallen ; also to Mr. Jeffcott of the Metrological and Mr. Melsom of the Electrical Departments.

The Report is accompanied by an Appendix, and is illustrated by Plates 1 to 22 and 49 Figs. in the letterpress.

APPENDIX.

The Equilibrium Curves and Constituents of Aluminium-Copper Alloys.—The constitution of the alloys has been investigated in some detail by a study of their cooling curves and structures in conjunction with quenching experiments, and the results have been embodied in a compact form in the equilibrium diagram, Fig. 33 (pages 204–205), in which the ordinates represent degrees of temperature (C. and F.) and the abscissæ percentages of copper and aluminium.

The Liquidus Curve, that is, the temperature curve at which liquid of any given composition begins to deposit solid is represented by the line ABCDEFGHJK, in which each circle marks an observed point. This curve, which was obtained by “direct” cooling, agrees well with that published by Dr. L. Guillet,* except that at about 46 per cent. of aluminium the authors have not found so marked a change of slope as he did. It contains several points of flexure, notably at B, D, H and J. The absolute rise of the curve from B to D is caused by the separation, probably of two compounds, in this range, of which the simplest molecular formulæ are Cu_4Al and Cu_3Al . The relative rise at H is due to the separation of the compound CuAl_2 whose existence has been known for some time. The point J (67 per cent. of aluminium) corresponds to the alloy of minimum melting point of the entire series which has a typical eutectic structure, Fig. 143, Plate 15.

The alloy corresponding to B, which is also a minimum point, does not however show a eutectic structure, Figs. 56–58, Plate 2,

* Revue de Métallurgie, 1905, page 568.

but appears to be a solid solution. At the time that this discovery was made it was, so far as the authors are aware, unique. A similar case, observed with copper-manganese alloys, has however been recently announced,* but without any attempt by the author to explain it. These are instances of some theoretical interest, and it appears worth the attempt to endeavour to account for them. Let the case of two metals A and B, Fig. 176, which form solid solutions, be considered. Let A be capable of dissolving n parts of B, and B n' parts of A, and let o be the minimum on the liquidus curve.

FIG. 176.

FIG. 177.

Then the alloys between n and o will consist of solid solutions of B in A with eutectic, and those between o and n' of solid solutions of A in B with eutectic. The alloys at o will be entirely eutectic, that is, a mixture of the two solid solutions.

Now let B be replaced by C which can be dissolved by A up to the point o . Two series of solid solutions will then result, the liquidus of each melting at o , Fig. 177. The alloy at the point o will then not show a eutectic (duplex) structure, but will consist of a *saturated solid solution* † of C in A. It is this limiting case which appears to

* Revue de Métallurgie, 1907, page 38.

† The meaning attached by the authors to the term "solid solution" is that given by Messrs. Heycock and Neville (Bakerian Lecture, 1903. Phil. Trans. Royal Society, vol. 202, page 7), viz. "the term implies that the two components are capable of being as uniformly mixed as in a liquid solution, and also implies

characterize the solubility relations of copper and aluminium at the point B, and the authors think this is the only explanation of the fact that this alloy does not show what has been generally recognized as the typical structure of a eutectic.

The Solidus Curve.—This determination is notoriously more difficult than that of the liquidus curve. The method recommended by Messrs. Heycock and Neville (*loc. cit.*) of studying polished and etched sections of chilled ingots has been extensively used. Differential cooling-curves have also rendered valuable information as to the chilling temperatures, by shortening the time required for locating the point at which the whole ingot has become solid. The solidus curve cannot be given in its entirety. From 16 per cent. aluminium upwards it appears to be $FefghHjJkK$, Fig. 33, the dots representing observed points. From 16 per cent. downwards all attempts to distinguish between "liquidus" and "solidus" have failed. At the point D (12.0 per cent.), where a compound of the empirical formula Cu_3Al separates, the liquidus and solidus necessarily coincide. But, apart from this exception, the phase rule requires that a liquid depositing a solid solution of two metals should produce initially a solid whose composition differs from that of the residual liquid. There can be little doubt but that, in this range of percentages, the solidus lies so near the liquidus that the present weapons of experimental attack are inadequate to the task of distinguishing between them.

Between 16 and 27 per cent. of aluminium the solidus curve falls rapidly from F to e, then turns and slopes downwards gradually to f, after which it falls steeply to h. From h to H the curve rises slightly, and after falling abruptly to j becomes a horizontal line, passing through J and continuing to k (95 per cent. of aluminium); from there it rises steeply to K. The horizontal line jJk corresponds

the possibility of continuous variation in the percentage composition of the mixture" . . . but "it does not imply the necessity of crystalline structure" . . . and "does not exclude the possibility that the same crystal may be, as is often the case, made up of layers of different composition."

to the separation of one and the same eutectic at about 540° C. ($1,004^{\circ}$ F.). The line gH corresponds to the appearance and growth to a maximum of a constituent designated δ . The authors are of opinion that the curve $hHjJkK$ may be accepted as a well-established solidus, but that, although $Fefgh$ (16 to 27 per cent.) is substantially correct in character, it does not possess the same degree of precision.

In addition to the foregoing, other evolutions of heat have been detected; some of them between the liquidus and solidus, for example, between 23 and 37 per cent. of aluminium—others considerably below the solidus, namely, between 7.35 and 16 per cent. Some of these have been shown to be accompanied by structural changes.

The diagram of equilibrium curves consists of a series of closed compartments, each of which contains one or more structural constituents designated by particular letters; and in order to facilitate their study the following brief account of them is given here. Excluding constituents which are obtained by chilling, the authors have obtained evidence of six, namely, α , α' , β , γ , δ , and ϵ .

α is a solid solution of aluminium in copper containing up to about 9.4 per cent.

Examples are given in Fig. 57, Plate 2, and Fig. 89, Plate 7.

α' is the compound Cu_4Al .

β „ „ „ Cu_3Al .

These are shown in Fig. 130, Plate 13, α' being the lighter of the two constituents. These formulæ represent molecules of minimum size. The compounds themselves may consist of multiples of these.

γ is a solid solution which may contain between 16 and 27 per cent. of aluminium, Fig. 132, Plate 14. (For a reference to γ' , see page 266.)

δ is the compound CuAl_2 , and is represented by the white grains in Figs. 139 and 140, Plate 15, and by the dark grains in Figs. 136–138, Plates 14 and 15.

ϵ is a solid solution of copper in aluminium containing very little copper, and is typified by the white structural constituent in Figs. 146, 147, and 148, Plate 16.

It will be most convenient to discuss the equilibrium between the phases of the alloys grouped under AB, BC, CD, &c. (*cf.* the liquidus curve).

*Group AB (containing from 0 to 7.35 per cent. of aluminium).—*On cooling the fluid alloys to the liquidus, there is a large heat-evolution, sufficient to maintain the temperature almost steady during solidification. Below this no heat-evolutions have been observed. The properties of the alloys are practically unaffected by heat-treatment. From the solidus downwards, the α is the sole constituent. This is the simplest group. The structure consists of golden-coloured grains of varying brightness.

*Group BC (aluminium 7.35 to 9.6).—*These alloys, as ordinarily prepared, are in a metastable condition, and consist of α with a conglomerate of $\alpha' + \beta$. At the temperature of the line Ba the solution begins to deposit α' , and this appears to continue until about 580° C. (1,076° F.) (line 1), where β undergoes a change as a result of which it can dissolve no more α' . The final product is a mixture of α , α' and β . (*Cf.* Fig. 63, Plate 3, where the light grains represent α , and the dark $\alpha' + \beta$.) On the other hand, when care is taken to cool the alloys very slowly from the solidus to enable the phases to take up their proper equilibria corresponding to any particular temperature, α is the sole product, at any rate up to about 9.4 per cent. of aluminium. (*Cf.* Fig. 89, Plate 7.)

*Group CD (aluminium 9.6 to 12.0 per cent.).—*At the solidus these alloys consist of solid solutions of α' in β , which remain unchanged until the temperature of the line ab is reached. Along this line the solution begins to deposit α' , and this continues until the temperature of the line 2 (about 530° C., 986° F.) is reached, when β can no longer hold α' in solution. The course of this deposition is well seen in Figs. 124–127, Plate 12. Fig. 124 shows the structure of the solid solution of α' in β , quenched above the line ab . This is acicular. The appearance of α' below ab and its gradual growth are indicated by the white grains, which are in

reality, yellow or golden, in Figs. 125-127, together with the gradual loss of acicular structure. The reverse change is shown in Figs. 120-123, but most clearly in Figs. 130, Plate 13, and 166, Plate 21. Fig. 130 represents α' (light) and β (dark)—both structureless; Fig. 166 shows the structure of the alloy quenched in water on a rising temperature at 550° C. (1,022° F.). It will be observed that, with the incipient solution of α' in β , the latter becomes acicular.

The isolation of substantially pure α' from the mixture was effected by placing a thin sheet of an alloy containing 10.70 per cent. of aluminium at the positive pole of a battery, using ferric chloride in hydrochloric acid and water as electrolyte. β as the more electropositive of the two constituents dissolved the more rapidly. Analyses of the crystalline residue thus obtained gave results agreeing closely with that required by the formula Cu_4Al , viz. 9.57 and 9.56 per cent. of aluminium (theoretical percentage = 9.60). The authors are accordingly of opinion that the yellow or golden grains (seen as white in Fig. 130) are the compound Cu_4Al , and that this exists neither in the liquid state nor in contact with the liquidus, but that it is only formed from solid solutions of the CD alloys or by prolonged heating of an alloy containing 9.6 per cent. of aluminium.

At the point D an alloy contains no Cu_4Al , and consists entirely of the β constituent, namely, Cu_3Al . The maximum, D, does not exactly correspond to this compound, but possibly it is slightly displaced by the impurities present. B is electropositive to α' , and when the CD alloys are etched with ferric chloride in hydrochloric acid and water, β is darkened.

These alloys undergo a further thermal change between 400° and 300° C. (752° and 572° F.) on falling temperatures, which however has not been connected with any structural change.

Group DE (aluminium 12.0-14.0 per cent.).—At the solidus these alloys consist of solid solutions of γ and β , which do not undergo any change until the temperature of the line *cb* is reached. Along this line γ is deposited from the solution, the deposition being

complete at the temperature of the line 3, at which β undergoes a polymorphic change. Fig. 167, Plate 21, shows the structure of an alloy containing 13.2 per cent. of aluminium quenched in water from 680° C. (1,256° F.), that is, just above the point at which γ would separate along *cb*. This consists of a solid solution of γ in β . There is also an evolution of heat at line 4 which is due to a change in the γ constituent.

Group EF (14–16 per cent. of aluminium).—These alloys on freezing form γ and a solid solution of γ and β , and the changes in the solution are similar during cooling to those in group DE. γ is electro-positive to β , and when these alloys are etched the γ constituent is darkened. (Cf. Figs. 168, Plate 21, and 133, Plate 14.) γ containing only traces of β (15.7 per cent. of aluminium) is shown in Fig. 169, Plate 21, which represents the structure of a polished but unetched surface. In this case β appears as the dark constituent, although its real colour is pale gold.

Group FG (16–27 per cent. of aluminium) [Liquidus FG, solidus Fefgh].—In this range an evolution of heat occurs along the line *defG*. Its intensity is increased, and the temperature at which it is developed is raised on augmenting the aluminium from 16 to about 20 per cent. In this range the thermal is unaccompanied by any detectable structural change, but between 20 and 27 per cent. a structural change is quite evident. As an illustration the behaviour of an alloy containing 23 per cent. may be considered. Above the line *efG* the structure is simplex, but at this line a very fine duplex structure becomes manifest. (Cf. Fig. 170, Plate 22, quenched from 840° C. (1,544° F.), that is, some 20° C. below the line.) It consists of a light and dark constituent. As the temperature falls the former grows at the expense of the latter. (Cf. Fig. 171 quenched from 700° C. (1,292° F.) and Fig. 172 quenched from 550° C. (1,022° F.), which reveals the last traces of the dark constituent.) At 500° C. (932° F.) the dark constituent entirely disappears. It has been found that between 860° and 520° C. (1,580° and 968° F.) these two constituents exist in

equilibrium and that there is a definite ratio of the two for any given temperature; further, that this ratio is the same whether the temperature be approached from above or below. These alloys may thus be classed as being thermally reversible.

Alloys containing more than 23 per cent. of aluminium show structures similar to those presented in Figs. 170-172 except in regard to a difference caused by the presence of liquid alloy below *efG*, which increases from 23-27 per cent. of that metal. This is seen in Fig. 173 which represents a 25-per-cent. alloy quenched in water from 800° C. (1,472° F.). The dark cores are duplex and are undergoing the change from dark to light material. The white borders represent metal which freezes below *efG* and has the same composition as that of the liquid.

The structures of an alloy containing 27.1 per cent. of aluminium are shown in Figs. 174 and 175. The former characterizes the alloy quenched only 17° C. below the liquidus, the white areas representing metal fluid at the moment of chilling; the latter indicates the structure of a chill casting and is almost homogeneous.

The authors are not at present prepared to give a fuller explanation of the nature of the constituents of this group.

Group GH (27-46 per cent. of aluminium) [Liquidus GH, solidus *hH*].—These alloys are duplex in structure, and consist of the γ and δ constituents. * [Although γ appears as γ' in the diagram, the authors are unaware of any structural or chemical difference between the two; which are distinguished solely by the fact that γ' represents γ which has undergone the change at the line *defG*.] At the liquidus γ' separates and grows with falling temperature. The line 5 indicates the temperature at which δ is formed. The liquidus and solidus meet at H, corresponding to the separation of the compound CuAl_2 . Along the line 6 there is a further heat evolution, apparently unassociated with structural change. The compound CuAl_2 has been isolated by the following method, but

* γ' is electro-negative to γ , and the latter therefore appears dark in etched specimens containing both constituents.

not in a perfectly pure state. When an alloy containing 55 per cent. of aluminium is melted, poured into an open-topped sand mould and allowed to cool, as soon as the temperature has fallen to about 570°C . ($1,058^{\circ}\text{F}$.) the crystallization of the compound CuAl_2 is clearly visible. If at this stage the still molten eutectic is tapped from the bottom, long acicular crystals of the compound remain behind.

But in this form the crystals are not chemically pure, since a portion of the eutectic still adheres mechanically to them. Cold *aqua regia* is without action on these crystals, but they are slowly dissolved by boiling. Mixtures of γ and δ are seen in Figs. 135, 136, 137 and 138, Plates 14 and 15. In these δ appears as the dark constituent, being more electro-positive than γ and dissolving more quickly when etched. But in Figs. 139–142 it appears as the light constituent, being electro-negative to the eutectic.

Group HJ (46–67 per cent. of aluminium) [Liquidus HJ, solidus H δ J].—At the liquidus δ crystallizes out and the liquid gradually becomes enriched with aluminium until it contains about 67 per cent., which mixture solidifies at about 540°C . ($1,004^{\circ}\text{F}$.). There is no further change, and the alloys at the ordinary temperature consist of δ + eutectic, Figs. 139–142, Plate 15.

Group JK (67–100 per cent. of aluminium) [Liquidus JK, solidus J δ K].—These alloys consist of solid solutions of copper in aluminium, with eutectic between 67 and 95 per cent. of aluminium.

*Comparison of results with those obtained by Dr. L. Guillet.**—As already stated there is very satisfactory agreement between Dr. Guillet's liquidus curve and that determined by the authors, except in one particular, which is however of minor importance. He experienced considerable difficulty in tracing the solidus curve, and regarded his published result as only approximately accurate. It is less

* "Étude théorique et industrielle des alliages de Cuivre et d'Aluminium." *Revue de Métallurgie*. Août 1905.

complete than that given in the present Report. His view that at about 66, 46-48, 30 and 11-12 per cent. of aluminium the alloys solidify at one temperature has been confirmed by the authors with one exception, namely, the 30 per cent. alloy appears to continue freezing through about 200°C . (392°F .), namely, from 790° - 586°C . ($1,454^{\circ}$ - $1,086^{\circ}\text{F}$.) (*cf.* Fig. 33, pages 204-205). Moreover the authors think the evidence justifies the conclusion that at 9.6 per cent. of aluminium the alloy crystallizes at one temperature.

As regards the number and character of the constituents the agreement between the two sets of results is, speaking broadly, satisfactory, but there is one important difference. Dr. Guillet specifies AlCu (corresponding to about 30 per cent. of aluminium) as one of the constituents of the alloys. He was however unable to isolate a compound of this composition, and an examination of his photo-micrographs does not, in the authors' opinion, establish his view. The evidence obtained by them argues against it. The alloys in the immediate neighbourhood of this particular composition solidify over a wide temperature range, and are duplex in structure, consisting of a mixture of the compound CuAl_2 (δ) and a solid solution of aluminium in copper (γ).

With respect to the constituent β , Dr. Guillet was unable to decide whether it consisted of the compound Cu_3Al or a solid solution. The authors' experiments have decided the question in favour of the former alternative.

The compound Cu_4Al , unsuspected by him, has been added.

*Comparison with Messrs. Heycock and Neville's Temperature Concentration Diagram of Copper-Tin Alloys.**—A comparison of the equilibrium curves of the copper-tin and the copper-aluminium alloys furnishes an interesting study of resemblances which could hardly have been suspected.

(1) In both cases the α crystals consist of a solid solution of the respective metal to the extent of not more than about 9 per cent. in

* Philosophical Transactions, Royal Society. 1903. Series A. Vol. 202, page 1. Bakerian Lecture. On the Constitution of the Copper-Tin Series of Alloys.

copper. The solid solutions on cooling from the solidus to the ordinary temperature undergo no thermal changes and represent the simplest group of the series.

(2) In both cases the range from 9 to about 45 per cent. of foreign metal (that is, tin or aluminium) has disclosed a most complex series of thermal disturbances between the liquidus and the ordinary temperatures.

(3) Between 45 and 100 per cent. of foreign metal (that is, tin or aluminium) the curves are comparatively simple.

(4) The number of constituents in the copper-tin series is 7, in the copper-aluminium series either 6 or 7.

*(5) The number of chemical compounds in each series is 3, and 2 of them have exactly corresponding formulæ.

Copper-Tin.

Copper-Aluminium.

(6) In both series one of these compounds never crystallizes from the liquid, but appears as a recrystallization out of a homogeneous solid. The compounds are Cu_3Sn and Cu_4Al . This resemblance is certainly most remarkable.

* Mr. Gulliver, having drawn the authors' attention to Shepherd and Blough's work discrediting the existence of the compounds Cu_4Sn and CuSn , they desire to omit these bodies from the above comparison.

Discussion on Friday, 15th February, 1907.

MR. EDWARD P. MARTIN, Past-President, said the Council regretted very much indeed the manner in which, from circumstances over which they had no control, the Report had been put aside from time to time. Circumstances had forced them to do so. He made that apology to the authors publicly, so that they might really appreciate what the Council thought of their work.

PROFESSOR CARPENTER, on behalf of his colleague Mr. Edwards and himself, thanked Mr. Martin for his kind reference to their work, and desired to add a few further words in connection with the Report. Those who were present at the last meeting when part of the main Report was read would doubtless remember the points then emphasized, and those who were not present at that meeting had probably seen some of the abstracts in the numerous notices in the technical and scientific press that had appeared since that date; and as time was precious he did not propose to refer to the main report except in one particular. On page 60 in the section headed (*h*) it was said, "In the corrosion tests, which were purposely made as severe as possible, alloys containing from 1 per cent. to 10 per cent. of aluminium have shown themselves to be practically incorrodible by sea-water, whether alone or bolted to a plate of mild steel. In these tests they showed themselves superior both to Muntz Metal and Naval Brass, which corroded appreciably." During the interval that had elapsed since the 18th January, a contribution to the discussion had been sent in by Messrs. Vivian and Sons (page 364) which confirmed that statement, with the difference that the protecting metal in their experiments was not mild steel but wrought-iron. The members would notice that in the case of the galvanic couples the 10 per cent. alloy bolted to iron showed no loss of weight—he might say that the experiments extended over twelve months—and similarly the 10 per cent. alloy protected by Muntz Metal also showed no loss of weight. He thought it was a satisfactory confirmation of at any rate one thing in the Report.

He proposed to devote a few minutes to the consideration of the Appendix to the Eighth Alloys Report, which represented work that was in progress at the time the main Report was written, and which had been finished, largely owing to the zeal of his colleague Mr. Edwards. [Professor Carpenter then read portions of the Appendix and Mr. Edwards pointed out the various references on Fig. 33 (pages 204-205).]

Finally, on behalf of his colleague and himself he expressed their high appreciation of the work of the staff of the Institution in reproducing so admirably the very large Report.

Mr. FREDERICK TOMLINSON, of the Broughton Copper Co., said that during the last few years he had had some practical experience in the manufacture and investigation of the properties of the various aluminium-alloys, but he had not expected, nor did he feel competent, to open a discussion on the Report of this important research. He simply had a few criticisms to offer. In regard to the figures the authors gave, he found that the yield-points were not in accordance with a large number of tests he had conducted during the last few years. Taken on the whole, they were on the high side; also the ratio between the yield-points and the tensile strength, as shown in the various Tables in the Report, was very erratic in most cases. With due deference to the operator who had conducted those tests and to the authors, he thought the yield-points given were too high, especially in regard to copper. For Alloy No. 1, which was practically pure copper, the authors gave about $4\frac{1}{2}$ tons per square inch, but with the best tough annealed copper the yield was never much over $3\frac{1}{2}$ tons per square inch; $2\frac{1}{2}$ tons per square inch would be the maximum figure for a copper of 99.9 per cent. purity, such as the copper referred to as No. 1 in the Report. Some investigators went so far as to say that pure electrolytic copper when annealed had practically no yield-point, that is, it commenced to yield as soon as the stress was put on. The other differences noted in the Report, with regard to the ratio between the yield and the tensile strength, he thought were due more to the erratic nature of these aluminium alloys.

(Mr. Frederick Tomlinson.)

The authors stated that they found practically no rise of temperature on the addition of aluminium to copper, but he thought that any workman who had had experience of the addition of aluminium to molten copper would contradict that statement. To be quite sure of the fact, he had had some experiments conducted. He eliminated all oxygen, using pure deoxidised copper, and melted the copper under a thick layer of charcoal, as recommended by the authors; after inserting a thermal-couple, he added the aluminium, and there was a considerable rise of temperature. He had a diagram which showed the actual rise, Fig. 178 (page 273). For an alloy containing 10 per cent. aluminium, the rise of temperature shown was about 200° F. On the same chart would be seen a comparison of the addition of tin and also zinc to the same quantity of copper, the conditions being the same in each instance; and in these latter cases no rise of temperature was observed.

The authors also pointed out that they found no difficulty in making an alloy of 5 per cent., although they had been told by some experimenters that there was a difficulty in doing so, as there was a tendency for it to thicken. He had never experienced that trouble himself, and did not believe there was any difficulty in making any of the alloys; they were all perfectly fluid if melted and aluminium added at the correct temperature. With reference to the melting temperature of the alloys, the authors said it was very important to cast these alloys at the proper temperature, but they very carefully evaded saying what was that proper temperature.

He was sorry to note one important omission in the Report, namely, the testing of aluminium alloys at elevated temperatures. He thought all engineers would agree that that would have been a most useful addition to such a research. In 1902, the late Mr. F. W. Webb gave a very interesting Paper * to the Institution of Civil Engineers, embodying his experience of alloys containing 7 per cent. of aluminium, which he had tried in the form of rolled rods for stay-bolts in locomotives, and the results were most disastrous. He said, "In two months' working, after running only 2,400 miles,

* Proceedings, The Institution of Civil Engineers, vol. cl, 1902, page 87.

FIG. 178.

Diagrams showing the Effect of the addition of 10 per cent. of Al, Zn, and Sn on the Cooling Curve of Copper.

(Mr. Frederick Tomlinson.)

the metal stays broke off in or close up to the tube plates." In that Paper Mr. Webb showed that the tensile strength of this particular alloy, of 7 per cent. aluminium at a temperature of 600° F., dropped about 50 per cent. From some experiments made just recently, he himself found that the drop in tensile strain at 600° F., although considerable, was not so great as that stated by Mr. Webb. He had taken four of the alloys, duplicates of the rods described in the present Report, in Table 24 (page 129), rolled to $\frac{1\frac{3}{8}}$ inch diameter. Unfortunately, at his disposal he had only four pieces of rod, Nos. 10, 13, 14 and 15. These he tested at 750° F. with the following results: In No. 10 he found the tensile strain dropped down to 20·8 tons per square inch, and the elongation was only 25 per cent.—it dropped from about 80 to 25 per cent.—and the reduction of area was 20 per cent. In No. 13 the tensile strength was 22·48 tons per square inch, the elongation 36 per cent., and the reduction of area 56 per cent. In No. 14 the tensile strength was 21·64 tons, the elongation 30 per cent, and the reduction of area 47·2 per cent. No. 15 was the most extraordinary; the tensile strength was 18·41 tons, the elongation 62 per cent., and the reduction of area 96·74 per cent. The appearance could be imagined; the test-piece was like a piece of lead, and drew out almost to a fine point. He mentioned those tests to show the importance of having some work done to indicate the behaviour of these alloys at elevated temperatures. His own experience, generally speaking, was that they were somewhat erratic. In years past he thought the uncertainty of aluminium alloys was no doubt due chiefly to the varying composition of the aluminium employed, but now aluminium could be obtained of a standard quality, and therefore that element of error was removed.

In regard to the Report as a whole, they were bound to be greatly impressed by the large amount of patient laborious work entailed in a research of that description; yet one felt, perhaps unfairly, that the practical results were small compared with the mass of work completed. Probably that was very often the case in research work of that description. In the present Report there appeared to be one fundamental practical advantage to engineers; it would give them more confidence in deciding upon the adoption of any of the alloys.

