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SUBJECT

Report on  
Studies on Solidification and Contraction in Steel  
Castings - The Free and Hindered Contraction  
of  
Alloy Cast Steels

by

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NAVY DEPARTMENT  
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Report on

Studies on Solidification and Contraction in Steel  
Castings - The Free and Hindered Contraction  
of  
Alloy Cast Steels.

NAVAL RESEARCH LABORATORY  
ANACOSTIA STATION  
Washington, D.C.

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## ABSTRACT

Studies are continued on the free and hindered contraction of cast steel. The contraction characteristics were obtained on eleven alloy steels whose carbon contents were similar. The contraction is hindered by means of springs and the resulting stresses and the amount of contraction correlated. Experimentation showed that the total contraction of the alloy steels was similar to that of a plain carbon steel.

This report on steel casting research is one of a series of reports on the basic principles of solidification and contraction in steel casting. The reports in this series that have been issued to date are as follows:

1. Studies on Solidification and Contraction and Their Relation to the Formation of Hot Tears in Steel Castings, March 1933.
2. Report on Solidification Studies on Cast Steel (Progress Report), Report No. M-1058, February 15, 1934.
3. Free and Hindered Contraction of Cast Carbon Steel, Report No. M-1075, December 20, 1934.
4. Report on Solidification Studies on Cast Steel (Progress Report), Report No. M-1122, January 2, 1935.
5. The Role of Hot Tears in Cast Steel (Final Report and Progress Reports M-1076 and M-1120), Report No. M-1122, August 15, 1935.
6. The Free and Hindered Contraction of Alloy Cast Steels, Report No. M-1123, January 13, 1936.

It is hoped that upon the final completion of these basic studies all the reports will be collected and presented in one complete monograph.

### AUTHORIZATION

1. The studies in steel casting research were originally authorized by the Bureau of Engineering letter QP/Castings(6-13-Ds) of 13 July 1928.

### STATEMENT OF PROBLEM

2. The object of this report is to present the data obtained from a study made on the properties of free and hindered contraction of several alloy cast steels.

### THEORETICAL CONSIDERATIONS

3. A study of the contraction taking place in the cooling of steel castings from the solidifying temperature of the steel to room temperature was first made by Körber and Schitzkowski (1)\*. Their data, however, were rather incomplete since various observations seemed to indicate that changes in the carbon content of cast steel would be responsible for variations in the linear contraction.

4. In the third report of this series (2), a study was made of the free and hindered contraction of cast steels of varying carbon contents. Several principles of a fundamental nature were disclosed by the data.

- (a) The total amount of free contraction of cast carbon steel decreases as the carbon content of the steel increases. The contraction varies from 2.47 percent for 0.08 percent carbon steel to 2.18 percent for 0.90 percent carbon steel.
- (b) The total amount of contraction taking place prior to reaching the critical range, in the case of the freely contracting bar, decreases as the carbon content of the steel increases.
- (c) The amounts of contraction obtained after the freely contracting bars have passed through the critical range are approximately equal.
- (d) In the case of the freely contracting and the lightly hindered contracting bars, the carbon content influences the rate of contraction markedly until the bars have contracted approximately 0.10 percent.
- (e) Hindered bars contract similarly to the freely contracting bars in that, at any temperature prior to the critical range, the amount of contraction is greater with decreasing carbon contents.
- (f) The total amounts of hindered contraction increase as the carbon content increases.

\*Numerals refer to articles in the bibliography, page

- (g) The percentage of the total contraction occurring before the critical range is reached decreases as the tension restraining the bar increases.
- (h) The hindered contraction data obtained with the lightest spring represent approximately the stresses encountered by the average commercial casting as the total contraction under this tension approximates the "patternmaker's shrinkage" of 3/16 of an inch per foot.
- (i) Slight variations from the normal manganese or silicon content of cast carbon steel do not result in measureable differences in the rate or total amount of free or hindered contraction.
- (j) The contraction taking place upon the solidification of cast steel, as approximated from the present available data, is 2.7 percent.
- (k) The rate of contraction as well as the strength of the steel may influence the formation of hot tears in steel castings.

5. The data thus pointed out that by varying the carbon content different amounts of contraction could be obtained. Since the carbon content was so influential in bringing about changes in contraction, it appeared likely that alloy additions would also change the characteristics of free and hindered contraction. Also, various conflicting opinions as to the effect of alloying elements upon contraction have been presented by members of commercial organizations, thereby pointing out the need for basic information on this subject.

6. In the planning of the research on the alloy steels, it was deemed necessary to maintain the carbon content at approximately the same percentage in all of the alloy steels studied. This was necessary in order to ascertain the effect of the alloy additions themselves. Thus the chemical analyses of the cast steels studied may differ slightly from those usually employed by the industry. It was planned, however, to maintain the alloy additions as near to those found in commercial use as possible. Several prominent steel founders were solicited with regard to typical compositions and from their replies a set of eleven alloy cast steels were prepared, studied, and compared with the contraction of the standard carbon cast steel. The carbon content chosen as a standard was 0.35 percent. This figure was adopted since a larger number of commercial cast steels call for a carbon content of 0.35 percent and a cast carbon steel had already been studied with this amount of carbon present. The manganese and silicon were maintained at approximately 0.75 percent and 0.35 percent, respectively, unless they were being used in the capacity of an alloy. The phosphorous and sulphur were kept below 0.04 percent.

#### METHODS USED IN TESTING

7. The procedure used in collecting the data on the free and the hindered contraction of alloy steels was similar to that employed in

obtaining the data on plain carbon steels (2).

- (a) Bar Design - The bars that were used in this study had large ends and a small central section fed by a horn gate, as it was deemed necessary to have a bar that cooled uniformly along its axis. The bars, as cast, were 30 inches long with a diameter at the center of  $1\frac{9}{16}$  inches (a cross-sectional area of 2 square inches) and a diameter at the ends of  $2\frac{1}{4}$  inches. Sections  $1\frac{3}{4}$  inches in diameter and 2 inches long, which acted as clamps on the stainless steel bolts, were at the ends of the bar and cast integrally with it.
- (b) Type of Sand - The sand used was a synthetic green sand made up using No. 40 washed silica sand as a base and mixed in the following proportions by volume:

500 parts silica sand  
19 parts Bentonite  
1 part Mogul  
5% (by weight) water

The mixture was mullied for five minutes and the following properties were obtained:

Permeability	180 cc/min
Compression strength	3.5 lbs/sq.in.
Shear strength	nil
Tensile strength	nil

The sand was reclaimed after it had been used. The properties of the reclaimed sand were approximately the same as those of a newly prepared sand.

- (c) Molding Procedure - Steel flasks constructed of 5-inch channel iron  $3\frac{1}{2}$  inches long and 10 inches wide were used as the mold containers. The sand was rammed lightly to a mold hardness number of about 50. A horn gate varying from 2 inches to  $\frac{3}{4}$  inch in diameter was used for the pouring gate. The  $\frac{3}{4}$  inch section, where the steel enters the mold cavity, was much smaller than the contraction bar at this point and hence froze before the bar, permitting very little feeding during the solidification of the bar.

A relieving block  $1\frac{1}{2}$  inches square, shaped similarly to the horn gate, was molded in a short distance away from the horn gate. This block was removed from the mold and, when the hindered bars contracted, the horn gate was able to move freely without being restricted by the molding sand. The surface of the mold cavity was not covered with a mold wash.

- (d) Assembling the Mold - A stainless steel bolt was placed in each end of the flask. One bolt tied the bar down to the flask and the other was fastened to the flat steel spring. The bolts were  $\frac{7}{8}$  of an inch in diameter and had a shank of 4 inches and a body 5 inches. Two grooves  $\frac{3}{8}$  inch wide and  $\frac{1}{8}$  inch deep were machined in the body end of the bolt. This permitted the metal, upon solidifying around

the bolts, to have a strong grip on them. The chilling action was so great that the bolts did not fuse into the cast metal.

