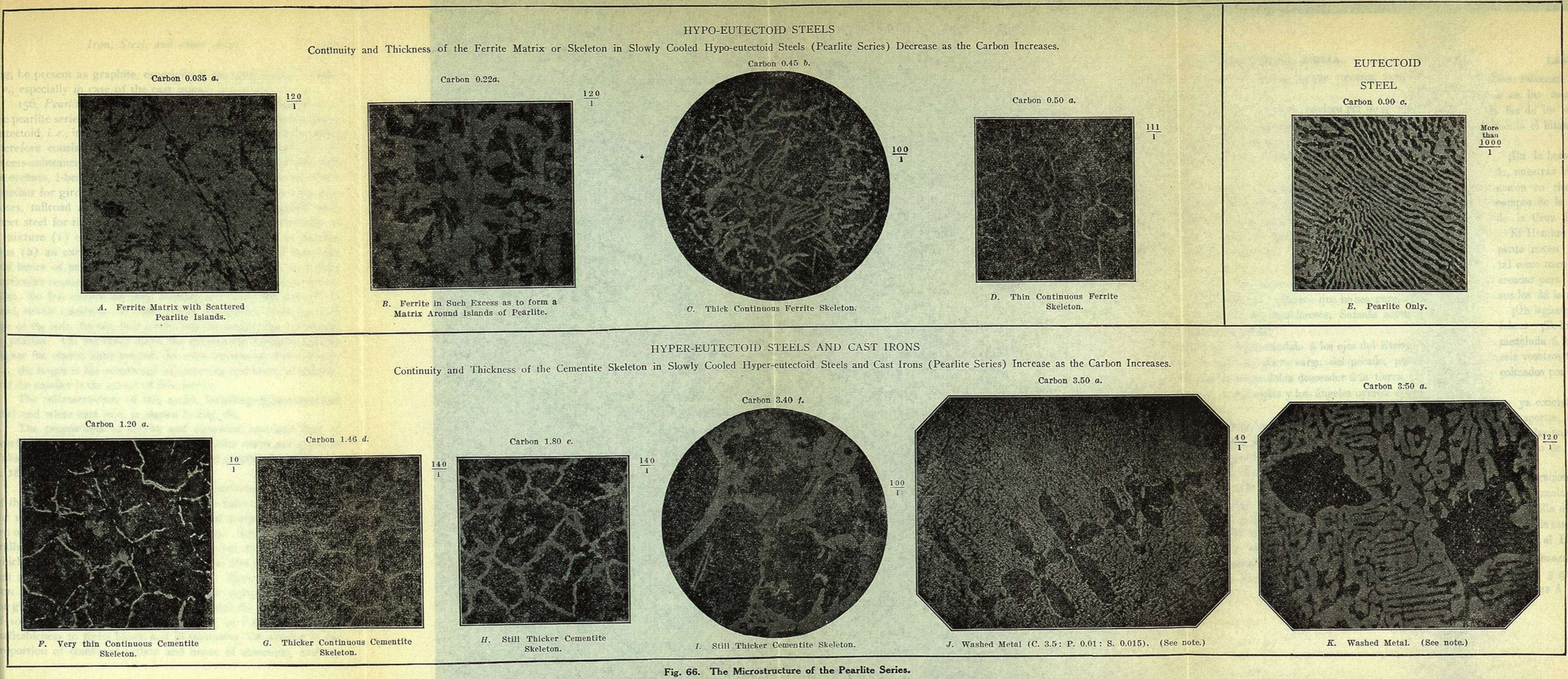


Fig. 66. The Microstructure of the Pearlite Series.

a. Prof. Wm. Campbell. *b.* Osmond, *Méthode Générale Pour l'Analyze Micrographique des Aciers au Carbone*, Pl. 3, Fig. 186. *c.* Osmond, *Baumaterialienkunde*, II, p. 53 *et seq.* Fig. 17. This micrograph is actually from part of one made by M. Osmond from steel of about 1.00 per cent of carbon; but the part here taken, as it does not show any of the cementite network, may be used to illustrate the structure of the normal structure of eutectoid steel which naturally lacks the cementite network. The reason for using this particular micrograph here is that it is so remarkably good. *d.* Roberts-Austen, Fifth Report Alloys *Research Comm.*, Fig. 43. *e.* Roberts-Austen, *Fifth Report Alloys Research Comm.*, Fig. 45. *f.* Stead, *The Metallographist*, p. 263 Fig. 7.

