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ABSTRACT

The fluidity of steel, as made for steel castings, is studied by the use of the spiral type fluidity mold. Careful attention is given to the control of experimental conditions and variables. Close duplication is maintained on the temperature control of the bath.

It was determined that the fluidity of steel is not affected by the carbon content and that deoxidation practice appeared to show marked changes in the fluidity of steel when other normal variables are constant.

Studies on the addition of copper show that copper increases the fluidity of cast steel.

AUTHORIZATION

1. The studies in steel castings were originally authorized by Bureau of Engineering letter QP/Castings (6-19-Ds) of 13 July 1928.

STATEMENT OF PROBLEM

2. The object of this progress report is to present basic principles and experimental information on the fluidity of cast steel.

KNOWN FACTS BEARING ON THE PROBLEM

3. In progress report No. M-1264 of 16 April, 1936, on the fluidity of cast steel, a careful study was made of the entire subject. The factors governing the fluidity of metal, and the published writings on the subject pertaining to cast iron and steel have been set forth in this report. Also a preliminary experimental study was carried on to ascertain the requirements necessary so that a quantitative investigation could be undertaken.

THEORETICAL CONSIDERATIONS

4. Since preparing progress report No. M-1264, there have been two investigations on the fluidity of cast steel that have appeared in the technical press. The salient features of these articles are summarized and reviewed briefly. During 1936, the Second Report of the Steel Casting Research Committee, Special Report No. 15 of the British Iron and Steel Institute, was published. Section III of this report was devoted to a study of "The Fluidity of Iron-Carbon and Other Iron Alloys" - J. H. Andrew, R. T. Percival and G. T. Bottomley.

5. The authors made a few preliminary experiments using the spiral mold fed by a horn gate that has become somewhat standard in this country and known as the Saeger-Bureau of Standards fluidity mold. Since the length of run was not sufficient, the horn gate was replaced with a straight down gate feeding into a small reservoir. A design of the mold used is shown in Figure 1 (Plate 1).

6. The alloys were melted in an oil-fired, crucible furnace. The crucible held a maximum of 25 pounds of melted metal, which served for two castings for each composition. The two tests were obtained at temperatures varying by about 50° C. (90° F.). Two thermocouples of tungsten-molybdenum were used in sheaths made of alundum cement to measure the temperature.

7. The mold was made with a core sand facing, backed with Yorkshire sand, and dried at 480° F.

8. The authors collected data on the following systems: Iron-carbon, iron-phosphorus, iron-silicon containing 0.4 percent of carbon and iron-manganese containing 0.5 percent of carbon.

IRON-CARBON

9. Twelve alloys ranging from 0.02 to 3.75 percent carbon were made and the results plotted. Two sets of temperature-fluidity curves for each alloy were constructed. In one set, the liquidus was selected as the point where the alloy possesses zero fluidity, and in the other the solidus was used. Figure 2 shows an example of these curves, which were then used for constructing a single curve showing the relationship between fluidity and composition at 1600 degrees Centigrade (2910° F.), as may be seen in Figure 3. As one would expect, the addition of carbon to iron increases the fluidity, provided the casting temperature is kept constant. This increase, however, is very slight over the peritectic range; that is, between 0.07 and 0.71 percent of carbon. With further increases of carbon beyond 0.71 percent, there is a noticeable continuous increase in fluidity up to the eutectic composition (4.3 percent carbon).

10. Fluidity values for each alloy were obtained from the fluidity-temperature curves at 10, 30 and 50 degrees Centigrade (18° F., 54° F., and 90° F.) respectively, above the point taken as zero fluidity. From these figures, the fluidity-composition curves shown in Figure 4 (Plate 2) were plotted, and it will be observed that the general form of the liquidus and solidus curves are similar. The liquidus series show a decrease in fluidity from pure iron to 0.07 percent carbon, then an increase to 0.17 percent, then constant fluidity between 0.17 percent and 0.71 percent carbon. This is followed by a decrease to a minimum of 1.8 percent of carbon, after which there is a steady increase up to 4.3 percent of carbon. In the solidus curves, there is a marked decrease in fluidity from 0.17 percent of carbon to 0.71 percent of carbon.

11. Correlating these results with the equilibrium diagram, it would appear that where the liquidus-solidus range is a maximum, the fluidity is a minimum and, therefore, it seems possible to forecast the comparative fluidity of an alloy of iron and carbon from its equilibrium diagram.

12. In the iron-phosphorus alloy series, the fluidity decreases, with an increase of phosphorus content, to a minimum of 2.6 percent of phosphorus, at which point the eutectic range commences. The fluidity curve shows a maximum value at the eutectic composition.

13. The iron-manganese alloys show an increase in fluidity up to about 3 percent manganese; from 3 to 14 percent the fluidity is nearly constant and above 14 percent it rises rapidly.

14. The iron-silicon series show a steady increase of

fluidity with an increase of silicon content.

15. It is believed that this work is open to serious criticism. The authors have erected from their basic data consisting of two points, a structure which in the final analysis should be considered little more than a supposition. In general, the authors have used two points of experimental data to establish a curve. This curve is then extrapolated to 1600 degrees Centigrade shown in Figure 3, to establish the relationship of the fluidity of iron-carbon alloys. The fluidity composition curve is also constructed with very little data as a basis.

16. The running quality of liquid malleable iron and steel was studied by W. Ruff*, his investigation being divided into four major complementary sections. The first section deals only with casting experiments in which the mold takes the usual form of a spiral. In the second section, the phenomena occurring within the flowing mass are studied by the determination of reductions in the rate of flow. In the third section, attention is paid to external influences determining the formation of marginal zones of certain definite kinds. Finally, the fourth section correlates all the preceding results in order to develop a new and simplified form of casting specimen - a form equally well adapted for use as a spoon test in the steel melting furnace.

17. Under the first part, Mr. Ruff made an extensive study of the method of gating a spiral and concluded that the straight down gate into the spiral gave the best results (Table 1, Plate 3). The author also studies the effects of pouring height and variation in size of the inlet cross-section upon the length of the spiral.

18. For the purpose of determining the velocities of flow, a special discharge method was developed by means of which it was shown by the author that the laws of flow as determined for other liquids were obeyed. In the case of metals that solidify readily these laws of flow operate jointly with thermal laws, and the combined effect is best ascertained by determining the conditions of flow when the length of run is at a maximum. The testing apparatus suggested by these considerations are explained by Mr. Ruff and recommendations made for their further application.

19. In commenting on this article, it may be said that the most serious objection to the work is insufficient emphasis on temperature control. Temperatures were taken by the optical pyrometer

* W. Ruff: The Running Quality of Liquid Malleable Iron and Steel. Iron and Steel Institute; Carnegie Scholarship Memoirs, 1936, Vol. 25, pp. 1-39.

and not checked. Also, the author theorizes at length and attaches rather complex explanations to features exhibited by the data that can be explained in a much more simple fashion. The information presented is, however, very worthwhile, and the careful study that the author has given to the subject makes it an excellent reference.

METHODS USED IN TESTING

20. It was recommended in the first progress report (No. M-1264) that an induction furnace be provided for the further study of fluidity of steel. The recommendation was approved and two induction furnaces were installed in June, 1937, preliminary fluidity tests being initiated on November 1, 1937.

21. The equipment and the methods used in this experimental work are presented in four major sections: (1) melting equipment and methods, (2) temperature equipment and control, (3) pouring operations, and (4) pattern and mold equipment, technique and handling methods. These subjects will be thoroughly discussed in the order given.

Melting Equipment and Methods

22. The melting furnace used in this work is of the high frequency induction type and operates on 960 cycles at a maximum safe power input of 100 kilowatts, the power being furnished by a motor-generator set rated to 1750 r.p.m., 800 volts, and 139 amperes, at 100% power factor. The power factor is controlled by a set of water cooled capacitors operated from the main control panel.

23. A 300 pound capacity silica crucible has been found to be best suited to the work and was purchased from the Joseph Dixon Company. The average life of this type of crucible is 12 melts. Previously, a basic Ajax magnesia crucible was tried, but the basic slag reacted rapidly with the quartz of the thermocouple sheath and had to be abandoned in favor of the acid process. The lining used around this crucible consists of gannister rammed solidly against the norcast shell, which forms the sheath into which the coils are permanently cast.

24. Armco iron was used for several fluidity heats, but at present the material being used consists of sheared SAE 1015 steel, and bar stock refined and cast from the half-ton, three phase arc furnace at this Laboratory. Enough metal is prepared in the arc furnace at one time for four subsequent fluidity series of 20 molds each. The crucible is charged with the proper type of metal and as it begins to melt, one pound of washed silica sand is added. This insures an acid slag which prolongs the service life of the silica crucible. If this precaution were not taken, there might be enough basic slag carried over by the metal from the arc furnace to react readily with the silica crucible and render it unfit for

extended use. The sand also serves to function as a protective layer for the molten steel against oxidation and loss of carbon.

25. In an effort to cut oxidation to a minimum and to obtain a dead melt, a reducing atmosphere was maintained over the metal by burning Pyrofax illuminating gas slightly on the carburizing side of neutral. An air gas burner of rather large volume was secured in place through a hole in the center of a refractory brick cover. This procedure was tried on several tests of Armco iron with varying carbon additions and was found to be of little practical value. It is possible that the moisture formed from burning the high hydrocarbon gas may have counteracted the beneficial results of the neutral, or slightly carburizing flame. Other atmospheres may possibly be tried later on, but for the present, this type of control has been abandoned.

Temperature Equipment and Control

26. As mentioned previously, thermocouples are employed as a means for measuring the temperature of the molten steel. An optical pyrometer is also used as a check method. A pair of couples, one of platinum - platinum 10% rhodium and the other of tungsten-molybdenum, are insulated from each other and placed together in a small fused quartz tube. This tube is then placed in a large fused quartz tube, 1-1/8 inch outside diameter with not less than 4 millimeter wall thickness. The assembly is then mounted in a thermocouple holder as shown in Plate 21, Figure 27, and the large quartz tube placed in a small electric muffle furnace for preheating to approximately 900° C. (Figure 28). This precaution is necessary since plunging a cold quartz tube into a bath of molten metal would result in cracking the tube and rendering the thermocouples unfit for further use. When the metal is all melted, alloys added, and sampling completed, the thermocouple and control assembly is quickly removed from the preheating furnace and mounted in position over the pot. The thermocouple hot junction is maintained about 2 inches below the surface of the metal at all times. If the tubes are placed too deeply in the metal, it has been found that in the last 5 or 10 minutes of testing, they often will bend at the surface of the metal and float to the top, thus invalidating the results. The cold junctions of the thermocouples are kept at a safe distance of 10 feet from the heat of the furnace.

27. A slip fit of the holder on to the bed frame permits the tube to be moved freely in elevation. A second sliding fit at the base of the bed frame allows complete adjustment in azimuth, and a ratchet attachment enables the tube to be fed deeper and deeper into the crucible as the volume of metal decreases when successive spirals are poured (Figure 29). The tubular part of the holder near the surface of the bath is constructed of heat resistant metal. Liberal clearances are allowed for all sliding fits and movable parts operating near the bath, in order to permit freedom of adjustment.

28. The thermocouples, as assembled, are used only once, as the high temperature, often ranging from 1500 to 1700 degrees Centigrade over a period of 20 minutes, changes their original crystal structure, making them brittle and unfit for repeated use. Also, the quartz of the protecting tubes becomes embrittled upon heating and prohibits use a second time. The tubes also fuse solidly around the wires at the hot junction and have to be broken away before the thermocouples can be renewed. The efficiency of the thermocouple wire for repeated use is destroyed, not only at the bead, but for all portions in the region immediately adjacent to the bead. It has been found necessary after each test to discard at least one inch of the platinum couple and three inches of the tungsten-molybdenum couple. At frequent intervals, the thermocouples are calibrated against a standard platinum-platinum, 10% rhodium couple in a small induction furnace and the optical pyrometer is also checked from time to time. The tungsten and molybdenum wire is purchased in lengths of 30 feet so that the cold junction may be brought directly to the instrument. The platinum couple is maintained at a length of about 5 feet with compensating leads continuing to the instrument. Both thermocouples are made from 18 gauge wire.

Pouring Operations

29. In order to facilitate complete control of pouring, a 500 pound electric hoist is used. This hoist is equipped with a five speed, push button control. Speedy response, accurate control of hoist, smoothness of running, dependency, and ease of operation are extremely important features in a hoist to be used in quantitative fluidity studies.

30. It was soon noticed that the first fluidity spiral poured from the furnace in each test run meant very little in the final analysis, as it was found the cold spout chilled the metal excessively. As a result, it is necessary to keep the furnace tilted at all times during pouring in order to maintain the metal at the highest possible level on the spout. This precaution also serves to aid in getting the metal into the mold with a minimum loss of time. Before the first mold is poured, a large ladle of metal is drawn to warm up the spout and eliminate the necessity of sacrificing the first mold for this purpose.

31. The pouring height has been standardized at 8 inches above the pouring basin of the fluidity mold, and this factor kept constant at all times. This eliminates a very important variable.

32. To facilitate the program, a flat-top, steel truck of the railway type is employed to hold the molds for pouring. This unit can be seen in Plate 22, Figure 30, and holds four molds at one time. It operates on a small track which runs directly across the front of the induction furnace. The molds are placed in their

proper position for pouring and numbered in the order of succession. As soon as one mold is poured, Figure 32, the car is manually pushed along the track until the next mold is in position. When the metal has sufficiently solidified for safe handling, the spent mold, Figure 36, is removed and another put in its place, this procedure being kept up until each of the series of approximately 20 molds is poured.

Fluidity Mold

33. The spiral fluidity mold was chosen for this work as it gives the most consistent results and is believed to be the best criterion of fluidity available today. The detailed form and dimensions of the fluidity mold are given in Plates 4, 5, and 6. The spiral pattern and the down gate are made out of brass and the pouring basin pattern and run-off reservoir are aluminum (Figures 23 and 24, Plate 20).

34. The flasks used are constructed of steel and have an inside dimension of 10 by 16 inches. The cope is 3 inches deep and the drag 4 inches deep.

35. The dead end of the spiral is vented to allow for an easy passage of gas.

36. The sand used for molding is a washed and graded silica sand and is mixed to proportions of 92% sand, 5% bentonite, and 3% water. A facing is used on all molds consisting entirely of new sand mixed to the above formula. This sand then goes into the heap and is used as regular backing sand for the molds of following tests.

37. The average tested values of the sand used for facing and backing are presented in table (2).

38. The mulling time for all mixes of each sand is three minutes, and the mold stands assembled for an average of two hours before it is poured (Figures 25 and 26, Plate 20).