A small quartz thermocouple protecting tube was run through the cope of the mold 1-1/2 inches from the end of the bolt that tied the cast bar down to the flask. This tube extended to the axis of the bar and the readings obtained by the platinum-platinum-rhodium thermocouple represented the temperature of the bar throughout the central 26 inches.

The flat springs used were made from heat-treated spring steel 2 inches by 10-1/2 inches and were the following thicknesses:

"C" springs 7/8 inch thick

"G" springs 9/16 inch thick

"E" springs 3/8 inch thick

The springs were calibrated very carefully in pounds, total load.

Ames dials, held by an arm bolted to the end of the flask, were used to measure the amount of contraction. A 16 mm film moving picture camera operated by a Telechiron synchronous motor recorded the amount of shrinkage and the temperature every 15 seconds. The temperature was recorded by a pyromillivoltmeter with a temperature range of 0-1600°C. The contraction was measured by Ames dials graduated to read to 1/1000 of an inch. The true free contraction of the bar was obtained with both ends of the bar free and two Ames dials to record the contraction.

The runner box, which was used for convenience during pouring, was slotted at the base so that the excess metal would run out and not act as a feeding head or restrict contraction.

- (e) Type of Steel - The steels were made in a 500 pound per hour Swindell 3 phase electric arc furnace. The basic double slag practice was used entirely during the collecting of the data presented in this report. In all cases, the steel-making conditions were duplicated as nearly as possible so that the data obtained could be carefully checked.
- (f) Pouring - The steel was poured from a teapot ladle so that the slag had very little opportunity to enter the mold. The pouring temperature of the steel entering the mold was between 2880°F (1582°C) and 2800°F (1538°C). Aluminum was added to the ladle prior to pouring in amounts equivalent to 500 grams per ton.
- (g) Recording and Duplicating of Data - After the bars had cooled to room temperature, the films, giving a photographic record of the temperature and shrinkage, were developed, projected, and the readings recorded.

Each time the contraction studies were made, the data were taken in duplicate. This required a duplicate set of conditions to produce

the four types of contraction. The results obtained were in excellent agreement; in fact, the discrepancies recorded were less than the average error indicated in the previous report (2). When the results obtained with the alloy compositions did not fall within the limits that had been arbitrarily set, the experiment was repeated and new data were obtained.

Shortly after the data were presented on the free and hindered contraction of carbon steels, a steel foundry executive pointed out that the data were collected, quite correctly, from steel poured within a relatively narrow temperature range. Since pouring temperature can vary considerably, it was deemed advisable to study the free and hindered contraction of the same heat of steel poured at high and low temperatures. One set of bars was, therefore, cast at approximately 2925°F and another set at approximately 2625°F, a difference of 300 degrees Fahrenheit in pouring temperature. The plotted data were very close together, within the limits of error of the test, and the final end-points were practically identical. This points out, as was expected, that the differences in pouring temperature had no effect on the duplication of the data or on the final results.

#### DATA OBTAINED

##### (a) Types of Alloy Steels

8. Studies were made of the free and the hindered contraction of the alloy steels listed in Table 1. A glance at the table will be sufficient to observe that only a small number of the many commercial alloy combinations have been studied. However, most of the single alloy steels and several important dual combinations are reported.

##### (b) Freely Contracting Bars

9. The data obtained from the freely contracting bars are given in Table 2 and shown graphically on Plates 1, 3, 5 and 7. The data, unfortunately, fall so close together that it was found impossible to show all of the curves on one plate. It was therefore necessary to classify them by chemical composition and to show them on four plates. The data for each type of contraction, however, will be considered as a unit.

10. Perhaps the most outstanding feature exhibited by the data is that the plain 0.35 percent carbon steel contracts more than the alloy steels studied. It is true, however, that the differences between the total contraction of the various alloys are small. A further study of Table 2 reveals that between the solidifying temperature and the critical range the nickel-chromium steel contracted the most and the vanadium steel the least, while between the critical range and room temperature the vanadium, the chromium, and the carbon steel contracted the most and the nickel-chromium steel the least. The amount of expansion during the critical was extremely low in the case of the molybdenum alloys, while the manganese steel expanded the most.

11. In general, the contraction curves of the various alloys are practically parallel at any one temperature prior to the critical

temperature range, with the nickel-manganese and the carbon steel contracting at the greatest rate and the molybdenum and nickel-chromium alloys at the slowest rate. In all, the maximum variation, except through the critical ranges, is only about 0.08 percent at any one temperature.

12. In Table 6, the critical temperatures of the freely contracting alloy steels are tabulated. All of the alloy steels except the vanadium have critical temperatures lower than that of the carbon steel. In general, it may be said that the lower the critical temperatures, the greater is the amount of contraction prior to the critical. A very interesting point concerning the critical range is the very slight expansion of the molybdenum and the manganese molybdenum alloy steels.

13. The maximum variation between the curves after the critical range is of the same order as that which exists prior to the critical range; that is, if the nickel-chromium alloy steel is disregarded. The nickel-manganese steel alternates with the carbon steel for the upper position until a low temperature is reached when, due to a decrease in the rate of contraction, it drops to the third position. The nickel steel contracts practically the same amount as the carbon steel. The nickel-chromium steel has the least amount of contraction; this is probably due to the low temperatures of its critical range.

(c) Light Hindered Contraction ("E" Spring)

14. It has previously been explained that in the study of hindered contraction the bars were restrained from contracting by springs of 3 different sizes. These springs were used to cause tensions in the bars similar to those encountered by castings. The conditions presented by these springs may not be comparable in magnitude to the stresses actually encountered in commercial castings, but they do give an indication as to the effects due to restricting contraction. The values in pounds per square inch shown on the curves were computed for the smallest diameter of the bar which has a cross-sectional area of two square inches.

15. The data obtained with the light "E" spring probably represent more closely the stresses encountered by the average commercial casting for the total contraction recorded under this tension approximates the "patternmaker's shrinkage" of  $3/16$  of an inch per foot (1.56 percent).

16. The hindered contraction data obtained from bars restrained by the light "E" spring are given in Table 3 and shown graphically on Plates 2, 4, 6 and 8. It may be noticed from Table 3 that the carbon steel reference curve now exhibits a low total contraction of 1.64 percent as compared to most of the alloy steels which range from 1.58 to 1.78 percent with the molybdenum steel exhibiting the most contraction and the nickel-manganese and the manganese the least. The table also indicates that the nickel-chromium steel had the largest amount of contraction prior to the critical range, while the vanadium alloy contracted the least. After passing through the critical range, the chromium steel contracted the most, while the nickel-chromium steel contracted very little, due undoubtedly to its low critical temperature. The molybdenum and manganese-molybdenum steels exhibited very little expansion during the critical range, though it was considerably more than that obtained when the bars were contracting freely.

17. Examination of the curves will show that there is a decided bend in the curves about 950°C indicating that a marked change appeared in the rate of contraction at about this temperature.

18. Variations between the fastest and slowest contracting steels result in a difference in stress equivalent to about 250 pounds per square inch at 1300°C and about 350 pounds per square inch at 1000°C. Thus, while the band of curves appears to be fairly wide, the actual difference in the stress on the bars at any one temperature is rather low.

19. The manganese-vanadium steel leads in the amount of contraction prior to the critical, but it is followed closely by the molybdenum and manganese-molybdenum steels. The lowest contraction rate alternates between the manganese, the nickel-manganese and the carbon steels.

20. In Table 6 are given the critical temperatures for the bars restrained by the light "E" spring. In general, about one-half of the steels have critical points that are slightly lower in temperature than those recorded when the bar was contracting freely. The nickel-chromium steel again has the lowest temperature, while the highest temperature is recorded by the vanadium steel.

21. The difference between the curves showing the greatest and the least contraction after the steels have passed through the critical range is about one and a half times that found above the critical range with the nickel-manganese in the lowest position and the manganese-vanadium and the molybdenum steels showing the greatest amount of contraction. The rate of contraction of the manganese-vanadium steel falls off rapidly within the 200°C to room temperature zone. This is a rather peculiar effect, though it is not exceptional, as approximately the same condition is found to exist with the nickel, manganese, and nickel-chromium alloy steels.