NOTE TO FIG. 66.

The purpose of this illustration is to show how the microstructure of the pearlite series, taken from end to end, corresponds to the proximate constitution of that series as set forth in Table 6 and Fig. 65.

Note, in particular, how, starting with pearlite alone with the eutectoid composition, 0.90 per cent carbon, as the carbon-content rises above or falls below this eutectoid proportion, an increasing proportion of the excess-substance appears, ferrite as the carbon decreases below 0.90 per cent, cementite as it increases beyond 0.90 per cent. The pearlite is dark, the excess ferrite and cementite are white, except in *E*, in which the pearlite occupies the whole figure, its cementite being white and its ferrite black.

With 0.50 per cent of carbon, there is a well-marked network of excess ferrite enclosing meshes consisting chiefly of pearlite, though laced through considerably with fine needles of excess ferrite, often well oriented. With 0.45 per cent of carbon the network of excess ferrite is thicker. With 0.22 per cent of carbon the excess ferrite now forms the greater mass, and the pearlite is reduced to islands in a sea of ferrite. With 0.035 per cent of carbon the pearlite is reduced to some thin scattered seams in a mass of ferrite.

With 1.20 per cent of carbon the 5 per cent excess cementite which should theoretically be present is represented by the fine white network, surrounding the dark meshes of pearlite. As the carbon rises to 1.46 and 1.80 this cementite network increases in thickness.

In the white cast iron, variety "washed metal," *J*, the black bat-like dendrites are "primary" austenite; i. e., that which froze out of the molten metal in cooling through region II. of Fig. 68. The faint white specks, shown better in the larger-scale micrograph *K*, are the cementite which formed within this austenite in cooling through region VIII., because of the decrease of solubility of cementite in austenite, as represented by the curve *SE*. The zebra-like ground mass in which this dendrite lies is the cementite-austenite eutectic which froze on crossing an imaginary line just below *aBc*. This line represents the freezing of a eutectic of austenite plus cementite, characteristic of white cast iron, instead of the eutectic of austenite plus graphite, characteristic of gray cast iron. Of this zebra mass, the white stripes are the eutectite cementite; the dark ones the eutectic austenite, which in further cooling to and past *PSP'* has changed into a mixture of excess cementite with pearlite too fine to be resolved by this magnification.

ing, be present as graphite, especially if the total carbon is high, *i. e.*, especially in case of the cast irons.

156. *Pearlite series.* — Most of the steel of commerce is of the pearlite series; and of this probably at least 95 per cent is hypo-eutectoid, *i. e.*, it contains less than 0.90 per cent of carbon, and it therefore consists of pearlite together with free ferrite as the excess-substance. This is true of all common structural steel such as eyebars, I-beams, angles, channels, steel columns, rivets, plates whether for girders, boilers, ships' hulls or other engineering purposes, railroad axles, tires and rails, fence and telegraph wire, sheet steel for tin plate, *etc., etc.* These all consist essentially of a mixture (1) of ferrite and cementite interstratified as pearlite, plus (2) an excess of free ferrite. The proportion of cementite and hence of pearlite which they contain is varied to meet their particular requirements. In general, the greater the need of ductility, the less carbon do they contain, and hence the less of the hard, brittle cementite; in other words, the greater is the percentage of the soft, ductile, free ferrite and the smaller the percentage of pearlite. On the other hand, the greater the strength and the higher the elastic limit needed, the more carbon do they contain, *i. e.*, the larger is the percentage of cementite and hence of pearlite, and the smaller is the excess of free ferrite.

The microstructure of this series, including hyper-eutectoid steel and white cast iron, is shown in Fig. 66.

The proportions of ferrite and cementite and also that of pearlite for the different parts of this pearlite series are given in Table 6, p. 184, and they are also indicated graphically in Fig. 65, p. 185.

157. *The graphito-pearlite or gray cast-iron series.* — Most of the cast irons used as such, *i. e.*, in the form of gray castings for engineering and indeed for industrial purposes in general, are of the second or graphito-pearlite series. Such cast iron generally contains in the neighborhood of 4 per cent of carbon of which some 2.00 to 3.50 per cent is present as free graphite, and the rest as cementite, or "combined carbon." Here belong all gray iron castings, whether for machinery, for piping, for columns, for girders, or other like purposes. In general the greater the need of softness to facilitate cutting to shape, or "tooling," and of malleableness to resist blows and ill-treatment, the smaller is the proportion of combined carbon and hence of cementite, and the

larger that of ferrite; in short the more closely does the ratio of cementite to ferrite approach that of the low-carbon engineering steels.