39. Green sand molds are used throughout this work for the reason that it was found that the variables could be much more accurately controlled.

40. In a dry sand mold the amount of bond and the initial water content must be accurately controlled, in the same manner as in the green sand practice. However, further control features must be maintained such as drying temperature, drying time, oven ventilating conditions, cooling conditions and final mold temperature. Thus, for quantitative work where the control of variables is most important, green sand molds give the best results. The length of run of steel is a little longer in the dry sand mold, but the accuracy of the run is not increased. Also, more misruns (fins) are found when dry sand molds are used.

41. The various operations involved in collecting a set of fluidity data are illustrated in Plates 20, 21, 22, 23, and 24.

DISCUSSION OF RESULTS

Preliminary Experiments.

42. A study was made under induction melting conditions of the fluidity mold designed to be used with the electric arc furnace as reported in M-1264. The cross sectional area of this design was 0.23 square inches, and was poured with a horn gate. Only a few tests were necessary to show that the spiral was not long enough for such a large cross section when the mold was used in the new induction furnace set up. The results obtained are as follows:

Fluidity Navy Type
Cross Sectional Area 0.23 sq. inches

Temperature ° C.	Inches Fluidity
1550	35.5
1560	39.5
1575	42+

43. A new spiral was designed (Plates 4, 5 and 6) with a cross sectional area of 0.105 square inches, and the runs obtained with this mold proved to be very satisfactory.

44. There existed some doubt as to just the proper type of gate that should be used. Andrew, Percival and Bottomley discarded the horn gate after the first preliminary run as the steel froze at the entrance to the spiral. Ruff made a study of the Bureau of Standards fluidity mold and other modifications (Table 1, Plate 3) and found that the horn gate type was responsible for a very high percent deviation of values. He also found that the longest runs and lowest percent deviation of values was obtained with gating method "D", without horn, pouring basin, or collecting basin under the inlet.

45. It was decided that since Ruff had obtained such excellent results his method should be studied. Also Andrews, Percival and Bottomley decided after preliminary experiments that the best results were obtained when the spiral led off from a small blind reservoir which was fed by a straight down gate. They, however, retained the pouring basin and overflow runner that was developed by Saeger.

46. It was thought that in order to obtain consistent results for quantitative work it would be necessary to maintain a definite head of liquid metal. This was not done by Ruff and though he reported excellent results by his "D" method of gating it was considered necessary by the authors that all possible variables be eliminated. Thus, adherence was maintained to the pouring basin with the overflow, regardless of the type of gating employed. The head of liquid metal in this case is, therefore, 2 inches.

47. Experimental work was undertaken to establish the proper gate that should be used. The horn gate and the straight down gate were the only two types deemed, on their past merit, worthy of consideration. In connection with the straight down gate, there was also the question of the possible use and size of a reservoir.

48. Ruff in his "D" design did not use a reservoir and he showed a smaller percentage deviation of values with this type than with his "C" design wherein a reservoir was used.

49. It was decided, however, that if it were at all possible to obtain fairly consistent results it would be better from the practical molding standpoint if the spiral could be run from a reservoir rather than directly from the down gate. Also, it was thought that the reservoir would allow for a smooth flow of metal into the spiral, due to the building up of a pool of metal. If, however, the spiral led off directly from the down gate, then the first spurt of metal that came down the gate would enter the spiral. Such a condition might lead to inconsistent results. Such inconsistencies were not encountered by Ruff but, nevertheless, the use of a blind reservoir appeared to the authors to be a very logical step.

50. Andrews and his co-workers found that in general there was very little difference in the length of the cast spiral if the blind reservoir was varied in size from small to large. For their work they standardized on a 1-1/2 inch diameter by 9/16 inch deep reservoir.

51. Two sizes of reservoirs were studied in the present investigation. The small one measured 1-1/2 inches in diameter by 1 inch deep, and the large one 2-1/2 inches in diameter by 2-1/2 inches deep. The results obtained are presented in Table 3. It may be seen that there is very little difference in the length of the runs obtained. It would appear, however, that by the use of the small reservoir the results were more consistent. Thus, the small reservoir was made standard for the straight down gate fluidity type mold.

52. A comparison of test data of the straight down gate type with the horn gate type as shown in Plate (7), was made by pouring, from the same base metal, fluidity tests at various temperatures. The plotted data and the characteristic curves obtained are illustrated in Plate (8), Figures 10 and 11. This experiment was repeated four times, a total of eight heats, and data so obtained are comparable to that shown.

53. The deviation of the individual points from the mean average is greater in the case of the horn gate type, and the first portion of the curve is also somewhat steeper. The latter point is not necessarily a disadvantage, but in general the accuracy of the test data on the horn gate type was not all that was desired. It

It is evident that the horn gate is responsible for this deviation, since the spiral and pouring basin were the same in both methods. Also, the cross section of the horn gate is the governing orifice and not the cross-sectional area of the spiral, which would seem to be the appropriate orifice.

54. From the above work, it was, therefore, decided to accept the straight down gate with the blind reservoir as the method for gating the fluidity test. The standard mold used in the experiments to follow is shown in detail in Plates 4, 5, and 6.

55. Since Ruff had reported only 3 percent deviation of values with his "D" type method of gating, it was thought best to study the new standard method and compare it against Ruff's Type D gate. The construction of this gate is shown in Figure 5, Plate 3, and no pouring basin or overflow runner was used.

56. Cast steel of 0.20 percent carbon was used for the study. After melting down, the temperature was raised to 1560 degrees Centigrade and the final additions made. The temperature dropped to approximately 1530 degrees Centigrade and testing was started. A very low power input was maintained on the furnace to prevent the bath from cooling, with a slight rise in temperature recorded during testing. The results are presented in Table 4.

57. A percentage deviation greater than that shown by Ruff was recorded by the tests and may be due to the fact that the cross sectional area of the spiral was different in the two cases. The cross-sectional area of the Bureau of Standards spiral used by Ruff was 0.066 square inch as compared to 0.105 square inch used in the reported tests.

58. The comparison tests showed, however, that the type of fluidity mold being used as a standard for these tests is quite sensitive and that the 3.9 percent deviation of values is well within acceptable limits.

59. Previous to the above comparison tests, a study was made with regard to the effect of the rate of pouring on the length of the fluidity spiral. This information is set forth in Table 5. It may be seen that if the pouring speed to fill the mold is maintained between 2 and 3 seconds, a comparable set of data will be obtained. Occasionally, the hoist operator in charge of pouring is checked by stop watch to ascertain the pouring speed. It has been found that on a set of data representing 20 molds the operator will be within the time limits set on an average of 18 molds out of the 20.

60. Certain investigators on the fluidity of cast iron have shown that variations in sand, moisture and bonding material make a considerable difference in the length to which cast iron will run in the fluidity mold. It is reasonable to believe that mold conditions

may also have a similar effect on the testing of steel, and since the size distribution of the sand can be maintained fairly constant, only variations in the moisture content and bentonite were studied. These results are tabulated in Table 6. For the test cast steel melting stock was used. The temperature was brought up to approximately 1550 degrees Centigrade, the final deoxidizers added, the thermocouples placed in the bath, and the testing started. An attempt was made to keep the temperature of the bath as nearly constant as possible, this being accomplished with a fair degree of success, as may be seen by a study of the data.

61. The conclusions to be drawn from the data are that small changes in the moisture content (3 to 5%) and the bentonite content (1 to 5%) are not sufficient to cause a material change in the running quality of the steel.

62. An investigation of the effect of carbon on the fluidity of steel was attempted by using sheared Armco iron as the base material. Various carbon contents were obtained by the addition of washed metal (3.55 percent carbon) to the charge.

63. The fluidity of the Armco iron was first studied. It was necessary, however, to run several heats of Armco iron in order to collect sufficient data to construct the curve of Figure 12, Plate 9. The reason for this was the fact that the high amount of iron oxide present in the bath reacted with the thermocouple tube, eroding it in a few minutes, and thereby causing the thermocouples to become short circuited.

64. An interesting fact, as viewed in the light of other data collected, is that Armco iron is more fluid throughout the superheat range employed than is cast steel.

65. It was noted that rather inconsistent results attended subsequent experiments on iron and carbon alloys prepared with Armco iron. The steels, of course, were highly rimming in character and fluidity data with correct temperature control were difficult to obtain.

66. The failure to collect data on an iron-carbon series appeared largely to lie with the induction type of melting where the metal is continually being stirred. If perhaps a dead melt could have been provided, as is possible in the crucible process, greater success might have been recorded.

67. Studies were, however, continued with the Armco base metal but additions of ferro-silicon and ferro-manganese were made to the charge, together with the washed metal. This resulted in the charge melting down with 0.35 to 0.55 percent manganese and from 0.20

to 0.35 percent silicon. Further additions, as finals, were made to bring the manganese and silicon to the required contents.

68. Five heats were run under the above conditions. The carbon contents on these heats were 0.41, 0.28, 0.20, 0.11 and 0.11 percent. The first 0.11 percent carbon heat finished low in manganese and silicon content, and hence was very effervescent and the data were not at all consistent. Also, it was necessary to discard the 0.41 percent carbon heat due to failure of the temperature control systems.

69. In two of the remaining three heats, those of 0.28 and 0.11 percent carbon, it was noticed that the metal rose in the fluidity mold, indicating that the heats were not dead, even though sufficient ferro-manganese and ferro-silicon had been added to the melts to ordinarily insure killed metal.

70. It has been previously mentioned that an atmosphere of Pyrofax gas was burned at the mouth of the crucible in an attempt to cut down the oxidation of the metal. This procedure was maintained on most of the Armco iron heats of the above series. The continual rise of the metal in the molds, however, was indicative that the gas atmosphere was not accomplishing all that was desired. Therefore, the use of the gas atmosphere was discontinued.

71. The data collected on the above three heats are plotted on Plate 10, Figure 13. Heats 53 and 54 had greater fluidity than was recorded by the 0.20 percent carbon steel of heat 52. The reasons for this are not apparent.

72. Attention should be called to certain phases of the procedure that were employed to maintain the bath of metal at a fairly constant composition. In preliminary tests it was found that during the 20 minutes required for testing the 20 to 22 molds, the manganese content of the bath would drop somewhere between 0.20 to 0.30 percent. It was, therefore, necessary that small additions of ferro-manganese be added to the bath at constant intervals during the 20 minutes in order to maintain the manganese at a constant value. The carbon and silicon did not vary more than 2 or 3 points from the beginning to the end of the heat. These minor losses were not considered sufficient to necessitate periodic additions.

73. Under some conditions the silicon would increase a few points during the test period.

74. In the next series of alloys that were studied it was decided not to use the sheared Armco iron, but to remelt the steel used in the previous fluidity heats. Ferro-manganese and ferro-silicon were added to the charge in sufficient amounts so that when the bath became melted down, it contained approximately 0.50 percent manganese and 0.25 percent silicon. Carbon additions in the form of washed metal were also made to the cold charge.

75. Ferro-manganese and ferro-silicon were also added just prior to testing for fluidity as the final deoxidation.

76. In this series, seven steels of the following carbon contents, 0.11, 0.20, 0.27, 0.33, 0.34, 0.56 and 0.86 were studied. It will be noted that only the 0.33 percent carbon steel was duplicated.

77. The data recorded on these steels are all plotted on Plate 11, Figure 14, so that it may be seen in what a narrow band they all lie. There appears to be no definite order as to their relative position. By this it is meant that the carbon content is not responsible for any marked increase in fluidity.

78. It will be noted that the lower portion of the curve usually consists of a straight line. At temperatures of about 1525 to 1550 degrees, Centigrade, the curves begin to bend over, and at temperatures of about 1700 degrees they are nearing the horizontal indicating that further increasing of temperature would not greatly increase the length of run.

79. The 0.33 and 0.34 percent carbon steels were the only ones run in duplicate. And while the analyses for carbon, manganese and silicon are nearly the same for both steels, the two curves obtained are somewhat different, the major difference being the angle of slope during the straight line portion of the curve.

80. A comparison of the 0.20 percent carbon steel of this series with the 0.20 carbon steel of the previous series as shown on Plate 10 brings out the interesting fact that the two curves practically coincide throughout their length (Plate 12).

81. The above two series of investigations may be considered to have been made on what may be called a synthetic cast steel, in that Armco iron was used as a base and carbon, manganese and silicon were added in sufficient quantities to obtain analyses that are typical of cast steel.

82. For further experimentation it was decided that well made steel for castings should be used. For this purpose, steel scrap was melted in a 3-phase basic electric arc furnace and converted into steel suitable for castings. The steel was poured into sand molds of a bar design that would facilitate charging into the 300 pound induction furnace. A total of 1200 pounds of useable steel casting stock was obtained from each arc furnace heat. This allowed four fluidity heats to be made from the same base stock.

83. The stock metal was normally finished at the following analysis: Carbon 0.15 - 0.25 percent, manganese 0.60 - 0.75 percent and silicon 0.28 - 0.38 percent, phosphorus 0.02 percent, sulphur 0.02 percent.

84. A very interesting set of data was recorded as the result

of heats 70 and 71. The stock metal used was 0.25 percent carbon. Only a small amount of manganese and silicon were added to heat 70 as finals. The heat was gassy and rose in the fluidity mold.

85. In heat 71 considerable ferro-silicon and ferro-manganese were added to obtain a killed heat. The steel was very quiet in the mold and analyses showed the silicon to be high. The curves obtained from these heats are shown on Plate 13, Figure 16. The killed heat appears quite normal as judged by following heats of the same type. The gassy or rimming heat definitely has a lower fluidity at the higher temperatures.

86. The information obtained on heats 70 and 71 was of such interest that it was decided to try further experiments along this same line but use a different stock metal from that used in the previous tests.

87. A stock of well made and killed steel containing 0.24% carbon was used for heats 72, 73 and 74. Heat 73 was slightly rimming, while heats 72 and 74 appeared dead. The curves obtained are shown in Plate 14, Figure 17.

88. The rimming heat has definitely lower fluidity properties than the killed heats. From the data presented it would appear that the 0.15 percent increase in silicon is responsible for increased fluidity. This point, however, should not be considered definite as in some cases curves constructed from duplicate data will show nearly the same deviation.

89. In the next three induction furnace heats a study was made of the effect of carbon content on the fluidity of steel. A steel casting stock of 0.15 percent carbon was used. Carbon additions in the form of wash metal were made to increase the carbon content of the bath.

