FERRO SILICON, CALCIUM SILICON, AND METALLIC CALCIUM AS LADLE INOCULANTS FOR GRAY IRON

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

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1949

This is to certify that the

thesis entitled

FERRO SILICON, CALCIUM SILICON, AND METALLIC CALCIUM AS LADLE INOCULANTS FOR GRAY IRON

presented by

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has been accepted towards fulfillment
of the requirements for

Masters degree in Mech. Engr.

L. C. Price

Major professor

Date May 26, 1949

O-169

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By

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A THESIS

Submitted to the School of Graduate Studies of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Mechanical Engineering

1949

ACKNOLEDGEMENT

The author wishes to express his sincere thanks to Professor Howard L. Womochel for his technical advice and guidance which made it possible to conduct the research reported in this thesis.

The author also wishes to take this opportunity to thank the many people who willingly contributed their time and effort during the course of this investigation.

Table of Contents

List of Figures

-From Survey of Published Literature-

-From Origional Research-

List of Microphotographs

I. INTRODUCTION

The subject of ladle inoculation of gray iron has been brought to the attention of the foundryman with increasing emphasis during the past twenty years. A series of papers on "High Test Cast Iron" by Smalley, Marbaker, and Coyle and Houston, published in the Transac tions of the American Foundryman's Association - 1929 (1) (2) (3)*, seemed to create an interest in the subject of inoculation. Since that time many papers, articles, and discussions have been presented on this subject and several theories to explain the inoculating action heve been formulated.

Although many of the papers have discussed ladle additions of calcium silicon and/or ferrosilicon, there has been a conspicuous lack of data comparing the relative effects of these inoculants on the physical properties of gray cast iron. Any mention in the literature of ladle additions of metallic calcium has been devoid of accompanying data on physical properties.

The purpose of this investigation is to present some data on the relative effects of calcium silicon, ferro silicon and calcium metal on the physical properties of gray cast iron. Since it would be possible

* Please refer to articles listed in the Bibliography.

to approach this subject from more than one angle, it was decided that a comparison would be made on commercial gray irons with similar final chemical analysis. It was hoped that, from the resulting data, some definite relations could be established as a comparison of these inoculants and some additional information could be presented on the theories of inoculation.

II. SURVEY OF PUBLISHED LITERATURE

A- Definition of Inoculation

The 1948 "Metals Handbook" (4) states that in general, inoculation may be defined as "the addition to molten metal of substances designed to form nuclei for crystallization." The purpose, value, and/or effects of cast iron inoculation have been listed in the literature and attempts have been made to describe the mechanism accompanying successful inoculation practice.

B- Purpose of Inoculation

The 1944 "Cast Metals Handbook" (5), remarks that " in many cases, cast irons are inoculated with late additions for the purpose of improving the structures and, consequently, the mechanical properties. Many different elements and combinations, such as ferrosilicon, calcium silicide, graphite, and numerous commercially prepared inoculants, are used for this purpose. In fact, practically any late addition appears capable of producing some effect."

Lownie(6) divides the various inoculants into two groups:

1- (Have sole duty of producing inoculating effects such as changing graphite distribution and reducing chill); Ca; Ca-Si, Ca-Si-Ti, Fe Si, graphite, Si-C, Si-Mn, Si-Mn-Zr, Si-Ti, and Si-Zr.

2- (Also exert the effect that a change in chemical

composition, alloying, has on the properties in addition to inoculation effects); Cr-Si-Mn-Ti-Ca, Cr-Si-Mn-Zr, Mo-Si, and Ni-Si.

Burgess and Bishop(7) consider those listed in group 1, above, as straight graphitizing inoculants and those in group 2 as stabilizing inoculants.

In as much as this thesis deals with group 1 (graphitizing) inoculants, and most of the literature surveyed covered the same group, some typical analysis for that type as listed in the "alloy Cast Irons Handbook" (8) will be given:

	%Ca	%Si	%C	%Mn	Others(%)
CaMetal	100				
Ca-Si	30-35	60-65			
Ca-Si-Ti	5-8	45-50	----------	----------	9-10 Ti
Fe-Si	-------	50-90			
Graphite	----------	100			
Si-C	-------	45-56	28-50		
Si-Mn	-------	47-54	--------	20-25	
Si-Mn-Zr	-------	60-65	---------	5-7	5-7 Zr.

C- Value of Inoculation

"The value or efficiency of a ladle inoculant depends on its ability to consistently perform certain functions when added as a late addition to cast iron."(7). The authors of this statement (Burgess and Bishop) enlarge upon it by stating that successful inoculation requires:

1- reduction of tendency to chill and

2- improvement of physical properties

a- development of high tensile and transverse strengths in irons possessing suitable base characterisitics

b- development of optimum transverse properties, impact resistance, and chill reductions at any given tensile strength level.

D- Effects of Inoculation

Effects of ladle inoculation, according to Lownie,(9) may be attributed primarily to the effect of the inoculant upon the size, shape, and distribution of the graphitic carbon in the iron. "It has been established by many investigators that the effect of the inoculant is to change the graphite from a fine, dendritically oriented pattern to a coarse randomly oriented pattern."

Lorig(10) says that ladle inoculation seems to be the only reliable method in which the microstructure of superheated gray iron can be kept from becoming dendritic. His microphotographs show absence of dendritic graphite and ferrite for Fe-Si treated irons as compared with the dendritic structure of the same irons without ladle treatment. "Noticable effects of ladle additions on structure are reduction in size and influence on shape and distribution of graphite flakes."

Smalley(1) reported that cupola iron which would have been white and brittle in small section, or of uncertain

properties in heavy section, produced normal graphite with a pearlite matrix after ladle treatment with Ca-Si.

Loria and Shephard(11) found that silicon- carbide inoculation controlled the chilling tendencies in alloyed and unalloyed irons. The chill depth was reduced and the structure of the chilled surface for wear resisting castings was refined.

"Ladle additions prevent bad supercooled structures, such as cellular eutectic graphite coupled with ferrite", according to Lemoine(12) who used both Fe-Si and Ca-Si in his experiments.

Boyles(13) states that ladle additions seem to increase the number of crystallization centers in the eutectic and therefore produce a small cell size. This has the effect of creating a normal grpahite structure in gray irons that would otherwise solidify in the dendritic graphite pattern.

E- Theories Concerning the Mechanism of Inoculation

Vanick(14) is inclined to believe that "the mechanism of inoculation has been traced to a reaction which, when executed in its proper time and place, forces the crystallization of graphite in the stable system. Commercial inoculants usually possess a high order of graphitizing power which is supplied through the presence of graphitizing elements plus deoxidizers and degasifers. Their important function of stabilizing the structure of the graphite leads to the production of a more dependable

range of physical properties for metal of the same composition."

Lownie(9) believes that the random graphite pattern is formed, during inoculation, by freezing directly into the iron-graphite system without carbide as a temporary phase. "Therefore the effect of the inoculant is to produce graphitization at the eutectic in those cases where graphitization would occur normally below the eutectic." He lists three theories for inoculating action:

1- Gas Theory; belief that inoculation is really deoxidation and reations between inoculant and dissolved gasses cause the inoculant effect. Lownie is skeptical about this action because chromium, a strong deoxidizer, produces carbides and not graphite.

2- Silicate Slime Theory; belief that submicroscopic slime of ferrous silicate inclusions acts as coarse graphite nuclei. This theory is supported by the fact that a silicon removing slag promotes abnormal, fine graphite.

3- Graphite Nuclei Theory; belief that graphite particles in the melt act as nuclei to accelerate the graphitiz tion phenomenon. This explanation for the action of an inoculant has been the most widely accepted although the original statement, made in 1920 by Piwowarsky(37) -"Molten cast iron contains graphite nuclei in suspension, which as the metal freezed or "sets", form the starting point of coarse graphite crystals." - has been extended in more recent discussions.

L Lownie(6) postulates that the process of nucleation appears in all of the theories as to the cause of inoculating effects and presents the following graph to demonstrate his explaination of the inoculation phenomenon:

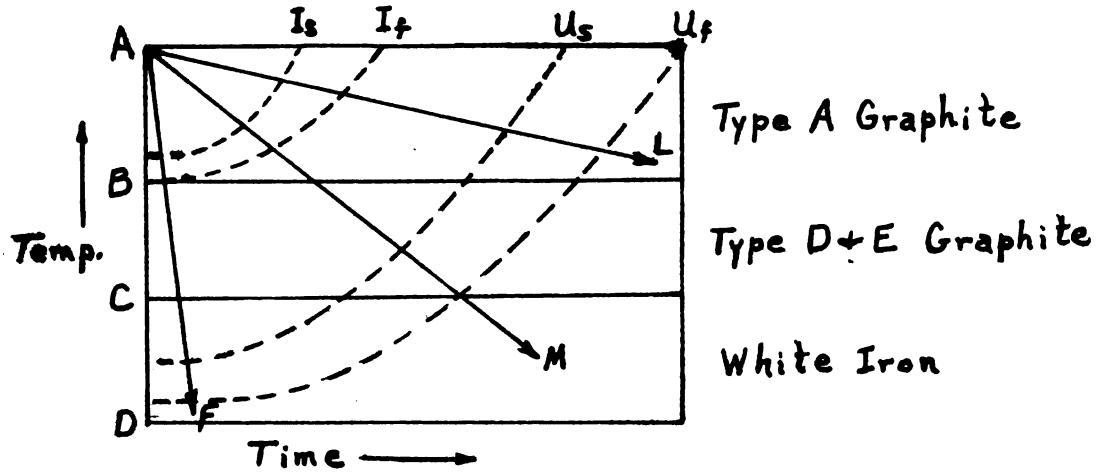


Fig.1. Representation of graphite formation, cooling rate and transformation range on time-temperature diagrams.

The purpose of this simplified diagram is to provide an aid to understandting, in a practical manner, how inoculants work. The temperature horizontal B indicates the division between the regions for normal and for interdendritic graphite formation, and C divides the regions where abnormal graphite is formed and where graphitization is suppressed. Cooling rates are represented by the arrows A F, A M, and A L for fast, medium, and slow cooling, respectively. The curved, dotted lines represent the start (subscript s) and finish (subscript f) of transformation for any particular cast iron. The composition and casting proceedure of the gray iron in question will determine the position of the dotted lines. Us and Uf are

typical transformation curves for uninoculated, medium carbon-medium silicon irons. Is and If indicate the relative position of the transformation curves for similar irons that have been completely inoculated.

When using this chart the section size (rate of cooling), composition, and inoculation effects determine what graphite formation will be obtained. The transformation curves for a low carbon-low silicon iron would be found to the right of Us and Uf and for high carbon-high silicon irons to the right. The former would require extremely slow cooling to form type A graphite and the later extremely fast cooling to form white iron. Type A graphite flakes, formed during long transformation periods at low cooling rates are longer and coarser than type D flakes formed during shorter transformation periods at faster rates. If the time consumed during transformation to type A in inoculated iron is similar to the time required for the uninoculated iron to transform to type D, although the rate may be faster in the later case, the graphite flake size should be similar. The presence of an increased number of graphite nuclei in the melt due to inoculation makes it much more likely that graphite will be formed in the normal graphite region.

Eash (15) reached the conclusion that "inoculation produces graphite nuclei which cause the iron to solidify in the iron graphite system. Grey irons, having fine

graphite in a dendritic pattern, solidify in the metastable iron-carbide system as white iron. The eutectic carbide subsequently decomposes in the solid state to form iron and graphite. Ladle inoculated gray irons, having random flake graphite, solidify in the stable iron-graphite system. The flake graphite forms during the freezing of the graphite-austenite eutectic. The iron- graphite eutectic temperature was found to be 36 to 70°F higher than the iron carbide eutectic in slowly cooled heavy section gray iron castings."

Park, Crosby, and Herzig (16) also ascribe to the theory that graphite forms directly from the melt along with the austenite as the eutectic temperature is reached. They believe that the austenite-cementite eutectic and the austenite-graphite eutectic must be very nearly similar in temperature and therefore hard to distinguish.

Boyles and Lorig (17) plotted cooling curves on a 3.0% C - 2.5% Si iron as inoculated with Ca-Si and after holding at temperature for an additional thirty minutes after the inoculating treatment. The solidification of the eutectic started at approximately 10°F lower for the iron which had been held for thirty minutes and the effect of seeding had worn off. The comparative shape of the curves after the start of the eutectic formation is of special significance. In the inoculated, which showed a normal graphite distribution, the temperature rose immediately and as a result the size of the flakes formed was larger almost immediately. The curve for the iron in which the inoculating effect had worn off remained at the

undercooling temperature for a longer period of time and sloped upward more gradually. This iron had a modified graphite structure due to the formation of most of the graphite as fine flakes before the temperature had leveled off.

Although there was no difference between the size or distribution of the primary dendrites there were many more crystallization centers for the formation of graphite in the normal iron. This resulted in an evolution of heat in a greater number of areas in the normal iron with a resulting rapid upswing of the curve which allowed for the formation of type A graphite. The modified iron showed a much larger area in the center of each crystallization point due to the greater distance between centers and the smaller evolution of heat involved.

D'Amico and Schneidewind (18) worked out 'S' curves to compare the start and finish for the austenite and eutectic transformations at constant temperature for several cast irons. Of special interest was the comparison between a eutectic iron (3.74% C - 2 .10% Si) with and without ladle inoculation using Ca-Si (.4% Si added).

The above researchers have developed the theory that the probable graphite pattern in a given iron is determined by:

1- the rate of cooling during solidification,

2 - the degree of undercooling experienced by virtue of its cooling rate during solidification and,

3 - the solidification characteristics of the iron. With rapid rates of cooling, appreciable undercooling accompanies solidification. In other word, the metal remains molten until a temperature well below the theoretical greezing point is reached; the faster the cooling, the greater the degree of undercooling. The graphite pattern is directly related to the degree of undercooling for any particular iron; the flakes become smaller and more dendritic as undercooling is increased.

An S curve may be drawn to represent the particular solidific tion characteristics of an iron and irons with different compositions will have different S curves. Each branch of the curve represants a particular graphite formation and corresponding points on different curves represent similar graphite patterns; therefore different irons will have different graphite patterns with si ilar amounts of undercooling. The upper branch of the curve (down to the knee) represents the normal graphite region. The middle portion(around the gradually curved part) is distinguished by a eutectiform graphite in dendritic distribution. In the lower part, mottled and white irons are found.

D'Amico and Schneidewind are convinced that the influence of factore (such as inoculation) which affect the nature of the graphite pattern would only be attributed to their ability to change the solificiaation characteristics

of an iron exposed to any given amount of undercooling. The effect of adding .4% silicon as Ca Si on the S curve is to move corresponding sections of it to the right and downward to an appreciable extent. "It is interesting to note that deoxidation with .4% Ca-Si has made it necessary to undercool iron B (eutectic composition) to 1450 F and 1750 F respectively, in order that white and mottled structures are obtained. The corresponding temperatures in the untreated iron are 1675 F and 1925 F. In other words, the tendencey to form gray iron, or the urge to graphitize, is much stronger in a deoxidized iron than in a plain iron of the same composition; the addition of a deoxidizer demands much more drastic undercooling for the formation of the metastable carbide phase."

It was determined that the addition of a deoxidizer does not raise its temperature of solidification and therefore this effect could not influence the graphite formation. The increased silicon content could not cause the extreme effects shown by the inoculant, as evidenced by comparing the S curves of base irons with similar differences in chemical composition.

Flinn and Reese (19) postulate that the properties of any gray cast iron are dependent on graphite distribution and the structure of the matrix. They believe that the fine, eutectiform, network type of graphite "fromed from eutectic cementite at emperatures below the eutectic, while the well distributed, larger, flake graphite

is formed at the eutectic." A normal distribution may be obtained if .5% Si is added to the ladle just before pouring. "The effect of this addition passes away with time (about 20 minutes) and therefore appears to be due to high silicon spots which promote the formation of an iron graphite eutectic." Inoculation seems to lessen the possibility of free ferrite formation by causing graphitization at solidification instead of at lower temperatrues by graphitization of cementite to graphite and lower carbon austenite.

