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Progress Report

on

The Fluidity of Cast Steel.

DEPARTMENT OF THE NAVY BUREAU OF ENGINEERING

BY

NAVAL RESEARCH LABORATORY

BELLEVUE, D. C.

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The Fluidity of Cast Steel.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

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ABSTRACT

The fluidity of cast steel is considered from both the theoretical and the practical viewpoint. Various types of tests are studied with an object of using the fluidity test at the furnace to indicate steel fluidity before the steel is tapped. Methods of recording fluidity on the pouring floor are also considered. A test is devised for indicating correct tapping conditions at the furnace. Recommendations are given for further work.

AUTHORIZATION

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

STATEMENT OF PROBLEM

2. The object of this report is to present the data obtained from a study of the fluidity of cast steel.

THEORETICAL CONSIDERATIONS

3. The viscosity of a substance (related to the degree of fluidity) is usually measured in terms of the length of time required for a definite quantity of the substance at a known temperature to flow through a prescribed orifice. A test of this nature, which is rather simple and accurate at relatively low temperatures, is exceedingly difficult to perform at higher temperatures, such as those required for molten steel. Many difficulties are encountered at molten steel temperatures since it is necessary to have an orifice that would not be eroded by molten steel. The orifice and the container must be maintained at the same temperature as the molten steel, for if they were not, the steel would be chilled and it would be extremely difficult to measure the volume and temperatures of the steel accurately. Records show that the rigorous requirements of this test have never been fulfilled in testing alloys with relatively high melting points.

4. Foundrymen have, therefore, found it necessary to devise a more simple method for the study of fluidity. This method determines the ability of a molten metal to fill a mold completely instead of determining the true fluidity of the metal. In general, this test consists of pouring molten metal into sand molds which contain a cavity in the form of a spiral. The study of fluidity thus takes on a slightly new aspect and is concerned primarily with the runnability of the metal.

5. In metals and alloys melting at relatively low temperatures, it appears that the maximum runnability is attained when the metal is in its most fluid state and that the fluidity increases as the temperature is raised above the melting point. It is not known whether or not these conditions apply to metals and alloys, such as iron and steel, melting at higher temperatures. It is evident, however, that the ability of a molten metal to fill a mold completely is influenced by the fluidity of the metal, the material of the mold and the conditions under which the mold is prepared. The runnability of a metal is, therefore, a rather complex property and a function of a series of factors. Some of these factors are: (1) Casting temperature of the metal; (2) viscosity of the liquid metal at temperatures between the pouring and solidifying temperatures; (3) heat exchanges between the metal and the mold; and (4) the factors governing solidification of the metal.

6. After a study of the work and complexities encountered by investigators preceding them (1), Saeger and Krynitsky (2), Berger (3), Portevin and Bastien (4), set forth the following principles: The factors that govern the freezing of an alloy are: **(A)** Those that relate to the

(C) Pouring Factors.

The metals must be poured in a continuous stream at a constant speed. The ability to duplicate the data and to make precision measurements depends to a great extent upon the pouring speed. The reservoir should provide a continuous flow of metal, without slag, to the spiral.

(D) Factors Depending on the Metal.

When liquid metal is poured into a mold, it flows through the more or less intricate design of the mold cavity as a result of the hydrostatic pressure of the liquid metal. A number of things combine to oppose this flow. The work which must be done when liquid particles are pushed past each other, or the internal friction or viscosity of the molten metal, is one factor opposing the flow. The flow of the metal through the mold is also retarded by the friction between the liquid and the surfaces of the mold cavity; this effect being influenced greatly by the grain size of the sand, the nature of the mold facing materials used, and the degree of packing of the sand.

The surface tension of the liquid metal, the oxide and other films that form also contribute toward opposing the flow of the metal through the mold.

The quantity of heat contained in the liquid metal entering the mold is balanced against the rate of transfer of heat from the metals to the mold and the heat capacity of the mold.

11. Portevin and Bastien (4) made a mathematical study of the fluidity of a pure metal and concluded that: (a) The fluidity of a metal varies with the temperature of the mold, following an equilateral hyperbola. The metal will be fluid indefinitely, if the temperature of the mold equals the melting point of the metal; (b) the curves showing fluidity as a function of casting temperature are straight lines, the angular coefficient of which depends on the specific heat of the liquid metal. These two laws were verified experimentally with the pure metals, zinc, cadmium and aluminum, which do not oxidize easily.

12. In addition to the physical properties of a liquid metal, two factors may influence the running quality of the metal. These are: (a) The process of solidification (interval of solidification), and (b) crystallization (crystal form and speed of crystallization).

13. Tests on binary alloys led Portevin and Bastein to formulate the two following laws:

(a) Fluidity varies inversely with the interval of solidification. It will be greatest when the melt is homogeneous (as in the case of pure metals, or eutectics), and is least for the saturated solid solutions.

(b) Fluidity depends on the crystal form adopted upon solidification and is relatively much greater when crystals are formed with convex faces (definite compounds), than when dendrites are formed (solid solutions).

14. The authors previously mentioned also state the following with regard to ternary alloys:

(a) The fluidity of a ternary eutectic is an absolute maximum with relation to the fluidities of the eutectics of the binary base systems.

(b) The fluidity of ternary alloys varies inversely with the interval of primary crystallization.

(c) The lines of the binary eutectics are the lines of the crest on the surface representing fluidity of a given alloy. Along these lines fluidity varies inversely with the interval of secondary crystallization.

15. The foregoing discussion may be summarized as follows:

The ability of a metal to fill a mold is distinct from its fluidity, and is a much more complex property. The fluidity of a metal is measured at a constant temperature with the metal and its container at a uniform temperature. Castability, however, is the performance of metal at unequal and changing temperatures. The metal cools and sometimes even begins to solidify as it fills the mold. The mold, of course, is always at a much lower temperature than that of the metal. The castability of an alloy is, therefore, controlled by the fluidity, which varies with temperature, the forces of crystallization within the metal, the surface tension, and many other foundry conditions which tend to influence the cooling of the metal in the mold.

16. The chief effect of the mold and dressing upon castability are due to the thermal properties, the porosity, and the cohesion of the mold material. The thermal properties of the metal play at least as important a part as the viscosity of the metal.

17. Castability increases with the amount of superheating and is inversely proportional to the differences between the melting point and the temperature of the mold.

18. The preceding discussion has emphasized the necessity of considering what constitutes the proper terminology to be employed in the remaining pages of this report. It appears that the terms "castability" or "runnability" are more technically correct. However, the term that is universally used in the industry is "fluidity." Since it has been shown that castability is a measure of the more complex and variable features of fluidity, and since the term "fluidity" is so thoroughly entrenched in the industry, there is little justification to cause confusion by adopting a new term. Therefore, in the succeeding pages of this report the words "castability" and "fluidity" are to be considered as interchangeable.

19. The literature on the quantitative measurements of the fluidity of steel is very meager. This fact, however, is not surprising when the difficulties of such measurements are considered. Fortunately, the study of the fluidity of cast iron has not presented as many difficulties, and some very excellent results have been reported upon this subject. Since cast iron is somewhat similar to steel in many ways it was decided that a review of the conclusions resulting from a study of the fluidity of cast iron would be beneficial.

20. Saeger and Krynitsky (2), using a fluidity spiral fed by a horn gate from a reservoir (Plate 1), studied the fluidity of cast iron. They poured their test spirals directly from an induction furnace. The pouring speed of the furnace was accurately controlled and was constant throughout the pouring interval. The temperature of the cast iron was measured by a platinum and platinum-rhodium thermocouple and a very close control of the temperature was maintained. Several test spirals poured at the same temperature showed a variation in the length of run of about three per cent. This is an extremely good check. The sensitivity of the method was found to be equivalent to 1.4 inches per 10°C. for cast iron. These authors concluded from their experiments that there is a linear relationship between the pouring temperature and the running properties of an ordinary cast iron.

21. Berger (3) employed the method proposed by Saito and Hayashi, as modified by Curry, in his investigations of fluidity. His method consisted of pouring into a basin that was connected to a downgate. The metal entered the basin and then flowed into the downgate, through a small filter and then into the spiral section. The diameter of the holes in the filter was slightly larger than that of the spiral section. The sensitivity of the method, when studying cast iron, was found to be about 1.7 inches run per 10°C.

22. The cast iron was melted in a coke fired crucible furnace. All temperature measurements were taken with an optical pyrometer.

23. It is doubtful whether correct temperature readings can be obtained by means of the optical pyrometer, particularly at low temperatures. Saeger and Krynitsky, and the present authors, have observed from experimental results that optical pyrometer measurements on small streams of metal of short duration are unreliable.

24. Berger does not state the method used in pouring the metal into the mold. This is indeed unfortunate, as the pouring operation is a very difficult one to control.

25. In spite of these faults, Berger is to be commended for the interesting results which he has obtained. Berger concludes that:
(a) With the casting temperature kept constant, the fluidity increases with the carbon content up to the eutectic concentrations (4.3 per cent carbon), and then decreases with higher carbon contents. (b) In the hypo-eutectic region, there is a sudden increase in fluidity around 4.0 per cent carbon. (c) With the carbon content kept constant, the

fluidity increases with the temperature. The relation is not linear but varies somewhat with the different carbon contents studied. (d) With constant temperature and a constant carbon content, the fluidity increases with the phosphorous concentration, passes through a maximum, and then decreases when phosphorous becomes higher. (e) In an iron with an initial silicon content less than 0.50 per cent, provided the carbon content is kept constant, a sudden decrease in fluidity takes place between 0.30 and 0.50 per cent silicon. This is followed by an increase in fluidity between 0.50 and 0.75 per cent silicon and another sudden decrease in fluidity, between 0.75 and 0.95 per cent silicon. With silicon contents higher than 0.95 the fluidity increases steadily until the percentage of silicon present reaches the eutectic concentration. (f) If ferro-silicon is added to an iron with an initial silicon content greater than 0.50 per cent, and the carbon content is kept constant, the fluidity increases very rapidly up to 0.75 per cent silicon and then increases more slowly until the eutectic concentration of silicon, for that particular carbon content, is reached. (g) Manganese increases fluidity in the hypo-eutectic region and decreases it in the hypo-eutectic zone. The effect of manganese upon fluidity is not very great except in the neighborhood of eutectic concentration. (h) Manganese does not seem to have a very marked effect upon the fluidity of iron-carbon-silicon alloys. However, the importance of its effect, and the nature of that effect, are essentially functions of the carbon and silicon content of the metal. (i) A general law may be formulated for cast irons as follows: The eutectic mixtures are those which possess the greater fluidity and, therefore, are those which are most likely to give perfect castings. If the hypo-eutectic compositions are considered the elements that seem to control fluidity are, listed in the order of their importance, carbon, phosphorous, and to a certain extent (under 1.00 per cent) silicon. As to manganese, its influence on fluidity is of little importance. The amount and direction of its influence are essentially a function of the composition of the metal considered.

26. Berger points out that these results bring together the opinions of foundrymen and steel men. Since the latter are usually working with silicon contents between 0.3 and 0.5 per cent, it is but natural that they would find an increase in viscosity when silicon increases. Iron foundrymen, on the other hand, generally keep in the neighborhood of one per cent silicon, and the results show that the fluidity of their metal should vary proportionally with the silicon content.

27. There is of course no certainty that carbon, silicon, manganese or phosphorous may affect the fluidity of steel as they do cast iron, since the variations of these elements in cast steel are small. In plain carbon steels the phosphorous, silicon and manganese vary only slightly, while the span of the carbon contents is from 0.18 to 0.50 per cent. Whether these carbon variations are enough to cause prominent or distinguishable changes in the fluidity is not known.

28. It seems quite evident that increased temperatures produce increased fluidity. This point appears to be well substantiated regardless of what metals are considered.

29. The results of the experiments by Berger, Saeger and Krynitsky did not agree as to the effects of changes in carbon content and temperature upon the fluidity of cast iron. Saeger and Krynitsky said that it was a linear relation, but Berger's work showed that this was not the case, though there did exist a general upward trend.

30. There has been very little information published on the fluidity of steel. The only work of any extent has been that reported by Gabino (5). He used a sand mold with a spiral cavity that was a modification of the mold used by Curry. The cross-section of the spiral was a trapezoid with a cross-sectional area of 0.093 square inches. The metal was poured through a central downgate that tapered into a small section before it entered a reservoir. The metal, after filling the reservoir, flowed out into the spiral.

31. The pouring methods that Gabino adopted were to tap the steel from the electric furnace into a ladle and then into a small crucible which was arranged at a definite pouring height from the test mold. Optical pyrometer readings were taken of the metal as it left the small crucible and entered the test mold.

32. Using the above technique, Gabino determined that dry sand molds gave longer runs than green sand molds, and that the moisture content of the green sand should be carefully controlled. He also observed that the use of different mold washes had no apparent effect on resulting fluidity. These results, though the first to be set forth on steel, confirmed the reasoning that had been applied to similar studies carried on with aluminum and cast iron.

33. The two most important conclusions that Gabino made from his studies were:

(a) That the fluidity of steel is linearly related to the temperature; and

(b) That silicon is indispensable in steel and must be present in order to obtain sufficient fluidity.

The first conclusion appeared to be founded on a limited set of data. The second statement was made after the author found that furnace steel ran only a short distance before silicon was added and three times as far after silicon was added to the furnace.