90. The data were obtained by pouring 12 to 14 fluidity molds on the rising temperature and from 5 to 6 molds as the bath was cooling down. Data taken below 1525 when the bath was cooling were usually of little value, unless certain precautions were taken which will be explained later in connection with other data.

91. The points taken during cooling usually fell in line with the heating points and were used as check information on heats. Whenever these points did not check within reasonable limits, the experimental work was repeated.

92. The effect of carbon content on the fluidity of steel may be seen in Plate 15, Figure 18. Carbon variations were similar to those found in the usual grade of steel castings. Only one curve could be drawn through the data as the data were so well bunched.

93. From the information as shown on this Plate, it may be said that carbon contents between the limits of 0.15 to 0.45 percent have no effect on the length of run that may be obtained in fluidity testing. In other words, within this range of carbon contents it is not possible to increase the fluidity by increasing the carbon content.

94. The data presented here were duplicated in heats 78, 79 and 80. The curve drawn was practically identical with that shown here; however, the points were a little more scattered.

95. It has been explained that the data recorded in these tests were collected for the most part on a rising temperature. To be more explicit, the steel casting stock was melted in the induction furnace. The finals were added at temperatures of about 1475 degrees Centigrade and testing proceeded as soon as the finals dissolved into the bath. Full power was put on the furnace and further tests taken as the superheat increased.

96. Fifteen minutes were required to superheat the bath from 1450 to 1700 degrees Centigrade.

97. It was decided that a study should be made of the fluidity characteristics obtained when the data were collected as the bath was cooling. This would require the addition of the final deoxidizers after the metal had been heated to approximately 1700 degrees Centigrade.

98. It was found that at temperatures below 1525 degrees Centigrade or thereabouts a light skin formed on top of the metal in contact with the air and upon the pouring of the fluidity mold this colder metal enters the mold and the length of run obtained falls below the real value. This condition may be corrected by turning on the power for approximately 15 seconds before pouring the mold. The bath immediately starts to move and the skin formed is carried down into the bath leaving a bath of a homogeneous temperature ready for the fluidity test.

99. Steel casting stock was again used to study the effect of carbon on the fluidity of steel with data being taken on the cooling of the melt. Steels of four carbon contents were made and deoxidized at 1700 degrees Centigrade, followed immediately by fluidity testing. Again, the data were so well bunched that only one curve could be drawn. In Plate 16, Figure 19, the data and the constructed curve obtained are shown.

100. This curve is compared with the heating curve in Plate 17. There appears to be slight differences in the shapes of the curves, though the differences obtained are not radical in departure. It would seem that the curves point out that the temperature at which final deoxidation is accomplished has a bearing on the shape of the curve obtained.

101. The differences that arise in these two curves should not be considered too seriously as it is quite possible that data covering nine heats may have enough dispersion to account for the curve discrepancies.

102. The information presented does, however, allow for the formulation of two conclusions:

- (1) The fluidity of steel is not appreciably affected by changes of from 0.15 to 0.70 percent in the carbon content.
- (2) For any plain carbon hypoeutectoid steel the temperature-fluidity relationship is not a straight line function.

103. The curve appears to be a straight line function up to temperatures of 1525 to 1550 degrees Centigrade. At higher temperatures the curve bends over quickly and flattens out.

104. The information presented in curve form on Plates 15, 16 and 17 is at considerable variance with that which has been previously published. In most cases, a straight line function was obtained and in some cases, as in the publication by Andrews and co-workers on the fluidity of iron alloys, an infinite fluidity at high superheat temperatures, was occasionally pictured.

105. Since it has been observed that the variations that exist in the carbon content of steel castings are not responsible for change toward obtaining increased fluidity in the melt, it was decided that the next logical step was to study the effect that various alloy additions had upon fluidity, when compared to the fluidity which may be obtained by a plain carbon steel.

106. Since a number of alloy combinations were to be studied, it was thought that a large quantity of a single melting stock would be necessary. Thus, several tons of sheared SAE 1015 were obtained.

107. The characteristic fluidity curve of this material was studied. Final addition of ferro-manganese and ferro-silicon were added to kill the heat and to bring the manganese content within the range of 0.60 - 0.75 percent and the silicon content between 0.28 and 0.38 percent in the steel ready for testing.

108. It may be seen from Plate 18, Figure 21, that the fluidity curve obtained on the rolled SAE 1015 stock material is slightly higher than the curve obtained by the testing of steel casting stock material. The reason for the increased fluidity with the change in melting stock is not known. However, the 0.31 carbon heat of 104 produced a fluidity curve, Figure 22, that practically duplicated the one shown in Figure 21.

109. There are many references in the literature to the effect that copper will increase the fluidity of steel. These references have

not been based on actual data collected but on the various observations of different individuals. There is, however, such a unanimity of opinion in this regard that it was decided that a study of the effect of copper on the fluidity should be undertaken as the first study in connection with the effect of alloys on the fluidity of steel.

110. The SAE 1015 melting stock was used and carbon (wash metal) was added to the charge in order to approximate 0.30 percent carbon heats. Three heats were made in the copper series, one with no copper added, one with a copper content of approximately 2 percent, and the third with a copper content of approximately 3.7 percent. The copper was added to the charge as bar stock. The curves obtained from plotting the data collected on these heats are shown on Plate 19, Figure 22. It may be readily seen that the steel containing 2 percent copper is more fluid than a steel of practically identical composition without the addition of copper. A further increase in fluidity is obtained by the use of increased copper contents. The increase, however, is not proportional.

111. These curves show that at 1500 degrees Centigrade, by the addition of 3.70 percent copper to a plain carbon steel, it is possible to increase the length of spiral run approximately seven inches. This is an increase of nearly $\frac{1}{3}$ of the length of flow at 1500 degrees Centigrade, and accounts for the fact that under commercial conditions the increased fluidity was recognized.

112. Further studies on the fluidity of alloy steels have been carefully planned by the Laboratory staff and tests are to be carried on with as much dispatch as possible during the coming year.

SUMMARY

113. Studies have been continued on the fluidity of cast steel with the use of the induction furnace as the melting apparatus.

114. The spiral fluidity mold was redesigned with a more appropriate spiral section and a more consistent gate and basin control. Tests performed showed that the mold so devised was very efficient and had a high accuracy of reproducibility of test results.

115. Temperature control of the steel bath was given considerable study. Apparatus was installed and a procedure initiated which allowed temperature reading taken by a tungsten-molybdenum couple to be checked by a platinum-platinum rhodium couple. Optical temperature control also acted as a third-way check.

116. Various types of carbon steels and iron-carbon alloys were studied in order to ascertain the effect of deoxidation and increasing carbon content on fluidity.

117. It was found that variations in carbon content, in the hypo-eutectoid range, had no effect upon the fluidity as determined

by the length of spiral run. It was, however, apparent in some cases that conditions of deoxidation did show quite a marked effect on the fluidity.

118. It was also ascertained that the fluidity-temperature relationship is not entirely a straight line function, but that above approximately 1550 degrees Centigrade, the fluidity no longer increases as the temperature increases, thereby causing the curve to bend over so that in the neighborhood of 1700 degrees Centigrade the curve is nearly parallel with the temperature axis.

119. A study of the effect of copper addition to a carbon steel showed that copper increased the fluidity of cast steel.

Table 1

Superior of samples obtained using a large and a small sized reservoir with the straight down gate fluidity test.

Temperature	Fluidity - Inches	Fluidity - Inches
	Large Reservoir	Small Reservoir
1550	22.5	20
1575	23	21.5
1600	24	22
1625	24.5	23

Table 1 is on Plate 3

Table 2

Sand Properties

	<u>Facing</u>	<u>Backing</u>
Moisture	2.9 - 3.1%	2.9 - 3.3%
Compression Strength	5.5 lbs. per sq. in.	5 lbs. per sq. in.
Permeability	112	115
A.F.A. Grain Size No.	63	63
Distribution:		

<u>Sieve U. S. Standard</u>	<u>% Retained</u>
6	0
12	0
20	0.04
30	0.26
40	2.72
50	12.50
70	38.44
100	31.78
140	11.54
200	2.22
270	0.30
pan	0.22

Table 3

Comparison of results obtained using a large and a small blind reservoir with the straight down gate fluidity mold.

<u>Temperature</u> <u>°C.</u>	<u>Fluidity - Inches</u>	
	<u>Large Reservoir</u> <u>2-1/2" d x 2-1/2"</u>	<u>Small Reservoir</u> <u>1-1/2" d x 1"</u>
1550	23.5	23
1570	26	25.5
1590	27	28
1610	31.5	30

Table 4

Deviation and Sensitivity Characteristics

<u>Type</u>	<u>Temperature °C.</u>	<u>Fluidity inches</u>
Standard	1526	21
"	1529	21
Ruff "D"	1529	20.5
" "	1529	20.5
Standard	1530	22.5
"	1530	19.5
Ruff "D"	1532	25.5
" "	1532	22.0
Standard	1535	- - misrun
"	1535	22.0
Ruff "D"	1540	22.5
" "	1540	18.5

Type of Mold

Deviation of values

Standard

Ruff "D"

%

3.9

8.1

Table 5

Study of Rate of Pouring

<u>Speed</u> <u>Sec. to fill Mold</u>	<u>Temperature</u> <u>°C.</u>	<u>Fluidity</u> <u>inches</u>
1 sec.	1570	
1.3 "	1570	30.5
1.7 "	1570	29.5
2.2 "	1575	28.0
2.5 "	1575	26.0
2.5 "	1575	26.5
3.0 "	1575	26.0
3.5 "	1580	25.0
3.5 "	1580	24.5
4.0 "	1578	22.0

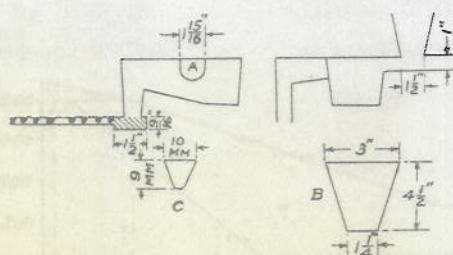
C - 0.27, Mn - 0.60, Si - 0.32

Table 6

Study of Bond and Water Variables on
A.F.A. No. 63 Washed Silica Sand

Sand Mix by Weight		Temperature °C.	Fluidity inches
% Bentonite	% Water		
1	3	1540	22
1	3	1545	22
1	3	1548	23.5
3	3	1540	23
3	3	1547	22.5
3	3	1550	23.5
5	3	1543	20.5
5	3	1545	22.5
5	3	1550	22
3	5	1560	23.5
3	5	1555	24.5
5	5	1560	24
5	5	1560	23
4	4	1555	24
4	4	1550	23

C - 0.25, Mn - 0.63, Si - 0.37



A - OVERFLOW
B - CONICAL FEEDER HEAD
C - SPIRAL SECTION

FIG. 1—FLUIDITY TEST CASTING DESIGN.

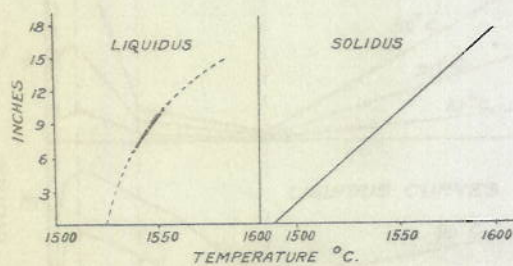


FIG. 2—FLUIDITY-TEMPERATURE CURVES OF A 0.17 PER CENT CARBON ALLOY, TAKING THE LIQUIDUS AND SOLIDUS RESPECTIVELY AS ZERO FLUIDITY.

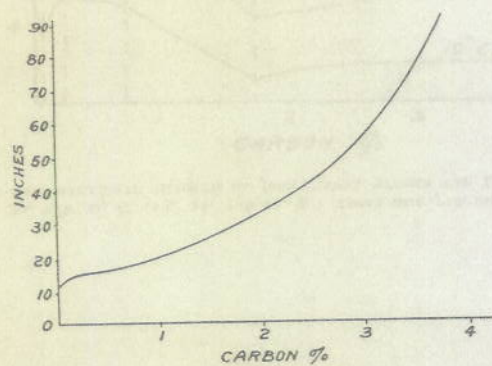


FIG. 3—FLUIDITY CURVE OF IRON—CARBON ALLOYS AT 1600° C. (2910° F.)

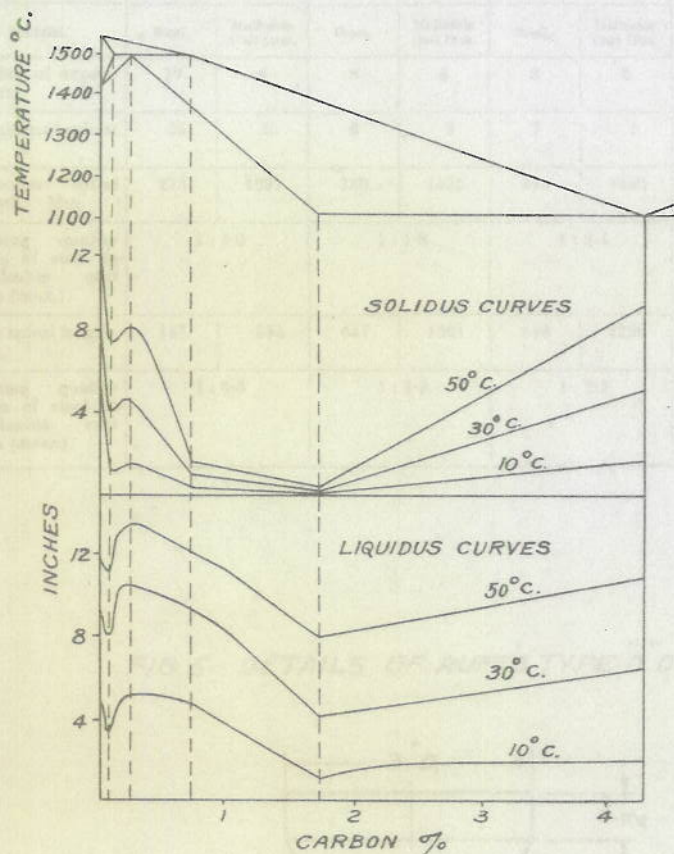


FIG. 4—CONSTITUTIONAL DIAGRAM OF IRON-CARBON ALLOYS AND FLUIDITY CURVES AT 10°, 30° AND 50° C. (18°, 54° AND 90° F.) ABOVE THE LIQUIDUS AND SOLIDUS.

TABLE I.—Spiral-Tests of Steel and Malleable Cast Iron for Different Gates.

