

DECARBURIZATION AND WELDING  
OF GRAY CAST IRON

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science in Metallurgical Engineering.

Signed

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DECARBURIZATION AND WELDING  
OF GRAY CAST IRON

INTRODUCTION

In tonnage production gray iron exceeds all other cast metals combined. Its applications are many; it is used for parts in the production of automobiles, farm implements, mining machinery and transportation equipment and for pipe, pipe fittings, and flanges. The wide range of strengths in gray irons (from 20,000 to more than 60,000 psi) and its great damping capacity, plus manufacturing economy, explain the extensive use of gray iron where high resistance to dynamic stress is not a governing factor.

Although gray iron has such a wide field of use and is used in great quantities in comparison with other cast metals, no completely satisfactory method of welding it has yet been developed. Repairs may be made satisfactorily, if suitable care is taken and if the welder is well trained in the technique to be used.

The purpose of this paper is to report an investigation of welding gray iron by a method useable for fabrication of large assemblies made up of gray iron castings. The method consists of decarburization of the gray iron surface to be welded and welding by use of a mild steel rod.

Decarburization is accomplished by heating in partially burnt natural gas. The surfaces to be welded are prepared

before they are decarburized. The pieces are arc-welded by use of a coated mild-steel electrode.



### DECARBURIZATION

Decarburization is defined in the Metals Handbook<sup>1/</sup> as, "the loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with the carbon." Much is known about the mechanism of carbon removal and the resulting structures, but there are still some points for which there is no proven explanation. Baukloh and Knapp,<sup>2/</sup> in discussing the use of dry hydrogen for decarburization give a good explanation of the mechanism and resulting structure, which is summarized in the following paragraph.

Carbon removal first occurs when the reacting medium comes in contact with the carbon in solid solution at the surface of the alloy. At temperatures below 750°C (1350°F) the iron produced from the initial reaction interferes with the further contact of the hydrogen with the carbon and forces the hydrogen to diffuse. As long as the diffusion of the reacting medium is slower than the reaction itself, the rate of diffusion governs the speed of the reaction, and is dependent upon the temperature, carbon content, and concentration of reacting medium, which are the factors governing the rate of diffusion. Above 750°C (1350°F) the rate of diffusion of carbon is greater than the rate of the reaction, and the slower process is the reaction itself, which takes place at the surface according to the conditions of equilibrium.

If the iron contains carbon in the form of graphite as well as in the combined form, the carbon in the form of graphite will go into solution to replenish the carbon in solution as it is removed, providing the temperature is in the austenitic region. If the temperature<sup>2/</sup> is less than the critical temperature, the graphite flakes will be left intact in a ferrite matrix in the decarburized zone.

Three main zones result from decarburization. Progressing from the surface toward the core, first is a layer essentially free of carbon, which at room temperature appears as ferrite; after that is a zone of varying carbon content increasing in carbon toward the core; and last is the core consisting of the original material. A general description of the mechanism and effects of decarburization has been given, and now some of the methods of decarburization and their related theories will be discussed.

#### METHODS OF DECARBURIZATION AND THEIR RELATED THEORIES

Many methods of decarburization have been used in the past. Some of the methods were used for the heat treatment of white iron castings, and others were used in the laboratory for the study of the effects of decarburization on various iron-carbon alloys. The decarburization of white iron castings has received much attention in the past, because of the great deal of laboratory work done to develop gaseous annealing for use in the production of malleable iron castings.

### Ore Process

The ore process was developed for the heat treatment of white iron castings for the production of malleable iron castings. The process consists of packing the castings, together with a mixture of hematite ore, into cast iron cans, which are sealed and charged into the annealing furnace. Ivor Jenkins<sup>3/</sup> explains the mechanism of decarburization as follows: "Decarburization during annealing in iron ore is due to reactions at the surface of the cast iron with gases generated inside the can. It has been shown that carbon removal is quite effective if the castings are separated by a space from the ore. The main decarburizing agent is carbon dioxide which is probably produced initially by reaction between air entrapped in the annealing can and carbon in the surface of the white iron. The carbon dioxide thus produced will react with the carbon in solution in the iron to produce carbon monoxide. The reducing gas, carbon monoxide, being generated at the surface of the iron is then free to reduce the iron ore present, and thus conversion back to carbon dioxide is effected, and the cycle of decarburization-oxide reduction maintained."

Jenkins goes on to say, "During the anneal, furnace flue gases penetrate through the permeable luted seal into the can so that the composition of the atmosphere surrounding the castings varies somewhat. If these gases are the products of complete combustion they will comprise, in the

main,  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{N}_2$ , and probably free oxygen, and will serve as regenerating agents for the CO being produced in the can, and will, momentarily at least, affect the course of the gas-solid reactions, depending upon the stage at which they enter. If this occurs when decarburization is still active, then the net result will be to hasten decarburization; if it is towards the end of the anneal, when the carbon concentration at and near to the surface of the iron is low, then oxidation and possibly oxide penetration may result.

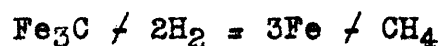
"On the other hand, if the flue gases are products of incomplete combustion, the above effects will not be so severe, and in the extreme cases could have quite the reverse effect where the gases are so highly reducing that some recarburization might result, especially on castings near to the point where the gases enter the can."

The ore process of decarburization was used by Ping-Chao Chen<sup>4/</sup> in his investigation of the possibilities of welding gray cast iron after decarburization. He found that scaling was bad, which reduced the amount of decarburization, and also that scaling increased with increased temperature and time. Chen suggested that perhaps a better luting material might be used. In view of Jenkins' findings, however, it might be easier and more advantageous to control the combustion reactions in the furnace.

#### Hydrogen Atmosphere

The chemical reaction involved in the decarburization

of iron carbon alloys proceeds in a similar manner regardless of the medium used. The chemical reaction involved in the decarburization by use of hydrogen is:



Baukloh and Knapp<sup>2/</sup> give the following explanation of the mechanism of decarburization by the use of hydrogen. "It is to be noted here that the  $\text{Fe}_3\text{C}$  does not occur in the free state but is distributed in greater or smaller proportion as a structural constituent of the iron (below the critical temperature). This fact serves to explain why it is that the hydrogen, once it has dissolved the carbon out of the surface of the iron, is forced to diffuse through the latter in order to continue to react with the carbon. Moreover, the methane which is produced can escape from the site of reaction only by diffusion. Hence, so long as the rate of diffusion of the reacting substances is small in comparison with that of the actual process of reaction, the former will be the slower process and will determine the rate of the reaction itself. But the mobility of the reacting constituents in the iron increases with rising temperature whilst the ability of the hydrogen to react with carbon diminishes. In particular, the rate of diffusion of carbon increases very rapidly between  $800^\circ\text{C}$  ( $1440^\circ\text{F}$ ) and  $900^\circ\text{C}$  ( $1620^\circ\text{F}$ ). It follows that above these limits of temperature the course of the reaction is determined no

longer by the diffusion but by the reactivity itself, the reaction taking place no longer within the material but on its surface, and the carbon removed by the hydrogen being replenished from within the core of the specimen."

Baukloh and Knapp<sup>2/</sup> state that when decarburization with hydrogen takes place below 720°C (1300°F) a ferritic boundary layer is formed containing lamellae of graphite. "Here the reaction between the hydrogen and graphite is very weak, with the result that the lamellae of graphite are maintained intact.

"Above the critical temperature the diffusion of carbon is more rapid than the rate of reaction between the carbon and hydrogen and the equilibrium can continuously be maintained from within the solid body and the reaction will occur only at the surface." When this condition exists the authors above state, "The diffusion of hydrogen is then no longer of any importance, and the mechanism of the reaction becomes a question of the chemical equilibrium between the individual reactants in the presence of iron at a given temperature. The significance of this lies in the fact that up to about 850°C (1530°F) the effect of hydrogen upon carbon-bearing iron is to form a ferritic boundary zone, or a transition zone with an increasing carbon content, whereas at higher temperatures the effect is one of uniform decarburization of the solid material throughout the whole cross-section."

Figure 1, 2, and 3 are adopted from Baukloh and Knapp. Figure 1 indicates the relationship between the reduction of carbon content and temperature for steels of different carbon content. Figure 2 shows the relationship time versus percent decarburization. Figure 3 shows a threefold relationship for original carbon content, temperature, and thickness of ferritic boundary layer, for different hydrogen pressures. It may be seen from this graph that the temperature range of the ferritic boundary zones decreases as the carbon content increases at pressures of 20 and 40 atmospheres. At 60 atmospheres the reaction between carbon and hydrogen is so intense that the ferritic boundary layer occurs even at higher temperatures. It also may be seen that as the carbon content increases, the thickness of the boundary layer decreases and decarburization is less. Baukloh and Knapp included in their work a discussion of the effects of decarburization of gray iron, but their experimental work was conducted using steels.

J. Bernstein<sup>5/</sup> found the structure shown in Figure 4 after decarburizing gray cast iron in dry hydrogen. The specimen was annealed 100 hours in dry hydrogen at 1000°C (1800°F). He states, "Some decarburization occurred at the surface, and in the adjacent zone the flake graphite structure had been replaced by very fine nodular graphite. The center of the section had the normal flake graphite structure.----In some areas these nodules appeared to

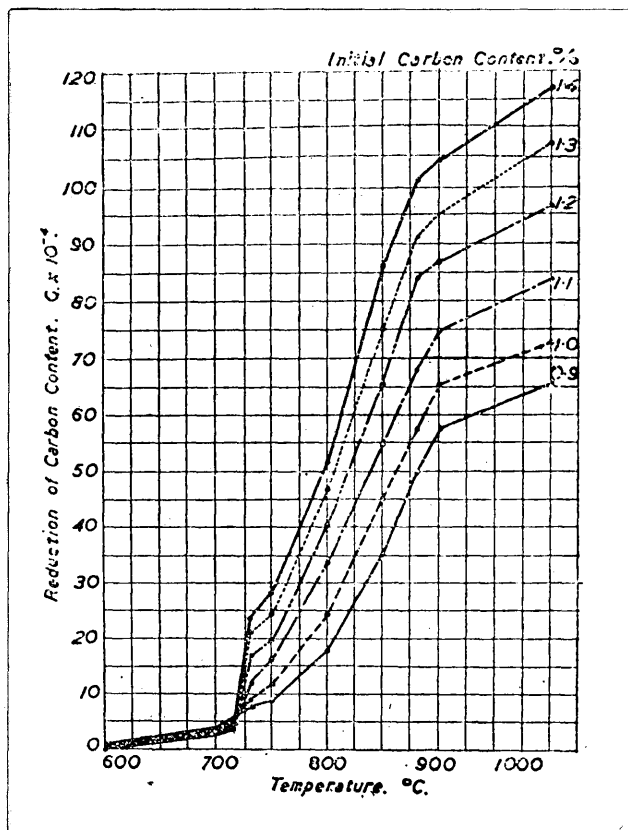


Figure 1--Reduction of carbon content in the original material in relationship to the temperature. (time of experiment, 7 hours; original carbon content, 0.9-1.4%.)



