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ULTRA-LIGHT ALLOYS AND THEIR UTILIZATION ON AIRCRAFT

By A. M. Portevin and R. DeFleury.

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PART I.

Definition and Mechanical Properties of Ultra-Light Alloys.

Definition.- We will arbitrarily call alloys having a specific gravity of less than 2 "ultra-light", in order to distinguish them from "light" alloys with a specific gravity of 2 to 3. Thus far it has been possible to make ultra-light alloys only by employing a large proportion of magnesium. This memorandum will therefore deal only with magnesium alloys having a specific gravity of less than 2.

Part III of the memorandum will explain the importance of the part taken by density in mechanical construction and the apparent narrowness of the classification adopted.

Magnesium is the sixth most abundant element on the surface of the globe, the five most abundant being silicon, aluminum, iron, calcium and sodium, in the order mentioned. The following list gives the proportion of the elements in the earth's crust.

SiO_2	38.2%
Al_2O_3	15.8
Fe_2O_3 and FeO	7.1
CaO	5.2

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* Translation, from French, of a paper read before the International Air Congress, London, 1923.

Na_2O	3.9
MgO	3.8
K_2O	3.2

The mineral compounds of magnesium must therefore be very abundant. We will make particular mention of:

The chlorides and sulphates.- the hydrous chloride, contained in sea water; carnallite, a double chloride of magnesium and potassium (Stassfurt deposits); sulphates, Kieserite (Stassfurt).

The carbonates.- giobertite, $MgCO_3$; dolomite, double carbonate of magnesium and calcium.

Anhydrous silicates.- chrysolite, pyroxene, amphibole.

Hydrous silicates.- Talc (the most common), serpentive, meerschaum.

For industrial purposes, the metal is now obtained from the chloride. The description of the electrolytic processes would be out of place here. We will, therefore, confine ourselves to giving a brief history of the processes employed in modern metallurgy and a bibliography, where those interested can find abundant information.

a) Chemical process (invented by Deville and Caron) employed, during the war, for the needs of national defense, consisting in the reduction of anhydrous magnesium chloride by sodium.

b) Direct reduction of the melted chloride (still employed in Germany). This process gives a product containing impurities about as follows: Si, 0.15%; Fe, 0.15%; Al, 0.05%; Pb, 0.05%; Zn, 0.04%; Cu, 0.03%; or, on the average, a total of 0.47% of impurities.

c) Double electrolyzers of the Ashcroft type (employed in England and France) enable the production of very pure metal (99.8%).

The present producers of magnesium are "The Magnesium Co., Ltd.", in England; the "Société d'Electro-Chemie et d'Electro-Metallurgie" and the "Acieries Electriques" of Ugine, in France; the "Griesheim Elektron," in Germany.

A thorough study of these alloys has been made during the last few years by "The Magnesium Co., Ltd., and by the "Société d'Electro-Chimie." Our aim being simply to give information of aeronautic interest, we have only extracted the following data:

a) Pure magnesium.- Specific gravity at 15°C (59°F), 1.72; melting point, 651°C (1204°F); boiling point, 1100°C (2012°F); specific heat, 0.25; coefficient of expansion, 0.000027; electric resistivity, 4.5 microhms/cm^3;

$$\left.\begin{array}{l} R = 18 - 22 \text{ kg per sq.mm}; \\ E = \ 8 - 13 \quad \text{"} \quad \text{"} \quad \text{"} \ ; \\ A = 8 - 13\%; \quad \Delta = 43; \\ \text{Modulus of elasticity, } 4200. \end{array}\right\} \text{On wiredrawn and annealed metal.}$$

Magnesium is used in the pure state for certain purposes, but it is generally better to improve its mechanical properties by the addition of various elements.

2. Alloys.- Most metals form with magnesium definite compounds, the solubility of which in magnesium in the solid state is generally small, the two exceptions being aluminum and cadmium. Equilibrium diagrams and measurements of electric resistivity, made by various persons, may be found in the "Revue de Metallurgie," Vol. V, 1908, including a resume of all the equilibrium diagrams established at that time. We are supplementing this by a bibliography of the more recent works of importance.

Although most of the equilibrium diagrams of the binary alloys are known, the same is not true of their mechanical properties. There is, in fact, no systematic treatise giving the effects produced on the mechanical properties of magnesium by the addition of various metals. All that has been published on this subject is contained in the density determinations of various alloys by Ludwick and a paper by Urasoff concerning the effect of cadmium on the hardness of magnesium, a subject which was taken up again during the past year by Guillet. In this connection, we are giving various supplementary information on the other mechanical properties of these alloys (Figs. 1 to 3), and especially on their strength, which has heretofore been established only by means of the ratio R/Δ, which cannot be defined "a priori" without the risk of being led to erroneous conclusions.

Figures 1 to 3, show the effect of several metals (aluminum, zinc, cadmium, copper) on the mechanical properties of magnesium. As to the modulus of elasticity, its increase is relatively more frequent than that of the mechanical properties exhibited in the diagrams (Figs. 1-3). In order to obtain an increase of 10% in the value of the modulus, an addition of 4 to 5% of aluminum or zinc or 8 to 10% of copper is required.

It is seen that cadmium increases the breaking strength and elastic limit in only a very slight degree. Magnesium-cadmium alloys are therefore of no great industrial importance. This is not true, however, of aluminum-magnesium and zinc-magnesium alloys, as shown by the curves in Figs. 1 and 2. As for the ternary alloys, we are giving, simply for illustration, figure No. 4 indicating the effect on the hardness produced by the simultaneous addition of aluminum and zinc.

The magnesium-aluminum-zinc ternary alloys are the most employed at the present time. Of course the properties of these alloys can be modified by working cold or by annealing. Fig. 5 gives the variation of R and A, in terms of the temperature at which it is worked, for the magnesium alloy containing 3% zinc and 0.5% aluminum.

Industrial types.- The first attempts to employ magnesium in the industries were made in 1910 in Germany, which was quite natural, considering the richness of the Stassfurt carnellite deposits. They do not seem to have been successful, however, and the different alloys successively proposed did not find any industrial market at that time.

In 1918, the technical sections of the allied armies found magnesium alloys on Zeppelins which were shot down. They were found, however, only in parts of secondary importance. At that time magnesium firing-pins of fuses were also found. The composition of these parts is given below.

