12 August 1935

NRL Report No. M-1182.

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FR-1182

NAVY DEPARTMENT

BUREAU OF ENGINEERING

Report on

Studies on Solidification and Contraction in Steel Castings - The Rate of Skin Formation.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D. C.

Number of Pages: Text - 11 Bibliography Tables - 12 Plates - 14

Authorization: Bu.Eng.ltr.QP/Castings (6-19-Ds) of 13 July 1928.

Date of Test: January 1932 to July 1935.

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Public Release

AUG 20 1935

ABSTRACT

In this report there are discussed the factors that would influence the velocity of solidification of a steel casting and the rate at which the skin forms. Studies were made on shapes of varying volumes and also on shapes of varying surface area of a constant volume. The numerical values obtained were used to calculate constants and formulas of solidification and to evaluate the importance of the theoretical considerations.

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AUTHORIZATION

1. The studies of steel castings, of which this report forms a part, were authorized by reference (a); references (b) and (c) are also pertinent to the subject of this report.

Reference: (a) Bu.Eng.ltr.QP/Castings (6-19-Ds) of 13 July 1928.
(b) N.R.L. Report No. M-1026 of 16 February 1934.
(c) N.R.L. Report No. M-1108 of 2 January 1935.

STATEMENT OF PROBLEM

2. The object of this report is to present data obtained from a study made on the solidification of cast carbon steel.

THEORETICAL CONSIDERATIONS

3. The primary function of a mold is to provide a receptacle for the molten steel; however, a further important function is to abstract heat from the molten steel and to dissipate it. The process of the abstraction of heat proceeds by two methods that are not entirely independent. The first is the chilling action that the cold mold has on the molten steel, and the second is the outward passage of heat by conduction through the walls of the mold.

4. The thermal conductivity of the mold material, its specific heat and density, affect the rate at which heat can be extracted from the center of the steel casting. The degree of initial chilling caused by the mold will depend on the relative specific heats of the steel and the mold materials.

5. For sand molds of the same dimensions, the greater the thermal conductivity, the greater will be the rate of cooling. If the sand molds are made of the same material, then the thicker the mold walls, the slower will be the rate of cooling. Owing to the poor thermal conductivity of molding sand, the decrease will not be proportional, but will tend to a limiting value beyond which greater thickness of sand will have little effect on the rate of cooling.

6. Thus, the conditions which determine solidification may be classified as external and internal. The external conditions are those which initiate and control the cooling of the steel and are determined by the mold characteristics; the internal conditions govern the cooling effect within the casting and are determined by the physical properties of the steel.

7. The procedure of solidification of steel, especially of ingot solidification, has been studied by several investigators, notably Desch (1)*, Matuschka (2), Benedicks (3), Fields(4), Nelson (5), and others. The committee on the Heterogeneity of Steel Ingots of the Iron and Steel Institute (6) has perhaps accomplished the most through its series of reports. These investigators explain fully the operation of freezing. In general, the cooling of the steel at first takes place chiefly by absorption of heat by the mold walls. Subsequently, cooling proceeds by transmission of heat through the mold. These two cooling actions occur simultaneously, but the first starts from a maximum value and decreases with time, and the second starts from a minimum value and increases with time up to a certain point when it slowly decreases again. The

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*Numbers refer to articles included in the bibliography.

first action (chilling) is capable of freezing at any part of the mold a considerable mass of steel. The freezing, therefore, can be considered to occur in three successive periods:

(1) Almost instantaneous freezing.
(2) Very rapid freezing.
(3) Comparatively slow freezing.

8. At the time of rapid solidification of the crust, a decrease in temperature in the interior of a large casting is not noticeable, while the molten metal lying adjacent to the chilling surface will pass rapidly through the range between the super-heated temperature and the freezing temperature.

9. The rapid solidification is followed by a slower decrease in the lower super-heat temperatures.

10. Due to the low heat conductivity of a sand mold, the velocity of solidification may be so slow that the excess temperature of the molten steel is dissipated before solidification has reached the central portion of the casting. Subsequently, the frozen zone conducts only the heat of solidification, while the portion still molten remains at a fixed temperature — the freezing temperature.

11. The chief factors influencing the solidification of steel castings are:

(1) Type, shape, and size of mold.
(2) Temperature of the steel above its melting point (super-heat).
(3) Physical properties of the steel.
(4) Temperature of the mold.

These various factors may be considered more fully.

Types, Shapes, and Size of Molds.