Crome (20) also ascribes to the theory that type A (normal) graphite flakes solidify form the liquid while type D (abnormal) graphite forms from the ausennite-cementite eutectic solid. He thinks that although the graphite nuclei may be actually dissolved in the melt there may still be enough points of carbon concentration due to inoculation that normal graphite will form.

Eash (15) is convinced that inoculation with silicon alloys is successful because high concentration of silicon exist immediately adjacent to the added particle so that the solubility of carbon in that immediate area is exceeded and hypereutectic graphite precipitated. These particles act as nuclei although the silicon might become uniformly dissolved in the melt. He believes that the removal of oxygen caused by ladle additions does not aid in the formation of normal graphite but would be more likely to promote iron carbide formation with resulting eutectiform graphite.

Mc Elwee (38) considers ladle additions such as Ti-Al-Si to be deoxidizing. He speculates that oxygen increases the chill and that ladle additions remove oxygen and therefore remove chill.

F- Data Concerning the Influence of Inoculation on Physical Properties.

Smalley (1) listed the results of physical tests on a 2 .8% C- 1.2 % Si cupola iron melted from 60% steel scrap and 40% high silicon pig with 120 ounces of Ca-Si added per ton of metal. Modulus of elasticity -28.6 x 10^6 p.s.i., tensile strength - 46,700 to 51,000 p.s.i., brinell hardness - 22 7 to 247, transverse properties (1 1/8" dia. on 12 " centers) - load- 4,800 to 4,850# and deflection-.12 to .14".

Another iron of 70% steel charge with 100 ounces of Ca Si added per ton gave E-27.8 x 10^6, tensile-46,000 p.s.i., brinell-255, transverse load-4,300# and deflection -.16". These irons picked up practically no calcium and approximately .1% Si.

Lorig (10) compared the physical properties of two irons without ladle additions, one with Ca-Si and one with Fe-Si ladle additions at various superheating temperatures from 2 350°F to 3150°F. The data was taken on irons prepared in a high frequency induction furnace with 125 # charges and similar melting schedules. The irons were poured at 2550°F unless superheated to a lower temperature. The ferro silicon used was the 75% Si grade but the grade of calcium silicide was not given. The ladle

additions were equivalent to .2% Si for Ca-Si additions and .5% Si for Fe-Si additions.

	Blank X	Blank O	Ca-Si	Fe-Si
Total C (%)	3.22	3.02	2 .99	2.88
% Si	1.87	2.21	2.21	2.12
Tensile p.s.i.	30,000	31,000	42,000	44,000
Transverse #	2,300	2,380	2,830	2,980
Deflection "	.245	.208	.395	.388
Brinell	179	188	193	199

Fig. 2- Physical test data for 2850° F superheat

	Blank X	Blank O	Ca-Si	Fe-Si
Total C(%)	3.19	2.96	2.89	2.81
% Si	1.87	2.19	2.07	2 .11
Tensile p.s.i.	29,800	34,400	48,000	48,500
Transverse #	2,400	2,470	3,200	3,190
Deflections "	.230	.207	.368	.400
Brinell	183	2 10	200	208

Fig.3-Physical test date for 2950° F superheat

It was noted by Long that the tensile and transverse strengths decreased to a minimum at approximately 2700° F, for the irons without ladle treatment, and then increased as the melting temperature was r ised. Inoculation with ferro-silicon or calcium-silicon eliminated this effect.

Crosby and Herzig (21) added Fe-Si to a base iron of 3.08% C - 2.17% Si, melted in a 30 lb. induction furnace from low carbon ingot iron and graphite. Comparison was made on physical tests with additions of 25,50,75, and 100 per cent silicon added as Fe-Si five minutes before pouring.

The superheat temperature was 2750° F and the irons were poured at 2650° F. The uninoculated iron had a dendritic graphite distribution and the inoculated irons contained normal graphite, with a pearlite matrix in all cases. The tensile and transverse properties increased up to 75% late additions of silicon and then decreased. The brinell hardness remained at approximately 215 in all instances. The tensile strength went from 37,500 to 46,000 and then dropped to 39,500 p.s.i.. The transverse load increased from 2,300 to 2,920 and then decreased to 2,450#. The transverse deflection increased from .190 to .318 and then decreased to .245". Type B-A.S. T. M. bars were used in these tests.

Roth (22) reported that ferro-silicon(80%Si grade) was used as an inoculant on 64 consecutive prodution heats to produce sixty thousand pound per square inch cupola iron. All heats exceeded the minimum requirement for tensile strength and many were without alloy additions. The amount of Fe-Si added to the 1600 pound ladles varied with the size of the castings to be poured. The average carbon content was 3.1% and the average silicon was 1.9%. The transverse strength exceeded 5,100# (1.2" dia. on 12" centers) in all cases and averaged 5,600#.

Hughes and Spenceley (23) presented data on 30 inch square, 5/8 inch thick band saw tablesproduced from ordinary cupola iron inoculated with ferro- silicon. The improvement in physical properties were listed as impact-2%, transverse strength-30%, transverse deflection- 2%,

tensile strength -32%, and brinell -2%.

Comstock and Strawther (24) compiled a considerable amount of data on the effect of inoculation with Fe-Si and Ti-Fe-Si (20% Ti-20% Si). Late additions were made two minutes before the melt was complete in each case. The superheating temperature was 2670°F and the pouring temperature was 2550°F in all cases. Transverse test results were taken on 1.2" diameter bars broken on 12" centers. These investigators showed no marked improvement caused by inoculation for base irons varying from 3.08 to 3.59% C and from 1.77 to 2.45% Si. Ladle additions up to .67% Fe-Si and up to 2% Fe-Ti were made. Base irons exhibited from 4,200 to 4,400# transverse strength and inoculation practice showed up to 300# improvement as a maximum. Tensile strengths were improved only slightly in most cases with an improvement of 3,000 p.s.i. maximum listed for Fe-Si additions and 8,000 p.s.i. for Fe-Ti. Base irons exhibited form 31,000 to 39,000 p.s.i. tensile strength.

Schnee and Barlow (25) developed an alloy containing 6% Al-12% Si-80% Cu (alloy 3) which they found to be the most suitable copper base alloy for use as an inoculating agent in gray iron. This alloy was compared with .5% ladle additions of silicon as Fe-Si. They found that one of the advantages of alloy 3 over Fe Si was that it did not promote the formation of shrinks and blowholes. The following tables list the comparison of physical properties for several irons. 1.2" diameter bars and 18" centers were used

for the transverse test and the tensile diameters were .800".

Addition	.5% Fe-Si	1% A.3
Tensile p s i	35,000	38,000
Brinell	185	210
Transverse load #	2,700	3,100
Deflection "	.350	.300
Resilience " #	670	705
% Si	1.56	1.52

Fig 4 3.2 5% C - 1.2 2 % Si mottled base iron

Addition	Base	.5% Fe-Si	1% A.3
Tensile p s i	30,000	32,000	37,000
Brinell	185	170	195
Transverse #	2,300	2,300	2,700
Deflection "	.230	.330	.320
Resilience	335	510	580
% Si.	1.81	2.32	1193
% C.	3.26	3.21	3.25

Fig 5 3.26% C - 1.81% Si base iron

Addition	Base	.5% Fe-Si	1% A.3
Tensile p s i	32,000	33,000	39,000
Brinell	190	170	2 20
Transverse #	2,400	2,600	3,100
Deflection "	.190	.310	.280
Resilience	290	550	660
% Si.	2.21	2 .6	2.33
% C.	3.03	2 .97	2.98

Fig. 6 3.03% C -2.21 % Si base iron (Heat A)

Addition	Base	.5% Fe-Si	1% A.3
Tensile p s i	32,000	34,000	42,000
Brinell	190	180	215
Transverse #	2,400	2,700	3,100
Deflection "	.190	.350	.310
Resilience	290	640	660
% Si.	2.21	2.35	2.2 5
% C.	3.03	3.08	2.97

Fig. 7 3.03% C - 2 .21% Si base iron (Heat B).

Nash (15) compared the physical properties attained after inoculation, using 85% Fe-Si and Ni(.35%Si and .7% Ni added), with the uninoculated iron. The transverse test bars were broken on 18" centers. The results were 39,700 psi tensile, 2,2 0 # transverse load, .253" transverse deflection, 22 ft # izod, .67" chill for the uninoculated iron with 3.05% C-1.88% Si- 1.0 % Ni. Corresponding results after inoculation were 43,600 psi, 3,100#. .381". 38 Ft # and .04" chill with 3.05% C-2.23% Si-1.7% Ni. Ladle inoculation provided normal graphite structures instead of the dendritic graphite structures found in the untreated iron.

In another paper, Nash (26) has shown the improvement possible by means of ladle additions to low carbon, austenitic cast irons. Increases in transverse properties for 14% Ni-6% Cu-2% Cr-2.25% C base irons were listed with 1% Si added as Fe Si to the Ladle(the total silicon of the irons in all cases ranged form 1 to 2%). Example: Transverse load 3,400 to 5,200#. transverse deflection .120 to

.680". Little or no effect from inoculation was noted if carbon was up to 2 .75%. The ladle addition of .7% Si as Fe Si improved a 3.0% C-2.0% Si-1.0% Ni iron from 4,600 to 5,800# transverse load, from .120 to .150" deflection, and from 44,000 to 58,000 psi tensile strength. The brinell hardness remained at 241.

Late additions of graphite have been used largely to reduce chill according to Dierker(36), Schneidewind (27), and Massari and Lindsay(28). Other physical properties did not change to any appreciable extent.

McElwee and Schneidewind(38)(27)(29) worked with graphitizing inoculants of the Ti-Al-Si type. The most successful has been a commercial alloy called Graphidox No. 2 (7.5% Ti, 20% Al, 20% Si, Balance Fe.). Two pounds per ton of metal was added to the ladle for several heats and the physical properties compared with base irons of similar chemical composition. Typical results follow: final analysis 3.1% C-2.12% Si, improvement from 2100 to 2700# and from .246 to .297" on transverse properties, tensile strength changed from 35,000 to 40,000 psi and chill form .40 to .25 inches.

Flinn and Reese(19) disclosed that ladle additions of .75% Si added as an alloy of 70% Si-10% Mn-1.64% Al- .1% Ti-balance Fe was the most successful out of several inoculating agents that were studied. Without ladle additions the physical properties were 41,000 psi tensile and 2,300# and .150" transverse load and deflection. After inoculation with the above alloy this iron tested 60,000 psi, 3600#

and .230". The inoculated iron had a fine grained, light gray fracture nd random graphite distribution. They pointed out that all successful inoculants considered contained silicon although some of the uncessful inoculants also contained silicon.

Burgess and Shrubsall(30) produced irons of a machinable grade, that would normally have been white, by means of ladle additions of Si-Mn-Zr type inoculating agents. For irons of 3.25% C-2.5% Si the transverse properties were improved from 1,800 to 2,100#, and from .150 to .250" for the most successful cases although there was but slight benefit in some instances. The tensile strength showed improvement of from 38,000 up to 45,000 psi and from 30,000 up to 46,000 psi. Chill depth was reduced.

Burgess and Bishop (7) presented the following conclusions concerning ladle additions of .25% Si as an alloy of Si-Mn-Zr (60-65% Si, 5-7% Mn, 5-7%Zr):

1-Chill depth greatly reduced in low C-low Si irons (2.75-3.0% C, 1-2% Si)

2-Tensile strength improved approximately 10,000 psi with low C and low Si(improved from 40,000 to 50,000 psi)

3-Transverse strength improved approximately 500# with low C and low Si(improved from 2,500 to 3,000#).

4-Transverse deflection improved approximately .100" in all cases(in low C-low Si from .160" to.290")

5-Fluidity improved slightly

6-Inoculant does not lose effect in less than 15 min.

7-Eliminates [illegible] even in low C-low Si irons.

8-Refines cell size

9-Renders high C-low Si or low C-1.22% Si completely gray in 1.2" section.

10-Larger amounts of inoculant(up to .8%) sometimes are necessary in low carbon equivalent irons to improve transverse strength and deflection.

Lownie(9) reported that ladle additions of Si-Mn-Fr were slightly superior to ladle additions of Fe-Si in the lower carbon equivalent irons. Physical tests on a 3.29% C, 2.05% Si iron showed the same effect with .45% Si added as an inoculant with either alloy. The base iron tested 2,400# and .290" for a 1.2" dia. bar on 18" centers, tensile 37,500 psi and 255 brinell. Comparison with the inoculated irons showed 2,600# and .380" transverse properties, 44,000 psi tensile and 210 brinell.

G- General Statements Concerning Inoculation Practice

Williams(31) commented that Ca-Si additions(about .4% Si added) did not show any advantage over Fe Si and was decidedly more expensive. The cupola process was mentioned as being an inoculation process. Soft iron from one cupola was added to white iron from the other cupola in the ladle and the effect was the same as inoculation.

Francis(32) claimed that the Si may be as low as 1% in a 2.9% C iron and inoculation with 100 to 120 ounces per ton of metal will still be successful.

Pearce(33), Hoyt(34), and Delbart and Potaszkin(35)

have reported that inoculation with Ca-Si was found to be very satisfactory.

III ORIGINAL RESEARCH

A - Scope of Investigation

The first part of the present investigation was conducted in order to compare the physical properties of similar gray cast irons which showed equivalent amounts of silicon pick-up after inoculation with ferrosilicon and calcium-silicon. Ladle additions were selected so that comparisons could be made after .1%, .3%, and .5% Si. pick up from either inoculating agent. Conditions were controled so that the obly variable would be the ladle inoculatn.used. For comparison between levels (1.e. -.1% .5% Si. pick up) the total silicon content would be variable.

The second part of the investigation involved inoculation with metallic calcium. Comparisons were made on the physical properties of the base iron, .5% Si. pick up from both Fe-Si and Ca-Si, and ladle additions of Ca. The variables introduced were the type of inoculant and the total silicon content. An attempt was made to eliminate the later variable by pouring a base iron with carbon and silicon contents similar to earlier irons after .5% Si had been introduced as a ladle addition. This base iron was ladle treated, with approximately .04, .11, and .22% Ca added, to find the relative effects of Ca inoculation.

The desired chemical compostion for the base iron was fixed at 2.85% C, 1.90% Si, .75% Mn,.10% Phos, and .08% S. An indirect arc, rocking type electric furnace of 250 pound capacity was used for melting.

Three 1.2" dia. by 21" (ASTM*. Type B) test bars, and two chill tests specimens were poured from each ladle to check results. Transverse tests were made on all bars. Representative samples from all heats were analyzed for the carbon and silicon content and were examined microscopically. The brinell hardness was taken on one bar from each ladle. Tensile specimens were broken on representative samples from the heats that were the most satisfactory.

The various properties were tabulated and important curves were drawn. The results were studied and conclusions were drawn regarding the inoculating effects of Fe*Si, Ca-Si, and Ca on the gray irons under investigation.

B - Melting Practice

1 - Preparation of Molds

The arbitration bar and chill test molds were prepared from Lake Michigan sand with oil and cereal binder. The molds were baked overnight and then those to be used for transverse test bars were washed with a commercial "pink" core wash shortly before pouring each heat. This practice provided 1.2" diameter bars that were fairly smooth after wire brushing.

2 - Estimating the Charges

Seven, 250 pound heats were poured during the course of this investigation. Computations were made to determine the required amounts of steel and various pig irons to produce the desired analysis for heat 1. After the carbon and silicon analyses for heat 1 were obtained, additional calculations were made to try to bring heat 2 closer to the desired analysis. This proceedure was carried out for each heat, although in some cases the deviations were slight. An adjustment was made in the ferrous sulpher additions for heats 4-7 to bring the sulpher content closer to .08%. Heats 1 through 6 contained similar amounts of each constituent in the charge but heat 7 required complete new calculations because the origional supply of low silicon pig was exhausted.

The approximate analyses for the steel and pig irons used as listed below were needed for the calculations.