	Firing-pins		Zeppelin parts
Magnesium	91.20	91.05	93.25
Aluminum	2.43	0.62	0.07
Copper	0.08	0.15	0.26
Silicon	0.02	0	0
Iron	traces	0.51	traces
Manganese	0.20	0	0.08
Lead	0.05	0.04	traces
Zinc	6.02	7.64	6.38

Since then there have been thrown on the market, in France and England as well as in Germany, tubing, section metal, sheet metal and castings.

The alloys produced in Germany give the following mechanical results, according to data published by Beckinsale and Atchison.

Wiredrawn metal: R = 25 to 27 kg/sq.mm (36000 to 38000 lb/sq.in.); A = 11 to 12%.

These alloys contain principally aluminum and zinc, but the latter always predominates. They are designated by the generic term "elektron." It is not proper, however, to include in this term all the magnesium-zinc-aluminum ternary alloys, as likewise all the ultra-light alloys of magnesium. This is an extension and generalization, whose commercial character is evident to everybody.

The alloys furnished by the "Société d'Electro-Chimie et d'Electro-Metallurgie" are likewise complex alloys giving:

R = 22 to 24 kg/sq.mm (31000 to 34000 lb./sq.in.);

E exceeds 15 " (21000 lb./sq.in.);

A = 12 to 16%.

Some alloys even give:

R = 26 to 27 (37000 to 38000);

A = 16 to 20%.

These commercial alloys are likewise complex alloys containing zinc and aluminum. In addition to these last metals, note should be made of the copper used in alloys for engine pistons (alloy with 12% copper).

<u>Resume</u>.- Two general classes of alloys are now being used: magnesium-aluminum-zinc, with or without other metals, and magnesium-copper. Recourse may be had to other alloys for particular purposes, or where special properties are required.

PART II.

Present Possibilities of Employing Ultra-Light Alloys on Aircraft and the Forms in Which They are Delivered.

The researches of which we have just spoken, bearing on the composition of the alloys, have not constituted the only recent enterprises of the kind. French and English investigators have been at work with equal perseverance improving various mechanical and thermal treatments, thus rendering it possible to subject the alloys to all the transformations which can reasonably be required of ordinary metals. Most of these problems have been solved and it may now be said that the large majority of the parts capable of being made of aluminum or aluminum alloys can now be obtained in magnesium or magnesium alloys. We will review the most important industrial processes employed with these alloys and the resulting products.

1. Casting.- This was one of the first processes employed (We have already spoken of castings made in 1918). Much progress has been made, especially in casting large parts (crankcases weighing over 30 kg (66 lb.)) and very thin parts (down to 1.8 mm (.071 in.)). The latter accomplishment, however, is of no great importance, since these alloys are used chiefly to increase the size of parts without increasing their weight.

Incidentally it may be noted that the chief factors of success are: absolute dryness of the molds; a suitable pouring temperature, always below 700°C (1292°F); greater care and stricter attention to details than for ordinary alloys.

This memorandum refers to parts cast either in sand or chill molds, the latter method being advantageously employed here, the same as for aluminum or other white alloys, when the number of each part to be cast is sufficiently large. Engine pistons and crankcases are thus cast.

2. Tubing and bars of various cross-section ("section metal").- All parts desired (parts of fuselage, etc.) can be obtained by means of the wiredrawing press. The billets must be prepared with sufficient care to avoid all defects, either internal or external. The wiredrawing temperature is about 400°C (752°F). The speed of drawing (which should be as low as possible) and the wiredrawing ratio here play a very important role. The wiredrawn parts resemble as closely as possible the completed parts as delivered to the trade.

3. Forging and stamping.- There is nothing particular to mention in regard to forging. Magnesium is forged very easily, as likewise most of its alloys. The stamping dies are heated, on account of the small heat capacity of the ultra-light alloys. The processes of forging and stamping magnesium have been carried out industrially and perfected in France during the last few years. It may even be said that, in the hands of experienced workmen, these operations are easier than for light aluminum al-

loys of high tensile strength. It is unnecessary to dwell on the importance of the solution of this problem for aeronautics.

4. Welding.- This problem has likewise been solved in France during the past year. Autogenous welding gives excellent results, when a suitable flux is employed, and can be used for all thicknesses. Non-usable crankcases, of German origin, could be repaired as if they were steel. In tensile and bending tests of the welded pieces, they broke outside the limits of the welds. Cadmium may be used for welds not exposed to any particular stress or for remedying defects which hurt only the external appearance of the parts.

5. Rolling.- Sheets of all thicknesses can be obtained, but here again it is an error to make them too thin, because we then lose the benefit of the general and local rigidity obtained with equality of weight, due to the lightness of the alloys.

6. Sheet metal working.- Starting with the sheet metal obtained by rolling, all the special problems presented in aircraft work can be solved. Here again the quality of the parts obtained depends on the skill and experience of the worker.

7. Lathe work.- Magnesium alloys can be worked with great facility and are comparable in this respect with brass.

These processes render it possible to make nearly all the parts (such as pistons, connecting-rods, crankcases, instruments and assemblies) for which light alloys seem to be of advantage on aircraft.

PART III.

Principles Governing the Use of Ultra-Light Alloys in Aircraft Construction.

1 - INTRODUCTION

Utilization of light metals.- The use of these metals presents, as regards strength of materials, problems which, if not new, are at least unusual and with which scientists, especially those not connected with aviation, are not generally familiar.

The small surface hardness of these metals, to take a simple illustration, enters into questions of assemblies and joints. It is therefore necessary to apportion appropriately the sections, surfaces, tightness and intervals; also to choose a suitable ratio between the thickness of the metal and the number of rivets. These are but a few of the details among many requiring attention. All the details, joined to the general considerations which we are going to develop, will assuredly lead to empirical rules such that the laws governing light-metal construction will be quite different from those governing heavy-metal construction. Let us endeavor to reason according to the factors which may intervene in the reduction of weight to the extreme, fundamental in aircraft.

2 - STRENGTH OF MATERIALS AND LIGHTNESS OF CONSTRUCTION.