34. In the last part of the article, written at a later date, Gabino tabulates fluidity vs. temperature and states that the data had been collected over a long period of time. These data are given as follows:

Temperature at the Furnace (°C.)	Corresponding Fluidity (Centimeters)
1550	70
1540	60 - 65
1530	55
1525	52.5 - 55
1520	52.5
1515	50
1510	47.5
1500	42.5
1495	40
1490	35

35. It also appears that Gabino changed his pouring technique somewhat by pouring directly from the ladle into the mold. The temperature of the metal entering the mold was ascertained in the following manner. The ladle was preheated until the external metal **form** showed a temperature of 120°C. which corresponded to an internal temperature of 720° to 750°C. at the time the ladle was ready for filling. An optical pyrometer was used to record the temperature of the steel as it left the furnace. It was found that a drop of 12°C. per minute existed for the first four to five minutes that the metal was in the ladle, and that during the next 11 to 15 minutes the loss was from 2° to 3° per minute. The time of tapping the furnace and the time at which the fluidity mold was filled, were recorded and the temperature of the metal was calculated from these data.

36. The data that Gabino presents are more in the nature of qualitative results. There are many points he has neglected, several points that need further confirmation, and one or two points which might have a different interpretation than that given to them.

37. In the first place it would seem that the changes in composition of the steel would account for fluidity changes. In this case, change in composition means not only the elements that are usually analyzed, but others, such as the gas content and the type and quantity of inclusions. Many foundrymen have observed and reported on the lack of fluidity due to incomplete deoxidation and also to over reduced conditions. Low fluidity resulting from over reduced conditions have been noted frequently in the acid practice. If, however, an addition of iron oxide is made to the furnace, the fluidity will increase considerably. It can thus be seen that fluidity may be related somewhat to the practice used in steel making. It seems reasonable to suppose that with changing conditions, such as those found in the refining of steel by the basic process, the fluidity of the steel will change. It will be shown later that the extent of deoxidation has considerable bearing on the fluidity. Gabino saw indications of this fact, but he attributed it to the silicon content present instead of to the deoxidation of the steel which had been brought about by the silicon addition. Results of a similar character would have been observed if Gabino had used **deoxidizers other than** silicon.

38. There can be no doubt but that fluidity varies with temperature. However, considerable doubt does arise in the accuracy of the measurements of the temperature. Optical temperature measurements are very unreliable, for in the first place, there is hardly enough time to obtain a reading on the small amount of steel necessary to fill a fluidity mold; and, in the second place, the stream that is used to fill the mold is so narrow and irregular in shape that it is impossible to get accurate readings. Temperatures calculated by assuming a definite drop in temperature after the time the furnace has been tapped and the tapping temperature recorded, are also in error, as the loss in temperature of the metal flowing over the cold lip is not known and factors to compensate for heating the lip are undeterminable. The use of a bottom pour ladle might solve the latter difficulty.

39. Temperature measurements of the steel in the furnace are extremely difficult to obtain and many devices have been used in order that the steel melter might know the temperature of the bath and whether or not the steel is ready to tap. The optical pyrometer has proved to be of little value since it is difficult to hold back the slag so that the metal may be sighted on, and such readings do not usually check each other. Likewise radiation pyrometers have not proved to be very satisfactory. The Fitterer carbon-silicon carbide thermocouple and the molybdenum tungsten thermocouple have been used with a fair degree of success in open hearth furnaces, but with little, if any, success in electric furnaces.

40. In general, the temperature of the bath has been determined by the set test. This test consists of bringing out of the furnace a small spoon full of metal and recording the time it takes to scum, or freeze over. This time is correlated to the tapping temperature as taken by an optical pyrometer. Considering how many variables there are in the taking of the sample and in the freezing of the sample, it is quite surprising to note that fair results are obtained. Steel foundry operators have found on various occasions that the set test did not tell them all that they wanted to know, since, even though the result of the set test was normal, the molds did not run or the metal appeared to be sluggish. There was, therefore, a need for a different type of a test, one in which the fluid life of the steel would be recorded. Then, if fluidity was not a linear function of temperature, which it did not seem to be in some cases, a measure of the running ability of the metal would be recorded, which after all, is the important practical consideration.

41. It was with this idea in mind that a study of the fluidity of steel was undertaken at this Laboratory. Fluidity of steel after tapping was considered to be of interest, but primary consideration was given to the fluidity of the steel before it left the furnace.

METHODS USED IN TESTING

42. There were several reasons that led to the adoption of the Bureau of Standards test mold in this study. In the first place, the mold was known in the industry in that it had been reported upon in the technical press and certain commercial organizations were using it. Secondarily, if a standard mold could be maintained, it would lead to wide use and all

results would be somewhat comparable. In the third place, the mold gave good sensitivity and reproducible runs.

43. The steel was melted in a five hundred pound per hour three phase electric arc furnace. The usual heat of steel consisted of 1000 or 1200 pounds.

DATA OBTAINED

44. A metal pattern of the Bureau of Standards fluidity design (Plates 1 and 2 and Table 1) was prepared and studied. On the preliminary tests it was found that the diameter of the smaller end of the horn gate (G-Plate 2 and G-Table 1) was too small. Other horn gates with diameters of 0.31, 0.36, 0.50 inches at (G) were constructed and the fluidity readings as shown in Table 2 were recorded. These tests were taken at the furnace with the following procedure. A large dipper was put into the furnace, filled with steel, brought out and the steel emptied into the reservoir (part 4 of the mold). A set test of the type universally used was taken at the same time so that an approximation of the conditions existing would be known.

45. It may be observed that at first very short runs were obtained before the finals were added, regardless of the size of the horn gate or the time of the set test. Also, the length of run did not progress uniformly with the increase in the diameter of the horn gate. After the final additions were made to the bath, the fluidity recorded was twice that noted prior to deoxidation.

46. The results obtained after tapping were erratic and of little value. The procedure used in this case consisted of pouring directly from the ladle into the mold reservoir.

47. The tests as reported in Table 2 were repeated several times and the data obtained were similar. The only evident fact disclosed by the data was that the largest gate gave the longest run, although there was not as much difference between the .31 inch and the .50 inch diameter gates as there was between the .25 and the .31 inch gates. The reason for this is that the cross sectional area of the .25 inch diameter gate (.045 square inch) is less than the cross sectional area of the spiral (.066 square inch). The other gates have cross sectional areas (at G) that are larger than that of the spiral section.

48. Since the runs obtained by the use of the 0.5 inch diameter gate were none too long, it was decided that this horn gate would be used in the following experiments.

49. The first period of study was followed by an extended practice period, during which experience was obtained in taking the test. The improved technique resulted in more comparable measurements and the results obtained in Table 3 are indicative of the conditions recorded.

50. It may be observed that while there is a steady increase in the fluidity during the refining period, the total length of run is

rather small. A fluidity about four times as great is recorded after the finals (FeSi-Fe Mn) have been added. The results obtained by previous investigators pointed out the fact that a longer run could be obtained in dry sand than in green sand. So it was decided to compare the running qualities in both the dry and green sand test molds in the hope that a longer run might be obtained during the refining period of the heat. The results of this comparison are set forth in Table 4.

51. It may be noted that there was very little increase in the length of run when a dry sand mold was used, in fact, the extra length obtained was not sufficient to warrant the added trouble of preparing the dry sand molds since considerable care in drying is necessary in order to eliminate undue mold shrinkage and the formation of fins. Green sand molds were therefore chosen as the standard. These molds were prepared one to two hours before they were used.

52. During this stage of the development of the test, Mr. French of the International Nickel Company offered the Laboratory the use of the fluidity mold that they had used to determine the effect of nickel on the fluidity of steel. The offer was accepted and the test mold studied. The shape and dimensions of the International Nickel test piece is illustrated on Plate 3 and tabulated in Table 1.

53. A comparison was made between the International Nickel and the Bureau of Standards test pieces (Table 5). During the refining period the usual low fluidity was recorded wherein the runs attained in the International Nickel mold were comparable to those found in the dry sand Bureau of Standards molds. Even a change of from 0.20 to 0.40 per cent carbon during the refining period failed to produce any marked effect on the fluidity. Fluidity tests taken after the finals were added showed that the International Nickel mold recorded runs that were slightly longer than those obtained with the Bureau of Standards mold.

54. Since there was little difference in the length of run, regardless of what type of test piece was used, before the finals were added it was decided to continue the experiments with the Bureau of Standards test piece.

55. It is evident from a study of Tables 2, 3, 4 and 5 that the measurements of fluidity obtained before the finals are added were not satisfactory as there was no progressive increase in fluidity of any magnitude as might be expected.

56. The lengths of run, after the finals had been added, were considerable and must have been the result of the final deoxidation of the steel. It was therefore assumed that if the spoonful of steel taken during the refining period were completely deoxidized, longer runs would be obtained. This was found to be correct, for in subsequent experiments, aluminum was added to the spoonful of steel and runs of much longer length were obtained.

57. A study was then carried on to ascertain what quantity of aluminum would give the longest run. Small strips of aluminum were

wound on a light steel rod in quantities of from 2 grams to 18 grams which corresponded from 0.25 to 2.25 grams of aluminum per pound of steel. The average capacity of the spoon was found to be 8 pounds of steel.

58. The results obtained from this study are presented on Plate 7. It may be noted that the greatest run was recorded when 1.5 grams of aluminum per pound of steel was added. The size of the aluminum additions appears to be quite critical, although there is actually very little difference in the fluidity obtained with additions between 1.5 and 1.75 grams of aluminum per pound of steel.

59. Several tests were then made during the refining period in which aluminum was added to the spoonful of steel. In Table 6 these data are presented. The variation in the lengths of the runs obtained from the beginning to the end of the heat is considerable. It is not known whether or not this is due partially to the condition of the heat or entirely to the increase of temperature of the bath. Case B shows how the fluidity has been affected by regulating the power input of the furnace. Further consideration of these points will be undertaken later.

60. Table 7 points out that a fair degree of accuracy is obtained when fluidity tests are taken in duplicate at various times throughout the refining period. A fluidity test taken just prior to the adding of the finals showed that when aluminum was added, the resulting fluidity was equivalent to the fluidity recorded after the finals when no aluminum was added. This condition was studied at great length, and in Table 8 some of the typical findings are reported. There is excellent agreement between the two sets of fluidity tests. It was very fortunate that such excellent agreements could be obtained, for then predictions as to the final fluidity of the steel could be made before the finals were added. There was also the possibility that with this type of test adjustments of the temperature, steel making conditions or other variables upon which the fluidity is dependent, could be made before the finals are added. There is usually too little time available to try to correct temperature or fluidity conditions between the time the finals are added and the furnace is tapped.

61. It happens, however, that there appears to be no definite correlation between the fluidity measurements and the temperature in Table 8, nor does there seem to be any correlation between the fluidity and the carbon content of the steels.

62. The tapping temperatures were taken by an optical pyrometer on the stream as it left the furnace. These temperatures were recorded about one minute after the fluidity tests were taken. Further tests are necessary to account for the inconsistencies that are found, such as, in several steels the carbon content and the tapping temperatures are about the same yet the fluidity will vary 3 or 4 inches. In some cases, higher tapping temperatures will give lower fluidity readings. These inconsistencies became more apparent when numerous tests were tabulated. Tables 6, 7 and 8 are substantiated by 320 individual fluidity tests.

63. About the time that data were being collected for Table 8, a study was undertaken of the various methods of pouring fluidity molds from the steel that had been tapped from the furnace. An indication of the type of results that were obtained may be seen in Table 9. The Bureau of Standards test spiral modified with the 0.50 horn gate was used and the metal was poured directly from the ladle into the mold reservoir through a conventional runner box. The bottom pour ladle and the teapot ladle each had a capacity of 1000 pounds, the top pour ladle a capacity of 2000 pounds and the hand shank a capacity of about 35 pounds.

64. The most consistent results were obtained from the teapot ladle. The hand shank gave fairly close pouring control but the running qualities were little different from those recorded when the teapot ladle was used. Fluidity spirals poured by the top pour ladle were of little value. Irregularities occurred in pouring a set of fluidity spirals by the teapot ladle, as may be seen in Table 10, where a study of fluidity vs. pouring temperature is recorded. A series of tests of diminishing fluidity with decreasing temperature as illustrated by heat 86 is not always recorded. In some cases, conditions similar to heat 83 are found where the length of run remains nearly constant though the temperature drop is about 200 degrees Fahrenheit. More often a condition similar to heat 73 is found where the fluidity varies up and down with no regard to temperature. In one case, heat 82, the test at the lowest pouring temperature indicated the greatest fluidity. These four sets of results were picked from numerous data to show what might be expected. It became evident from this study that the pouring speed and the character of the flow were the two most important variables, and that if consistent results were to be expected, a control better than that possible to attain with a large movable ladle was necessary.

65. Many observations on the procedure of taking fluidity tests at the furnace has led to the conclusion that with the use of steel, the spiral portion of the mold is solid before the metal has had an opportunity to fill up the reservoir to the over flow level. This statement is based on the fact that six pounds of metal will give practically the same spiral run as will 9 pounds of metal, even though in the former case the reservoir will be only half full when the test is completed, and in the latter case, there would be enough metal so that a considerable amount would overflow from the full reservoir. Thus, since the reservoir was not acting as a constant pressure head, it was decided to perform several test runs without it. The metal was therefore poured directly down the horn gate. The results obtained by pouring directly into the horn gate, as compared with those obtained with the Bureau of Standards mold, are listed in Table 11. In general, pouring directly into the horn gate results in longer runs, but the data are very erratic. The erratic nature of the runs can best be explained by the fact that the reservoir type of mold permits a more constant and even flow of the metal as it enters the spiral.