They might decide to adopt them or discard them, but having the results of this valuable research before them would give them every confidence to decide, one way or the other, whether they should use aluminium alloys for any particular purpose.

Professor J. O. ARNOLD congratulated Mr. Longmuir on the able manner in which he had planned the campaign of the research, and most sincerely congratulated the authors on the able manner in which they had carried out the tests. He desired also to express his thanks for the admirable manner in which the Report had been printed and particularly for the addition of the Index. He did not intend to go fully into the Report, as it would be impossible; the mass of valuable work contained in it would take hours of criticism, favourable or otherwise. He gathered from the statements of the authors, made with reference to the results on pages 93 and 95, that they found in re-melting alloys high in aluminium that there was no oxidation of the aluminium. He believed from a practical point of view there was usually a considerable amount of oxidation of the aluminium, a thing which would be naturally expected, as aluminium was so powerful a deoxidiser, so powerful as at high temperatures to decompose carbonic-oxide itself. That was a very important point, and if it could be dealt with to show practical metallurgists how to avoid the oxidation in the manner achieved by the authors, the result would be of considerable practical value. He noticed that the authors had succeeded in getting results in which a protected couple—a couple cased with fire-clay—gave approximately the same results as the bare couple (page 199). There again in practice there was very often found under certain conditions a very much larger difference than that tabulated by the authors, and that was another point upon which he thought some explanation might be given.

An extremely interesting note was given (page 222) as to the resemblance of Alloy No. 13 to Swedish Bessemer steel, particularly in connection with the static tests. The kinetic or dynamic tests made for the authors at the University of Sheffield showed that Alloy No. 13 under dynamic stress was much superior to Swedish Bessemer, although the static results were the same. Swedish Bessemer

(Professor J. O. Arnold.)

endured, under standard conditions, under the system of testing at Sheffield, 350 alternations before breaking, whereas the alloy stood in round numbers 700, or just about twice the endurance.

He wished now to proceed to deal in a broad, general manner with two points which would have to be taken up by scientific men generally. One had reference to the recalescence curves upon which the diagram and the various curves in the Report were founded. He believed he had pointed out before to the Institution that there were two methods of taking those recalescence curves, one which might be called direct and the other which might be called differential. His view was that the differential method involved a considerable risk of error. He had gone into it very carefully, and it seemed to him that the differential apparatus as employed generally—he was not speaking of any particular apparatus—involved at least seven disturbing influences, so that it was only possible to get a vertical datum line when the plus and minus errors, which were unknown quantities, exactly balanced each other. A committee had been appointed, and in connection with the authorities of the National Physical Laboratory the University of Sheffield had been making a careful series of tests on a selected steel, taken differentially and taken directly, and it would be his pleasure to compare those curves with the curves of Dr. Glazebrook and the authors at the National Physical Laboratory on the following day. He hoped they would come to a happy settlement on the question, so as to find out which was the more accurate method of recording such extremely important curves, curves which must be correct, or improper theories would be founded upon them.

The second point with which he wanted to deal was one of still wider importance, namely, the question of the inadequacy, the recognised inadequacy, of static tests, that is, of tensile tests. It had been known perfectly well that it was possible to get excellent tensile tests from steel and excellent bends (because after all a bend was only a static test; there was one side in tension and the other in compression); and yet in engineering practice that very material would snap almost like glass. He was sorry to say in his practice he had very many cases of that sort to deal with. The result had

been that a large number of tests had been devised to supplement the static test, and in that connection he wished to express his astonishment at hearing at Liège that a well-known French scientist actually suggested the abandonment of the static or tensile test, and suggested that engineers should rely entirely upon the shock test. Of course it was very difficult to argue patiently with a proposition of that sort, because static tests would always exist, and the mechanical engineer must take either an elastic limit or a maximum stress for his datum line to obtain his factor of safety. Therefore all the auxiliary tests could never replace the static tests. Nevertheless, they were of very considerable importance. The difficulty at the present moment was that each deviser of a machine or modification of the kinetic testing of steel had the greatest belief in the possibilities of his own machine. So far as the system he had devised at Sheffield was concerned, he was fully aware that it had considerable limitations; but in a great many cases it would pick out steel liable to fracture in practice, which the tensile test indicated to be quite good, and that was a somewhat important result.

The machine at the National Physical Laboratory he thought was a modification of that of Professor Osborne Reynolds, and applied a distributed stress over the whole piece. That was a point which was rather unfortunate, because his experience was that in practice a sudden fracture almost invariably commenced on the skin; and on going further into the matter he was of opinion that the fractures which had been put down to fatigue never broke under the true Wöhler fatigue-test at all. There was some new phenomenon which it was very urgent should be fully investigated both in the interests of engineers and metallurgists. He had been going into the matter very carefully, and recently he did some work for his friend Mr. Stead, which had very much astonished both of them. Mr. Stead made a series of alloys, and ran the phosphorus up until he got it up to 0.5 per cent. Every metallurgist knew that to put in steel containing 0.5 per cent. of phosphorus to resist shock or alternation would be an act of folly. Mr. Stead tested this series with a rising phosphorus on the ordinary Wöhler machine, in which the test was applied below the elastic limit, and they were tested at Sheffield on

(Professor J. O. Arnold.)

the machine in which the stress was slightly above the elastic limit. Mr. Stead's results on the Wöhler test showed that the more phosphorus the steel contained, the more it was capable of resisting alternation and shock. The tests at Sheffield went in just the opposite direction, and the fragility co-ordinate formed a straight line as the phosphorus rose. It was extremely important that mechanical engineers should revise their views on the matter of fatigue-testing, and he hoped to bring forward a Paper on that subject.

Dr. RICHARD SELIGMAN said that having had some experience of the alloys, he was able to answer the question which Professor Arnold had raised with regard to the oxidation of rich aluminium alloys on re-melting. There was undoubtedly a slight oxidation on re-melting any of the lighter alloys, but it was extremely slight if the temperature were not unduly raised and not sufficient to alter appreciably the percentage composition of the metal. Mr. Tomlinson had spoken about the yield-points found by the authors, and had observed that it was said in some cases copper had no yield-point at all. He himself was very much surprised when he read the Report to find that aluminium was given a yield-point, as he had never yet been able to discover a definite point of this kind. With regard to the temperature of mixing, he was not quite sure that he understood the point raised; he thought the authors stated that any rise of temperature was due to de-oxidation.

Professor CARPENTER said the rise of temperature was due to the oxidation of the aluminium.

Dr. SELIGMAN asked whether Mr. Tomlinson wished it to be understood that the rise in temperature was due to other causes, because if so it would be very simple to settle the point by adding just sufficient aluminium to reduce all copper-oxide present, when any excess of aluminium subsequently added should, according to Mr. Tomlinson, produce a rise of temperature. His experience, however, was that it did not do so.

With regard to the whole subject of the Report, he could not claim to speak as a practical man, but he had been associated with the practical man for a long time, and thought he might speak for him. The experience they had had was chiefly at the light end of the series, the alloys rich in aluminium, and his remarks therefore would be chiefly concerned with those. He was certain that many valuable results would be obtained from the work of the authors; but he thought that work would require some digestion before it could be utilised, and in some cases he was certain the results obtained would require slight emendation and perhaps extension. For instance, the authors condemned rather strongly the device of re-melting the alloys before finally casting them. He was not sure they had understood exactly why that device was adopted in the works of the British Aluminium Co. For large castings, such as propellers and things of that kind, of which the Company used to make a large number, he did not think it was essential to re-cast the metal, rather differing from the authors in that view. If the mix was a very large one, the possibility of error in making it was comparatively small. On the other hand, for casting work where a number of small castings were made, it was very desirable to make the alloy first in large quantities and so secure a fairly definite composition, and to re-cast afterwards; otherwise, when only casting a few pounds at a time, the ordinary foundryman could not be trusted to get alloys of very definite composition. In other ways he thought perhaps the methods which the authors used must for the time being remain ideals to be striven after, rather than practical methods which the foundryman could use. As an illustration, he might take the method by which the authors prepared their sand castings. The great disadvantage of those alloys was the shrinkage and the consequent difficulty of preparing sound test-bars; and to avoid that the authors gave their castings a gate and head many times the size of the casting. He did not think that was a very practical method; he could not imagine a propeller cast under those conditions, and perhaps the mechanical results obtained by the authors would not be quite on all fours with those which would be obtained in practice. Undoubtedly the shrinkage was a very great disadvantage, and he

(Dr. Richard Seligman.)

only hoped that some other method of getting over the difficulty would be found.

He believed the authors had misunderstood the reasons which led the British Aluminium Co. to adopt the use of the 50 per cent. mixture for making the alloys. The Company did not think that the alloys made by that method were any better; the device was merely a convenience, and a great convenience. In the first place, in casting small amounts of metal it was convenient to use the 50 per cent. of alloy owing to its brittleness, which enabled it to be broken up, as the authors had pointed out, into a fine powder, and the amount required weighed with great accuracy. Later on in the Report, the authors said that in making alloys rich in aluminium it was possible to keep the temperature down, and that was perhaps the most important point of all. The general remarks made in the Report with regard to the importance of keeping a low temperature were undoubtedly remarks which he could absolutely confirm. The vast majority of complaints as to the poor qualities of cast-aluminium alloys were due to overheating of the alloy during casting. Numerous samples of that kind had come to them from all over the country, and, in almost every case, the diagnosis had been the same—overheating of the metal. But although he absolutely agreed with that, he thought there was some slight error in the quantitative details given on page 92. They said that an alloy cast at 650°C . ($1,202^{\circ}\text{F}$.) was good, but on raising the temperature to 707°C . ($1,304^{\circ}\text{F}$.) they got a drop of 50 per cent. in the tensile strength. On the other hand, raising it another 20°C . approximately, the strength of the alloy went up. The actual figures were 9.68 for the alloy cast at 650°C ., 4.89 for the alloy cast at 707°C ., and 7.04 for the alloy cast at 724°C . 650°C . was very little above the melting point of the metal, and in dealing with large quantities, say half-ton lots, it was impossible not to heat beyond that. The actual casting temperature used in practice was round about 700°C ., the metal being previously heated to 710° to 715°C . He did not think the authors would suggest that the alloys his Company had shown to them had a tensile strength as low as 4.9. He thought there must be an error there which required clearing up. He could not

pretend to speak with anything like the authority of Mr. Tomlinson on the other end of the series, but he was very much surprised to learn the comparative results of cast and rolled 10 per cent. bronze, because his Company had always found such a marked improvement in rolling the alloys. Their experience was, however, comparatively very limited. The observation of the bad qualities of metal when heated was confirmed by the practical experience of his Company; this experience was not very great, but it was known that a 10 per cent. alloy, for instance, would not stand the high temperature.

He was afraid he must disagree with the conclusion of the authors as to the relative use of the rich copper and rich aluminium alloys, and he based that disagreement on the vast excess of light alloys demanded of his Company as compared with the heavy alloys. With regard to the examination of ternary alloys, he would like to commend to the author's consideration, or to the consideration of those who were controlling the research, the examination of alloys containing zinc as well as copper and aluminium. He felt certain that the results they obtained would be even more valuable than those they had obtained with copper. Finally, he had to thank the authors for the kind mention they had made of his colleagues in the British Aluminium Co. and himself, and to say that any help the Company had been able to give the authors had been most gladly rendered.

Captain H. RIAL SANKEY exhibited a workshop bend-testing machine, Fig. 179, Plate 23, and said that by the courtesy of Dr. Glazebrook and the authors he had been able to test in that bending-machine the remainder of Professor Arnold's test-pieces. Each test-piece was 4 inches long and either $\frac{3}{8}$ inch square or $\frac{3}{8}$ inch round, and was secured at one end in a fixed grip and at the other in a movable grip, the free length of the test-piece between the grips being $1\frac{3}{4}$ inches. The movable grip formed part of a small steel-casting to which a handle about 3 feet long was pivoted; a spring interposed between a projection on this casting and one side of the lever limited their relative motions in one direction, and a fixed stop on the casting limited it in the other. On moving the handle

(Captain H. Riall Sankey.)

towards the spring, the latter was compressed until the effort was sufficient to bend the test-piece. The amount of compression of the spring was evidently a measure of the bending effort and, by means of a multiplying lever, carrying a pencil, the bending effort could be recorded on a piece of paper fastened to a horizontal disc pivoted to the small steel-casting. This paper was ruled with concentric circles, which formed a scale of bending effort expressed in pound-feet, Figs. 180-182. This scale could be calibrated by means of a spring-balance applied to the handle. Thus, if the point of application of the spring-balance was 3 feet from the fixed grip and the spring-balance marked 30 lbs., the bending effort was $3 \times 30 = 90$ lb.-feet,

Records of Hand-Bending Tests (Sankey).

FIG. 180.

Alloy No. 1.
0·10 per cent. Al.
 $\frac{3}{8}$ " round test-piece.

FIG. 181.

Alloy No. 13.
9·90 per cent. Al.
 $\frac{3}{8}$ " square test-piece.

FIG. 182.

0·30 per cent.
Carbon Steel.
 $\frac{3}{8}$ " square test-piece.

and the pencil ought to be on the circle marked 90 lb.-feet. If not, the spring could be adjusted until it was so. When the test-piece had been bent through the desired angle (approximately 45° has been taken as the standard), the handle was moved in the opposite direction. The handle then came up against the stop on the casting already mentioned, and the recording pencil returned to zero, so that the bending effort was not registered when bending in that direction. The test-piece was bent back to its original position and beyond to 45° in the opposite direction when a ratchet came into action, and the disc carrying the paper was rotated one tooth of the ratchet wheel. On again bending in the original direction the spring was compressed, and the pencil again recorded the bending effort,

but moved this time along a different line to that registering the effort applied during the first bend. The operation was continued, bending the test-piece backwards and forwards until it broke.

FIG. 183.

*Comparison of Results of Hand-Bending Tests (Sankey).
Alternating-Stress Tests (Arnold) and Impact Tests (Izod), with the Energy
absorbed in Breaking Test-pieces (Sankey).*

(Sankey's and Arnold's tests were made on same Test-pieces.)

It would be seen that the number of bends was recorded, as well as the bending effort of each bend from right to left. If the definition of one bend was bending the test-piece from 45° in one direction to 45° in the opposite direction, the number of lines on the diagram multiplied by two was approximately the number of

(Captain H. Riall Sankey.)

bends.* Samples of the records obtained were given to a reduced scale in Figs. 180, 181 and 182.

The results obtained were plotted in Figs. 183 and 184. The number of bends obtained for the $\frac{3}{8}$ -inch square and for the $\frac{3}{8}$ -inch

FIG. 184.

Comparison of Bending-Effort (Sankey), with Yield-Point in Simple Tension and Alternating Stress (Stanton).

(Made on same pieces as Arnold's tests, page 196.)

diameter test-pieces were given in Fig. 183, and it would be seen that they followed generally the figures given by Professor Arnold,

* The exact formula is $2 \times \text{number of lines on diagram} - 2.5 + X$, where X is the number of bends represented by the last line, and which may be 2 or anything down to a small fraction of 1, depending on the position of the handle when the test-piece finally breaks.

except in the case of Alloys Nos. 13 and 9, and that in every case they followed very closely the impact figures obtained with the Izod machine. In the case of Alloy No. 13 the number of bends was far less than that which might have been expected from Arnold's figures, and all four specimens snapped off short without warning and with quite a loud report. With all the other test-pieces small cracks appeared, and gave warning before actual breakage occurred. Alloys Nos. 6 and 9 were specially tough, and recorded a very large number of bends.

It might be of interest to point out that in the case of a similar comparison made with chrome-vanadium steel, subjected to various heat treatments, the number of bends obtained by slow bending agreed closely with Arnold's figures whatever heat treatment the material had been subjected to, whereas the impact figures did not agree when the material had been treated at temperatures below 800° C., but did agree for all heat treatments above that temperature.*

With regard to the bending-effort, it would be seen on reference to Fig. 184 that on the average the number of pound-feet observed were fairly proportional to the yield-point in simple tension given in the Report, Fig. 32 (page 194). The agreement with the alternating-stress test of Dr. Stanton was, however, still closer. On the average 100 lb.-feet recorded by the hand bending-machine *with the $\frac{3}{8}$ square specimens* corresponded to a yield-point of 15 tons per square inch. The average bending-effort expressed in pound-feet multiplied by twice the number of bends gave the energy required to break the test-piece. These calculations had been made, and the results were plotted in Figs. 183 and 185 (page 286). The great amount of energy to break Alloys Nos. 6 and 9 should be noticed, far greater than that required by steel. A noticeable point was the growth of the bending-effort which, with some of the alloys, was considerable (as would be seen, for instance, in Figs. 180-182, by the increase in length of the second bending line). The most important point, however, and one he desired to emphasise, was the relation between the bending-effort and the yield-point of the material. It was pointed out very

* Proceedings 1904, page 1250, Fig. 5.

(Captain H. Riall Sankey.)

clearly by the authors (page 67) that in the case of aluminium the primitive yield-point in simple tension was substantially the same figure as the true yield-point obtained by means of Dr. Stanton's alternating-stress testing machine. He thought it was one of the most important deductions of the research. In the case of steel, however, the yield-point obtained by simple tension was an artificial figure considerably higher than the true yield-point obtained by means of Dr. Stanton's experiments, Fig. 32 (page 194).

Hand-Bending Effort, Alternation and Yield-Point Tests on the same Steel Specimens.

FIG. 185.

Comparison of Number of Bends, and Energy absorbed to break Test-piece (Sankey).

FIG. 186.

Comparison of Bending Effort (Sankey) with Yield-Point (Arnold).

It was of interest to know whether the bending-effort recorded by the hand-bending machine was proportional to the true (or natural) yield-point or to the primitive (or artificial) yield-point. For this purpose six specimens of plain carbon-steel, kindly provided by Professor Arnold, had been tested, and the results and other particulars were given in Figs. 185 and 186. It would be seen that the bending-effort was approximately the same for all the specimens, and *slightly less* than that of the copper-aluminium alloy No. 13. The record obtained with a test-piece of 0.3 per cent. carbon rolled

steel was reproduced in Fig. 182. A steel of this type corresponded nearly with the steel referred to by the authors at page 222, and with which they had compared Alloy No. 13. It would be seen on comparing Fig. 183 and Fig. 186 that the number of bends for the steel was greater than for Alloy No. 13, but that the bending-effort was very nearly the same. As already pointed out, with $\frac{3}{8}$ -inch square test-pieces 100 lb.-feet corresponded to a yield-stress of 15 tons per square inch, from which it could be argued that the yield-stress of the steel as recorded by the hand-bending machine was a little less than 15 tons per square inch, and this was the order of figure obtained by Dr. Stanton for the true or natural yield-point of such a steel. As a confirmation it might be pointed out, on referring to Fig. 186, that some of the test-pieces were "rolled" and others were "drawn," and in the latter the yield-point had been further artificially raised to 36 and 39 tons per square inch; nevertheless there was no substantial increase in the bending-effort. For instance, the two samples of 0.25 carbon-steel, one "rolled" and the other "drawn," required 92 and 95 lb.-feet bending-effort, whereas the artificial yield-points were 24.1 and 36.7 lbs. per square inch respectively. Therefore he thought it could be said that by means of this hand-bending machine the artificial yield-point of steels, whether produced by forging or rolling or drawing, was, so to speak, broken down and the true or natural yield-point was determined. This was an important matter in the case of steels used for machinery.

Mr. BERTRAM BLOUNT expressed his thanks at being allowed to say something on such an interesting and valuable Report, an outcome of the labours of the Institution which must be gratifying to all members. The Report was so voluminous that, although he, like many others, had devoted a considerable time to its perusal, he doubted whether anyone, certainly not himself, could claim to be familiar with it from cover to cover. But probably the members had arrived at some opinion as to its worth, and he thought there could be no question as to what that opinion was. It seemed to him that it was a most elaborate collection of facts, some of which were potentially valuable. The value of such a document might be

(Mr. Bertram Blount.)

judged as much by the omissions as by the contents. One of the previous speakers had pointed out (page 274) a particular direction in which the research would have been of the highest value, but unfortunately from reasons of time and no doubt other considerations it had been omitted, namely, the behaviour of the alloys, particularly Alloy No. 13, containing 9.9 per cent. of aluminium, at high temperatures. That alloy was a very remarkable substance. Its properties, though not known exactly, were fairly well known a good many years ago, inasmuch as, although it was a copper-aluminium alloy, it closely approximated mechanically to mild steel. Its behaviour at the temperatures to which steel was subjected—especially piston-steel, with which it was compared in the Report—would have been exceedingly interesting; as it was, there was a description of the behaviour of the alloy after it had been heated to such temperatures, but not its behaviour in the testing machine at those temperatures.

Another interesting omission was in the behaviour of the alloys in their resistance to corrosion, not as regards sea-water and tap-water, which were dealt with in the Report, but under more severe conditions. Such an omission pointed to gaps that might be filled to everybody's practical advantage. It was well known that sometimes the engineer, especially the mining engineer, encountered troublesome problems in providing an alloy which should be mechanically good and at the same time resistant to corrosive liquids, such as mine waters, and the best efforts of engineers had been often taxed to find appropriate alloys of that kind. He himself had used alloys of that class from time to time, but never with perfect satisfaction, and that was a direction in which he thought further inquiry might usefully be made. In that connection it had to be remembered that now possibly for the first time engineers had the opportunity of preparing alloys of that description, of good purity, from the two metals that had been used in the research, copper and aluminium, and at the same time alloys not of unobtainable purity. The alloys were not merely laboratory alloys. An inquiry of that nature concerning resistance to corrosion might add vastly to the value of the investigation.

He much desired to learn which of the two contending parties was right, one of whom categorically averred that copper and aluminium in uniting evolved heat, the other contending that nothing of the sort took place. As a previous speaker had pointed out, the experiment was so simple that he marvelled there should be any debate on the matter, and he thought it should be put on record once and for all which was right. He expressed no opinion himself. He was brought up in the belief that copper and aluminium united with the evolution of heat, but he had never tried the experiment.

There was one other thing of the highest interest to all those who concerned themselves with the testing and examination of metals, namely, the inadequacy of static tests. He thought everyone was agreed about that, but what they were not agreed about was the nature of ancillary tests that could be made, and what form of non-static test was best, and in that respect he thought there was a great deal yet to be learned, and that the final word had not been said as to the form of machine to be adopted.

The PRESIDENT said the Paper had created so good a discussion, and so many prominent members of the Institution had still so much to say upon the matter, that the Council had determined to adjourn the discussion to a meeting to be held on the 1st March, when Sir William White had promised to re-open the debate. He thought the members would agree that the subject was of sufficient importance to be worthy of the closest possible investigation and discussion, so that there might be a record of all that was known with regard to the very interesting subject dealt with in the Report.

Dr. R. T. GLAZEBROOK remarked that the strength tests at high temperature were now in progress at the Laboratory and would be pushed on rapidly, but he could not make a promise that the results would be ready by the 1st March.

Discussion on Friday, 1st March 1907.

The CHAIRMAN, Mr. Hay F. Donaldson, Member of Council, before the Discussion was proceeded with, asked Mr. Rosenhain to offer some remarks on certain points in connection with further investigation.

Mr. WALTER ROSENHAIN said he had to lay before the Institution the results of a few experiments, that had been made at the National Physical Laboratory since the last meeting, on the tensile strength of one of the copper-aluminium alloys at high temperatures. The results were to be regarded as entirely preliminary, and he hoped would be considerably amplified in sufficient time to be communicated in writing for incorporation in the discussion of the Report. Fig. 187 (page 291) showed the general arrangement of the furnace as used for carrying out the tests. The furnace consisted of a porcelain tube, about 2 inches in diameter, wound on the outside with nickel wire, very much after the manner of some furnaces Professor Carpenter had described in previous Papers, the nickel wire being wound more closely at the ends than in the middle, in order to secure as uniform a distribution of temperature as possible, because it was realised that one of the difficulties in carrying out satisfactory tests of that kind was to secure that the whole of the test-piece should be at one temperature and to know what that temperature really was. The porcelain tube with its nickel winding, which was heated electrically, was insulated thermally by a thick layer of sand contained in a large iron tube and held by bolted plates top and bottom. The construction of the furnace was very simple, but it was very successful, and it escaped breakage when the test-pieces were broken, a thing that was rather difficult to secure. It had been secured first of all by attaching the furnace by a clamp to a large steel shank, which held the test-piece to the beam of the testing-machine, and the furnace itself was suspended by two wires from that clamp. The clamp was movable, and the whole thing could be run up the shank when a new specimen had to be inserted. The furnace was held to the

upper shank by a sliding fit in a metal plate, so as to prevent any oscillation of the shank breaking the tube.

The whole of the shanks, both at the top and the bottom, were packed with asbestos wool and wound with asbestos cloth, in order to further deaden any shock which might occur when the specimen

High Temperature Tests on Rolled Bars of Alloy No. 13.

FIG. 188.

*Mean Results of the
15-minute exposures.
(See Table 85, page 293.)*

Alloy No. 13. 2.9% AL.

broke. The packing with asbestos had the further advantage of securing uniformity of temperature in the furnace. The temperature was measured by a platinum-iridium thermo-couple whose wires entered the furnace on opposite sides of the lower shank; the couple itself was bared at its extreme end and held in close contact

(Mr. Walter Rosenhain.)

with the surface of the test-piece, by being wrapped tightly to it with several windings of asbestos thread. That was not an ideal arrangement. It only measured the temperature of the surface of the specimen, but care was taken during the experiments to keep the temperature of the furnace constant at the desired point for a sufficient length of time to be sure that the whole of the test-piece had attained the temperature recorded by the thermo-couple. The observation of the yield-point of a specimen heated in that way was not very easy, but he hoped to arrange for it in a later experiment. In the results he gave that evening he was unable to define it. A certain amount of creeping appeared to occur even at comparatively low loads, but the means of measuring that were not good enough to base any satisfactory conclusions upon the observations.