General principles.- In fact, as regards the problem of light-metal construction, there seems to be two methods of solution:

1. The employment of special high-resistance steels;

2. The employment of light metals and especially of magnesium, the lightest of them all.

Let us now note the following very important point. With equality of weight, the first method implies the employment of very slender pieces, because of the greater density of steel, while the second method implies the employment of more massive pieces, because of the feebler mechanical characteristics of the light metals. Moreover, there is a tendency to compare the values of two metals of very different densities and to establish a parallel between the ratio of the densities D/D' and that of the strengths R/R'.

These two ratios, however, are not sufficient. We shall see that the ratio of the moduli of elasticity plays a role no less fundamental and almost always even more limitative, than the ratio of the strengths, in the case of extremely light aeronautical construction. There is nothing which should be astonishing in this, since stresses and strains are inseparable in the question of the strength of materials.

Before carrying the comparison further, it is important to comprehend a few general truths, almost axioms, in the realm of applied mechanics. These axioms are, moreover, frequently misunderstood, in the absence of practical experience, as regards the employment of light metals. In order to present them in a more striking manner, we will express them in the form of theorems. Some unforeseen practical consequences will perhaps follow this exposition.

<u>Theorem 1</u>.- With a given substance, the lightening of a structure or part, considered in static or kinetic equilibrium, i.e., subjected to couples, is effected by a judicious "volumetric dispersion" of the substance.

In fact, the problem consists in lengthening the lever arms of the opposing couples, i.e., the distances of application, and in proportionally diminishing the stresses or resisting sections.

<u>Theorem 2</u>.- The volumetric dispersion of the material is involved not only in the planes of the couples occasioned by the principal stresses "charges" and "surcharges", not only in the transverse planes themselves, whole sections by sections, but also partial sections by sections and even points by points and this in proportion to the resolution of the frame into its ultimate parts.

In fact, the work of a part progressively lightened by the dispersion of the material, brings successively into evidence at least three factors, which limit the actual factor of safety, in the simplest case, for example, that of a plain girder or tubular strut.

Factor 1. The part must withstand, as a whole, the total stresses for which it is designed. The lightening is effected, it seems, by dispersing the material without limit, "at least theoretically," in the sole direction of the orientation of the stresses, i.e., in the plane of the latter.

Factor 2.- An exaggerated dispersion being obtained in the direction of the stresses under consideration, it follows that, in a direction which seems to bear no relation to the foregoing, the part ceases to present the general rigidity required to withstand the transverse warping and bending of the entire member. This is the case of a too narrow girder placed edgewise or of a solid strut as compared with a hollow one. Security against local bending and buckling is obtained by a suitable dispersion of the material in an appropriate supplemental direction, usually normal to the stresses. The above-mentioned plane should be thick. Even theoretically, it seems that this dispersion can be without limit. This is where the third factor comes in.

Factor 3.- When the dispersion relative to the second factor is exaggerated, the material may be found distributed locally in very small zones or in very thin sections in such manner as to cause local bends and buckling, which may, moreover, exist without any relation to the causes governing factors 1 or 2. It is necessary to invent still another term, i.e., to give a local volume, and so on. This is, for example, the case of a tube resisting compression, whose inside diameter is considerably increased and the thickness of its walls excessively reduced. It is also the case of a very thin sheet of metal under tension, in which the transmission of the stresses through its points of attachment (rivets) causes local wrinkling. Girders which have been able to support their total theoretical load only when their walls are corrugated are illustrations of factor 3. The causes governing factor 3 usually depend, moreover, on accessory requirements and circumstances, such as the need of frequent dismantling and assembling, the need of tightening nuts or of various manipulations, the strength requirements in vibratory and even calorific fields, the expansion being of the same order of magnitude as the elastic distortions. They may also proceed, without our being able to estimate the principle stresses themselves, from the fact that a homogeneous substance comprises in its mass an assembly of superabundant connections, whose transverse resultants are not offset by too thin sheets. In the case of wood, hygrometric conditions alone may cause warping.

Corollaries.- Several important observations belong here. If the strength is simply to limit the admissible stresses (or safety factor), for the first cause the value of the modulus of elasticity must intervene to the same extent, at least, in order to limit the admissible distortions resulting from causes 2 and 3. It is only at this cost that the factor of safety is homogeneous for the member as a whole and in detail. In fact, we must remember that, in the matter of construction, with the very great strength which metallurgists have succeeded in giving special metals, we are always limited in practice in the matter of dispersion by the value of the modulus of elasticity, on which no appreciable improvement has been made. The importance of this property has not been understood.

Theorem 3.- The employment of special very strong metals is usually disappointing as regards increased safety in extremely light structures. This is due to the fact that the modulus of elasticity has not experienced an improvement corresponding to that of the strength and that, in this case, the maximum admissible dispersion of matter, part by part and point by point, depends entirely and directly on the value of the modulus of elasticity. We cannot, therefore, reduce the amount of matter nor the thickness of the sections, in spite of the increased strength, without diminishing the safety factor in other ways.

3 - THE PARTICULAR CASE OF THE LIGHT METALS.

Comparative strength of materials.- Hence, it seems to us that each of the three ratios, D/D', R/R' and E/E', are of fundamental importance in comparing the value of two substances of a different nature, for the purpose of obtaining ultra-light construction. The rough determination of the values of these ratios for steel, aluminum and magnesium procured us surprising results. The three ratios are practically of the same order of magnitude in comparisons of these metals, whether cast, forged or rolled. Hence we have $D/D' = R/R' = E/E' = C$.

It does not concern a general law of matter but a particular remark which perhaps is of some importance (See DeFleury, "Lecture before the Society for the Encouragement of National Industry," May, 1922). This would singularly limit the possibilities of metallurgists in the researches which we shall suggest regarding the very desirable improvement of the modulus of elasticity. On comparing aluminum with steel, we obtain $C = 2.7 = 1/0.37$. For magnesium compared with steel, we obtain $C = 4.2 = 1/0.24$. For magnesium compared with aluminum, we obtain $C = 1.6 = 1/0.60$. These values correspond to the following numbers.

	D	R		E	
		kg/mm²	lb./sq.in.	kg/mm²	lb./sq.in.
Forged steel	7.5	100-110	142200-156460	20000	28447000
Duralumin	2.8	38-40	54000- 56890	7500	10667600
Rolled magnesium	1.8	25-30	35559- 42670	4800	6827300

On comparing these values with those found experimentally, we find that, from the viewpoint of strength, the light metals compare favorably with special steels. On the other hand, we must remember that the moduli of elasticity are in reality also equal to those calculated according to the ratios of the densities. This means that the safety factors of light-metal structures are largely satisfied by the strengths they already possess and that their "volumetric dispersions" are limited only by the modulus of elasticity.