66. During all the preceding experiments there has been a desire to increase the sensitivity of the fluidity test, and likewise a reluctance to depart from the standard developed by the Bureau of Standards. It was thought, however, that if the test spiral were of similar design,

but had larger sections, the departure from the original standard would not be considered radical. Thus a pattern embodying the design of Plate 4 and dimensions of Table 1 was constructed. The spiral cross sectional area of the new design, known hereafter as the Navy design, is about three and a half times larger than that of the Bureau of Standards design. Preliminary tests (Table 12), showed that the run was twice as long. In this test the usual 12 grams of aluminum was added to the spoonful of steel. It seemed advisable, however, because of the new size of the spiral, to make a few tests to ascertain if this was still the correct amount of aluminum to add to obtain the maximum fluidity. Varying amounts of aluminum were added to the spoonful of molten steel, and it was found (Plate 8) that 1.5 grams of aluminum per pound of steel gave the longest run.

67. In Tables 13 and 14 there are set forth data on the comparison of fluidity tests taken before and after the final additions were made, and the type of runs that may be expected during the refining period. It may be noted from Table 13 that there was a very close check between the test spirals poured with the aluminum killed steel and the fluidity tests that were poured after the ferro silicon-ferro manganese additions. Once in a very great while a condition similar to that listed under Heat 162 was found when the two did not check; in fact, showed a considerable disagreement.

68. The results shown in Table 14 are typical of fluidity conditions found in most heats. Results of this nature have been duplicated in 35 to 40 heats representing about 200 individual fluidity tests. In general, most of the heats had an increase in fluidity as shown in Case A, where the power was applied in such a manner that the temperature of the bath rose slowly as the refining period progressed. Case B, represents a heat in which the power input was too high at the beginning of the heat with drastic manipulations of the power input in the latter part of the refining period. The significance of these tests during the refining period will be discussed at greater length after subsequent tests are reported.

69. Results similar to Tables 13 and 14 were found upon further testing. It was thought that perhaps the reason for the poor correlation between tapping temperature and fluidity lay in the technique of taking the fluidity samples. If the molten steel could be held in a reservoir by a stopper until the spoonful of metal had been completely emptied, before the stopper was removed a run under more constant conditions would perhaps result. Thus, there would be no splash or swirl of steel entering the spiral, and the height from which the spoonful of steel was poured would no longer be a factor in the taking of the sample.

70. Experimentation was started along the lines of thought given above by first developing a new type of reservoir and pouring head (Plates 5 and 6).

71. It was decided that since aluminum had to be added to the spoonful of steel it would be advisable to make the stopper an aluminum disk. The aluminum disk is inserted at A, Plate 6, and holds the steel in the conical reservoir until the molten steel dissolves and penetrates

it, running into the well (B). The overflow from well (B) flows through the passage (C) into the regular horn gate (D) and so to the spiral (E).

72. A study of this aluminum disk type of fluidity mold during the refining period was made and results reported in Table 15. It may be seen that during the early part of the refining period when the temperature of the bath was low, a short fluidity run was recorded. Also a considerable length of time was required for the molten steel to penetrate the aluminum disk. As the temperature of the metal increased, the fluidity increased and the time required for the molten steel to penetrate the aluminum disk decreased, until in some cases, when a light weight disk was used, the steel would penetrate the disk before the spoon had been completely emptied. From these results it appeared that temperature alone would be responsible for the fluidity reading recorded, since the hotter the steel, the sooner the penetration of the disk and therefore, the longer the fluidity spiral. The method is subject to wide variations in the lengths of run and small manipulations of the bath temperature would be rather noticeable. It is rather difficult to determine whether or not the fluidity results obtained are a straight line function of the temperature, but from general observations this does not seem to be the case. This is due undoubtedly to the time necessary for dissolving the disk.

73. Further studies were carried on at some length to determine the type of checks obtained when the tests were duplicated. In Table 16, some of the conditions found are set forth. It is rather definite that the results as a whole do not check each other. The reason for the poor results is the variations that exist in the time required for the metal to penetrate the aluminum disk. It is not known why there should be a variation in these times, but it has been assumed that the manner in which the disk fits into the pouring top is largely responsible. It has been noticed in some cases the disk dropped into place easily, whereas, in other cases force had to be exerted in order to put the disk in place. Everything else, such as the method of pouring, the size of the spoonful of steel and the time to pour it are maintained as constant as practicable.

74. The method was modified by substituting lead disks for those of aluminum. These tests reported in Table 17, show the same erratic results. The steel penetrated the lead very quickly even though the lead disks were rather thick. The results obtained were in no way superior to those recorded under the standard methods.

75. The disk method appeared at first to have certain possibilities, in that variations in pouring technique would be overcome. However, serious disadvantages arose, not only in the technique of the test, but there was considerable difficulty for the low temperature molten steel to break through the aluminum disks, even when the disk is relatively thin. At high temperatures the steel breaks through the thick disks so quickly that there is hardly enough time to empty the spoon. The critical characteristics of the test are not those desired, since the lower the temperature, the more variation there is in the run, while at high temperatures the

mold is completely filled under several different conditions. Thus, the test depends on the temperature of the steel and the fluidity is of secondary importance.

76. Several tests were carried on during the time the preceding data were taken, wherein a study was made of the fluidity of steel after tapping. In these experiments the Navy mold and the teapot pour ladle were used. In Table 18 are set forth results that are typical of those obtained. In general, it may be said that there is no correlation between temperature and length of run. In one or two cases a run much greater than that usually found was recorded by using aluminum disks to stop off the flow until a large reservoir of metal was obtained. The results thus obtained were sufficient to point out that the horn gate type of fluidity mold is not adapted to the study of fluidity on the pouring floor where it is very difficult to keep conditions of pouring height and pouring speed constant. These conclusions led to the consideration of another type of mold with a reservoir below the spiral. A design similar to the one used by Gabino was chosen and constructed so that it would fit onto the standard Navy spiral (Plate 9).

77. The Gabino type mold was then studied on the pouring floor. An attempt was made to keep the ladle at a constant pouring height and to maintain a uniform pouring speed. The steel was poured from a teapot ladle and the runner box was slotted at the bottom so that it was impossible for a head of metal to be maintained. Table 19 shows the fluidity and the corresponding metal temperature as obtained with the Gabino mold. The run lengths recorded with this mold were much longer than those obtained with the Navy type mold. It was found that if two molds were poured at the same temperature the lengths of the runs obtained would compare very well.

78. The Gabino type mold produced such good runs on the pouring floor that it was decided to try the mold at the furnace and to compare these results with those obtained by using the standard Navy mold. A series of fluidity tests were taken every ten minutes during the refining period of the heat. During this time the power input of furnace was maintained as constant as possible, so that there would be no large variations in the temperature of the metal. In general, the length of spiral recorded with the Gabino type mold was twice that found in the Navy mold. These results are tabulated in Table 20. One of the disadvantages of using this mold is that with only a small amount of metal available in the spoon test, no drainage gate could be made in the bottom of the runner gate; consequently, the steel built up a small head in the runner gate. Variations in the quantity of metal in the spoon therefore resulted in variations in the height of the head in the runner gate, which in turn, may influence the length of run in the Gabino type mold.

79. However, the Navy type fluidity mold gives good results at the furnace and there does not appear to be a need for greater lengths of spiral runs; so further consideration of the Gabino mold at the furnace was not deemed necessary. It does, however, exhibit excellent possibilities when used on the pouring floor.

80. During this investigation of fluidity two other types of tests have been studied; one type as proposed by Mr. R.A. Bull, has been termed the "Bar Fluidity" test, the other proposed by Mr. George Batty, is known as the "Shankability" test.

81. The "Bar Fluidity" test consists of a molded bar thirty-six inches long tapered from one inch in diameter at the gate to one-eighth of an inch diameter at the other end. A vent hole is punched through the cope at the small end.

82. It is necessary to have about seven pounds of steel to run this bar. The procedure employed in pouring the bar at the furnace is essentially the same as that used when pouring a spiral fluidity mold. A large spoon is slagged and heated in the furnace, brought out with a spoonful of metal, and moved close to the runner gate where it is quickly emptied. The mold is set on a slightly inclined plane of five to ten degrees during pouring. The length of the bar is recorded as the fluidity.

83. In Table 21 are listed some of the results that were obtained by using the bar method. It was found that aluminum additions to the steel were not necessary for this type of fluidity mold when the test was taken during the refining period. It was also noticed that the test would check itself within reasonable limits. One rather unfavorable point was exhibited by the data, in that a distance of from twenty-eight to thirty inches of run was usually recorded. If the steel is thoroughly killed it will run the full distance of thirty-six inches.

84. It is rather difficult to decide just what the test shows. If the diameter of the bar was constant, then it could be said that the test would represent the distance from the gate that such a section could be run. This is not the case when a bar of a varying diameter is used. If, for example, the diameter of the bar is one-fourth inch at the place where the steel stopped running, does this mean that the steel is unable to run a 1/4-inch section? The answer is obviously in the negative. If the 1/4-inch section was nearer the gate, or if the 1/4-inch section led directly from the one-inch section, then the small section would undoubtedly have run. The cooling effect of the sand plays an important part in this test, for as the bar becomes smaller the ratio of the perimeter to the area increases. This is an undesirable effect in a fluidity test, as there are already too many variables without adding cross-sectional area and surface perimeter to the list.

85. It might also be added that the mold is more difficult to prepare and takes longer to mold than any of the spiral type molds. It thus seems that a spiral type mold is better adapted to the study of fluidity.

86. The "Shankability" test is somewhat similar to the usual set test. A small cup with an overflow lip is made in oil sand and baked. The test is performed by bringing out of the furnace a spoonful of steel and quickly filling the cup to the overflow spout. At this moment a stop-watch is started and the length of time required for the surface of the molten steel to film over is recorded.

87. It is Mr. Batty's opinion that the shankability test should not be considered as a really satisfactory index of the true fluidity of the steel. It does indicate, however, what might be called the "shankability" of the steel, in that it records the presumed over-reduced condition which is inimical to proper and economical shanking of metal. It also should be mentioned that the index of shankability is not the same for different types of steels. For example, a plain carbon steel may be considered in a satisfactory condition to tap when the shankability test gives a count of 45 seconds, whereas, in making chromium molybdenum alloy steel a similar test of thirty seconds is more than adequate to run castings of dimensions and sections similar to those which would require the much longer filming time in plain carbon steel.

88. The shankability test, therefore, may not properly be called a fluidity test that may safely be applied to various types of steel, although it does provide a useful index for each type of steel when the steels have to be manipulated in hand shanks or small pouring ladles between the parent ladle and the molds.

89. Several preliminary studies have been made at this Laboratory with the "shankability" test but a large set of data were not collected since the primary object has been to establish a fluidity mold where measurements of length could be recorded rather than measurements of time. However, it seems that the "shankability" test or a spoon set test might very well be correlated with a spiral fluidity test and in this way observe the deficiences of either method. Mr. Batty, the proposer of the method, has already pointed out that in some steels, especially the alloy steels, the shankability is not a true indication of the runnability or fluidity of the metal within the molds. Plans have, therefore, been made to study the shankability test in the immediate future and to compare the results obtained with those of the spiral fluidity test.

90. Several attempts were made to maintain the steel bath at a constant temperature during the refining period of the heat, so that a series of fluidity molds could be poured in an endeavor to ascertain if the fluidity increased as the refining period progressed. It was thought that if the power input could be made fairly constant the temperature of the bath would equalize and that tests taken at intervals would record changes in fluidity due to the progress of refining. However, the ideal conditions were never attained. In the first place, the temperature of the steel continued to rise even though the power input was carefully controlled over an hour period. Under these conditions the fluidity increased, which of course was logical to expect with an increase in temperature.

91. On another occasion the temperature again increased, though the fluidity during the refining period remained about the same, and still at another time the fluidity dropped even though the temperature apparently increased.

92. It was further decided that it was doubtful if an increase in fluidity would show during the refining period, since the method of

taking the fluidity tests would not necessarily show the extent to which the metal had been refined, as each spoonful of steel is completely killed (degassified) by the aluminum addition. Thus, changes in the temperature of the steel may be the only differences that are recorded. If such a condition is true, and it is reasonable to believe that it is, then there has been developed no fluidity method that will give information on the progress of the refining period. However, this deficiency is not as bad as it appears, for the tests taken during the refining period, when aluminum is added, check very well with those tests made just before the metal is tapped from the furnace; that is, of course, if the temperature of the bath has not been markedly altered. Thus, all tests taken during the refining period are indications of what can be expected of the metal if it were tapped immediately. This is a point worth knowing, since adjustments in the power input can be made to alter temperature conditions in case the fluidity is not what is desired.

93. Various methods of temperature determination were studied at the furnace but none were successful. It is very difficult to record even close approximations of the temperature of the bath in a three phase electric arc furnace. Optical readings are difficult to obtain as it is nearly impossible to hold the slag back so that the readings may be taken on the bare metal. Up to the present time all installations of the Fitterer silicon carbide-carbon thermocouple in electric furnaces have proved unsatisfactory, as they are so large that a permanent installation must be made in the roof of the furnace. The tungsten-molybdenum couple has been tried but no refractory could be found to withstand the rapid temperature changes caused by placing a relatively cold thermocouple into a steel bath. In this case, also, the thermocouple should be mounted on the furnace roof so that it will hang down into the furnace and be heated gradually with the furnace.

94. With the small 500 pound per hour furnace there is hardly sufficient space to make a thermocouple installation in the roof and if it were accomplished the roof would be weakened materially, so much so, that the roof would last only a few heats.