The iron founder usually looks at the other side of the question. As we cannot eat our cake and keep it, the less carbon is present as cementite the more must be present as graphite if the total carbon is approximately constant, as is usually the case. Hence the greater the softness and malleableness needed, the more graphite is usually present. Hence the founder regards graphite as a source of softness. But this is simply the opposite view of the same fact, and the whole subject is made much clearer if we look at the other side of the shield, and recognize that softness and malleableness are to be had by having the soft and malleable ferrite and the soft graphite instead of the hard, brittle cementite. From this point of view the whole matter is as clear as crystal; from the opposite it is foggy. (See §§ 327 to 332, pp. 431 to 437.)

Without here* developing this view at greater length, let us recognize clearly that, as the gray-cast-iron or graphito-pearlite series as a whole appears to be simply the pearlite or steel-white-cast-iron series plus graphite, so any individual gray cast iron is simply a metallic matrix of steel or white cast iron, as the case may be, in which flakes of a wholly non-metallic and as it were foreign body, graphite, are scattered.

158. This Conception Tested. — As this conception of matrix plus graphite is essential, we may here see how well it tallies with the grayness itself of this iron, by which we mean the grayness of its fracture. It usually contains some 4 per cent of carbon all told, of which perhaps 3 per cent by weight or about 10 per cent by volume is in the form of flakes of graphite of considerable size, often ⅛ of an inch across, existing within the iron as a nearly continuous skeleton. When such iron is broken, rupture, following the path of least resistance, travels along the weak faces of the flakes of graphite, instead of through the strong metallic matrix, with the consequence that in the fracture nothing but graphite is seen. But that the graphite which we now see is nothing but a veneering is readily shown by brushing one of these fractures with a wire brush. The flakes of graphite are quickly scraped off, exposing the whiteness of the metallic

*The Author has elaborated this subject in the *Proceedings of the American Society for Testing Materials*, II, p. 246, 1902.

matrix beneath, a whiteness to be sure still stained by the adhering traces of graphite, as our fingers after pencil-sharpening are still stained after we have blown away the powdered graphite shavings.

Of course interspersing a weak, foreign substance like graphite through a metallic matrix of steel must both weaken and embrittle that steel. Hence the relative weakness and brittleness of cast iron; against which are to be weighed, first, its greater cheapness, since all steels are the product of purifying cast iron and hence are more expensive than it; and further the cheapness with which, thanks to its fusibility, fluidity, and expansion when solidifying, it is cast into forms into which the more infusible steel can be cast only with difficulty, and can be forged or rolled only with great outlay of power, and of fuel for heating it to a forging heat.

159. The Austenite Series. — To this belong all forms of hardened, and of hardened and tempered steel, such as cutting tools, whether for cutting wood, metals or other substances, springs, dies, the points of armor-piercing projectiles, and the face of projectile-resisting armor.

As the pearlite and graphito-pearlite series increase in hardness and brittleness as their cementite or "combined" carbon increases, so does the austenite series as its carbon-content increases. Whence we may generalize and say that each of these three series increases in hardness and brittleness as its combined-carbon-content increases. But increasing carbon-content increases the hardness and brittleness of the austenite state far more than that of the pearlite state. Thus the hardness and ductility of low-carbon steel, say of 0.10 per cent of carbon is but slightly affected by sudden cooling; whereas steel of say 0.50 per cent of carbon, while it can be bent double without cracking when cooled slowly, *i. e.*, when in the pearlite state, yet when in the hardened, *i. e.*, suddenly cooled or austenite state it can take no appreciable permanent set before breaking. Fig. 67 illustrates this.

Much the same is true of the hardness proper, the resistance to abrasion and indentation. When slowly cooled, *i. e.*, in the pearlite state, the hardness of such steel is about what should be expected in view of its ductility. It is indeed harder under the file than low-carbon steel, but the difference is not a conspicuous one. But whereas very low-carbon steel when suddenly cooled is not appreciably harder than when cooled slowly, high-carbon steel (of say 1.25 per cent of carbon) when suddenly cooled is so hard as to scratch glass.