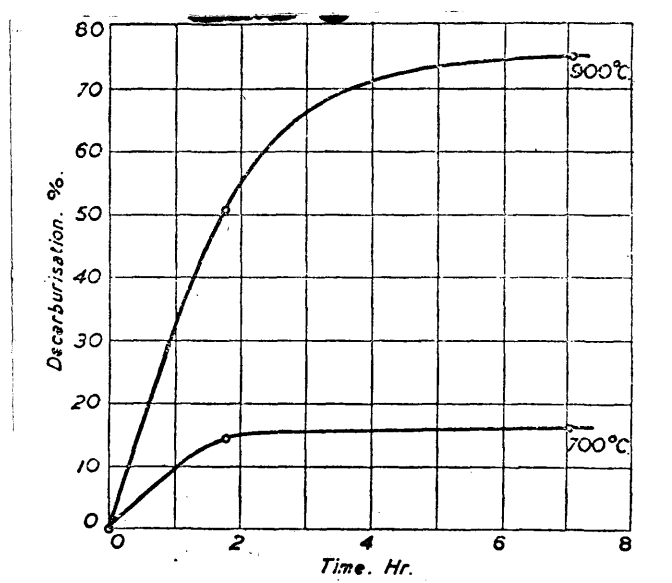


Figure 2--Percentage decarburization in relation to time.

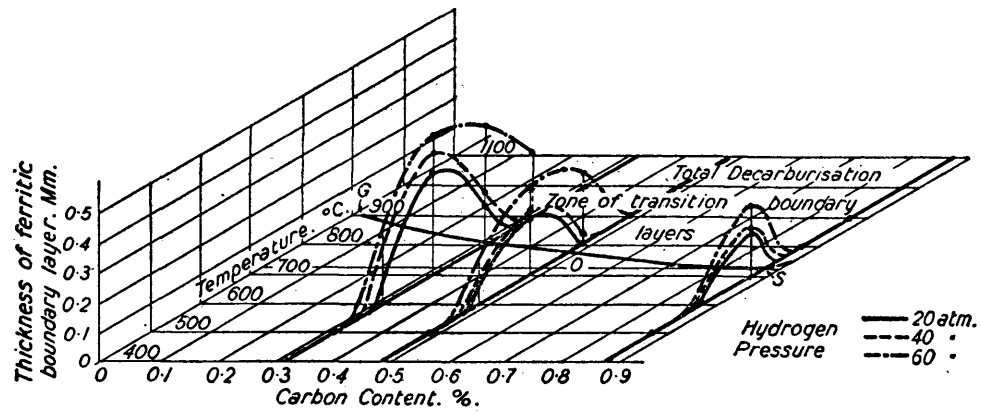


Figure 3--Formation of boundary layers in relation to the temperature and carbon content, for hydrogen pressures of 20, 40, and 60 atmospheres. (Duration of experiment, 3 hours.)



Figure 4--Structure of gray-iron specimen annealed for 100 hours at 1000°C (1800°F) in pure dry hydrogen. 60X (picric acid etch.)

consist of remnants of graphite flakes upon which further precipitation of graphite had taken place during the anneal.----Chemical analysis confirmed that little decarburization had taken place."

In other experiments on decarburization of white iron, Bernstein found that pure dried hydrogen has a limited decarburizing effect. Figure 5 shows the curves obtained when the rate of decarburization, expressed in terms of grams per square meter of surface of the sample per hour, has been plotted against the time of annealing. He says of these, "The curve for moist hydrogen is typical of that obtained where decarburization is effected by a surface reaction the rate of which is controlled by a diffusion process. The curves obtained for annealing in dried hydrogen show that decarburization under these conditions is an extremely slow process which tends to become slower with increasing time."

Decarburization by the use of hydrogen has the advantage that the iron does not become oxidized, but this is relatively unimportant in view of Bernstein's work showing that hydrogen is a very poor decarburant.

#### Hydrogen/Water-Vapor Atmosphere

From the preceding discussion and Figure 5 it may be concluded that the hydrogen/water-vapor atmosphere is much superior to the pure dry hydrogen atmosphere. The chemical

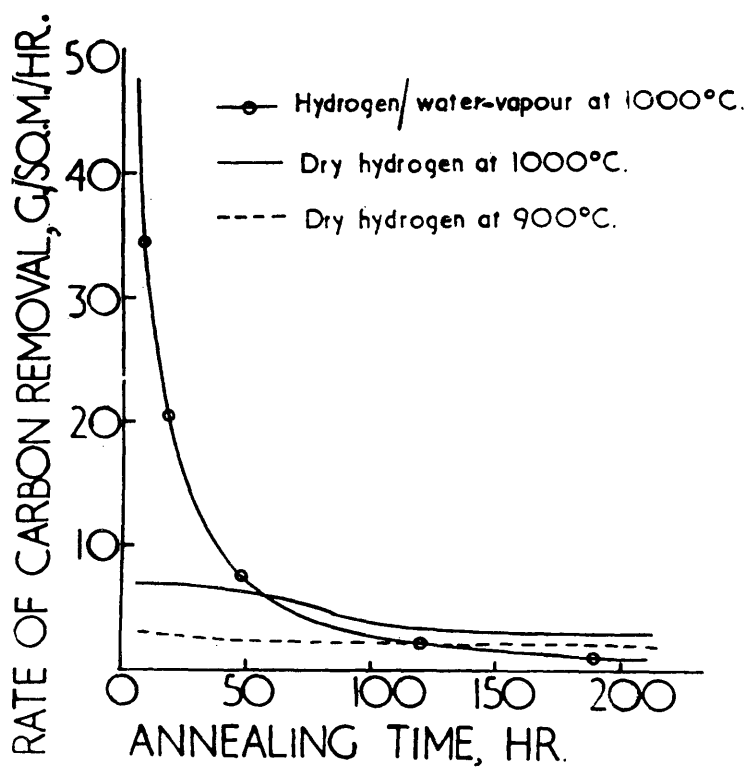
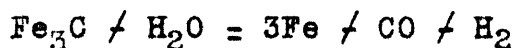


Figure 5--Rate of decarburization of white iron in dry hydrogen and in hydrogen/water-vapor atmospheres.

reaction involved in this process is:



The presence of even small amounts of water-vapor in hydrogen accelerates the decarburization many fold. The main difficulty when decarburizing with oxygen, water-vapor, or carbon dioxide is the oxide scale, which forms a layer through which the oxidizing gases diffuse very slowly. Hydrogen is very important in the decarburization, as it serves to keep the surface of the iron free of oxide scale so that the water-vapor may come in contact with the carbon and react.

Figure 6 shows the result obtained by J. Bernstein<sup>5/</sup> in decarburizing gray-iron, having the same composition as that used in Figure 4, in moist hydrogen. The composition of the iron used in his experiments is nearly the same as that of the iron to be used in the experiments cited in this paper. The structures obtained were very complex.

Bernstein states, "This is taken from a sample annealed for 100 hours at 1000°C (1800°F). The outer zone consisted of ferrite with an oxide phase replacing the original pattern of graphite. This was followed by a zone containing a mixture of ferrite and pearlite in increasing amount, and then by a relatively deep zone containing fine graphite nodules in a matrix of pearlite. Following this the normal gray-iron structure was obtained."

Since the hydrogen/water-vapor and the carbon

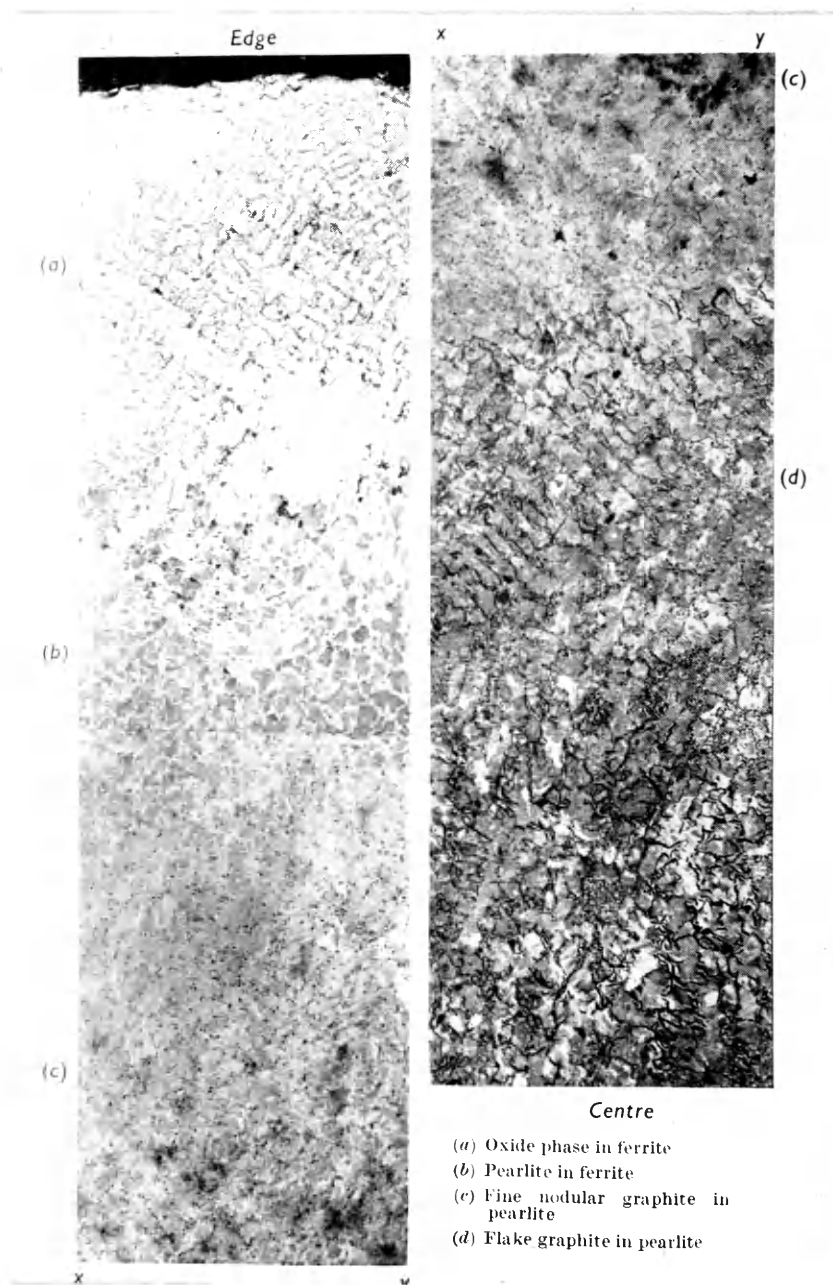


Figure 6--Structure of gray-iron specimen annealed for 100 hours at 1000°C (1800°F) in a hydrogen/water-vapor atmosphere. 60X Micrograph cut at x-y and reduced two-thirds linear in reproduction. (4% picric acid etch.)

monoxide/carbon dioxide atmospheres are so alike in their reactions and mechanism of decarburization, further discussion will be included with that of carbon monoxide/carbon dioxide.

#### Carbon Dioxide/Carbon Monoxide Atmosphere

In the ore process earlier described, decarburization was actually accomplished by a gaseous atmosphere; therefore it is to be expected that decarburization could take place if a suitable mixture of carbon dioxide and carbon monoxide were introduced from an outside source into a chamber containing the hot iron casting. The overall heating and cooling cycle could be reduced considerably because the solid mass to be heated would be greatly reduced. A British patent<sup>3/</sup> was issued as long ago as 1897 for the decarburization of cast iron by carbon dioxide.