95. It is indeed unfortunate that temperature measurements of the furnace bath could not be taken at the time that the fluidity tests were made, in order that direct temperature fluidity correlations could be obtained. The tapping temperature, however, can be obtained with a fair degree of accuracy. Therefore, it would be possible to attempt a correlation between tapping temperature and the fluidity of the steel taken immediately before tapping. This was done (Tables 10 and 16) and as previously explained the results were more of a qualitative than a quantitative nature. However, the fluidity test does give the furnace operator a good idea of the condition and temperature of the metal before it leaves the furnace. Continued use of such a test would, in a short time, be of more value to a furnace operator than the set test. In view of the probable use of the fluidity test the following procedure is set forth.

(A) A pattern is made, usually in brass or aluminum, according to the plans of Plate 4. This pattern may be molded in a small flask of about 10"x15", 4-inch drag and 3-inch cope with green sand, in about 5 minutes. The mold is assembled at the furnace and a pouring top is put in place over the reservoir (Plates 10 and 11).

(B) A large dipper that will hold from eight to ten pounds of steel is placed in the furnace and carefully covered with slag and allowed to heat so that it will not act too strongly as a chill (Plate 12).

(C) The spoon is dipped deep into the bath and a spoonful of steel is withdrawn from the furnace (Plate 13), when the dipper crosses the furnace door sill aluminum (1.5 grams per pound of steel) is added to the liquid steel in the dipper (Plate 14). The aluminum may be added by winding aluminum strips on a metal rod. The aluminum should be stirred vigorously into the steel (Plate 15).

(D) The dipper is moved steadily and continuously to a position just over the pouring top (Plate 16), where it is turned and the steel poured quickly (Plate 17). The mold is then broken up and the spiral measured (Plate 18).

SUMMARY

96. A complete study has been made of all the literature on the subject of fluidity and a discussion of testing for fluidity is presented.

97. Over 1200 fluidity tests have been made in an attempt to develop a fluidity test for steel to be used both before tapping at the furnace and after tapping on the pouring floor.

98. A test has been developed for use at the furnace that gives an indication of the fluidity of the steel, its temperature and general condition before the final additions are made and the steel tapped. Care must be exercised in following the procedure, for failure to follow a definite routine will result in large variations in the length of spiral obtained. The variables of this method which will effect the length of spiral are as follows: (a) cold dipper, (b) large variations in the quantity of metal in the dipper, (c) pouring height of the dipper, (d) speed of pouring, (e) spilling of metal into mold before pouring.

99. A fluidity test has been developed for the study of fluidity on the pouring floor. This test compensates somewhat for the many variables that are present when tests are taken from crane operated ladles.

100. The results show that there are many variables connected with the tests that are difficult to control and standardize. The measurement of temperatures of the furnace bath were impracticable.

101. The spiral type fluidity mold is the best constructed test for use in the study of fluidity.

102. Further study of the relationship of fluidity to temperature, composition and condition of the metal is necessary before quantitative results can be presented.

RECOMMENDATIONS

103. All steel manufacturers know the importance that is attached to the fluidity of steel, but no one knows it better than the steel casting producer. The subject of steel fluidity to these people is a vital issue and one wherein a more complete knowledge is desirable.

104. The preliminary studies of this report point out that a number of testing variables must be eliminated before quantitative information can be collected. Also some provision must be made wherein the temperature of the steel can be accurately recorded. It is believed that these things may be accomplished if the fluidity study were carried out using an induction furnace set up. A 250-pound motor generator induction furnace of about 100 kilowatts is desired. This furnace should be so constructed that it can be bottom poured, so that the fluidity mold could be placed directly under the nozzle. Thus, the pouring height would be constant and since the pouring speed could be controlled, this would also be a constant. Temperature measurements can be made with either the platinum platinum-rhodium or the tungsten-molybdenum thermocouples and steel bath temperatures can be controlled more accurately than with any other type of steel melting equipment.

105. It can easily be seen from the foregoing analysis that the solution of the fluidity problem will be a direct aid not only to the Navy's foundries, but also to the entire steel industry. If the interested bureaus consider the study and solution of the problems relating to fluidity to be of sufficient importance, it is recommended that serious consideration be given to the purchase of a motor generator induction furnace of about 300 pounds steel capacity so that the problem may be actively prosecuted.

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TABLE 1

DIMENSIONS VARIED IN DIFFERENT TYPES OF FLUIDITY MOLDS

Type of Mold	Horn Gate								Down Gate		Pouring Basin		Spiral				Cross-Sectional Area
	A	B	C	D	E	F	G	H	J	K	L	M	N	R	Y	Z	
Bureau of Standards	2.30	2.07	0.20	0.25	0.30	0.70	0.25	4.30	1.00	0.70	0.50	0.60	1.30	0.14	0.30	0.36	0.0665
B.S. - First Modification	2.30	2.07	0.20	0.25	0.30	0.70	0.31	4.30	1.00	0.70	0.50	0.60	1.30	0.14	0.30	0.36	0.0665
B.S. - Second Modification	2.30	2.07	0.20	0.25	0.30	0.70	0.36	4.30	1.00	0.70	0.50	0.60	1.30	0.14	0.30	0.36	0.0665
B.S. - Third Modification	2.30	2.07	0.20	0.25	0.30	0.70	0.50	4.30	1.00	0.70	0.50	0.60	1.30	0.14	0.30	0.36	0.0665
International Nickel Co.	2.30	2.07	0.20	0.25	0.375	0.75	0.50	4.30	1.00	0.75	0.50	0.60	1.30	0.14	0.375	0.45	0.0857
Navy	2.375	2.19	0.125	0.19	0.50	1.00	0.625	4.50	1.25	1.00	0.625	0.725	2.00	0.25	0.50	0.625	0.239

TABLE 2

STUDY OF VARYING THE DIAMETER OF THE HORN GATE IN THE BUREAU OF STANDARDS FLUIDITY MOLD.

Mold Type	Time and Position of Test	Fluidity for Various Horn Gate Diameters (Inches)				Set Test (Seconds)
		.25	.31	.36	.50	
Green	During refining period.	.5	2.0	1.0	4.0	19
Green	After final additions.	1.0	4.3	4.3	7.5	16
Dry	After final additions.	3.0	8.2	6.7	9.0	16
Green	During pouring.	1.0	6.5	2.5	5.5	
		0.0	3.0	6.0	6.0	

TABLE 3

USING THE 0.50" HORN GATE IN BUREAU OF STANDARDS FLUIDITY MOLD.

Mold Type	Time and Position of Test	Fluidity (Inches)	Set Test (Seconds)
Green	During refining period (early)	1.0	8
Green	During refining period	1.5	-
Green	During refining period (middle)	2.0	11
Green	During refining period	2.4	-
Green	During refining period (late)	3.5	18
Green	After final additions	12.0	23
Green	After final additions	15.0	23

TABLE 4

VARYING MOLD TYPES USING THE 0.50" HORN GATE IN BUREAU OF STANDARDS FLUIDITY MOLD.

Mold Type	Time and Position of Test	Fluidity (Inches)
Green	During refining period (early)	1.3
Dry	During refining period (early)	1.5
Green	During refining period (middle)	2.3
Dry	During refining period (middle)	2.0
Green	During refining period (late)	3.1
Dry	During refining period (late)	4.2
Green	After final additions	15.0
Dry	After final additions	17.8
Green	After final additions	17.0
Dry	After final additions	18.5

TABLE 5

COMPARISON BETWEEN THE INTERNATIONAL NICKEL FLUIDITY MOLD AND THE BUREAU OF STANDARDS TYPE MOLD. (GREEN SAND MOLDS).

Mold Type	Time and Position of Test	Fluidity (Inches)	Carbon Content
Bureau of Standards	3/4 hr. after refining slag put on.	1.2	0.20
Bureau of Standards	1 hr. after refining slag put on.	1.5	0.20
International Nickel	1 hr. after refining slag put on.	3.5	0.20
Bureau of Standards	1-1/4 hrs. after refining slag put on.	1.5	0.20
International Nickel	1-1/4 hrs. after refining slag put on.	2.0	0.20
Bureau of Standards	1-1/2 hrs. after refining slag put on.	2.5	0.40
International Nickel	1-1/2 hrs. after refining slag put on.	2.8	0.40
Bureau of Standards	1 hr.40 min. after refining slag put on.	2.5	0.40
International Nickel	1 hr.40 min. after refining slag put on.	3.5	0.40
Finals added 1 hr. 45 min. after refining slag put on.			
Bureau of Standards		15.5	
Bureau of Standards	5 min. after finals were added.	16.0	
International Nickel	5 min. after finals were added.	21.0	
International Nickel	5 min. after finals were added.	23.0	
Bureau of Standards	10 min. after finals were added.	17.7	
International Nickel	10 min. after finals were added.	24.2	
International Nickel	10 min. after finals were added.	25.0	

TABLE 6

ALUMINUM ADDITIONS (1.50 GMS./LB.) TO BUREAU OF STANDARDS TYPE FLUIDITY MOLD DURING THE REFINING PERIOD.

Lapsed Time After Putting on the Refining Slag.	Fluidity (Inches)	
	Case A	Case B
30 minutes	2.2	4.0
40	3.5	6.5
50	4.5	8.7*
1 hour	6.7	5.2
1 hour 10 minutes	8.2	9.5+
1 hour 20 minutes	9.7	12.7*
1 hour 30 minutes	10.5	8.7+
1 hour 35 minutes	13.5	
1 hour 35 minutes	14.0	13.0

Note: * Power cut back drastically.
+ Power increased considerably.

TABLE 7

DUPLICATION OF DATA DURING THE REFINING PERIOD.

Lapsed Time After Putting on the Refining Slag	Fluidity (Inches)
55 minutes	8.2
57 minutes	9.0
1 hour 5 minutes	9.2
1 hour 7 minutes	10.0
	9.5
1 hour 15 minutes	12.0
1 hour 17 minutes	11.5
1 hour 18 minutes	Finals
1 hour 20 minutes	12.0
1 hour 20 minutes	13.5

TABLE 8

COMPARISON OF ALUMINUM KILLED FLUIDITIES TO CHECK FLUIDITIES AFTER FINALS (FeSi-FeMn).

Heat	Aluminum Added Just Prior to Final Additions	No Aluminum Added After Final Additions	Tapping Temperature °F.	Per Cent Carbon
124	15.0	15.0	3000	0.23
107	12.5	12.0	3000	0.08
117	13.5	13.5	2920	0.30
114	14.5	14.5	2900	0.31
113	11.7	12.0	2880	0.32
112	10.5	11.2	2980	0.33
110	13.5	13.5	2980	0.16
108	9.8	10.7	2970	0.29
101	10.0	10.0	2960	0.45
84	10.8	10.5	2910	0.27
109	19.5	20.7	3000	0.22
120	12.0	11.8	3030	0.29

TABLE 9

VARIOUS METHODS OF POURING FLUIDITY MOLDS AFTER TAPPING INTO A LADLE.

Position During Pouring	Method of Pouring	Fluidity (Inches)	Tapping Temperature - °F.
Beginning of pouring	Handshank	9.5	2980
End of pouring	Handshank	3.0	2790
Beginning of pouring	Bottom pour ladle	6.3	2960
End of pouring	Bottom pour ladle	5.0	2800
Beginning of pouring	Top pour ladle	3.5	2970
End of pouring	Top pour ladle	0.3	2730
Beginning of pouring	Tea pot pour ladle	8.7	2980
End of pouring	Tea pot pour ladle	3.5	2750

TABLE 10

FLUIDITY VS. POURING TEMPERATURE - USING TEAPOT POUR LADLE - NO ADDITION OF ALUMINUM.

Heat 73	Carbon Content 0.44%						
Temperature	2990	2920	2890	2840	2790	2750	
Fluidity	10.0	5.0	7.5	3	6	3	
Heat 82	**Carbon Content 0.38%**						
Temperature	2980	2900	2840	2790			
Fluidity	9.5	4.5	8.5	16.5			
Heat 83	**Carbon Content 0.30%**						
Temperature	3030	3000	2950	2900	2840	2800	
Fluidity	6.0	4.5	4	4	4.5	4	
Heat 86	**Carbon Content 0.18%**						
Temperature	3000	2930	2890	2830	2800	2760	2730
Fluidity	6.5	4.5	3.5	3.0	2.5	1.0	0

TABLE 11

COMPARISON OF FLUIDITY IN MOLDS WITH AND WITHOUT A RESERVOIR. BUREAU OF STANDARDS TYPE.

Type of Mold	Elapsed Time After Putting on the Refining Slag.	Fluidity (Inches)	
		Case A	Case B
Bureau of Standards	1 hour	7	14
H.G.F.*	1 hour	8.5	26
Bureau of Standards	1 hour 20 minutes	8.5	23
H.G.F.*	1 hour 20 minutes	11.0	23
Bureau of Standards	1 hour 30 minutes	15.5	22.5
H.G.F.*	1 hour 30 minutes	20.0	18.0

H.G.F.* - Horn Gate Fluidity - No reservoir used into which the metal first flowed.

TABLE 12

COMPARISON BETWEEN THE BUREAU OF STANDARDS AND THE NAVY FLUIDITY MOLDS. (GREEN SAND MOLDS).

Mold Type	Time After Putting on Refining Slag.	Added Aluminum Gms./lb. of steel	Fluidity (Inches)
Bureau of Standards	1 hour 25 minutes	1.50	18.0
Navy	1 hour 25 minutes	1.50	35.0
Bureau of Standards	1 hour 28 minutes	1.50	16.5
Navy	1 hour 28 minutes	1.50	34.0
Bureau of Standards	1 hour 35 minutes	1.50	17.0
Navy	1 hour 35 minutes	1.50	34.0
Bureau of Standards	1 hour 37 minutes	1.50	16.8
Navy	1 hour 37 minutes	1.50	37.0
	1 hour 40 minutes	Finals added	
Bureau of Standards	1 hour 45 minutes	None	15.0
Navy	1 hour 45 minutes	None	31.0
Bureau of Standards	1 hour 50 minutes	None	17.2
Navy	1 hour 50 minutes	None	34.0

TABLE 13

COMPARISON OF ALUMINUM KILLED FLUIDITIES TO CHECK FLUIDITIES AFTER FINALS (FeSi-FeMn) IN NAVY FLUIDITY MOLD.