	%C	%Si	%Mn	%Phos	%S.
A*-Lot 1 pig	3.70	3.60	1.05	.188	.017
B -Old low Si Pig	4.28	.70	.46	.109	.038
C -Steel	.05	.15	.40	.020	.020
D -Charcoal iron	4.22	1.67	.43	.190	.018
E -New low Si pig	4.12	1.23	.88	.240	.033

Fig. 8-Approximate Analysis of Steel and Pig Irons

One to four pounds of silvery pig(code F), ferro-silicon containing 25% silicon, was included in the original charge for all heats, Small amounts of Fe S (code G) were added to each heat a few minutes before tapping. The sulphur content of this alloy was 56%.

The calculations necessary for figuring the charge for heat 1 will be used as an example of the method used for all heats (see Fig.9).

*Code letter for lot 1 pig; code letters for other constituents of the charge are placed in a similar position in Fig. 8.

Code	Weight	#C	#Si	#Mn	#P	#S
A	(115#)	4.25	4.14	1.32	.216	.020
B	(70#)	3.00	.49	.32	.076	.027
C	(64#)	.03	.10	.26	.013	.013
F	(1#)		.25			
G	(1/4#)					.140
Total		7.28#	4.98#	1.90#	.307#	.200#
Estimated %		2.91	1.99	.76	.12	.08

Fig. 9-Sample calculations for computing charge; heat 1.

3 - Charging the Furnace

A Detroit electric rocking furnace of the indirect arc type, silminite lining was used to melt the charge. The capacity of the furnace was 250#, therefore the charges had to be carefully placed to avoid contact with the fragile carbon electrodes. The steel was sheared into small pieces and placed on the furnace bottom along with the silvery pig. The large pigs, which had been wire brushed were then put in and the charge was ready for melting.

4 - Melting and Superheating

The electrodes were brought into position and the current turned on. The average total K W during the heats was approximately 125. After a considerable portion of the charge had melted the rocking mechanism was turned on. The Fes Additions were added, after the iron had become molten, at an average time of 75 minutes after the furnace had been started.

All of the heats, with the exception of number 1, required from 90 to 95 minutes to reach the desired superheating temperature (2900 F). Heat 1 required 140 minutes before tapping when it becoame necessary to chip out and replace an electrode which stuck and could not be properly adjusted.

Tapping temperatures, as measured with an optical pyrometer, were 2900 F, with the exception of Heat 7 which reached 2950 F before tapping. An attempt was made, during a trial run between heats 1 and 2, to check the superheating temperature with an rayotube mounted in the furnace door. The experimental set up proved unsuccesful and was not

subsequently used during this investigation.

5- Inoculation Procedure

Small, preheated ladles were used for pouring the test bars. Approximately 35# of metal was tapped into each ladle and then it was carried to a scale to check on the net weight. Ladle additions of dry Fe-Si or Ca-Si were made to the stream of iron as it was tapped and the ladles were rotated to provide for maximum inoculating action. With the exception of heat 7, for which the scale was not used, all ladles were brought up to 35# before pouring. Ladle additions of metallic calcium were made by rapidly 'dunking' the Ca under the metal surface and agitating it until the inoculating action had taken place. This was accomplished, without hazard, by wiring the desired amount of Ca to one end of a 10 ft pipe and manipulating the opposite end.

Heat 1 was used as a trial heat to determine the amount of silicon pick up form various amounts of Fe-Si and Ca-Si added to the ladles. It was determined, by chemical analysis, that all of the Si added as Fe-Si was picked up by the iron. For Ca-Si, it was found, a computed .4% Si addition picked up .3% Si and a computed .7% Si addition picked up .5% Si. The calculations involved in determining involved indetermining the required amount of inoculant to add to each 35# ladle follow:

.1% addition of Si .035# Si per ladle

(For 90% Fe-Si) .1% Si x 454 g/# 17.7 g Fe-Si/ ladle.

(For Fe-Si) .1% Si 18 g, .3% Si 53g, and .5% Si 88g.

(For 60% Ca-Si) .1% Si x 454 26.4 g Ca-Si/ladle.

(For Ca-Si) .1% Si 2 6g, .4% Si 105g, and .7% Si 184 g.

The ladle additions of calcium metal to heats 4 and 7 provided successful inoculating action. Evidently the calcium was not introduced quickly enough into the metal bath for heats 5 and 6, and was not sufficiently agitated for satisfactory inoculating action. The physical properties for heats 5 and 6 will therefore not be entered in this thesis. The pouring temperatures, as measured on the optical pyrometer for all aldles in heats 5 and 6, were checked with a chromel-alumel thermocuple so these heats provided some useful information which will be included under the next section titled 'Checks on Pouring Temperature.'

Heat 4 provided a comparison between the base iron, Fe-Si, Ca-Si, and metallic Ca additions. The 10 gram Ca addition was equivalent to $\frac{10G\ Ca/ladle \times 100}{35\#/ladle \times 454G/\#} = .06\%Ca$

The scales were not used for heat 7 but an estimation of the weights for each ladle with Ca added was made and the estimated Ca additions were .04%, .11%, and .22%.

6-Checks on Pouring Temperature

Several checks were made during the investigation to determine whether the pouring temperature as measured with an optical pyrometer could be relied upon to give an accurate and uniform pouring temperature for all test bars.

A fine wire, platinum-platinum rhodium couple was used on the trial heat, poured between 1 and 2, as a check. This produced the following results from four ladles:

Optical Pyrometer		Plat. - Plat.Rhod. Couple	
Apparent	True Temp.	M.V.Reading	Temp.
2350 F	2570 F	14.8	2615 F
2300	2510	14.7	2600
2440	2665	15.25	2680
2365	2585	14.9	2630

A similar comparison on four ladles form heat 4 provided more accurate results. The mv reading on three ladles was equivalent to 2550 F and for the fourth 2595 F as compared with an apparnent 2400 or 2625 F true temperature on the optical. The millivoltmeter readings raached a constant value during this later test and it was indicated that the actual pouring temperature for all heats was 2550 F although they were checked at 2625 F on the optical.

A larger chromel-alumel couple which had been preheated in a small resistance furnace was used in conjunction with heats 5 and 6. The results from all of the ladles are tabulated below for compariton:

Optical	Chromel-Alumel	Difference
2675 F	2515 F	160 F
2675	2505	170
2665	2505	160
2625	2510	115
2625	2480	145
2625	2455	170
26 00	2440	185
2600	2390	210
2570	2390	180

The optical readings were always higher than the thermocouple readings with differences ranging from 115 to 210° F(average 166, mean 170°F). The larger chromel-alumel couple evidently did not have sufficient time to reach equilibrium with the molten metal before the pyrometer indicated that the desired pouring temperature had been reached.

The bulk of the data on temperature measurement points to a fairly reliable comparison between thermocouple readings and optical pyrometer readings. From this it was concluded that the apparent temperature reading of 2400° on the optical pyrometer, which had been used to determine the time for casting, was equivalent to approximately 2550°F in all cases and the possible variable of pouring temperature had been virtually eliminated for all heats.

7-Casting Proceedure

Two wedge chill tests and three vertical arbitration bar molds were poured for each ladle throughlut this project. For heats 1,2, and 3, the ladles were tapped and cast in pairs with Fe-Si added to the first ladle and Ca-Si to the second in each instance. Increasing amounts of the inoculating agents were added to successive pairs during the progress of the heats. The first four ladles for heat 4 were used to compare .5% Si pick up from Fe-Si and Ca-Si; ladles 5 and 6 were tapped and cast as a pair with metallic calcium added to the last one. Increasing amounts of Ca were added to alternate ladles from heat 7 to compare with those without ladle

additions.

The total time required to tap heats 1,2, and 3, varied from 20 to 15 minutes. Heats 4 and 7 required but 10 minutes for tapping. Each ladle was poured when it reached the desired pouring temperature. It should be noted that the larger additions of Ca-Si and metallic Ca required approximately two minutes additional time before casting. Apparently this was due to the exothermic action of calcium when added to the molten iron.

C- Investigation Proceedure and Results

1- Chemical Analysis

Samples for chemical analysis were taken from the top half of the 1.2" Dia. test bars after they had been broken. The surface was gound clean and drillings were obtained from three different places along the bar.

The total carbon content of a representative bar from the first and last of each heat, as well as additional checks for heats 1 and 2, was determined. A carbon train was used to determine the carbon content: samples were burned in a combustion boat and the resulting CO_2 was collected in an absorbtion bottle and weighed. Standard samples were checked at the start and finish of each set of carbon determinations.

Silicon determinations were made on a representative bar from each ladle for heats 1 through 4, and from the first and last ladle of heat 7. The method used for silicon analysis follows: dissolve with HNO_3 and fume with perchloric acid, cool and dilute, filter through platinum cones using No 42 filter paper, wash alternately with warm 5% HCl and distilled water, ignite in crucible and weigh as SiO_2 . Standard samples were analyzed to check the determinations.

A check on the sulphur content, using titration; was made on bars from the first and last ladle of heat 3.

A tabulation of the results from the chemical analysis has been recorded in Fig. 10. The code letters and numbers used in this table indicate the heat number, inoculating

agent, and percent of inoculant added. Fig 11 has been used to tabulate the code letters and their meanings. This code will apply to all data taken during the investigation

Carbon (%)	Silicon (%)	
1F1 - 3.05	1F1 - 1.93	1C1 - 1.98
LF5 - 3.05	1F3 - 2.15	1C3 - 2.02
1C5 - 2.99	1F5 - 2.36	1C5 - 2.2 0
		1C7 - 2.34
2C1 - 2.66	2F1 - 2.24	2C1 - 2 .26
2F3 - 2.63	2F3 - 2.51	2C4 - 2.50
2C4 - 2.59	2F5 - 2.76	2C7 - 2.81
2C7 - 2.53		
3F1 - 2.88	3F1 - 1.98	3C1 - 1.93
3C7- 2.76	3F3 - 2.16	3C4 - 2.14
	3F5 - 2.33	3C7 - 2.36
4F5A - 3.02	4F5A - 2.42	4C7A - 2.43
4C - 3.03	4F5B - 2.42	4C7B - 2.44
	4B - 1.97	4C - 2.05
7B1 - 2.93	7B1 - 2.23	7C3 - 2.2 4
7C3 - 2.87		

Sulphur (%) 3F1 - .06
3C7 - .05

Fig. - Chemical analysis

Heat 1

1F1 - .1% Fe-Si*	1C1 - .1% Ca-Si
1F3 - .3% Fe-Si	1C3 - .3% Ca-Si
1F5 - .5% Fe-Si	1C5 - .5% Ca-Si
	1C7 - .7% Ca-Si

Heat 2

2F1 - .1% Fe-Si	2C1 - .1% Ca-Si
2F3 - .3% Fe-Si	2C4 - .4% Ca-Si
2F5 - .5% Fe-Si	2C7 - .7% Ca-Si

Heat 3

3F1 - .1% Fe-Si	3C1 - .1% Ca-Si
3F3 - .3% Fe-Si	3C4 - .4% Ca-Si
3F5 - .5% Fe-Si	3C7 - .7% Ca-Si

Heat 4

4F5A - .5% Fe-Si	4C7A - .7% Ca-Si
4F5B - .5% Fe-Si	4C7B - .7% Ca-Si
4B -No addition	4C - .06% Ca

Heat 7

7B1 - No addition	7C1 - .04% Ca
7B2 - No addition	7C2 - .11% Ca
7B3 - No addition	7C3 - .22% Ca

* Indicated .1% Si added as Fe Si (similar notations are used for other additions)

Fig.11 - Description of Code Letters and Numbers

2- Transverse Strength and Deflection

The 1.2" diameter by 21" long, arbitration bars were wire brushed to provide a clean surface. A hand operated Olsen tester was used to break the bars. The load was applied midway between 18" centers. A dial gage was set up to measure the deflection at the midpoint. The results of the transverse tests for all bars was tabulated by heats in Figures 12 though 16.

Code	Load (#)	Deflection	Code	Load(#)	Deflection
1F1	2060	.189"	1C1	2312	.230"
	2238	.221		2342	.240
	2171	.203		2386	.258
1F3	2133	.232"	1C3	2692	.370
	2003	.202		2073	.228
	2142	.222		2428	.294
1F5	2203	.255	1C5	2668	.347"
	22 51	.262		2513	.302
	2274	.275		2730	.365
			1C7	2164	.242"
				2801	.398

Fig. 12 - Transverse Load and Deflection for Heat L

Code	Load(#)	Deflection	Code	Load(#)	Deflection
2F1	2123	.169"	2C1	2224	.174"
	1774	.120		2155	.172
	2014	.150		2273	.174
2F3	2124	.165"	2C4	3017	.337"
	2335	.191		2926	.320
	2369	.198		3142	.372
2F5	2322	.218"	2C7	3016	.355"
	2224	.182		3016	.365
	2197	.175		3115	.355

Fig 13 - Transverse Load and Deflection for Heat 2

Code	Load(#)	Deflection	Code	Load(#)	Deflection
3F1	2210	.175"	3C1	2377	.230"
	2226	.176		2332	.227
	2180	.173		2187	.204
3F3	2156	.225"	3C4	2560	.303
	2270	.218		2457	.265
	2248	.212		2660	.329
3F5	2479	.252"		2826	.339"
	2562	.281		3031	.385
	2461	.258		2920	.347

Fig. - Transverse Load and Deflection for Heat 3

Code	Load(#)	Deflection	Code	Load(#)	Deflection
4F5A	2269	.284"	4C7A	2645	.374"
	2265	.280		2557	.334
	2256	.274		2280	.265
4F5B	2078	.238"	4C7B	2505	.333"
	2276	.280		2623	.334
	2235	.281		2528	.265
4B	1848	.185"	4C	2232	.242"
	2110	.235		2516	.303
	2168	.233		2507	.308

Fig. 15 -Transverse Load and Deflection for Heat 4.

Code	Load(#)	Deflection	Code	Load(#)	Deflection
7B1	2145	.201"	7C1	2235	.2 20"
	2224	.210		2207	.210
	2235	.238		2060	.195
7B2	1845	.150"	7C2	2580	.305"
	2215	.200		2560	.299
	2160	.185		2565	.290
7B3	2000	.165"	7C3	2705	.321"
	2105	.187		2610	.303
				2675	.321

Fig. 16 -Transverse Load and Deflection for Heat 7.

3-Chill Depth

The wedge shaped chill test specimens were broken and the measurements for total and clean chill depth were recorded. The clear chill included the white iron fracture only while the total chill included the mottled gray and white fracture(total distance from the sharp edge to the completely gray fracture). Some of the specimens exhibited fractures that did not have any section which was entirely gray. In that case the total chill measured 3 3/16", which was the maximum possible depth for the test pieces used in this investigation. The results, according to heat number, were recorded in Figs. 17 through 20. The chill tests for heat 4 were lost.

Chill Depth in Sixteenths of an Inch

Code	Total	Clear	Code	Total	Clear
1F1	20	11	1C1	14	8
	18	10		16	8
1F3	15	8	1C3	7	5
	11	6		7	6
1F5	10	7	1C5	6	5
	10	6		6	5
			1C7	6	5

Fig. 17 -Chill Depth for Heat 1.

Chill Depth in Sixteenths of an Inch

Code	Total	Clear	Code	Total	Clear
2F1	19	10	2C1	22	15
	12	7		25	16
2F3	18	11	2C4	7	5
	21	13		7	5
2F5	12	8	2C7	5	3
	12	8		5	4

Fig. 18 - Chill Depth for Heat 2.

Chill Depth in Sixteenths of an Inch

Code	Total	Clear	Code	Total	Clear
3F1	33	19	3C1	15	10
	33	20		14	10
3F3	14	9	3C4	7	5
	14	9		7	5
3F5	8	6	3C7	4	3
	8	6		6	4

Fig. 19 - Chill Depth for Heat 3.

Chill Depth in Sixteenths of an Inch

Code	Total	Clear	Code	Total	Clear
7B1	15	9	7C1	18	9
	19	11		17	8
7B 2	33	16	7C2	10	6
	33	17		10	6
7B3	33	16	7C3	9	4
	33	15		8	4

Fig. 20 - Chill Depth for Heat 7.

4 - Brinell Hardness

The samples for hardness tests were cut 3/4" thick and were taken adjacent to the fracture of the 1.2" dia. test bars. After grinding, the brinell impressions were made using a 3,000 Kg load on a 10 mn steel ball. The data from these tests are recorded in Fig 21 for all heats.