A later method for malleablizing cast iron entailed heating the castings in a closed muffle. The atmosphere consisted of air diluted with carbon monoxide-rich cooled gases formed in the muffle. The oxygen effected the decarburization; the carbon monoxide was added to control the oxidation of the carbon and to prevent that of the iron. The lack of annealing equipment which would ensure the necessary control over the process prevented the use of the above methods.

The recent advances in furnaces and control apparatus and the development of processes for the heat treatment of

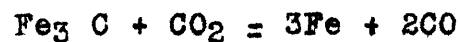


both ferrous and non-ferrous metals in a prepared atmosphere, allow excellent control of the surface characteristics of the charge during the heating operation.

The most active decarburizing agents are water vapor and carbon dioxide. To prevent oxidation of the iron, suitable quantities of hydrogen and carbon monoxide should be present in an atmosphere.

The mechanism of decarburization of iron-carbon alloys at annealing temperatures has been discussed rather fully, but there are some qualities peculiar to carbon dioxide/carbon monoxide and hydrogen/water vapor atmosphere that should be discussed.

The reaction involved in the removal of carbon in iron by carbon dioxide is:



At the temperature of annealing, the diffusion of carbon in iron is more rapid than the reaction taking place at the surface; therefore the rate of reaction controls the rate of decarburization.

D. Polder<sup>6/</sup> found by calculation that at 910°C (1640°F) the rate of diffusion of carbon in alpha iron is 2.8 times as great as that in gamma iron, and at temperatures slightly below this the ratio is even greater. This would indicate that a temperature slightly below 910°C (1640°F) would be a very good annealing temperature.

Figure 7 is a reproduction of curves presented by Ivor

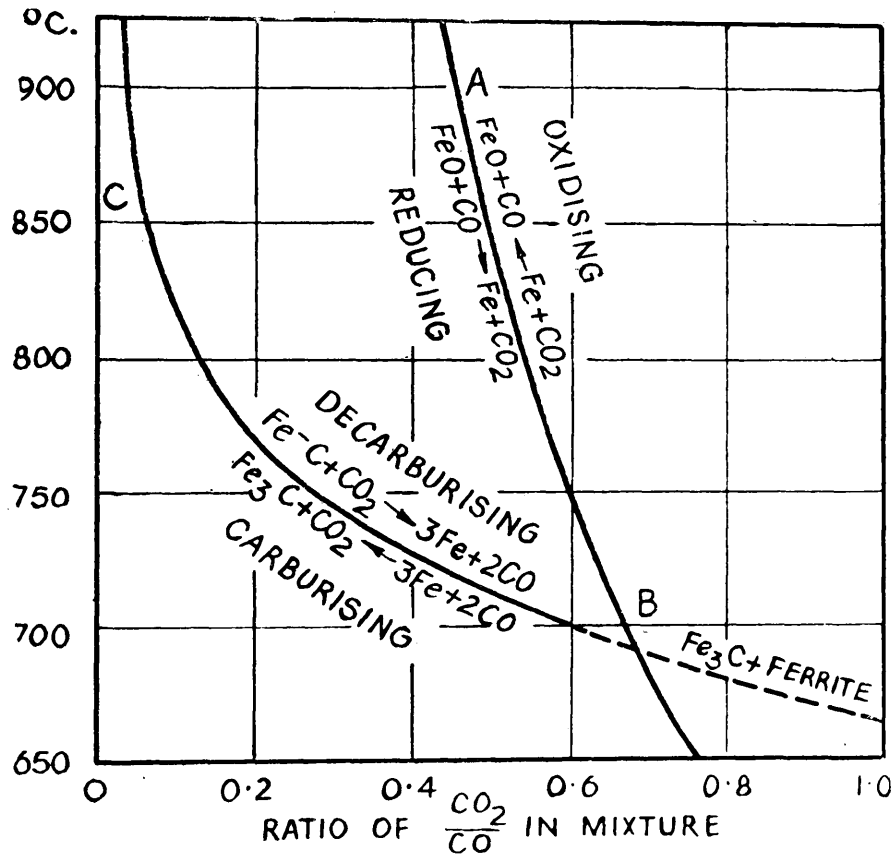


Figure 7-- $\text{CO}_2/\text{CO}$  ratios for oxidation, reduction, carburization, and decarburization.

Jenkins<sup>3/</sup>. These curves indicate the  $\text{CO}_2/\text{CO}$  ratios for oxidation, reduction, carburization, and decarburization. The area included between the two curves is the area in which decarburization takes place but not iron oxidation at various temperatures.

It is to be expected that carbon loss from a gray iron will be greater than that from white iron, all annealing conditions being identical, because of the greater carbon content. This, however, is not always the case. The greater the combined carbon (a more easily oxidized form than graphite), the greater will be the loss of carbon. Another factor governing the amount of carbon removal is the silicon content; as the silicon increases, the amount of carbon removal decreases, and with high silicon contents practically no carbon removal will result from annealing. Hatfield<sup>2/</sup> states, "Here is interesting proof that free carbon does not oxidize unless it has first recombined with the iron. Silicon reduces the solubility of carbon in iron, and hence the fact that with increasing silicon content the loss of carbon decreases." These conclusions were verified in this research.

#### Equipment for Gaseous Annealing

Gaseous annealing has the advantages that the time at the maximum annealing temperature required for a given degree of decarburization is reduced, the overall annealing time is less, and castings cooled in the controlled

atmosphere exhibit a clean, oxide free surface, slightly matte-finished, because of surface break-up caused by decarburization.

The principle of the annealing of cast iron by the modern gaseous process is explained by Ivor Jenkins<sup>3/</sup> as follows: "The atmosphere discharged from the annealing furnace is rich in hydrogen and carbon monoxide. If both of these gases are partly re-converted to water vapor and carbon dioxide, respectively, by controlled combustion with an oxidising gas whilst still retaining a mixture non-oxidising to iron, they can then be returned to the furnace and the cycle of operations repeated indefinitely. Theoretically it would be necessary to commence only with the quantity of gas initially present in the chamber. Any moderate leakage of gas will be compensated for by the increase in volume resulting from the decarburising reaction. A logical step from this stage is to dispense entirely with a prepared controlled atmosphere and to allow the charge of castings to generate its own initial atmosphere by reaction between the furnace gases and the carbon in the iron, and then to circulate and regenerate the reducing gases thus produced by the controlled addition of an oxidising gas."

The ore process is in itself regenerative. In the above described method the ore is replaced by an outside supply of oxygen. Circulation of the spent furnace gases can be carried out either externally or internally. An internal circulation method is more economical because of

Decreased heat loss. Circulation may be accomplished by a high-speed fan which has the added advantages of thoroughly mixing the oxidizing gas with the furnace atmosphere and of uniform circulation through the charge.

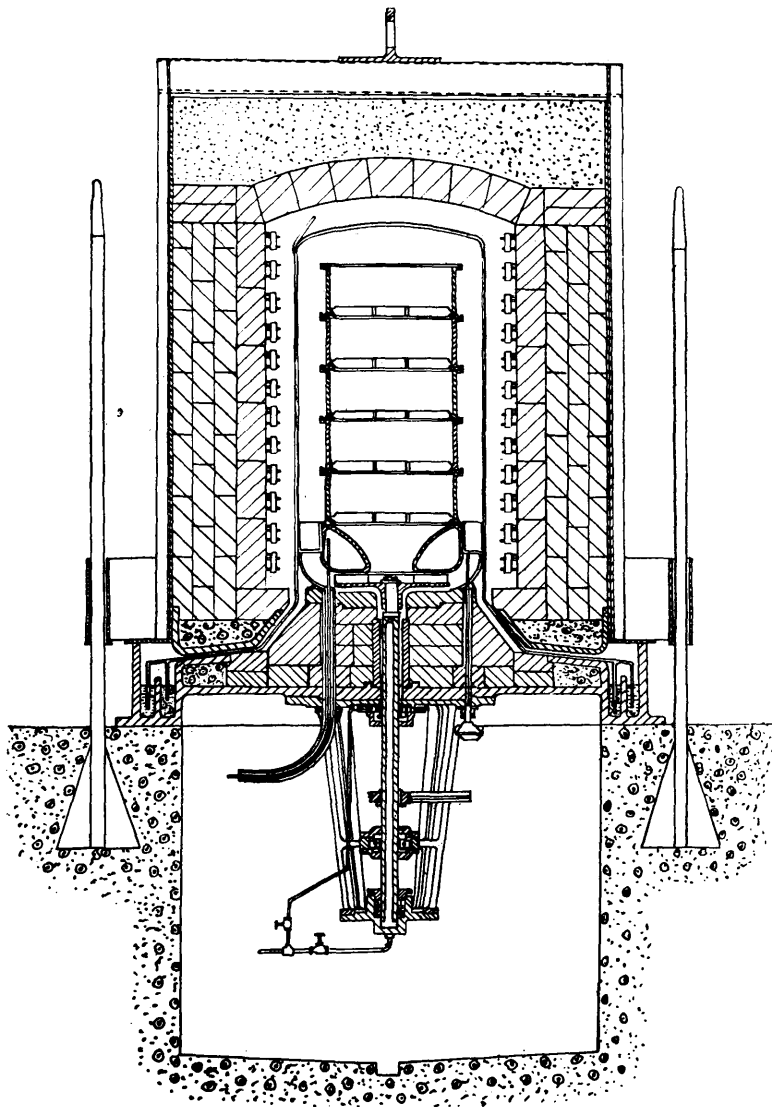
Either air or steam may be added for regeneration of the furnace atmosphere. Air has the advantage of low cost, since the only cost is that for the power required to run the blower. In contrast to this, steam, which must be generated from water, requires an added expense for heat, which cost is further increased since the water-vapor carbon reaction is endothermic. The steam regeneration process has many advantages, however, in that the nitrogen content of the atmosphere, theoretically at least, will never be greater than the quantity of nitrogen resulting from the air originally in the furnace chamber. The atmosphere, virtually undiluted by any inert gases, is a mixture of active gases including carbon dioxide, carbon monoxide, hydrogen, and water-vapor. This allows operation with a higher concentration of decarburizing gases without danger of oxidation of the iron.

The cost of producing the steam may be greatly reduced by removing a small portion of the reacted atmosphere from the annealing chamber, for combustion in a small boiler, because the gas generated from the reaction between steam and the carbon produces a high grade water gas which has a very high calorific value.

A description of the operation of the equipment used for atmosphere regeneration as taken from Ivor Jenkins<sup>3/</sup> is as follows: "A typical furnace designed for the treatment of thin-section work is shown in Figure 8. The furnace is of the vertical cylindrical type with a fixed hearth, on which rests an open cast stool, supporting trays having perforated bases and loaded with castings. The whole is contained in a lightweight heat-resisting steel shell, the lower flanged end of which rests in a double-ring seal, one ring being of sand and the outer of oil. An electric furnace is dropped over the bell.

"Circulation of the atmosphere inside the bell is effected by means of a high-speed centrifugal fan located below the bottom tray and driven via a cooled shaft. The furnace gases are drawn down through the trays and thrown outwards to mix with the incoming air or steam which is introduced through the hearth, and the whole then passes up the annulus between the bell and the trays and then down through the charge. The temperature of the latter is indicated by means of a thermocouple passing through the hearth and in contact with the bottom tray. The furnace has a separate pyrometer which controls the annealing cycle and temperature through suitable relays and switchgear, etc.