Heat	Aluminum Added Just Prior to Final Additions	No Aluminum Added After Final Additions	Pouring Temperature °F.	Per Cent Carbon
129	32	33	3000	0.36
135	38	38	2990	0.36
138	26	26	2960	0.34
144	30	31	2950	0.34
149	30	30	2930	0.39
148	28	28.5	2900	0.35
162	32	42	3020	0.33

TABLE 14

ALUMINUM ADDITIONS (1.5 GM./LB. OF STEEL) TO NAVY MOLD DURING THE REFINING PERIOD.

Lapsed Time After Putting on the Refining Slag	Fluidity (Inches)	
	Case A	Case B
30 minutes	8.0	6.5
40 minutes	10.5	12.0
50 minutes	13.0	18.0
1 hour	16.0	24.0
1 hour 10 minutes	18.5	31.5*
1 hour 20 minutes	24.0	25.0
1 hour 30 minutes	29.0	26.5+
1 hour 35 minutes	33.0	35.0
1 hour 37 minutes finals added		
1 hour 40 minutes (No aluminum)	33.5	36.0
Tapping temperature	2980	3000

* Power decreased after fluidity was taken.

\+ Power increased considerably after fluidity was taken.

TABLE 15

COMPARISON BETWEEN THE RESERVOIR TYPE AND THE ALUMINUM DISK-WELL CONSTRUCTION TYPE FLUIDITY MOLDS (GREEN SAND, NAVY DESIGN) DURING THE REFINING PERIOD.

Time and Temp. in Refining Period	Aluminum Gm./lbs. of steel	Type	Fluidity (Inches)	Time in Seconds for Steel to Penetrate the Al.
Early - low	1.50	Standard	20	-
	1.50	Disk	2	15
	1.25	Disk	7	10
Middle - medium	1.50	Standard	28	-
	1.50	Disk	18	4
	0.50	Disk	28	1/2
	0.50	Disk	28	1/2
Late - high	1.50	Standard	39	-
	0.50	Disk	42	0
	0.75	Disk	42	0
	1.00	Disk	42	1/4
	1.25	Disk	38	1/2
	1.50	Disk	36	3
	1.50	Standard	38.5	-

TABLE 16

DUPLICATION OF FLUIDITY RUNS WITH THE DISK-WELL CONSTRUCTION.

Time and Temp.	Aluminum Gm./lbs. of Steel	Type	Fluidity (Inches)	Time in Seconds for Steel to Penetrate thru the Aluminum
134	1.50	Standard	34	-
Late in refining	1.00	Disk	42	1.3
period.	1.00	Disk	17	4.1
Temperature medium	1.25	Disk	42	1.2
	1.25	Disk	13.5	7.7
	1.50	Disk	14.0	6.0
136	1.25	Disk	11.0	10
Early in refining	1.25	Disk	12.5	8.5
period.	1.50	Standard	20.0	-
Temperature low				
Late in refining	1.25	Disk	34	2
period.	1.25	Disk	39	1
Temperature high	1.50	Disk	30.5	5
	1.50	Disk	32	2-1/2
	1.50	Standard	38	-
138	1.50	Standard	38	-
Late in refining	1.25	Disk	34	4.5
period.	1.25	Disk	24	6.0
Temperature high	1.25	Disk	41	3.0
	1.50	Disk	30	4.2
	1.50	Disk	33.5	4.5
	1.50	Disk	42	1.0
	1.50	Standard	37	-

TABLE 17

SUBSTITUTION OF LEAD DISKS FOR ALUMINUM IN THE DISK-WELL CONSTRUCTION.

	Gms./lb. of Steel			Fluidity	Time for Molten Steel to Penetrate
Time and Temp.	Aluminum	Lead	Type	(Inches)	Through Disk (Sec.)
Late in refining period.					
Low temperature	1.50	–	Standard	21	–
		5.50	Disk	21	1
	1.25	–	Disk	10	6
		5.50	Disk	24	1.5
	1.25		Disk	19	4.5
	1.50		Standard	23	–
Late – high	1.50		Standard	35	–
		5.50	Disk	26.5	Indeterminate*
		5.50	Disk	27.0	Indeterminate*
		11.00	Disk	23	Indeterminate*
		5.50	Disk	27	Indeterminate*
	1.25		Disk	33	Indeterminate*
	1.50		Standard	36	–

* The steel penetrated the disk before the spoon-ladle was emptied.

TABLE 18

FLUIDITY AFTER TAPPING, USING NAVY MOLD AND TEAPOT POUR LADLE.

Heat 140	Carbon content 0.26%						
Temperature	2860	2840	2820	2800			
Fluidity	16	9	7	33.5			
Aluminum disks	–		10 gms.	10 gms.			
Heat 160	Carbon content 0.34%						
Temperature	2810	2800	2800	2790	2780	2720	2700
Fluidity	4	5.5	5.5	14	4.5	3	6.5
Aluminum disks	–	–	–	6 gms.	6 gms.	–	–
Heat 161	Carbon content 0.40%						
Temperature	2860	2830	2820	2800	2800	2780	2770
Fluidity	4.5	3.5	6.0	4.0	4.0	0.5	2.0
Aluminum disks	–	–	–	4 gms.	4 gms.	–	–

TABLE 19

FLUIDITY AFTER TAPPING, USING THE GABINO FLUIDITY TYPE AND THE TEAPOT POUR LADLE.

	No. 165		No. 168	
Pouring Position	Fluidity (Inches)	Temperature (°F.)	Fluidity (Inches)	Temperature (°F.)
Spoon ladle	35	3000	33	3000
At furnace	34	3000	-	-
Poured by	17	2920	12	2900
Teapot ladle	17	2920	12	2910
Teapot ladle	21	2890	10	2860
Teapot ladle	19	2890	10.5	2860
Teapot ladle	13	2870	8.5	2830
Teapot ladle	14	2870	8.0	2820
Teapot ladle	5.5	2840	5.0	2800
Teapot ladle	7.5	2840	6.0	2790
Teapot ladle	4.7	2790		
Teapot ladle	4.3	2790		

TABLE 20

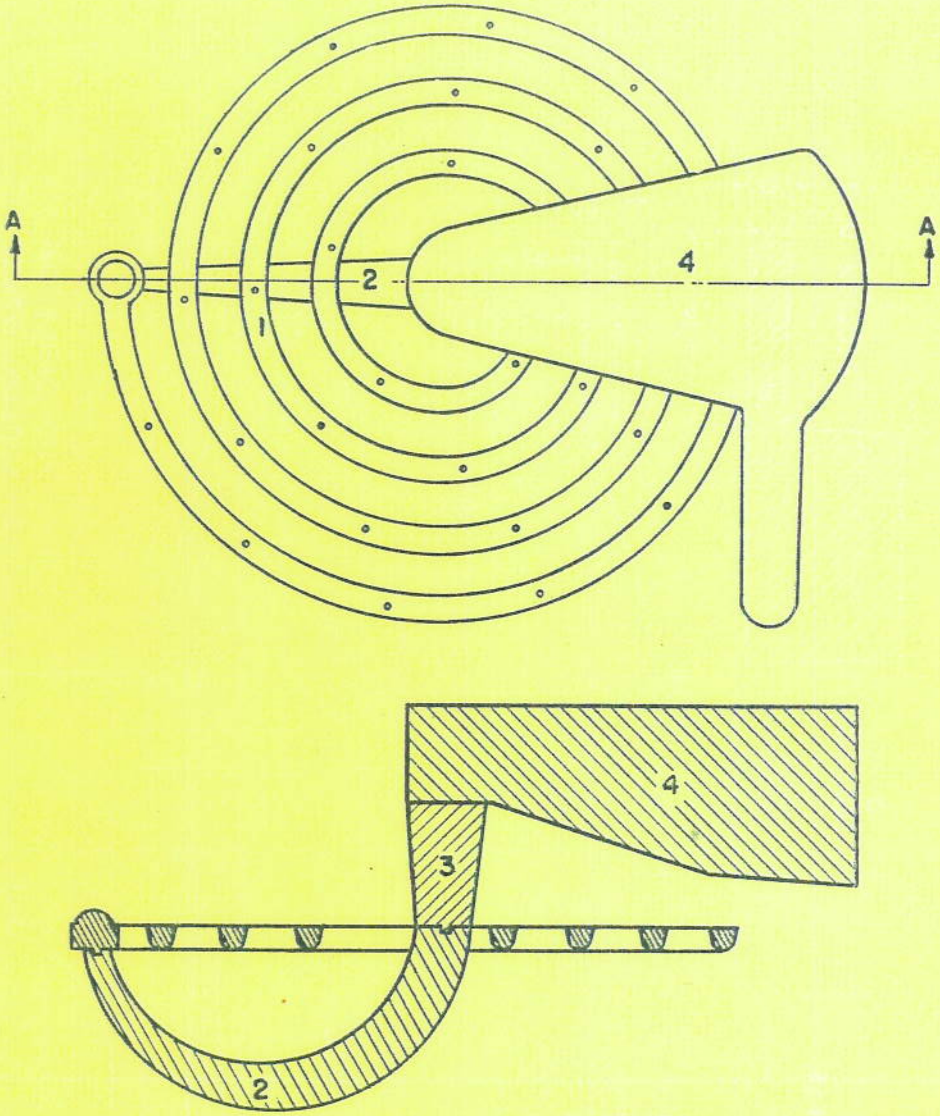
COMPARISON OF NAVY TYPE FLUIDITY AND GABINO TYPE FLUIDITY AT THE FURNACE.

Time after Putting on Refining Slag	Test	Grams Aluminum per Pound of Steel	Fluidity (Inches)
15 minutes	Navy	1.50	22.0
	Gabino	1.50	35.0
25 minutes	Navy	1.50	20.0
	Gabino	1.50	33.5
30 minutes	Navy	1.50	20.0
	Gabino	1.50	34.0
40 minutes	Navy	1.50	14.0
	Gabino	1.50	32.5
50 minutes	Navy	1.50	14.0
	Gabino	1.50	32.0
60 minutes	Navy	1.50	15.0
	Gabino	1.50	31.0
70 minutes	Navy	1.50	17.0
	Gabino	1.50	32.5

TABLE 21

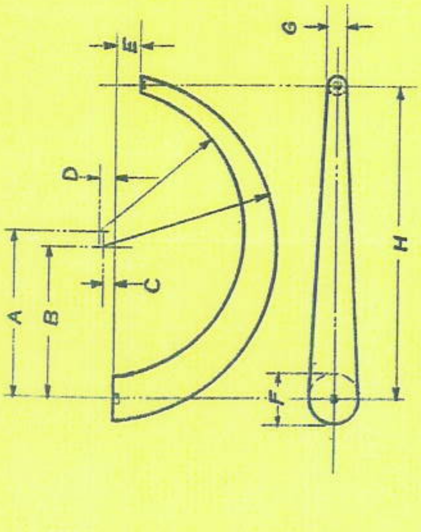
BAR FLUIDITY TEST (R.A. BULL)

Heat No.	Period Test Taken	Test	Aluminum - Grams per lb. of Steel	Fluidity (Inches)
123	Refining	Bar	1.5	36.0
123	Refining	Bar	-	28.8
123	Refining	Navy	1.5	25.0
127	Refining	Bar	-	31.5
127	Refining	Bar	-	29.0
127	Refining	Navy	1.5	37.0
130	Refining	Bar	-	28.0
130	Refining	Bar	-	29.0
130	Refining	Navy	1.5	29.0
142	Refining	Bar	-	22.5
142	Refining	Bar	-	24.0
142	Refining	Navy	1.5	38.5
162	Refining	Bar	-	26.0
162	Refining	Bar	-	31.0
162	Refining	Navy	1.5	32.0
165	Refining	Bar	-	27.2
165	Refining	Navy	1.5	36.0
165	After finals	Bar	-	35.0
165	After finals	Navy	-	35.0
166	Refining	Bar	-	32.0
166	Refining	Navy	1.5	31.0
166	After finals	Bar	-	36.0
166	After finals	Navy	-	31.5