The tests were made on Alloy No. 13 (9.9 per cent. of aluminium) in the rolled state; the specimens were 2 inches long, of the standard section, and were turned from the rolled bars available from previous experiments. At the ordinary temperature this alloy showed a tenacity of about 36 tons and an elongation of about 28 per cent. The figures at 200° C. were nearly the same. The elongation rose with the temperature, slightly at first, but more rapidly as higher temperatures were reached, and the tensile strength fell in a corresponding manner, considerably more rapidly when 300° C. was passed.

In order to give an idea of the agreement between duplicate tests, he pointed out that at 400° C. one specimen showed an ultimate stress of 24.6 and another an ultimate stress of 25.6, while the elongation came out at 47 and 48 per cent. respectively. The other figures were in similar agreement. That showed that the conditions of the experiment were known with sufficient accuracy to be kept constant from one sample to another. (Samples of the actual broken specimens were exhibited.)

Mr. WALTER ROSENHAIN wrote subsequently that the tensile tests at high temperatures which he had described at the Meeting had now been carried further at the National Physical Laboratory, and might be regarded as complete so far as Alloys No. 13 (9.9 per cent. Al) and No. 8 (6.73 per cent. Al) were concerned.

The apparatus and mode of procedure were those already described, but, in addition, the effect was tried of keeping the specimens for some considerable time at the temperature in question before making the test. The time of the exposure was stated in Table 85 (below). No well-defined yield-point could be observed in any of these tests. Table 85 contained the results of observations on Alloy No. 13 (9.9 per cent. Al), while those of Table 86 (page 294) referred to Alloy No. 8 (6.7 per cent. Al). The mean results of the 15 minutes' tests on Alloy No. 13 were plotted on Fig. 188 (page 291). Values for the tenacity and elongation of these alloys at the ordinary temperature were taken from the Report, and the results already communicated were also included.

TABLE 85.

Tests on Rolled Bars of Alloy No. 13 (9.90 per cent. Al).

Temperature.	Time in Minutes.	Ultimate Stress.	Mean.	Elongation on 2 inches.
Ordinary.	—	Tons per sq. in. 38.1	38.1	Per cent. 28.8
200° C.	$\left\{ \begin{array}{l} 15 \\ 15 \end{array} \right.$	$\left\{ \begin{array}{l} 36.4 \\ 36.4 \end{array} \right.$	36.4	$\left\{ \begin{array}{l} 38.0 \\ 35.0 \end{array} \right.$
250° C.	30	31.7	31.7	21.5
300° C.	$\left\{ \begin{array}{l} 15 \\ 15 \\ 15 \end{array} \right.$	$\left\{ \begin{array}{l} 34.2 \\ 34.1 \\ 31.9 \end{array} \right.$	33.4	$\left\{ \begin{array}{l} 39.0 \\ 40.0 \\ 18.5 \end{array} \right.$
350° C.	$\left\{ \begin{array}{l} 30 \\ 60 \end{array} \right.$	$\left\{ \begin{array}{l} 32.7 \\ 32.9 \end{array} \right.$	32.8	$\left\{ \begin{array}{l} 33.0 \\ 27.5 \end{array} \right.$
400° C.	$\left\{ \begin{array}{l} 15 \\ 15 \\ 30 \end{array} \right.$	$\left\{ \begin{array}{l} 24.6 \\ 25.6 \\ 21.9 \end{array} \right.$	24.0	$\left\{ \begin{array}{l} 48.0 \\ 47.0 \\ 29.0 \end{array} \right.$
450° C.	$\left\{ \begin{array}{l} 45 \\ 45 \\ 120 \end{array} \right.$	$\left\{ \begin{array}{l} 22.8 \\ 19.4 \\ 24.8 \end{array} \right.$	22.3	$\left\{ \begin{array}{l} 30.5 \\ 32.5 \\ 31.5 \end{array} \right.$
500° C.	$\left\{ \begin{array}{l} 15 \\ 15 \\ 30 \\ 120 \\ 15 \end{array} \right.$	$\left\{ \begin{array}{l} 9.1 \\ 12.2 \\ 13.0 \\ 11.6 \\ 14.9 \end{array} \right.$	12.1	$\left\{ \begin{array}{l} 42.0 \\ 77.0 \\ 76.2 \\ 45.0 \\ 92.5 \end{array} \right.$
550° C.	15	9.1	9.1	10.2

(Mr. Walter Rosenhain.)

TABLE 86.

Tests on Rolled Bars of Alloy No. 8 (6.73 per cent. Al).

Temperature.	Time in Minutes.	Ultimate Stress.	Mean.	Elongation on 2 inches.
		Tons per sq. in.		Per cent.
Ordinary	—	28.8	28.8	71.0
250° C.	{ 30 30	{ 23.8 23.6 }	23.7	{ 25.5 29.0
300° C.	{ 30 30	{ 20.8 20.5 }	20.7	{ 24.5 25.0
350° C.	30	19.2	19.2	17.5
400° C.	{ 30 30	{ 17.9 18.0 }	17.9	{ 18.0 14.0
450° C.	{ 30 90	{ 13.4 13.3 }	13.3	{ 10.0 9.0
500° C.	30	10.9	10.9	14.0

A study of Table 85 showed that in Alloy No. 13, although the figures were a little irregular, there was a steady decrease of tenacity as the temperature rose. Up to 350° C. the alloy maintained its strength fairly well, but from 400° C. upwards the alloy became rapidly weaker. The elongations shown in this Table were very erratic, the alloys at these temperatures being, apparently, very sensitive to differences in the rate and manner of applying the load. On the whole, the results indicated that up to 500° C. the fall in tenacity was accompanied by a rise in ductility.

The results of Table 86 showed a regular fall of tenacity with rising temperature, the fall being more rapid above 400° C. In contrast with the results found for Alloy No. 13, this alloy (No. 8) showed a marked and regular *decrease* of elongation with increasing temperature. It must, however, be stated that the specimens of Alloy No. 8 (6.73 per cent. Al) uniformly fractured either at the gauge-marks or in the screw-thread at the end of the specimen. This accounted for the low values of the elongations found in this series of tests, but at the same time indicated a considerable degree

of sensitiveness in the alloy, which tended to the production of a "short" fracture wherever the surface had been cut. It therefore appeared that, for use at temperatures up to 350°C ., Alloy No. 13 was far preferable to Alloy No. 8, both as regards tenacity and ductility. It was interesting to notice that the divergent behaviour of these two alloys at high temperatures corresponded with the fact that the two alloys belonged to different groups in the constitutional diagram given in the Report, Fig. 33 (pages 204-205).

Sir WILLIAM H. WHITE, K.C.B., Past-President, as Chairman of the Alloys Research Committee, said his first and very pleasant duty was on behalf of the Committee to express their grateful thanks to the Broughton Copper Co. and the British Aluminium Co. for the generous manner in which they had supported the Committee in the conduct of the experiments. In both cases the representatives of the Company, who were members of the Committee, had been most ready to meet any requirements that were made upon them, not merely for the supply of material, but, as the authors had said in the Report, in giving facilities for visits of Professor Carpenter and Mr. Edwards to the works, and helping in every way. When one remembered the attitude sometimes assumed by manufacturers towards researches of that kind, the generous manner in which those two firms had behaved throughout deserved the special recognition of the Institution.

With regard to the authors of the Report, he need say very little, because every speaker had recorded recognition of the value of the work done and its magnitude; but there was one feature that he would like to dwell upon. Professor Carpenter, as he was leaving for a new sphere of work, might have somewhat relaxed his efforts at the National Physical Laboratory, and no one could have been surprised if he had done so. His conduct, however, was exactly the reverse. When the Committee knew he was entering upon another sphere of work, he was the first to suggest the desirability of pushing the research on to a definite stage at which his responsibility might finally cease, and the responsibility of his successor commence; and in order to reach that result he had to work what in shipbuilding

(Sir William H. White, K.C.B.)

parlance was called "double tides," and he did not spare himself, nor did Mr. Edwards fail to back him up in that endeavour. The result was before the members. He was confident that anyone who had looked through the specimens exhibited, the results of tests, could not fail to be struck with the enormous amount of work that had been done and well done. Then, in the preparation of the Report, it was not merely a splendid summary of experimental data, but he thought the members would all agree with him that in good arrangement and its literary aspect—and there was a literary aspect even to a Report on an experimental research—it stood pre-eminent, and they had to congratulate the authors on what they had done in that respect.

Passing to the work itself and its results, the Institution, while encouraging and aiding research, must naturally always think of it from the practical engineering side. There were many features in the Report that were of strictly scientific interest, but the Institution, while welcoming those parts of the Report, was more directly concerned with the applications of the research to engineering practice. In passing, he might allude to a matter which he understood had excited some interest at the last meeting, when Professor Arnold referred to some difference of opinion as to the best method of dealing with cooling curves and the records of such curves. It might be that some of the members of the Institution had an impression that the difference of opinion was of a nature to affect the results from the practical engineer's side. It was nothing of the kind. There was practical agreement, and always had been, as to what might be called the critical points in the curves, corresponding to temperatures at which sudden changes of condition occurred. There had never been any difference with regard to those critical points, which were the points engineers were chiefly concerned with in dealing with materials in practical work. The difference of opinion to which Professor Arnold had alluded was of a strictly scientific nature, and related to the best method of determining with the greatest possible accuracy the form of the curve tracing out the variations of temperature with time. In regard to that matter, as was stated by Professor Arnold, an arrangement had been made

by the Main Committee for the appointment of a Sub-Committee consisting of those members of the Main Committee who were most skilled in those matters. These gentlemen were asked to confer together and endeavour to reach a definite result. That conference had taken place. It had led to a unanimous decision in the sense he had just indicated as to what the points of difference really were, and it had led to the practical conclusion that the best way of dealing with the strictly scientific side of the question would be to prepare Papers containing particulars of alternative methods that had been followed at Sheffield and at the National Physical Laboratory, and to present these Papers for discussion before a purely scientific Society, such as the Physical Society or the Royal Society. He had taken the trouble to explain the position, simply that there should be no misunderstanding whatever as to the nature and the range of difference of opinion, because while highly important from the scientific side, and of much wider application than to that particular research, there was a danger that some of the members of the Institution who listened to the discussion might have had an exaggerated idea of what was really involved.

Coming to the practical utility of the conclusions reached in the Report, he noticed that Mr. Tomlinson, at the last meeting, had alluded (page 274), and with great justice, to the apparently small effect on practice which appeared to be probable from a large amount of the work that had been done. That was a perfectly fair criticism. On the other hand, he was sure Mr. Tomlinson would agree with him when he said that it was an achievement to have cleared the ground, and to have reduced the necessity for further research to industrially important limits, as had been done by the authors. He had been interested in alloys of aluminium and copper for many years, and had endeavoured repeatedly to obtain exact information as to the range in the rich copper alloys or the rich aluminium alloys which would have any practical claim to consideration, and he had not been able to obtain exact and definite information until he saw the Report. It was now generally established and known from the Report that alloys of industrial value, at the rich copper end of the series, only went up to 11 per cent. of aluminium and 89 per cent.

(Sir William H. White, K.C.B.)

of copper, and that some alloy less rich in copper would probably mark the limit likely to find use in common practice. He quite agreed that at that end the alloys were found which were likely to prove of the greatest industrial value for purposes where a high tensile strength and a high yield-point were of importance. But he thought it would also be found that the rich aluminium end of the series would have a practical value, and possibly an increasingly practical value. Taking first of all the rich copper alloys, what struck him in going through the Report was that there was full information given with regard to the effect of various forms of treatment upon the material; that effect was traced out in the Report in considerable detail.

The investigation of the effect of temperature was now being commenced, and Mr. Rosenhain had shown that evening the beginning of the work; but when it came to the use of the material, say the alloys which in their general characteristics bore a close resemblance to mild steel, it would be desirable and necessary to know a great deal more than had yet been discovered. He was not in the least intending to depreciate what had been done; he only wanted to dwell upon the incompleteness of the information, even after a large amount of work had been devoted to the research. For example, if it was desired to use in structures that remarkable alloy of copper and aluminium which was equal in strength to mild steel, it would be necessary to know what it would be worth in the form of plates of such dimensions as would be required in practice, and what would be the effect upon the material of mechanical processes, such as punching, drilling, riveting, and so on; what would be the possibility of getting a suitable material for rivets to use in those plates; and what would be the effect of the processes of shaping the plates if they were put into a structure such as the hull of a ship. All those were points which still required investigation. It was nearly thirty years ago that he very seriously considered the use of the material known as Naval Brass as a substitute for steel for the bottom plating of ships. Any material of that kind, if it could be obtained in proper sizes and possessed the necessary working qualities, would be of great advantage in that it would avoid the corrosion and foulness

which occurred in steel-bottomed ships. It was for that reason the matter was considered. At that time the question of cost really settled it, and it could not be gone on with, but enough was seen to show that if it were necessary to do so in special cases, it was possible to use Naval Brass for the purpose. As far as the tests in the Report went, the alloy which so closely resembled mild steel might also be used, provided that it could be proved that the material would bear ship-yard processes, and that fastenings could be obtained which would enable the proper proportion of the strength of the unpierced plates to be developed. That was only one illustration.

Going to the other end of the series, there were many parts of structures, and of ships' structures in particular, where high tensile strength was not required. For example, above the "strength-deck" of a great Atlantic steamship, like one of the new Cunarders with which he had been concerned very deeply during the last two or three years, there were large superstructures situated above the true top of the girder, which enabled the ship to resist longitudinal bending. Those superstructures contained a large proportion of the passenger accommodation, but nobody expected them to contribute to the longitudinal strength of the ship. Now, if it were possible to obtain a material, such as one of the rich aluminium alloys, at a reasonable cost, necessary stiffness could be secured from such a material, and by its use shipbuilders might save enormously in the weight which was necessary, if mild steel were employed. These examples only illustrated the possibilities arising from an enquiry such as this research; and he was certain that when engineers found time to look into the Report, to master its details, and to consider the results with reference to their particular branches of practice, it would be found that it was a perfect treasury of valuable information. The question of further extensions of the research was not one for that meeting, but it had been considered by the Committee, and recommendations would be made to the Council. He had no doubt the Council would, as they had always done, adopt the recommendations of the Committee, and he hoped that, although much had been done already, it would be found possible to go further with great advantage.

(Sir William H. White, K.C.B.)

The corrosion tests were very striking. In regard to those corrosion tests one of the speakers, he thought Mr. Blount, pointed out, with perfect propriety, that the tests so far made did not cover all the conditions of practice. That had been recognised by the Committee from the first, and by the courtesy of the Admiralty it had now been arranged—as was always intended—to carry on corrosion tests on samples immersed in sea-water at Portsmouth under conditions which would enable direct comparisons to be made with corresponding tests that had been carried out by the Admiralty for many years on other metals and alloys. In that respect therefore it might be hoped before long to have fuller and more exact information representing the conditions of practice. But so far as the tests had gone the results were most remarkable, and he thought not altogether such as would have been expected. In the uses of aluminium alloys that had been made in special cases, as for example in yachts built to compete for the “America Cup,” the questions of corrosion and rapid deterioration had been most serious. Vessels had suffered to an extent that was never expected. The French Government did not go on with the torpedo boat built of aluminium alloy by Mr. Yarrow, although the boat was a perfect success and had ample structural strength, and was much lighter than a steel-built boat. She had to be lifted on board, so that there was a very severe test of her strength in the lifting. But the want of durability demonstrated in this experiment showed that it was not desirable to repeat it. If new departures were made on the basis of the new research, it was a very important fact for all concerned that many practical suggestions had been made in the Report in regard to the best processes of casting and most suitable treatment of the alloys. He was not surprised to find that gentlemen who had experience of a practical nature with aluminium alloys did not altogether agree with those suggestions. He did not expect that Professor Carpenter was surprised. It was extremely difficult even for a scientific man like Professor Carpenter to grasp all the conditions of practice, because he had to work under laboratory conditions, but while that was true, it was also true that very often work done under laboratory conditions suggested to those, who were carrying out practical processes in

factories, precautions and methods that were of enormous advantage subsequently. In that way he believed it would be found that eventually those concerned with the manufacture of copper and aluminium and their alloys would admit the value of the research.

There was one passage in Professor Arnold's remarks to which he wished to allude, namely, the defence of the continued use of static tests of materials (page 277). No one recognised more fully than he did the value of dynamic tests, but there could be no doubt that for structural purposes—he was not speaking now of machines but of structures—the knowledge given to the engineer by means of static tests was of immense importance. There was a tendency when some new and useful process was introduced to suppose that it must necessarily supplant what had gone before. He thought there was nothing more absurd than that sort of thinking, that the new broom was going to sweep everything else out. His experience was that it was well not to be too hasty in giving up a tried method of procedure. The new method should as a rule be used as a supplement, rather than a substitute. Engineers were always open to new suggestions and new methods, but there was no method of testing he had ever heard of that was going to be so comprehensive as to take the place of all others. He was very glad indeed that Professor Arnold on that point spoke out in the manner he did. Perhaps those who were so much in favour of dynamic tests did not mean to go so far as their words seemed to convey. He was entirely with Professor Arnold in thinking that, whatever might be done in the matter of dynamic tests, it would be unwise to abandon or lessen seriously inquiries made by old-established methods of testing. Action taken by the Standards Committee not so very long ago, in taking immense trouble to lay down what was hoped would become uniform conditions of carrying out static tests, indicated that the great body of practising engineers in this country were of the same opinion.

He would conclude as he had begun, by saying that the Institution was to be congratulated on the fact that the research had been put in hand, that it had been so generously aided by the manufacturers of materials, and that it had fallen into the hands of

(Sir William H. White, K.C.B.)

such a capable experimentalist as Professor Carpenter, who, with the resources of the National Physical Laboratory, and with the aid of Mr. Edwards, had produced a very excellent Report.

Mr. C. HUMPHREY WINGFIELD said that two methods of testing by alternating stresses were used in the Research, and at the last meeting a third was described by Captain Sankey. He noticed in

FIG. 189.

Alternate-bending Tests. (Influence of Angle of Deflection on Results.)

previous references* to the Arnold test that a very considerable difference in the number of alternations required to produce fracture resulted from a comparatively small difference in the angle through which the specimens were bent. This did not matter with a mechanically moved device such as Professor Arnold's, because the angle was

* Proceedings 1904, pp. 1242, 1284, and 1317. On the latter page $1\frac{1}{2}$ should be $1\frac{1}{3}$. On page 1284, line 11 from bottom, $1\frac{1}{2}$ should be $1\frac{1}{3}$. In these instances the angles were about 15° and $10\frac{1}{2}^\circ$. In the present Paper it was about 7° . No quantitative comparison could be drawn between Professor Arnold's figures and those now presented, as it would be seen the angle of 7° was outside the range of his experiments, and no doubt they lay on a different curve corresponding to the different materials used.

necessarily always precisely the same; but it occurred to him that if Captain Sankey's machine was equally sensitive, that is, if a small difference of angle made a large difference in the number of alternations, the machine would not be adapted to the purpose for which it was intended, namely, that of a good, solid, every-day testing machine suitable for use in the workshop as well as in the laboratory. With Captain Sankey's permission he had himself made a series of tests in order to settle this point, and, as samples of the copper-aluminium alloys were not available, he made these tests with mild steel, cut from a bar of very uniform quality, and the results were plotted on a curve, Fig. 189. In this machine the specimens were bent backwards and forwards, through an angle of nominally 45° , on either side of their normal position, until they broke. Captain Sankey used no other angle, and he had therefore marked it "Standard Angle" on the diagram. He himself had tried, however, the results of bending through smaller angles, and he found that, as the angle through which the test-piece was bent was diminished, the number of bends required to break the piece increased slowly at first, while at small angles they increased at a very rapid rate indeed. Near 10° , for instance, a difference of one degree increased or diminished the result by as much as 55 alternations. Therefore small angles would never do for workshop tests. Near the "standard angle," however, the curve was very nearly horizontal. Whether 45° or 46° were taken made a difference of only one alternation, and as he found it easy, without special precautions, to keep within a fraction of one degree of the intended angle, there was no doubt that accurate results were got under the conditions which would be found in an ordinary workshop. He regarded the closeness of the spots to the curve as an indication that the machine was very accurate for the purpose for which it was intended.

The machine not only registered the number of bends required to break a specimen, but also the bending effort or "moment" in "lb.-feet" required to effect each bend. He had plotted the maximum moment for each experiment, and it would be seen to be only slightly affected by the angle. The work in foot-lbs. expended in producing fracture was beginning to be regarded as an important item in the physical qualities of a specimen, and this could be

(Mr. C. Humphrey Wingfield.)

obtained by multiplying the pressure on the handle by the total distance moved by the hand.

He had plotted this also, and the curve of work done would be seen to rise as the angle diminished.

On Fig. 190 he had plotted the properties of several alloys, and he thought this, now familiar, form of diagram would be of interest, as it gave by a graphic representation what was shown by figures in the

FIG. 190.
*Comparison of Mechanical Properties of Alloys Nos. 13 and 37
with two Steels.*

Reference— Proc. 1907,
pp. 138 and 222.

Proc. 1907,
p. 129.

Proc. 1904,
p. 1203.

Proc. 1907,
p. 245.

Report. The first two diagrams showed the properties of 0.35 per cent. carbon-steel side by side with those of Alloy No. 13. The true yield-point of the steel was almost exactly the same as the true yield-point of Alloy No. 13; the ultimate stress was identical, and the elongation nearly the same (26 per cent. as against 29 per cent.). The percentage reduction of area for Alloy No. 13 was 30.8. It was not given in the Report for the steel, but this figure corresponded closely with that of other samples of steel of similar composition. It could be seen at a glance how alike the two figures were.

Another alloy spoken of by the authors on page 245 as not unlikely to have an industrial future, where lightness and strength were required, was No. 37; and in order to compare it with the others,

he had plotted its characteristics on the diagram. He was surprised to find that they had selected a cold-drawn specimen, and the little narrow diagram to the right of Fig. 190 was not calculated to make one quite agree with the prediction of its having a very useful future. It looked very poor by the side of any other that had been put down. The yield-point, it was true, was a large percentage of the ultimate strength. It had 20 per cent. reduction of area, but the elongation was only 7.5. A large reduction was good where the elongation was ample, but where the latter was small a large reduction showed the material did not stretch uniformly, but had a tendency to local weakness contrary to what was generally believed. Therefore a large reduction of area, unless accompanied by a correspondingly large elongation, indicated a less reliable material than one with a more moderate reduction of area. Cold-drawn material had a very limited application, being of course only good for wire, and rods of simple and uniform section. He had plotted the same alloy hot-rolled, and that was much more promising; the area which represented ductility was very much larger, but the ultimate stress was less. He did not think, however, that in alloys of that description the strength was so very important, because a great deal of the material could be used without giving a very great weight. Just for comparison he had shown the properties of raw chrome-vanadium steel, and it would be seen that it had nearly the same ductility as Alloy No. 37, hot-rolled, and of course much greater ultimate strength. Apropos of the prophecy as to the future of cold-drawn material of this description, he had in his hands the results of some German experiments,* with copper-aluminium alloys containing a small amount of iron. One of them was 89.3 per cent. copper, 8.9 aluminium, and 1.3 iron; and another was 88.1 copper, 8.6 aluminium, and 2.8 iron. The point brought out in those experiments was, that while the alloy appeared to be very nice when first cold-drawn, and very promising as to its future, the experimenters waited from a year to two-and-a-half years

* Verhandlungen des Vereins zur Beförderung des Gewerbefleisses, Berlin, April 1906, pages 177-184. See also an abridged Report in the Proceedings of the Institution of Civil Engineers, vol. clxvii, 1906, page 450.

(Mr. C. Humphrey Wingfield.)

before they committed themselves to an opinion about it, and at the end of that time they found the cold-drawn alloys were cracking up, some longitudinally and some across, and that that particular pair of alloys was no good at all. When hot-rolled, however, no such effect was noticed; after two-and-a-half years it was as good as ever.

The authors had gone to some trouble to examine into the properties of the alloys as applied to cooking utensils, which was quite an important matter, as nobody wanted to be dosed with dissolved metal. They had dealt in that connection with various vegetable acids, but curiously enough had left out salt. It was true that the effect of cold sea-water had been considered, but he did not see that hot salt-water was mentioned, and cooks were constantly using hot salt-water in their saucepans. This was, he believed, a comparatively powerful solvent of aluminium, and he hoped its effects would be ascertained and embodied in the Report.

In the tests for corrosion he was much interested to find that the electrolytic order of the alloys, as compared with Muntz Metal and other brasses, was entirely reversed when fresh water was substituted for sea-water. He had pointed out before* that sometimes people, when they desired to know the relative corrodibility of metal under certain conditions, seemed to think it quite good enough to put the metals into hydrochloric or other acids, and assumed that they would be in the same order under all conditions, but the authors had brought out quite clearly that that was not a reliable assumption.