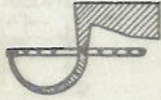
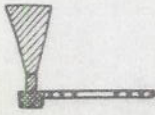
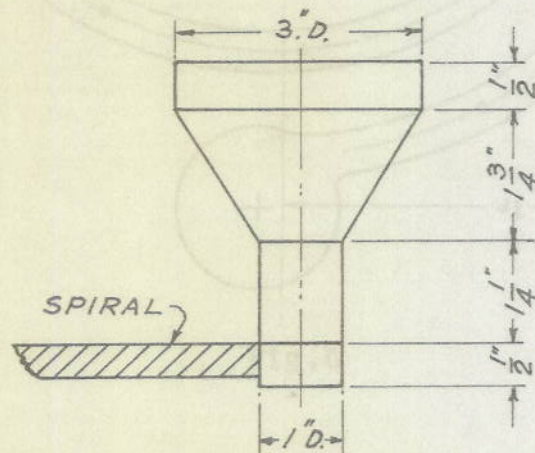
Method of Gating:	A		B		C		D		E	
										
Material.	Steel.	Malleable Cast Iron.	Steel.	Malleable Cast Iron.	Steel.	Malleable Cast Iron.	Steel.	Malleable Cast Iron.	Steel.	Malleable Cast Iron.
Number of experiments.	10	6	8	6	8	6	37	13	5	6
Deviation of values, %.	25	5	6	3	7	7	3	2	3	6
Maximum spiral length. Mm.	275	1091	780	1435	615	1480	940	flowed to end	745	flowed to end
Running quality ratio of steel to malleable cast iron (max.).	1 : 4.0		1 : 1.8		1 : 2.4		1 : 1.6		1 : 2.1	
Mean spiral length. Mm.	147	933	647	1261	548	1230	753	1365	616	1314
Running quality ratio of steel to malleable cast iron (mean).	1 : 6.3		1 : 1.9		1 : 2.2		1 : 1.8		1 : 2.1	

FIG. 5- DETAILS OF RUFF'S TYPE "D" DESIGN



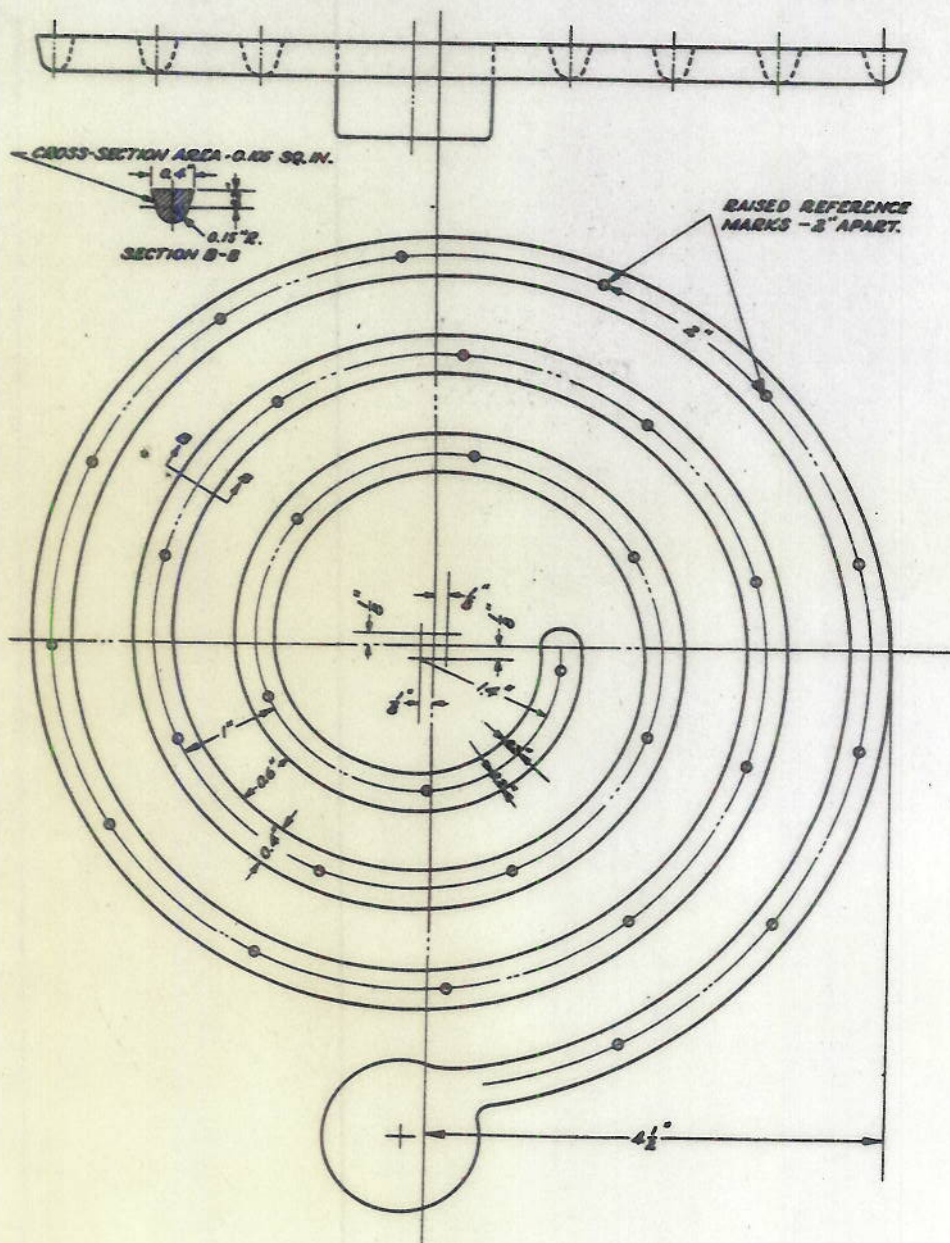
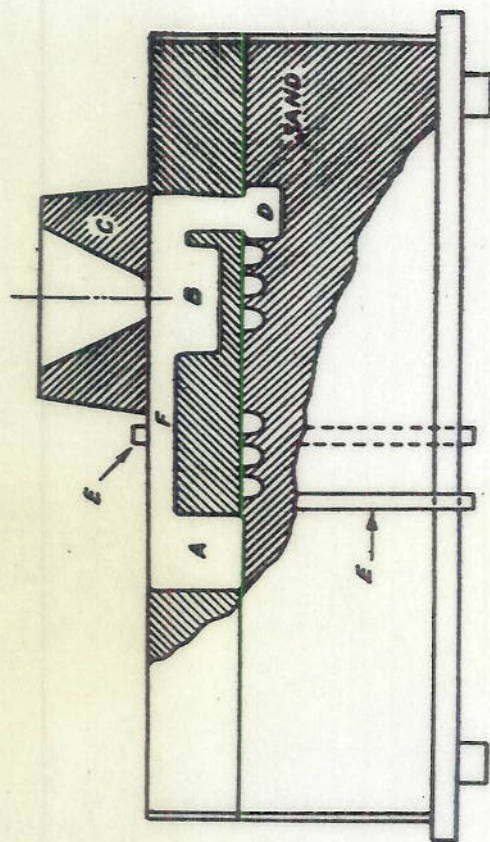
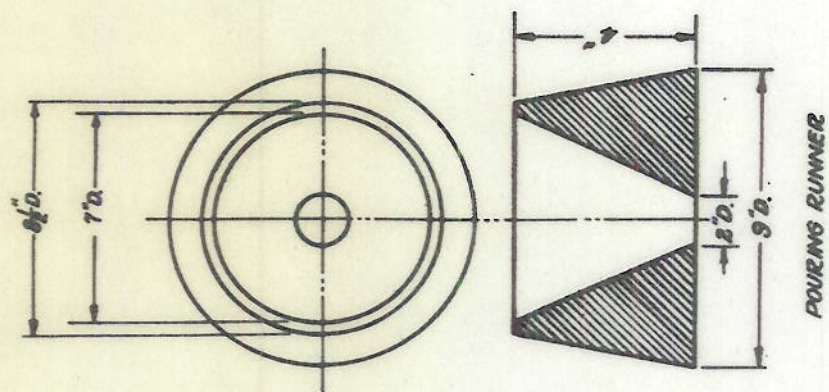


Fig. 6



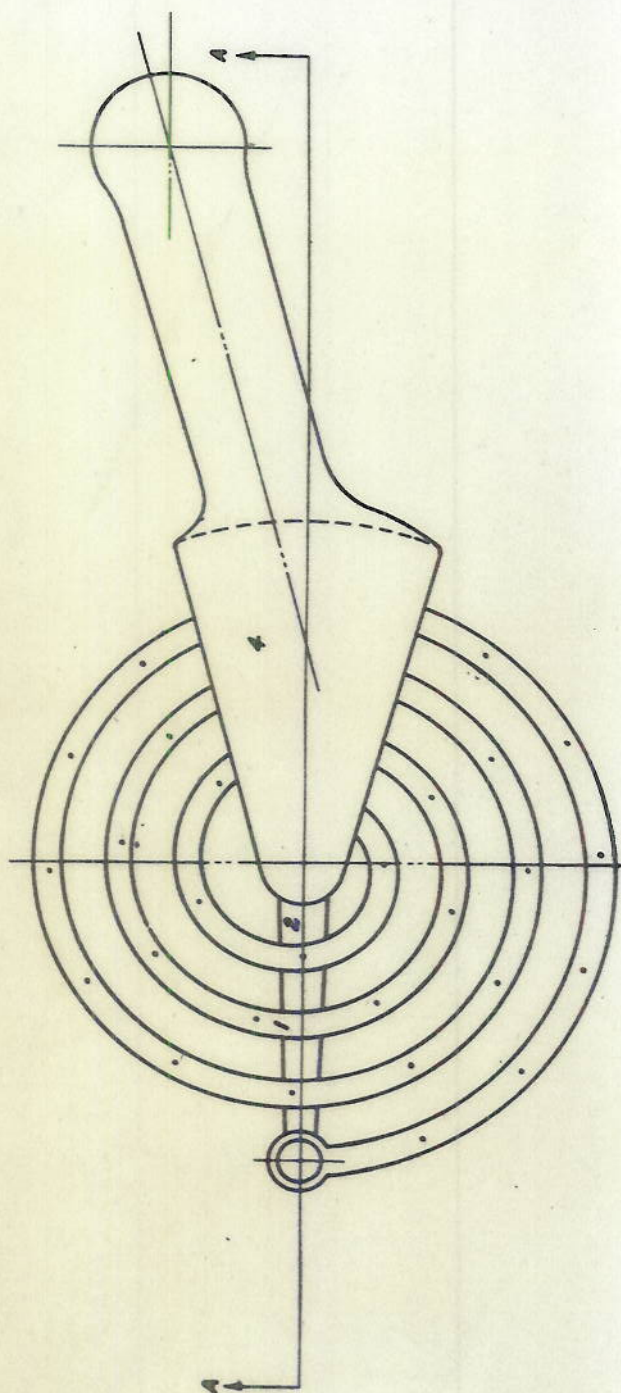
Plate 5

LEGEND
 A - OVERFLOW RESERVOIR.
 B - POURING BASIN OR WELL.
 C - POURING RUNNER.
 D - POURING BUTT.
 E - MOLD CLAMPS.
 F - OVERFLOW TROUGH.



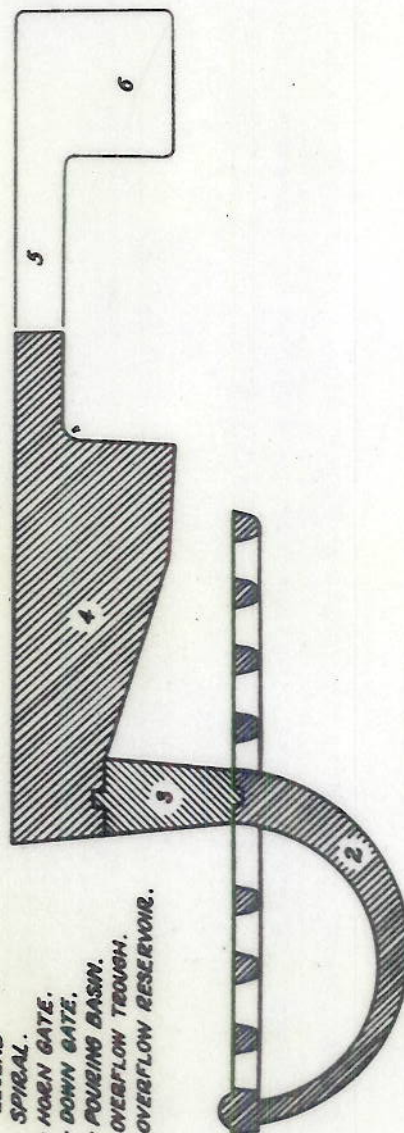
MOLD ASSEMBLY

Fig. 3



LEGEND

- 1 - SPIRAL.
- 2 - HOEN GATE.
- 3 - DOWN GATE.
- 4 - POURING BASIN.
- 5 - OVERFLOW TROUGH.
- 6 - OVERFLOW RESERVOIR.