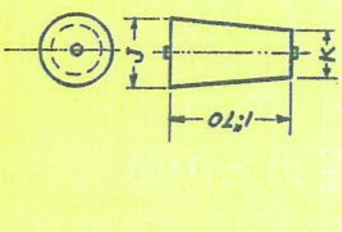


SECTION A—A

PLATE I



2-HORN GATE



3-DOWN GATE

4—POURING BASIN AND OVERFLOW

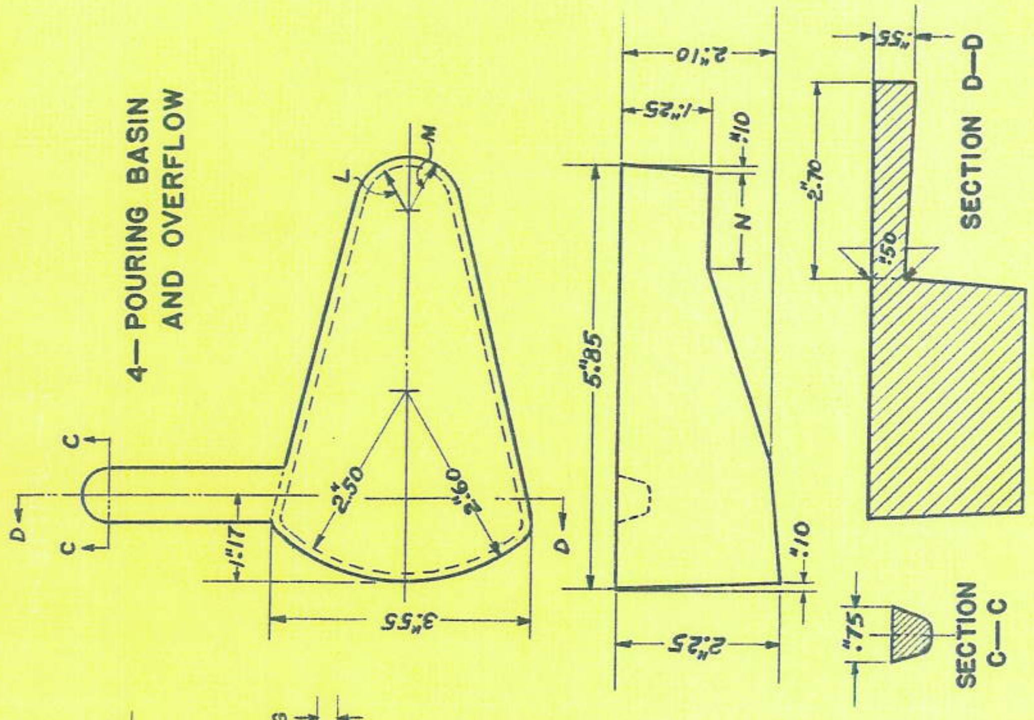


PLATE 2

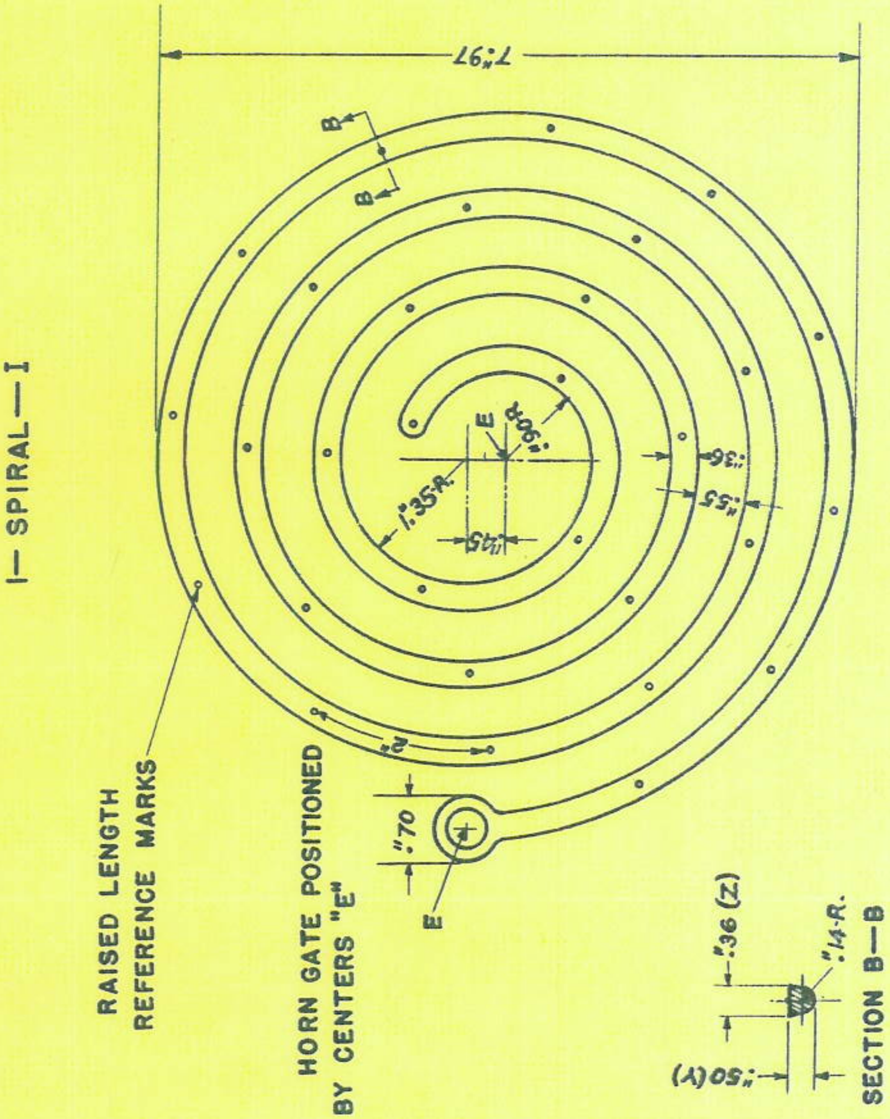
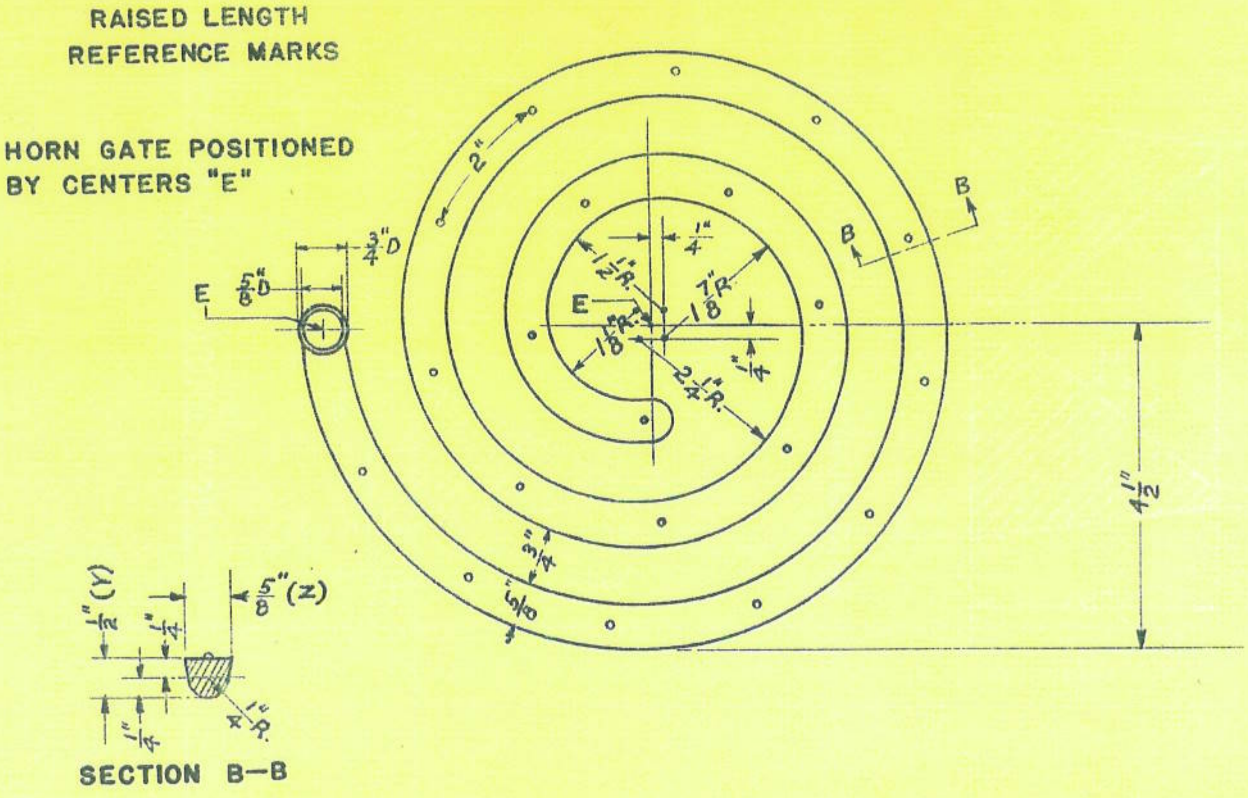

I — SPIRAL — I
RAISED LENGTH REFERENCE MARKS
HORN GATE POSITIONED BY CENTERS "E"
7.97"
B
B
E
E
.90"R
1.35"R.
.45"
.36"
.55"
2"
.70"
.36 (Z)
.14"R.
.50"(Y)
SECTION B—B

PLATE 3

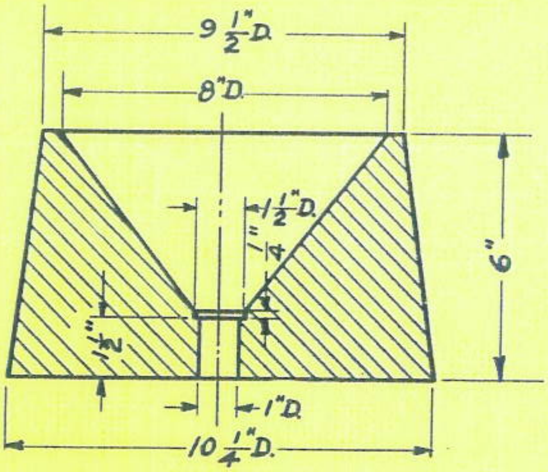
I—SPIRAL—II



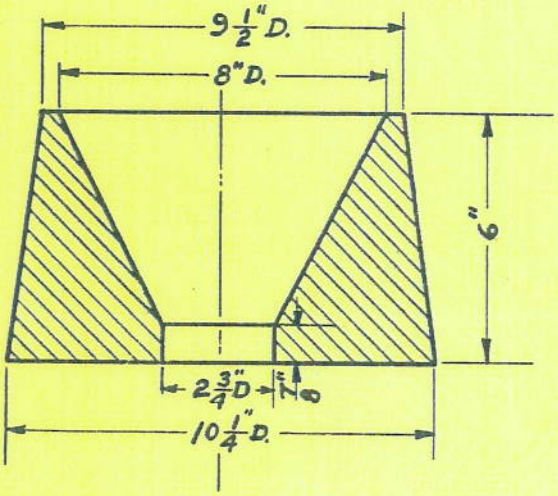
RAISED LENGTH REFERENCE MARKS

HORN GATE POSITIONED BY CENTERS "E"