Mr. JOHN W. WAINWRIGHT wished to speak more especially as to the actual manufacture from certain aluminium-copper alloys. Some of them might be a little old, but any points found during manufacture might be of service, if brought out. When the Cowles Co. came over to England some years ago Messrs. Thomas Bolton and Sons made a number of experiments with air vessels for the Whitehead torpedoes, the cylinders being about a foot in diameter, and made of an alloy of 10 per cent. of aluminium. It was then thought that, by forging, the cylinders would be materially increased

* Proceedings 1905, Part 4, page 997.

in strength, but it was found that although the reduction in thickness of the walls was 50 per cent., the strength was not appreciably greater than that of the original casting, and that was in complete agreement with the Report.

Professor CARPENTER asked whether that was only with the 10 per cent. alloy.

Mr. WAINWRIGHT said he referred only to the 10 per cent. alloy. Later, they made a great many tubes for the Admiralty with 1 and 2 per cent. of aluminium in copper. They did not make any elaborate tests of those, but several curious things came out during the manufacture, notably surface cracking. In the manufacture of metal tubes the reduction of metal was brought about in the usual way by a central mandril and external die, the tube being drawn through. In brass tubes it was necessary that sufficient reduction should be made at each drawing, otherwise, when the metal was subsequently heated, the tube might fly from end to end, and crack right through, owing to the work put upon it not being transferred equally through the whole substance, thus causing a state of tension. The same effect was produced if considerable reduction were made in tubes without the internal mandril supporting them. In the case of ordinary copper tubes it was not noticeable at all, but it occurred to some extent in very thick copper tubes; they did not split through, but simply cracked on the surface. In the aluminium-copper alloys the effect was very marked, more so in the 2 per cent. than in the 1 per cent. The cracks were similar to those that occurred in the thick copper he had mentioned, but whereas in the copper the behaviour was confined to exceptionally thick tubes, with the 2 per cent. aluminium alloy it obtained also in tubes of moderate size and thickness, unless a very much greater amount of work was put upon them than was customary in brass and copper. Very much more labour than usual was entailed in producing an absolutely good surface.

With regard to the torsion test, in his opinion that did not depend nearly so much on the nature of the material as upon the

(Mr. John W. Wainwright.)

precise condition it was in. He had known many cases where two pieces out of the same original billet of copper had given very different results, with scarcely any perceptible difference in treatment. With regard to copper-aluminium wire, Messrs. Bolton and Sons also made some experiments years ago with hard-drawn copper-aluminium wire intended for telegraph wires, but the figures unfortunately were not preserved. The strength of the wire was very much more than copper, but the torsion test did not come out well at all.

Mr. J. E. STEAD said that he was sorry he was absent from the previous meeting when the Eighth Report was discussed. He was, however, glad to be present at the adjourned discussion. As a Member of the Committee he was pleased to congratulate the authors for having done such valuable work, and produced one of the most complete researches of the series of previous reports presented. It was indeed true, as the authors had remarked, that their work was, to a certain extent, corroboration of what had previously been done by Dr. Guillet and others, but, as the confirmation of such previous work established the facts beyond doubt, the honours must be divided. From a practical point of view, the fact that the really useful alloys could, with care, be made into good reliable castings equal to forged material in physical properties, by the simple plan of rapid cooling in the moulds, was most important and quite new.

The similarity in properties of Swedish 0.35 per cent. carbon-steel, and copper-aluminium alloy (10 per cent. Al) was remarkable. There was, however, one property absent in the latter which marked a clear dividing line between the two, and that is, the property which coarse-structured steel possessed of being refined by heating. The acicular structure produced on quenching the 9.9 per cent. alloy as in steel was probably due to the tendency towards separation of one of the constituents as fine crystallites, which were, however, not really free, but contained a considerable quantity of the second softer constituent in solid solution.

It was interesting to note that the complicated cooling-curve diagram of the copper-aluminium alloy resembled, in many features,

that of Messrs. Heycock and Neville's copper-tin alloys, and the fact that the two series of alloys yielded two definite chemical compounds, corresponding to those in the copper-tin series, was noteworthy, and scarcely what one would expect from *a priori* reasoning, tin and aluminium being so essentially different in chemical and other properties.

It would appear that, in Table 54 (page 185), the hardness numbers were given on the basis of Mr. Benedick's formula. He, Mr. Stead, suggested that, considering that Brinell's hardness numbers were in general use, it would be advisable if a seventh column giving these figures were appended for comparison with the others in column No. 6. The marked difference between the hardness numbers obtained by varying the pressure was clearly shown by comparing columns 4 and 6. He quite agreed with the authors that standard conditions for testing by Brinell's method should be those recommended by Brinell himself, namely, a 10 mm. ball and 3,000 kg. pressure. Any variations from these must lead to more or less widely differing results. Exception, however, might be allowed for the system in use by some engineers, who, for the purpose of testing the relative hardness of rail heads, employed a ball of 19 to 20 mm. diameter and a pressure of 50 tons. The multitudinous variety of mechanical tests, which had been applied to the same material by the authors, was most useful and should go far to assist engineers in determining what tests were really most valuable for their purpose.

He, Mr. Stead, had quite recently made a similar comparison on a series of soft steels with variable content of phosphorus, and had had the valuable co-operation of Mons. Frémont of Paris, and Professor Arnold of Sheffield, and as the results confirmed some of those contained in the Report, he had pleasure in stating them here. The series consisting of three steels contained about 0·3 per cent. carbon, with other constituents constant excepting the phosphorus, which was respectively 0·04, 0·30 and 0·50 per cent. The ingots were made small so as to avoid axial segregation, and were forged to suitable size for testing. The results obtained were as follows :—

(Mr. J. E. Stead.)

Tensile Tests.

No.	Phosphorus.	Yield-Point.	Ultimate Stress.	Elongation in 6 inches.	Reduction of area.
	Per cent.	Tons per square inch.	Tons per square inch.	Per cent.	Per cent.
1	0·040	20·4	33·1	23·00	52·0
2	0·300	25·4	39·9	23·00	45·3
3	0·500	32·00	44·2	20·00	45·3

Alternation of Stresses by the Wöhler Method.

Tensile stress 15 tons
 Range of stress 30 „
 Revolutions per minute 1200

No.	Phosphorus.	Revolutions to Fracture.	Ratio.
	Per cent.		
1	0·04	61,085	1
2	0·30	167,690	2·74
3	0·50	651,490	10·65

Impact Tests by Mons. Frémont.

The tests were made on saw-cut notched-bars, 10 mm. by 8 mm. section :—

No. 1 with 0·04 per cent. phosphorus broke with an expense of work = 8 kg.
 „ 2 „ 0·30 „ „ „ „ „ „ = 1 „
 „ 3 „ 0·50 „ „ „ „ „ „ = 1 „

The tenacities calculated from the results were respectively as follows, namely :—

No. 1	with 0.04 per cent. phosphorus	.	.	50 kg. per mm ² .
" 2	" 0.30 "	"	"	62 "
" 3	" 0.50 "	"	"	85 "

These results were remarkably near to those obtained in the Buckton machine, with the exception of the third, which was lower. Mons. Frémont remarked that these steels were all brittle. Even No. 1 should have been more resistant, whilst in Nos. 2 and 3, the brittleness was normal for steels of corresponding tenacity, for they could not bear the notch. "They may, however, not be of superior quality."

Alternation-Strain Tests.

These were made by Professor Arnold. The mean results of duplicate tests were as follows: namely, the bars were $\frac{3}{8}$ inch square. Alternations 660 per minute. Deflection of the test piece 3 inches above the die-face was $\frac{3}{8}$ inch on each side.

No.	Phosphorus.	Reversals to Fracture.	Ratio.
	Per cent.		
1	0.04	271	100
2	0.30	200	73
3	0.50	100	37

Professor Arnold remarked that No. 1 was only of moderately good capacity to resist alternating stresses. No. 2 was unsuitable for bolts and alternating parts of high-speed engines, whilst No. 3 was rotten.

Slow Alternating-Bend Tests.

The tests were made in Middlesbrough by bending strips $\frac{3}{8}$ inch by $\frac{3}{16}$ inch by 3 inches backwards and forwards, through an angle of 30° until they broke.

(Mr. J. E. Stead.)

No.	Phosphorus.	Reversals to Fracture.	Ratio.
	Per cent.		
1	0.04	605	100
2	0.30	446	73
3	0.50	150	24

These ratios compared fairly well with those given by Professor Arnold's machine. The tensile and Wöhler results would lead to the conclusion that the steel containing the highest phosphorus was the best, whereas the notched bars and bend tests appeared to indicate that the reverse was the case, but the impact tests did not appear to indicate more information than affording the tenacity of hard steels. The Wöhler results increased in value with the increase of yield-point, thus exactly confirming the corresponding results of the authors.

He would like the authors to state whether, or not, the alloys with between 7.7 and 9.9 per cent. of aluminium, after rolling, were stronger in the direction of rolling than in the transverse direction, and whether longitudinal and cross-sections differed in micro-structure. In the phosphorus-steels referred to, there was a very material difference. Cross-sections were exceedingly weak as compared with longitudinal strips, and this was caused by the objectionable habit of the more highly phosphorised parts to separate and finally solidify round the primary crystals in the ingots when freezing in the moulds, and to the way these envelopes, during the rolling or forging, became elongated into plates or threads, a condition clearly revealed under the microscope. Although when the stresses were applied to the metal in the direction it was rolled, the material stood up well; it easily broke when the stresses were applied to the steel at right angles to that direction. Steels for structural purposes, when in use in engines, etc., were subjected to stresses in many directions, and it was almost certain that high-

phosphorus steels, if used for such purposes, would fail at an early period, owing to the development of longitudinal cracks, similar to those observed by Signor Schanzer in a phosphoretic propeller-shaft which failed prematurely.*

There appeared to be no doubt that the alloy, provided it were not weaker transversely to the direction of rolling, with just under 10 per cent. aluminium, was by far the most serviceable all-round metal, and that this was indicated perfectly by the tensile and alternation of stress tests. There could also be little doubt that for parts of machinery liable to failure by sheer fatigue, this alloy would stand longer than the 7.7 per cent. alloy, and it was obvious that, if the two alloys were subjected to stresses above, or near to, the low yield-point of the 7.7 per cent. alloy, the latter would be the first to fail. It would appear that resistance to slight bendings backwards and forwards was not of itself a generally useful guide, and supplementary information was therefore necessary. This could be afforded by the determination of the elastic limit or yield-point. If such machines as that of Professor Arnold, and of Captain Sankey, could be made to record the coincident energy absorbed, as well as the reversals, or, if previous to making the alternating-bend tests the bending moment were determined, or the energy required to make a single full bend, and this were multiplied by the number of reversals, a most useful figure would be obtained, and this, with the number of bends to produce fracture, would enable one to make valuable classifications of the metals tested.

The alternating-bend test was an immense improvement on the old-fashioned simple bending, and might well be substituted for it. As an indication for ductility no test could be better, but extreme ductility was not always an advantage. The most ductile steels, with a yield-point of 12 tons or thereabouts per square inch, had to his own knowledge failed by fatigue, where wrought-irons with a yield-point of about 18 tons had stood well; yet the latter would certainly break down prematurely under the alternation-bend testing.

* Transactions, Institution of Naval Architects, 1900, page 249.

(Mr. J. E. Stead.)

In conclusion, he would only add that little but praise was due to the authors of the Report. It was a type of the work such as the National Physical Laboratory was created to accomplish, and such as the nation expected to get.

Professor A. K. HUNTINGTON said there was no doubt that the work in connection with the Report was most admirably done. He had nothing but praise for it, and he hardly liked to criticise it. At the same time, there were various points which were open to criticism. At the opening of the Report, under (a), the authors had referred to the number of alloys they had found of industrial and technical importance, but he ventured to think that that was perhaps claiming a little too much for the work, because all the alloys of any industrial importance in the aluminium and copper series had been known for many years. So far back as thirty years ago, when he was working with Dr. Percy, the latter certainly knew that alloys of aluminium and copper exceeding about 10 per cent. were of no special value.* At that time the alloys at the other end of the series, the rich aluminium alloys, had not been much investigated. Aluminium then was exceedingly expensive, and therefore a great deal could not be done with it, but more recently that end of the series had been thoroughly searched in order to obtain metal suitable for motor-car work and for such purposes where lightness was required. The authors took a similar line in connection with paragraph (b), but he would pass that over.

In paragraph (1) at the bottom of page 58, the authors said: "In view of the doubt which exists at the present time as to whether copper and its alloys possess true yield-points, it is important to record that from 0.1 to 9 per cent. of aluminium the alloys possessed clearly marked yield-points." He was not himself aware that there was any doubt about the yield-point in alloys of copper. There always had been some doubt in the minds of a good many people as to whether copper itself had a true yield-point, but with

* In 1900, when he, Professor Huntington, was testing these alloys (see diagrams, page 320) they were well known to the Admiralty at Portsmouth, and were in use.

regard to the alloys of copper it was something new to him to hear there was any doubt whatever about the matter. Certainly he had no doubt about it himself, because he had been dealing with the alloys for more than twenty-five years, testing them all the time—not merely isolated tests, but series of tests, with objects of a definite practical character; and probably for ten or fifteen years at least he had been making hot tests on all sorts of alloys of copper, ranging from the ordinary temperature up to 1,000° F. in static tests and 650° F. in alternating tests using bars one inch in diameter. Therefore, perhaps, he might claim to have had some little experience of such points.

In paragraph (4) the authors referred to the tenacity and ductility of the widely known "aluminium bronze" or "gold," containing 10 per cent. of aluminium, having been found to be as good in the form of small chill-castings as in the rolled bar, and they said, as far as they knew, that result had no parallel. That statement was open to question. He believed that those who had studied the matter would be able to say that it was not altogether an isolated case. If it were thought out, it would be seen that the question of the properties of a casting largely depended on the state of the crystalline arrangement and on the more or less freedom from pores. If the metal could be got into a very dense condition, with the crystals of a suitable size, by chilling, there was no reason why properties should not be obtained approaching, if not even surpassing, those obtained by rolling. In that respect he might mention that quite recently he had succeeded in obtaining an alloy of copper, very rich in copper, which actually had a higher specific gravity in the cast condition than it had in the rolled condition. That at first sight seemed a somewhat startling thing, and he made a great many experiments in order to be quite sure of the facts, but there was no doubt whatever about them. It all pointed in the same direction, that it was purely a question of obtaining a metal in a suitable condition. He thought it was pretty well admitted amongst steel manufacturers that very good results could be obtained from cast metal, quite as good as from rolled, but the difficulty was to get it in practice and on a large scale. The experiments in the Report of course were not on a large scale.

Professor CARPENTER asked whether Professor Huntington had actually quoted an instance of a metal that had the same ultimate strength and elongation in the cast as well as in the rolled.

Professor HUNTINGTON said he had not actually quoted it, and he preferred not to quote the actual metal. He had mentioned those facts, not in any way to depreciate the work that had been done by the authors, but merely to point out that they must not look upon it altogether as an isolated case, and to show that such things required looking into a little more thoroughly.

Under (*d*, page 59) the authors said that the research had brought to light several striking instances of the profound influence of a small quantity of aluminium upon copper, but he thought that the effect of small quantities of aluminium was pretty widely known. Aluminium was constantly being added to copper with the object of removing the oxygen and getting the copper into a sound condition, and not only was it being added to copper, but about 1/10th per cent. of aluminium was constantly being added to all sorts of copper alloys.

With regard to the torsional test, the authors said that the behaviour in torsional stress of the alloy containing from 0.1 to 7.35 per cent. of aluminium was one of the outstanding features of the Report. Years ago he (Professor Huntington) made some tests on some aluminium-copper alloys. The tests were not carried very far, as he had not a large amount of material. It was sent to him with the definite object of advising on the use of aluminium-copper in certain practical work where safety was a very important consideration. Those results were shown in Table 87 (page 317). His reason for putting them there was that the members might compare the ultimate resistance obtained by torsion with the breaking strain obtained in the ordinary tensile test. The figures gave the tensile test and the torsional test made with the Thurston machine, which, as many members knew, drew a diagram, and by measurements on that diagram it was possible to get a great many useful data. In the first test the metal was heated to 800° C., and then quenched at 760°, being heated above the 760° in order to give

TABLE 87.

7 Dec. 1900. *Copper-Aluminium.* $Al = 7.15$ per cent., $Fe = 0.115$ per cent., $Si = 0.027$ per cent.

Tensile Machine.					Thurston Torsional Machine.		
Quenched.	Yield-Point.	Breaking Load.	Elongation.	Reduction of Area.	Yield-Point.	Breaking Load.	Moment of Rupture.
—	Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.	Tons per sq. in.	Tons per sq. in.	
760° C.	4.26	23.86	91.0	73	4.35	38.72	688°
760° C.	4.30	24.33	94.5	75	3.68	39.50	879°
760° C.	4.83	24.40	86.0	77	—	—	—

24 Jan. 1901. *Copper-Aluminium.* $Al = 6.54$ per cent., $Fe = 0.11$ per cent., $Si = 0.023$ per cent.

Annealed.	—	—	—	—	—	—	—
2 hrs. 600° C.	6.25	26.27	83.5	77	4.01	40.40	750°
2 hrs. 600° C.	6.53	25.95	81.5	75	4.46	36.53	804°

6 March 1901. *Copper-Manganese.* $Mn = 5.32$ per cent., $Fe = 0.24$ per cent.

Annealed.	—	—	—	—	—	—	—
2 hrs. 600° C.	5.68	19.63	57.5	75	3.90	20.75	938°
—	—	—	—	—	3.23	22.54	1367°

(Professor A. K. Huntington.)

a little time in which to quench. Comparing the tests on the two machines it would be seen that the yield-point, the elongation, and the reduction of area agreed very well, but the breaking load on the torsional machine was 38.72 and 39.5 against 23.8 and 24.3 on the tensile machine. That was an enormous difference—a difference between 24 and nearly 40. The metal was commercially pure, being copper with 7.15 aluminium, 0.115 of iron, and 0.027 of silicon. The other copper-aluminium alloy in the Table, which had very much about the same quantity of aluminium, showed the same abnormal result as regards the breaking load. That was, he thought, an isolated case amongst alloys, to get such a difference on the torsional machine as compared with the tensile. For comparison he had put in the Table an alloy of copper-manganese, which gave a normal condition of things. On the tensile machine it was about 19½, and on the torsional machine a little over 20—a very close agreement. In all other alloys which he had examined the breaking load obtained by the torsional machine had been the same for the same material as would be obtained on the tensile machine, but in the case of the aluminium alloys which he had examined there was the enormous difference he had mentioned. That was a very important point indeed, and one that had made him look rather askance at copper-aluminium alloys. He thought the result was to be attributed to the fact that the aluminium alloys took up work in a most extraordinary manner, and the breaking strain rapidly increased as the work was put on. The aluminium seemed to give to the alloy the power of rapidly absorbing the work. That was a very nice thing up to a certain point, but it had to be recollected that it could not be stopped, and when one had to deal, as was commonly the case, with metal in a condition of movement, then it was going gradually to get stiffer and stiffer, and ultimately it would break. He therefore looked upon this stiffening rather as a disadvantage in aluminium alloys than an advantage. This peculiar behaviour of aluminium in causing the alloys in which it was contained rapidly to take up the work was a thing that required very carefully looking into. It probably explained the results obtained by Professor Arnold given in the Report.

In paragraph (g) hardness was referred to (page 59), and a comparison drawn with steel of 0.45 per cent. carbon, which was roughly a rail steel, but the authors did not point out in that paragraph a thing of vast importance practically—that although the alloy had that hardness, it had at the same time very great brittleness. It was perfectly useless to have an alloy which had the hardness of 0.45 carbon-steel if it had the brittleness of a piece of glass. [Professor Huntington here broke a piece of metal with a key.] That specimen was some metal which he happened to have at hand, and which he had brought down for the enjoyment of railway engineers. He had in fact been in the habit of using that alloy for years in order to make up mixtures, because such an alloy could be crushed up very readily and thus save a lot of trouble. It was a 15½ per cent. aluminium-copper alloy. He was pointing out some of those things, because it appeared to him the Report was a little too academic; it drew attention to things that were of no practical use, and did not deal sufficiently with the practical point of view, which was of course the point of view that had most to be taken into account by the members of the Institution. The equilibrium curve, shown in Fig. 33 (pages 204–205), was a very nice one, and a valuable piece of work, but he did not think it was a piece of work that was of very great use to the Institution; it would be more useful to the members of the Physical Society or the Faraday Society. The whole range of usefulness of the alloys to the members of the Institution lay between 1 and about 10 per cent. of aluminium at one end, and between 1 and about 6 per cent., roughly, at the other end; and the complicated diagram had no practical bearing whatever, although it was of great scientific interest, and personally he welcomed such diagrams. Professor Tammann, of Goettingen, and his students were doing a great deal of work of that kind. It was most useful work, because much had to be done yet to get to the end of two component alloys, and after that there would be three components to deal with, and four components, and so on, and it would mean a tremendous amount of work before it could all be got through.

FIG. 191.—*Annealed Bronze.*

16 Jan. 1900.

Zn, 40 per cent.

FIG. 192.—*Aluminium-Bronze.*

7 Dec. 1900.

Al, 7.15 %; Fe, 0.115 %; Si, 0.027 %.

FIG. 193.

Annealed Electrolytic Copper.

13 March 1906.

As, Trace. Sb, Nil. Bi, 0.0005 %.

Se, Te, Trace.

He had brought some diagrams, Figs. 191 to 193 (page 320), which he thought might be of interest. He wanted to point out that in such investigations it did not do to rush into the middle of the whole thing; it was necessary to begin carefully at the beginning and investigate the component metals first. Some years ago he made a few experiments with aluminium-bronzes at various temperatures, which experiments were shown on the diagrams, and he wanted the members to compare them with those made at various temperatures on copper. In the early tests a great many years ago he did not use as pure a copper as he was using now. He was gradually led to suspect that some of the results obtained with copper alloys were really traceable to the inherent properties of the copper itself, and to be sure about that it was necessary to get actually pure copper, or as nearly pure as possible. Fig. 193 was a pure electrolytic copper.* Taking the curve of the breaking loads and comparing it with the curve of the aluminium-bronze breaking loads, Fig. 192, he had not any doubt that if there were three or four more points for the aluminium-copper, the diagrams would be identical in general characteristics, but the points shown were sufficient to indicate general agreement between the curves. The point on the copper curve where it commenced to become flat was the point at which the test piece ceased to neck before fracture. At that temperature the metal became short and worthless, and the result was that, the elongation having become very poor, the line wandered about to a certain extent. Comparing the elongation with that of the aluminium-bronze, one found precisely the same character of curve in each. The curve was not due to the alloy, but to properties inherent in the copper, and certainly up to 7 per cent. it had not been modified. Similar curves were obtained for the reduction of area. If dynamic tests were taken instead of static tests, then it would be found that very minute amounts indeed of impurities very seriously affected the tests when making hot tests. When the hot tests were made on an alternating machine the effect of a minute amount of certain impurities on the

* Arsenic, trace; antimony, nil; bismuth, 0.0005; selenium and tellurium, trace. A "trace" implies here less than 0.005 per cent.

(Professor A. K. Huntington.)

elongation showed up very much, whereas it did not in the ordinary static test to anything like the same extent. [*See additional communication, page 357.*]

Mr. W. COBBETT BARKER said his reason for speaking was that he happened to have been engaged industrially in connection with copper-aluminium alloys for years at his foundry in Ramsbottom, near Manchester; and during the last eighteen months he had been specially interested in 10 per cent. aluminium alloys, and alloys in the neighbourhood of 5 to 11 per cent. He found that his own experiences were on very much the same lines as the authors', although his own tests had been naturally of a purely workshop character. The extreme hardness of the material which was referred to was always regarded as a purely chemical statement. The alloy was practically worthless when it exceeded 10 per cent.; and he doubted whether the 11 per cent. was of any practical value at all. Most of the alloys that he exhibited, which bent rather well, cold or hot, and forged, were about 9.30 per cent., but when 10 per cent. was reached he found, as the authors said, that they began to get very much stiffer and the ductility rapidly decreased. In workshop practice he started making some very large aluminium-bronze shafts, 4 inches in diameter, and considerable difficulty was met with, owing to the oxide. It was necessary to re-melt and re-melt and mix again on altogether different lines. Sir William White had said that manufacturers were rather chary in giving any assistance to investigators, but naturally they did not propose to give away any little improvements they had found out at the expenditure of time and cash.

Mr. C. H. WINGFIELD asked whether Mr. Barker had found in his practical work any heating taking place when the aluminium and copper were mixed. There was a difference of opinion about that.

Mr. BARKER said he had certainly found it so, but it might be, as Professor Carpenter had suggested, that the copper was not very

pure. With regard to the question of the oxide, he found that, in stirring with a wrought-iron rod, the iron was dissolved away very rapidly, and it had been suggested that this might be due to rust on the rod. In Lancashire the climate was moist, and it was difficult to prevent iron from rusting; therefore it might have been due to that fact. A cast-iron rod was often better than a wrought-iron one to stir the pure aluminium.

It was most important to have proper copper, and he was glad to see that that point had been emphasized, because his firm had made test after test in an endeavour to get a suitable copper. The copper he had used had not been analyzed, but he found some kinds of copper gave vastly better tests than others. He had discovered—by experience and experiment, while others might have found it by chemical analysis—that it would be worthless trying to use some coppers.

The question of other metals had been raised, and he might mention that he had done considerable work with alloys, rich in aluminium, but containing no copper, which he had found were of no particular value for his purposes in rich aluminium alloys. In some cases at chemical works copper could not be used, and zinc was substituted for it, and some exceedingly good results were obtained from aluminium and zinc alloys, such as were well known to a good many practical men. In that connection a great deal had to be learned from experience, and, with a new metal about which nothing was known to begin with, many experiments were required before it could be known precisely what could be done with the metal.