The first conclusion is that of theorem 4, that strengths above 38 - 40 kg (84 - 88 lb.) for duralumin and above 25 - 30 kg (55 - 66 lb.) for magnesium are illusory and useless, because the moduli are respectively below 7500 and 4800. This concerns, of course, only very light structural parts and not massive parts devoid of flexibility.

The superiority of light metals over steel does not therefore consist in an exceptionally high but useless strength. It is the result of two factors which are the proper role of the section, on the one hand, and the general notion of charges and surcharges, on the other hand. We will discuss them very briefly, on the supposition that we have the following entirely satisfactory relation. $D/D' = R/R' = E/E'$.

General notion of charges and surcharges and effect of the section.- Every part or assembly works statically or kinetically simultaneously in "charge" and "surcharge." The "charge" is the weight of the part or its inertia. The "surcharge" is the stress withstood or transmitted. Formula (1) shows immediately that it suffices, as regards the charge alone, for the light-metal part to possess, for the sake of equal security, as regards strength, inertia and distortions, sections equal, point by point, to those of the same part in steel. In fact, according to formula (1), the stresses, strengths and moduli of elasticity are all proportional to the mass, i.e., to the density of the substance. It is immediately evident that the weight of the part or assembly is proportional to the density. As regards the charge, the superiority of the light metal, for a light structure, is therefore formidable and beyond question from all viewpoints. As regards surcharges, it is evidently necessary to increase the sections in proportion to the density, which seems, at first thought, to eliminate all advantage..

In reality, this increase of section more than compensates, by the increase in the moments of inertia and in the general and local rigidity of the light metal part, for the feeble modulus of elasticity of the latter, aside from the improvement of the resulting moments of strength. Herein lies what we call the "effect of the section."

The necessary conclusion is that, with equal security and equal complexity of the framework, the lightest metal enables an important lightening of the structures. A light metal, by reason of formula (1), may be considered, with reference to steel, as a substance already dispersed locally, i.e., equivalent to a complex element already assembled, with the further advantage of continuity and homogeneity. Only a microcellular or "microrecular" structure could make steels comparable to the light metals. This depends, however, on improvement in the means at the disposal of the engineers. The light metals, however, would also benefit from such progress and resume their advantage. We predict the triumph of the principle of light metals in massive pieces over special steels in thin pieces.

4 - CONSTRUCTIVE REMARKS.

LAWS GOVERNING TRANSPOSITION OF MATERIALS.

Remarks.- If we wish, for example, to substitute light metals, for heavy metals or inversely, in any member or structure, we must consider certain principles, which all follow, moreover, from the foregoing chapters. For example, we will start with the hypothesis that a steel member, which has been lightened to the limit, gives practically perfect satisfaction, i.e., the factor of safety is homogeneous as regards strength and also as regards the modulus of elasticity at its various degrees of occurrence in the member. We wish to substitute a light metal member presenting the same homogeneous factor of safety, in all the essential parts and accessories, both as regards the strength and the modulus of elasticity.

Transposition.- The first result to be obtained is equal local rigidity of the elementary sheet metal, for example, according to the factors in the preceding chapter. In order to effect this calculation, we must base it on the deformations (i.e., on equal deflections) of two sheets of the same width and length, occasioned by the same secondary stress. Then the bending moments (2), the deflections (3) and the resisting moments (4) of the sections of two girders are, respectively, of the most general form:

$$\alpha PL \qquad \alpha P'L' \qquad (2)$$

$$\beta (PL^3/LI) \qquad \beta (P'I'^3/E'I') \qquad (3)$$

$$\gamma (I/V)R \qquad \gamma (I'/V')R \qquad (4)$$

V and V' being the distances from the neutral fiber to the most stressed fiber. There are coefficients which vary in the most general way, with the method of setting, the nature of the load and its position, overhung or between supports, factors of safety, etc.

Our method of calculating consists in establishing the ratios of the data to be compared. Of course we always assume the validity of equation (1):

$$D/D' = R/R' = E/E' = C.$$

In the case of metal sheets, the thicknesses e and e' are represented by V and V'. If we assume the equality of the deflections (formula (3)) representing the flexibility under the same stress, we obtain

$$e'/e = \sqrt[3]{C} \tag{5}$$

For the same local rigidity, sheet aluminum, as compared with 1 mm (.039 in.) sheet steel, must, according to the ratio, have a thickness of 1.4 mm (.055 in.) and sheet magnesium 1.62 mm (.064 in.). A sheet of magnesium, as compared with a 1 mm (.039 in.) sheet of aluminum, must have, according to the same ratio, a thickness of 1.15 mm (.045 in.). If it is a question of sheet metal for covering surfaces of indefinite extent, there is a saving of weight for equal rigidity, as compared with steel, of 48% for aluminum and 61% for magnesium.

The second result to be obtained, if it concerns an I section, for example, the local rigidity having been obtained by the preceding condition, is an equal transverse rigidity for the steel and the light-metal girder. Here V and V' are the widths of the wings. The moments of inertia are therefore

$$I = \lambda e V^3 \text{ and } I' = \lambda e' V'^3 = \lambda e \sqrt[3]{C} = V'^3 \qquad (6)$$

The deflections (formula (3)) must be equal for equal stresses, in order to obtain the same disturbing deformation limit on the neutral fiber, with equal stresses on equal lengths. Thus we obtain $EI = E'I'$. If we substitute for I and I' their value derived from formula (6), we obtain $V'^3/V^3 = \sqrt[3]{C^2}$.

The width of the steel wing being taken as unity, the width of the aluminum wing must be 1.24, according to the formula, and that of magnesium 1.38. If the width of aluminum is taken as unity, that of magnesium must be 1.11.

If the problem concerns tubes, we find, likewise, that an aluminum and a magnesium tube are equivalent, as regards rigidity and buckling, when the thicknesses are in the ratio of 1:1.11 and in the same ratio for the moduli of elasticity. We find that the substitution of magnesium for aluminum in a given problem would require one size larger in diameter and thickness as given in the standardization tables of the French air service. Under these conditions there is a considerable saving in weight, although considered only in connection with surcharges, the problem of the "charges proper" being quite different and much more favorable to light metals.