In short the hardening power, whether measured by the hardness or by the brittleness induced, increases with the carbon-content.

160. Uses of the Austenite Series. — Although there are very many and very varied uses for the austenite series, yet the actual quantity of metal used for most of them is relatively small, when compared with the enormous quantities of the pearlite and

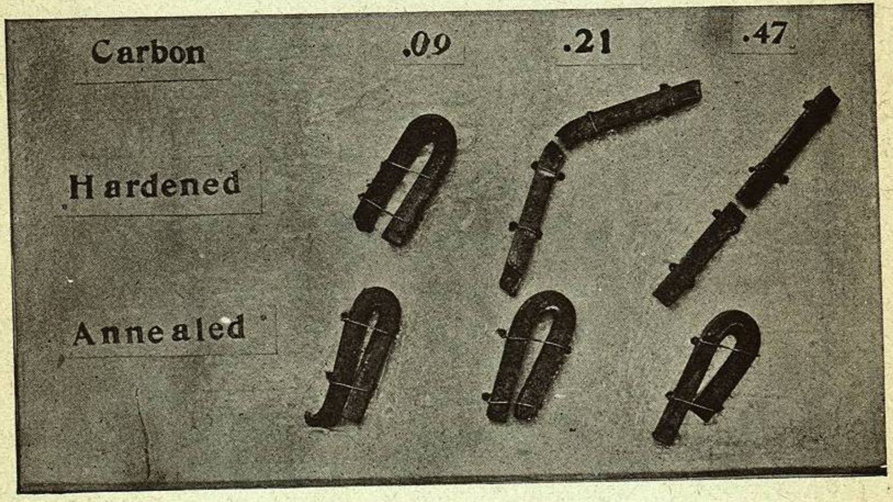
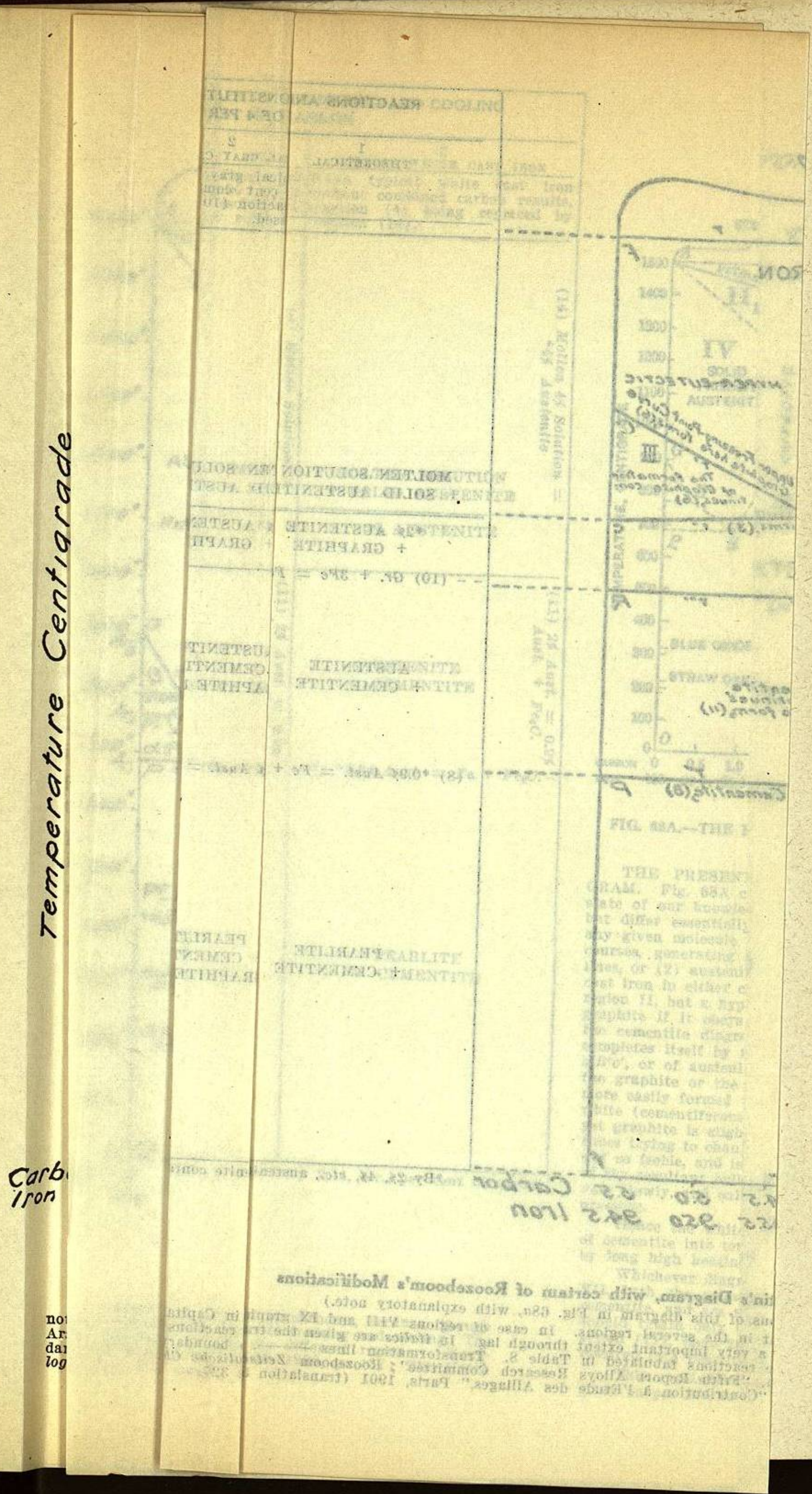