PLATE 4

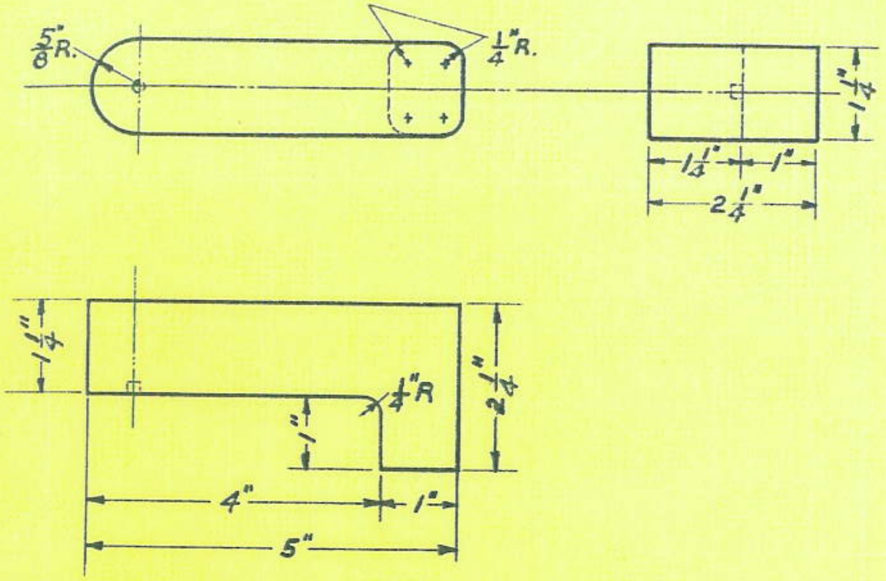


POURING TOP FOR ALUMINUM DISK

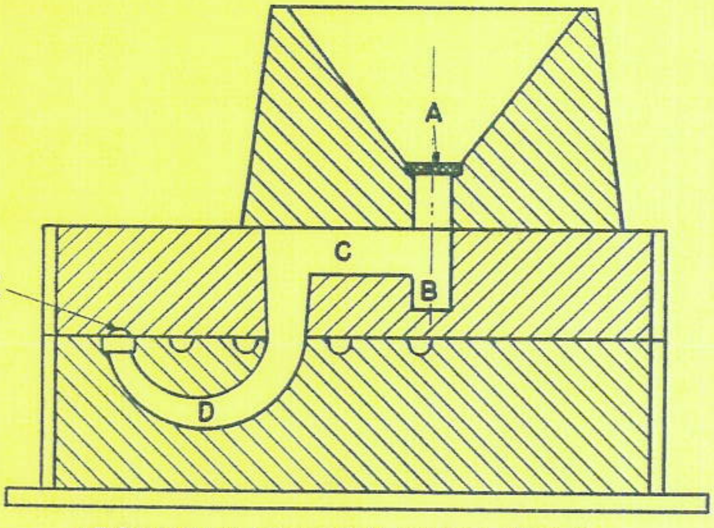


ORDINARY POURING TOP

PLATE 5



POURING BASIN USED WITH ALUMINUM DISK



ASSEMBLY OF DISK TYPE MOLD

PLATE 6

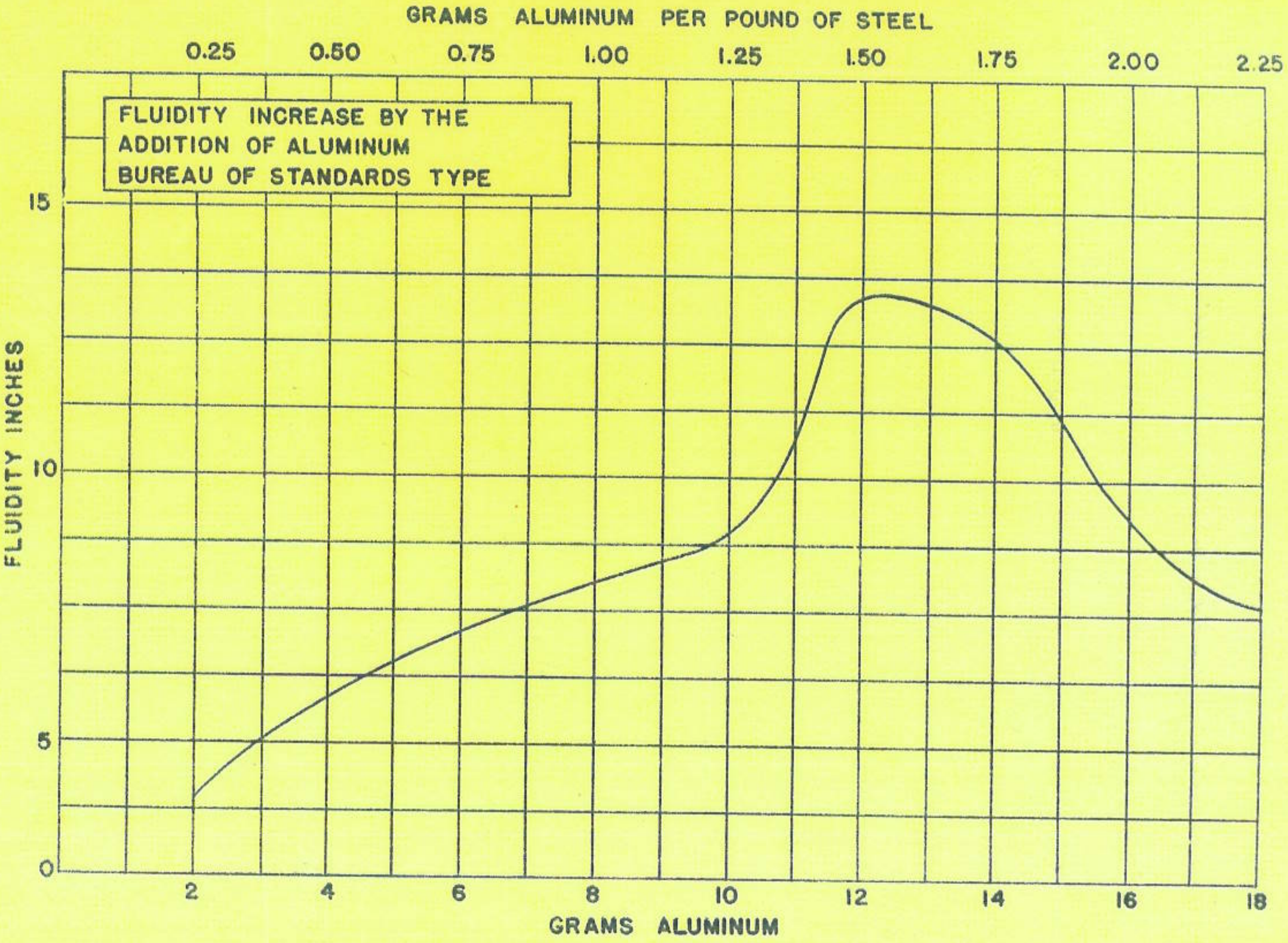

GRAMS ALUMINUM PER POUND OF STEEL
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
FLUIDITY INCREASE BY THE
ADDITION OF ALUMINUM
BUREAU OF STANDARDS TYPE
FLUIDITY INCHES
15
10
5
0
2
4
6
8
10
12
14
16
18
GRAMS ALUMINUM

PLATE 7

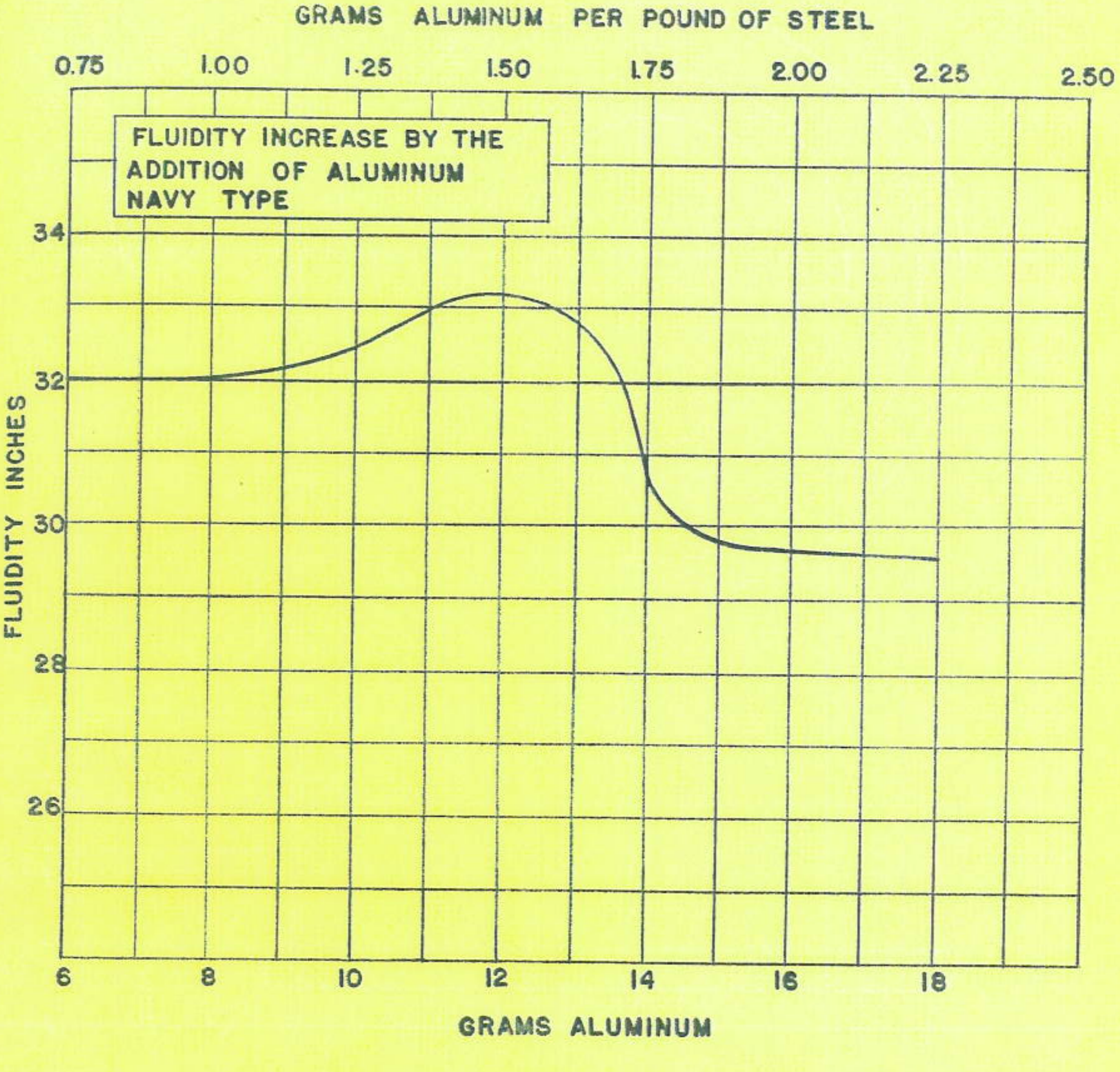

GRAMS ALUMINUM PER POUND OF STEEL
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
FLUIDITY INCREASE BY THE ADDITION OF ALUMINUM NAVY TYPE
FLUIDITY INCHES
34
32
30
28
26
6
8
10
12
14
16
18
GRAMS ALUMINUM

PLATE 8

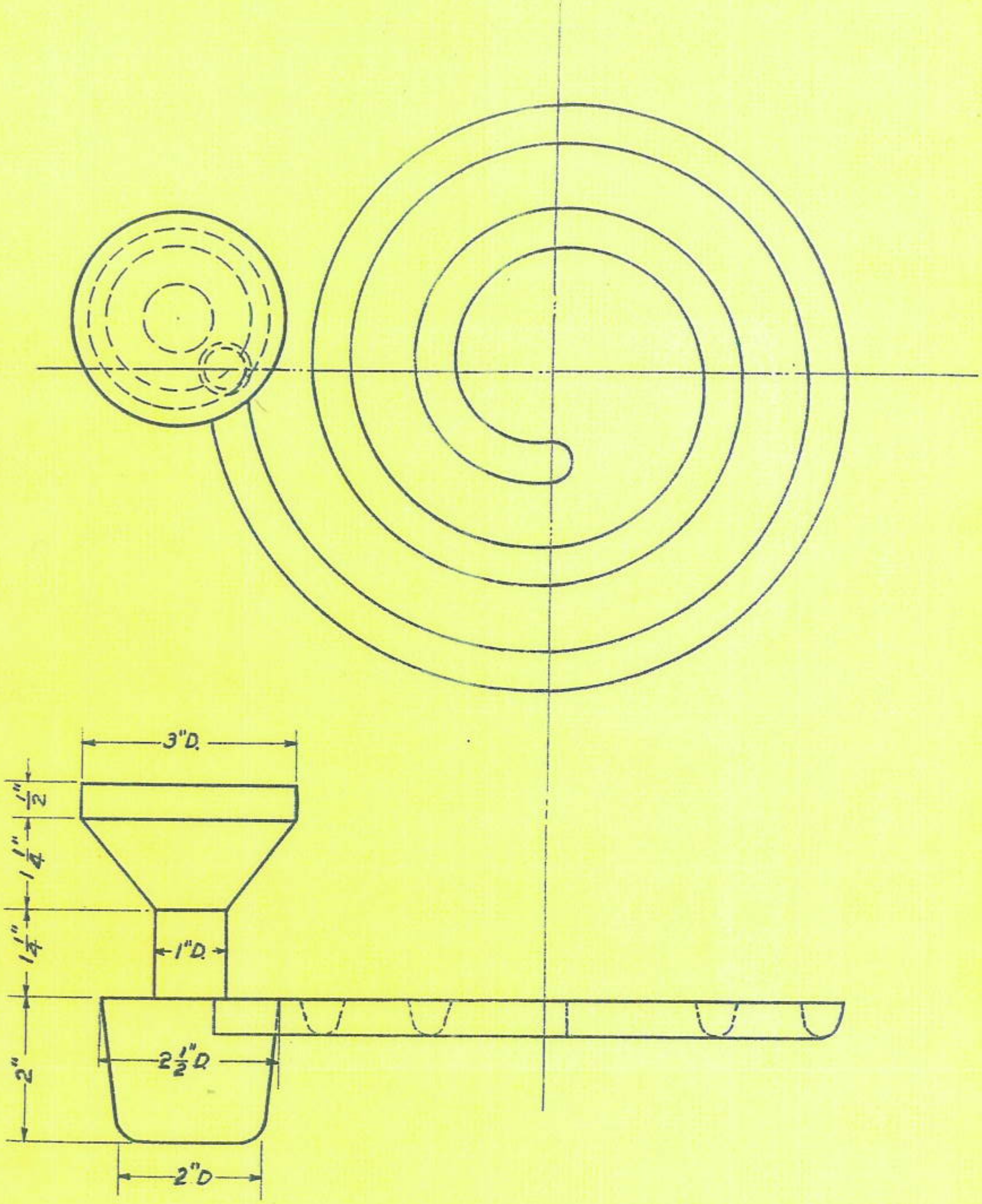
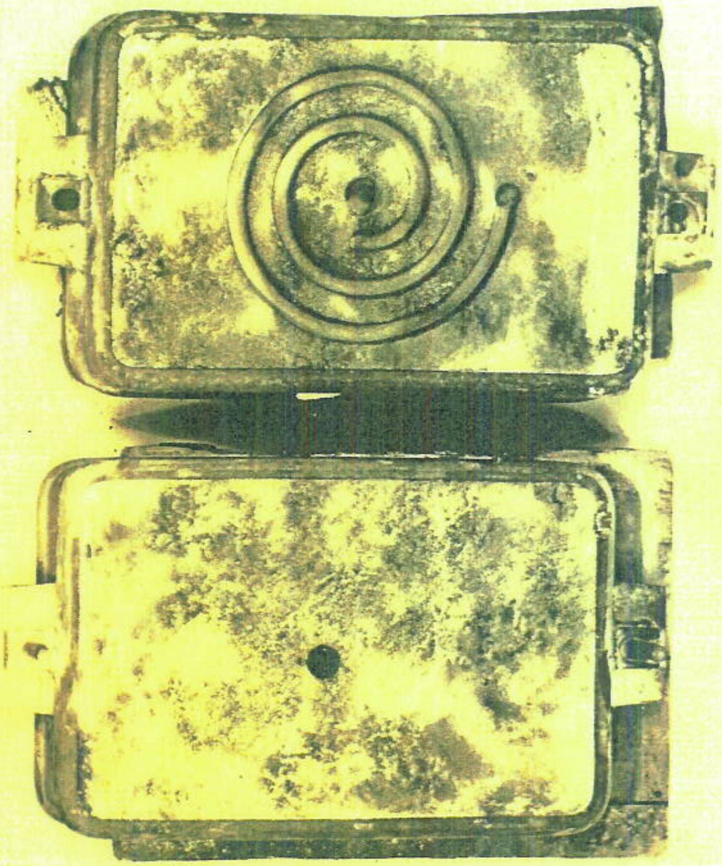