If it concerns a system of girders crossing one another transversely, we find that the law of transverse rigidity does not come into play, which still further improves the conditions of rigidity.

In connection with the problems of strength, we find, if we maintain safety factors corresponding to the rigidities already defined for the purpose of obtaining the maximum lightening, that it is necessary, in order not to increase the cross-section, to increase the distance of the extreme fibers from the neutral axis, in substituting a light metal for steel.

Hence we have at our command a supplementary margin of lightening, whose proportion varies according to each particular case, judgment and experience remaining almost the sole ultimate criteria. The principle, however, still obtains, the sense of which the mechanic should, at least to some extent, acquire. If, for example, it is a question of thin airplane wings, the employment of steel is necessary. If it is a question of thick wings the employment of light metals is required and conversely.

The conclusion is more general, however, and has some of the importance of a rule of construction. In order to be made as bulky as possible, a part or assembly must be made of light metal and, inversely, light metal structures require a large volume and large sections. This relates to the work of withstanding the surcharges. In fact, the sections do not need to be reinforced, if it is only a question of "charges," or of the part relative to these charges, as we have already explained. This gives an overwhelming advantage to the light metals.

Consequences from the structural viewpoint.- One general consequence follows, namely, that the light metals, in their method of employ, require structural proportions and methods entirely different from ordinary metals. Any transposition of the materials cannot, therefore, consist in a simple substitution, element by element, but necessitates a new detailed study of the whole airplane. Here is the chief difficulty which, in common with all other practical difficulties, can only be solved by approximations or by a slow and methodical experimentation.

Perfect knowledge of light metals will be acquired when their important uses shall have justified expensive metallurgical researches. On the other hand, structural progress is under the precarious necessity of being sustained by materials, many of whose characteristics have not yet been practically determined. The methods of employing light alloys are beginning to be known. Those for magnesium need to be improved.

The materials whose empirical employment is the best known in aeronautic construction is wood, because it has been long used. Let us note, however, in passing, that wood, at least in the direction of the grain, conforms fairly well to the proportionalities on which our considerations have been based. This explains why the latter, even less dense than the light metals, continues to be used, in spite of the disadvantages arising from its great hygrometric distortions.

An example.- We have shown why the value of the modulus of elasticity is limitative in extremely lightened parts. This may also hold true for even quite massive parts, when subjected to severe stresses. It seems, for example, that the construction of aviation engines encounters some difficulties in producing engines with cylinders in rows, when the power exceeds 500 HP. These difficulties have, moreover, been encountered simultaneously in different countries. The crankcases and crankshafts break in these engines. This difficulty may be due to the fact that the great length of the crankcase subjects it to all the stresses brought into action, including an excessive torsion which reacts on both crankshaft and crankcase. These reactions cause considerable deformation and it is feared that the investigation of special steels alone for the crankshaft may end in delusive and disconcerting results. The real solution may consist, on the contrary, in giving the crankcase a shape especially designed to offset the torsion.

It may be noted that the torsion is proportional to the modulus of elasticity of the materials employed. The substitution of magnesium, in even massive castings, in place of aluminum, must be the occasion for a very thorough investigation of the supplementary torsions, in many cases, since we have seen that the moduli of these two metals are in the ratio of their respective densities.

Overlooking the latter point might cause mistakes, when the necessity of eliminating dead weight on airplanes has led to the substitution of magnesium for aluminum for all large castings or forgings. We may conclude, from this particular point, given as an example among a thousand possible ones, that not only must the parts but also the design of the whole airplane be adapted to the use of light metals.

Effect on the cost of construction.- Lightness, like every other desirable quality, must be paid for. Even if producers, in quest of economical methods, should tomorrow be in a position to supply us with magnesium, for example, at the same price by volume or weight, the lighter magnesium structures would even then cost more than similar ones of aluminum. Aluminum structures will likewise remain more expensive than steel. The reasons follow from formula (1):

$$D/D' = R/R' = E/E'.$$

It has already led us to conclude that we could obtain appreciably lighter structures, but that the maximum lightening, in case of simple charge (surcharges considered zero, an extreme case) would lead to the same volume of metal as the minimum limit. Since there is, however, some surcharge, the volume of the lighter metal must be greater than that of the heavier metal.

It is only the volume which affects the transformation cost of the metal in tubes, sheets or bars, at least for similar processes. Where the volume is greater, the total cost, due to the transformation factor alone, is greater. Thus structures of lighter metal will always be more expensive than those of heavier metal, but they will have the advantage of less weight for equal strength, if properly constructed.

In aviation, any saving in weight means a corresponding gain in the carrying capacity, which enables such a rapid amortization, that the increase in the original cost is of very little account.

From the standpoint of the future, there is an element of superiority, more important than the preceding, in favor of light metals. We know that any increase in size above a certain maximum, calculable for each mode of construction, with any given material, necessitates an increase in the "charge proper", i.e., in the dead weight, so that there remains no margin available for increasing the "surcharge" or carrying capacity. This is a general rule which applies to airplanes, as well as ships and bridges. Light metals extend the limit of the carrying capacity and change the scale of possibilities, which is well worth some additional cost.

CONCLUSIONS

1. No special steels, however strong, seem capable of competing, as regards the problem of maximum lightness of construction, with the light and especially the ultra-light alloys. For

them to do so, their moduli of elasticity would have to be improved in the same proportion as their strengths, if they are to present any marked superiority in comparison with ordinary steels. Then, for the portion of the stresses relative to the "proper charge" at least, the lightest metals present overwhelming advantages over the heavy metals. They also do this as regards the surcharge alone.

2. The small modulus of elasticity of the light metals, rather than their strength, in the present state of their metallurgy, place limits to the lightness of structures. They are already in the same case as that of special steels in comparison with ordinary steels. The endeavor to obtain strengths above about 36 kg (79.4 lb.) for duralumin and 24 kg (52.9 lb.) for magnesium, therefore seem illusory, the same as the attempts to employ steels with a strength of over 100 kg (220.5 lb.).

3. The employment of a lighter metal enables appropriate constructive conceptions and interpretations, quite different from those designed for a heavier metal, the two metals here compared being magnesium and aluminum.

4. The special mode of construction is what we have called "that of employing light metals in massive pieces" and "large sections," which we have contrasted with "the employment of heavy metals in slender pieces."