The question had been raised at various times of utilizing the rich aluminium alloys for shipbuilding purposes. It would probably be found that the adoption of a rich aluminium alloy for this purpose must be proceeded with very cautiously indeed, and only after prolonged trial, as sea-air, sea-water, salt-spray, and salt of any chlorine variety was usually most destructive when aluminium formed a considerable proportion of the alloy. Japanning, painting, or otherwise coating the metal was seldom completely successful, and any small surface exposed to the influence of common salt rapidly deteriorated, if indeed it did not disintegrate and crumble away.

(Mr. W. Cobbett Barker.)

The compilation of this Report should prove of great service to founders, and much valuable time might be saved if the results of repeated experiments were confirmed and tabulated for easy reference. It might perhaps have been pointed out for the benefit of the busy manufacturer if a particularly hard alloy was also brittle. Though glass was known to be very hard, it was scarcely suitable for machine building.

Professor H. C. H. CARPENTER, in replying, dealt first with Mr. Tomlinson's remarks (page 271). The first point made by him was that the yield-points were not in accordance with his results, and that they were too high, more particularly the alloys which were low in aluminium. In that connection he would refer members to Fig. 20 (page 141), which gave the stress-strain diagrams of the alloys; and he thought that Mr. Tomlinson would admit that the evidence was pretty clear from that figure that the yield-stress of the alloy containing 0.1 per cent. of aluminium was certainly as much as 5 tons or rather over. This, of course, was on the assumption that stress-strain diagrams yielded trustworthy indications of yield-stress. The evidence he thought had justified the authors in giving these figures as the yield-stresses. Then there was the very interesting question of the rise of temperature, which had been referred to by several speakers, when aluminium was added to copper. In the first place he wished to read exactly what was said in the Report. On page 87 they were speaking of the manufacture of the alloys, and had reached the condition when the copper was fluid in the crucible and was about to have aluminium added to it, and then they went on to say: "The view generally held is that under these conditions the aluminium and copper combine with a disengagement of so much energy that a 'white heat' is attained. This has been found to be very destructive of the crucibles, which are useless after nine or ten heats. The authors have not found that the solution of aluminium in molten copper is attended with this great rise of temperature, provided the copper has been protected from oxidation. Under these conditions mixing occurs with a barely sensible increase of temperature. But

it *has* been their experience that, if the copper contains oxygen, a very marked evolution of heat does occur. Accordingly the rise of temperature should be attributed, not, as has sometimes been done, to the combination of aluminium and copper, but to that of aluminium and oxygen, one of the most powerfully exothermic chemical syntheses known." In making that statement they had regard simply to the addition of aluminium to copper in manufacturing. They made no measurements of rise of temperature, and referred, not to any small rise of temperature, but to the production of the white heat. On that point they were perfectly clear. Mr. Tomlinson maintained that, apart from that particular reaction, namely, the reaction between aluminium and oxygen, there was a reaction between aluminium and copper which was attended with the evolution of heat. He was not quite sure whether Mr. Tomlinson's view was that the reaction was sufficient to account for the production of white heat.

Mr. TOMLINSON said he did not think so. The white heat and the flash heat were certainly due to the combination of the aluminium and the oxygen in the copper.

Professor CARPENTER said that since the last meeting he had been in communication with Mr. Tomlinson as to that point, and Mr. Tomlinson had been kind enough to give him the figures he had obtained. He had made experiments, taking care as far as possible to remove oxygen from the copper, and then measuring the rise of temperature when aluminium was added, and he (Professor Carpenter) would quote from the tests which were made in the preparation of the alloy that had been so much referred to—the 10 per cent. alloy. In the first place Mr. Tomlinson found a rise of 232° F., or about 130° C., and in the second place he found a rise of 195° F., about 108° C. If that rise of temperature were due only to the reaction between aluminium and copper the figures ought to be the same, because the aluminium and copper were added in the same proportions, namely, the proportions required to produce the 10 per cent. alloy; and the fact that Mr. Tomlinson found

(Professor H. C. H. Carpenter.)

different figures was evidence that he had not got rid of all his oxygen.

Mr. TOMLINSON pointed out that in the first instance, where there was a rise of 232° F., he used two pounds of alloy, and when the temperature was only 195° F., he used 180 grammes. Therefore he thought the difference was accounted for by the proportion of radiation.

Professor CARPENTER was prepared to admit that point. The authors had made the same experiment, and they had not found a rise of anything like that amount. They had adopted two different methods of de-oxidation. In the one case they added sufficient phosphorus to remove oxygen and leave about 0.2 per cent. of phosphorus in the material, and they got a rise of only 40° C. Then they made the experiment under different conditions, de-oxidizing merely with carbon and borax, and they got about 44° C. Those results agreed well with one another, and they did two things; they confirmed Mr. Tomlinson's statement that there was a rise of temperature when aluminium was added to copper, and they confirmed the statement in the Report that when the trouble was taken to remove the oxygen there was only a rise of about 40° C., which was a barely perceptible rise of temperature. He thought that point was therefore cleared up. It was a very interesting one, and the authors were very much obliged to Mr. Tomlinson for having drawn attention to the matter; because the members would notice that at about 9.6 per cent. there was a compound to which the authors had ascribed the formula of Cu_4Al , and it was possible that the compound had a heat of formation which was actually responsible for that rise of temperature. They were very glad that Mr. Tomlinson had confirmed their statement that the 5 per cent. alloy did not present any special difficulties of manufacture.

Mr. Tomlinson had also challenged them on the casting temperatures, and had said that, while they laid great stress on the importance of casting at the right temperature, they carefully avoided saying what that temperature was. He was afraid that was

true; but the position was something like the following, that they had found they had not had time as a rule to make temperature measurements during the interval that elapsed between taking the crucible out of the furnace and actually teeming. After the necessary stirring had been done, the removal of the dross and so on, they usually had to pour pretty quickly in order to get the entire metal to flow, and they would like to confine themselves to the general statement that the nearer the alloy could be poured to the temperature of incipient solidification, consistent with thorough fluidity, the better. He thought that was a very general experience, and one Mr. Longmuir found in his pioneer work on the subject.

Then Mr. Tomlinson had commented on the omission of strength tests at various temperatures, but that deficiency had been supplied by the kindness of Mr. Rosenhain, to whom the authors wished to give their very grateful thanks for the work he had done. His contribution to the discussion would undoubtedly be a very valuable one.

Passing on to deal with the remarks of Professor Arnold (page 275), the latter had said that the authors affirmed that on remelting alloys, high in aluminium, there was no oxidation. He was sorry that Professor Arnold was not present that evening, because he had not been able to discover that any such statement was made in the Report. On the contrary, if reference were made to page 93, it would be seen that the authors were speaking of the remelting of a particular alloy, and said, "The casts were made at as nearly as possible the same temperature, namely, when the fluid surface, after being skimmed, did not oxidise to a coloured film." That meant that at high temperatures they found a coloured film was formed, and they kept skimming it off until the temperature had fallen so low that after a particular skimming the coloured film did not form. On that point they agreed entirely with Dr. Seligman, who had said there was a slight oxidation; but they thought that the film which formed on the surface protected the remainder of the metal very thoroughly from oxidation, and that is why they were able to get such closely agreeing analyses of the products on cooling. Professor Arnold had also commented on the fact that they obtained the

(Professor H. C. H. Carpenter.)

same temperature results whether they used protected or unprotected couples (page 275); and he had been rather astonished at that result. They did not use the protection for the mere pleasure of doing so; they used it because it was necessary. He might say that they had made experiments at an early stage of the research, and found that if they used a bare junction they obtained an alloy formed between the copper-aluminium and the platinum-iridium, and therefore the junction became untrustworthy. The protection used was a Morgan fire-clay tube, $\frac{1}{16}$ inch in thickness, No. 1417. He thought that information would enable anybody to test that point themselves.

With reference to Dr. Seligman, he was surprised to find a yield-point given for aluminium, and in that connection it would be well to quote the exact words that were used in the Paper. On page 113 they were referring to the yield-points, and there said: "Accordingly, in each tensile-stress test of 2-inch gauge length the first permanent set was noted by means of dividers. The load at which this occurred is included in the Tables and diagrams as the yield-point. As far as possible, a uniform rate of loading was used throughout the tests." They did not find, as far as he remembered, that there was quite as marked a permanent set at the yield-point in the case of the rich-aluminium alloys as in the case of the rich-copper ones, but they got very fairly concordant results by taking that as their basis of measurement.

Professor HUNTINGTON asked how near the authors reckoned to measure with the dividers.

Professor CARPENTER said about 0.03 inch.

Professor HUNTINGTON said he had been using the dividers for that purpose for a great many years, and found he could measure to less than 0.003 inch.

Dr. SELIGMAN believed that his remarks had only referred to pure aluminums, not to the light aluminium alloys.

Professor CARPENTER did not think the authors found any marked difference on the introduction of copper into the aluminium. Then Dr. Seligman had gone on to say (page 279) that they had condemned the device of re-melting the alloys before finally casting them. He did not think they had quite done that, and he would like to refer to pages 64 and 65, where it was said that "there was no need to re-melt the alloys rich in copper in order to obtain thorough mixing, obviate brittleness, and secure the best mechanical properties." At the top of page 65, in section 3, they said: "Alloys rich in aluminium can also be satisfactorily made with only one melting. This conclusion is intended to apply only to small castings." At that point they had not committed themselves to any dogmatic statement, but merely said that so far as their experience was concerned the first cast melted was as good as the last one.

Mr. W. COBBETT BARKER said that in the case of heavy castings he thought that was to be taken very cautiously. The authors did not commit themselves to the statement that in heavy castings it was not necessary to re-melt. He himself thought it was.

Professor CARPENTER said that Dr. Seligman also observed that the authors had misunderstood the reasons for the 50 per cent. alloy (page 280). On page 92 it was said, "In making these alloys it is of great advantage to proceed from pure aluminium and the 50 per cent. alloy. The freezing points of the two materials lie near together . . . and the working temperature need not be raised above 700° C." Therefore they actually stated a definite reason for using a 50 per cent. alloy, and they entirely agreed with Dr. Seligman in the other matter, namely, that the very brittleness of the alloy was a great advantage in making up charges. He thought Dr. Seligman had not quite understood Table 6 (page 92), because he had declared that the authors gave certain results obtained at a casting temperature of 650° C., and got an ultimate stress of 9.68 tons, and that on having a casting temperature of 707° C. the stress dropped to 4.89, and that on casting at a still higher temperature, namely, 724° C., it rose again to 7.04. That was not quite the correct way

(Professor H. C. H. Carpenter.)

of putting it. The figures were given in the order in which the casts were made. They first of all cast at 650° C., then at 724° C., and obtained a very marked lowering of ultimate strength; then they re-melted that alloy and cast again at 707° C., and got a still greater lowering of the strength. All the conclusion that could be drawn from that was that the bad effects of casting at too high a temperature, namely 724° C., were not entirely removed by re-melting, but were still further accentuated by the next casting at 707° C. Dr. Seligman had also commented on the comparatively bad results of the 10 per cent. rolled bronze, relative to the casting. But that was hardly a fair way of putting it. The rolled 10 per cent. alloy was as good as anything that was made industrially. *What the authors had done was to make the same alloy in the form of castings in such a way as to give it just as good properties.* They were extremely interested in getting that particular fact confirmed by Mr. Wainwright.

The authors were much obliged to Captain Sankey for the description of his workshop bend-testing machine and for the tests he had carried out on the alloys by its means, and it was very interesting to find that he got such good figures with No. 9, which contained $7\frac{1}{2}$ per cent. of aluminium. He thought the fact that Captain Sankey's figures agreed so well with Professor Arnold's indicated that the latter's must be regarded as a repeating bending-machine, and not in the least comparable with Dr. Stanton's machine, where the material was kept within the yield-point. Mr. Bertram Blount had compared the 10 per cent. bronze with mild steel, but he himself thought a 0.35 per cent. carbon-steel was more accurately described as a medium carbon-steel. The other points raised by him were dealt with in the reply to Mr. Tomlinson (*loc. cit.*). The contributions to the discussion that evening had been mainly of the order of independent pieces of information, which would undoubtedly form a valuable appendix to the Report.

The authors were greatly indebted to Mr. Rosenhain for his determination of high temperature tensile test of Alloys Nos. 8 and 13 (page 292). They were interested to observe that the practical conclusion to be drawn from his tests of No. 13, namely, that "up to

350° C. the alloy maintained its strength fairly well, but from 400° C. upwards the alloy became rapidly weaker" agreed with that drawn by them from their own experiments, carried out in a different way, and recorded in Table 53 and Fig. 29 (pages 178-179). They also found 400° C. to be the decisive temperature (page 177). Their purpose in drawing attention to this was to point out that a good deal of information could be obtained from simple experiments, carried out in a way which did not involve the use of a rather special apparatus such as that devised by Mr. Rosenhain.

He did not want to make a point of difference with Mr. Wingfield whether Alloy No. 37 was of greater industrial promise in the hot-rolled than in the cold-drawn condition. Undoubtedly Mr. Wingfield's practical experience was very much greater than their own, and they gathered that Mr. Wingfield looked favourably on the material in at any rate the rolled form.

With regard to Mr. Stead's remarks (page 308), it was a great pleasure to the authors that where they had overlapped with Dr. Guillet their results had agreed, except in one important respect. Mr. Stead had asked for an extra column in regard to the hardness numbers, which would make the numbers actual Brinell numbers. They much regretted they could not comply with this request, the reason being that their ball was not of the standard size, namely, 10 mm. diameter, recommended by Mr. Brinell (*see* page 183 of the Report). They were much obliged for the interesting tests of phosphoric steels submitted by him. With regard to whether they had noticed any difference between the tensile strength of longitudinal and transverse sections of the alloys, they had not at any rate in the alloys rich in aluminium, particularly in the form of sheets. They made a great many experiments of that type, and finally gave up testing them in both forms because they got such regular results. In regard to Mr. Stead's last question, as to whether orientation still persisted in a 10 per cent. alloy in melting, he would rather not say anything more at the present time, except that they were working on that extremely interesting point.

With reference to Professor Huntington's remarks (page 314), the Professor had said that alloys of industrial value had been well

(Professor H. C. H. Carpenter.)

known for thirty years. In a sense that was perfectly true, but in a sense also it was not quite an adequate description of the facts, because he thought Dr. Seligman would bear him out when he said that the quality of commercial aluminium had very much improved during the last seven or eight years, and that the modern copper-aluminium alloys were not the same by any means that they were thirty years ago. Anybody who wished to test that point had merely to refer to Professor Tetmajer's splendid research on that subject.

With regard to the similarity of properties of the 10 per cent. alloy in the cast and [rolled condition, they were extremely glad to find that there was another alloy, although he was sorry Professor Huntington had not seen his way to give the composition. In the correspondence on the Second Alloys Report, Professor Hudson Beare * quoted a copper-phosphorus alloy which he declared had similar properties. He wrote to Professor Hudson Beare on the subject, and the reply was that it was unfortunately a mistake. *He believed that, as far as published work was concerned, the instance he had mentioned was unique.* The authors had also found, like Professor Huntington, that the ultimate torsional stress was greater than the ultimate tensile stress of the rich copper alloys, although not to anything like the extent that was indicated in the diagrams. But with regard to the statement that the alloys easily took up work, although that was true for the alloys in the cold, it certainly was not true for them when hot, because it was that very fact which explained why the primitive yield-point of the alloys as hot-rolled was practically the true yield-point, and not, as in the case of steels, a purely artificial figure.

Professor HUNTINGTON said that certainly was so. At a very low temperature it gave up its work.

Professor CARPENTER said Professor Huntington had also condemned them for laying stress upon the hardness of the 15 per

* Proceedings, 1893, page 178.

cent. of aluminium on the ground that they had suppressed the equally important information that it was very brittle. In that connection, he would refer to page 224, where, referring to the alloys of intermediate composition, it was said "From 15 to 18 per cent. they are very hard, but very brittle." That was a plain statement by which he did not think anyone could be misled. The reply to Mr. Barker's remarks as to the brittleness of hard alloys was contained in that made to Professor Huntington on the same topic.

It was somewhat dangerous in these days to condemn a piece of work as unpractical, and Professor Huntington could hardly have been more unfortunate in his choice of an illustration taken from the Report. He had said that the equilibrium-curve diagram, Fig. 33 (pages 204-205), "had no practical bearing whatever." So far from this being necessarily the case, there were those who held that its complete elucidation should *precede* any investigation of a more practical nature, that it should be made the very foundation of a research of this kind. (See Mr. Gulliver's Communication, page 345.) Moreover only two days since he had received an inquiry from the manager of a works manufacturing these alloys as to where he could obtain a copy of this very diagram.

Finally, on behalf of his colleague and himself, he expressed their thanks to the members for the interest they had taken in this very voluminous Report, and particularly to those members who had contributed to the discussion. He wished to add the authors were greatly touched by Sir William White's extremely cordial reference to their work.

On the motion of the Chairman, a vote of thanks was accorded to the authors of the Report, which was carried with acclamation.

Communications.

Mons. PIERRE BREUIL wrote that he was of opinion that the Report of Messrs. Carpenter and Edwards was worthy of the highest praise on account of the care with which it had been conducted, and the method, elegance, and prudence with which the conclusions had been arrived at. He was pleased to be able to give some information on an alloy of copper and aluminium which he had had the occasion to study, and which was very closely the same as the alloy containing 9.90 per cent. of aluminium (Alloy No. 13). The inventor of this alloy had discovered the method of casting it with the minimum of impurities; incidentally, impurities were of frequent occurrence with the alloys of copper and aluminium. This alloy could be easily forged at all temperatures. Tensile tests on cast specimens 12 mm. (0.47 in.) in diameter gave the following results, shown in Table 88.

The results of these tests, so far as they related to the metal in its natural or in its quenched condition, taught nothing new, but they confirmed the results of the authors. They were, however, of earlier date, having been carried out in December 1904. The tests made with the heated specimens were, he believed, new. They were specially interesting because they established the fact that the 9.90 per cent. aluminium-copper alloy did not lose, so to speak, any of its mechanical properties when heated.

In Table 89 (page 336) were given the compression tests made with specimens 10 mm. (0.39 in.) diameter and 15 mm. (0.59 in.) in height made from the same material.

The irregularities in the results were evidently such as to prevent coming to any very definite conclusions; nevertheless it could be said:

(1.) That reheating only slightly modified the mechanical compressive properties of the metal; its malleability was, however, less when reheated than in the cast condition.

(2.) Quenching increased the elastic limit, somewhat diminished the ultimate stress, and greatly diminished the malleability from

TABLE 88.

Nature of Treatment of the Metal.		Apparent Limit of Elasticity.		Ultimate Stress.		Elongation.	Reduction of Area $\frac{S-s}{s}$
		Kgs. per mm. ²	Tons per sq. in.	Kgs. per mm. ²	Tons per sq. in.	Per cent.	
I. Tests made at ordinary temperature—							
Raw metal	1st test-piece	19.0	12.06	44.7	28.38	36.0	0.43
	2nd test-piece	18.8	11.94	44.2	28.06	30.0	0.25
	3rd test-piece	20.8	13.21	43.9	27.87	32.0	0.26
Quenched in water at	550° C. (1,022° F.)	19.7	12.51	43.1	27.36	23.2	0.22
	800° C. (1,472° F.)	22.1	14.03	48.0	30.48	13.3	0.12
	900° C. (1,652° F.)	29.6	18.79	52.9	33.59	12.6	0.15
II. Tests made at various temperatures—							
Tensile tests made at	150° C. (302° F.)	25.4	16.13	43.1	27.36	15.0	0.23
	175° C. (347° F.)	21.4	13.59	42.8	27.17	16.5	0.21
	200° C. (392° F.)	18.7	11.87	39.0	24.76	13.0	0.19
	235° C. (455° F.)	30.1	19.11	41.0	26.03	13.5	0.20
	260° C. (500° F.)	22.4	14.22	41.8	26.54	16.0	0.23

(Mons. Pierre Breuil.)

TABLE 89.

Nature of Treatment of the Metal.		Apparent Limit of Elasticity.		Ultimate Stress.		Reduction in length at rupture.
		Kgs. per mm. ²	Tons per sq. in.	Kgs. per mm. ²	Tons. per sq. in.	Per cent.
Raw cast metal.		31.8	20.19	121.0	76.83	50.3
Metal quickly heated at	550° C. (1,022° F.)	42.6	27.05	131.3	83.37	28.0
	650° C. (1,202° F.)	39.8	25.27	133.7	84.89	33.3
	750° C. (1,382° F.)	31.8	20.19	117.1	74.35	29.6
	850° C. (1,562° F.)	39.8	25.27	132.2	83.94	32.0
	950° C. (1,742° F.)	47.7	30.28	133.3	84.64	26.5
Metal quenched in water at	550° C. (1,022° F.)	35.9	22.79	132.4	84.06	30.0
	650° C. (1,202° F.)	96.8	61.46	132.4	84.06	13.2
	750° C. (1,382° F.)	51.5	32.70	133.3	84.64	27.2
	850° C. (1,562° F.)	79.6	50.54	95.8	60.82	10.2
	950° C. (1,742° F.)	102.5	65.07	108.8	69.07	8.0

temperatures of 850° C. (1,562° F.) and above especially; that is to say, at temperatures when the metal was completely in the acicular condition, a fact which was first pointed out by Dr. Campbell, and which he (Mons. Breuil) later confirmed at a slightly earlier date than Dr. Guillet.

He had studied the bending tests of a specimen 20 mm. (0.79 in.) square and 100 mm. (3.94 ins.) between the supports, and had obtained the following results:—

TABLE 90.

Test-Piece.	Elastic Limit. (Total.)	Breaking Load.	Deflection at point of rupture.
	Kgs. Tons.	Kgs. Tons.	mm.
Raw casting untreated . . .	2,125 2.09	4,500 4.43	15 (0.59 in.)
Raw casting quenched at 850° (1562° F.)	2,120 2.08	5,625 5.53	13.5 (0.53 in.)

As regards impact, similar square specimens placed on supports 100 mm. (3.94 ins.) apart and struck with a tup weighing 20 kgs. (44 lbs.), had given the following results:—

Specimen as cast: rupture was produced by 116 kg.m. (839 ft.-lbs.) (apparent). The deflection was 30.5 mm. (1.2 in.).

Specimen quenched at 900° C. (1,652° F.). Rupture was produced by 24 kg.m. (173.5 ft.-lbs.), apparent. Deflection was 7.8 mm. (0.31 in.).

The ordinary Brinell coefficients for these latter specimens were: as cast, 133; when quenched at 900° C., 227. These figures corresponded well with those obtained by Messrs. Carpenter and Edwards.

Finally, he would point out that the results obtained with heated tensile specimens with the alloy under consideration were the same as those obtained with other alloys, and he would refer to a brass consisting of 61.2 per cent. of copper and 37.8 zinc, with a few

(Mons. Pierre Breuil.)

impurities, which gave the following results with hot tensile test-pieces:—

TABLE 91.

Tests made at the following Temperatures.	Elastic Limit.		Ultimate Stress.		Elonga- tion.	Reduction of Area.
	Kgs. per mm. ²	Tons per sq. in.	Kgs. per mm. ²	Tons per sq. in.		
15° C. (59° F.)	9.55	6.06	50.3	31.94	54.3	0.67
260° C. (500° F.)	11.11	7.05	50.9	32.32	50.9	0.67
300° C. (572° F.)	9.55	6.06	50.6	32.13	50.6	0.59
325° C. (617° F.)	10.3	6.54	50.3	31.94	50.3	0.59

The test-pieces were 20 mm. (0.79 in.) diameter, and were raw from the rolls.

The authors of the Report could have found interesting particulars of trials made with an alloy of 95.12 per cent. of copper and 4.88 of aluminium, and with an alloy of 92.25 per cent. of copper and 7.4 of aluminium, in an important research made by Mons. E. Le Blant, Engineer of the Eastern Railway of France at Paris, and presented to the Congress of Methods of Testing of 1900. Tensile tests were made with hot specimens of both these alloys up to 500° C. (932° F.), and also with an alternating-bending test up to 350° C. (662° F.). Both these alloys have proved themselves to be, as regards laboratory tests, far superior to copper-manganese alloy and to ordinary copper. The 7.4 per cent. aluminium alloy was specially remarkable in respect of the alternating-bending test when in the form of locomotive boiler-stays; at 200° C. (392° F.) temperature this alloy had withstood 8,000 bendings of 3.5 mm. (1.38 ins.) amplitude before rupture, whereas the 4.88 per cent. aluminium alloy broke with 3,500 bendings, very soft steel broke with 3,200, 4.5 per cent. copper-manganese with 750, and ordinary copper with 400 to 500 bendings; nevertheless the two copper-aluminium alloys had given far less satisfactory practical results in the form of stays (which appeared abnormal) because, according

to the opinion of Mons. Le Blant, riveting had affected the copper-aluminium alloys more than the others. The tests made by Mons. Le Blant were in agreement with those of Dr. Stanton and of Professor Arnold, as quoted by Messrs. Carpenter and Edwards.

As regards the photo-micrographs, he was not quite of the same opinion as the authors. The 9.90 per cent. alloy (Alloy No. 13) began to show a modification of structure when quenched at 550°C . ($1,022^{\circ}\text{F}$.) to 600°C . ($1,112^{\circ}\text{F}$.), that is to say, the dark constituent was diminished and the pale gold constituent was marked with small black granules, as was shown by Fig. 194, Plate 23.