"Provision is made for the periodical extraction of a sample of gas from the annealing chamber, and the proportion of carbon dioxide, the only gas that need be determined to



[Courtesy of The General Electric Company, Limited

Figure 8--Malleabilizing furnace (vertical cylindrical type.)

control the process, is registered on an automatic gas-analysis recorder. In the case of steam regeneration, auxiliary gear includes a small boiler for generation of the steam, heated by waste gases from the annealing chamber, the steam being preheated by excess gases discharged from the furnace. For air generation, only a blower and flow gauge, with an appropriate control valve, are required."

Although most of the discussion presented to this point has concerned white iron, it is applicable to gray iron also since the difference between the two is principally in the carbon form and content.

In white iron the early part of the anneal causes graphitization; whereas in gray iron graphitization has already taken place. The primary structure of gray iron is graphite and pearlite, which often has small amounts of ferrite and/or cementite in it. Above the critical temperature austenite is found, increasing in quantity as the temperature is raised and as more graphite is dissolved to maintain equilibrium at that temperature. As decarburization proceeds, there is diffusion of carbon from the carbon-rich interior to the surface, and more graphite dissolves to maintain the equilibrium conditions of maximum solid solubility. The rate of solution of graphite in austenite, in gray iron, however, is much slower than the rate of solution of cementite in austenite, in white iron.

The gaseous annealing equipment used for white iron



should be very applicable to decarburization of gray iron in view of the fact that very close control may be maintained over the process.

Professor M. C. Smith of the Colorado School of Mines suggested a much simpler method in which a gas fired furnace would provide not only the heat for annealing, but also the atmosphere for decarburization. John Dow<sup>8/</sup> found in his work that an air/gas ratio of less than 4 to 1 is noncombustible. In Narayan's<sup>9/</sup> work and also in the author's work it was found that an air/gas ratio of less than 4 to 1 is necessary to obtain decarburization. For this reason a modification of the original idea will be necessary.

A suggested modification is to use only a portion of the hot burnt gas and add natural gas to it to obtain the desired carbon dioxide/carbon monoxide ratio. The reacted gas from the annealing chamber could then be returned for combustion in the furnace.

With the principles of various media, used for decarburization of iron-carbon alloys, before use, and an idea of the operation of equipment used for decarburization given, we now turn to a discussion of the experiments performed.

#### GRAY IRON DECARBURIZATION EXPERIMENTS AND DISCUSSION

The thesis written by S. N. Anant Narayan<sup>9/</sup> was used as a basis for experiments on the decarburization of gray iron. In this work, air and natural gas were passed into a tube for combustion and the exhaust gases passed into an

annealing furnace containing the iron specimen. The heat treatment consisted of heating the iron for 8 hours at 1000°C (1800°F) in an atmosphere consisting of the products of combustion of air and gas in the ratio of 3.5 to 1.

### Equipment

A picture of the decarburizing equipment, as used at the end of the experiments, is shown in Figure 9. At first compressed air from the laboratory supply line was used, but the fluctuation of the air supply was far too great for close control. Later the Cenco-Pressovac 4 pump was obtained and installed with a surge bottle to smooth out surges caused by the stroke of the pump. Control of the air flow was accomplished by means of a pinch cock on the bleed-off hose.

Control of the natural gas flow was maintained by manual adjustment of the outlet valve. The air and gas flow was measured with U-tube flow meters filled with a slightly acidified aqueous solution containing a few drops of methyl-orange indicator. The flow meters were calibrated in cubic feet of water displacement per minute. To measure the difference in the height of the water column, the back was scaled off in centimeters. The graph of cubic feet per minute versus the height of the water column in centimeters is given in Figure 10 for gas and Figure 11 for air.

The gas and air were mixed and burned in an alundum tube

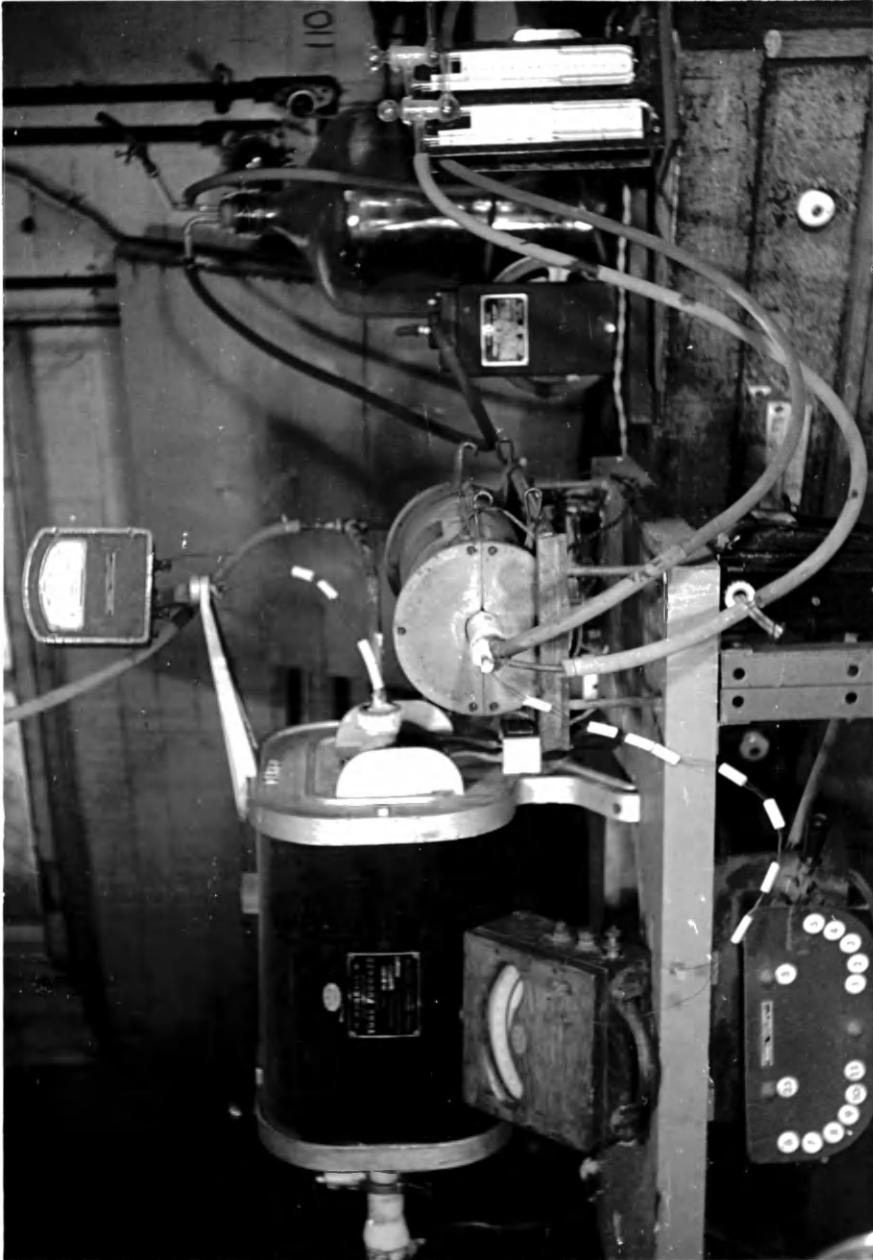


Figure 9--Photograph of decarburizing equipment.