The second principle, if applied (which is to be desired), will probably only prepare more surely the way for the first, on more restricted bases of experimentation.

5. This study also brings out the fundamental and preponderant importance, often unappreciated, to be attributed to the modulus of elasticity of materials, as related to their densities, not only when it is desired to employ them for making extremely light structures, but also when it is desired to draw judicious conclusions for or against metal construction, for or against this or that material or for or against this or that mode of construction.

6. In aeronautic structures, which must be as light as possible, the lightest metal, namely magnesium, is expected to bring constructive facilities of the first order and to present marked advantages over heavier metals, including even aluminum.

SUMMARY

The problem of lightening aircraft by using lighter metals has been considered under its double aspect:

1. Metallurgical, by the production of ultra-light alloys with satisfactory elastic and mechanical properties.

2. Structural, by establishing principles and rules governing the use of these ultra-light alloys.

These two aspects cannot be separated. Ignorance of the principles, just enunciated in Part III, will just as certainly lead to mistakes and failures as the use of ultra-light mater-

ials of inferior quality, although the failure due to the former cause is often attributed to the latter. We thus run the risk of paralyzing progress and compromising the future of these new materials before which there is opening up a considerable field of application.

It is therefore necessary to adopt for the parts and structures, entirely new designs, adapted to the new materials. It is only on this condition that the industrial production of these ultra-light alloys will bear its best fruit and that metallurgical progress will not remain barren of results.

It is well to recall that the creation of the magnesium industry in France is the work of Mr. Gall.

In conclusion, we wish to thank our immediate collaborators, Messrs. Pierre Lefebvre-Carnot and François Le Chatelier, in the technical and scientific researches and in the industrial development of the ultra-light alloys.

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Translated by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

Fig.1

Metal wiredrawn and annealed.

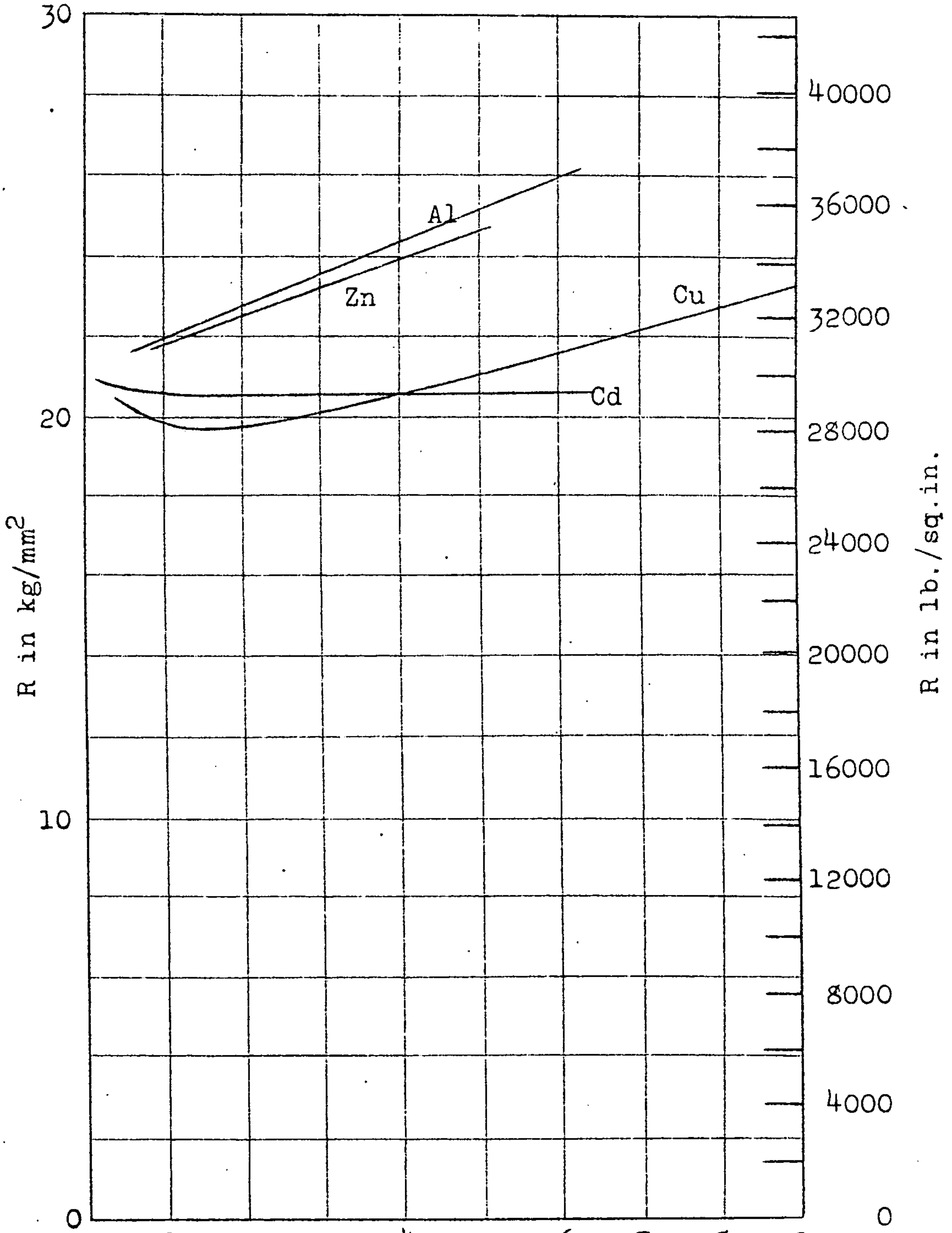

Fig.1 R in kg/mm^2 and lb./sq.in. Variation of R plotted against composition of alloys.