Code	Brinell No	Code	Brinell No.
1F1	207	1C1	197
1F3	201	1C3	197
1F5	207	1C5	197
		1C7	207
2F1	229	2C1	229
2F3	223	2C4	229
2F5	217	2C7	229
3F1	217	3C1	212
3F3	207	3C4	201
3F5	207	3C7	223
4F5A	192	4C7A	201
4F5B	197	4C7B	197
4B	201	4C	197
7B1	212	7C1	212
7B2	212	7C2	207
7B3	212	7C3	212

Fig. 21 - Brinell Hardness Numbers (Heats 1, 2, 3, 4 and 7).

5- Tensile Strength

Specimens for tensile strength were taken from the lower half of the 1.2" dia. test bar adjacent to the fracture. The nominal diameter for the tensile test was .800". A universal testing machine was used to break the tensile specimens and the breaking loads were recorded. The ultimate tensile strengths for heats 3,4, and 7 were listed in Fig. 22.

Code	Dia.(")	Area(Sq.")	Load(#)	Tensile Steength
3F1	.799	.5014	18,420	36,800 psi
3F3	.799	.5014	19,030	38,000
3F5	.799	.5014	20,410	40,700
3C1	.799	.5014	19,220	38,400
3C4	.800	.5027	18,310	36,600
3C7	.798	.5001	21,500	43,000
4F5A	.799	.5014	18,070	36,000
4F5B	.799	.5014	18,750	37,400
4C7A	.801	.5039	21,380	42,400
4C7B	.800	.502 7	21,2 70	42,300
4B	.799	.5014	18,760	37,400
4C	.799	.5014	22,230	44,400
7B1	.798	.5001	19,720	39,400
7B2	.799	.5014	18,440	36,800
7B3	.799	.5014	18,980	37,800
7C1	.799	.5014	19,440	38,800
7C2	.798	.5011	22,710	45,400
7C3	.799	.5014	24,220	48,400

Fig. 22 - Ultimate Tensile Strength (Heats 3,4, and 7).

6 - Microscopic Examination

Samples for examination of core and surface microstructures were cut from the brinell hardness specimens after the hardness readings had been recorded. Polishing and etching was accomplished in the following manner:

1- Rough grind on side of grinding wheel.

2- Polish on 120 grit paper disc.

3- Flat polish on #1 emery paper.

4- Wet polish on wax wheel using #320 abrasive.

5- Wet polish on wax wheel using #600 abrasive.

6- Alternate polish and etch on wet silk wheel using 'Met polish'.

7- Slight etch with 2% Picral-2% Nital solution for examination of graphite distribution at 100x.

8- Re-Etch for exaimination of matrix structure and graphite distribution at higher magnification.

After the microstructures had been examined, and the results tabulated, representative samples were chosen for microphotographs to accompany this paper.

The data on microscopic examination has been assembled, by heats, in Figs. 23 through 27. No particular differences in the structure of the pearlitic matrix was found, therefore only the amount of ferrite and its distribution was recorded. Graphite patterns were observed to fall in either type A, type D, or mixtures of these types. In general, the A graphite was approximately size 5 and the D graphite size 7, therefore only the type was recorded. These designations for graphite distribution and size were according to AFA specifications.

Code	Surface	Core
1F1	Similar amounts of D and A graphite Medium amt. of Fe. with A graphite Small amt. of Fe. with D graphite	A Graphite- Small amts. of Fe.
1F5	Largely D gr..with fairly large amt. of Fe- Some A gr with medium amt of Fe.	A graphite- A little more Fe. than 1F1
1C1	Largely A gr. with small amt. of Fe. - Some D gr. with small amt. of Fe.	A graphite- No ferrite
1C7	A graphite- Small amount of Fe.	A graphite- No ferrite

Fig. 23 - Graphite Distribtuion and Microstructures for Heat 1.

Code	Surface	Core
2F1	D gr.-Fairly large amt. of Fe.	Largely D gr- medium amt. of Fe, some A gr. with no Fe
2F5	D gr. - fairly large amt of Fe	Mixed: D gr-fairly large amt. of Fe, and A gr. with medium amt. of Fe
2C1	D gr. - Fairly large amt. of Fe	Largely D gr - small amt of Fe A little more A gr than 2F1 with no Fe
2C7	A gr - Fairly large Amt. of Fe	A graphite - medium amt. of Fe

Fig. 24 - Graphite Distribution and Microstructures for Heat 2.

Code	Surface	Core
3F1	D gr.- Fairly large amt. of Fe	Mixed: D gr. - medium amt. of Fe, and A gr. and no Fe
3F2	D gr. - Fairly large amt. of Fe	A graphite - Very small amt. of Fe
3F5	Mixed: D gr.- medium amt. of Fe, and A gr,- medium amt. of Fe	A graphite - Small amt. of Fe
3C1	Mixed: D gr-medium amt of Fe, and A gr.- medium amt. of Fe	A graphite - No ferrite
3C4	Largely A gr.- small amt of Fe, some D gr.- medium amt. of Fe	A graphite - No ferrite
3C7	A gr.- very small amt. of Fe, some flakes at surface were smaller	A graphite - No ferrite

Fig. 25 - Graphite Distribution and Microstructures ofr Heat 3

Code	Surface	Core
4F5A	A gr.- small amt. of Fe, smaller flakes at surface	A graphite - Very small amt. of Fe
4F5B	A gr.- small amt. of Fe, small amt. of D gr. with medium amt. of Fe	A graphite - Small amt. of Fe
4C7A	A gr.- very small amt. of Fe, some flakes at surface were smaller	A graphite - No ferrite
4C7B	A gr. - small amt. of Fe, smaller flakes at surface	A graphite - Small amt. of Fe
4B	Mixed: D gr- medium amt. of Fe, and A gr.- medium amt. of Fe	A graphite - Medium amt. of Fe
4C M	Mixed: D gr - medium amt. of Fe, and A gr.- small amt. of Fe	A graphite - Small amt. of Fe

Fig. 26 - Graphite Distribution and Microstructures for Heat 4

Code	Surface	Core
7B1	D graphite - medium amt of Fe	Largely A gr. with small amt. of Fe, some D Gr. with medium amt. of Fe
7B3	D gr. - Fairly large amt of Fe	Largely A gr. with medium amt. of Fe, some D gr. with farily large amt. of Fe
7C1	D graphite - medium amt. of Fe	Largely A gr. with very small amt. of Fe, lesser amt. of D gr. than 7B1 with small amt. of Fe
7C2	D graphite - Medium Amt. of Fe	A graphite - Small amt of Fe
7C3	A gr. with very small amt. of Fe, some smaller flakes with medium amt. of Fe	A graphite - Very small amt. of Fe

Fig. 27 - Graphite Distribution and Microstructures for Heat 7

7 - Microphotography

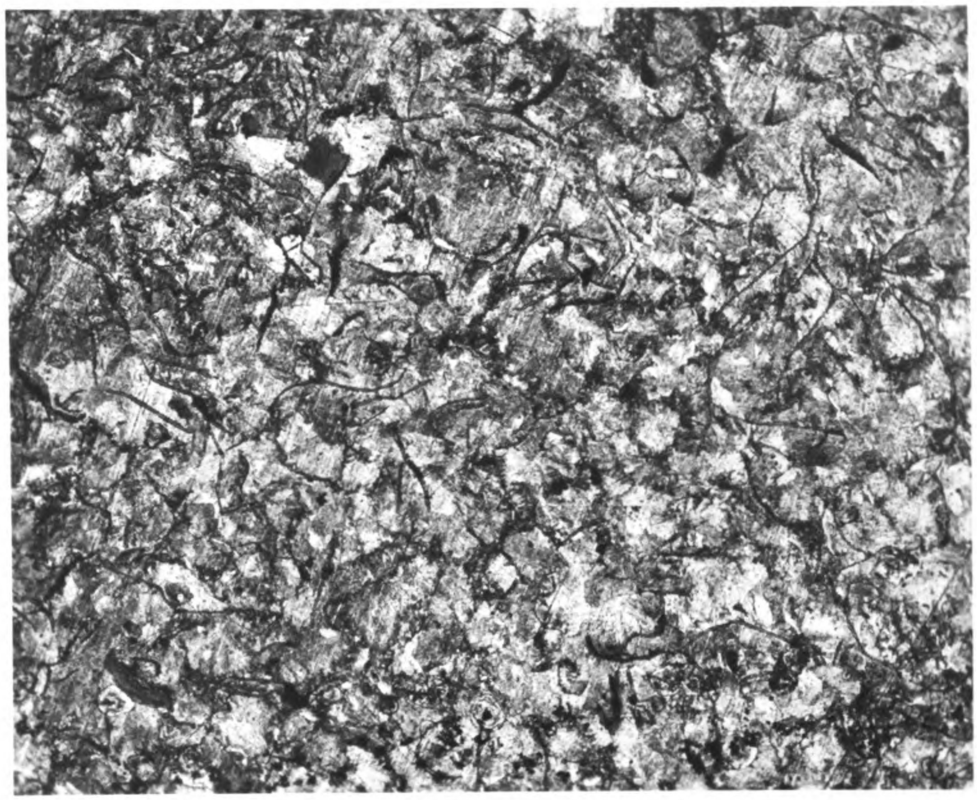
Microphotographs at 100x were taken to represent the types of graphite distribution which were encountered in this investigation. A magnification of 250x was used to compare the microstructures and graphite distributuions for the maximum addition of Fe-Si with that of Ca-Si; also to compare the maximum addition of metallic calcium with the base metal. Although it would have been possible to present many more microphotographs in this paper, it was felt that the micros which were taken represented all of the significant comparisons that could have been made by this method.

A B&L 'Research Metallograph' with tungsten arc was used for taking the micro's. The following combinations were used:

	Objective	Eypiece	Bellows Setting	Exposure Time
100x -	8X	5x	63.5 cm.	4 sec.
250x -	21X	5x	61.5 cm.	10 sec.

Eastman 'Wratten' metallographic plates with M Q developer was used for the negatives and 'Azo' paper with D72 developer for the prints.

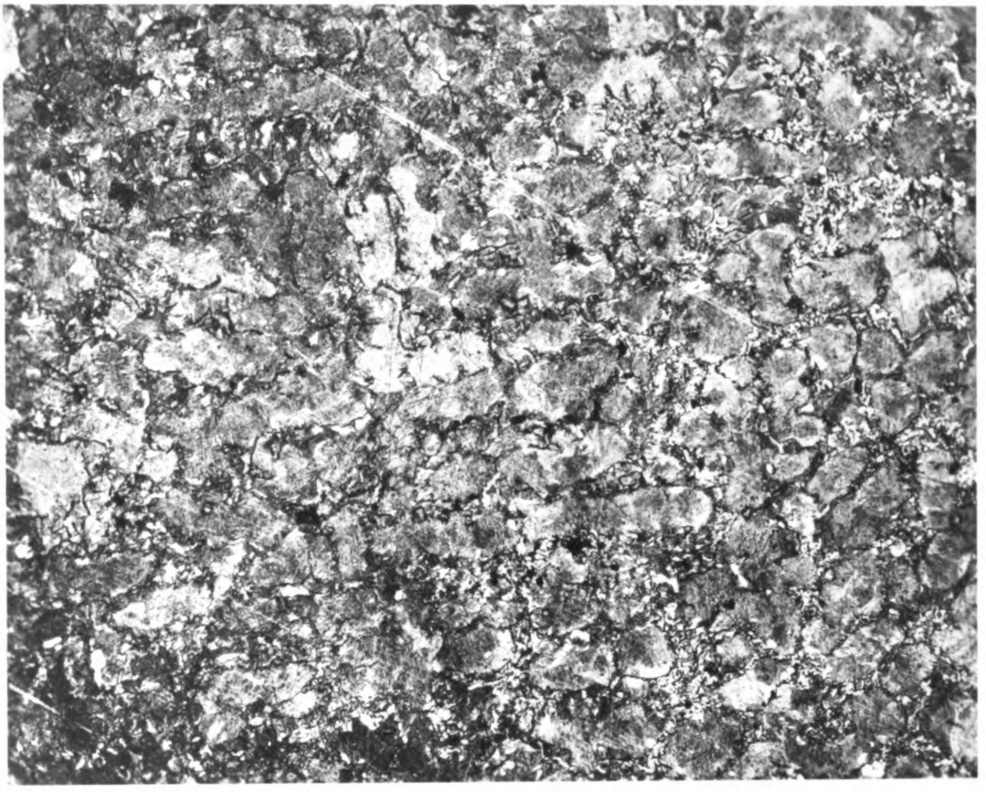
The etchant was a 2% nital-2% picral solution. The specimens for Micros at 100x were etched for 1 sec. only to bring out the graphite distribution and those for 250x were etched for 4 sec. to bring out the matrix structure.



M 1 loo X

3C7- Light etch with 2% picral-2% nital solution.

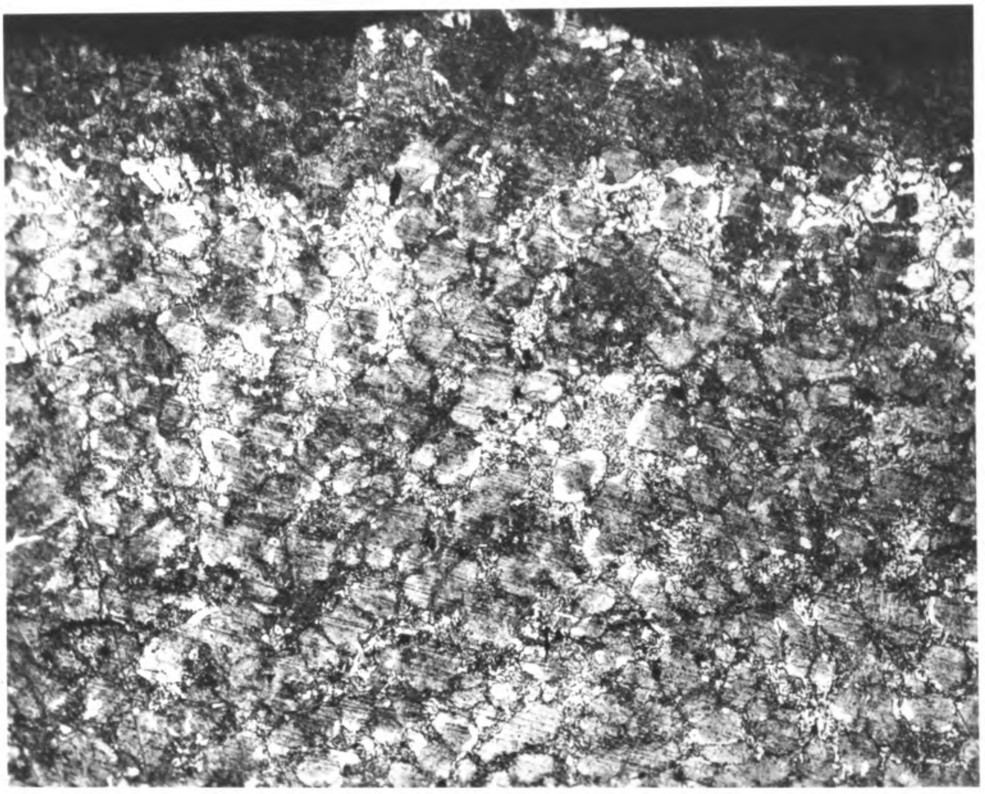
Type A (normal) graphite distribution.



M 2 100 X

3F1- Light etch with 2% picral-2% nital solution.