(d) Medium Hindered Contraction ("G" Spring)

22. The data recorded with the medium "G" spring probably approximate conditions existing in castings which, due to design or to unusually high mold resistance, are unable to contract appreciably.

23. The data pertaining to the bars hindered by the medium "G" spring are set forth in Table 4. The contraction curves are to be found on Plates 1, 3, 5 and 7.

24. The total contraction varies from 0.88 percent for the nickel-chromium steel to 1.05 percent in the case of the molybdenum steel. This contraction corresponds to a stress of from 6,150 to 7,350 pounds per square inch, respectively. The 0.92 percent contraction of the carbon steel is very nearly the lowest amount of contraction recorded.

25. The different critical temperatures, as shown on Plate 6, are again generally responsible for the different amounts of contraction before and after the critical range. The chromium steel has the least contraction before, and the most after, the critical range, whereas the nickel-chromium steel, because of its low critical temperature, has most of its contraction prior to the critical range. The greatest expansion during the critical range is that recorded by the manganese steel, while the molybdenum alloys again show only a small amount of expansion. The carbon and the vanadium steels have the highest critical temperatures and the nickel-chromium steel has the lowest.

26. Variations between the fastest and slowest contracting steels in the neighborhood of 1300 to 1000 degrees result in a difference in stress varying from 300 pounds per square inch at 1300 degrees Centigrade to 500 pounds per square inch at 1000 degrees Centigrade.

27. At temperatures above 1300°C, the curves representing the contraction of the various steels cross each other and change positions so often that little can be said definitely except that the rates of contraction of the various alloy steels differ considerably. In general, it can be said that at any one temperature the nickel-manganese steel contracts the least prior to the critical, while the manganese-molybdenum and the molybdenum steels contract the most. This condition is likewise true after the critical range.

28. The variation between the curves after the critical is over twice as great as that before the critical range is reached. The three nickel alloys exhibited the least amount of total hindered contraction.

(e) Heavy Hindered Contraction ("C" Spring)

29. The tensions exerted by the strong "C" spring are probably greater than any encountered in commercial practice, but the data indicate how these unusually high stresses would affect contraction. The data obtained by hindering the contraction of the bar with the heavy "C" spring are tabulated in Tables 5 and 6 and illustrated on Plates 2, 4, 6 and 8.

30. The total contraction varies from 0.37 percent for the nickel-chromium steel to 0.53 percent attained by the manganese-vanadium steel, the carbon steel contracting 0.47 percent.

31. In general, the critical temperatures are slightly above those found in the freely contracting bar. The general condition that the lower the temperature at which the critical range occurs, the greater will be the amount of contraction prior to the critical range again exists. Thus, the nickel-chromium steel again leads by attaining 0.37 percent contraction before the critical range is reached. The carbon steel shows the smallest percentage of contraction.

32. The chromium and carbon steels have the greatest amount of contraction after the critical range, whereas the nickel-chromium steel contracts very little, in fact, only an amount equal to the expansion that took place when the steel passed through the critical range.

33. The manganese steel exhibited considerable expansion during the critical range and, under this heavy spring, the molybdenum alloys again expanded the least.

34. The variation between the high molybdenum curve and the slowest contracting nickel-manganese curve from 1400 to 1000°C is only 0.03 percent. This is equivalent to a difference in stress of about 650 pounds per square inch. The curves representing the different alloys cross each other to such an extent that it is nearly impossible to point to any one alloy and to make predictions as to its ability to resist high contraction stresses.

35. The rate at which contraction takes place changes distinctly in two places. The curves flatten out between 1350 and 1200°C and then, around

1000 to 950°C, there is a decided bend in the curve. At the lower temperatures, certain alloys show a considerable drop in the rate of contraction, while other alloys have very little reduction in their rates of contraction. The decrease in the rate of contraction is most noticeable with the nickel-manganese and the manganese-vanadium steels. The rates for the nickel, the vanadium, and the manganese-silicon steels also fall off appreciably.

36. The low final position of the nickel-chromium steel is probably due to its low critical temperature. All of the other steels are closely grouped except the manganese-vanadium steel which has a high end point due to its constant rate of contraction.

37. The effect of resistance upon contraction is illustrated on Plate 9. The data shown are representative curves and were calculated from the average contraction of the bars at temperature intervals of 50°C. It should be noted that in the freely contracting bars the rate of contraction increased uniformly from the solidifying temperature to about 1200°C. From 1200°C to the critical temperature, the rate of contraction is practically constant.

38. The bars which were restrained in contraction by the heavy "C" spring had an entirely different rate of contraction. In this case, the bar apparently yielded at the higher temperatures. The strength of the steel apparently increased slowly with the drop in temperature, since the amount of yielding is decreasing slowly as the temperature drops until at approximately 1200°C the strength is sufficient to cause an increase in the rate of contraction. Again at 1000°C the rate of contraction increases markedly.

39. It is very unfortunate that studies on the free and hindered contraction of an austenitic steel could not be made as data were desired on steels having no critical range. Such a study would have been extremely beneficial for then the effect of the critical range on the total contraction would be known. Permission to make this study was refused by the Bureau of Engineering (Reference: EP/Castings (10-14-Ds) of 29 October 1935) because "The use for 18-8 and Manganese Steel Castings is so limited and the castings are of such size that it is not considered necessary nor desirable to include these alloys in problem No. M-8."

#### CONCLUSIONS AND SUMMARY

##### (a) Discussion of the Practical Features as Exhibited by the Data.

40. The total amounts of free contraction of the common types of low alloy cast steels are about the same, or slightly less than that of a plain carbon steel of the corresponding carbon content. This point, however, is not of great practical importance, since steel castings are seldom, if ever, in such a form as to allow them to contract freely. Thus a more practical viewpoint would be obtained by considering the hindered contraction characteristics. The light "E" spring produces stresses approximately the same as those encountered by the average commercial casting. Under those conditions, the amounts of total contraction for the alloy steels vary from 1.58 percent (practically 3/16-inch per foot) to 1.78 percent (nearly 7/32-inch per foot). Since the carbon steel, which acts as the reference point, contracts 1.64 percent (nearly 13/64-inch per foot), it occupies

a position that is intermediate to the alloy steels ( $\pm 1/64$ -inch per foot). It thus appears that for all practical purposes the carbon steel and the alloy steels are similar. This condition holds true only as long as the percentage total contraction is considered. The rates of contraction, the position of the critical points, and the expansion during the critical range may or may not be similar to the contraction characteristics of a plain carbon steel.

41. The statements given above concerning the hindered contraction under the light "E" spring are also true when more drastic conditions of hindered contraction are applied, such as those presented by the "G" and "C" springs.

42. It has been pointed out that, at any one temperature, there is a variation in the amount of contraction of the alloy steels. Although the difference between the steels contracting the fastest and those contracting the slowest is not great, important stress differences are recorded under hindered contraction at the higher temperatures. For example, under the heavy "C" spring at  $1300^{\circ}\text{C}$ , the vanadium steel bar is under a stress of 900 pounds per square inch at its smallest section, while the nickel-manganese steel has only a stress of 420 pounds acting upon it. Thus, at these high temperatures under large amounts of hindered contraction, the vanadium steel is subject to over twice the amount of stress that is acting on the nickel-manganese steel. Furthermore, it is not until a temperature of  $1100^{\circ}\text{C}$  is reached that the nickel-chromium steel must withstand the same stress as that to which the vanadium steel is submitted at  $1300^{\circ}\text{C}$ .

43. The condition stated above has no bearing on the ultimate strength of the steel, however, except that it shows that the slower contracting steel may have a lower yield strength at the higher temperatures. This was pointed out when it was explained that the bars in contracting could only develop a stress equal to their yield strength. When the yield strength was exceeded, the steel yielded, thus causing a relieving of the stress. Upon further contraction of the steel, the stress is again built up to the yield strength. Thus the vanadium steel has, at  $1300^{\circ}\text{C}$ , about twice the yield strength of a nickel-manganese steel. This is important from a practical standpoint for it gives an indication of the yield strengths of the alloy steels when contraction has been hindered at high temperatures.