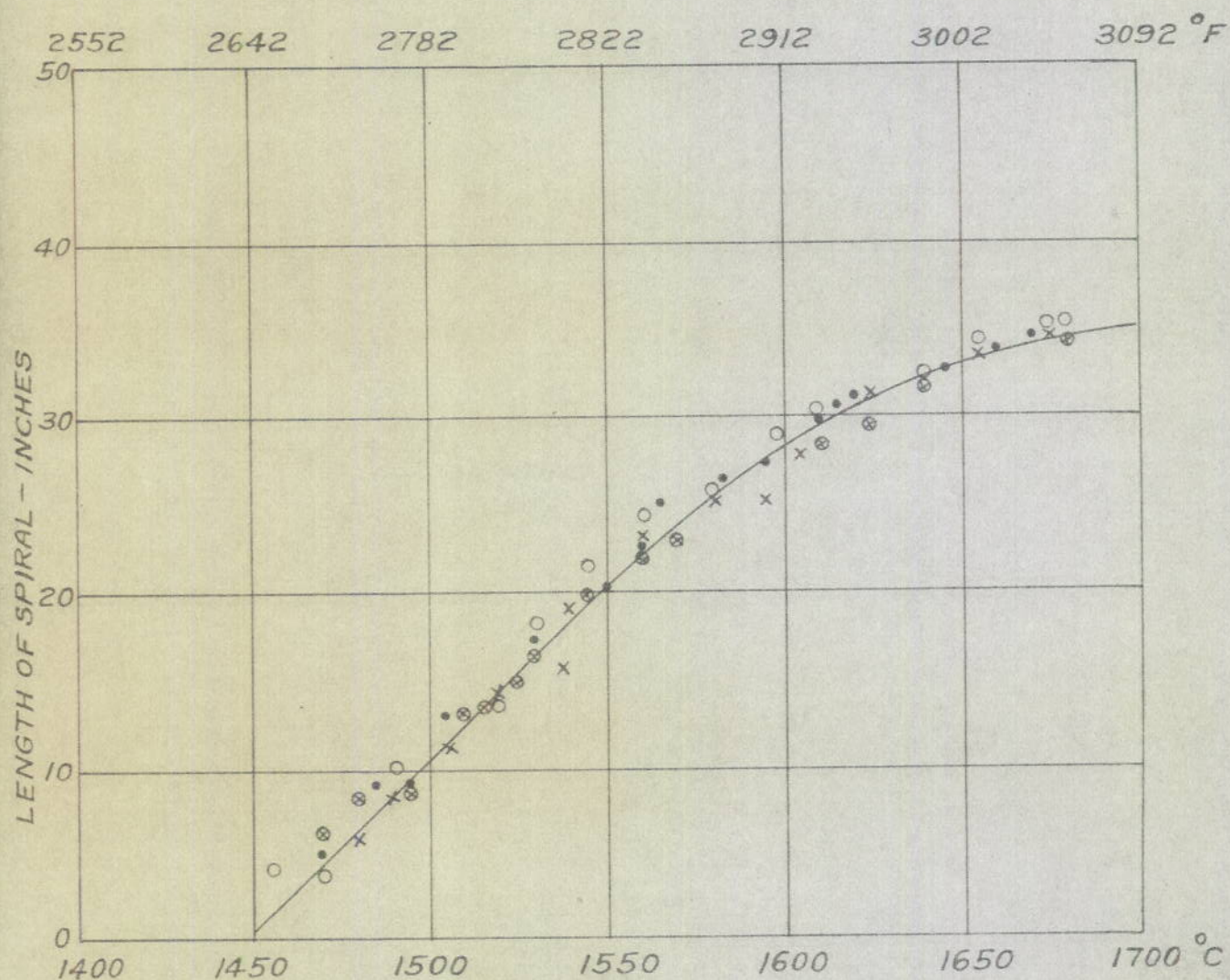


SECTION A-A

Fig. 3

FIG. 19 - EFFECT OF CARBON ON THE FLUIDITY OF STEEL
DATA TAKEN ON COOLING OF THE MELT.

	C	Mn	Si	HEAT NO.
○	0.16	0.69	0.37	84
×	0.30	0.69	0.30	85
•	0.46	0.77	0.31	86
⊗	0.70	0.80	0.36	87



COMPARISON OF THE TYPE OF GATING USED WITH THE FLUIDITY MOLD.

○ - HEATING DATA
x - COOLING DATA

STEEL
C-0.24, Mn-0.63, Si-0.28

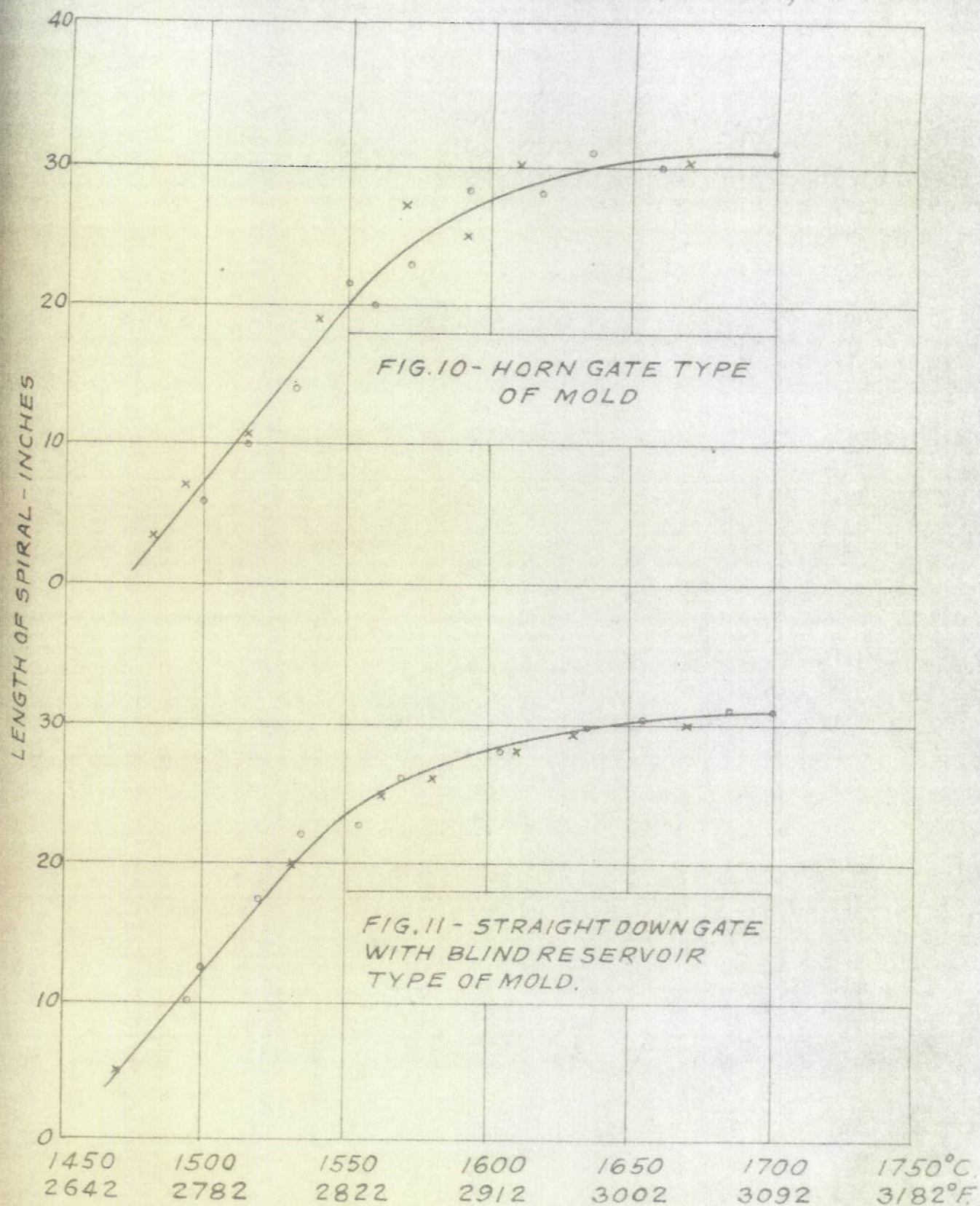


FIG. 12 - FLUIDITY OF ARMCO IRON.

	C	Mn	Si	HEAT NO.
○ -	0.007	0.01	0.001	40
x -	0.017	0.02	0.001	102

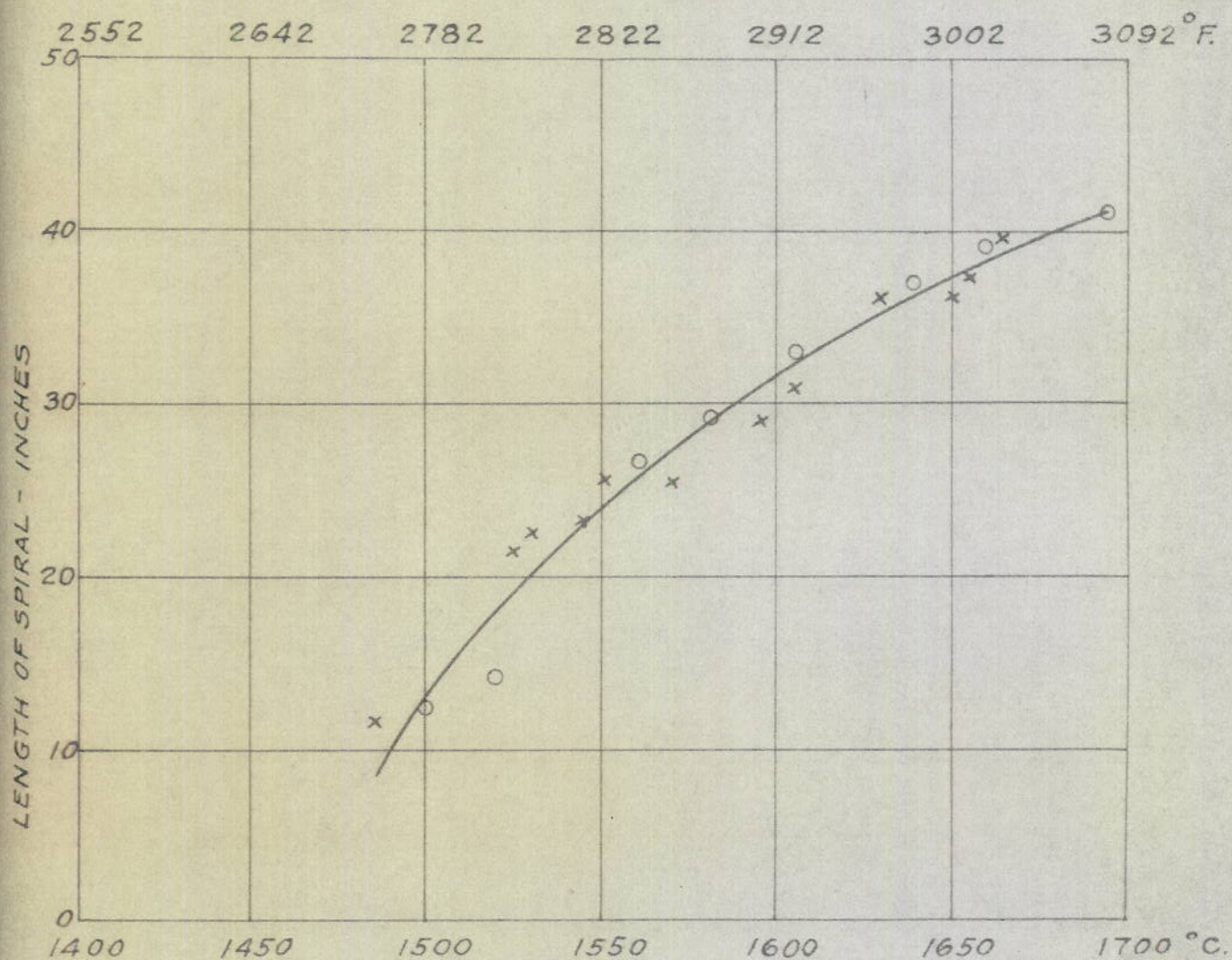


FIG.13 - THE FLUIDITY OF IRON-CARBON ALLOYS
ARMCO IRON MELTING STOCK

	C	Mn	Si	HEAT NO.
————	0.11	0.60	0.40	54
-----	0.28	0.62	0.35	53
- - - - -	0.20	0.65	0.38	52

MATERIAL FROM ARMCO IRON
PLUS WASH METAL.

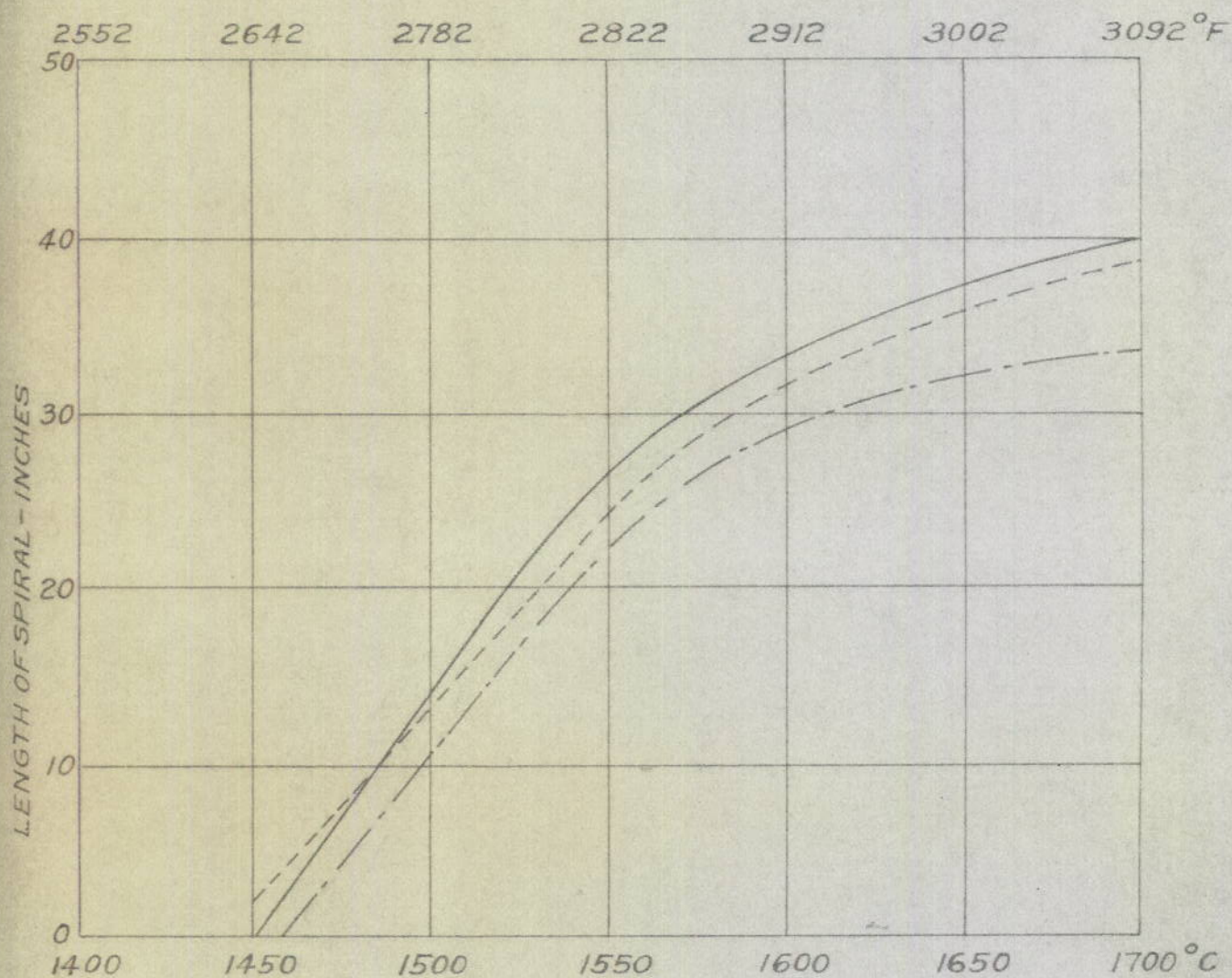


FIG. 14 - THE RUNNING QUALITIES OF VARIOUS CARBON STEELS
REMELTED IRON-CARBON ALLOYS USED AS MELTING STOCK.