Fig. 67. The Hardening Power Increases with the Carbon-content.

graphito-pearlite series in use. Not only is the sudden cooling, upon which the preservation of the austenite state depends, in itself expensive because of the care which it requires, but the metal itself is brittle, both from its very nature and from the stress which the sudden and hence unequal cooling induces. Hence members of this series are in general used only where their hardness (cutting tools, dies, projectiles and armor) or their high elastic limit (springs) is indispensable; and in many cases the brittleness which accompanies this hardness has to be specially guarded against by putting only one part of a given object into this austenite condition, and uniting this brittle part



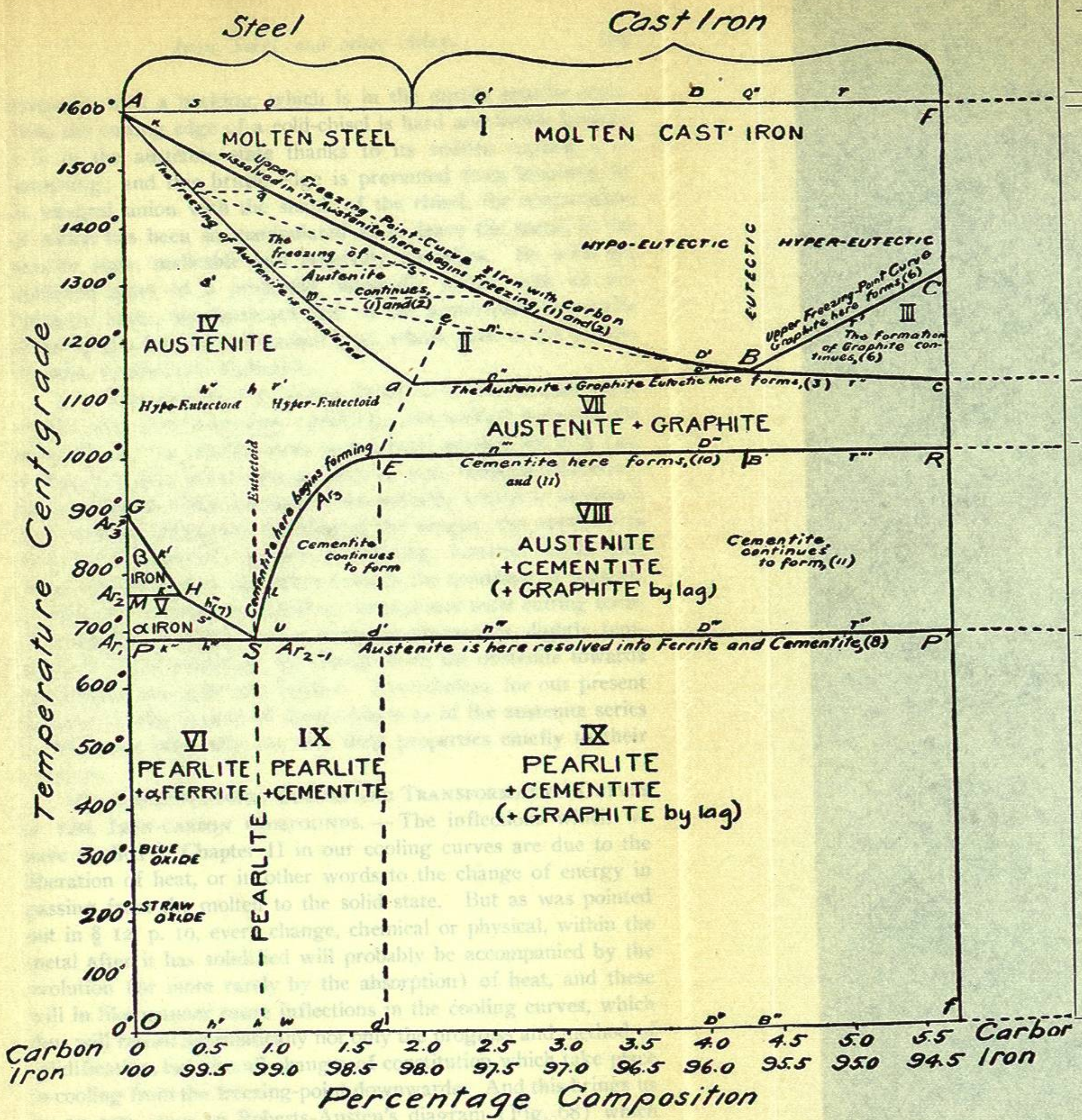


Fig. 68, Roberts-Austin's Diagram, with certain of Roozeboom's Modifications

(See modifications of this diagram in Fig. 68*a*, with explanatory note.)

Legend: In CAPITAL LETTERS are indicated the constituents theoretically present in the several regions. In case of regions VIII and IX graphite is also given in Capital Letters in parentheses, because, though not theoretically a normal constituent of either of these regions, it is habitually present to a very important extent through lag. In *italics* are given the transformations and reactions which occur in freezing and cooling. The Arabic numbers in parentheses following this italic lettering refer to the numbers of the reactions tabulated in Table 8. Transformation lines ———. (These are also boundary lines of the different