44. It can be seen that the apparent yield strength and not the true yield strength of the steels are recorded as the stresses upon the bars at any one temperature vary considerably with the type of contraction. For example, the vanadium steel at 1300 degrees Centigrade has contracted .064 percent when restrained by the "G" spring and only .044 percent when restrained by the "C" spring. The bars, therefore, are under a stress of 465 pounds per square inch when the "G" spring is used and under a stress of 920 pounds per square inch when the "C" spring is used. As the bars cannot maintain a stress greater than their yield strength, the values given above are the apparent yield strengths of the material under these two conditions. The only difference in the conditions when these two springs are used is the rate at which the stress is applied. The true yield strength would be indicated only if the stresses were applied at such a rate that no contraction would take place. Under these conditions the stresses on the bars would be equivalent to the yield strengths of the steels.

45. The apparent yield strength is recorded only under conditions of hindered contraction which produce rate of contraction-time curves similar to that shown in Plate 7, and then only at those temperatures at which the curves have a negative slope. In other words, at those temperatures at which the rate of contraction is decreasing. A curve showing the average rate of contraction with the "C" spring has the same trend as that of the curve for the rate of contraction with the "C" spring (Plate 9). However, the contraction data recorded when the "E" spring was used produced a curve of a different type which exhibited no decrease in the rate of contraction at the high temperatures. Under these conditions it appears that the apparent yield strength is not reached even at the high temperatures and that only the plastic flow of the metal is recorded.

(b) Summary

46. The free contraction of a plain 0.35 percent carbon steel is greater than that of any of the alloy steels studied. The total percentage of free contraction varies from 2.27 percent, attained by the nickel-chromium steel, to 2.40 percent, recorded by the nickel steel.

47. The amount of contraction taking place in both freely contracting and hindered contracting bars prior to reaching the critical range is, in general, dependent upon the temperature at which the critical range occurs.

48. The total amount of hindered contraction obtained corresponds closely to those values exhibited by the plain carbon steel. The final position of the different alloys varies somewhat with different amounts of tensions on the bars.

49. The amount of expansion shown by the alloys during the critical range varied considerably. In general, the amount of expansion under hindered contraction is greater than that recorded under the freely contracting conditions.

50. Differences in the pouring temperature of the steel have no effect on the total amount of contraction in the solid state or on the shape of the contraction curve.

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TABLE I  
Analyses of the Alloy Steels

No.	Type	C	Mn	Si	Percent		Cu	Mo	Va
					Ni	Cr			
1	Carbon	0.35	0.74	0.37	-	-	-	-	-
2	Manganese	0.32	1.32	0.41	-	-	-	-	-
3	Nickel	0.34	0.64	0.41	3.00	-	-	-	-
4	Chromium	0.35	0.75	0.35	-	1.03	-	-	-
5	Copper	0.36	0.72	0.35	-	-	1.39	-	-
6	Molybdenum	0.37	0.77	0.35	-	-	-	0.39	-
7	Vanadium	0.32	0.65	0.37	-	-	-	-	0.25
8	Manganese-silicon	0.36	1.35	1.15	-	-	-	-	-
9	Nickel-manganese	0.32	1.24	0.30	1.46	-	-	-	-
10	Manganese-molybdenum	0.35	1.18	0.30	-	-	-	0.37	-
11	Manganese-vanadium	0.37	1.41	0.30	-	-	-	-	0.16
12	Nickel-chromium	0.37	0.73	0.34	2.88	0.91	-	-	-

TABLE 2

Data on Freely Contracting Cast Steel Bars

No.	Type of Steel	Percent Contraction Before Criti- cal Range	Percent Expansion Passing Thru Criti- cal Range	Percent Contraction After Criti- cal Range	Percent Total Contraction
1	Carbon	1.47	0.10	1.03	2.40
2	Manganese	1.74	0.26	0.88	2.38
3	Nickel	1.72	0.20	0.87	2.40
4	Chromium	1.46	0.14	1.02	2.34
5	Copper	1.49	0.14	1.00	2.35
6	Molybdenum	1.65	0.04	0.72	2.33
7	Vanadium	1.40	0.09	1.02	2.32
8	Manganese-Silicon	1.54	0.14	0.96	2.35
9	Nickel-Manganese	1.70	0.19	0.86	2.37
10	Manganese-Molybdenum	1.68	0.02	0.66	2.32
11	Manganese-Vanadium	1.50	0.13	0.96	2.33
12	Nickel-Chromium	1.95	0.04	0.36	2.27

TABLE 3

Data on Cast Steel Bars Restrained by Light "E" Spring

No.	Type of Steel	Percent Contraction Before Criti- cal Range	Percent Expansion Passing Thru Criti- cal Range	Percent Contraction After Criti- cal Range	Percent Total Contraction
1	Carbon	0.92	0.18	0.90	1.64
2	Manganese	1.12	0.27	0.73	1.58
3	Nickel	1.13	0.25	0.75	1.64
4	Chromium	0.93	0.24	0.97	1.65
5	Copper	0.99	0.19	0.90	1.70
6	Molybdenum	1.28	0.10	0.61	1.78
7	Vanadium	0.90	0.15	0.93	1.67
8	Manganese-Silicon	1.03	0.20	0.88	1.72
9	Nickel-Manganese	1.06	0.26	0.76	1.58
10	Manganese-Molybdenum	1.25	0.09	0.57	1.72
11	Manganese-Vanadium	1.08	0.22	0.85	1.72
12	Nickel-Chromium	1.48	0.14	0.26	1.60

TABLE 4

Data on Cast Steel Bars Restrained by Medium

<u>No.</u>	<u>Type of Steel</u>	<u>Percent Contraction Before Cri- tical Range</u>	<u>Percent Expansion Passing Thru Criti- cal Range</u>	<u>P: C: A: c</u>
1	Carbon	0.46	0.24	
2	Manganese	0.60	0.33	
3	Nickel	0.56	0.28	
4	Chromium	0.41	0.21	
5	Copper	0.49	0.21	
6	Molybdenum	0.67	0.14	
7	Vanadium	0.45	0.11	
8	Manganese-Silicon	0.56	0.22	
9	Nickel-Manganese	0.55	0.28	
10	Manganese-Molybdenum	0.64	0.10	
11	Manganese-Vanadium	0.55	0.24	
12	Nickel-Chromium	0.87	0.20	