Fig.2

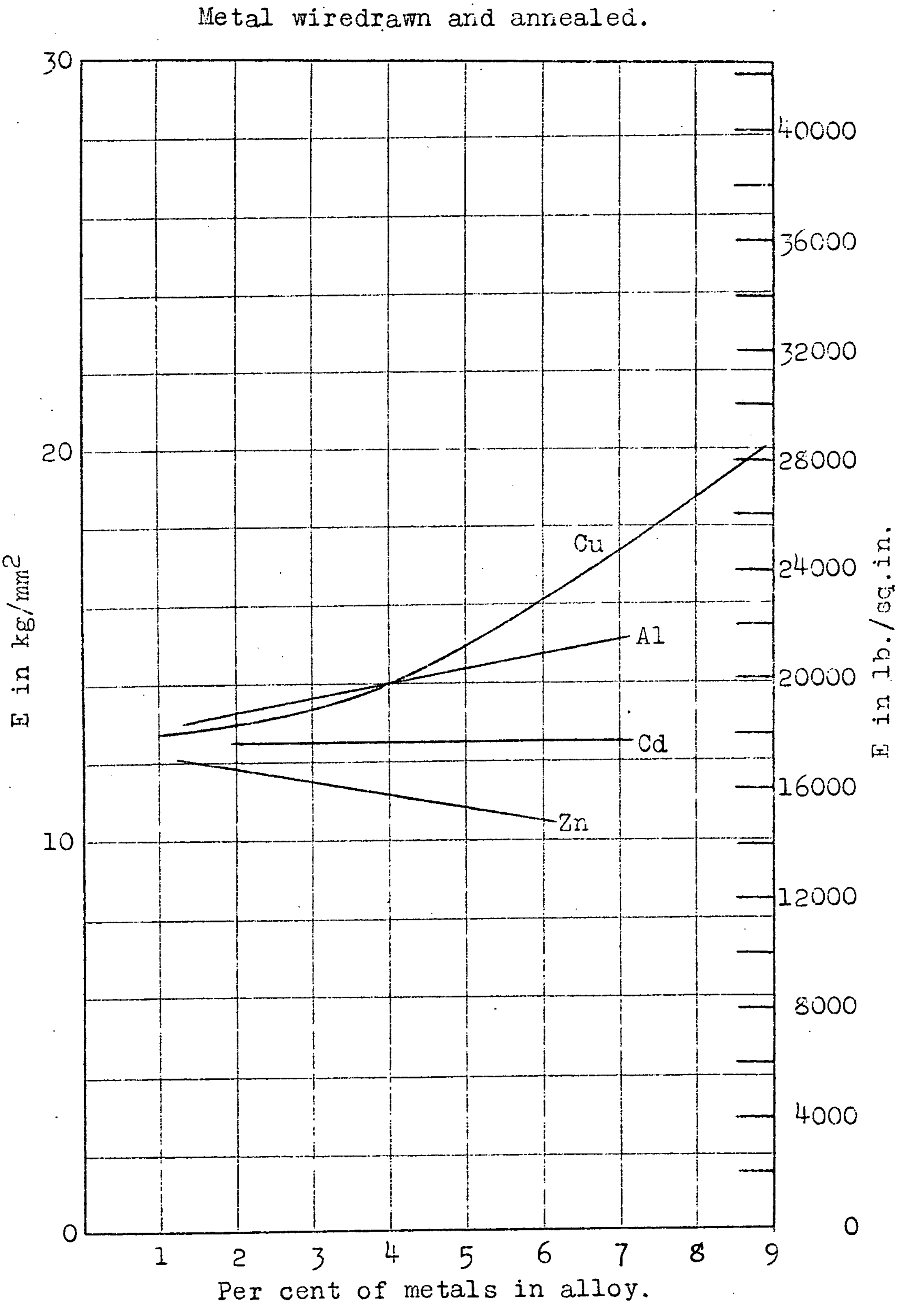

Fig.2 E in kg/mm^2 and lb./sq.in. (tension) Variations of E plotted against composition of alloys.