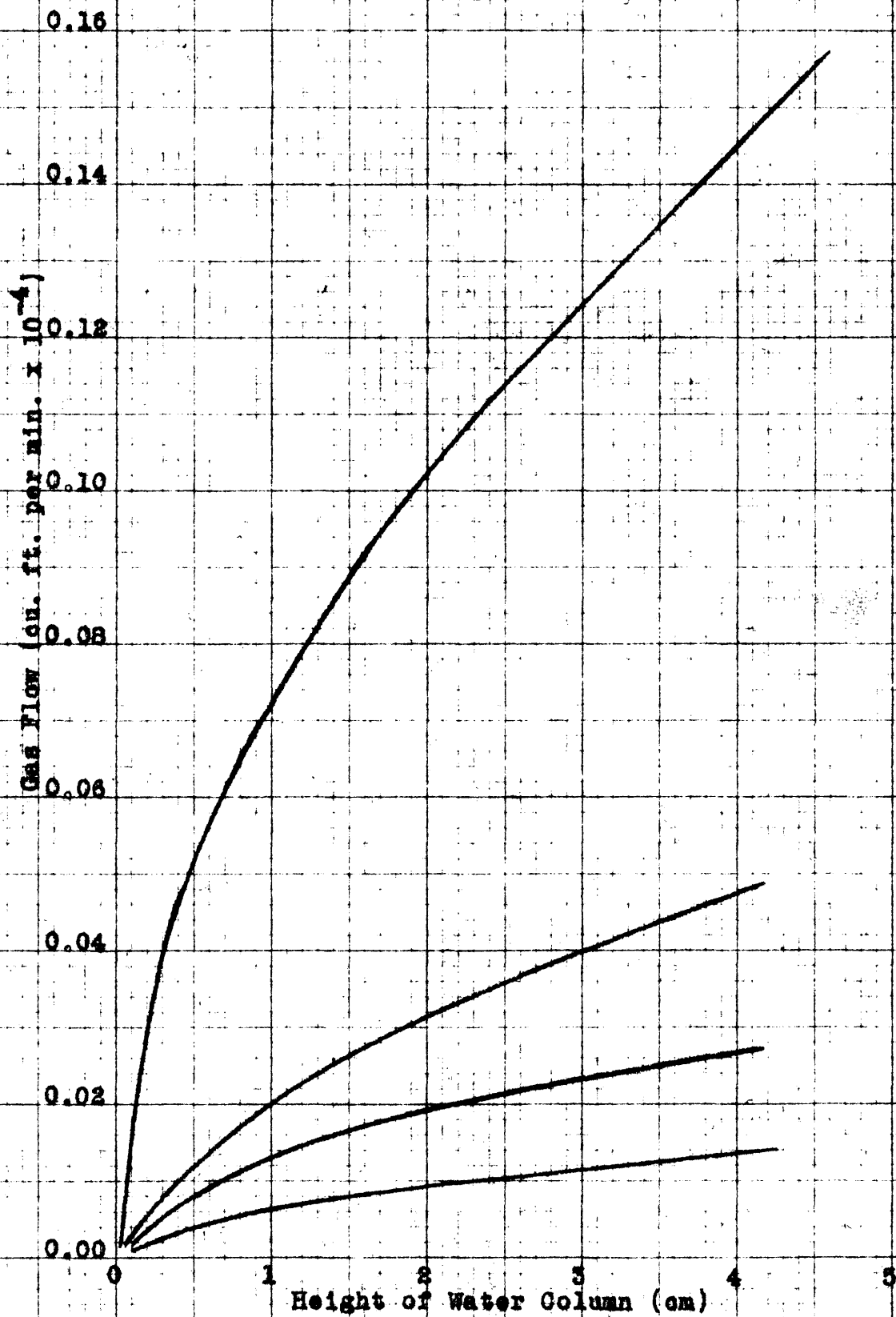


Figure 10--Calibration of Air Flowmeter

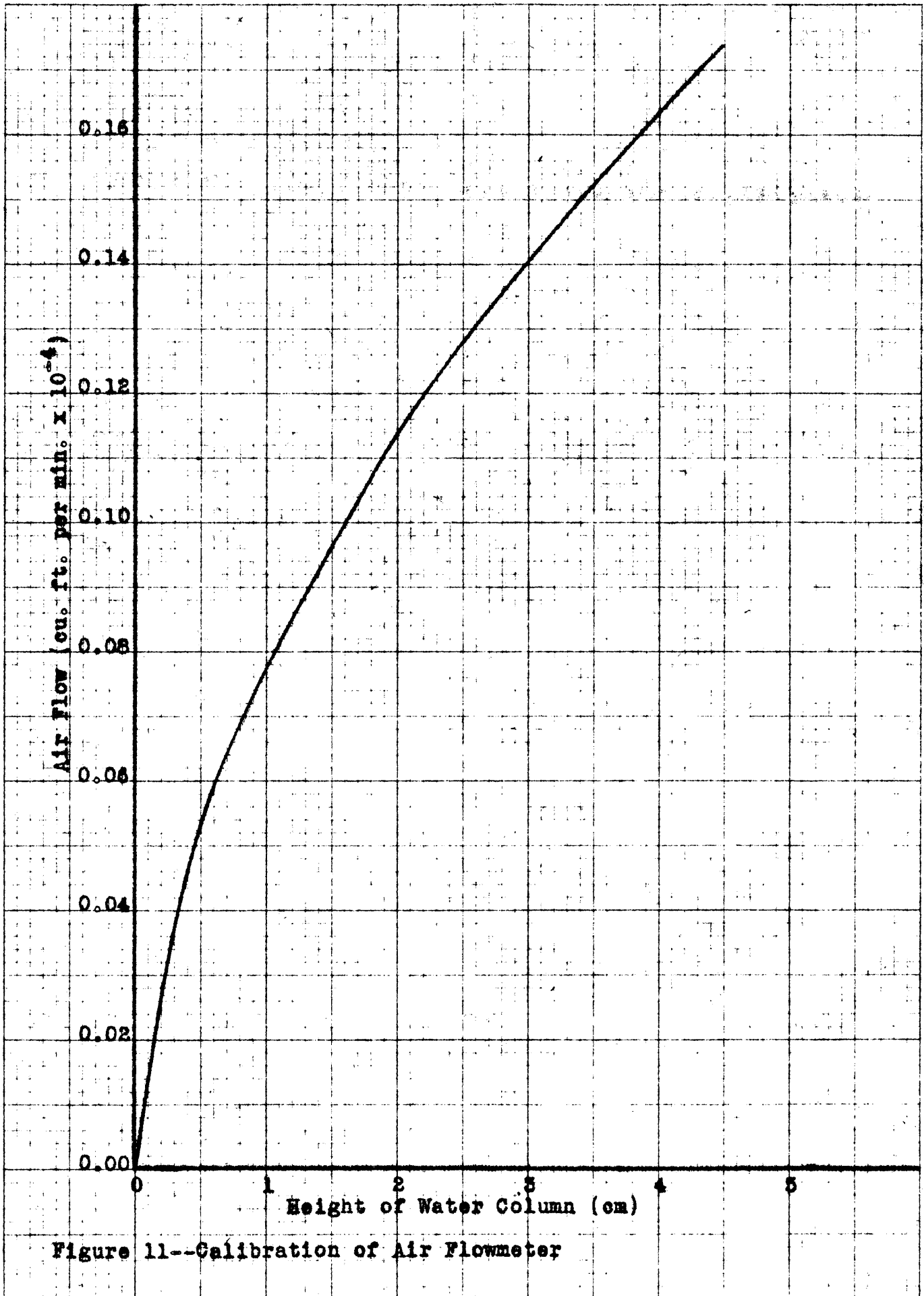


Figure 11--Calibration of Air Flowmeter

that was heated in a multiple unit electric tube furnace with a rheostat manual control. Steel plugs were machined to fit the tube. These plugs were drilled to allow for gas inlet and outlet by means of copper tubing brazed to the plug. Plaster of paris mixed with a very dilute solution of acetic acid was used to lute the plugs in place. (A much harder and stronger material is obtained with the addition of the acetic acid.) A piece of chromel wire was wadded into a loose ball and placed in the combustion tube to aid in heating the gas throughout the cross-section to aid combustion.

The copper lead from the combustion furnace was brazed to a tee joint. One lead from the tee joint was used to obtain samples of the burnt gas, while the other lead, also of copper, was used to conduct the atmosphere to the annealing furnace, and was connected to the alundum tube of the annealing furnace in the manner previously described.

A Burrell high temperature furnace, with transformer control and carborundum heating elements, was used for annealing. The exit gases were burned in a bunsen burner. The temperatures of the atmospheres in the two furnaces were indicated by direct-reading millivoltmeter-type instruments with chromel-alumel thermocouples sealed inside the tube.

The burnt gas was analyzed with a Burrell Premier Model VB gas analyzer, Figure 12. This apparatus is fully described in "Methods of the Chemists of the U. S. Steel

## BURRELL PREMIER MODEL

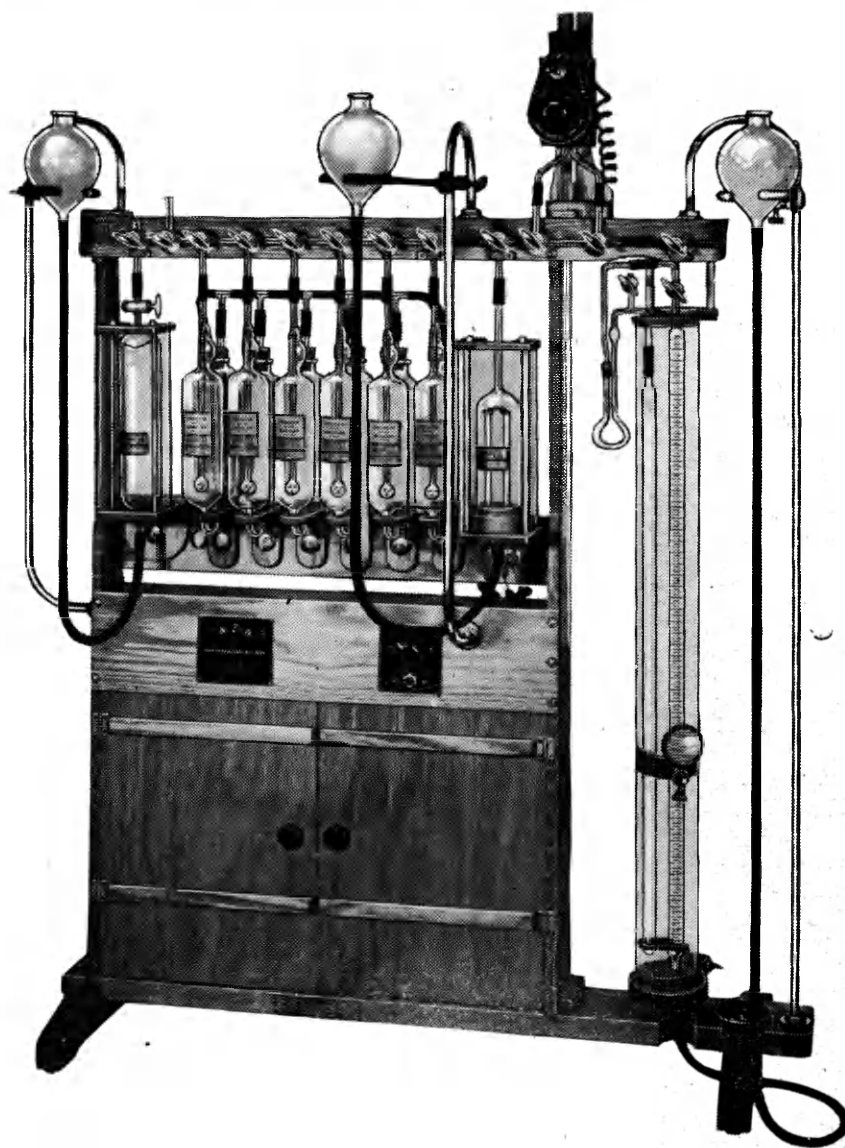


Figure 12--Burrell premier cabinet model VB gas analyzer.

Corporation for the Sampling and Analysis of Gases." Analysis was made for carbon dioxide and carbon monoxide using the ratio of these as the control figure.

### Material

The iron for these experiments was of the following analysis:

Total Carbon	- 3.28%
Combined Carbon	- 0.68%
Silicon	- 1.99%

This iron was cast into round bars and flat tensile specimens. The tensile bars were cast according to A.S.T.M. <sup>10</sup>/ specifications for sheet test bars, and were 5/16-inch thick. (This is not a standard test bar for cast iron.)

Two groups of experiments were conducted, the first to determine the best conditions for decarburization and the second to determine the effect of decarburization and heat treatment on the tensile strength of the iron.

### Experiments on Decarburization

Specimens approximately 1/2 inch in length, were cut from the round bars for use in these experiments. These samples were given heat treatments as tabulated in Table I, and were cooled three minutes in the gaseous atmosphere, three minutes in air, and then were quenched in water. After the heat treatment the specimens were cut lengthwise, and half of each specimen was mounted in bakelite to facilitate polishing for microscopic examination. The specimens were etched with a 5 percent picral solution to reveal the ferrite formed during the heat treatment.



Table I

Sample No.	Treatment Temp. OF	Time hr.	Volume Air cfm.	Air/Gas Ratio	% by Vol. CO <sub>2</sub>	Vol. CO	CO <sub>2</sub> /CO Ratio	Ferrite	Depth mm.	Total Decarb.
1T	1820	8	0.088	6.47	4.0	11.3	0.354	0.0410	1.0250	
2Ra										
3R	1800	8	0.077	5.13	2.1	14.6	0.144	0.1537	1.7425	
4R	1820	8	0.060	4.00	1.0	15.6	0.064	0.2768	1.4350	
5R	1830	8	0.104	4.00	1.7	14.5	0.117	0	2.3575	
6R	1820	8	0.104	2.60	0.9	13.4	0.067	0.2562	1.6500	
7R	1800	8	0.088	1.90	4.0	14.4	0.027	0	0	
8R	1710	8	0.108	2.35	0.6	14.3	0.042	0.2560	1.4350	
9R	1510	8	0.120	2.60	0.8	13.9	0.058	0.3075	0.3075	
10R	1510	8	0.140	3.05	1.4	15.0	0.093	0.3900	0.3900	
11R	1540	8	0.163	3.47	1.6	12.3	0.130	0.4100	0.4100	
12R	1560	8	0.185	3.94	1.9	11.1	0.170	0.6457	0.6457	
13R <sup>b</sup>	1710	8	0.190	4.20	2.2	10.0	0.220	0.7585	0.8500	
14R	1730	8	0.190	4.75	3.3	8.4	0.390	0.6560	1.0250	
15R	1720	8	0.190	4.00	2.8	8.4	0.333	0.5824	0.7000	
16R	1700	8	0.190	3.58	2.4	9.2	0.260	0	0.9225	
17R	1700	8	0.190	3.58	2.4	8.0	0.300	0.6667	0.9225	
18R	1700	8	0.172	3.24	2.0	7.9	0.255	0.5075	0.9736	
19R	1720	11	0.190	3.58	2.6	6.6	0.394	0.6150	1.1500	
19S	1720	11	0.190	3.58	2.6	6.6	0.394	1.0250	1.8040	

(a) No heat treatment given this sample.