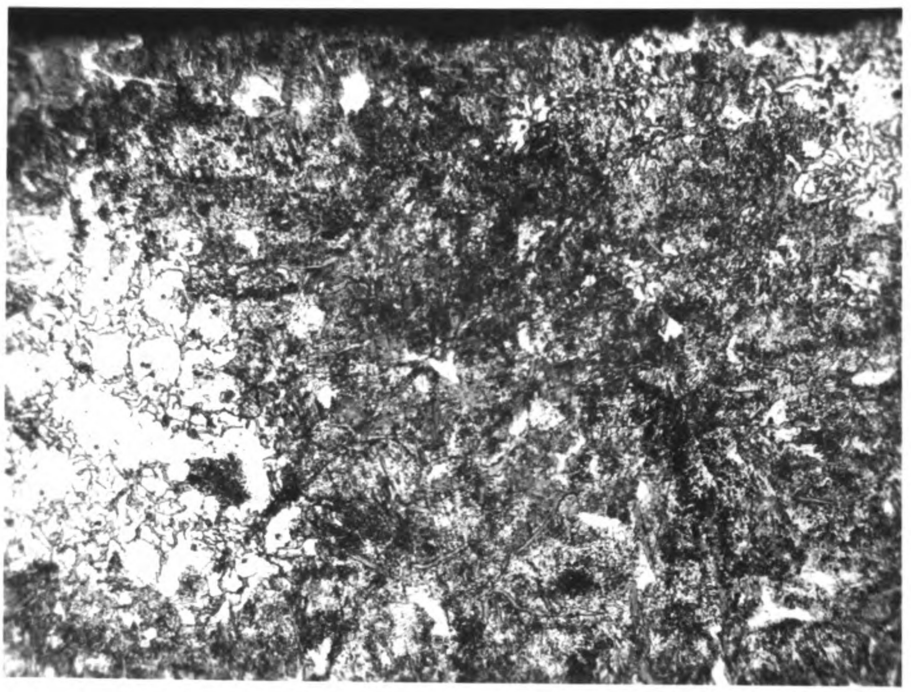
Mixed graphite distribution- type A and D.



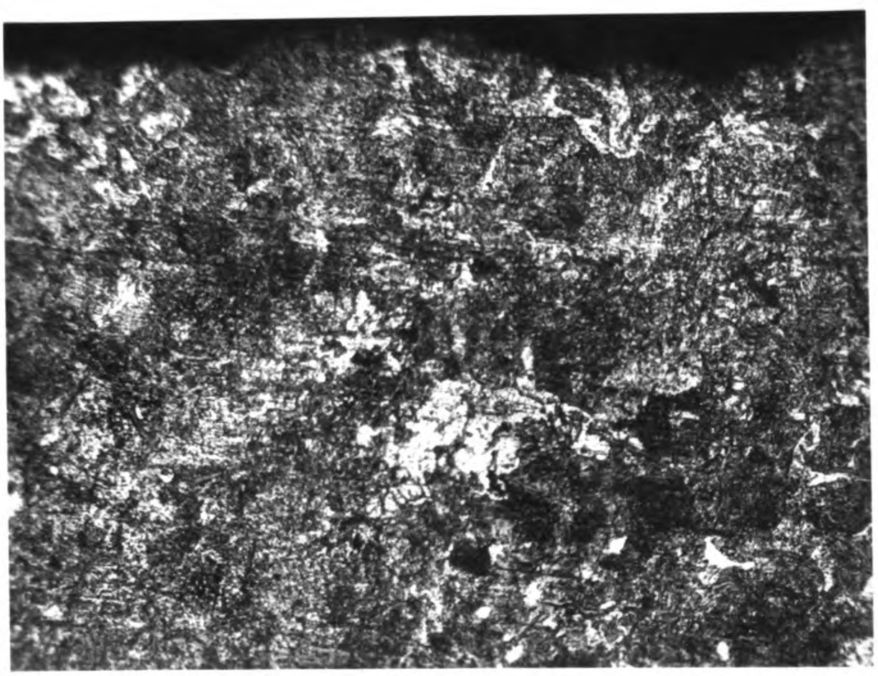
M 3 100 X

7B3- Light etch with 2% picral-2% nital solution.

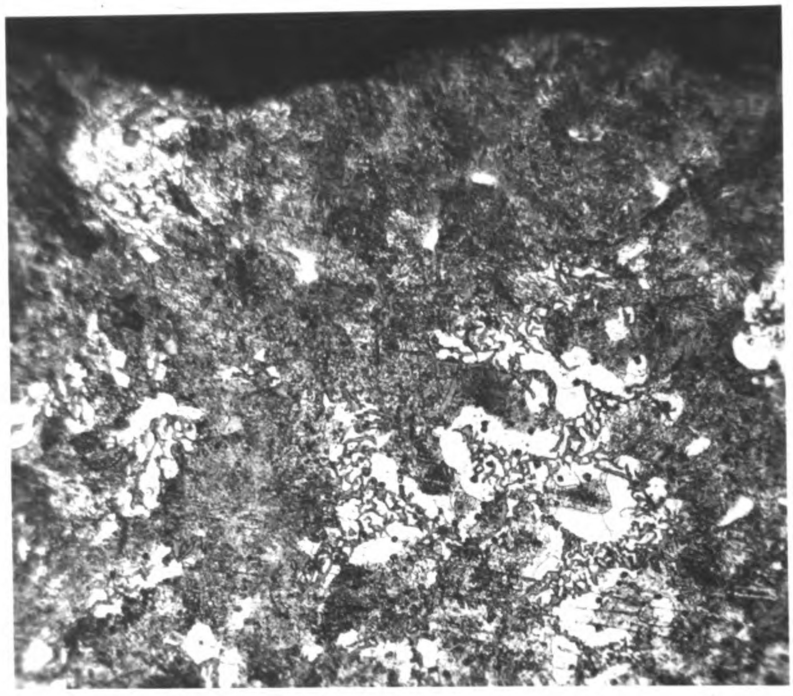
Type D graphite distribution.



M 4 2% Picral-2% Nital Etch 250 X
3F5- Surface- Mixed, D graphite with ferrite and A graphite with some ferrite (.5% Si pick up from Fe Si).

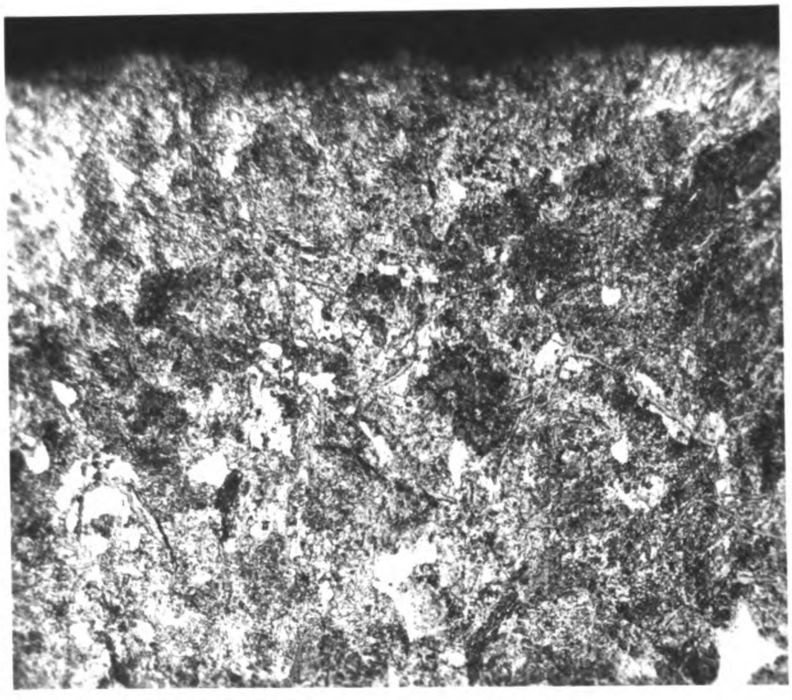


M 5 2% Picral-2% Nital Etch 250 X
3C7- Surface- A graphite with some ferrite
(.5% Si pick up from Ca-Si).



M 6 2% Picral-2% Nital Etch 250 X

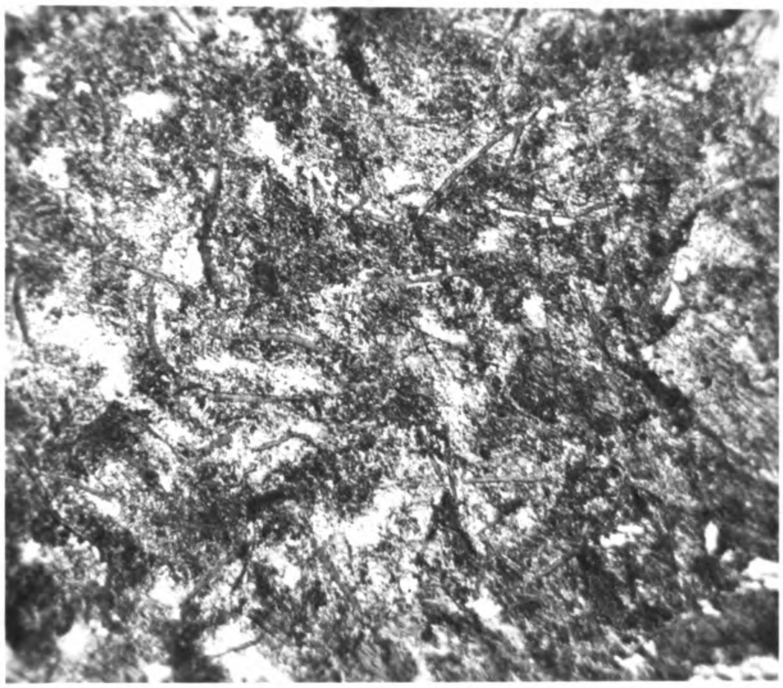
7B3-Surface-Type D graphite with fairley large amount of ferrite (Base iron, heat 7).



M 7 2% Picral-2% Nital Etch 250 X

7C3-Surface-Type A graphite with small amount of ferrite (.22% Ca added, heat 7)

M 8 2% Picral-2% Nital Etch 250-X
7B3-Core-Largely A graphite and some D graphite, some ferrite (Base iron, heat 7)



M9 2% Picral-2% Nital Etch 250 X
7C3 Core-Type A graphite very small amount of ferrite (.22% Ca added, heat 7)

8 - Condensation of Data, and Curves for Physical Properties

The accumulated data from the investigation was condensed and various curves were plotted in order that the physical properties resulting from different inoculants might be more easily compared. The average carbon content for each heat was recorded. The transverse test data was plotted from the best bar out of each ladle. The average values would have been incorrect in many cases because of possible surface defects on one or two of the bars from the ladle in question. The average value for chill was listed in the condensed data. The Brinell hardness showed no significant differences so it was recorded on the data sheets only. The condensed data concerning Fe-Si vs Ca-Si as inoculating agents was recorded in Fig. 28. The condensed data for base irons vs metallic calcium ladle additions was listed in Fig. 29.

A plot of the bending load vs the deflection was made in Fig. 30,to compare the effect of the inoculatns on the transverse properties. Curves for the physical properties vs the actual % Si pick up (Figs 31 and 32), vs the carbon equivalent (Figs. 33 and 34), and vs the % silicon (Figs. 35 and 36) were drawn from the first four heats to compare Fe-Si with Ca-Si ladle additions. The results from heats 3 and 4 were included in this paper as representative curves. The physical properties were plotted against the % Ca added (Fig. 37), for heats 4 and 7, to determine the effects of inoculation with metallic calcium. Curves were plotted in Fig 38 to compare the effects of Ca*Si additions on the

physical properties with the effects of Calcium metal Additions. The properties were plotted vs the % Ca added. The Ca-Si (30% Ca) additions of 26,105, and 184 grams were equivalent to .05, .20, and .35% metallic calcium added, respectively.

The actual % Si pick up to use for plotting Figs. 31 and 32 was based on the assumption that an addition of .1% Si as either Fe-Si or Ca-Si actually resulted in a .1% Si pick up. The actual % Si pick up was determined, for each ladle, from the chemical analysis for computed .3 and .5% Si pick up respectively. The actual % Si pick up for each ladle with Ca-Si additions was alos figured. Additions of .4 and .7% Si as Ca-Si were calculated to result in .3 and .5% Si pick up to compare with Fe-Si inoculation. The actual % Si pick up based on the chemical analysis follows: (Example for 1F3; %Si for 1F3-% Si for 1F1 2.15 - 1.97 .18 .18 .10 .28% Si pick up, actual)

For calculated .3% Si pick up

.3% Si added as Fe-Si	.4% added as Ca-Si
1F3 - .28%	1C5 - .41%(.5% Si added)
2F3 - .37	2C4 - .34
3F3 - .28	2C4 -.31

For calculated .5% Si pick up

.5% Si added as Fe-Si	.7% Si added as Ca-Si
1F5 - .49%	1C7 - .55%
2F5 - .62	2C7 - .65
3F5 - .45	3C7 - .55
4F5A- .45*	4C7A - .46
4F5B - .45	4C7B - .47

* (1.97% Si base iron)

		.1% Si PU*		.3% Si PU		.5% Si PU	
		Fe-Si	Ca-Si	Fe-Si	Ca-Si	Fe-Si	Ca-Si
	Code	1F1	1C1	1F3	1C5	1F5	1C7
Heat 1	% Si	1.97	1.89	2.15	2.20	2.36	2.34
	T.S.-#	2238	2386	2142	2730	2274	2801
	T.D.-"	.221	.258	.222	.365	.275	.394
	T.Ch.	19	15	13	6	10	6
	C.C.	11	8	7	5	7	5
	Brinell	207	197	201	197	207	207
	C Eq-%	3169	3.68	3.77	3.79	3.84	3.85
	Code	2F1	2C1	2F3	2C4	2F5	2C7
Heat 2	% Si	2.24	2.24	2.51	2.50	2.76	2.81
2.60%C	T.S.-#	2123	2273	2369	3142	2322	3115
	T.D.-"	.169	.174	.198	.372	.218	.355
	T.Ch.	15	24	20	7	12	5
	C.C.	10	16	12	5	8	4
	Brinell	229	229	223	229	217	229
	C Eq-%	3.35	3.35	3.44	3.42	3.51	3.54
	Code	3F1	3C1	3F3	3C4	3F5	3C7
Heat 3	%Si	1.98	1.93	2.16	2.14	2.33	2.36
2.82%C	T.S.-#	2226	2377	2270	2660	2562	3031
	T.D.-"	.176	.230	.218	.329	.281	.385
	T.Ch.	33	15	14	7	8	5
	C.C.	20	10	9	5	6	4
	Brinell	217	212	207	201	207	223
	C Eq-%	3.48	3.46	3.54	3.53	3.60	3.61
	Tensile	36800	38400	38000	36600	40700	43000

Code	4F5A	4C7A
% Si	2.42	2.43
T.S.-#	2269	2645
T. D.-"	.284	.374
Brinell	192	201
C Eq-%	3.83	3.83
Tensile	36000	42400
Code	4F5B	4C7B
% Si	2.42	2.44
T.S.-#	2276	2623
T.D.-"	.288	.334
Brinell	197	197
C Eq-%	3.83	3.83
Tensile	37400	42300