TABLE 5

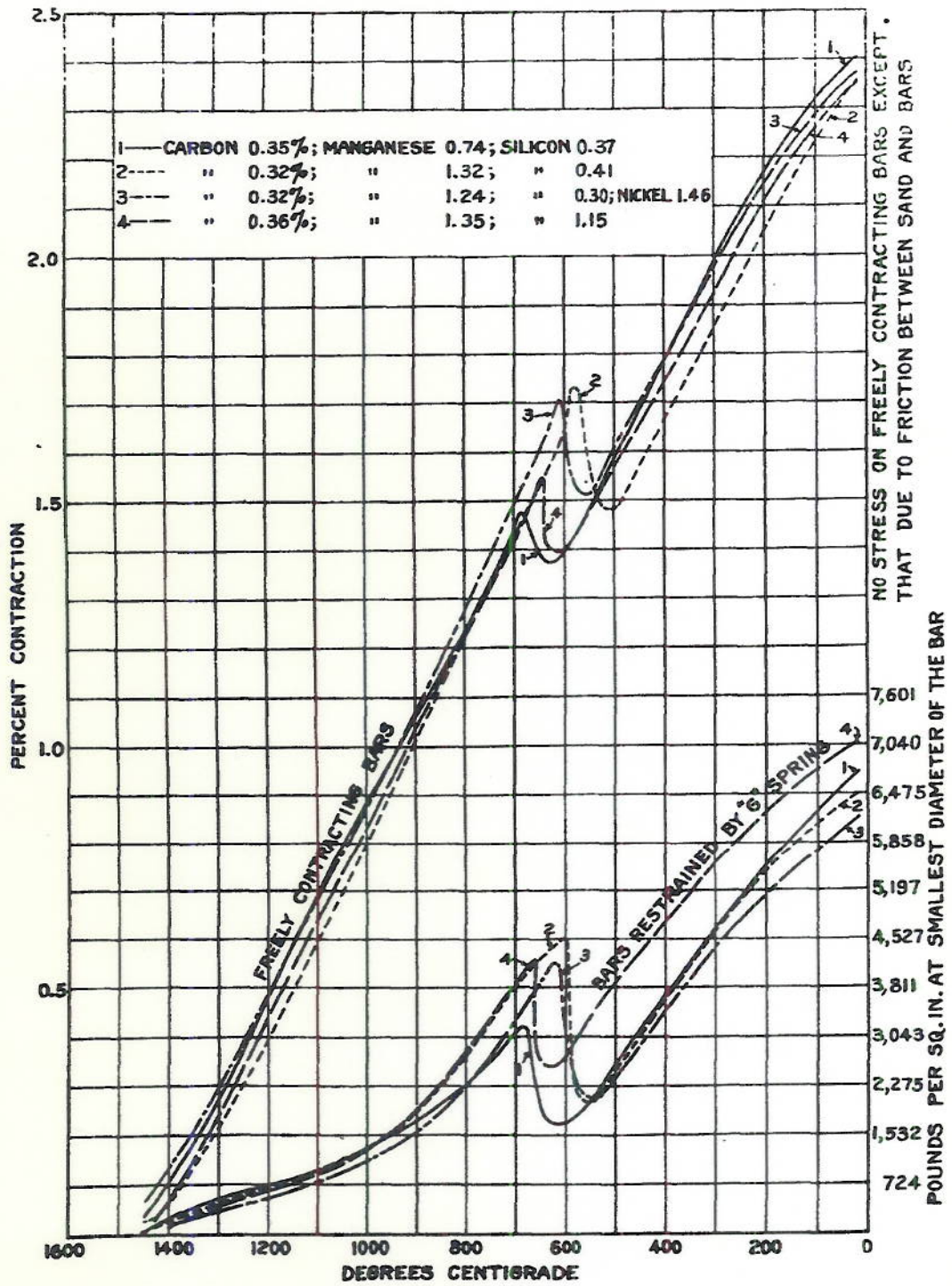
Data on Cast Steel Bars Restrained by Strong "C" Spring

No.	Type of Steel	Percent Contraction Before Cri- tical Range	Percent Expansion Passing Thru Criti- cal Range	Percent Contraction After Cri- tical Range	Percent Total Contraction
1	Carbon	0.20	0.15	0.42	0.47
2	Manganese	0.28	0.22	0.39	0.46
3	Nickel	0.24	0.18	0.35	0.40
4	Chromium	0.21	0.17	0.43	0.47
5	Copper	0.25	0.17	0.41	0.48
6	Molybdenum	0.31	0.12	0.30	0.49
7	Vanadium	0.21	0.12	0.35	0.44
8	Manganese-Silicon	0.24	0.16	0.35	0.43
9	Nickel-Manganese	0.23	0.18	0.38	0.44
10	Manganese-Molybdenum	0.26	0.09	0.28	0.45
11	Manganese-Vanadium	0.24	0.16	0.45	0.53
12	Nickel-Chromium	0.37	0.17	0.17	0.37

TABLE 6

Critical Points on Cooling from Solidifying Temperature

No.	Type of Steel	Critical Points in Degrees Centigrade							
		Higher Critical				Lower Critical			
		Free	E	G	C	Free	E	G	C
1	Vanadium	690	685	685	690	620	600	595	595
2	Carbon	690	660	690	675	635	570	515	595
3	Chromium	670	680	680	680	615	640	645	620
4	Manganese-Silicon	650	645	655	640	620	620	630	585
5	Copper	645	660	685	670	605	600	600	600
6	Manganese-Vanadium	640	660	655	650	605	605	610	565
7	Nickel-Manganese	610	595	635	600	560	550	550	525
8	Nickel	600	620	610	615	545	550	550	540
9	Manganese	580	605	605	605	510	525	555	535
10	Molybdenum	565	575	580	590	530	450	445	470
11	Manganese-Molybdenum	550	550	590	530	470	440	460	450
12	Nickel-Chromium	430	415	460	440	320	270	280	280