With regard to the formation of the acicular constituent, he had always insisted on the fact that, when the alloy was composed almost entirely of this constituent, crystalline joints were produced, at the edges of which the needles stopped, and then changed their direction. Dr. L. Guillet had questioned this fact, but he was anxious to prove his point, and therefore submitted Fig. 195, which indicated three crystals (not very well formed, however) showing the change in direction of the needles. This photograph was not very good and certainly much inferior to those of the authors, which, in his opinion, deserved the greatest praise.

Mr. GEORGE E. BUTTENSCHAW wrote calling attention to the following points, which, in his opinion, could with advantage furnish the subject-matter for still further investigation. The statements made on page 181, that "the slowly cooled alloys, which represent more nearly the stable condition, have no industrial value," and on page 175, that "It has already been shown in the present research that a slow cooling of the 10 per cent. aluminium-bronze from 800°C . ($1,472^{\circ}\text{F}$.) ruins both the chill and sand castings and the rolled bar, the effect on the ductility being particularly fatal," seemed to the writer to be points which required more than passing consideration, especially as they appeared to touch upon the cause of difficulties which often were experienced in bronze founding with probably these, as well as with other bronze alloys.

Reference had been made, in the Appendix, to the similarity between the equilibrium-curves of the copper-tin and the aluminium-

(Mr. George E. Buttenshaw.)

copper alloys, and the writer would like to add further that the microscopical examination of the 10 per cent. aluminium alloy exhibited a striking structural resemblance to that of the copper-zinc bronzes, in which the basis was about 60 per cent. copper, 40 per cent. zinc, and containing about 1.5 per cent. iron.

The writer had not often met with the aluminium-copper alloys in foundry practice, probably owing to their more costly nature or difficulty of working; but it was of interest that the copper-zinc bronzes having a duplex structure possessed a similar property to the aluminium-copper alloys of 10 per cent. aluminium of deteriorating under the influence of abnormally slow cooling. As an illustration of this the writer submitted Fig. 196, Plate 23, which was a photomicrograph of such a copper-zinc alloy, as before described, as cast under normal conditions in sand as a test-piece, and which gave an ultimate tensile stress of 30 tons per square inch with an elongation of 31 per cent. measured on 8 inches. Fig. 197 showed the same quenched from 750°C . ($1,382^{\circ}\text{F}$.) and yielding an ultimate tensile stress of 35.4 tons per square inch with 12 per cent. elongation. Now referring to Fig. 198, quite another state of affairs was seen, the half marked "b" was a micrograph of the same bronze cast into a large propeller blade weighing, as cast, 3,300 lbs., and which took 24 hours to cool down to 300°C . (752°F .). A test-piece cut out of the thickest part (that is, the flange) yielded 16.5 tons per square inch with an elongation of 9 per cent. Another test-piece from the same part, re-heated to 750°C . and cooled out more rapidly (about 3 hours to the air temperature), gave the structure as seen on the half marked "a" of Fig. 198, accompanied by an ultimate tensile stress of 28 tons per square inch with 26 per cent. elongation in 8 inches.

From these experiments it was evident that the duplex structure underwent considerable changes, and these changes, the writer ventured to suggest, much resembled those of the metastable aluminium-copper bronzes. A further noteworthy observation with respect to Fig. 198 (half "b") was that this casting after machining, on being exposed to a shower of rain, quickly assumed a rusty appearance. A chemical examination of the red-brown coating

revealed iron, and it was further observed that the quicker cooled alloy did not take this rusty appearance for some time, in some cases not at all. This might suggest that, in the case of the metastable aluminium-copper alloys, other results would be obtained with the corrosion tests if samples were selected which had undergone abnormally slow cooling.

In the case of Fig. 198 the primary or " α " crystals appeared to grow, under the influence of slow cooling, at the expense of the " β " crystals, or dark surrounding medium, until finally these " α " crystals reached a limit beyond which their composition was no longer stable, and they proceeded to decompose. When this point was reached the desired mechanical properties of the alloy were totally lost. It seemed also conclusive from this that the metals were originally in solution and not compounds.

Turning from this to its aspect in relation to the foundry: for instance, where a specification for the mechanical test of a bronze, based on results obtainable with test-piece castings, was given, how widely different were the results obtained in a large casting from those allowed for in the calculation of its dimensions; and, worse still, this lack of efficiency was often cloaked in the foundry by adopting some ingenious means of making the test-piece show up well, by such means as hidden chills in the sand surrounding the test-pieces which were cast with the main casting, or by first placing prepared test-pieces in the mould, and thus allowing a previously-prepared piece to be "burnt on." The writer had seen all these subterfuges resorted to in many unexpected instances, and it was to such research work as that under discussion that we must look to to bring about a better solution of difficulties such as these. The writer had devoted some attention to this point from the standpoint that it was doubtless possible, by means of the introduction of other elements, to obtain greater stability of the duplex structure under variations of temperature, probably by some such influence as that described by the late Sir William Roberts-Austen, who called attention to the effect upon iron of elements of greater or less atomic volumes than the iron itself. This opened up a possible field for useful and much-needed research.

MONS. CHARLES D'ALBERT wrote that the alloy used commercially in France for automobiles was not so pure as stated in the Report, the great majority of these alloys containing from 12 to 20 per cent. of zinc. The best alloy known was one containing 6 per cent. of copper, as stated in the Report, but it was not much used owing to its high price and the difficulty of obtaining sound castings. The highest tensile strength obtained with aluminium castings was with an alloy of 15 to 20 per cent. of zinc, 3 to 6 per cent. of copper, and the remainder of aluminium, the highest strain attaining 30 kgs. per mm.² (19 tons per square inch). This could only be obtained by the Cothias process.

Some years ago light rapid gun-cartridges had been made with an alloy of aluminium and copper, and had given very fair results with black C2 powder, but cordite in its old form melted them. Time-fuses were made mostly of alloys of aluminium with 10 per cent. of zinc, giving the highest practical resistance and hardness; but pure aluminium specially cast and compressed under a relatively high pressure was also used, and in this state was obtained the highest possible security, especially as regards chemical re-actions. In the pure state a density of 2.56 would become 3.0 with 10 per cent. of zinc. In 1906 about 1,000 tons of aluminium were used solely in the automobile industry.

Dr. LÉON GUILLET wrote to congratulate the authors on the important work that they had carried out, which presented the same great interest which one expected to find in the Reports to the Alloys Research Committee. He was also pleased to find that the authors' work confirmed the study which he had previously published; and notwithstanding that their work was far more detailed and extensive than his own, he desired to make a few observations.

Referring to the almost identical results obtained with the 10 per cent. aluminium alloy whether rolled or cast in chill, he was of opinion that these results could easily be produced, if the alloy was very homogeneous, and this could be obtained without difficulty, either by double melting or by using copper and a copper-aluminium alloy, rich in aluminium. He was surprised that Naval Brass did not

resist the effect of sea-water as well as the copper-aluminium alloys rich in copper, and some trials he had made seemed to show that the powers of resistance were the same in both cases, but that the resistance of Muntz Metal ($\text{Cu} = 60$, $\text{Zn} = 40$) was distinctly less. As the result of some theoretical trials made by himself he had advised a firm to use this alloy for projectors; the results obtained were excellent, and this alloy was easily gilded, easily bent, and did not change its shape after long use.

He did not agree with the authors in respect of the segregation of alloys rich in copper; several analyses he had made had proved that considerable segregation occurred when the proportion of aluminium exceeded 9 to 10 per cent., and that this segregation was the cause of the frequent difficulties met with by the makers of copper-aluminium alloys. For this reason industrial copper-aluminium alloys could not exceed 8 per cent. of aluminium when they had to be rolled or drawn.

The influence of mechanical treatment on these alloys was very great. In the "*Revue de Métallurgie*," 1905, he (Dr. Guillet) had given examples in which the ultimate stress had been doubled and the elongation increased in the same proportion.

The results obtained by him differed in two respects from those of the authors:—

(1) Messrs. Carpenter and Edwards had found that the "transformation points" on cooling were always lower than the transformation points on heating. A curve published by himself showed that his results were not quite the same; he admitted, however, that some of these points were not sufficiently accurately determined to be able to mark them with precision.

(2) Referring to the "liquidus" curve, Fig. 33 (pages 204–205), the authors had found that the curve did not rise from 44.5 to 50 per cent. of aluminium; he (Dr. Guillet) thought that there was a rise, but only a very slight one.

Although he intended very shortly to publish a treatise in which he would establish the close relationship that existed between some of the copper alloys, he desired now to call attention to the similarity in the constitution of certain copper-aluminium alloys and brasses, namely, the alloys containing from 8.6 to 11.8 per cent.

(Dr. Léon Guillet.)

of aluminium and those brasses which could be forged when hot (copper from 53 to 55 per cent.).

Dr. GUILLET sent a further communication on the Appendix to the Report :—

(1) "*Solidus*" Curves.—There was a contradiction in respect of the "solidus" indicated at page 261 by $FefghHjJkK$ and that given at page 265 by the group $FG:Fdefgh$.

(2) *Constituents*.— γ' was not mentioned in the list of constituents, and hence no hint was given as to its nature.

(3) *Group BC* (page 263).—One read: "At the temperature of the line Ba the solution begins to deposit a' "—Was there not a printer's error, and should a be replaced by a' ? The area below βa was in effect limited by the vertical line through β , which corresponded to the solution a and not to a' . Moreover, below 1 on the diagram $a + \beta$ had been marked and not $a' + \beta$. What were the constituents of the alloys occupying the area of the diagram between $\beta 6$ and the lines 1 and 2?

(4) *Groups DE and EF* (pages 264–265).—Why were these two groups separated by the point E, and to what did this point correspond?

(5) *Group FG* (page 265).—There was a structural change along the line efG ; and between ef and the temperature of 500°C . approximately there were two constituents. Hence this space should not be designated by a single letter γ' . Moreover, the change taking place at 500°C . ought to be marked on the diagram by a line. The diagram showed that the line efG corresponded to the invariable transformation :

The line efG ought therefore to be horizontal.

(6) *Group GH* (page 266).—To what did the line hH correspond, and what were the constituents of the alloy in the space $g5Hh$? The line 5 stopped arbitrarily at H, which thus became a multiple point; full explanation appeared to be necessary.

(7) *Line Hj of the Diagram*.—The existence of this line did not appear to be justified, because (see page 267, group HJ) it was stated

that δ or Cu_2Al crystallized from the "liquidus;" moreover, there was no intermediate point between H and j to determine Hj . The delineation of Hj ought moreover to be completed by a vertical line starting from j and separating the alloys below HjJ into two regions, namely, δ and the eutectic + δ .

Finally, the diagram would be much clearer if the various lines corresponding to the "solidus," to the "liquidus," to a structural change, and to an evolution of heat without structural change, were differently indicated.

Mr. G. H. GULLIVER wrote it was to be regretted that, in the anxiety to give their labours a practical value, the authors had concentrated their attention chiefly on the mechanical properties of the commercially useful aluminium-bronzes before correctly determining the equilibrium diagram for this series of alloys. The equilibrium diagram, Fig. 33 (pages 204-205), was obviously incorrect in several particulars. An attempt had therefore been made by the writer to construct a new diagram which, while theoretically possible, was yet in accordance with the ascertained data, but, on account of the rather meagre information supplied, some difficulty had been experienced. This difficulty was greatly increased by the unmethodical manner in which the chilling and slow cooling experiments seemed to have been carried out. However accurately the liquidus curve for these alloys might now have been determined, there was no doubt that practically all the work required to locate the solidus and transformation curves yet remained to be done.

The explanation given by the authors for the non-appearance of eutectic at the point B seemed possible enough theoretically, but was rather contradicted by the fact that typical eutectic structures were very evident in alloys containing from 9.5 to 12 per cent. aluminium when quenched from 900°C . ($1,652^\circ \text{F}$.), after heating for some time at this temperature, as could be seen by an inspection of Figs. 90 to 119. The reference, given in this connection, to the recent investigation of the copper-manganese alloys* was unfortunate,

* Wologdine, *Revue de Métallurgie*, January 1907, page 25.

(Mr. G. H. Gulliver.)

since each of the micrographs given of the alloys of this series, which were supposed to consist of a single solid solution, showed two distinct constituents.

Another case in which a minimum point on the liquidus was said not to correspond with the formation of a eutectic was that of the aluminium-magnesium alloys.* A minimum point on the curve occurred at 35 per cent. magnesium, and a maximum, corresponding to the definite compound Al_3Mg_4 , at 55 per cent. magnesium; the alloys between these two compositions were stated to consist each

FIG. 199.

FIG. 201.

of a single solid solution, but no photo-micrographs were given in support of this contention, except one of the 55 per cent. alloy, which showed marked traces of a second constituent.

It might be pointed out that there was one type of curve in which a minimum point on the liquidus did not correspond with a eutectic; but this did not appear to fit the present example of the aluminium-copper alloys. In Fig. 199 the liquidus showed a minimum point, but the curve was *continuous*; the solidus was also a continuous curve which touched the liquidus at the minimum point, this same point being the minimum also for the solidus. A liquid of any composition froze as a single solid solution, but there was a certain

* Grube, Zeitschrift Anorg. Chemie, 1905, vol. 45, page 225.

range of solidification, with change of composition of the solid phase, for all liquids except that of which the composition corresponded to the minimum point of the curve; this liquid froze at constant temperature. An example of this type of curve was furnished by mixtures of mercuric bromide and iodide.*

The evidence for a phase α' as distinguished from α was very incomplete, and the suggestion that α' was the compound Cu_4Al seemed unlikely both from the shape of the curve and from the micrographic evidence. The analysis obtained in the case of the 10.70 per cent. aluminium alloy could hardly be considered as satisfactory proof of the existence of a definite compound Cu_4Al , after all the work done in recent years discrediting the results of similar analyses. The vertical line through D indicated that at all temperatures from D down to 500°C . (932°F .) the metal showed only one constituent, namely, the pure compound Cu_3Al . This was not borne out by Figs. 116 to 119, Plate 11. If we supposed that the compound Cu_3Al was formed on solidification of the 12.44 per cent. alloy, it would appear that this substance could exist in solution over a certain range of composition so that the areas below CD and DE, which were marked as corresponding with solutions of $\alpha' + \beta$ and $\beta + \gamma$, were more conveniently represented as one area, corresponding with a single solution β , in conformity with the usual system of notation. No attempt was made by the authors to insert a solidus curve between A and F; this was to be regretted, since such an attempt would have shown them the difficulty of devising a solidus to agree with their transformation lines.

With regard to the EF alloys, and the reference given on page 265 to Fig. 133, Plate 14, the description led one to believe that the percentages of aluminium shown above Figs. 132 and 133 must have been interchanged inadvertently.† Again, in Figs. 168, Plate 21, and 133 the dark areas, and in Fig. 169 the light areas—both said to be γ —represented the primary crystallization, which, one would consider, should be β .

* Reinders, *Zeitschrift Phys. Chemie*, 1900, vol. 32, page 494.

† The illustrations have now been transposed.

(Mr. G. H. Gulliver.)

In the Appendix (page 266), in considering the GH alloys, it was said that line 5 indicated the temperature at which δ (CuAl_2) was formed: was not the line H*h* intended here? It was theoretically impossible for CuAl_2 to separate along line 5, and there seemed no good reason why the dotted line connecting 5 to H should have been inserted on the diagram. The very small evolutions of heat corresponding to points on line 6, and the temperatures of these points led to the belief that they were the result of the solidification of small quantities of eutectic, due to too rapid cooling of the metals containing from 27 to 46 per cent. Al. The micrographic evidence did not seem to have definitely fixed the points *j* and *k*. There were other particulars to which exception might be taken, but it would be more profitable to curtail this criticism in favour of new suggestions. It should be pointed out, however, that in the comparison made between these alloys and those of copper and tin, on page 269 of the Appendix, paragraph 5, the compounds Cu_4Sn and CuSn , supposed to have been found by Heycock and Neville,* had been discredited by the later work of Shepherd and Blough,† and that now only the single compound Cu_3Sn remained. This compound, Cu_3Sn , did not crystallize from the liquid, but only from solid alloys: compare paragraph 6 (page 269).

To proceed now to the suggested new diagram which was shown in Fig. 200 (page 349), the liquidus had been retained without alteration, though no mention was made in the Report of any precautions taken to prevent surfusion. Some uncertainty still existed with regard to the position of the point B. This was given by the authors in the main Report as occurring at 7.8 per cent. aluminium and $1,030^\circ \text{C}$. ($1,886^\circ \text{F}$.), and in the Appendix as 7.35 per cent. aluminium and $1,030^\circ \text{C}$.; Dr. Guillet fixed it at 8.6 per cent. aluminium and $1,050^\circ \text{C}$. ($1,922^\circ \text{F}$.). For reasons already partly explained, the writer thought that a eutectic was formed, corresponding to the minimum point B, and he had indicated this by the horizontal *ab*. The point *a* was put at

* Heycock and Neville, Philosophical Transactions, Royal Society, 1904, vol. 202, page 1.

† Shepherd and Blough, Journal Phys. Chem., 1906, vol. 10, page 630.

FIG. 200.

(Mr. G. H. Gulliver.)

7 per cent. aluminium and b was fixed at 10.5 per cent. The position of a was fixed arbitrarily, because no data were available, and it was not contended that it must lie at 7 per cent., though it could not be far from B ; Aa had been drawn straight since its real shape was unknown. The point b was fixed at about 10.5 per cent. by noting that in Fig. 70, Plate 4, the chill casting of the 9.9 per cent. alloy showed two structural constituents, namely, α crystals and a conglomerate, considered by the writer as evidence for the eutectic, while in Fig. 73, Plate 5, the chill casting with 10.78 per cent. aluminium showed only one constituent, although the change which occurred at a lower temperature had commenced.

FIG. 202.

FIG. 203.

From 10.5 to 14 per cent. aluminium the metals on solidification consisted of only one solid solution already designated β . The solidus in this part of the diagram was drawn in Fig. 200 (page 349) as a continuous curve from b to c , and touched the liquidus at the point C , 12.4 per cent. aluminium. Perhaps a short explanation of this would be tolerated for the benefit of those not very familiar with equilibrium diagrams. Consider the case in which two metals could unite to form only one definite compound: then, in general, the liquidus for the complete series of alloys of the two metals, A and B , had the form given in Fig. 201 (page 346); the curve shows two minima, E_1 and E_2 , corresponding to two eutectics, and an intermediate

maximum, J , corresponding to the definite compound A_xB_y . If the two metals and the compound were mutually insoluble in each other, the complete equilibrium diagram was as shown in Fig. 202. An alloy intermediate in composition between C and E_1 consisted, when just solid, of crystals of pure A surrounded by eutectic E_1 , which was a conglomerate of pure A and the pure compound A_xB_y . An alloy between E_1 and J solidified as crystals of the compound A_xB_y with the eutectic E_1 . At J the compound was unmixed with eutectic and solidified at constant temperature. Between J and E_2 the metal continued to deposit crystals of A_xB_y , but the eutectic was now E_2 , which was a conglomerate of pure A_xB_y and pure B . Lastly, the liquid between E_2 and D solidified as crystals of pure B surrounded by eutectic E_2 .

If there were not this perfect state of mutual insolubility between the compound A_xB_y and the metals A and B , the equilibrium diagram took a form resembling that of Fig. 203. In this case, alloys of composition between C and H_1 consisted of a single solid solution α , which might vary in composition from pure A to H_1 . From H_1 to E_1 the metals consisted of crystals of α , having the composition H_1 , surrounded by more or less of eutectic E_1 , which was now a conglomerate of α crystals of composition H_1 , and β crystals of composition K_1 . From E_1 to K_1 the metals showed crystals of β , having the composition K_1 , surrounded by the same eutectic E_1 . From K_1 to H_2 the alloys consisted of one homogeneous solid solution which might vary in composition from K_1 through J (A_xB_y) to H_2 . At J the metal solidified completely at constant temperature as the pure compound A_xB_y , but all other metals between K_1 and H_2 had a more or less extended range of solidification. The solidus curve K_1JH_2 was continuous, and touched the liquidus E_1JE_2 , which was also continuous, at the point J . To the right of H_2 the conditions were similar to those which prevailed to the left of K_1 , but the α solution was replaced by another γ .

Returning to the copper-aluminium alloys, it was found that by assuming the existence of a mutual solubility between Cu_3Al and the adjacent phases a curve bCc could be drawn which agreed with the facts and the micro-sections given in the Report.

(Mr. G. H. Gulliver.)

The lines aa' , bb' , and cb' , which indicated the changes occurring in the completely solid metals, only differed from those given by the authors in so far as they must conform to the solidus suggested by the writer. Thus, aa' was drawn from a instead of from B , but the lower part had been left vertical at 10 per cent. aluminium instead of running to b' . bb' was drawn from b , 10.5 per cent. aluminium, and was somewhat curved in its upper part until 12.4 per cent. was reached, after which it was vertical; and $b'c$ was not produced upwards to meet the liquidus. The marked points were taken directly from the authors' curves. As already noted, the 12.44 per cent. alloy, Figs. 116 to 119, Plate 11, was not homogeneous. If the compound Cu_3Al were really formed, this would indicate that the line bb' should be brought somewhat more to the right, say to 13 per cent. aluminium. The 12.44 per cent. alloy would then show only one constituent if rapidly quenched above about $1,000^\circ C.$ ($1,832^\circ F.$), but two constituents would appear if the metal were retained at a lower temperature. In this region no attempt had been made to continue the diagram below the transformation line at about $570^\circ C.$ ($1,058^\circ F.$).

Again considering the solidus, the horizontal cdD , Fig. 200, had been drawn through the observed point d at $970^\circ C.$ ($1,778^\circ F.$), and 16 per cent. aluminium, at which composition the phase γ began to appear. The line dd' was drawn vertical at 16 per cent. The compartment for γ was left practically unchanged except that it was not prolonged above cd to the liquidus, as in Fig. 33.

A second horizontal, e_1e_2E at $875^\circ C.$ ($1,607^\circ F.$), had been drawn to correspond with a row of observed points. It was true that these points did not lie on a horizontal line, and the highest had been taken as representing the most probable temperature for e_1e_2E . This line represented the change from γ to γ' . If e_2 were not coincident with e_1 there should be an area below e_1e_2 to represent mixtures of $\gamma + \gamma'$. A short line had been drawn from e_1 to e_3 , a point on e_2f_1 , to indicate such an area, but no information was found which could serve to fix this line.

A third horizontal f_1f_2F was drawn through the line of observed points at about $620^\circ C.$ ($1,148^\circ F.$). The writer did not agree with

the authors that this indicated the change from γ' to CuAl_2 ; CuAl_2 could not appear until the line gG , 590°C . ($1,094^\circ \text{F}$.) was reached. The solid which crystallized immediately below f_2F had been called δ , but this hypothetical body was not identical with the δ of the authors, who had applied the letter to the compound CuAl_2 . The lines $f_1f'_1$, $f_2f'_2$, gg' , Ghh' , and kk' had been drawn vertical. The remainder of the diagram called for no particular comment.

With the reservation that some of the points could not be very closely located for lack of data, it was contended that Fig. 200 (page 349) fitted the facts, including Dr. Guillet's results, so far as they were known, and that the diagram was in conformity with the latest knowledge of the subject of alloys, a statement which could hardly be said to apply to the authors' figure. That the structures obtained in accordance with Fig. 200 would be practically identical with those set forth on pages 263-267 would become apparent by a close study of the diagram. The comparison would be made here but for the amount of space required for the complete discussion; it had been partially suggested in the foregoing remarks. The writer hastened to add that he did not consider Fig. 200 as anything approaching to finality, but simply as a fair representation of our present knowledge. He would also wish to point out that his conclusions were necessarily based on an examination of the photomicrographs, which could not form so reliable a guide as the sections themselves.

It was much to be regretted that chilling experiments were not performed at temperatures other than those indicated as critical temperatures by the pyrometer, since the assumption that all structural changes were accompanied by thermal changes which could be detected by pyrometric means could not be justified. In the chilling experiments actually performed no great care seemed to have been taken to allow the metal to reach a state of equilibrium before the quenching operation, and it was very evident that an entirely fresh investigation was necessary for the accurate determination of the diagram below the liquidus.

In this note attention had been chiefly confined to the Appendix of the Report, because the writer considered that the equilibrium

(Mr. G. H. Gulliver.)

relations of the two metals should be worked out as fully as possible before proceeding to determine the physical and mechanical properties of their alloys. The results set forth in the main Report must, however, prove of great service to those who manufactured or used aluminium-bronzes and light alloys. The comparison between the 10 per cent. bronze and the Swedish Bessemer steel with 0.35 per cent. carbon was especially interesting. On page 92, paragraph (b), it was said that in making rich aluminium alloys from the pure metals the copper must first be melted down. Why was it not possible to dissolve the copper in the molten aluminium, and thus avoid the objectionable high temperature? With regard to the re-melting experiments described on page 164, and illustrated by Figs. 81 to 83, Plate 6, was the metal well stirred after each re-melt, or simply poured without stirring?

In conclusion, the writer wished to express his great appreciation of the increase in our knowledge of the very complicated series of aluminium-copper alloys due to the labours of the authors, the results of which marked a very distinct advance since the experiments of Dr. Guillet. The low temperature transformations, only briefly mentioned in the Report, would seem to promise particularly interesting information in the future.

Mr. R. A. HADFIELD regretted that it was not possible for him to be present at the Meetings, but wished to compliment the authors on their excellent Report, which represented a mass of information requiring time for assimilation by those concerned. Though some of the previous speakers seemed to think the alloys produced were of no practical value, he would remind them that similar remarks had been made before regarding iron-alloys, some of which had afterwards been found to possess important practical value. No doubt this would prove to be the case with some of these aluminium-copper alloys. Instead, therefore, of regarding the results of the research as small, as one previous speaker appeared to do, he would regard them as most important. In fact, work by Professor Carpenter might be relied upon to be not only interesting but valuable.