Note: * .1% Si pick up

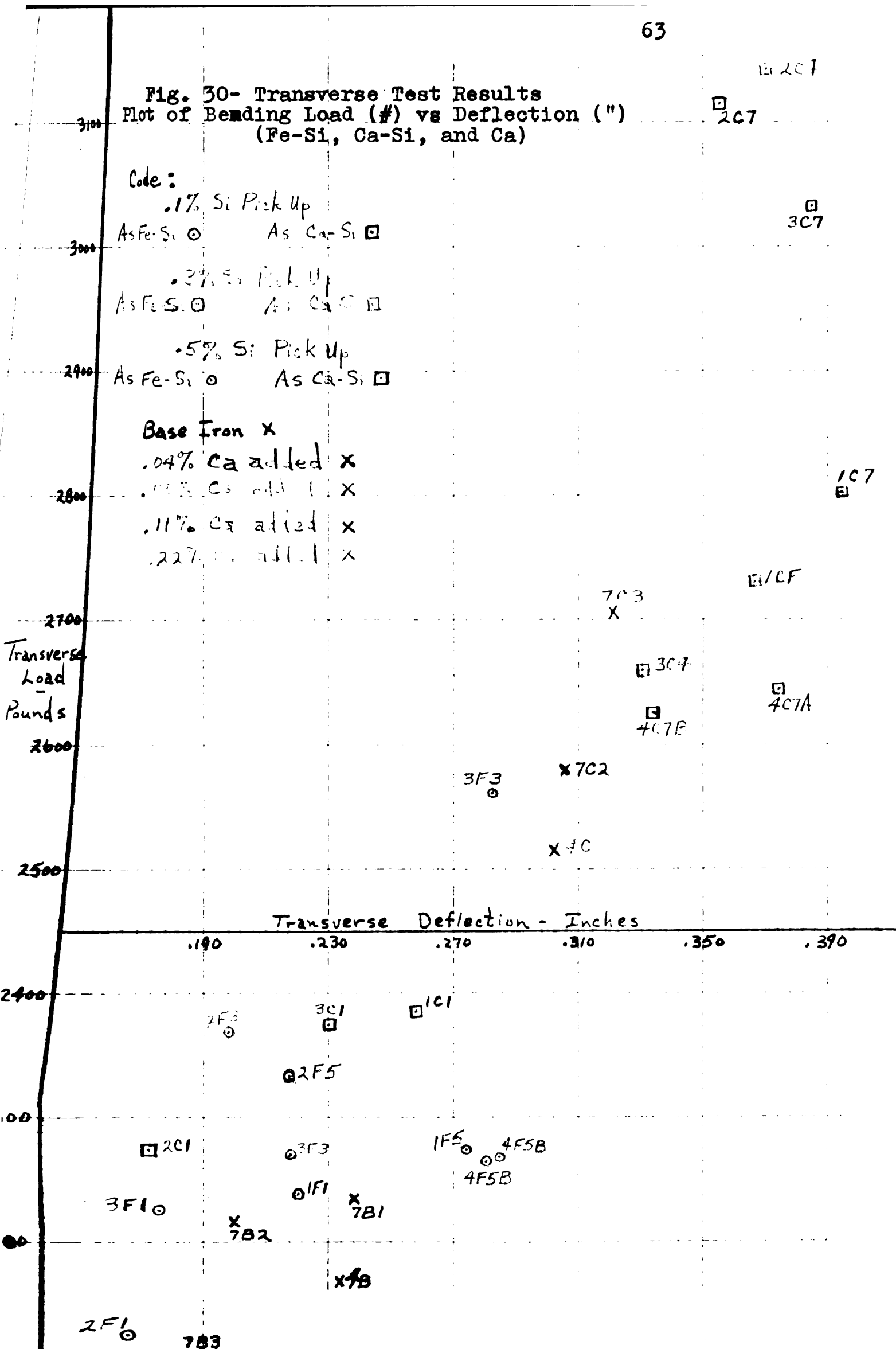
T. S. - Transverse Strength
T. D. - Transverse deflection
T. Ch - Total chill(16th of an")
C. Ch - Clear chill(16th of an")
C Eq - Carbon equivalent (C 1/3 Si)
Tensile (given in psi)

Fig 28 - Condensed Data on Physical Properties for Fe-Si Vs Ca-Si

	Base Iron	Ca Added
Heat 4	4B	4C - .06% Ca added
3.02%C	2168# - .235"	2 516# - .303
2.01% Si	201 Brinell	197 Brinell
C 1/3 Si -3.69%	37,400 psi	44,400 psi
Heat 7	7B1	7C1 - .04% Ca added
2.90% C	2235# - .238"	2235# - .220
2.24% Si	Chill-17 and 10	Chill - 18 and 9
C 1/3 Si-3.65%	212 Brinell	212 Brinell
	39,400 psi	38,800 psi
	7B2	7C2 - .11% Ca added
	2215# - .200"	2580# - .305"
	Chill-33 and 17	Chill-10 and 6
	212 Brinell	207 Brinell
	36,800 psi	45,400
	7B3	7C3 - .22% Ca added
	2105# - .187"	2705# - .321"
	Chill-33 and 16	Chill-9 and 4
	212 Brinell	212 Brinell
	37,800 psi	48,400 psi

Fig 29 - Condensed Data on Physical Properties for Base Irons vs Ca Additions

Fig. 30- Transverse Test Results
Plot of Bending Load (#) vs Deflection (")
(Fe-Si, Ca-Si, and Ca)



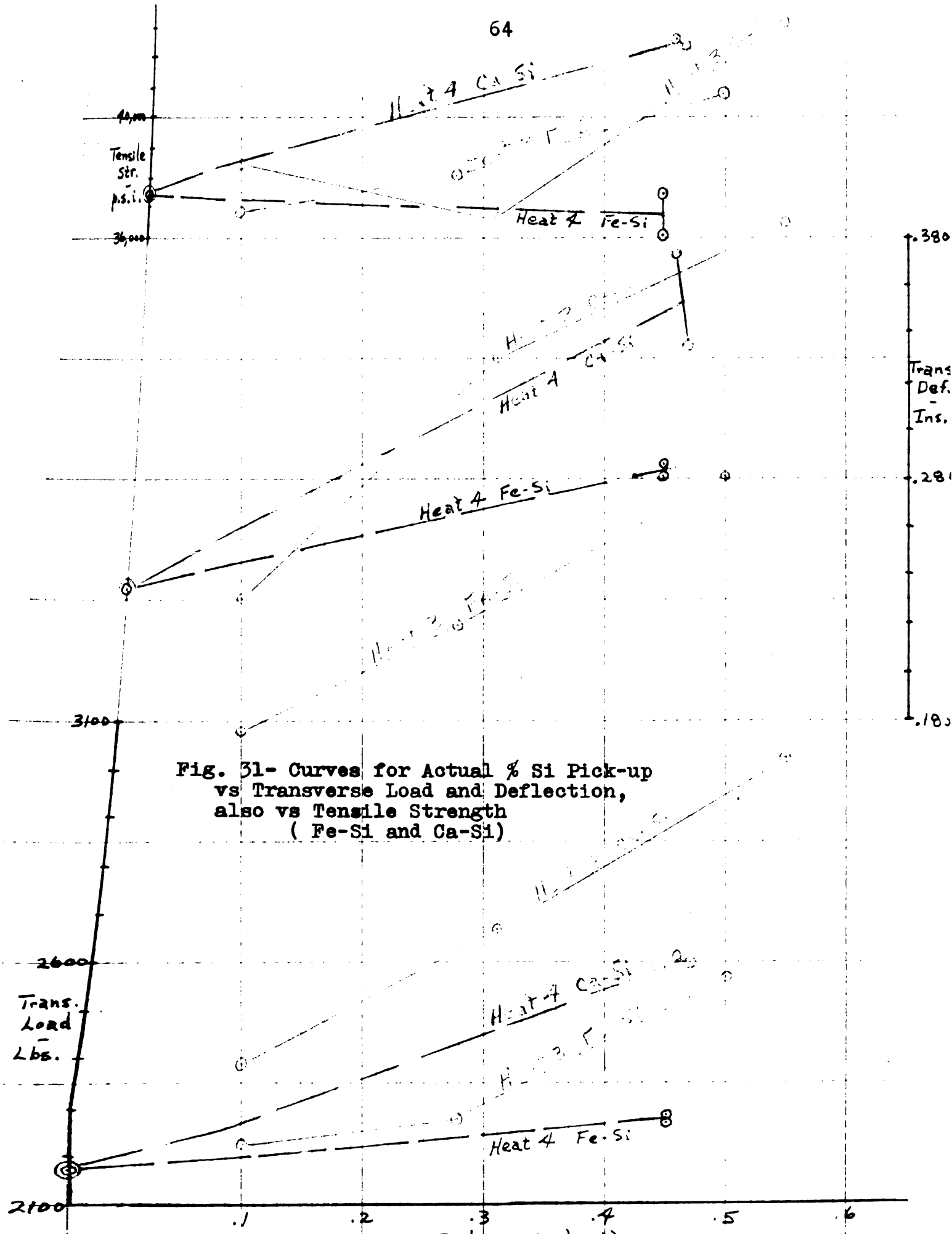
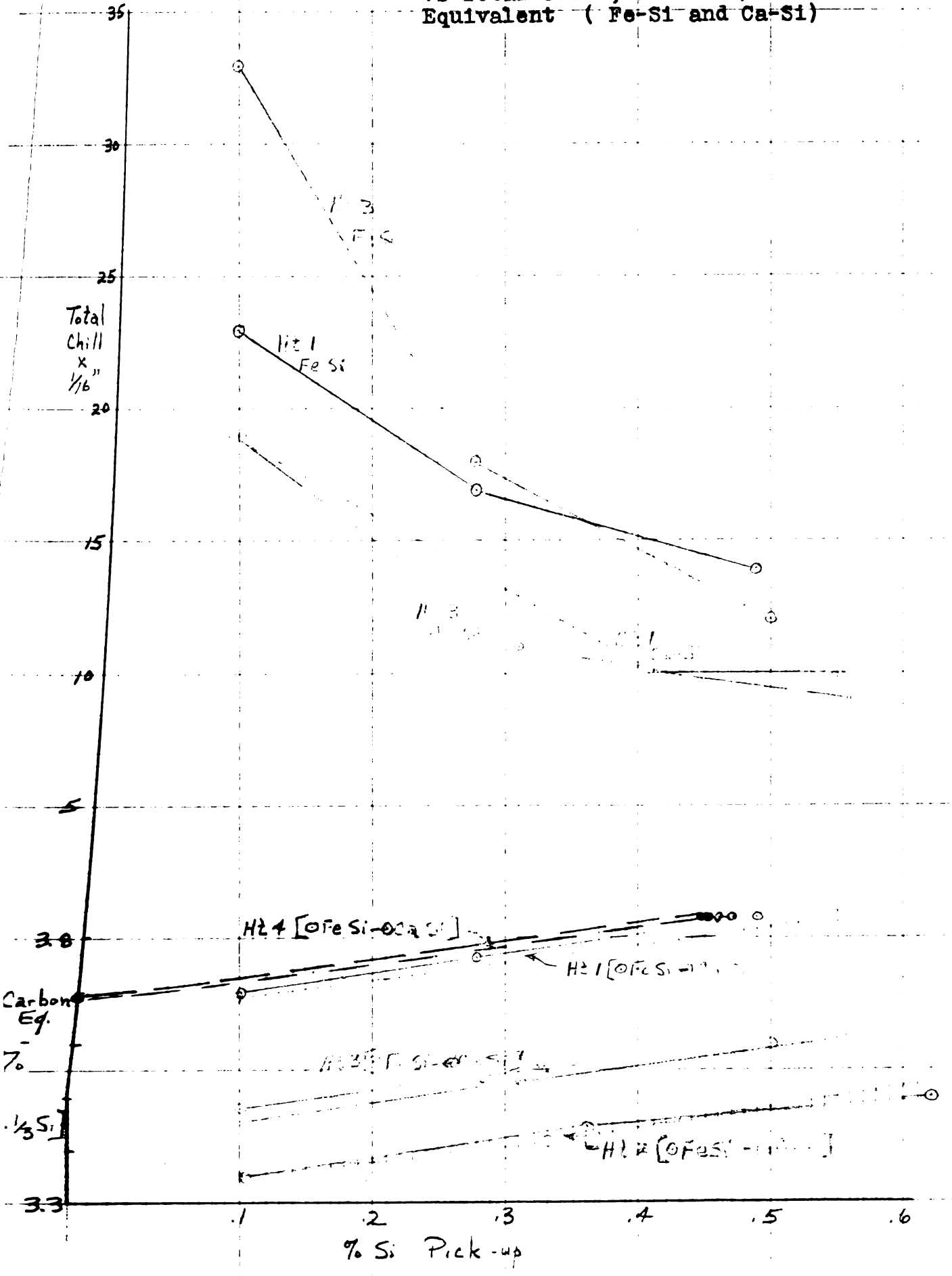


Fig. 31- Curves for Actual % Si Pick-up vs Transverse Load and Deflection, also vs Tensile Strength (Fe-Si and Ca-Si)

Fig. 32- Curves for Actual % Si Pick-up vs Total Chill, also vs % Carbon Equivalent (Fe-Si and Ca-Si)



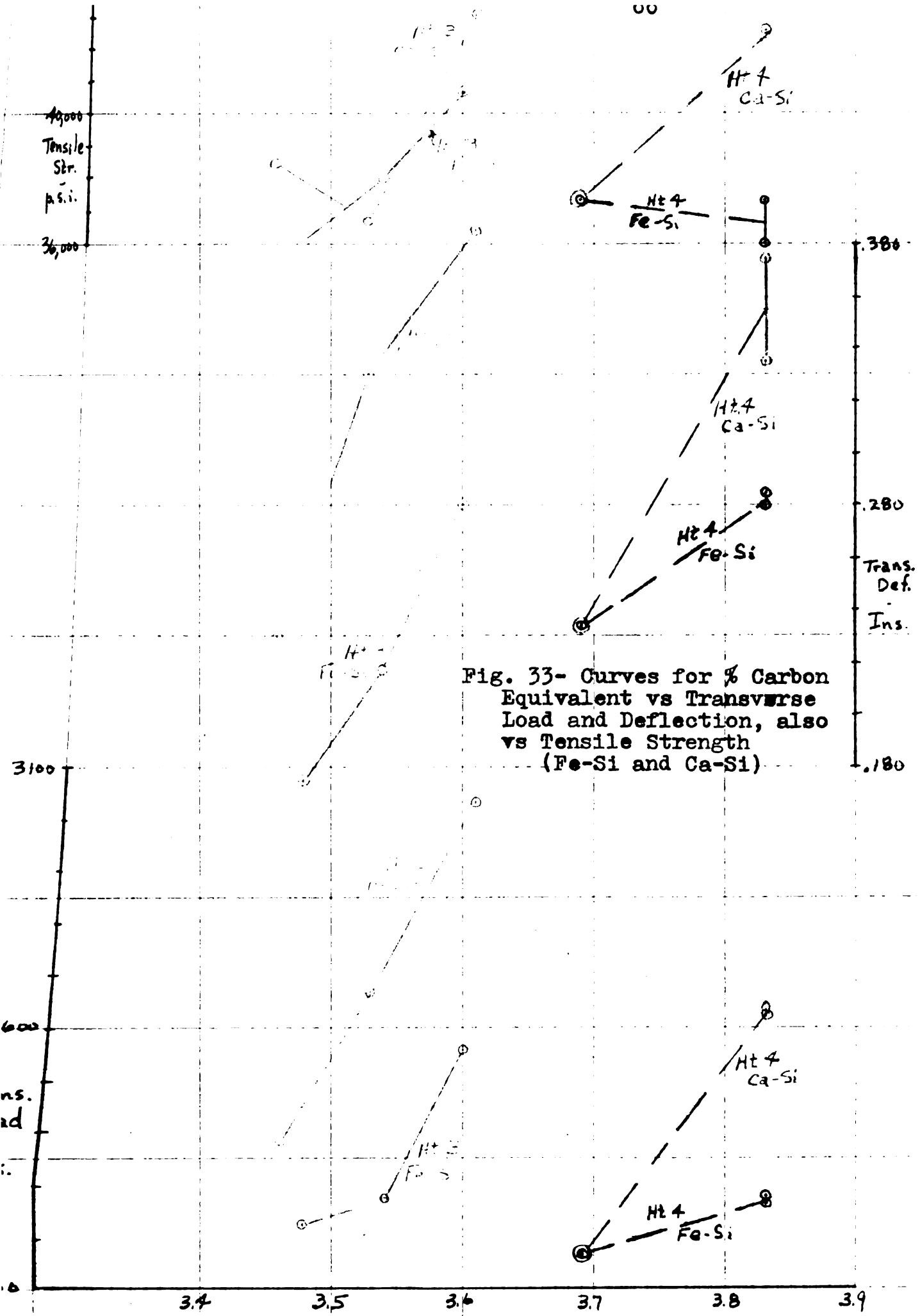
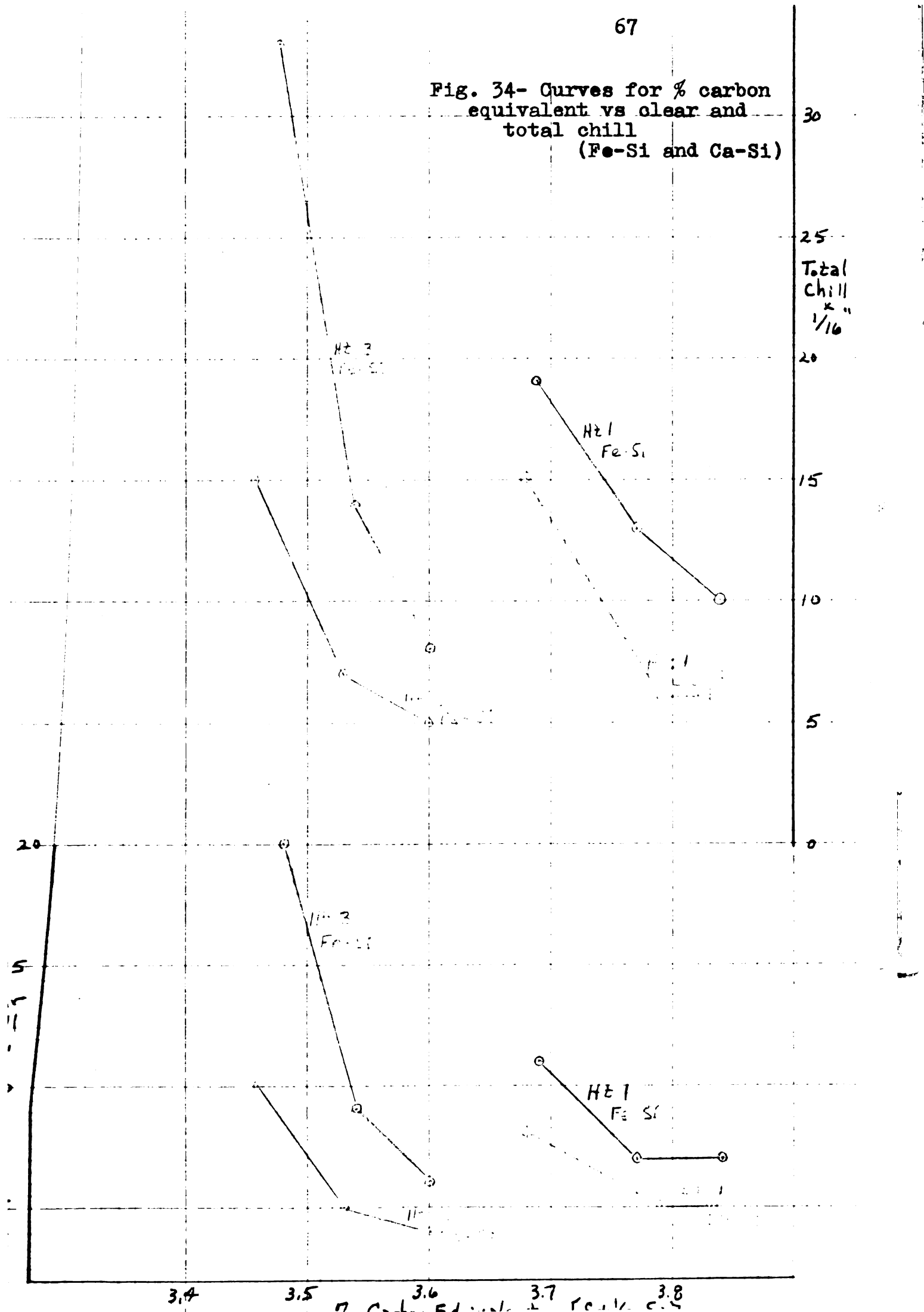