(b) Changed from original 8-inch to 4-inch multiple unit electric combustion furnace.

Table I (continued)

Sample No.	Treatment Temp. of °F	Time hr.	Volume Air	cfm. Gas	Air/Gas Ratio	% CO <sub>2</sub> by Vol.	Vol. CO	CO <sub>2</sub> /CO Ratio	Ferrite	Depth mm. Total Decarb.
20R <sup>a</sup>	1710	12	0.167	0.079	2.11	1.3	6.4	0.203	0.6150	0.9640
20S	1710	12	0.167	0.079	2.11	1.3	6.4	0.203	1.1200	1.3800
21R	1710	12	0.130	0.058	2.28	1.3	6.5	0.200	0.5540	1.0000
21S	1710	12	0.130	0.058	2.28	1.3	6.5	0.200	1.4300	1.5200
22R	1700	12	0.114	0.045	2.53	1.3	6.5	0.200	0.6667	1.3333
22S	1700	12	0.114	0.045	2.53	1.3	6.5	0.200	1.1300	1.4500
23R <sup>b</sup>	1700	12	0.088	0.035	2.50	1.1	8.0	0.137	0.4100	1.0200
24R	1700	8	0.105	0.057	1.84	1.1	6.8	0.164	0.3590	0.9220
25R	1700	12	0.105	0.057	1.84	1.1	6.8	0.164	0.3380	0.8710
26R	1700	10	0.105	0.057	1.84	1.1	6.8	0.164	0.4100	1.1800
27R	1730	10	0.114	0.058	2.00	1.0	7.6	0.131	0.7200	1.0300
28R	1730	10	0.130	0.045	2.90	1.8	5.4	0.333	0.7500	0.9500
29R	1730	10	0.129	0.044	2.90	1.7	5.7	0.298	0.8500	1.0000

(a) Changed from laboratory compressed air supply to Cenco Pressovac 4.

(b) Changed from 4-inch to 12-inch multiple unit electric combustion furnace.

The depth of ferrite formation and the total depth of decarburization were measured with a filar micrometer which is placed in the tube of the microscope in place of the huygenian eyepiece. The filar micrometer was calibrated with a Bausch and Lomb stage micrometer, at a magnification of 25X which was used throughout the experiments for these measurements.

Samples 1T (cut from tensile bar) and 2R (cut from round bar) were polished and etched to compare the original microstructures of the two types of castings. The two microstructures were found to be the same. The microstructure of the untreated gray iron is shown in Figure 13. The graphite flake size is small and the distribution is good. The amount of steadite appears to be great, because of the coarse pearlite also present in the austenitic grain boundary.

Heat treatment at 1800°F with various  $\text{CO}_2/\text{CO}$  ratios was found to be very ineffective. Although the total depth of decarburization is very good, the depth of ferrite is very small. This is, possibly, the result of the rapid diffusion of carbon and the rapid solution of graphite at this temperature. Examination of the microstructure of sample 6R, typical of this group, shows a decided segregation in a layer between the core and the decarburized zone. Very small specks of ferrite were found in the core of the specimen, caused by graphitization during the heat treatment. A photograph of the polished specimen mounted in bakelite, and

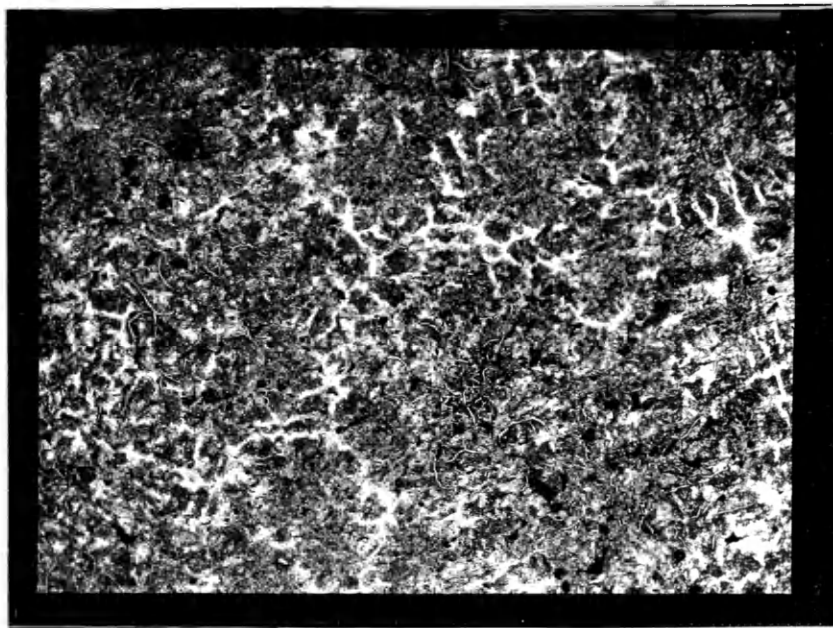


Figure 13--Microstructure of the untreated gray iron.  
100X (nital etch.)

a photomicrograph of the steadite concentration, near the lower left-hand corner of the specimen, are shown in Figure 14.

Although the total depth of decarburization was not as great when treated at 1500°F as was obtained at 1800°F, the depth of ferrite is much greater. An interesting point noted in this group of specimens is that the zone of varying carbon content is not apparent at 25X, the magnification used to measure the depth of decarburization. Graphite flakes are visible in the ferrite layer as shown in Figure 15. This indicates that the carbon diffusion through the ferrite is more rapid than is solution of the graphite.

Graphite flakes cannot be tolerated in the ferrite layer since the carbon content of the metal may still be very high and thus cause the same difficulty in welding that this research is attempting to eliminate. For this reason it was decided to raise the temperature. Since the steadite segregation was found at 1800°F, the melting point of steadite, it was not possible to go that high. It was decided to use a temperature of about 1700°F for succeeding experiments. This temperature is slightly above the ferrite to austenite transition temperature, and so gives a high solubility for carbon in iron. This treatment temperature eliminated the graphite flakes in the ferrite layer.

The heating elements in the combustion furnace burned out after treatment to sample 13R had been given. No

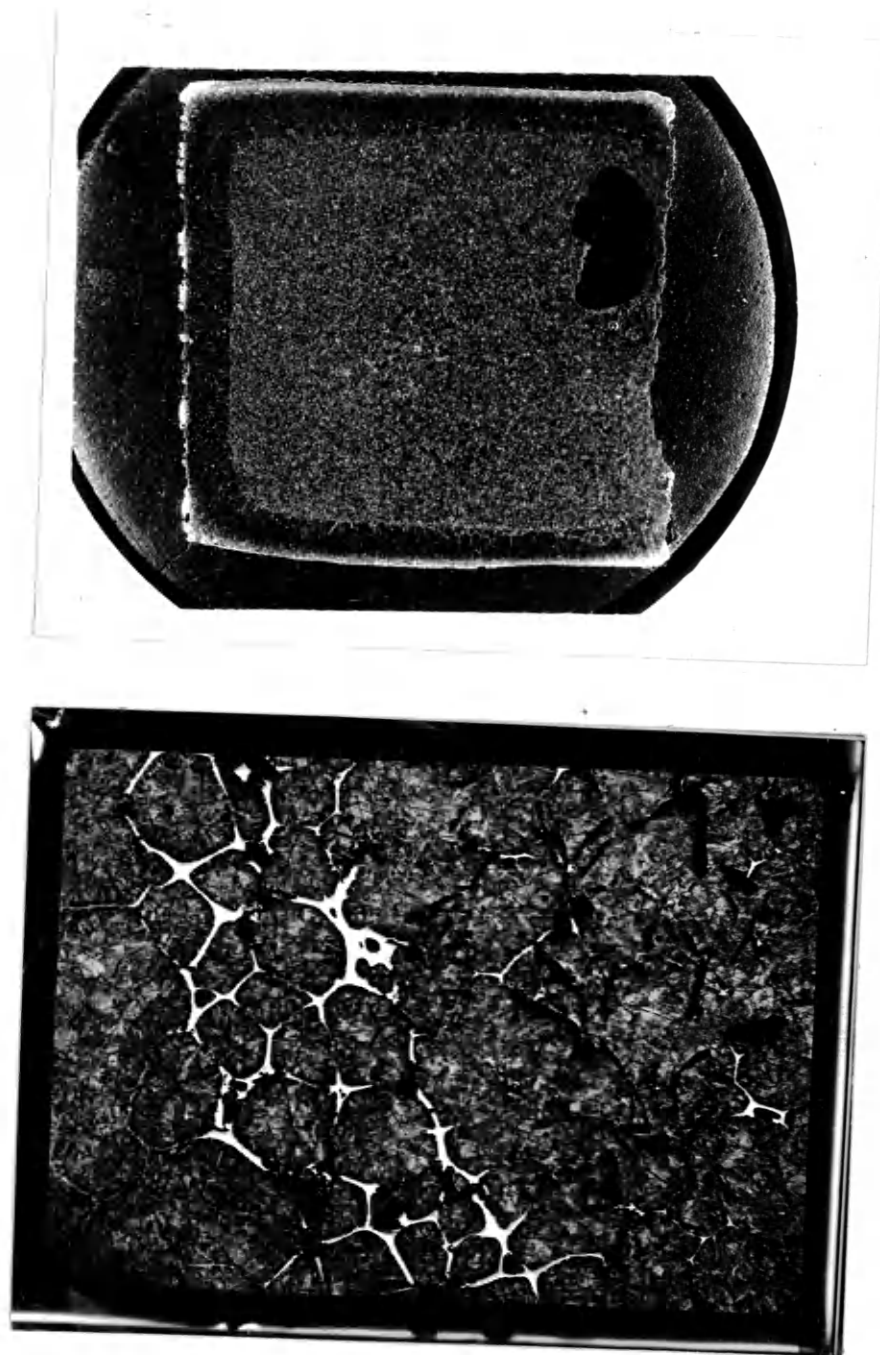


Figure 14--(top) Photograph of polished specimen 6R, 4X  
(picral etch.)

(bottom) Microphotograph of steadite concentra-  
tion, near lower left hand corner, 100X  
(picral etch.)



Figure 15--Microstructure of ferrite layer of sample 12R  
100X (picral etch.)

replacement elements for this 8-inch furnace were obtainable so the furnace was replaced by a 4-inch furnace of the same design. The change in furnaces gave much higher  $\text{CO}_2/\text{CO}$  ratios for the same air/gas ratio. The 4-inch furnace burned out, and a 12-inch furnace of the same design was used for experiments from 23R to the end of the laboratory work.

To obtain a more easily controlled and more nearly constant air supply, a Cenco Pressovac 4 pump was placed in service starting with sample 20R. In experiments 19 through 22 a sample of iron of the same analysis as that used by Narayan<sup>2/</sup> was placed in the furnace with the regular sample to ascertain the effect on a different type of iron under the same heat treating conditions. It may readily be seen from the table that the iron used by Narayan has a much greater depth of ferrite. A comparison of the zones of decarburization may be made from the photographs in Figure 16.