As regards the addition of aluminium causing an increase of temperature, surely this would only occur provided oxidation took place; at any rate, it was so when aluminium was added to iron. When with such alloys increase of temperature took place, analysis showed that this had been brought about by the oxidation of some of the aluminium. Iron alloys containing comparatively high percentages of aluminium were found to be particularly sluggish and could not be readily poured, showing that the mere addition of aluminium did not cause an increase of temperature.

In conclusion, he thought that the Report added greatly to our knowledge on this important subject, and that Mechanical Engineers would consider the sums placed at the disposal of the Alloys Research Committee had been well spent.

Mr. A. HARVEY, of the British Aluminium Co., wrote that with regard to alloys rich in copper, in the case of large castings, such as aluminium-bronze solid propellers, better results both as regards tensile strength and elongation were undoubtedly obtained in casting from the second melting. Further, a much cleaner and more homogeneous casting was obtained.

The results of the sea-water corrosion tests should further help the use of aluminium-bronze for such castings as propellers, propeller-nuts, cones, &c. The writer had had a large experience in the manufacture of propellers containing 10 per cent. of aluminium. These castings had always come well up to the Admiralty specification as regards tensile strength, elastic limit and elongation, and had given satisfaction as to their non-corrosive properties. With reference to the casting of aluminium-alloy test-bars, the method described by the authors did not commend itself to the writer. In casting a bar of this shape there was a tendency for the shoulders and ends of the bar to prevent proper contraction taking place. A better method was to cast a parallel bar, afterwards turning the same to the required testing dimensions. The results of cast and rolled 10 per cent. aluminium-bronze were very interesting. It might be added that this alloy lent itself very readily to ordinary forging, and that excellent drop forgings could be obtained from it.

(Mr. A. Harvey.)

Respecting the alloys rich in aluminium, there was no doubt whatever that successful casting depended to a very great extent on casting at a proper temperature. Unfortunately this was not understood by all founders, and the writer had investigated many cases where the metal had been badly burnt and rendered useless. This was the result of the low melting point, as compared with other metals, not being fully realized, and also to casters charging the crucibles and leaving the metal to melt with the same time allowance as they had been used to in dealing with brass melting. This overheating was very detrimental to the metal, and its bad effect was not altogether overcome by the addition of new metal, as was commonly supposed.

With respect to the 50 per cent. aluminium-copper alloy, the writer introduced this method of adding copper to molten aluminium after having had considerable experience (dating from the time of the Cowles Co.) in making aluminium-copper alloys by the older method of stirring copper into the molten aluminium. By the use of the rich alloy, the bad results of overheating the aluminium were entirely obviated, as the alloy had a lower melting point than pure aluminium. The copper was also, by this method, introduced in a cleaner state, and consequently better all-round results were obtained from castings. As stated by the authors, the rich alloy lent itself readily to weighing out charges, thus facilitating the making of any required percentage of alloy.

In testing, it was usual to obtain a considerably greater strength from a longitudinal bar than from a transverse one, and probably the slight difference obtained by the authors was due to the ingots having been cross-rolled during the first stages of the rolling. The writer fully agreed with the authors that the best results were obtained from an alloy containing about 4 per cent. copper. A peculiar feature of this alloy, and one which did not appear from the results shown in Tables 80 and 81 (pages 250-251), was that occasionally a greater tensile strength was obtained from an annealed bar than from an unannealed one. This was apparently due to the hardening action which took place during the elongation of the bar whilst in the testing machine. With this 4 per cent. copper-

aluminium alloy the writer had obtained 22 tons per square inch tensile strength with 12 per cent. elongation on an annealed rolled bar, and believed this to be a record test for the alloy. The views of the writer were not in accordance with those of the authors that the heavy alloys were more promising than the light alloys. On the contrary, there was a much greater demand for light alloys, and this demand was steadily increasing.

The authors having treated the binary alloys so fully, the writer would strongly recommend an exhaustive research into the properties of ternary alloys, especially those containing zinc. This metal, when alloyed with aluminium, gave excellent results both in light and heavy alloys. In conclusion, he wished to thank the authors for their kind appreciation of his and his colleagues' efforts; any help they were able to render was readily given.

Professor A. K. HUNTINGTON wrote, in continuation of his remarks on pages 314-322, that the curve for a 9.9 per cent. aluminium-bronze tested at high temperatures, shown by Mr. Rosenhain during the discussion, did not contain sufficient points to be certain of its exact shape. It had been suggested that the curve as shown was correct, and that for theoretical reasons it might be expected to differ from alloys with less aluminium such as those tested by himself. It might be so, but he thought there was not sufficient evidence to decide the point at present as regards aluminium-copper. He would, however, call attention to the curves, Fig. 191 (page 320), of a copper-zinc alloy with about 40 per cent. of the latter metal based on tests made by him a long time ago, but never published. It would be seen that they closely resembled the curves for copper and for aluminium-copper, in spite of the alloy containing 40 per cent. of zinc. This alloy would contain both α and β structural constituents, being rich in the latter, which commenced to appear after 36 per cent. of zinc was present. There was not the difference between a 9.9 per cent. aluminium-copper alloy and a 40 per cent. zinc-copper alloy that might at first be supposed, 5 per cent. of zinc having the same effect as 1 per cent. of aluminium in determining the structure. The β solution appeared mixed with the α solution

(Professor A. K. Huntington.)

when there was more than 8 per cent.* of aluminium present in the copper. Nor did the 9.9 per cent. aluminium-copper curve appear likely to differ from the 7.39 per cent. curve on account of, the formation of a compound of aluminium and copper, Cu_4Al , for zinc formed its first compound with copper at about 33 per cent., and we had seen that 40 per cent. did not cause the curve to differ essentially from that of copper itself.

In view of the remarks on page 67 (*d*) the yield-point curve of the copper-zinc alloy had interest. The importance of these critical points in metals and alloys at temperatures such as were ordinarily attained in practice was very great, and it was a subject more suited perhaps than any other in the domain of metallurgy for investigation by the National Physical Laboratory. Taking, say, copper as a base, it would not improbably be found that the addition of another metal would shift the critical points more or less in one direction or the other. Such tests would have to be made with machines of different types. With a machine erected in 1900, which bent an inch bar backwards and forwards slightly beyond its elastic limit, whilst kept accurately at temperatures ranging up to 650° F., it had been found that the effects of quite minute quantities of impurities were very apparent, whereas they would not appear at all on an ordinary tensile-test machine.

At the meeting, time did not admit of discussing the question of corrosion. In the year 1894 he (Professor Huntington) was called upon to investigate this matter and provide a remedy in a particular case. Then and subsequently some thousands of tests had been made. Many of these tests were carried out by determining the electromotive force of pairs of metals and alloys mostly in sea water under varying conditions. At first a mirror-galvanometer was used, but since 1902 an Ostwald capillary electrometer, which was an extremely convenient instrument for the purpose. At the commencement, a piece of apparatus was devised which admitted

* 9 per cent. according to the authors, if the alloy had been fully annealed. Writing from memory, he thought Mr. Rosenhain's curve was based on unannealed metal.

of testing any portion of the metal under examination, no matter how minute. This was a great advantage, as it eliminated local differences which would vitiate the result in some cases, if the electromotive force were taken with the whole piece immersed.

It was not so surprising that alloys up to 10 per cent. of aluminium-copper should not corrode as easily as Muntz Metal or Naval Brass in sea water, if we considered that a very stable compound of copper with 11 per cent. of aluminium having a high heat of formation existed, and that the solutions with less than 11 per cent. aluminium would consist of this plus copper. The compound showed on the curve as a distinct maximum. In the case of copper-zinc this was not so; although there was every reason to believe there was a compound with 33 per cent. zinc, it did not show as a maximum on the curve, and it might be safely concluded that it had not the high heat of formation of the 11 per cent. aluminium-copper. It would naturally follow that in a couple the Muntz Metal would dissolve first. The behaviour of the alloy in fresh water referred to in the Report was not so obvious, but the results observed were often due to secondary causes, which might call for prolonged and carefully thought out experiments.

On page 67 (*e*) it was stated that a 5 per cent. aluminium alloy tended to *pipe*. This was an unusual application of the word. Apparently it was intended to imply that a hollow tended to form in the centre of the metal, which however could not be peculiar to the 5 per cent. alloy. It would depend on the way the work was applied, as in the Mannesmann method of starting a central hollow in tube-making.

The matter which caused perhaps more comment in the discussion than anything else was the effect of re-melting the alloys (page 87). The authors, as a result of their experiments, considered that it was unnecessary to melt an aluminium-copper alloy several times in order to obtain sound castings. It was true they limited this *dictum* to small castings (page 91), giving as their reason that "In large castings the difficulties of securing thorough mixing are much greater." As a matter of fact, however, there was no difficulty whatever in obtaining a perfectly homogeneous mixture of the constituent metals either in

(Professor A. K. Huntington.)

small or large castings without re-melting. It was a very common thing in works to assign bad mixing as the cause of faulty castings. It was however very rarely the cause, as could easily be shown on examining such metal under the microscope after polishing it and if necessary etching it. That the difficulty of making sound 10 per cent. aluminium-copper castings was, nevertheless, a real one, there was no doubt whatever. A considerable number of years ago a filter-press maker who was using this alloy successfully told the writer that it was not until the alloy had been melted ten times that they obtained the best results. Some years later he was asked how he was getting on with the alloy, and the reply was that he had given it up, as the trouble with it was greater than the gain.

The real source of the trouble was probably oxide of aluminium produced *in situ*, which could only be got to separate from the metal with very great difficulty. It was the separation of this oxide which was brought about by the re-meltings, which enabled the metal to flow freely, which it could not previously do owing to the presence of the pellicles of oxide throughout its mass. Heyn and Bauer* stated that tin deoxidized molten copper forming SnO_2 , part of which formed coarse, very well-defined crystals, the rest remaining entangled as a thin pellicle, which made the molten metal behave as if viscous. It was well known in the foundry that copper-tin bronze was best made from ingots re-melted. In making up the aluminium-copper the authors apparently used "cathode copper" which would be free from oxide, and they took every precaution to exclude air during melting. The writer was in the habit of doing this himself, and got clean castings even when using "cathode copper" which had been melted and cast into ingots. It was obvious that in making large castings the conditions were not so easy, though it was not improbable that when the cause of the trouble was understood in the foundries better castings would be produced with less expenditure of fuel and labour than at present. There was no reason why copper in the cathode condition should not be used; and, with proper precautions to exclude air as much as

* Mitteilungen der Königlichen Materialprüfungsanstalt, 1904; Revue de Métallurgie, 1905, page 364.

possible in melting, there was no reason apparent why a considerable improvement should not be effected. Incidentally it might be remarked that sand castings only $\frac{5}{8}$ inch diameter were liable to be chilled to some extent, and the results consequently unreliable.

The increase in the size of the crystals after each melt, observed by the authors (page 164), might be explained also by the gradual removal of the oxide pellicle on re-melting a number of times. The presence of the pellicle would interfere with free crystallization, and its removal would tend to the growth of larger crystals. No one was more desirous than himself of encouraging the application of physical methods to metallurgical research, but in doing so the metallurgical facts must be clearly understood and kept in sight. This the authors hardly appeared to have done in their suggested explanation, based on the hypothesis of "liquid crystals." Apart from the fact that nothing resembling Lehmann's anisotropic liquids had ever been observed in metals, it must be borne in mind that the crystals seen in the sections were not those of a primary product of crystallization from the liquid state, but of a complex which had separated from solid solution. Something of the nature of proof was required before one could accept such an explanation as that proposed.

Leaving theory on one side, the writer again expressed his appreciation of the way the work entrusted to the authors had been done. The field to be covered was very large, and they could not be expected to accomplish it all in so short a time, or even to grasp all the practical aspects.

Mr. WILLIAM MILLS suggested that the most commercially useful third metal with which to experiment in conjunction with aluminium-copper alloys would be zinc; and that a strong useful alloy, though difficult to cast solid, might be made of approximately the following proportions: copper 70 per cent., aluminium 10 per cent., zinc 20 per cent. He also urged the value of testing the most promising alloys at various temperatures.

Mr. G. N. SHAWCROSS wrote that whilst welcoming the research on behalf of metallurgists connected with the brass

(Mr. G. N. Shawcross.)

foundry, he considered that the real problem to be solved lay in obtaining the good tensile tests shown in Table 17 (page 114) on much larger and more complex sand castings than the very small 7-inch by $\frac{5}{8}$ -inch slabs cast by the authors (page 88, line 18). Experiments made at Horwich on an alloy of 8 per cent. Al + 92 per cent. Cu sand cast in slabs $1\frac{1}{4}$ inch thick and 4 inches wide, showed some agreement with the authors' figures as regarded tenacity, but with an elongation on 2 inches of 20 per cent., and these results were only what could be obtained by other less expensive alloys in brass foundry work.

Whilst, then, the good elongations given in Table 17 (page 114) were worthy of study, it had to be borne in mind that these were measured on such small test-pieces, and he thought it would have been of far more interest to engineers generally had more generously proportioned bars of, say, 2 inches diameter, been used for the sand-cast tests, and the tests machined from these. Had this been done, he thought Professor Carpenter could not have recorded such elongations as those on Table 17. He suggested this point of working with larger test-bars to the Alloys Research Committee as one for their attention in future work.

The authors would no doubt agree that the uses of chilled castings or rolled bars were difficult to apply in engineering practice, such uses even for the latter being limited chiefly to stays, screwed bars, etc.

It was interesting to note that the addition of 0.1 per cent. aluminium was highly detrimental to electrical conductivity of copper, especially since its great value in increasing ductility and good twist deformation would on that account be somewhat nullified for copper castings. Such a method, however, would assist in reworking old copper scrap, and the authors were to be congratulated on their observations. He could confirm the note that the addition of aluminium to molten copper did not give the high increase of temperature so usually attributed to it, provided the copper was properly protected from oxidation.

Turning to the aluminium end, he noticed that the best all-round tensile test in Table 71 (page 232) was obtained by the alloy

containing 3.76 per cent. copper when cast in sand. This gave 7.49 tons tenacity with 5 per cent. elongation on 2 inches. The writer had made an investigation into these alloys, in order to find which metals when alloyed with aluminium gave promise of greatest strength combined with toughness and low specific gravity. Some four years ago, like the authors, he concluded that copper as a strengthener of aluminium would be superseded by other means, and after trials an alloy of aluminium and zinc was found to offer a better solution to this question. In the metallurgical laboratory of the Horwich Technical School, there had been obtained sand-cast bars giving tenacities of 7.0 to 8.25 tons per square inch with varying elongations of 4 to 8 per cent. on 2 inches. These were obtained from alloys of 10 to 12 per cent. zinc with aluminium, no other metal being added. In conclusion, it would appear that the research so ably carried out by the authors practically confirmed what had been recognised by metallurgists and engineers for some time.

Mr. LEONARD SUMNER, of the Broughton Copper Co., wrote that in the discussion Mr. Tomlinson had referred (page 272) to a Paper read by the late Mr. F. W. Webb before the Institution of Civil Engineers, in which he gave instances of failure of 7 per cent. aluminium-copper rods. It would appear, however, that the drop in tensile strength at high temperatures did not altogether account for the manner in which these aluminium-copper rods broke off. Assuming the stays in the water space of the boiler attained to a temperature of 600° F., then at this temperature Mr. Webb gave figures for the 7 per cent. aluminium-copper rod and also for an ordinary copper rod showing the apparent superior mechanical qualities of the aluminium-copper, yet these rods fractured badly in the water space. Notwithstanding this apparent inferiority, copper rods did not fail in this manner. This behaviour showed the necessity there was for carrying out further tests on these alloys at elevated temperatures. Such tests should include not only static, but as far as possible dynamic tests.

The authors remarked (page 138) that the yield-point of steel was high, due to stiffening caused by mechanical treatment; this would also apply to the tests made on the alloys as given on

(Mr. Leonard Sumner.)

Table 24 (page 129). The last few passes through the rolls would cause the rods to become somewhat hardened.

In Table 25 (page 132) the authors gave their results on the annealed bars, but it would appear that the heat treatment to which these bars had been subjected had ruined the alloys containing from about 9 per cent. aluminium and upwards. Take, for instance, No. 13: the authors gave the following for the annealed bar—yield-point 15.5 tons, tensile strength 28.5 tons, elongation 6.5 per cent., and reduction of area 10.2 per cent. Tests made at the Broughton Copper Works after annealing at 1,350° F. gave for No. 13—yield 14.8 tons, tensile 37.92 tons, elongation 34 per cent., and reduction of area 33.6 per cent. This was also interesting, as it showed that a properly annealed bar of No. 13 gave results which agreed with the authors' finding, and that the elastic ratio of this alloy was 0.39. This was identical with the Bessemer steel mentioned.

One important feature of the Report was the corrosion test. These alloys appear to be incorrodible in sea-water. Take, for instance, Alloy No. 13: it had all the good qualities of steel with the additional advantage that it did not corrode. It would seem, therefore, that this metal should be employed largely by marine engineers, notwithstanding its extra cost. However, experiments in contaminated waters would appear desirable.

In the manufacture of aluminium-copper tubes containing up to 3 per cent. aluminium, the writer found no such defect as mentioned by one speaker. If the copper and aluminium were of good quality, the resultant alloys would stand working hot and cold practically as well as ordinary tough copper.

Messrs. VIVIAN AND SONS, of the Hafod Copper Works, Swansea, forwarded results of tests made at their works by Mr. A. Sinclair on the corrosion of metals and alloys in the presence of sea-water.

The metals and alloys were strips of similar size, filed true and chemically cleaned before first emersion. Each strip was washed, dried and weighed monthly, when the sea-water was changed. The loss in weight month by month was fairly regular. The duration of the trials was twelve months. The sea-water was pure, taken

from a bay on the Bristol Channel. The copper was pure electrolytic, rolled; the spelter was high quality commercial; and the aluminium was high quality commercial. The iron was ordinary wrought (hoop iron).

No. 3 trial was Muntz Metal with 1 per cent. aluminium added.

No. 4 trial was Muntz Metal, 60 per cent. copper and 40 per cent. zinc.

No. 5 trial was 90 per cent. copper and 10 per cent. aluminium.

SEA-WATER CORROSION TESTS.

1. Iron, alone loses 0·0090 lb. per square foot per month.
2. Copper, „ „ 0·0026 „ „ „ „ „ „
3. 1 per cent. Aluminium Alloy „ 0·0025 „ „ „ „ „ „
4. Muntz Metal „ 0·0013 „ „ „ „ „ „
5. 10 per cent. Aluminium Alloy „ 0·0008 „ „ „ „ „ „

Galvanic Couples.

Iron and 1 per cent. Alloy.

6. Iron loses 0·0212 lb. per square foot per month.
- 1 per cent. Alloy gains 0·0001 „ „ „ „ „ „

Iron and 10 per cent. Alloy.

7. Iron loses 0·0208 lb. per square foot per month.
- 10 per cent. Alloy „ 0·0000 „ „ „ „ „ „

Iron and Copper.

8. Iron loses 0·0124 lb. per square foot per month.
- Copper „ 0·0003 „ „ „ „ „ „

Iron and Muntz Metal.

9. Iron loses 0·0122 lb. per square foot per month.
- Muntz Metal „ 0·0006 „ „ „ „ „ „

Copper and 10 per cent. Aluminium Alloy.

10. Copper loses 0·0086 lb. per square foot per month.
- 10 per cent. Alloy „ 0·0018 „ „ „ „ „ „

Muntz Metal and 10 per cent. Alloy.

11. Muntz Metal loses 0·0070 lb. per square foot per month.
- 10 per cent. Alloy „ 0·0000 „ „ „ „ „ „

(Messrs. Vivian and Sons.)

Copper and 1 per cent. Alloy.

12.	Copper	. . .	. loses	0·0060 lb. per square foot per month.
	1 per cent. Alloy	. . .	„	0·0000 „ „ „ „ „

Muntz Metal and 1 per cent. Alloy.

13.	Muntz Metal	. . .	. loses	0·0058 lb. per square foot per month.
	1 per cent. Alloy	. . .	„	0·0006 „ „ „ „ „

1 per cent. and 10 per cent. Alloys.

14.	1 per cent. Alloy	. . .	. loses	0·0058 lb. per square foot per month.
	10 per cent. Alloy	. . .	„	0·0004 „ „ „ „ „

Muntz Metal and Copper.

15.	Muntz Metal	. . .	. loses	0·0038 lb. per square foot per month.
	Copper	. . .	„	0·0004 „ „ „ „ „

Sea-Water Corrosion Tests of Metals and Alloys.—Experiments 1, 2, 3, 4, and 5 showed that, when suspended singly in sea-water, all were subject to corrosion descending in quantity from iron to the 10 per cent. aluminium alloy. Nos. 3 and 4 corroborated in a marked degree No. 2 and Muntz Metal set out in Table 63 (page 218), whilst No. 5 approximately did so, it being the lowest in the scale.

Sea-Water Corrosion Tests of Galvanic Couples of Metals and Alloys.—The immunity from corrosion of aluminium alloys, when in contact with other metals, was clearly marked in experiments Nos. 6, 7, 11, 12, 13, and 14, and it was of special mark that in 10 and 12 it was the copper that was corroded and not the alloy, as was anticipated. The special features of these experiments were the remarkable behaviour of the wrought-iron as evidenced in Nos. 6, 7, 8, and 9, where the corrosion was so much greater with aluminium alloys than with copper or brass, which would seem to point, that where iron or steel have to be in contact with other metals or alloys in sea-water, copper and brass were preferable to aluminium alloys. Mild steel having been used in the Research Committee's experiments would, no doubt, account for the higher corrosive effects in the wrought-iron, one being more readily attacked than the other.

Professor CARPENTER and Mr. EDWARDS wrote that they desired to express their cordial thanks for the friendly and, in some cases, too flattering terms in which the communications were couched, and their appreciation of the value both of the criticisms and the additional information that had been supplied.

Mons. Pierre Breuil's contribution (page 334) was especially welcome, because it contained data with regard to the mechanical properties of an alloy containing about 10 per cent. of aluminium when tested at various temperatures. His conclusion that "they established the fact that the 9.90 per cent. aluminium-copper alloy did not lose, so to speak, any of its mechanical properties when heated" must, however, be strictly confined to the temperature limits quoted, namely, between 150° and 260° C. Both Mr. Rosenhain's and the authors' experiments showed that at 400° C. the ultimate stress had fallen considerably (page 292 and Table 53, page 178).

The abstract of Mons. E. Le Blant's tests on two aluminium-copper alloys, containing 4.88 and 7.4 per cent. of aluminium at elevated temperatures was equally valuable, because it indicated the kind of behaviour that might be expected from the authors' alloys, Nos. 6 and 9, with 5.07 and 7.35 per cent. respectively of that metal under similar conditions. The authors were particularly interested to notice the remarkably satisfactory results given by the 7.4 per cent. alloy in an alternating bending test "when in the form of locomotive boiler-stays." They recalled the high values obtained by Professor Arnold (Table 59, page 196) in similar tests.

They did not think that any difference of opinion as regards essentials existed between Mons. Breuil and themselves, and they were agreed that the effect of quenching the 9.90 per cent. aluminium-bronze at about 600° C. was a structural change in the dark constituent. Certain similarities between the 10 per cent. aluminium-bronze and brass containing about 40 per cent. of zinc had been pointed out by Mons. Breuil, Mr. Buttenshaw, Dr. Guillet, and Professor Huntington, and were of great interest, especially that with regard to deterioration of mechanical qualities under very slow cooling. The authors agreed with Mr. Buttenshaw that, if their corrosion tests had been carried out on "abnormally"

(Messrs. Carpenter and Edwards.)

slowly-cooled specimens, the results would almost certainly have been different, or at any rate with No. 13, which had a duplex structure.

They observed that Dr. Guillet was not prepared to maintain that the results of his determinations of the heating and cooling curves differed essentially from their own, and with regard to the liquidus curve, between 44.5 and 50 per cent. of aluminium, they would point out that both investigations showed a rise of temperature in this range, which was in his case absolute, in their case relative, and that this might be explained by a difference in the rate of cooling of the alloys. With regard to his communication on the Appendix to the Report they would take his points in the order of his enumeration.

(1.) The contradiction in respect of the solidus was due to a misprint on page 265, which has been set right in the Report as finally published. The correct solidus was as stated on page 261, namely, $FefghHjJkK$.

(2.) The constituent designated by the letter γ' represented γ which had undergone the change commencing at the line efG (see footnote to page 266).

(3.) *Group BC.* The alloys of this group on freezing formed the same solid solution ($\alpha' + \beta$) as the *CD* group, together with the α of the *AB* group. This ($\alpha' + \beta$) solution deposited α' at the temperature of the line Ba . Hence the alloys, when allowed to cool directly after freezing, consisted, at temperatures below the line Ba , of α , α' and β , the amount of α' being of course small. It must be remembered, however, that in this state the alloys were metastable, and that if they were brought to a stable condition (by sufficiently slow cooling) α was the only constituent, when the aluminium did not exceed about 9.4 per cent.

(4.) *Groups DE and EF.*—The difference between these two groups was that, on freezing, the *DE* alloys formed a solid solution of $\beta + \gamma$, whereas the *EF* alloys formed the same solid solution $+\gamma$.

(5.) *Group FG.*—With Dr. Guillet's interpretation the authors were in agreement, and accordingly the line efG had been drawn horizontal.