Fig. 33- Curves for % Carbon Equivalent vs Transverse Load and Deflection, also vs Tensile Strength (Fe-Si and Ca-Si)

Fig. 34- Curves for % carbon equivalent vs clear and total chill (Fe-Si and Ca-Si)



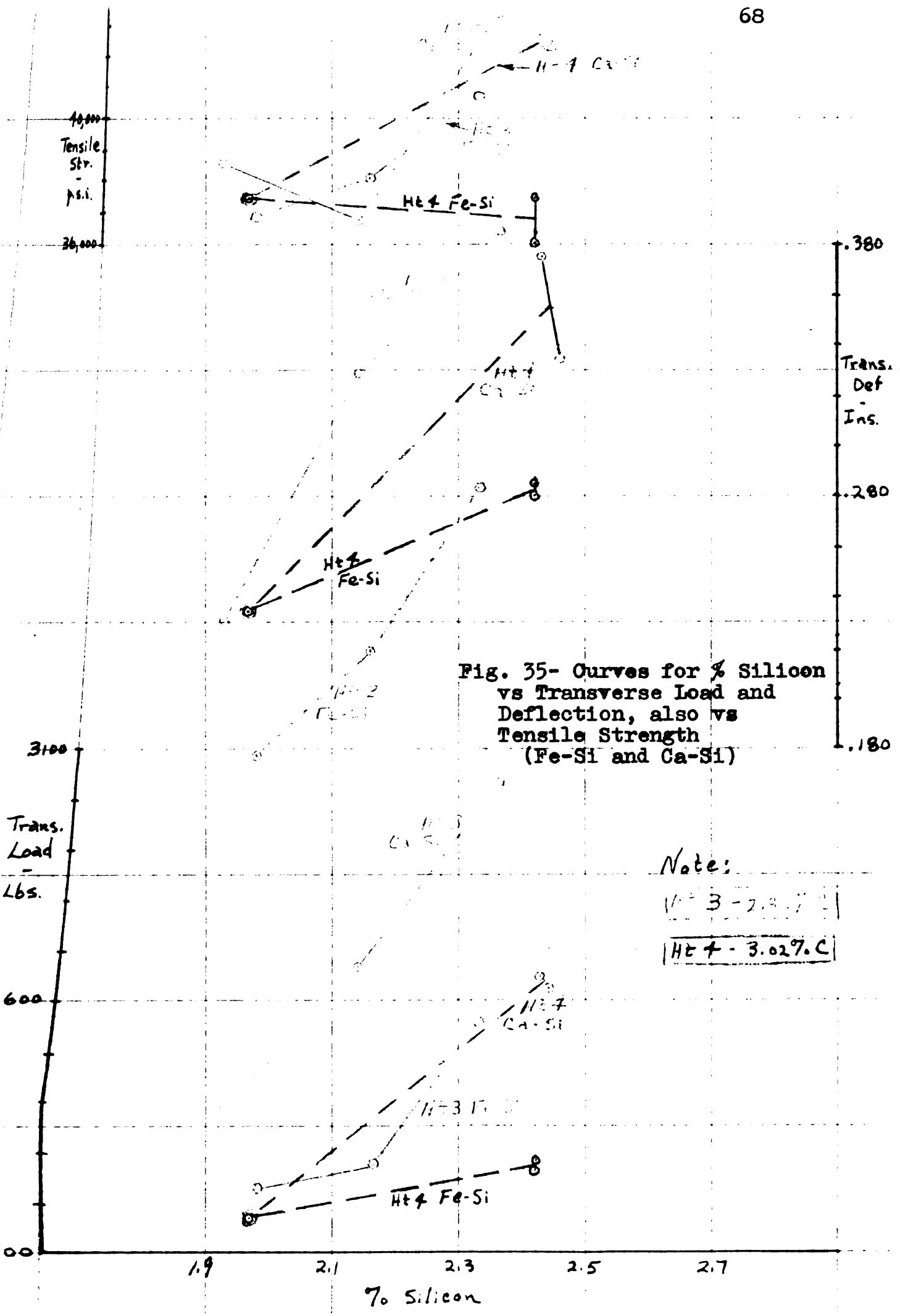


Fig. 35- Curves for % Silicon vs Transverse Load and Deflection, also vs Tensile Strength (Fe-Si and Ca-Si)

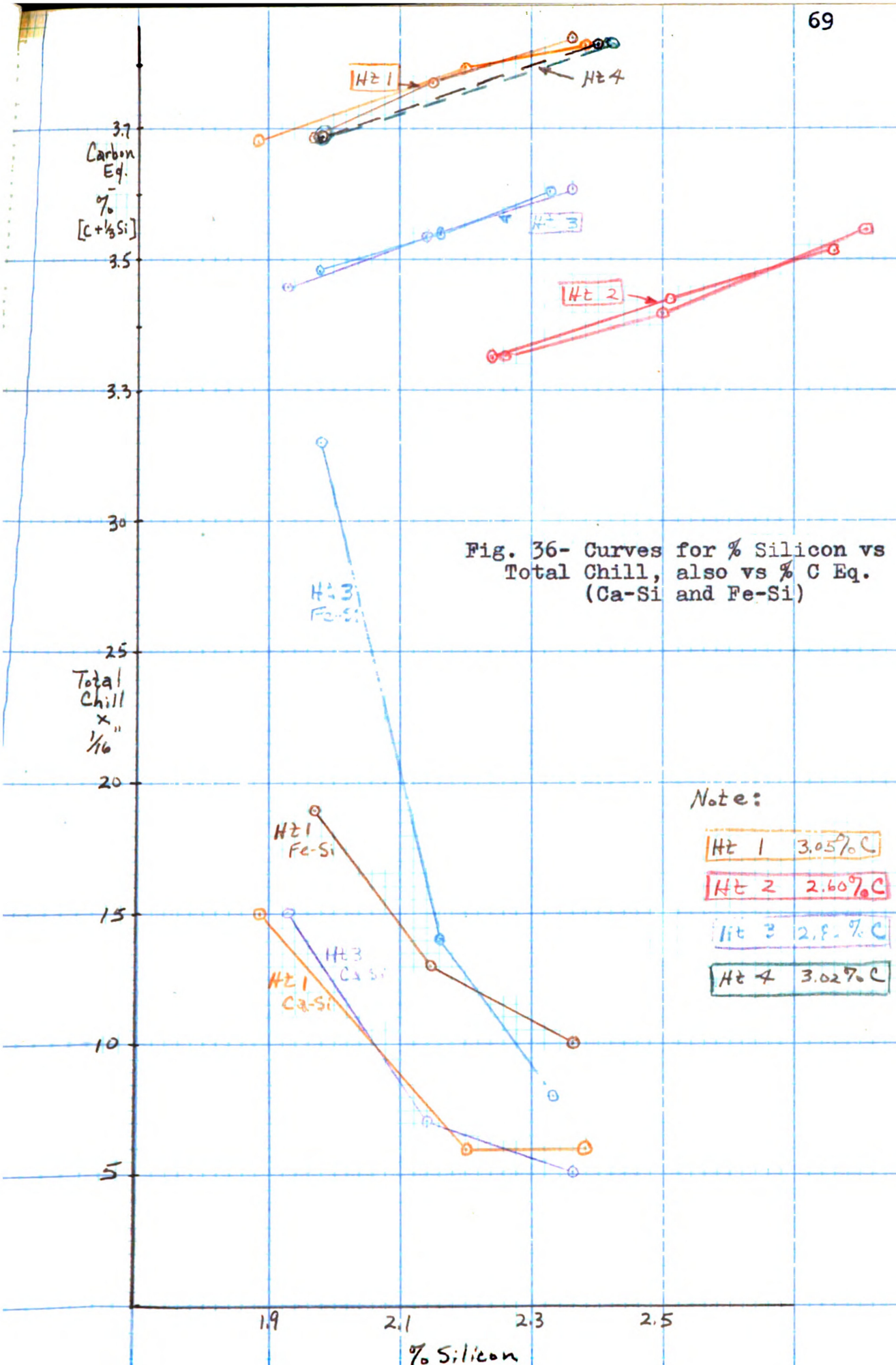
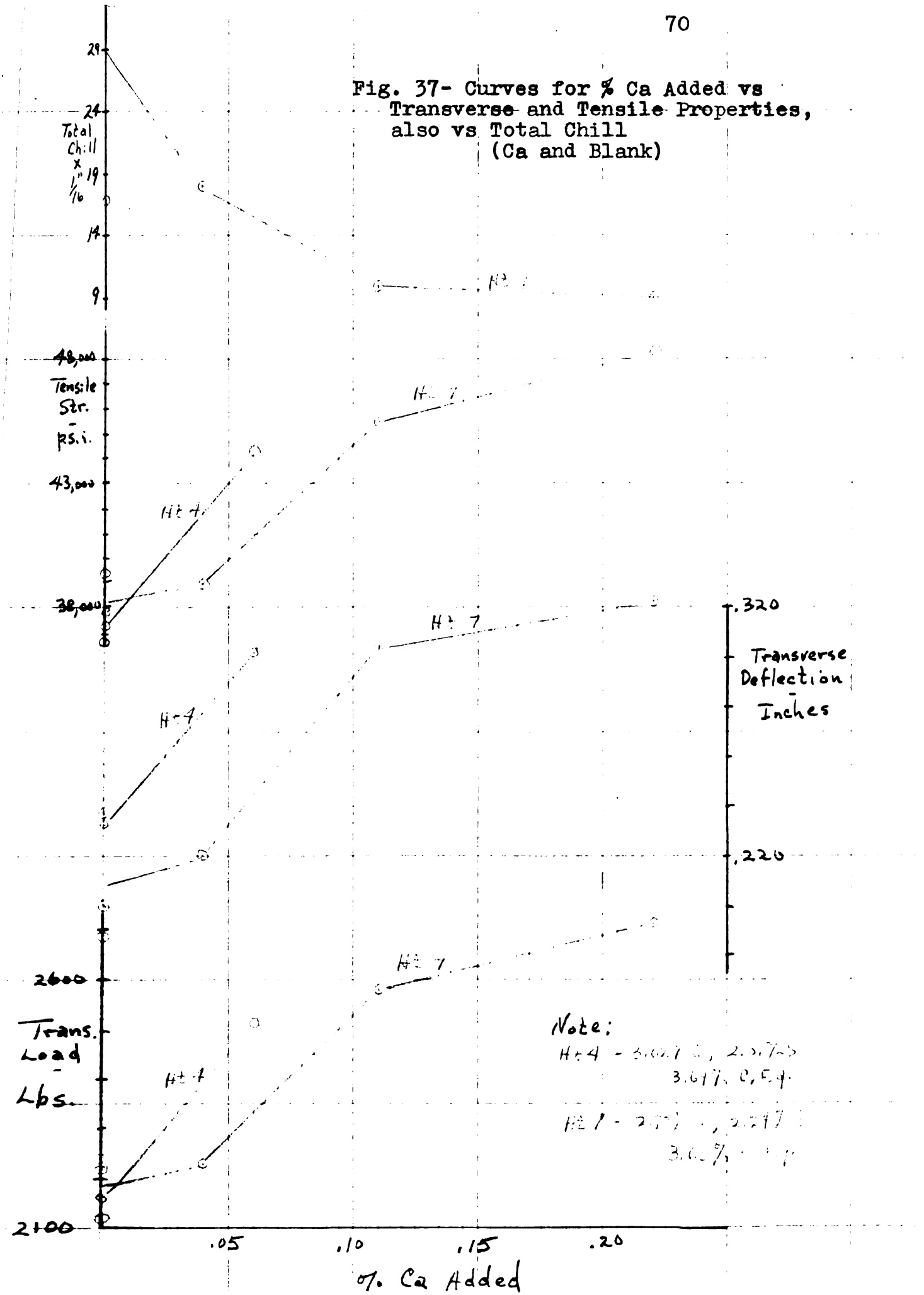


Fig. 36- Curves for % Silicon vs Total Chill, also vs % C Eq. (Ca-Si and Fe-Si)

Fig. 37- Curves for % Ca Added vs Transverse and Tensile Properties, also vs Total Chill (Ca and Blank)