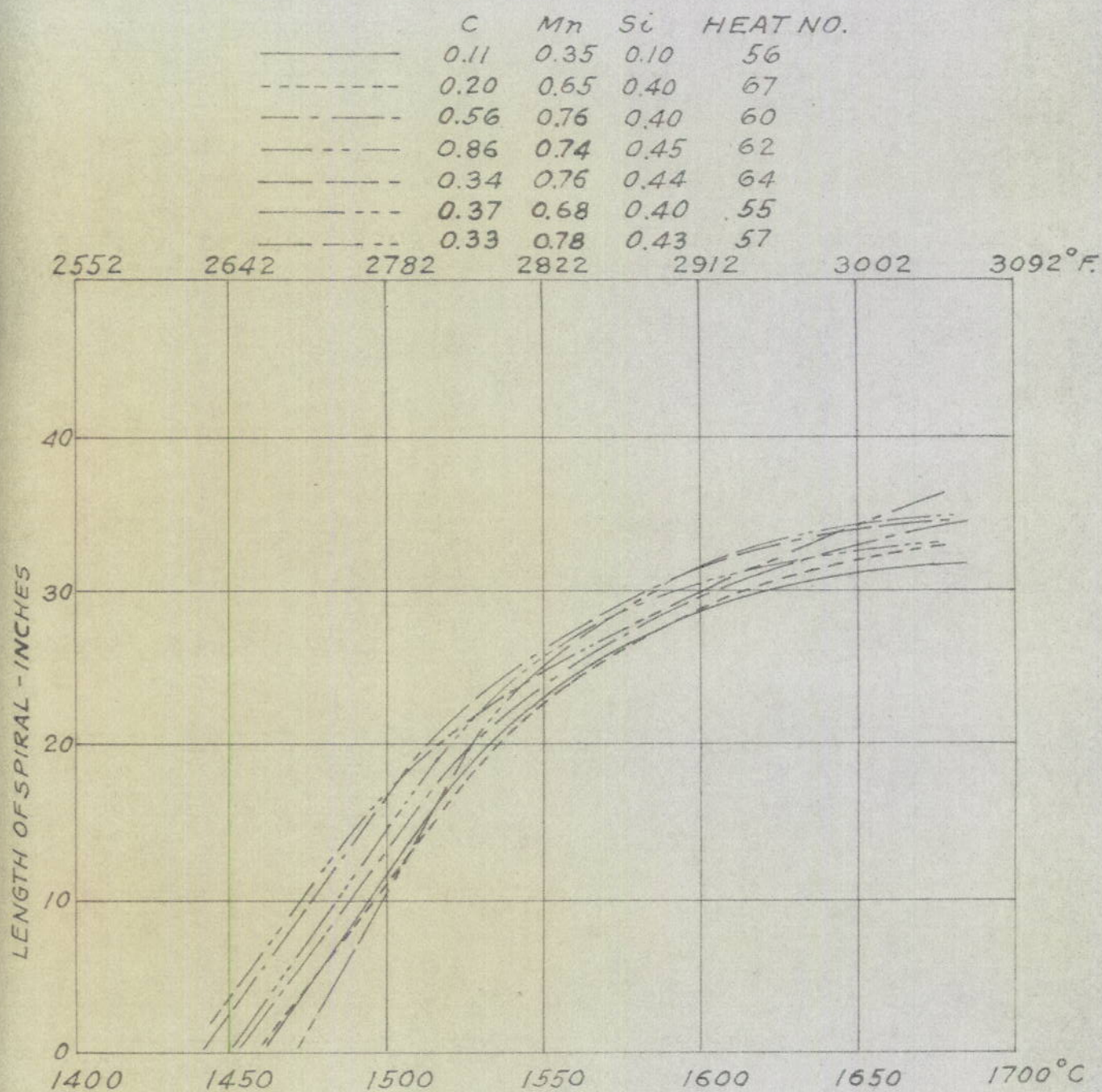


FIG. 15 - COMPARISON OF RESULTS OBTAINED WITH 0.20% CARBON STEEL AS MADE FROM ARMC0 IRON STOCK AND CARBON (#52) AND AFTER REMELTING (#67)

	C	Mn	Si	HEAT NO.
-----	0.20	0.65	0.40	67
-----	0.20	0.65	0.38	52

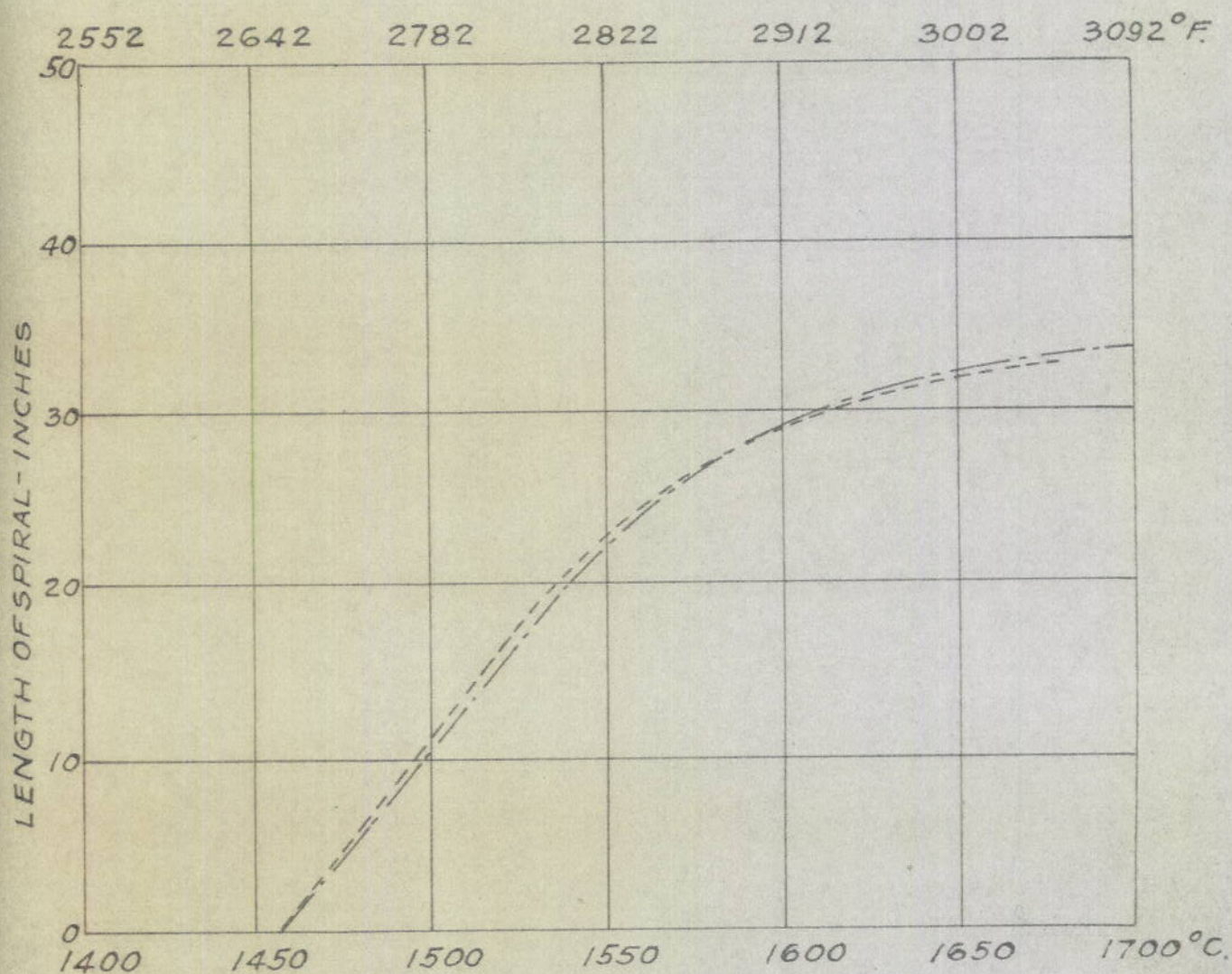


FIG. 16 - EFFECT OF KILLED AND RIMMING HEATS ON THE FLUIDITY OF STEEL

	C	Mn	Si	HEAT NO.
○ -	0.23	0.65	0.50	71
x -	0.23	0.27	0.14	70

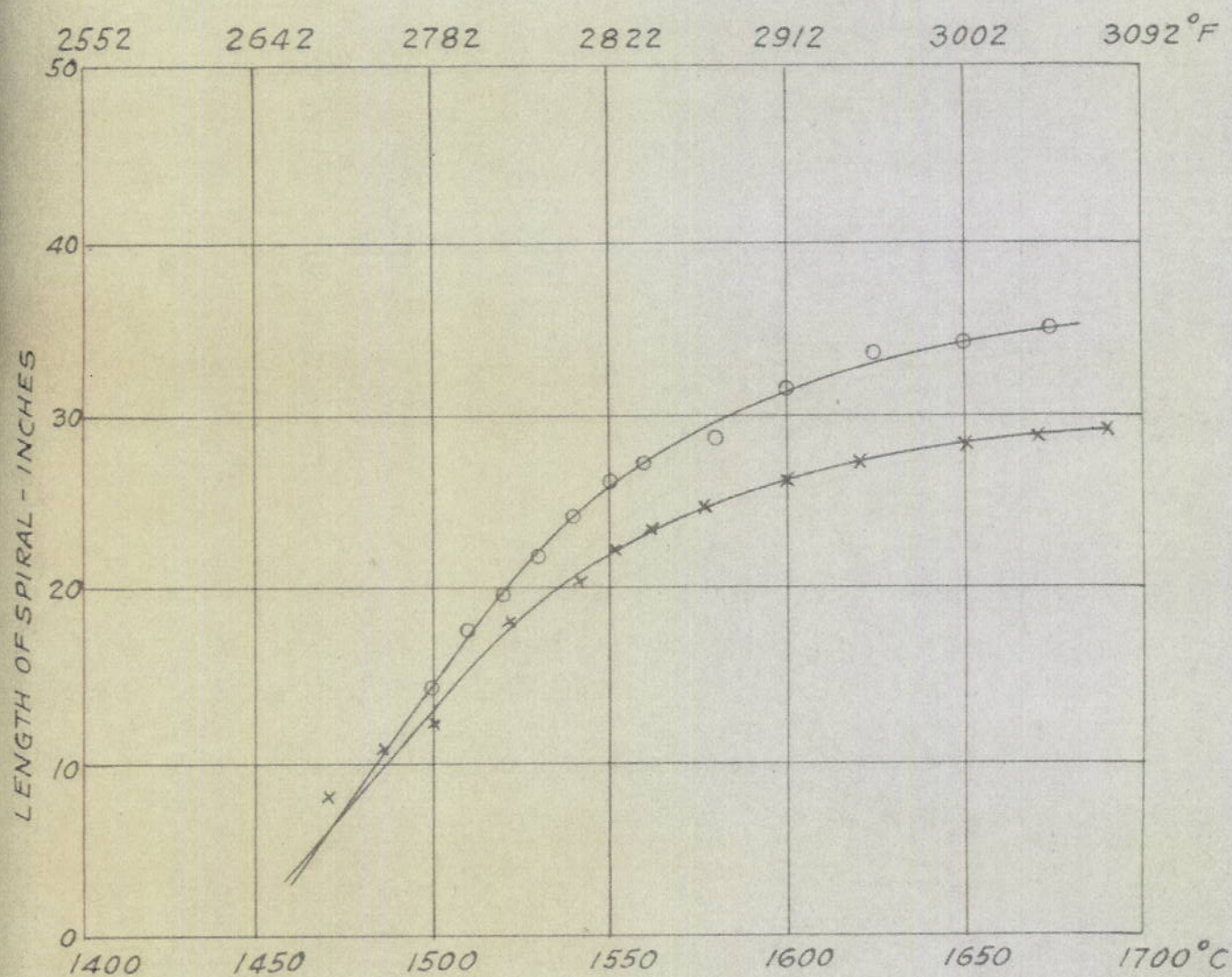


FIG. 17 - FLUIDITY DIFFERENCES THAT APPEAR
TO EXIST DUE TO CONDITIONS OF DEOXIDATIONS.