Fig.3

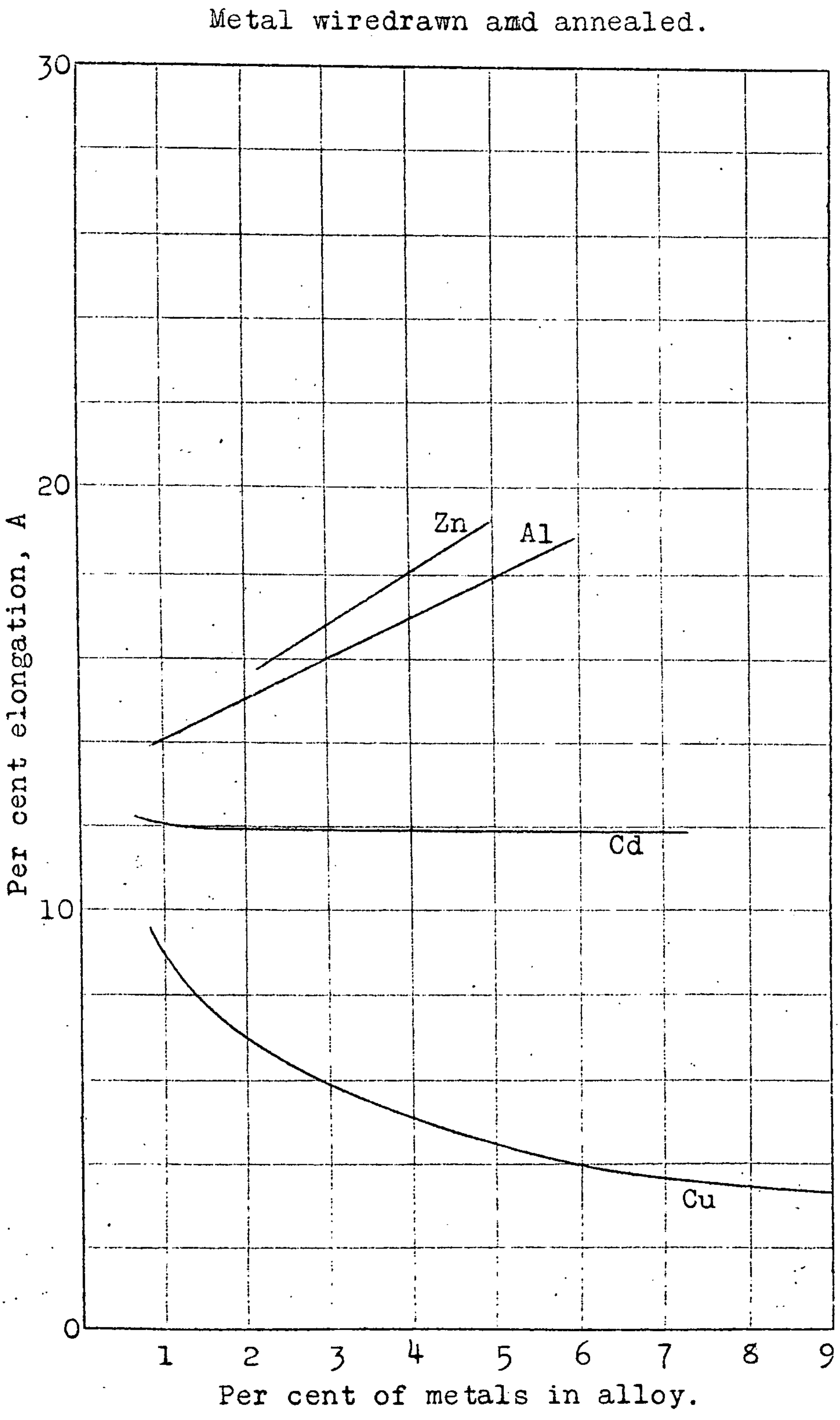

Fig.3 Per cent elongation (A) under tension. Variations plotted against composition of alloys.

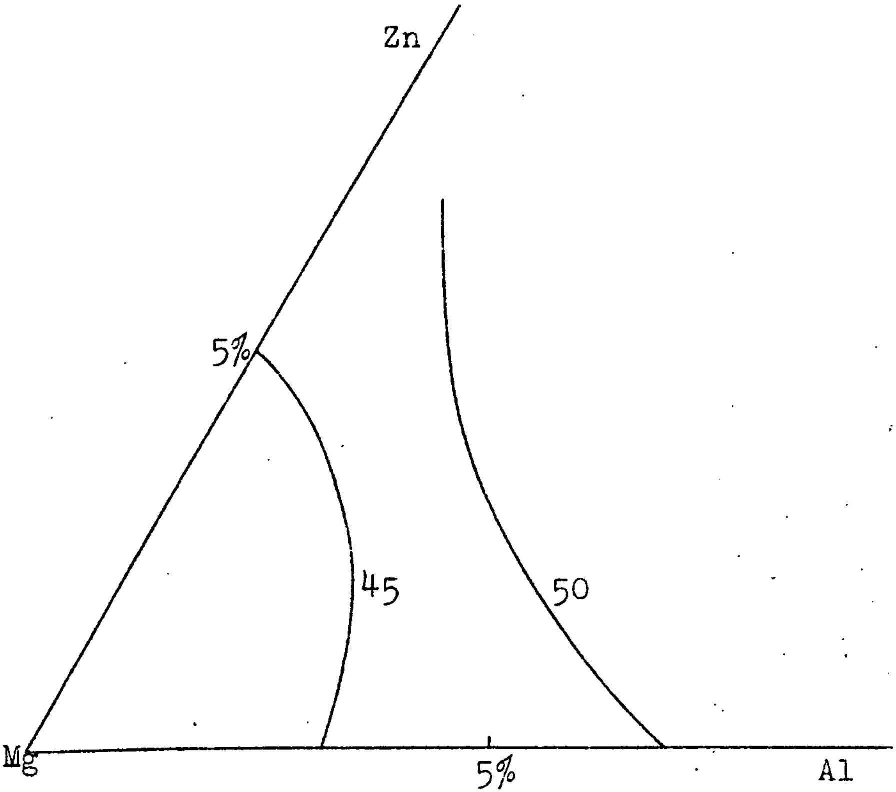

Fig. 4 Alloys of Mg, Al and Zn. Hardness according to Brinnell test.

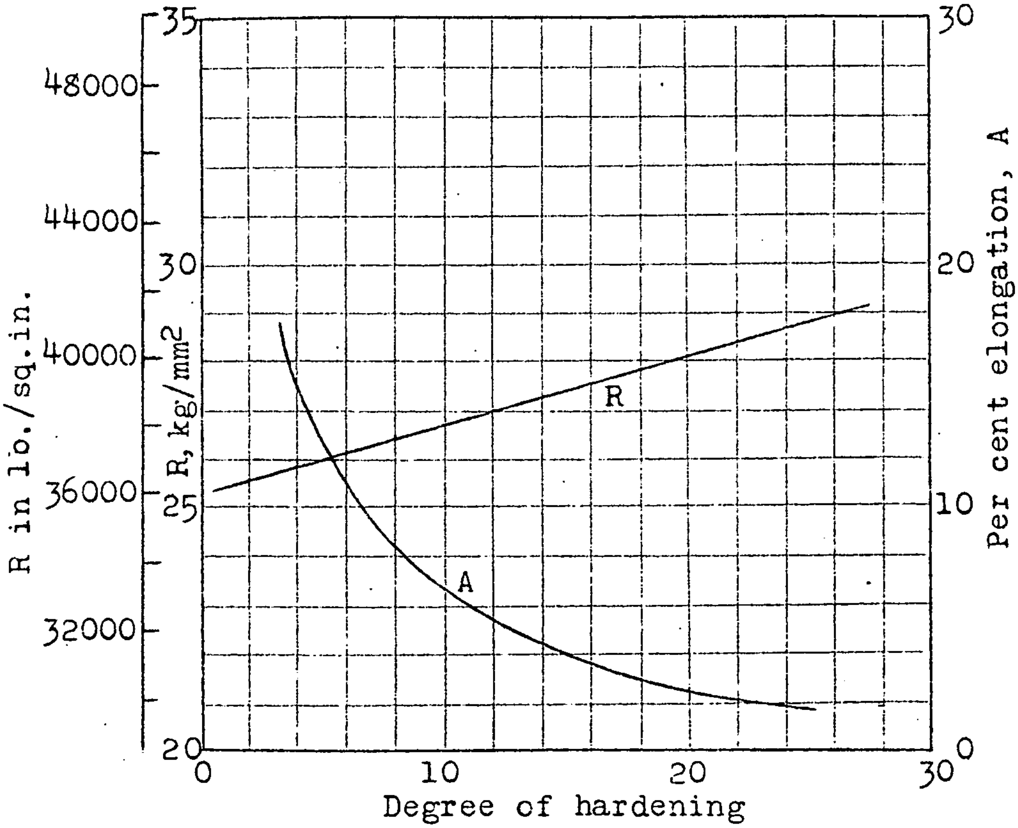

Fig. 5 Variation of R and A plotted against degree of hardening.