PLATE 9



OPEN FLUIDITY MOLD

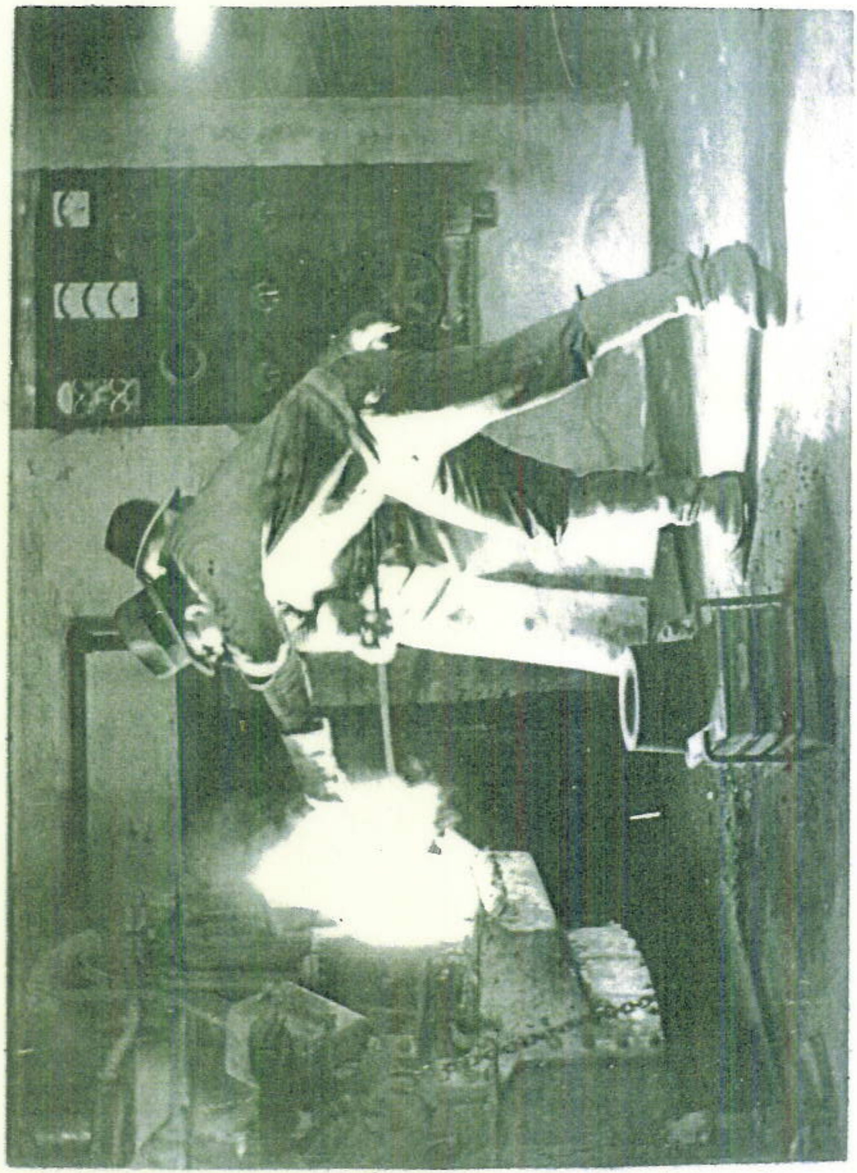
PLATE 10

SLAGGING THE DIPPER

PLATE 12

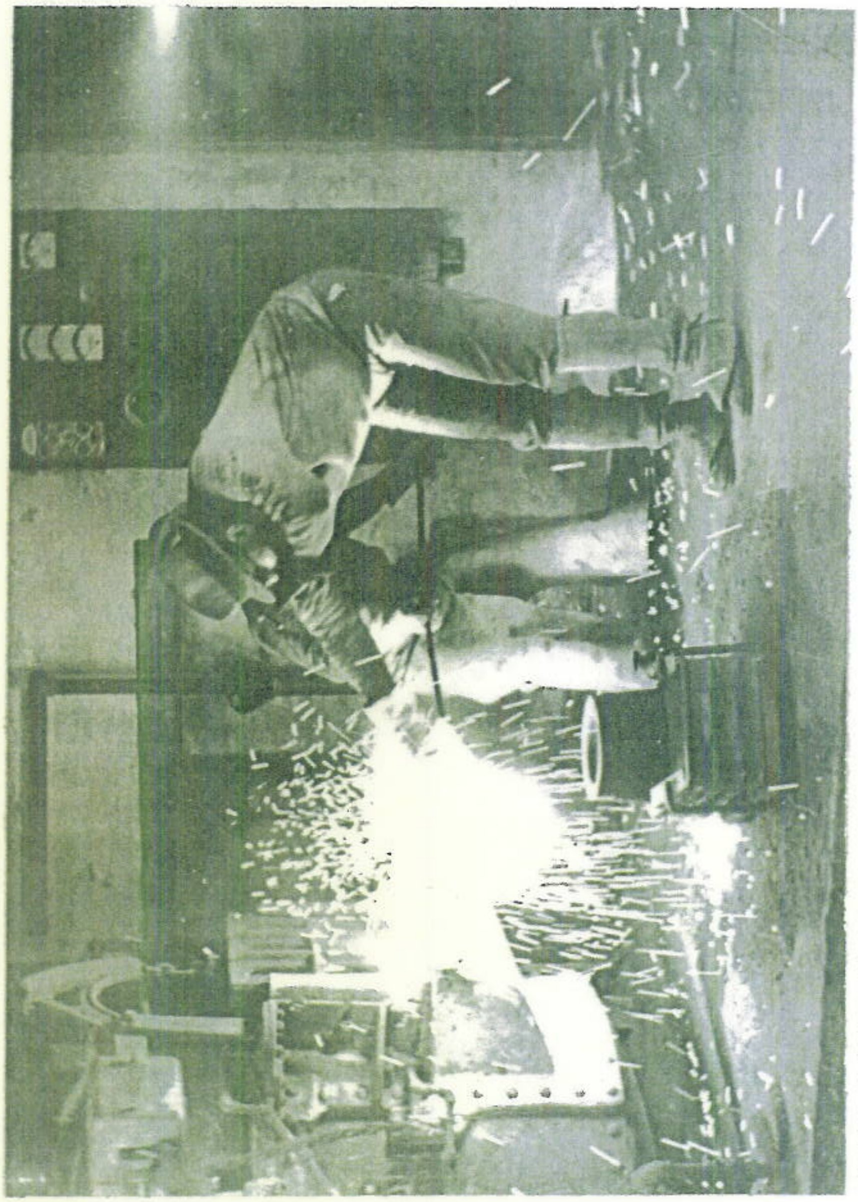
A FULL DIPPER BEING WITHDRAWN FROM THE FURNACE.

PLATE 13



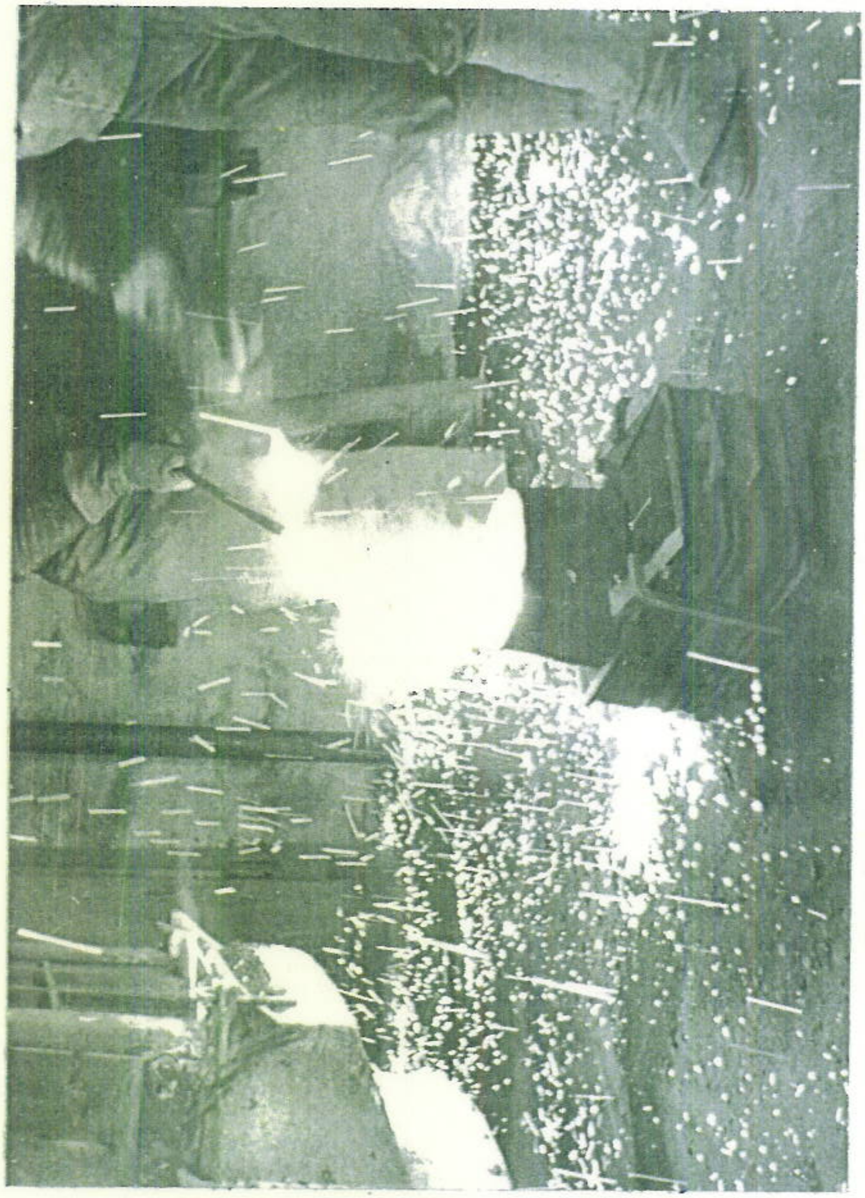
PUTTING IN THE ALUMINUM

PLATE 14



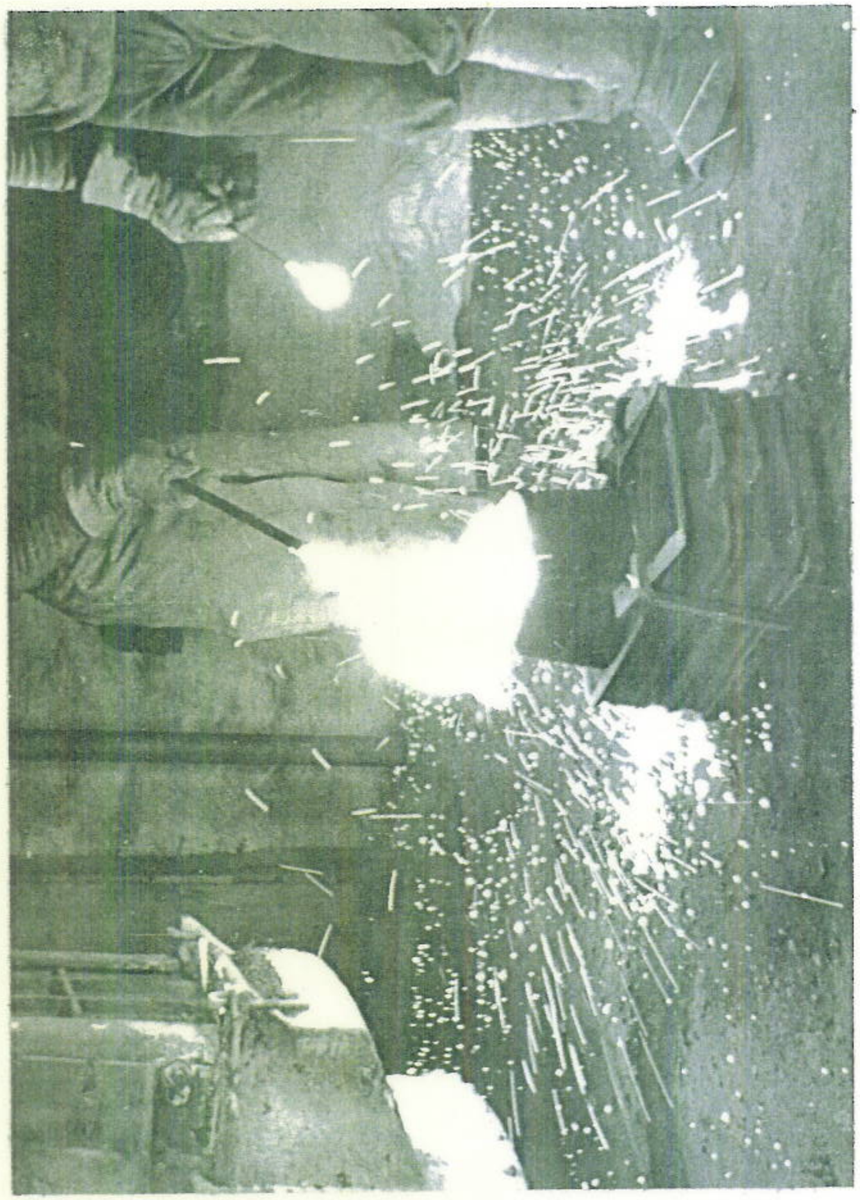
STIRRING THE ALUMINUM WHILE TRANSPORTING THE STEEL

PLATE 15



DIPPER IN POSITION FOR POURING

PLATE 16



POURING OF THE STEEL

PLATE 17

THE FLUIDITY SPIRAL

PLATE 18