This verified the findings of Hatfield<sup>2/</sup> that increasing silicon content decreases the carbon loss for a given heat treatment. The iron used for these experiments contained 1.99 percent silicon, as was stated earlier, and the iron used by Narayan contained 1.40 percent silicon. From the experiments run to this point, it was concluded that the depth of ferrite formation would never be very great, so experiments as to time were performed in order to fix this



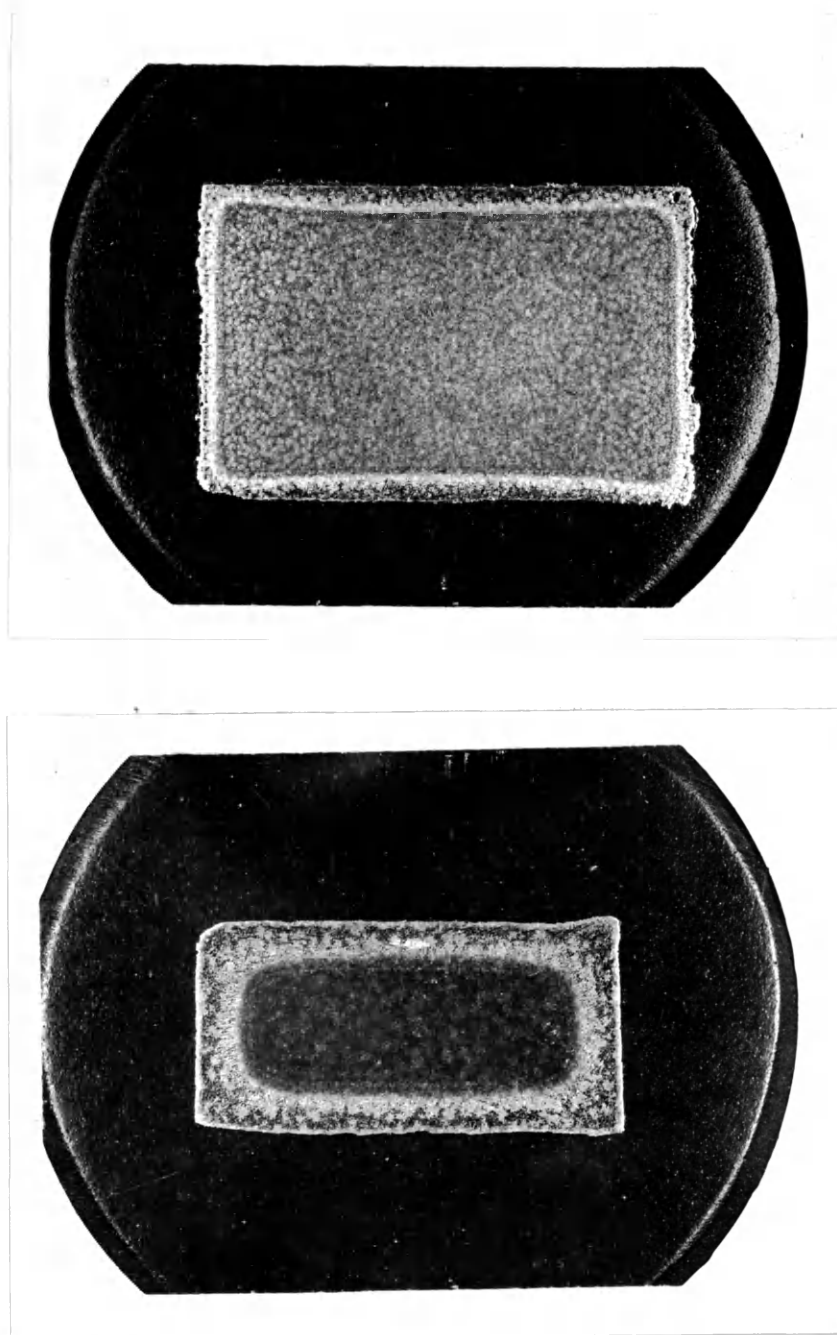


Figure 16--(top) Photograph of polished specimen 20R, 4X  
(picral etch.)

(bottom) Photograph of polished specimen 20S,  
4X (picral etch.)

variable for decarburization of the tensile bars.

From experiments 24R, 25R, and 26R, it was determined that 10 hours was a convenient length of time for heat treatment. All succeeding experiments were run for 10 hours including a few with variation of  $\text{CO}_2/\text{CO}$  ratio in the hope that a condition might be found that would give a little greater depth of ferrite. The conditions used for the heat treatment of sample 29R gave the best decarburized layer obtained.

The top photograph in Figure 17 shows the polished and etched surface of the sample. The bottom picture is a photomicrograph of the core of the specimen. A more uniform microstructure is shown in the heat treated specimen than was found in the original specimen, making the true structure of the steadite visible.

The photomicrograph, Figure 18, of the ferrite layer of sample 29R, shows a spheroidized pearlite in a matrix of ferrite. Polarized light shows the spheroidized structure very well. The structure of the specimen, after decarburization, is now known, and the conditions necessary to obtain decarburization have been established. The next point to be discussed is the effect of the heat treatment and of the decarburized layer formed during heat treatment on the tensile strength of the bar.

#### Testing

Two types of tests were made to determine the strength

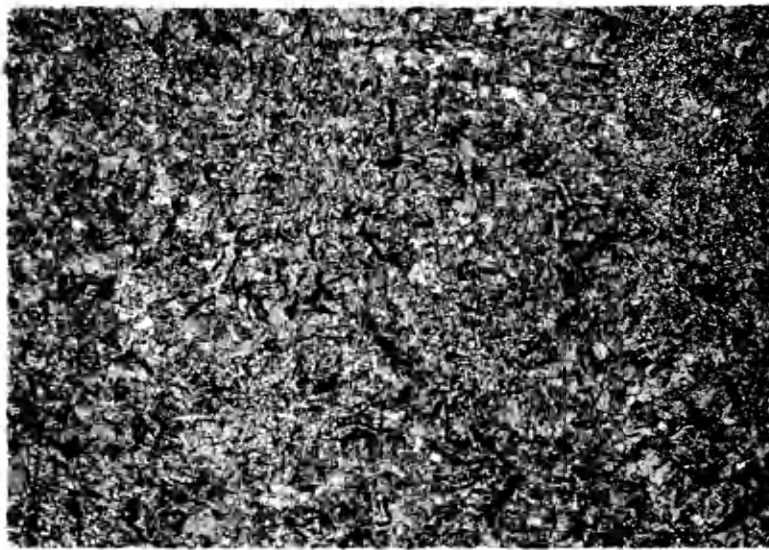
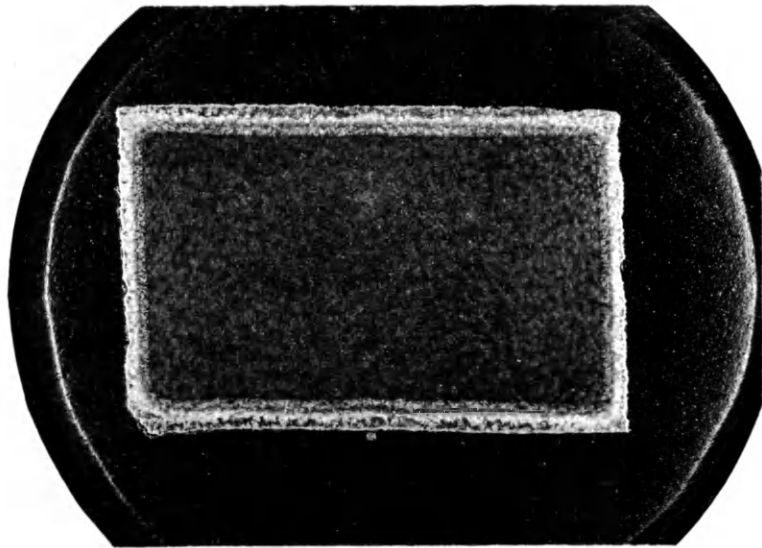


Figure 17--(top) Photograph of polished specimen 29R, 4X  
(picral etch.)

(bottom) Microstructure of the core of sample  
29R, 100X (picral etch.)

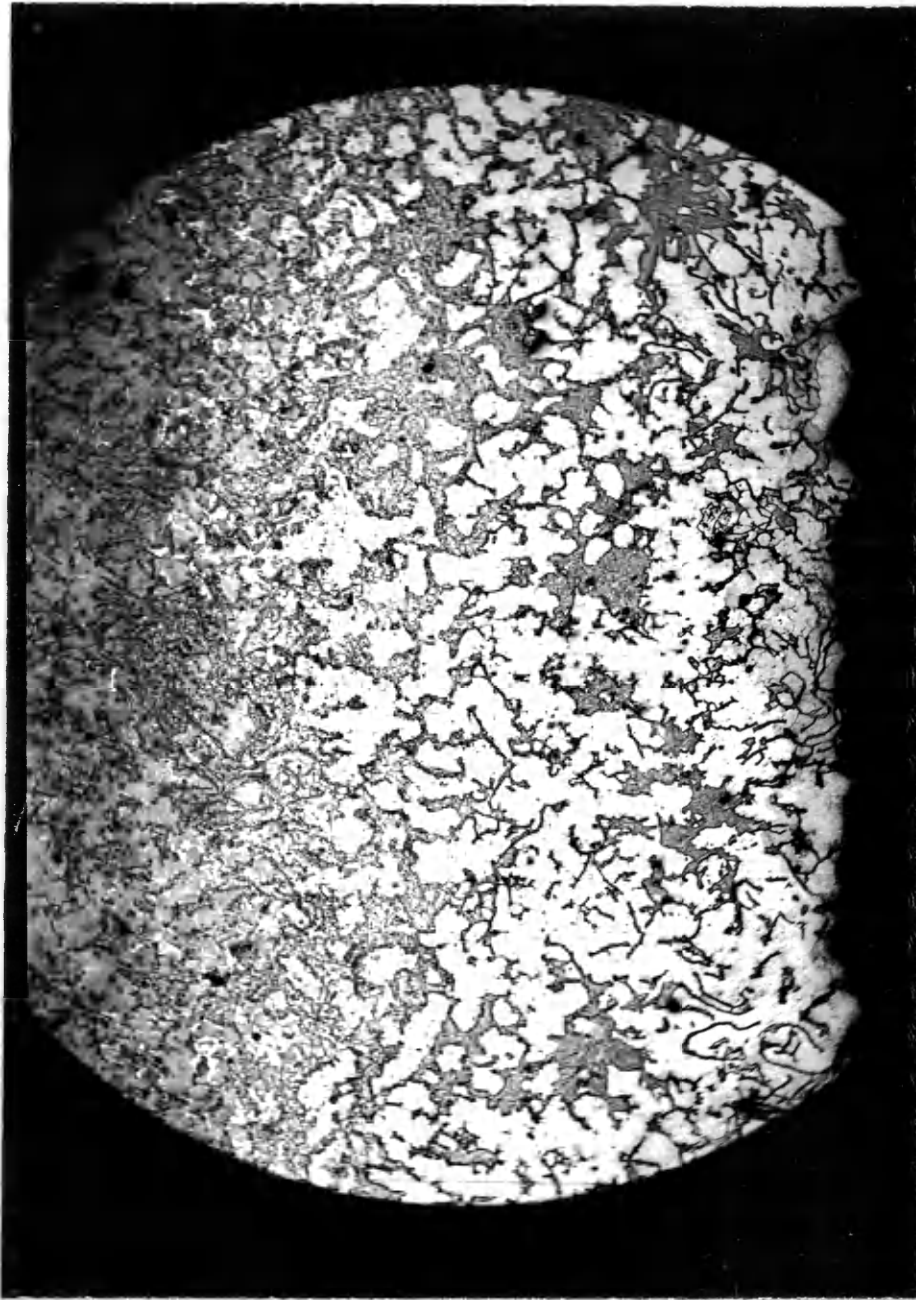


Figure 18--Microstructure of the ferrite layer of sample 29R, 100X (picral etch.)

of these bars, a tensile test and a flexure test. For the tensile test, five untreated bars were tested to determine the original tensile strength, then three of the treated bars were tested. Also, two bars were heat treated in a neutral atmosphere to determine the effects of the heat treatment, without decarburization. The results are shown in Table II.