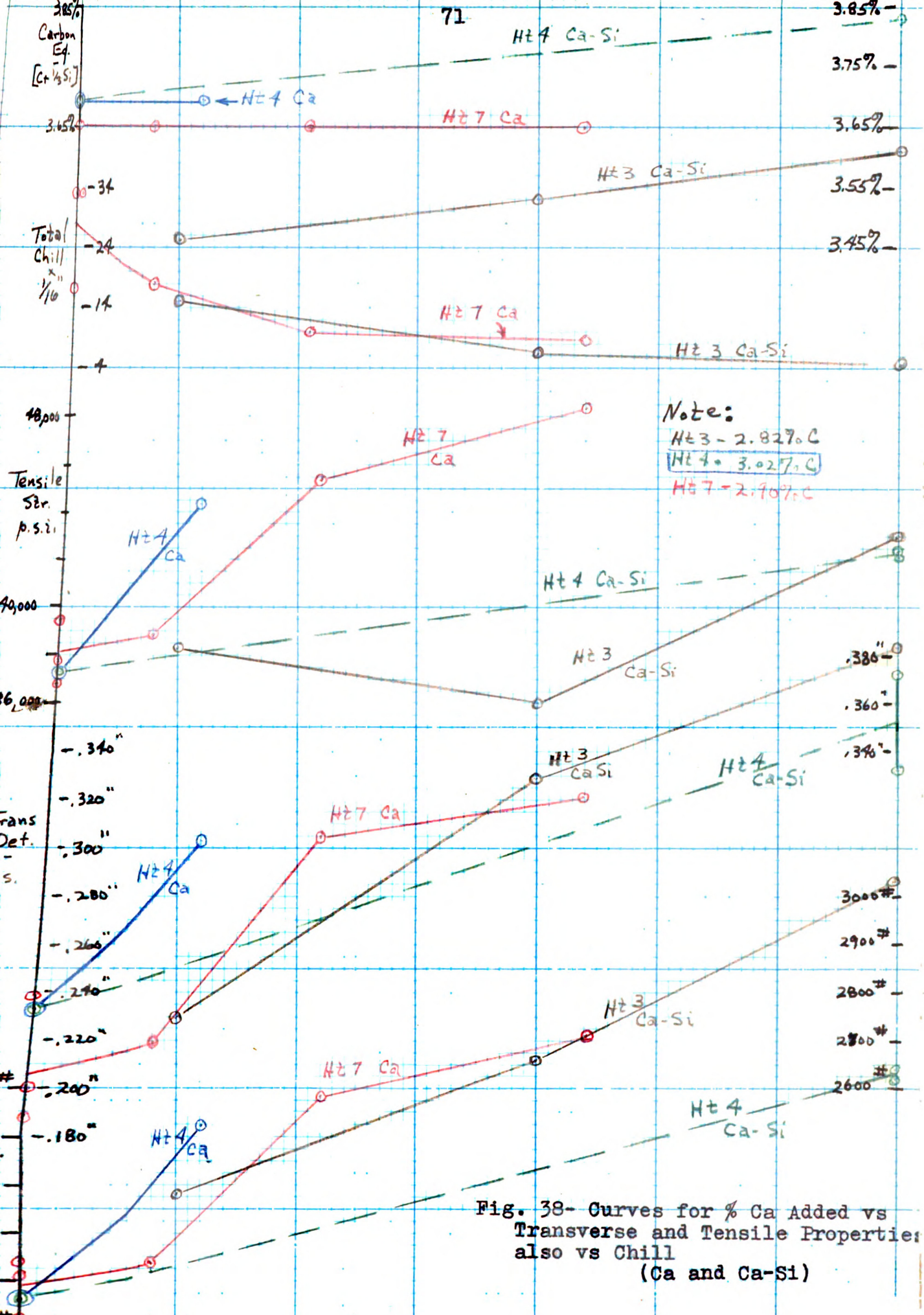


Fig. 38- Curves for % Ca Added vs Transverse and Tensile Properties also vs Chill
(Ca and Ca-Si)

D - Discussion

1 - Chemical Composition

The desirability of having similar chemical compositions for the comparison of Fe-Si with Ca-Si has been previously expressed in this paper. In all cases the silicon contents for each pair of ladles using these inoculants were very close (average difference ~.03%: maximum difference -.05%). During the tapping of the heats the carbon content decreased as much as .16% in one instance but the maximum difference noted for any pair of ladles was .06%. The sulphur content was analyzed at .05 to .06% for heat 3 but was adjusted to meet the desired .08% in the later heats. Other constituents were believed to be similar to the desired analysis by calculation and were not determined analytically.

Heats 1,3 and 4 were close to the desired carbon and silicon analysis for the base iron. Heat 7 was adjusted to provide a silicon content, for an iron with Ca additions, similar to the total silicon acquired after a silicon bearing inoculant (.3 to.7% Si added) had been added. The carbon content for heat 7 was similar to that desired.

The curves for carbon equivalent vs % Si, at the top of Fig. 36, show that heats 1 and 4 were very similar as to total silicon and carbon equivalent at all levels. Heat 3 was similar to these in regards to total silicon but the carbon equivalent was less. Heat 2 had a considerably higher silicon content but its low carbon

content placed it far below the other heats for carbon equivalent. The curves at the top of Fig 38 indicated that heat 7 was between heats 3 and 4 for carbon equivalent.

The data on chemical analysis has shown that heats 3, 4, and 7 had comprable compositions and might be readilly compared; therefore these heats were chosen for representative curves. The curves at the bottom of Fig 32 indicated that the % Si pick up from Fe-Si or Ca-Si was practically the same at all levels throughout the heat, another factor to promote reliable comparisons.

2 - Transverse strength and Deflection

The accumulated evidence on the transverse properties of the irons under investigation conclusively pointed to the superiority of Ca-Si over Fe-Si as an inoculating agent. The data on ladle additions of metallic calcium indicated that Ca (up to .22% Ca added) was at least as good as Ca-Si and possibly even more effective.

The only data in the published literature comparing Ca-Si with Fe-Si additions (see page 19) could not be considered satisfactory beacause additions of .2% Si as Ca-Si were compared with .5% Si as Fe-Si. The fact that the physical properties of these irons were comprable, although much less Ca-Si had been added, suggested the possibility that Ca-Si was more effective as an inovulant. One author (see page 23) stated that Ca-Si showed no advantage over Fe-Si with .4% Si added in either case. There was no data supporting this statement, therefore it could be given little if any consideration as a reliable source if infor-

mation. No data concerning Ca inoculation was discovered in the literature.

The curves in Fig 31 showed that in heat 3 a .5% Si pic k up from a Fe-Si ladle addition provided the same transverse properties as a .2% Si pick up form a Ca-Si addition. All of the other heats presented a less favorable comparison for Fe-Si. At .5% Si pick up for both inoculants in heat 3, the Fe-Si addition showed 2560# and .280" while the Ca-Si addition showed 2940# and .370".

Fig. 33 indicated that in general the lower carbon equivalent irons provided superior transverse strength and inferior transverse deflection when comparing Fe-Si or Ca-Si additions between heats. It was noted that the transverse load dropped from 3035# for heat 3 to 2625# for heat 4 with an approximate .5% Si pick up from Ca-Si. With Fe-Si the drop was from 2,560# to 2,275#. The transverse deflection stayed at about the same level for both high and low carbon equivalent irons at the maximum additions of Fe-Si and Ca-Si. For Ca-Si heat 3 was .385" and heat 4 was .350" average; for Fe-Si there was no change from .280".

The plot of transverse properties vs the total % silicon in Fig. 35 also revealed the extent of the impovement gained in all cases by using Ca-Si as an inoculant.

Fig. 37 indicated that increasing amounts of Ca improved the transverse properties. In Fig. 38, comparisons were made for the transverse properties between Ca and Ca-Si ladle additions. Even though the carbon equivalent

of heat 7 was greater than heat 3 the transverse strength and deflection were similar for similar amounts of Ca added. For heat 4 the small addition of Ca improved the transverse properties to a greater extent than similar amounts of Ca added as Ca-Si. It should be noted that although the lines for Ca-Si in heat 4 were dotted, indicating that no intermediate values were determined, the probability that the actual values would fall near to this curve would be great (compare with Ca-Si additions for heat 3, Fig 31).

The transverse breaking load has been recorded vs the transverse deflection for the representative bar from each ladle poured during this investigation. With but one exception, all of the points representing base irons, .1% Si pick up from Ca-Si and Fe-Si, .3% and .5% Si pick up from Fe-Si, and a .04% addition of metallic calcium fall in the lower left hand corner (.150" to .2 85" deflection and 2,100# to 2,400# load). The lone point in the upper left hand corner was the .5% Si pick up from Fe-Si for heat 3. In the upper right hand corner (.300" to .395" deflection and 2,500# to 3,150#) the points representing .3% and .5% Si pick up from Ca-Si, and Ca additions from .05% to .22% were located. This would indicate the definite advantage to be gained by using Ca-Si or Ca as an inoculant, rather than Fe-Si, to improve the transverse properties.

3 - Chill Characteristics

Ca-Si and Ca were found to be more effective chill reducers than Fe-Si, particularly when comparing the smaller additions of these inoculants. The curves for clear chill

followed the same pattern as those for total chill, so usually the characteristic curves for total chill were presented. Curves from he ts 1, 3 and 7 were used to compare the chill tendencies of the different inoculants.

Fig. 32 shows that the greatest differenee between Ca-Si and Fe-Si occurs at the .1% Si pick up level for heat 3 (33/16" for Fe-Si and 15/16" for Ca-Si). On heat 1 the comparison was 1 9/16" for Fe-Si to 15/16" for Ca-Si. At the .5% Si pick up level the corresponding differences were from 8 to 5 and from 10 to 6 sixteenths respectively for heats 1 and 3. An examination of the curves indicated that .3% Si addition as Ca-Si was as effective as a .5% Si addition from Fe-Si.

The curves in Fig. 34 included the clear chill and total chill vs the carbon equivalent. Ca-Si inoculation was as effective, in all proportions, for reducing chill on a low carbon equivalent iron (3.55% average) as for a higher carbon equivalent iron (3.75% average). This was not true for Fe-Si additions as evidenced by the curves for heats 3 and 1, respectively.

The plot for chill depth vs .% silicon presented an excellent graphical picture of the superiority of Ca-Si, as a chill reducing inoculant, over Fe-Si. The curves for Ca-Si additions were observed to coincide while the Fe-Si curves were considerably higher for heats 1 and 3.

The curves comparing the effect on chill from Ca additions in heat 7 with Ca-Si additions in heat 3 followed approximately the same path with increasing Ca additions. It was concluded that Ca and Ca-Si were similar in their

action on chill and were both superior to Fe- Si inoculation.

4 - Hardness

The data for Brinell hardness (Fig 21) did not show any significant trend for comparing the effects of the different inoculants on this property. The maximum spread during the entire course of this investigation was from 192 to 229, a difference of 37 points. Heat 3 was the most erratic of all with a variation from 201 to 223 BHN. The variation on ther heats was from 5 to 12 hardness numbers.

5 - Tensile Strength

The available data for comparing the effects of Fe-Si with Ca-Si inoculation on the tensile strength indicated that Ca-Si was more effective than Fe-Si with the maximum additions of each. The curves for heat 3, Fig 31, showed a dip in the curve for Ca-Si with .3% Si pick up that could not be accounted for, although at the maxium additions Ca-Si was superior to Fe-Si.

In Fig. 33 the evidence pointed to the conclusion that Ca-Si provided similar improvement on the tensile strength for two irons which exhibited differnet carbon equivalents. In contrast, additions of .5% Si as Fe to a higher carbon equivalent iron actually resulted in a slightly lower tensile strength while on a lower ca rbon equivalent iron the improvement was only slightly lower than for silimar additions of Ca-Si. Evidently the lower carbon content of heat 3 as compared with heat 4 was the main

factor contributing to the above effects from Fe-Si because the total silicon contents were similar (see top of Fig 35.).

Inoculation with metallic calcium was definitely superior to the other inoculants in regards to improvements of tensile properties. In Fig.38 the tensile curves for Ca additions exhibited a decided rise as compared with similar amounts of Ca added as Ca-Si. Improvement developed by .22% metallic Ca added to the ladle amounted to 10,000 psi. The maximum improvement noted from Ca-Si was approximately 5,000 psi and for Fe-Si 4,000 psi.

6 - Graphite Distribution and Microstructure

Although there were no significant differences noted in the pearlite matrix structures throughout this investigation, variations were noted in the amounts of ferrite and in the graphite distributions. According to several papers presented in the discussion of the published literature the physical properties were improved when the microstructure and graphite distribution were improved. This correlation was noted in the present investigation.

When comparing Ca-Si with Fe-Si ladle additions for heats 1,3 and 4 it was found that the principle differences in microstructure occured at or near the surface of the test bars. In all of these heats the core graphite distributions were normal (Micro 1), and the Ca-Si additions exhibited somewhat less free ferrite in the core.

The maximum addition of Ca-Si (.5% Si pick up) produced type A graphite with a very small amount of ferrite for these heats (Micro 5). The maximum Fe-Si addition (.5% Si pick up) produced a mixed graphite structure (Micro2) at the surface with more ferrite in heats 1 and 3 (Micro4), and was similar to Ca-Si for heat 4. Smaller additions of these inoculants for heats 1 and 3 indicated in the surface graphite distribution for Ca-Si at similar levels.

Heat 2 showed that inoculation with Ca-Si provided improvements in the graphite distribution over Fe-Si for similar amounts added to the ladles. In fact, at the surface, the maximum addition of Fe-Si resulted in D type graphite formation (Micro3) and inoculation with a similar amount of Ca-Si produced a normal graphite structure.

Improvements were noted as a result of metallic calcium additions to the base iron of heat 7. The base iron exhibited type D graphite at the surface (Micro6), which was mixed with type A graphite in the core (Micro8). An addition of .22% Ca in the ladle produced a normal graphite pattern throughout with much less free ferrite. (Micros 7 and 9) Smaller additions of Ca caused lesser improvements in the distribution of the graphite and ferrite. It was noted that the maximum additions of Ca-Si and Ca used during this investigation always produced irons with normal graphite distributions and little or no free ferrite.

E - Summary and Conclusions

Fe-Si and Ca-Si have been widely used as inoculants since the paratice of making late additions to gray cast iron was started. An investigation has been carried out to determine the relative effectiveness of these inoculants and also to make comparisons with ladle additions of metallic calcium.

Although considerable attention has been given to inoculation theory and practice in the metallurgical literature there has been little or no data given which presented a valid comparison between the effects of Ca-Si and Fe-Si inoculation. The effect of the presence of Ca in the inoculating agent, or as an inoculant by itself has not been discussed in any of the literature.

Data was presented in this investigation on base irons of 2.6% C - 2.15% Si and 3.82 to 3.05% C - 1.93 to2.01% Si for Fe-Si and Ca-Si ladle additions. Data for inoculation with metallic calcium on base irons of 3.02% C -2.01% Si and 2.90% C- 2.24% Si was also presented.

Comparisons were made of the effects of Fe-Si, Ca-Si and Ca on the transverse strength and deflection, tensile strength, chill depth, hardness, graphite distribution and microstructure. It was concluded that, as inoculants, Ca and Ca-Si were definitely superior to Fe-Si in all instances, except that no significant differences were observed in the hardness data.

The relative effects on the various properties are summarized below:

1- Transverse strength and deflection - At all levels of silicon pick up from Fe-Si and Ca-Si (.1% to .5%), Ca-Si was superior. The advantage of using Ca-Si over Fe-Si increased as the amounts of the additions increased. The effect os a .2% Si pick up from Ca-Si was equivalent to that of a .5% Si pick up from Fe-Si. Ladle additions of metallic calcium were equal to or better than similar additions of Ca added as Ca-Si up to .22% Ca(maximum Ca metal addition).

2- Tensile strength - Additions of Ca were far superior to Ca-Si and Fe-Si in their effect on the tensile strength. Ca-Si was somewhat better than Fe-Si in this respect.

3- Chill depth - Ca and Ca-Si inoculation produced similar effects on the reduction of chill. In all instances Ca-Si, and therefore Ca, was superior to Fe-Si for chill reduction. An addition of .5% Si as Fe-Si was no more effective than a .3% silicon pick up from Ca-Si.

4 - Graphite distribution and microstructure - Distinctive differences were noted in the graphite distribution and the amount of free ferrite at the surface of test bars from ladles inoculated with Fe-Si, Ca-Si and Ca. The effects of Ca and Ca-Si were similar in that normal graphite sturctures with very little free ferrite were produced throughout the samples with the larger additions of these inoculants. In some instances, type D graphite with a considerable amount of free ferrite were observed near the surface of irons inoculated with a .5% addition of Si as Fe-Si. Comparisons of smaller additions, at similar levels, showed that Ca-Si

always produced less D graphite and less ferrite near the surface than Fe-Si.

The presence of calcium in the most successful inoculating agents suggested that the solidification characteristics of the base irons investigated were influenced by the resulting greater exothermic action from additions of this element.

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