regions.) Boundary and other lines which are not transformation lines – – –. *References:* Roberts-Austen, "Fifth Report Alloys Research Committee"; Roozeboom *Zeitschrift für physikalische Chemie*, XXXIV, 1900, p. 437; *The Metallographist*, III, p. 293; "Le Fer et l'Acier au Point de Vue de la Doctrine des Phases," "Contribution à l'Etude des Alliages," Paris, 1901 (translation by F. Osmond), p. 327.

REACTIONS AND CHANGES OF CONSTITUTION IN THE FREEZING AND COOLING OF CAST IRON OF 4 PER CENT OF CARBON

1 THEORETICAL	2 TYPICAL GRAY CAST IRON	3 TYPICAL WHITE CAST IRON
	When typical gray cast iron of 2.00 per cent combined carbon results, reaction (10) being wholly suppressed.	When typical white cast iron without combined carbon results, reaction (4) being replaced by reaction (14).
(4) *Molten Solution = *2% Aust. + Gr.*	(4) *Molten Solution = *2% Aust. + Gr.*	(14) *Molten 4% Solution = *4% Austenite*
MOLTEN SOLUTION + SOLID AUSTENITE	MOLTEN SOLUTION + SOLID AUSTENITE	MOLTEN SOLUTION + SOLID AUSTENITE
*2% AUSTENITE + GRAPHITE	*2% AUSTENITE + GRAPHITE	2% AUSTENITE
(10) *Gr. + 3Fe = Fe_3C*		
(11) *4% Aust. = 0.9% Aust. + Fe_3C.*	(11) *2% Aust. = 0.9% Aust. + Fe_3C.*	(11) *2% Aust. = 0.9% Aust. + Fe_3C.*
AUSTENITE + CEMENTITE	AUSTENITE + CEMENTITE (+ GRAPHITE by lag)	AUSTENITE + CEMENTITE
(8) **0.9% Aust. = Fe + Fe_3C.*	(8) **0.9% Aust. = Fe + Fe_3C.*	(8) **0.9% Aust. = Fe + Fe_3C.*
PEARLITE + CEMENTITE	PEARLITE + CEMENTITE (+ GRAPHITE by lag)	PEARLITE + CEMENTITE

*By 2%, 4%, *etc.*, austenite is meant, austenite containing respectively 2, 4, *etc.*, per cent of carbon.