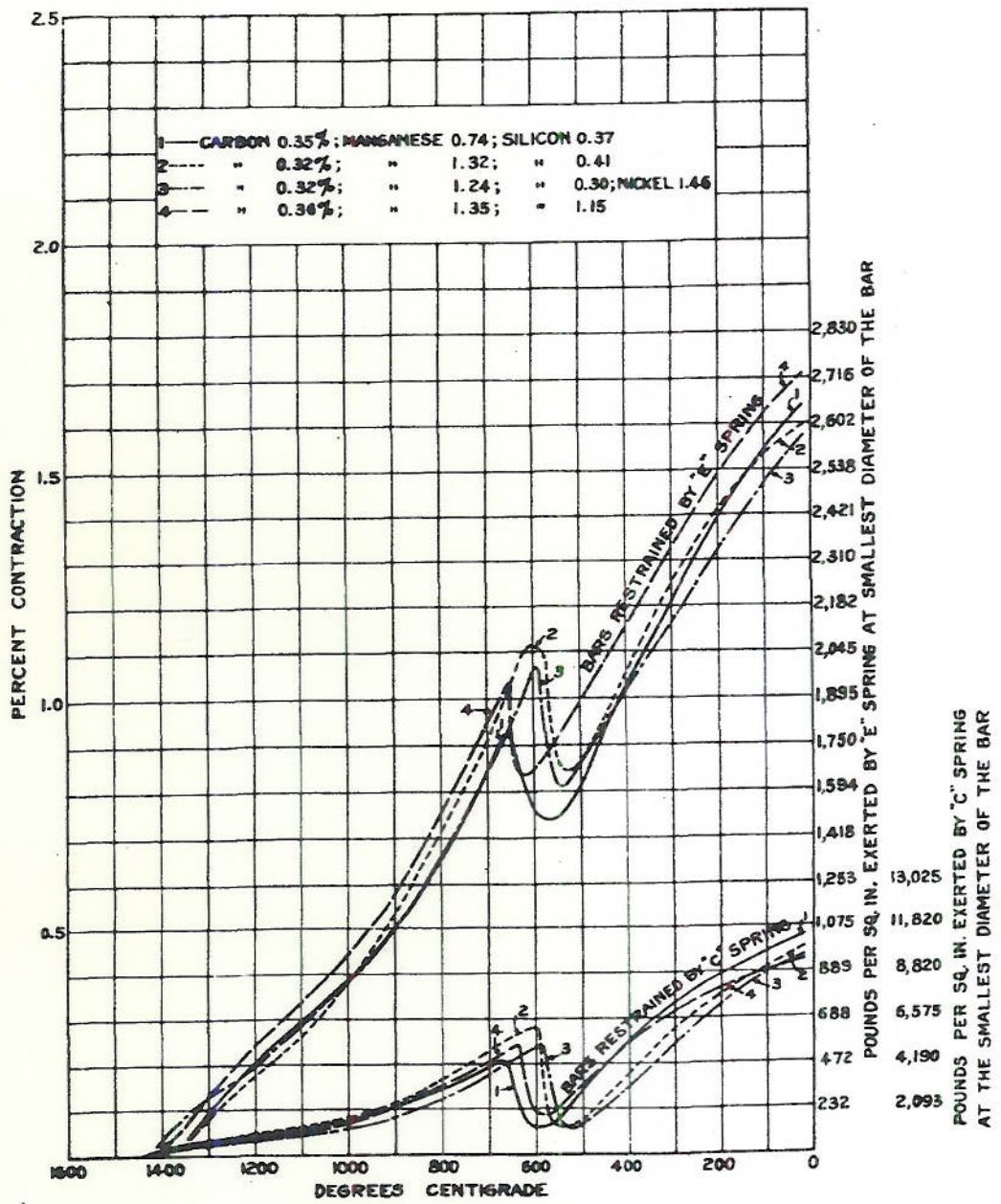


PLATE 2

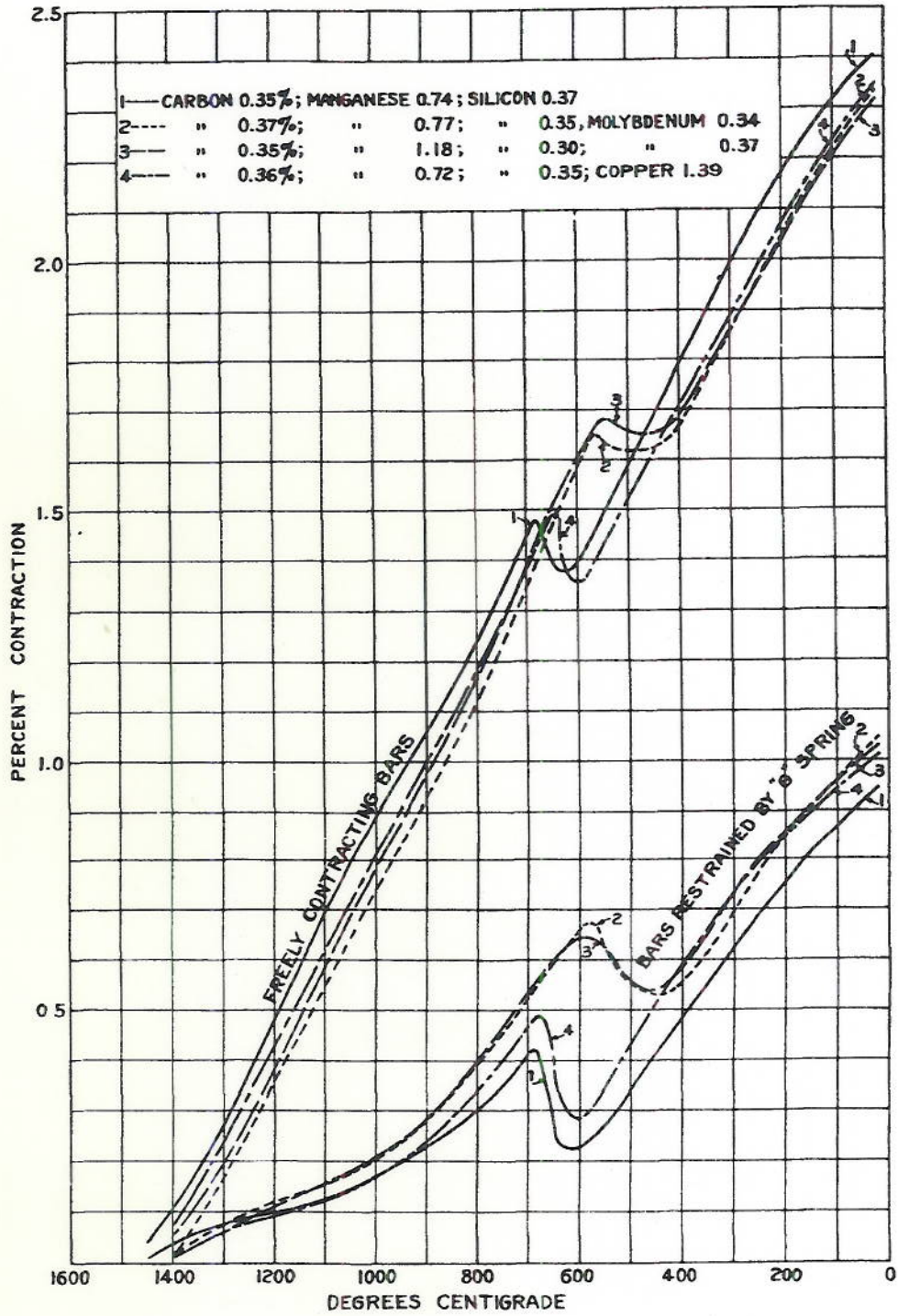
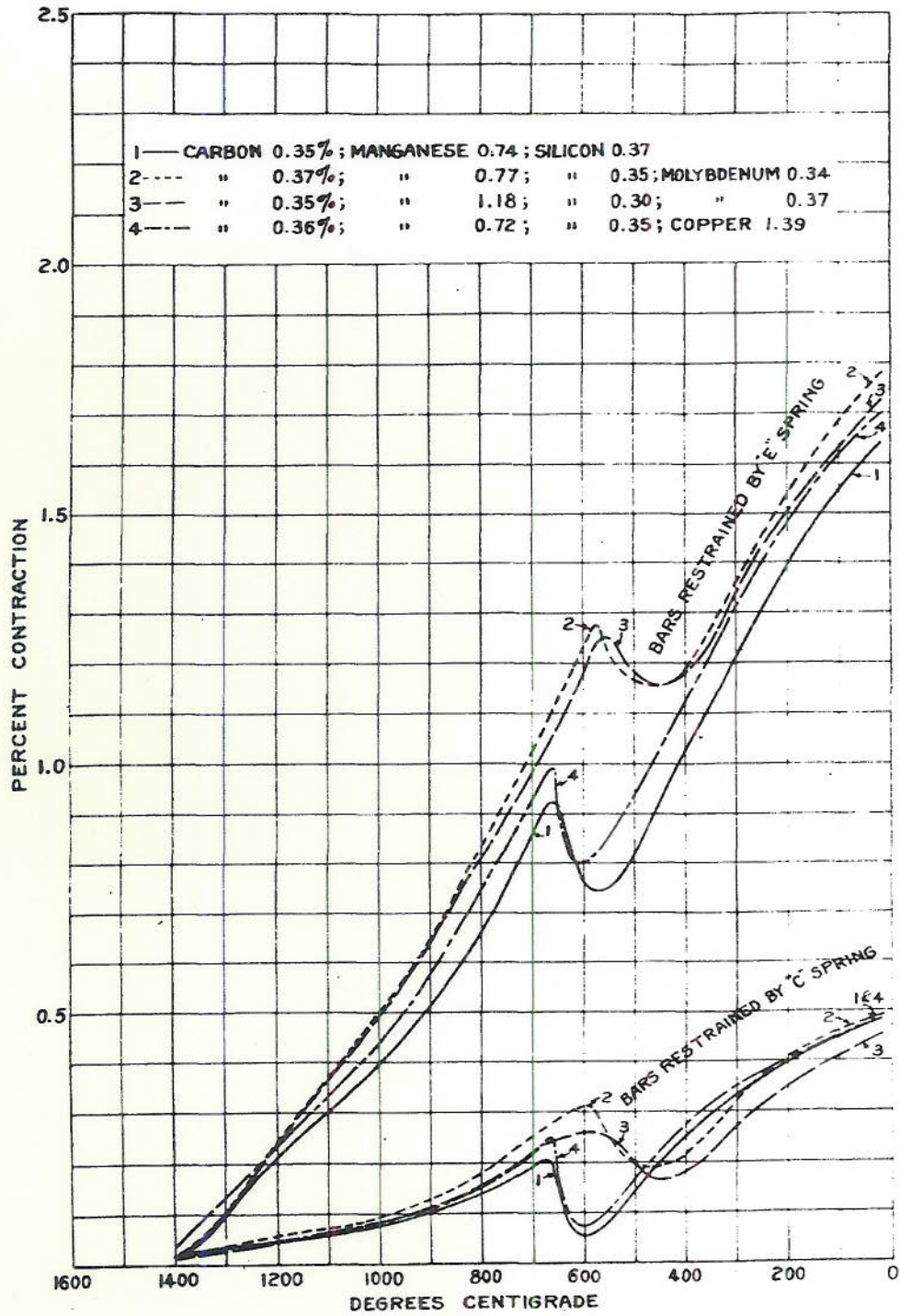