Table II

Sample No.	Depth of		Cross-Sectional Area in <sup>2</sup>	Ultimate Strength psi
	Decarburization Ferrite mm.	Total mm.		
1 <sup>a</sup>			0.1615	41,800
2			0.1597	42,400
3			0.1750	45,800
4			0.1600	42,800
5			0.1658	41,250
30T <sup>b</sup>	0.2768	0.6150	0.1617	24,850
31T	0.3075	0.6150	0.1622	25,750
32T	0.3280	0.5125	0.1590	22,000
35T <sup>c</sup>			0.1578	40,600
36T			0.1633	43,740

- (a) No heat treatment for samples 1-5.  
 (b) Heat treatment same as for 29R on 30T-32T.  
 (c) Heat treatment, 8 hours at 1730°, no decarburization. Cooled in the same manner as the decarburized samples.

The elongation was approximately 0.5 percent in 2 inches for all specimens.

The flexure test was made on the same type of tensile bars used for the tensile test, since only comparative results were desired. The bars were laid on edge, on knife edges 7 inches apart. The results are shown in Table III. The deflection of treated and untreated samples was nearly constant for a given load.

Table III

Sample No.	Depth of Decarburization		Dimension		Load at Rupture lb.
	Ferrite mm.	Total mm.	Thickness in.	Depth in.	
1 <sup>a</sup>			0.317	0.525	620
2			0.320	0.528	630
3			0.317	0.511	620
4			0.307	0.507	600
33T <sup>b</sup>	0.5125	0.6150	0.331	0.535	400
34T	0.5330	0.7175	0.315	0.510	370

(a) No heat treatment for samples 1-4.

(b) Heat treatment same as for 29R on 33T-34T.

The results obtained definitely indicate that a cast iron section to be used in fabrication by welding after decarburization will have to be greater in cross-section than the original design to give the strength desired in the final assembly. Also, they indicate that a low silicon iron must be used in order to obtain desirable depths of decarburization.

## WELDING

The surfaces to be joined when welding cast iron contain carbon both in the combined form and in the free form. These surfaces must be melted to fuse with the filler metal in order to produce a sound weld. When the metal becomes molten, both the graphite and combined carbon go into solution. Because of the mass of cold metal adjacent to the weld, a quenching effect takes place which chills the molten metal to form white iron, a very hard and brittle material, at the edges of the zone of fusion. Silicon and carbon are removed (burned out) during the heating, and this reduction tends to increase the opportunity for white iron formation. Pre-heating the sections to be welded and insulation to reduce the rate of cooling after welding will reduce the thickness of this hard brittle layer and may eliminate it completely. It can also be avoided by using an electrode containing a high concentration of some graphitizing agent, and nickel alloy rods are widely used to produce machinable welds in gray iron.

In the heat-affected region adjacent to the zone of fusion there is another brittle zone, similar in structure to a high-carbon steel, where the cast iron has been heated into the gamma region, has dissolved carbon to above the euteotoid percentage, and has cooled so rapidly that the excess carbon was precipitated as  $Fe_3C$  rather than graphite.

Electrode composition cannot affect this action; it can be overcome only by slow cooling to allow graphitization of proeutectoid  $Fe_3C$ , or by avoiding the carbon pickup in the first place.

Since it is dissolution of carbon by molten weld metal which results in embrittlement of the zone of fusion and dissolution of carbon by austenite which results in embrittlement of the adjacent heat-affected region, it was thought that elimination of carbon from the region to be welded, by means of a preliminary decarburization treatment, would eliminate the difficulties involved in welding cast iron. Decarburization to produce a ferrite layer of sufficient depth on the surfaces to be joined should permit them to be welded with ordinary mild steel electrodes and by the techniques commonly used to weld low-carbon steels.

The possibilities of this method have already been verified by the work of Chen<sup>4/</sup>, who found that by decarburizing the outer skin of the cast iron, a weld having very good properties could be obtained by gas welding, using a mild steel rod as filler metal. Narayan<sup>9/</sup> obtained welds with good properties by arc welding, with a mild steel rod, cast iron which had a decarburized layer on the surface.

#### WELDING EXPERIMENTS

The bars which were broken to determine the tensile properties of the untreated iron were used as specimens for



the welding experiments. The ends of the two pieces to be joined were ground on the flat sides so as to form ninety-degree V when the two pieces were butted together.

The two pieces of the bar were then decarburized simultaneously, using the same conditions as those used for sample 29R. Before the two decarburized pieces were joined, a light build-up of mild steel was arc welded onto each face of the joint. The pieces were then clamped in place with C clamps and welded. The weld bead to be laid was so short that tabs were placed on each side of the joint for starting and breaking the arc. After each pass the metal was allowed to cool to a temperature such that the metal could be touched with the bare hand.

Welding was done with a 3/32-inch type E-6012 coated mild-steel electrode using direct current, reverse polarity. After the weld had been made, the excess metal was ground off to give constant dimensions through the neck of the test bar. The result of the tensile test on this bar was 14,660 psi, a value only about half the strength of the decarburized bar.

A cross-section of this weld is shown in Figure 19. A small portion of the parent metal is seen in the weld metal at the top where the specimen broke. The black areas in the weld metal are slag inclusions. The heat-affected region extends rather far into the parent metal. The decarburized layer visible in this section is much thinner than was that obtained under the same conditions in sample 29R.

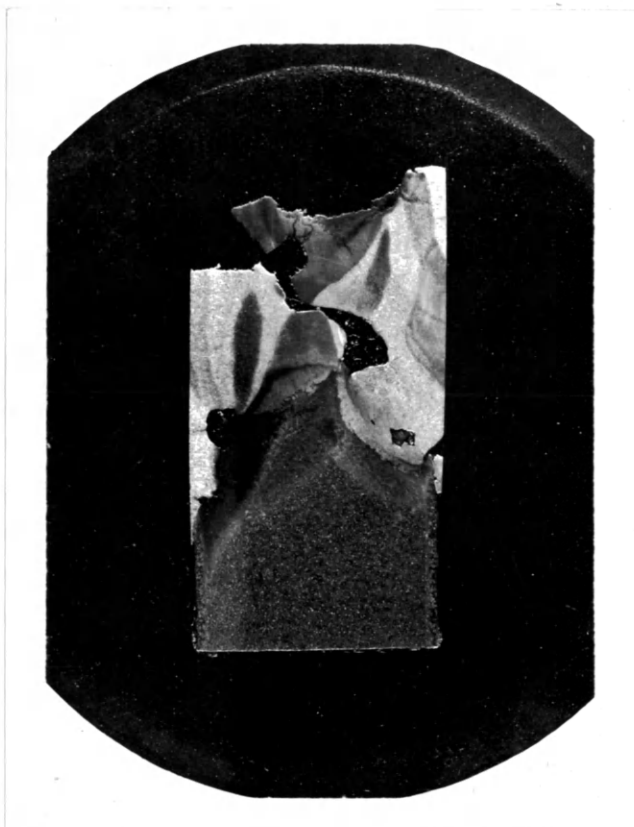


Figure 19--Photograph of weld cross-section 4X (nital etch)

The second weld is shown in Figure 20. This sample broke when the starting tabs were hit to detach them. The sample broke at the edge of the weld. The dark areas between the weld metal (white) and the parent metal are the metal that was deposited before the two pieces were joined. The black area, a slag inclusion, shows that no fusion was obtained at the root.

The small size of the specimen accentuated the difficulties of welding; more important, penetration of the zone of fusion could not be reduced to a depth which was less than the thickness of the decarburized layer. For these reasons, the test welds were unsuccessful, and no further welds were attempted. Fortunately, it had been demonstrated by previous investigations that the welding itself offered no serious problems if a decarburized layer of sufficient depth could be produced on the iron. In this particular iron, such a layer could not be produced.

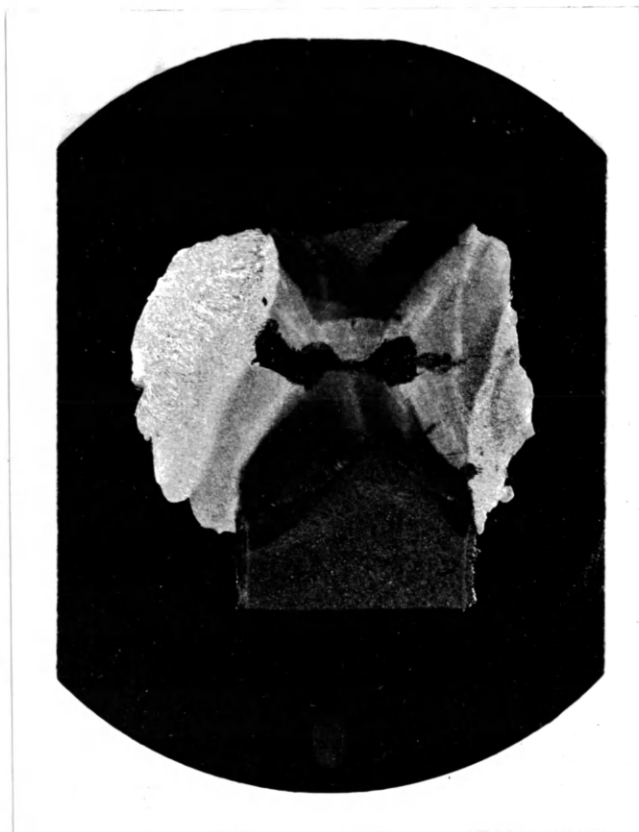


Figure 20--Photograph of weld cross-section 4X (nital etch)

### SUMMARY AND CONCLUSIONS

Cast iron can be decarburized by the ore process, or by prolonged heating in a hydrogen atmosphere, a hydrogen/water-vapor atmosphere, a carbon dioxide/carbon monoxide atmosphere, or in a mixture of these such as is found in an atmosphere consisting of the products of partial combustion of natural gas. The factors governing carbon removal are time, temperature, and carbon dioxide/carbon monoxide ratio. Composition of the iron is also of importance, because carbon and silicon content (and probably other elements) affect rate of decarburization.

The decarburized layer on gray iron reduces the tensile strength of the iron. For this reason the method of welding cast iron must probably be limited to such applications as low-pressure valve bodies, ornamental work, and other similar uses in which the strength of the fabricated article is not of primary importance, or where an increase in section is possible to compensate for the reduction in properties which accompanies decarburization.

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