	C	Mn	Si	HEAT NO.
x -	0.18	0.60	0.30	72
o -	0.17	0.45	0.15	73
• -	0.20	0.65	0.45	74

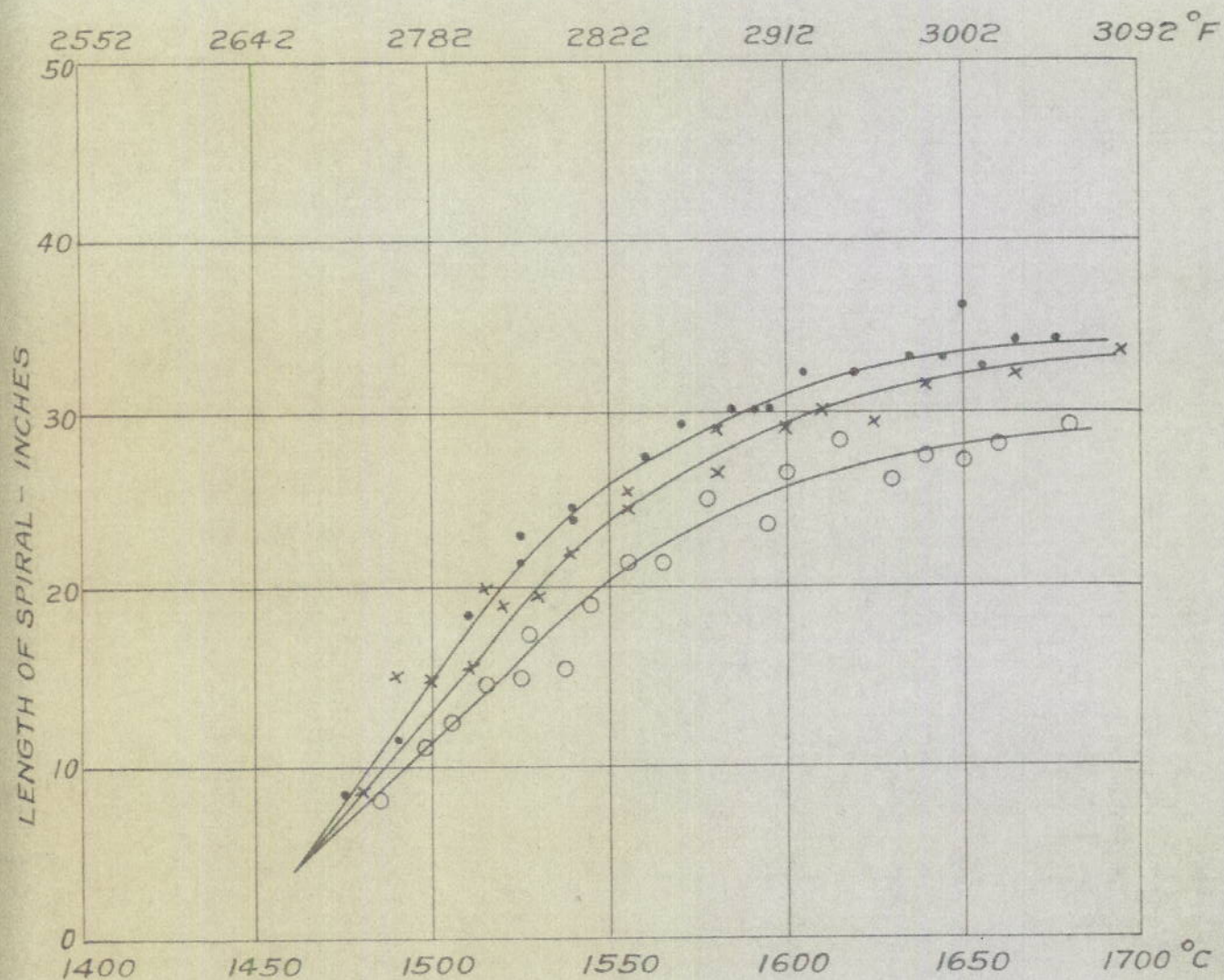


FIG. 18 - EFFECT OF CARBON CONTENT ON THE FLUIDITY OF STEEL

	C	Mn	Si	P	S	HEAT NO.
• -	0.16	0.59	0.28	0.02	0.02	81
○ -	0.29	0.73	0.35			82
x -	0.44	0.71	0.34			83

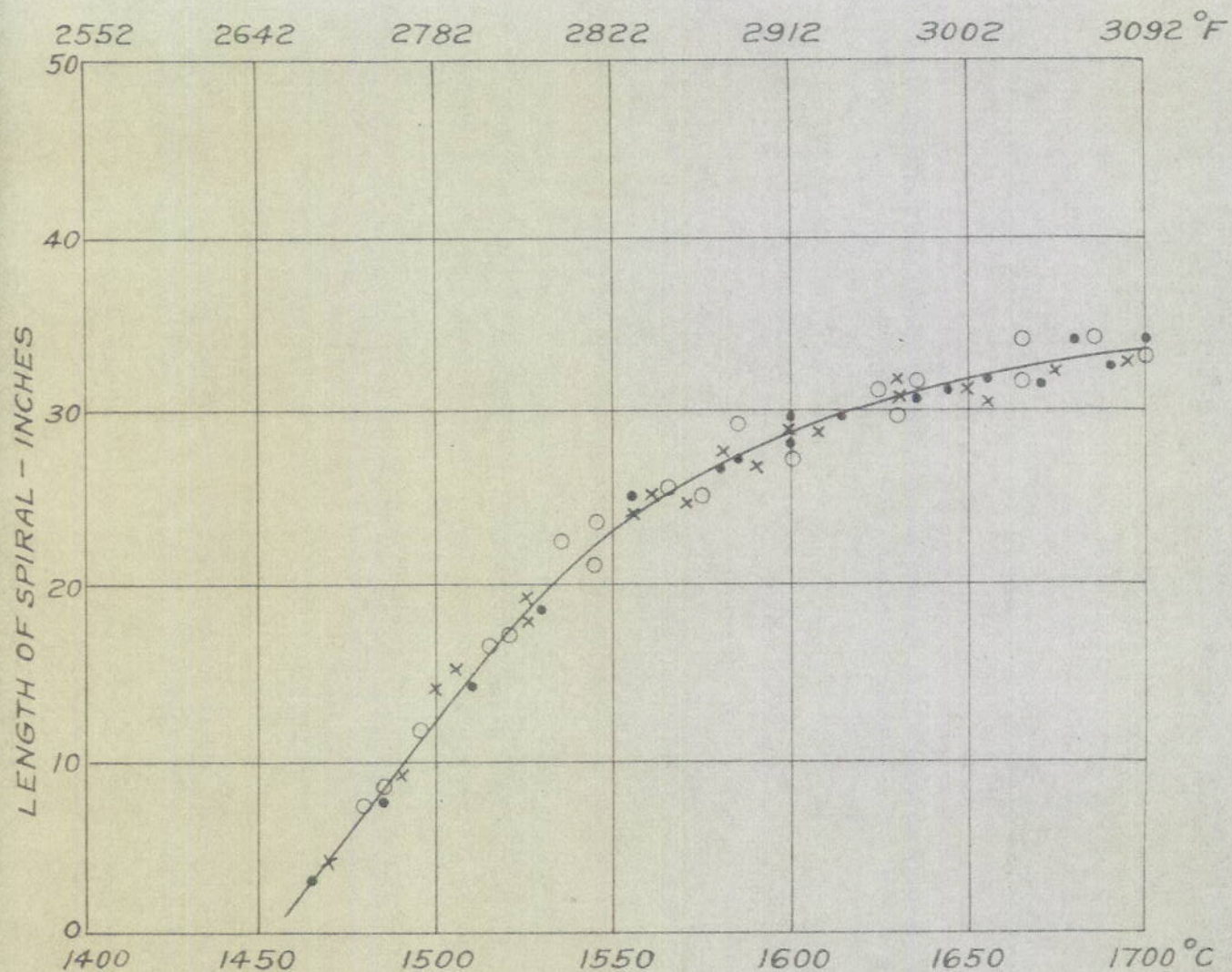


FIG. 20 - FLUIDITY CURVE CHARACTERISTICS DEPENDING
ON DATA TAKEN WHILE MELT WAS COOLING OR HEATING.

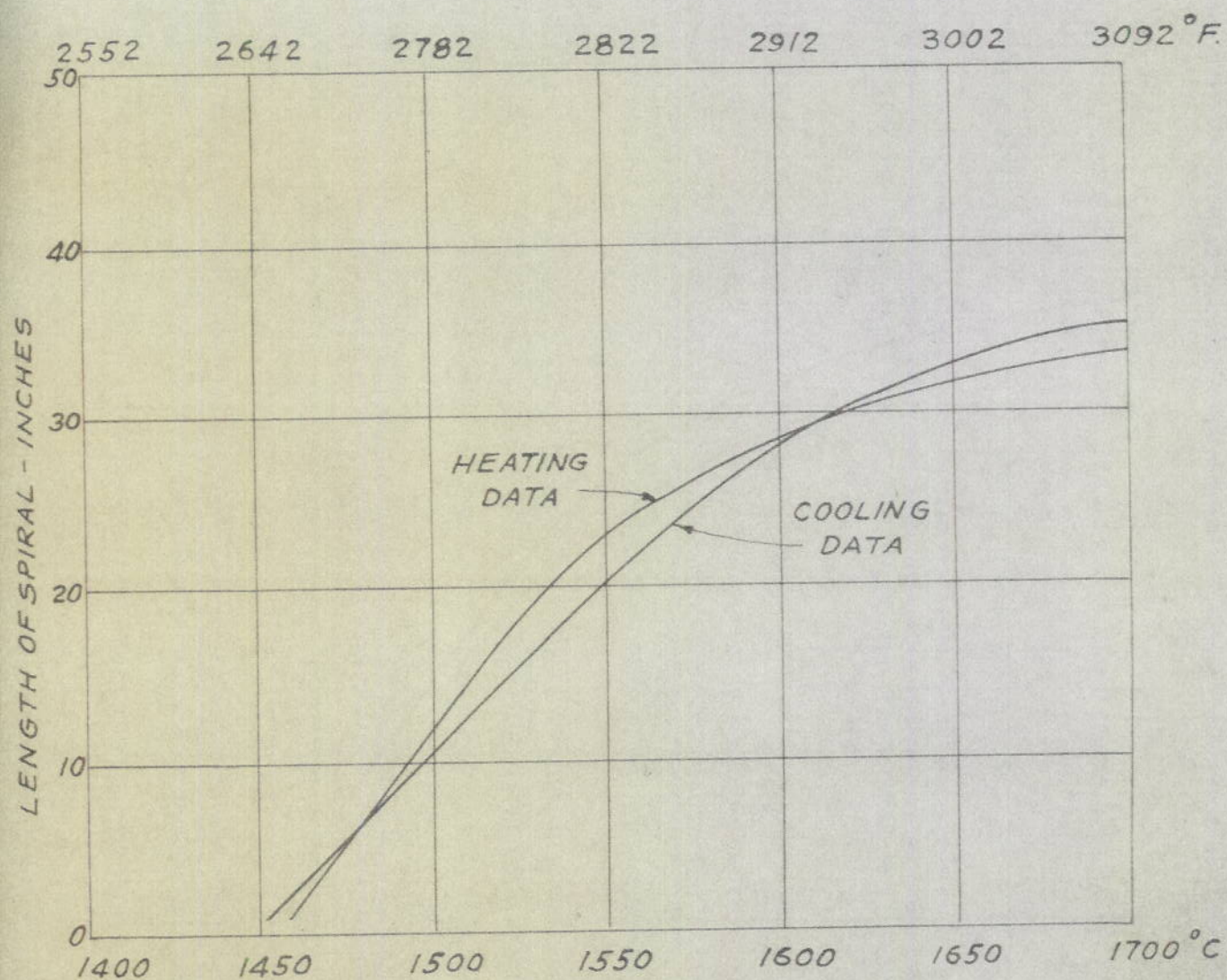


FIG. 21 - COMPARISON OF DIFFERENT MELTING STOCK
STEELS ON FLUIDITY.

MELTING STOCK	C	Mn	Si	HEAT NO.
STEEL CASTINGS	0.16	0.59	0.28	81
S.A.E. 1015	0.11	0.64	0.29	103

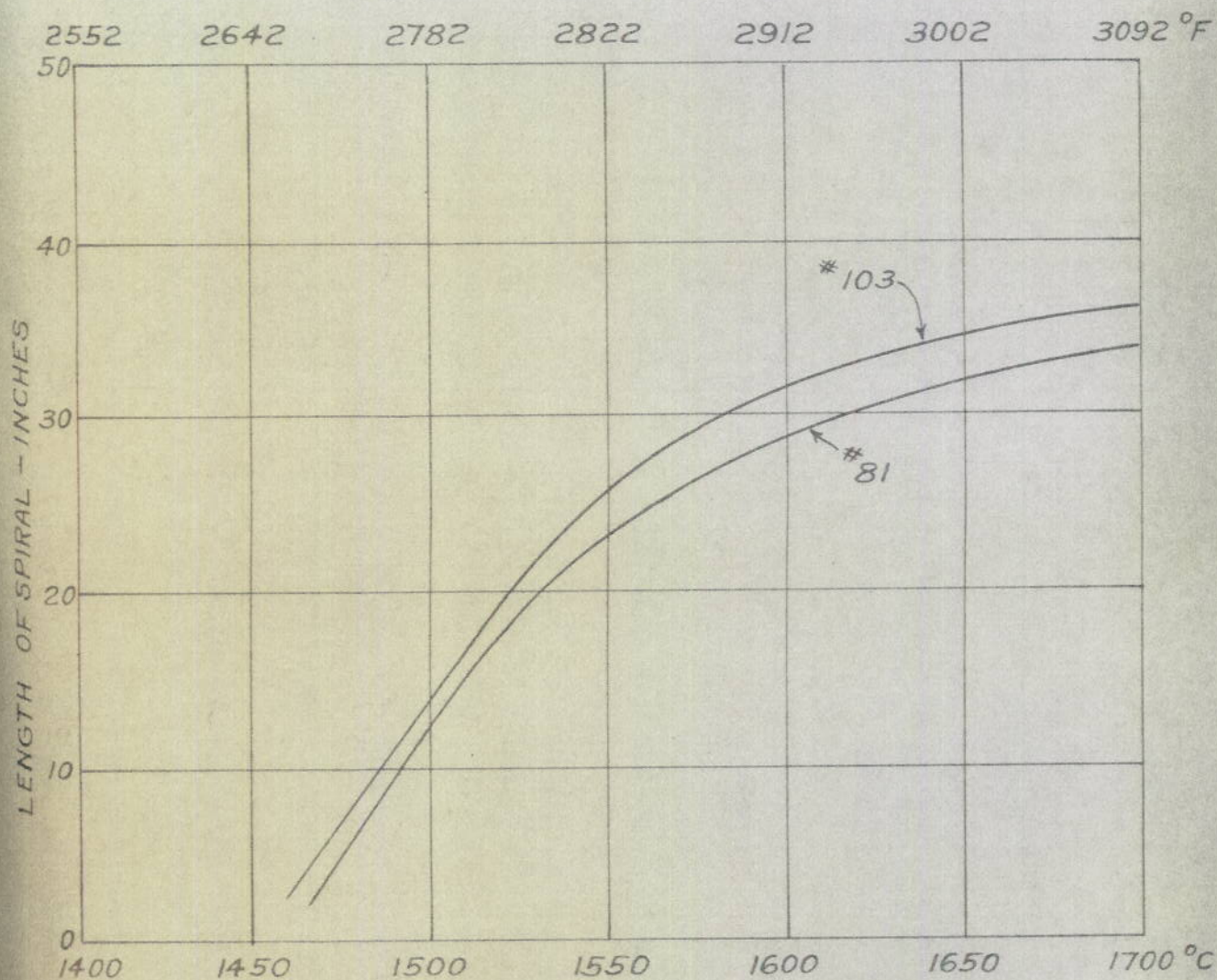
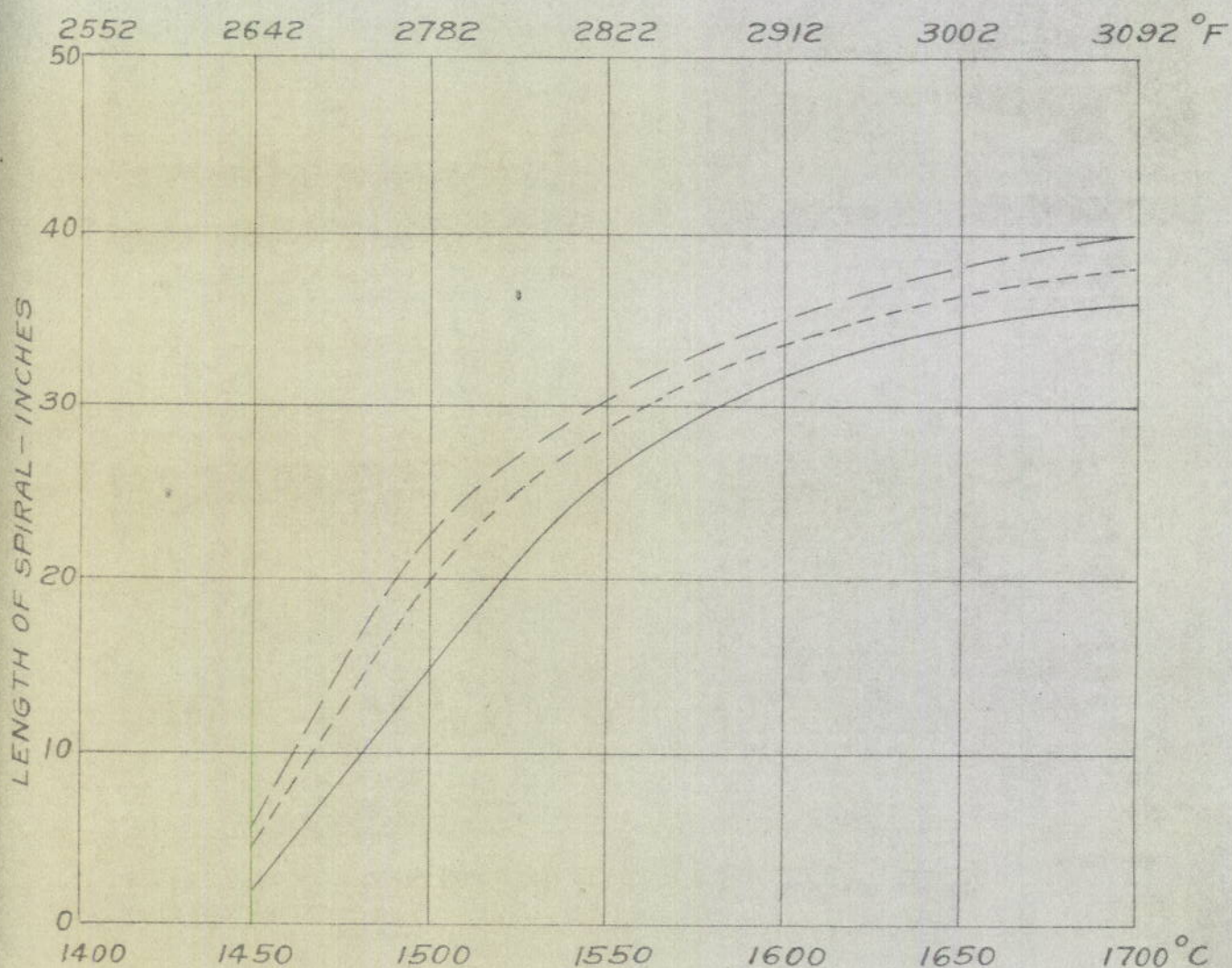