(6.) *Group GH.*—The line $g5$ corresponded to the formation, and the line hH to the freezing of the compound $CuAl_2$. The constituents in the area $g5Hh$ were $\gamma' + \text{liquid } CuAl_2$. The authors desired to amend the drawing of the line $g5H$, and in the finally published diagram, Fig. 204 (page 370), it appeared horizontal.

(7.) *Line Hj of the diagram.*—It was quite true that no intermediate points between H and j had been found, and if the compound $CuAl_2$ did not dissolve aluminium, the line Hj should be vertical. The authors would point out that the line Hj corresponded to a range of hardly more than 1 per cent. of aluminium.

They were in entire agreement with Dr. Guillet's suggestion as to rendering the diagram clearer, and ventured to hope that in its final form, Fig. 204 (page 370), it would be found satisfactory in this respect.

It was quite obvious from Mr. G. H. Gulliver's communication that he had not thoroughly understood the work embodied in the Appendix. Accordingly the authors would endeavour to enlighten him on the difficulties he had encountered in studying their results. They were interested to observe that his opening sentence (page 345), "It was to be regretted that, in the anxiety to give their labours a practical value, the authors had concentrated their attention chiefly on the mechanical properties of the commercially useful aluminium-bronzes before correctly determining the equilibrium diagram for this series of alloys," constituted as diametrically opposite a view of the place of an equilibrium diagram in a research of this type to that enunciated by Professor Huntington as it was possible to imagine. They thought that, of the two views, a great deal more could be said in favour of Mr. Gulliver's. No doubt, in the strictest scientific sense, the study of the equilibrium curves should constitute the basis of a research on a new series of alloys; and doubtless the possibilities of varying the mechanical properties of such a series could not be considered to have been thoroughly exhausted until such curves were accurately determined. The authors, however, would venture to remind Mr. Gulliver that probably not a single equilibrium diagram of any series of alloys was yet accurately and fully known. They would select as a test case that of the iron-

FIG. 205.

FIG. 204 (compare Fig. 33, pages 204-205).

carbon alloys as being the best known, and to which by far the greatest amount of study had been devoted. The first diagram which had any pretensions to completeness was that of Roozeboom; it had since been modified and amplified by the labours notably of Osmond, H. Le Chatelier, Charpy, Wust, and Benedicks; and yet, so far as the authors were aware, it had added nothing to what was previously known with regard to the possibilities of varying the mechanical properties of the alloys by thermal treatment. They agreed neither with Professor Huntington's nor Mr. Gulliver's criticisms of the place of the equilibrium diagram in the research in the unqualified forms in which they were stated. For the reasons given above they had, so to speak, steered a middle course and had endeavoured to keep the balance between the practical and scientific aspects of the case.

Mr. Gulliver's next sentences constituted an almost unqualified condemnation of the authors' equilibrium diagram. Thus he said (page 345): (a) "There was no doubt that practically all the work required to locate the solidus and transformation curves yet remained to be done"; (b) that "an attempt had therefore been made by the writer," that is, Mr. Gulliver, "to construct a new diagram which, while theoretically possible, was yet in accordance with the ascertained data"; (c) but that difficulties were experienced on account of the "unmethodical manner in which the chilling and slow cooling experiments seemed to have been carried out." The authors ventured to think that it would have been advisable if, before making such statements, Mr. Gulliver had endeavoured to make himself more thoroughly acquainted with the facts of the case. With regard to (a) the future must decide; in respect of (b) the authors would presently offer some remarks; while, as regards (c) his use of the word "seemed" betrayed a doubt which should have imparted greater caution to his indictment. On this point they would reassure him that every care had been taken to realise the experimental conditions which the admirable work of Heycock and Neville in England, and Shepherd in America, had shown to be essential for the accurate determination of equilibrium curves.

(Messrs. Carpenter and Edwards.)

Mr. Gulliver wrote that "the explanation given by the authors for the non-appearance of eutectic at the point B seemed possible enough theoretically, but was rather contradicted" by the photographs. He also gave another example of a minimum point on a liquidus curve which was not characterised by a eutectic structure, asserting however that "this did not appear to fit the present example of the aluminium-copper alloys." Finally he directed attention to the photographs of alloys containing from 9.5 to 12.0 per cent. of aluminium quenched from 900° C. as showing typical eutectic structures. The authors would firstly point out that *none* of these alloys corresponded to the minimum at B (7.35 per cent. of aluminium). If this alloy (No. 9) was quenched immediately below the liquidus, no trace of eutectic was present; the simplex structure of α alone was evident. Secondly, they would observe that the photo-micrographs alluded to by Mr. Gulliver were *not* "typical eutectic structures." Such types were almost invariably produced when a solid solution was prevented by quenching, from depositing a dissolved body. As no objection that had been brought forward against their own explanation had been sustained, and the evidence was strongly in favour of it, they regarded it as at any rate holding the field for the present.

Mr. Gulliver's reference to the authors' quotation of copper-manganese alloys in the above connection constituted a criticism not of them but of Mons. Wologdine. They had accepted the last-named's conclusions from his photo-micrographs, whereas Mr. Gulliver evidently regarded them as incorrect. Accordingly they would refer him to settle this point with Mons. Wologdine.

The evidence for the existence of a constituent α' , as distinct from α , was regarded by Mr. Gulliver as incomplete, and "the suggestion that α' was the compound Cu_4Al , seemed" to him "unlikely, both from the shape of the curve and from the micrographic evidence." The shape of the *liquidus* curve had no bearing on the question, since it was not to be expected that a compound which only formed from the solid metals would have any effect on it. The micrographic evidence was in no way opposed to the existence of a compound Cu_4Al , but actually supported it.

Thus it had been shown that α , containing 7.35 per cent. of aluminium, when suitably heat-treated, would dissolve more aluminium, and was not saturated until it contained about 9.4 per cent., which was approximately that required by the formula Cu_4Al (9.6 per cent.). But if this were again heated, it would be decomposed below its melting-point, α , containing 7.35 per cent., being one of the products. This alone was sufficient evidence to demonstrate the existence of two bodies. Also it might theoretically be expected from the above that, in the case of the CD alloys the yellow grains which were deposited from the solid solution along the line ab would be saturated, that is, would contain about 9.4 per cent., since the solution contained excess of aluminium and the deposition occurred at temperatures below that at which the above-mentioned decomposition took place. They agreed with Mr. Gulliver that the result of their attempt to isolate substantially pure α' from the 10.70 per cent. alloy did not *by itself* constitute "satisfactory proof" of its existence, but they would point out that it was in harmony with the other evidence bearing on this matter.

Mr. Gulliver did not appear to credit the existence of the compound Cu_3Al . On this point however there could not be the slightest doubt, since the liquidus curve clearly indicated such a compound. The alloy containing 12.44 per cent. of aluminium corresponded to the compound Cu_3Al , *but not exactly to the maximum D*, and, as was shown in the photograph Fig. 116, Plate 11, contained a little of the γ constituent. The authors had stated (Appendix, page 264) that the maximum D was possibly slightly displaced by the impurities present.

With respect to Mr. Gulliver's contention (page 347) that "the areas below CD and DE, which were marked as corresponding with solutions of $\alpha' + \beta$ and $\beta + \gamma$, were more conveniently represented as one area, corresponding with a single solution β ," they were of opinion that a β solid solution which deposited α' (a yellow, malleable, and ductile body) ought to be regarded as different from a β solid solution which deposited γ (a grey, hard, and brittle body). Accordingly they held that these facts warranted them in adhering

(Messrs. Carpenter and Edwards.)

to the original diagram in this respect. Mr. Gulliver wrote "No attempt was made by the authors to insert a solidus curve between A and F; this was to be regretted, since such an attempt would have shown them the difficulty of devising a solidus to agree with their transformation lines." In reply they would state that a large number of experiments were made, and much time was spent in trying to locate the solidus for these areas, but without success. There was however no difficulty in inserting a theoretical solidus, as shown in the accompanying sketch, Fig. 205 (page 370). With regard to the interchanging of the Figs. 132 and 133, Plate 14, this was quite correct. It had been emphasized when the Report was read on 18th January. Mr. Gulliver regarded the dark areas of Fig. 168, Plate 21, and Fig. 133, Plate 14, and the light areas of Fig. 169, Plate 21, as the primary crystals. The case of Fig. 168 was outside consideration, since the dark areas represented material which did not freeze from the liquid at all, but was deposited from the solid solution. With regard to the other two cases, a reference to the equilibrium diagram would show that his view was incorrect, since the percentage composition of these alloys was very near that at which the β constituent disappears. Moreover the *light* areas of Fig. 133 and the *dark* areas of Fig. 169 were quite typical examples of primary crystals which did not show a well-defined dendritic structure, owing to the relative amount of the other constituent being very large.

With regard to Mr. Gulliver's questions (page 348) as to lines 5 and *hH* the authors would reply that line 5 corresponded to the formation, *but not the separation in the solid state*, of the compound CuAl_2 , which remained liquid until the line *hH* was reached. He suggested that "the very small evolutions of heat corresponding to points on line 6, and the temperatures of these points led to the belief that they were the result of the solidification of small quantities of eutectic, due to the too rapid cooling of the metals containing from 27 to 46 per cent. Al." Not only did the photographs show no such body as the eutectic, but a study of the diagram would render it evident that such an assumption was theoretically impossible. For instance, all the alloys of group GH commenced

to freeze by depositing γ' , which was richer in copper than the mother liquor. This selective freezing continued until the composition of the liquor corresponded to that of the compound CuAl_2 , when the whole solidified at one temperature. Hence it was impossible for any portion of the alloys to attain a composition represented on the right of *H*. As regards the statement that "the micrographic evidence did not seem to have definitely fixed the points *j* and *k*," the former was known to within 1 per cent., the latter to within 2 per cent. of aluminium.

The authors were much obliged to Mr. Gulliver for drawing their attention to Shepherd and Blough's correction of Heycock and Neville's work on copper-tin alloys, and a footnote had been inserted in the Appendix (page 269) suitably modifying the comparison between copper-tins and copper-aluminums originally made. They thought that Mr. Gulliver's objections to their equilibrium diagram had been shown to be invalid, and that, with the exception of two slight modifications, which were the result of Dr. Guillet's criticism, it could at the present time be regarded as the nearest approximation of the known facts. Consequently they found it unnecessary to discuss in detail the alternative diagram put forward by him in Fig. 200 (page 349), and they desired to state that it would have been wiser on his part to have waited for their reply to his criticisms, which were largely based on misunderstanding, before proceeding to reconstruct their curves. Mr. Gulliver stated that his diagram had been constructed from the data given in the Report. They found unfortunately that several of the observed points had been put in wrong places, and that others had been altogether omitted. Consequently his curves could have no pretension to be either accurate or complete.

Although no mention had been made in the Report of precautions taken to prevent surfusion, these had been taken in a number of cases, more especially in the neighbourhood of *B* by adding a nucleus of solid to the molten alloy just above the freezing-point. The fact that the point *B* was placed at 7.8 per cent. of aluminium in the main Report, and at 7.35 per cent. in the Appendix, was due to experiments having been continued after the former had been

(Messrs. Carpenter and Edwards.)

prepared. They regarded the latter figure as correct, and it would replace the former in the final diagram. It must be noticed, however, that there was no mention in the Appendix of the 7.35 per cent. alloy freezing at 1,030° C., as stated by Mr. Gulliver. They had already shown (page 372) that it was unnecessary to consider the position of a hypothetical point *a*. With regard to the equally hypothetical point *b*, this was fixed by him at about 10.5 per cent. (page 350) "by noting that in Fig. 70, Plate 4, the chill casting of the 9.9 per cent. alloy showed two structural constituents, namely, *a* crystals and a conglomerate, considered by the writer as evidence for the eutectic." Such reasoning showed that he could not have understood the authors' work, since this was exactly what would be expected between *O* and *n'* in Fig. 177 (page 260).

His statement that "in Fig. 73, Plate 5, the chill casting with 10.78 per cent. of aluminium showed only one constituent" was incorrect. There were two well-defined constituents, a dark and a light, seen also in Figs. 72 and 74. There was no need for him to "assume" what was clearly indicated on the authors' equilibrium diagram and in the photographs in the Report, namely, that Cu_3Al and the adjacent phases were mutually soluble in each other. Mr. Gulliver again emphasised the fact that the 12.44 per cent. alloy (Figs. 116-119, Plate 11) was not homogeneous, and stated "if the compound Cu_3Al were really formed, this would indicate that the line *bb'* should be brought somewhat more to the right, say to 13 per cent. of aluminium." A careful study of the photographs referred to would have shown him that the dark constituent was not α but γ , and hence that *too much* aluminium was present. They would again refer him to the Appendix.

Mr. Gulliver went on to say (page 352), "The 12.44 per cent. alloy would then show only one constituent if rapidly quenched above about 1,000° C., but two constituents would appear if the metal were retained at a lower temperature." As was indicated in the authors' diagram, this particular alloy contained only one constituent if quenched at any temperature above 550° C. The alloy containing 12.0 per cent. (maximum *D*) contained only one constituent at any temperature between the liquidus and the ordinary temperature.

The above facts proved Mr. Gulliver's line bb' to be altogether incorrect. His solidus cdD was in contradiction with known facts. Alloys to the right of d , quenched above dD did *not* contain β which necessarily followed from it. Thus the authors had no choice but to deny Mr. Gulliver's final conclusion that "Fig. 200 (page 349), fitted the facts, including Dr. Guillet's results, so far as they were known." In reply to his question (page 354) relating to the manufacture of the rich aluminium alloys "Why was it not possible to dissolve the copper in the molten aluminium, and thus avoid the objectionable high temperature?" they would reply that under the suggested conditions the rate of solution of the copper was very low, and it was difficult to ensure getting a homogeneous alloy. The answer to his question as to the re-melting experiments was that the metal was *well* stirred.

They were much indebted to Mr. Hadfield for his high appreciation of their work and his interesting suggestion (page 354) as regards the analogy between the action of aluminium on (a) copper, (b) iron, and would refer him to their reply to Mr. Tomlinson for a full discussion of the matter.

Professor Huntington's contribution (page 357) was of great interest, and with much of it they were in entire agreement. They were not aware, however, nor had his correction convinced them that their use of the word "pipe" was unusual. His explanation of the increase in the size of the crystals of the 10 per cent. bronze found by them was doubtless, as theirs was, *tentative*. The difficulty seemed to be not so much to keep "metallurgical facts" in sight, as to realise the limitations of the methods of metallurgical research in current use. Readers were referred to pages 164-166, which the authors thought contained a sufficient reply to Professor Huntington's reference to "liquid crystals."

With regard to Mr. Shawcross's suggestion (page 362), that "it would have been of far more interest to engineers generally had more generously proportioned bars of, say, 2 inches diameter, been used for the sand-cast tests, and the tests machined from these," they would point out, in view of the large number of tests undertaken, how greatly this would have added to the cost of the research both in material and in the labour of machining. They observed that his

(Messrs. Carpenter and Edwards.)

experience of the temperature-effect of adding aluminium to molten copper agreed with theirs.

The difference, quoted by Mr. Leonard Sumner (page 364), between the tensile test of Alloy No. 13 annealed at the Broughton Copper Works and that annealed by the authors did not indicate any real discrepancy of results, and was explained entirely by the difference of (a) annealing temperature, (b) duration of heat-treatment at annealing temperature, and (c) rate of cooling in the tests.

As noticed on pages 270 and 365, the agreement between Messrs. Vivian and Sons and the authors' corrosion-tests was most satisfactory.

"Cathode" Copper. $\times 120$ diams.

Fig. 48.

Unetched.

Fig. 49.

Etched.

Fig. 50.

"Lake" Copper.
Unetched.

$\times 120$ diams.

Fig. 51.

Etched.

Fig. 52.

Aluminium.
Lightly-Etched.

$\times 120$ diams.

Fig. 53.

Deeply-Etched.

*Aluminium.
Lightly-Etched.*

$\times 800$ diams

Fig. 55.

Deeply-Etched.

Fig. 54.

Figs. 56, 57, and 58, Typical Structures of Alloys containing not more than 7.35 % Al.

$\times 120$ diams.

Fig. 56.

Sand Casting.

Fig. 57.

Chill Casting.

Fig. 58.

Rolled Bar.

Fig. 59. Alloy No. 13. (9.90 % Al.)

Sand Casting.

$\times 800$ d.

Alloys Nos. 10 and 11. (8.12% and 8.67% Al.) $\times 120$ diams.

8.12% .

8.67% .

Fig. 60.

Sand Casting.

Fig. 63.

Sand Casting.

Fig. 61.

Chill Casting.

Fig. 64.

Chill Casting.

Fig. 62.

Rolled Bar.

Fig. 65.

Rolled Bar.

Alloys No. 12 and 13. (9.38% and 9.90% Al.) $\times 120$ diams.

9.38%

9.90%.

Fig. 66.

Sand Casting.

Fig. 69.

Sand Casting.

Fig. 67.

Chill Casting.

Fig. 70.

Chill Casting.

Fig. 68.

Rolled Bar.

Fig. 71.

Rolled Bar.

Alloys No. 14 and 15. (10.78% and 11.73% Al.) $\times 120$ diams.

10.78%.

11.73%.

Fig. 72.

Sand Casting.

Fig. 75.

Sand Casting.

Fig. 73.

Chill Casting.

Fig. 76.

Chill Casting.

Fig. 74.

Rolled Bar.

Fig. 77.

Rolled Bar.

Alloy No. 15, and special Alloy like No. 13. (13.02% and 9.86% Al.)
× 120 diams.

Fig. 78. 13.02%. Sand Casting.

Fig. 79. Chill Casting.

Fig. 80. Rolled Bar.

Fig. 81. 9.86%. First Cast.

Fig. 82. Second Cast.

Fig. 83. Third Cast.

$\times 120$ diams.

Alloy No. 12. (9.38% Al.)

Fig. 84.

Quenched from 800° C.

Fig. 85.

Quenched from 900° C.

Alloy No. 10. (8.12% Al.)
Untreated.

Fig. 86.

Alloy No. 11. (8.67% Al.)
After 4 hours at 800° C.

Alloy No. 11. (8.67% Al.)
Untreated.

Fig. 88.

Alloy No. 11. (8.67% Al.)
After 4 hours at 800° C.

*Recrystallization Experiments with Alloy No. 13 (9.90% Al.) at 900° C.
(1,652° F.) × 120 diams.*

Fig. 90. *Rolled Bar. Untreated.*

Fig. 91. *After 1-3 hours.*

Fig. 92. *After 7 hours.*

Fig. 93. *After 14 hours.*

Fig. 94. *After 20 hours.*

Fig. 95. *After 28 hours.*

Recrystallization Experiments with Alloy No. 14 (10.78% Al.) at 900° C. (1,652°F.)

× 100 diams. Pl. 9.

Fig. 96. Rolled Bar. Untreated.

Fig. 97. After 1 hour.

Fig. 98. After 3 hours.

Fig. 99. After 7 hours.

Fig. 100. After 14 hours.

Fig. 101. After 20 hours.

Fig. 102. After 30 hours.

Fig. 103. After 50 hours.

Recrystallization Experiments with Alloy No. 14 (10.78% Al.) at 900 C. (1,652° F.) × 700 diams. Pl. 10.

Fig. 104. Original Acicular Structure.

Fig. 105. Honeycomb Structure.

Fig. 106. Banded Structure.

Fig. 107. Banded Structure.

Fig. 108. Coarse and Fine Banded Structures.

Fig. 109. After 20 hours.

Fig. 110. After 30 hours.

Fig. 111. Alloy No. 13. (9.90% Al.) Quenched from 900° C. × 100 d.

Recrystallization Experiments with Alloy No. 15. (11.73% Al.)

Pl. 11.

Fig. 112. $\times 100$ d.
Untreated Alloy.

Fig. 113. $\times 100$ d.
After 8 hours at 900° C.

Fig. 114. $\times 100$ d.
After 8 hours at 900° C.

Fig. 115. $\times 700$ d.
Coarsely Banded Structure.

Alloy containing 12.44% Al., corresponding to Cu_3Al .

Fig. 116. As Cast. $\times 100$ d.

Fig. 117. As Cast. $\times 700$ d.

Fig. 118. $\times 100$ d.
After 8 hours at 900° C.

Fig. 119 $\times 700$ d.
After 8 hours at 900° C.

Quenching Experiments with small pieces of Alloy No. 13. (9·90% Al.)

On a RISING temperature.

× 100 diams.

Pl. 12.

Fig. 120. Quenched at 600° C.

Fig. 121. Quenched at 700° C.

Fig. 122. Quenched at 800° C.

Fig. 123. Quenched at 900° C.

On a FALLING temperature.

Fig. 124. Quenched at 820° C.

Fig. 125. Quenched at 700° C.

Fig. 126. Quenched at 530° C.

Fig. 127. Quenched at 480° C.

Alloy No. 13. (9.90% Al.) $\times 120$ diams.

Fig. 128. *Rolled.*

Fig. 129. *Banded Structure produced by a short annealing.*

Fig. 130. *After prolonged annealing.*

Fig. 131. *Acicular Structure produced by quenching from 900° C. (1,652° F.)*

Sand Castings.

$\times 120$ diams.

Fig. 132.

15.38% Al.

Fig. 133.

20.7% Al.

Fig. 134.

27.1% Al.

Fig. 135.

29.1% Al.

Fig. 136.

35.1% Al.

Fig. 137.

40.0% Al.

Sand Castings.

$\times 120$ diams.

Fig. 138.

44.9% Al.

Fig. 139.

49.9% Al.

Fig. 140.

55.3% Al.

Fig. 141.

60.6% Al.

Fig. 142.

64.2% Al.

Fig. 143.

66.5% Al.

Sand Castings. × 120 diams.

Fig. 144.

68·3% Al.

Fig. 145.

71·0% Al.

Fig 146.

80·1% Al.

Fig. 147.

84·0% Al.

Fig. 148.

89·3% Al.

ALLOYS RESEARCH.

Plate 17.

× 120 diams.

Alloy No. 33. (0.00% Cu.)

Fig. 149.

Sand Casting.

Fig. 150.

Chill Casting.

Alloy No. 35. (1.90% Cu.)

Fig. 151.

Sand Casting.

Fig. 152.

Chill Casting.

Alloy No. 37. (3.76% Cu.)

Fig. 153.

Sand Casting.

Fig. 154.

Chill Casting.

Alloy No. 41. (8.08% Cu.) $\times 120$ diams.

Fig. 155.

Sand Casting.

Fig. 156.

Chill Casting.

Alloy No. 38. Slowly cooled. (4.97% Cu.)

Fig. 157.

$\times 120$ d.

Fig. 158.

$\times 800$ d.

Fig. 159. *Sand Casting of Alloy containing 50% Cu and 50% Al.*
Half-size.

Fig. 160. Rich Al Alloys.

Tensile Tests. (Parallel portion 2 1/4 inches.)

Copper per cent.

Downloaded from pme.sagepub.com at UNIV OF GUELPH on June 4, 2016

Copper per cent.

Plate 19.

Fig. 161. Rich Cu Alloys.

Aluminium per cent.

Fig. 162. Rich Cu Alloys. (Parallel portion 10½ inches.)

Yield	6.0	5.5	8.0	11.5	11.5	9.8	11.4	10.0	10.4	15.5	20.0	14.0	Point.
Ultimate	14.01	15.25	16.86	19.25	22.97	25.56	27.78	28.45	29.00	32.87	35.72	37.34	Stress.
Elongation	48.25	44.00	43.00	44.75	53.12	59.62	55.25	55.37	60.75	42.00	23.75	14.50	% on 8 ins.
Redu. of Area	92.00	90.00	90.00	87.60	84.86	80.48	78.71	75.10	76.83	52.52	49.40		Per cent.

Al. %	0.10	1.06	2.10	2.99	4.05	5.07	5.76	6.73	7.35	8.12	8.67	9.90
No.	1	2	3	4	5	6	7	8	9	10	11	13

Corrosion Pieces. (¼ full size.)

Fig. 163.

Fig. 164.

Fig. 165. Moulding Box.

× 120 diams.

Fig. 166. 10.75% Al.
Obtained in same condition as Fig. 130,
Plate 13, and quenched on a rising
temperature from 550° C. (1,022° F.)

Fig. 167. 13.2% Al.
Quenched from 680° C.
(1,256° F.)

Fig. 168. 14.2% Al.
Etched.
Dark areas = γ Constituent.
Light " = β "

Fig. 169. 15.7% Al.
Unetched.
Dark areas = β Constituent.
Light " = γ "

× 120 diams.

Fig. 170. 23% Al.
Quenched from 840° C. (1,544° F.)

Fig. 171. 23% Al.
Quenched from 700° C. (1,292° F.)

Fig. 172. 23% Al.
Quenched from 550° C. (1,022° F.)

Fig. 173. 25% Al.
Quenched from 800° C. (1,472° F.)

Fig. 174. 27.1% Al.
Quenched from 840° C. (1,544° F.)

Fig. 175. 27.1% Al.
As cast in chill.

(Captain H. Riall Sankey's remarks.)

Fig. 179. Workshop Bend-testing Machine (Sankey).

(Mons. Pierre Breuil's communication.)

Alloy resembling No. 13. 9.9% Al. $\times 400$ diams.

Fig. 194.

Quenched at 550°C. ($1,022^{\circ}\text{F.}$)

Fig. 195.

Quenched at 850°C. ($1,562^{\circ}\text{F.}$)

(Mr. George E. Buttenshaw's communication.)

A Copper-Zinc Alloy.

$\times 100$ diams.

Fig. 196.

Fig. 197.

Cast. Normal. Quenched from 750°C. ($1,382^{\circ}\text{F.}$)

Fig. 198.

Propeller Blade.

a. Re-heated to 750°C.

b. Cast.