PLATE 3



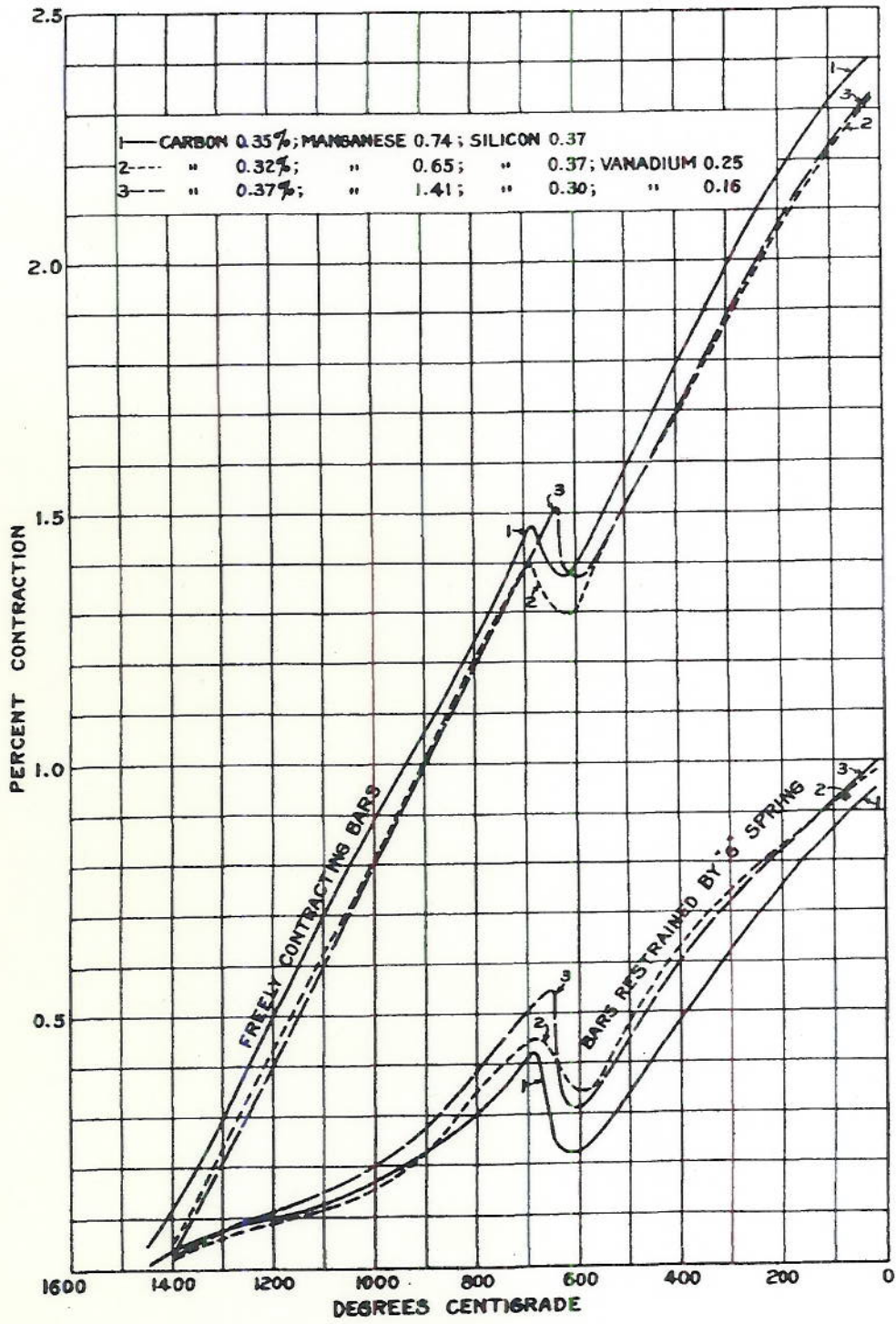


PLATE 5

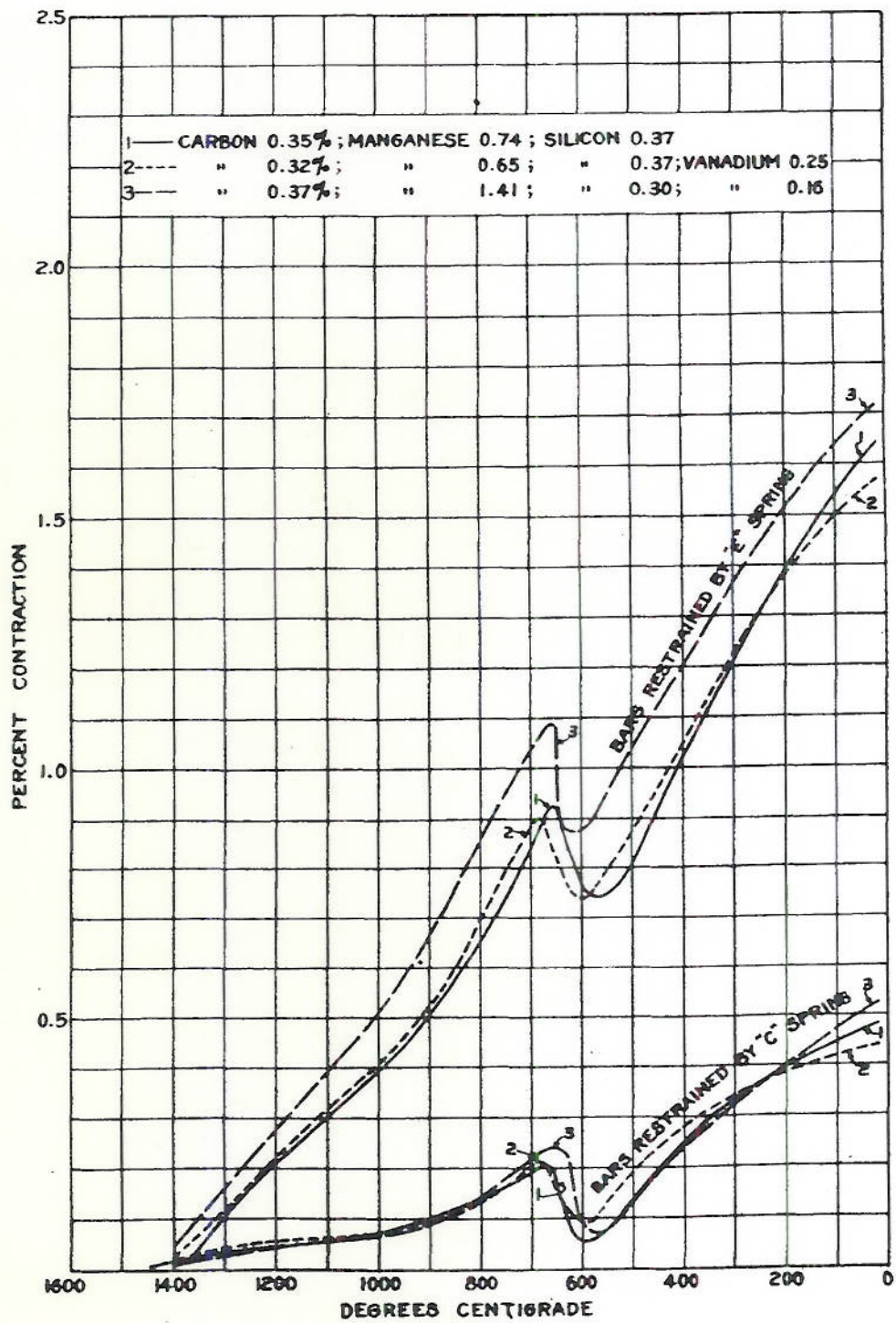
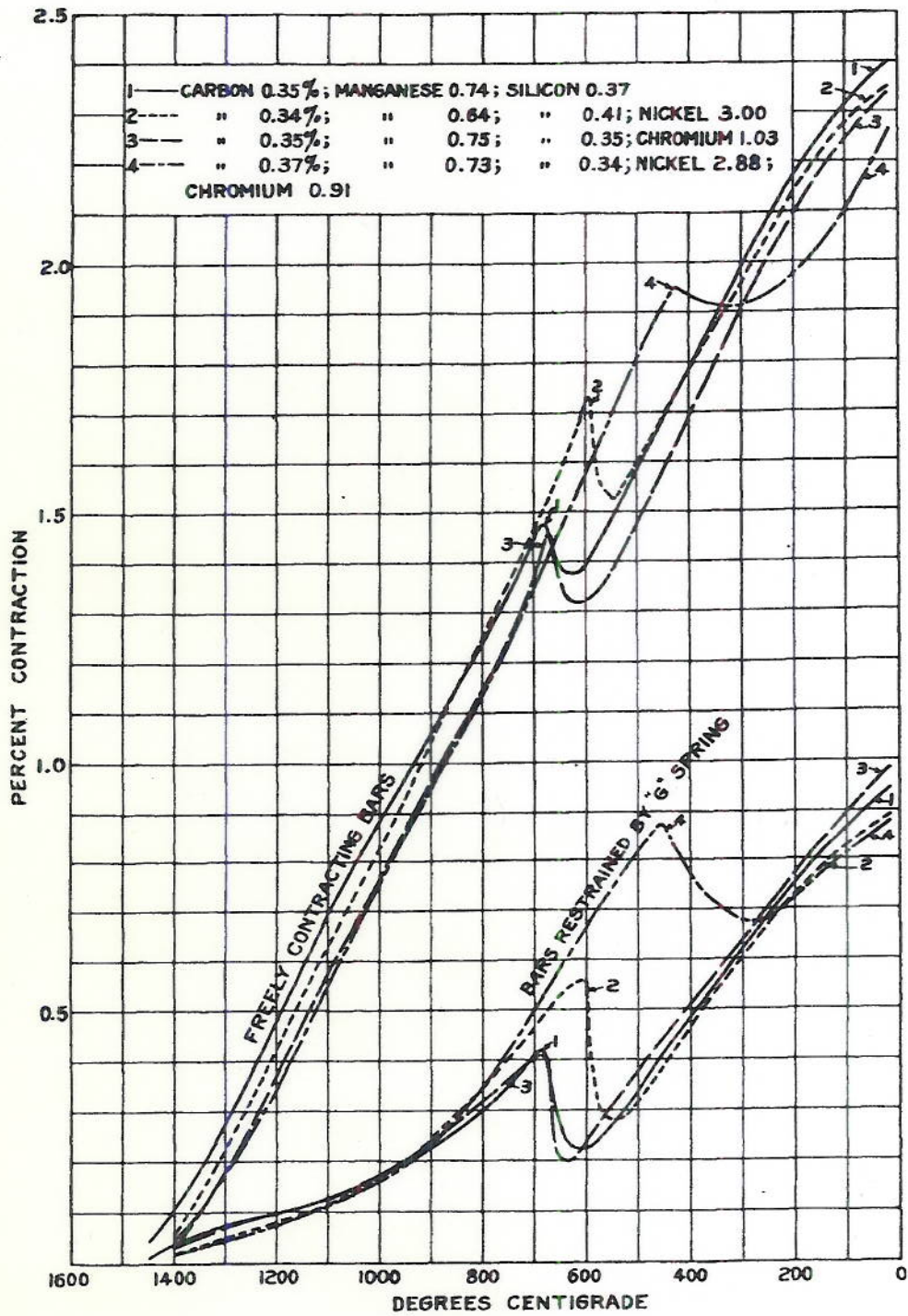
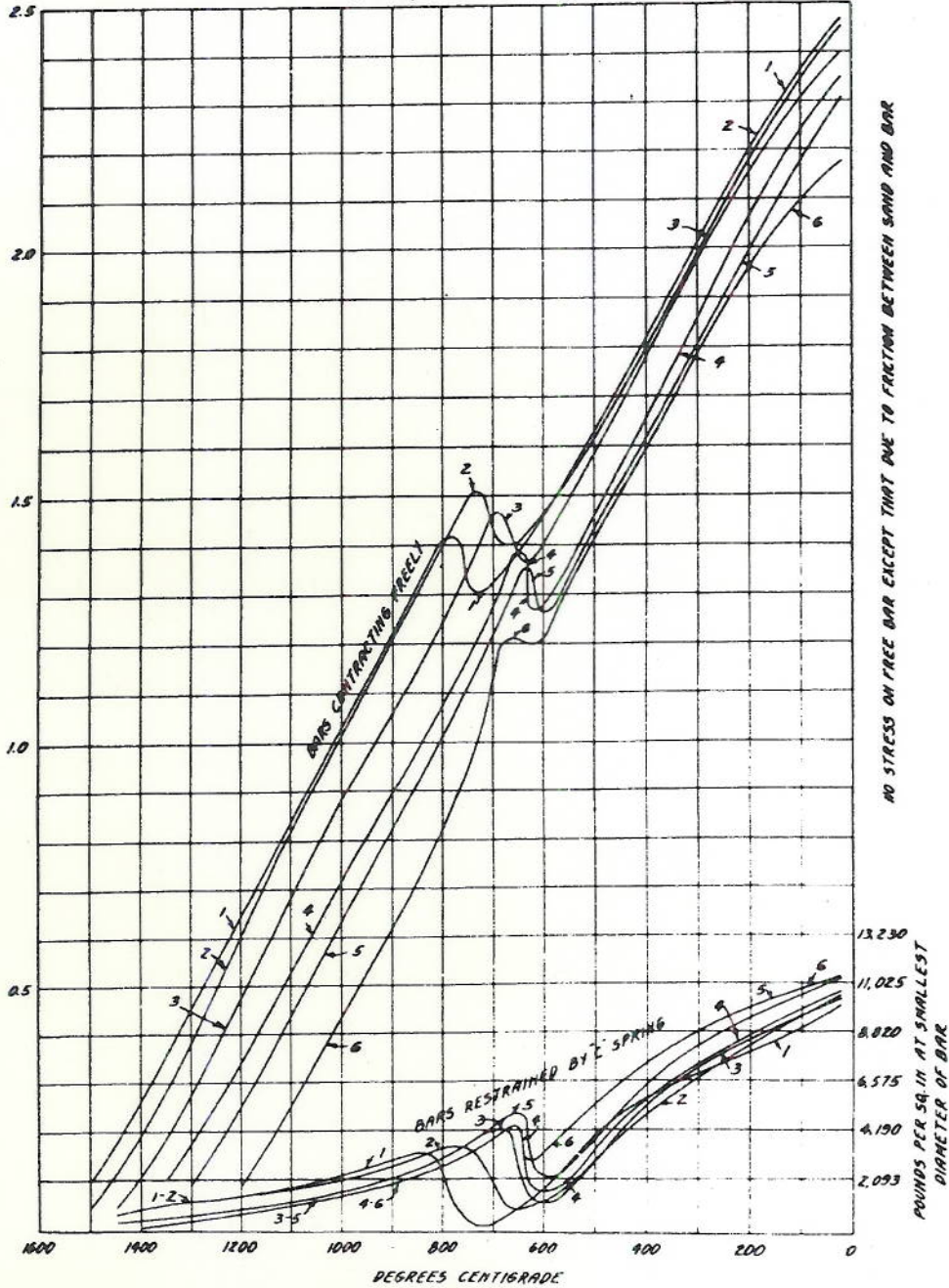


PLATE 6



CONTRACTION OF PLAIN CARBON STEELS

- 1-0.08% CARBON
- 2-0.14% "
- 3-0.35% "
- 4-0.45% "
- 5-0.55% "
- 6-0.90% "



NO STRESS ON FREE BAR EXCEPT THAT DUE TO FRICTION BETWEEN SAND AND BAR

PLATE 8