FIG. 22 - THE EFFECT OF COPPER ON THE FLUIDITY OF STEEL
MELTING STOCK-S.A.E. 1015

	C	Mn	Si	Cu	HEAT NO.
————	0.31	0.78	0.37	0.06	104
-----	0.31	0.77	0.32	2.11	89
— — —	0.30	0.75	0.31	3.70	90



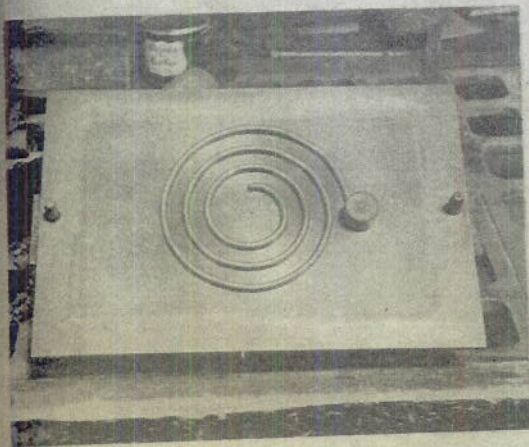


FIG. 23 - DRAG SECTION OF FLUIDITY SPIRAL PATTERN SHOWING BLIND RESERVOIR

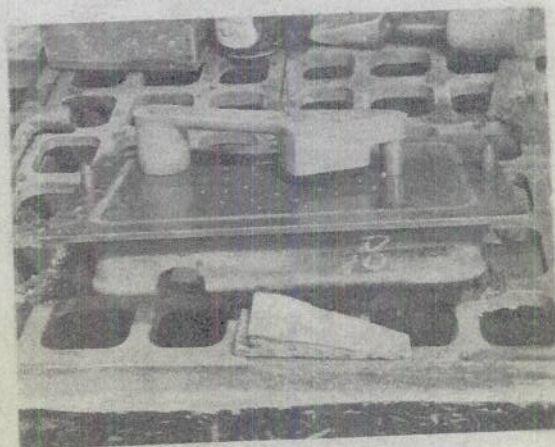


FIG. 24 - COPE SECTION OF PATTERN, WITH POURING BASIN PATTERN IN PLACE, AND SHOWING RAISED REFERENCE MARKS.



FIG. 25 - SAND MOLD READY FOR CLOSING.



FIG. 26 - ASSEMBLED AND CLAMPED MOLD READY FOR USE.

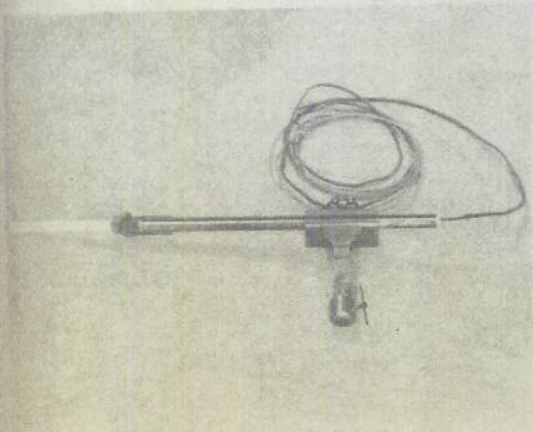


FIG. 27 - THERMOCOUPLE ASSEMBLY READY FOR PREHEATING.

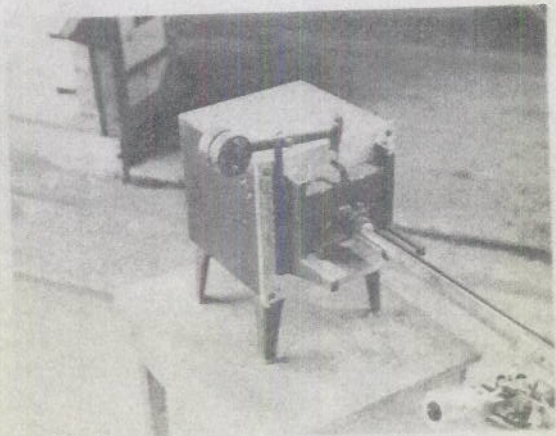


FIG. 28 - PREHEATING THE THERMOCOUPLE.

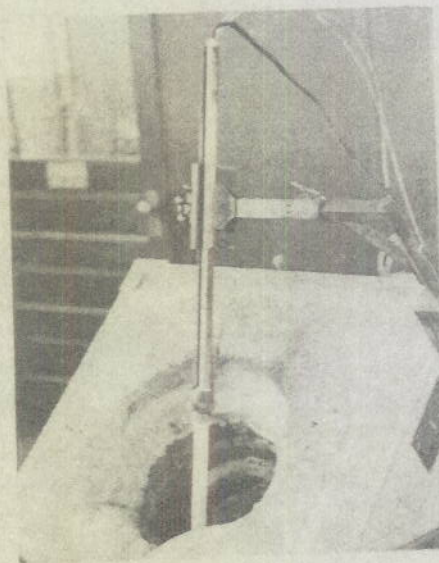


FIG. 29 - PREHEATED THERMOCOUPLE AND ASSEMBLY MOUNTED TO BED-FRAME.

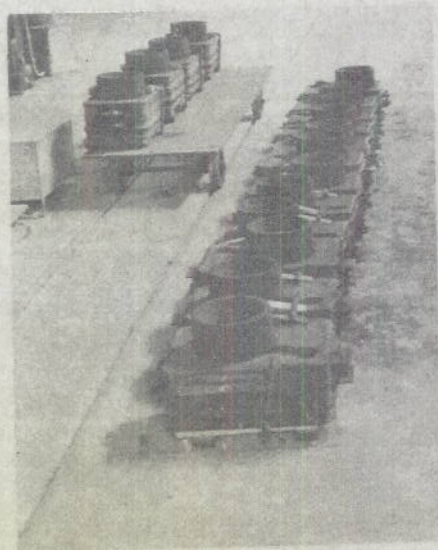


FIG. 30- MOLDS READY FOR USE
WITH TRUCK LOADED.

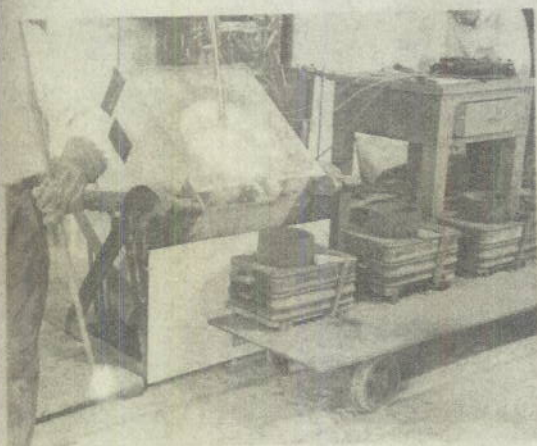


FIG. 31- TRUCK AND FIRST MOLD IN PLACE
READY FOR TESTING.



FIG. 32 - THE ASSEMBLY DURING PROCESS
OF POURING.

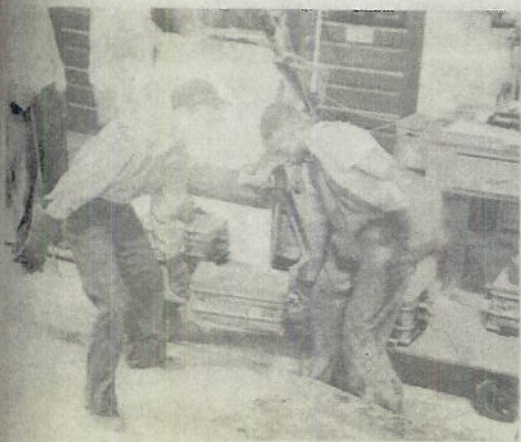


FIG. 33- REMOVING THE FLUIDITY MOLD
AFTER POURING.



FIG. 34- ADDING FERROMANGANESE
TO THE MELT.

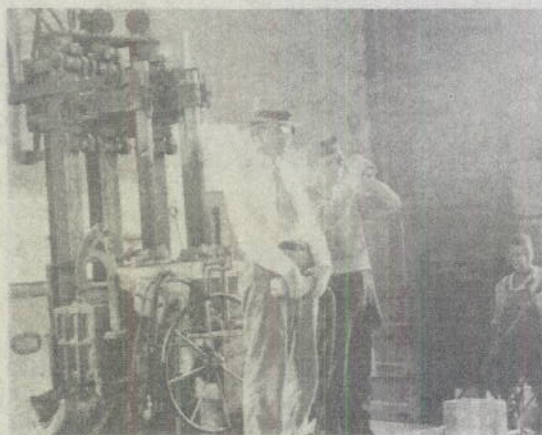


FIG. 35- HOIST OPERATOR AND OPTICAL
PYROMETER OPERATOR.



FIG. 36-ADJUSTMENT OF THERMOCOUPLE.

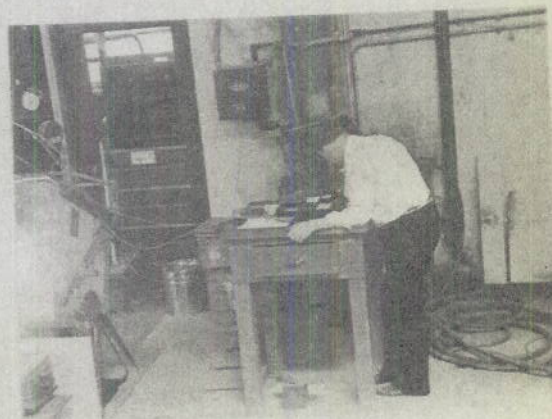


FIG. 37-RECORDING OF TEMPERATURES.

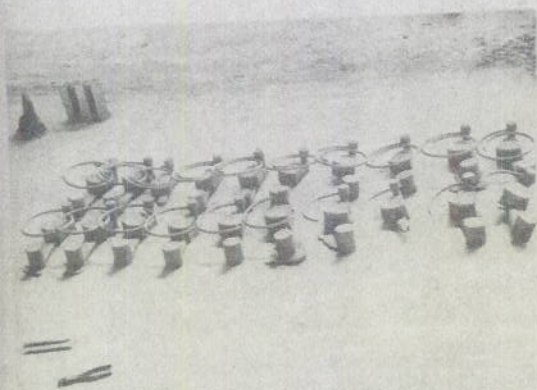


FIG. 38-SPIRALS READY FOR CHECKING LENGTHS.

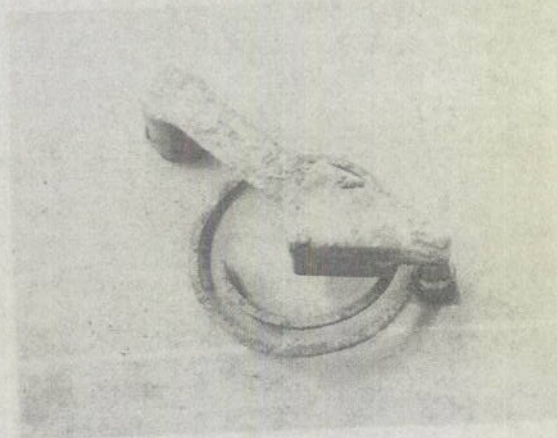


FIG. 39-SINGLE FLUIDITY SPIRAL