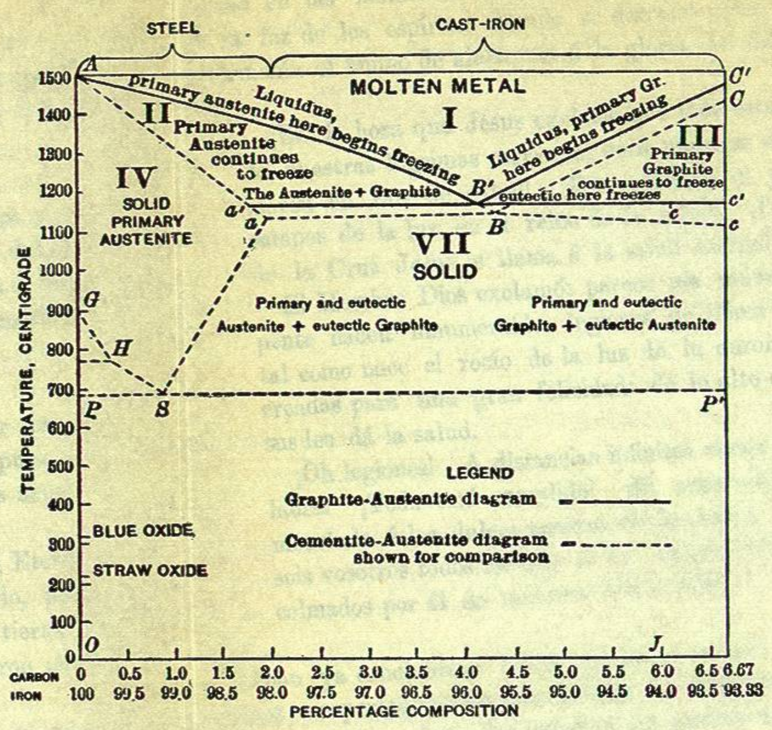


FIG. 68A.—THE PRESENT FORM OF THE CARBON-IRON EQUILIBRIUM DIAGRAM.

THE PRESENT FORM OF THE CARBON-IRON EQUILIBRIUM DIAGRAM. Fig. 68A corresponds much more closely than Fig. 68 to the present state of our knowledge. The two are alike in their left-hand, or steel, part, but differ essentially in their right-hand part. According to Fig. 68A, when any given molecule of molten cast iron freezes it has the choice between two courses, generating either (1) austenite and graphite, as shown in unbroken lines, or (2) austenite and cementite as shown in broken lines. A hypo-eutectic cast iron in either case begins freezing as primary austenite in cooling through region II, but a hypereutectic one in cooling through region III yields primary graphite if it obeys the graphite diagram, and primary cementite if it obeys the cementite diagram. So, too, whether hypo- or hypereutectic, its freezing completes itself by forming a eutectic of austenite + graphite on cooling past *a'B'c'*, or of austenite + cementite on cooling past *aBc*, according to whether the graphite or the cementite diagram is obeyed. Though cementite is rather more easily formed than graphite, so that quickly frozen (chilled) cast iron is white (cementiferous, p 279), while that slowly frozen is gray (graphitiferous), yet graphite is slightly the more stable of the two, so that cementite is at all times trying to change into graphite. *Fe_3C = Gr. 3 Fe.* But this effort is in itself so feeble, and is so far opposed by the internal pressure which the creation of the resultant bulky graphite sets up, that the graphitization takes place only very slowly, and only when the iron is so hot and soft as to yield easily to this pressure.

Hence the whiteness of chilled castings (p. 279), and the slow conversion of cementite into temper-graphite in making white cast iron gray and malleable by long high heating (p. 282).

Whichever diagram is obeyed, in cooling from *a'B'c'* or *aBc* through region VII, both the primary austenite and that of the eutectic gradually generate cementite, and are so impoverished in carbon till, on reaching *PSP'* (*ArI*) they should retain only 0.90% of carbon in solution and so become hardenite, (reaction (11), page 203). On cooling past *PSP' ArI*, this hardenite as usual is resolved into pearlite (reaction (7), p. 203).

This explanation of the transformations in cast iron should replace those given on pp. 276 to 282 and elsewhere.