12. The types of molds or mold compositions do not vary widely for, in the general part, they are composed of sand. Some types of molds are made in such a manner that they will collapse after pouring. In such cases, relieving blocks, coke, straw rope, and the like are placed in the backing-up sand. These materials break up the continuity of the sand extending from the mold-metal interface to the exterior of the mold and thus change the thermal conductivity. Whether or not there would be a perceptible change in the velocity of solidification or the rate of skin formation has not been studied, but it is thought that it would be very small.

13. Changes in the solidification velocity may be obtained by the use of various mold materials, but unlike the ingot mold where the use of copper leads to a considerable increase in the velocity of solidification over the usual cast iron mold, the variation in sand molds would result in possibly little more than a perceptible change. This point will be taken up in detail in discussing the experimental data.

14. Other factors influencing the velocity of solidification are the shape and size of the mold. The characteristics of the mold determine the length of time it takes before solidification is complete. As the rate of cooling decreases, the time required for the steel to pass through the freezing range increases and the velocity of solidification is altered. The shape and size of the mold also governs, to a certain degree, the temperature gradient throughout the steel casting, for in small sections the chilling effect may bring about complete solidification, whereas in larger sections solidification will proceed for considerable periods after the chilling action has been exhausted.

Temperature of the Steel Above its Melting Point

15. The initial rate of skin formation is decreased by pouring casting with super-heated steel. This is explained by the fact that the excess heat must first be extracted from the super-heated steel before solidification can begin. The effect of super-heat on the solidification of ingots was studied experimentally by Matuschka (2) and calculated by Schwartz (7). The effect of super-heat on the solidification of steel in a sand mold is shown in Fig. 1. For comparison, the calculated curve by Schwartz of a steel ingot is reproduced. It will be noticed that the effect of super-heat on the velocity of solidification of steel is not as great in a sand mold as it is in a cast iron mold.

Physical Properties of Steel

16. R. Heggie (8) has pointed out that his experimental data on cooling curves indicated that a state of dynamic heat balance exists in a freezing mass. The data obtained by B. Matuschka on plain carbon and nickel-chrome steels corroborate this theory. The term "dynamic heat balance" is used to denote that the latent heat evolved in freezing at any particular moment is just sufficient to balance the heat removed at the surface of the mold. Many producers of steel casting assume that as steel solidifies it passes through a pasty or mushy state of low viscosity. Professor Andrews (9) in discussing this subject stated that when a determination of the freezing point of a steel was made, it was found that the greater mass of the steel became solid at a constant temperature, even though there were a rather wide difference between the liquidus and solidus. This showed that a greater portion of the steel became solid and that a very small amount of liquid remained.

17. In a discussion on the same subject, C. Desch (6a) stated that there is no evidence for the assumption that liquid steel becomes very viscous or passes into a pasty stage since the viscosities of molten metals are low, even close to the melting point. While there is no data as to the actual viscosity of molten steel, there is no reason to suppose that it differs in that respect from other metals, and common experience would suggest that steel is highly fluid. It thus differs from molten silicates, which are extraordinarily viscous when first melted and become fluid only at temperatures far above their melting point. That is explained by their degree of molecular association; but metals, including steel, are known, from the lowering of their freezing points and from other facts, to consist mainly of single atoms. Their viscosity should, therefore, be low.

18. The authors' experimental work corroborates the points brought forward by Professors Andrews and Desch. There is, in castings that have

been bled late in their solidification, porous steel adhering to the walls of the cavity. The presence of this condition is due to the slow transition from the liquid to the solid state and consists of an aggregate of crystal skeletons, continuous in the sense that the projections of adjacent skeletons touch one another or have grown together, but containing liquid steel in the interstices.

Temperature of the Mold

19. The rate of solidification of a metal in a mold depends to a certain extent upon the temperature of the mold prior to pouring. A. Schwartz has calculated that,for steel ingots poured into cast iron molds,heating the mold is equivalent to super-heating the steel. It is therefore evident that the rate of solidification is less in molds heated prior to pouring.

20. It has been assumed that with ordinary pouring conditions the temperature at the mold-metal interface immediately after pouring is 1100° - 1200°C (2012° - 2192°F) in a sand mold and 900° - 1000°C (1652° - 1832°F) in a cast iron ingot mold. In view of the difficulties of experimental determination, the steepness of the temperature gradient between the exterior of the casting and its axis has been largely a matter of surmise. Calculations have been made on ingots by N. Lightfoot (6c)(6d) and by S. Saito (10) which quite fully set out the temperature gradients that may be expected in an ingot. A study of the temperature gradient of a 9-inch sphere casting was made both as to the metal temperature gradient and the mold temperature gradient. These data are set forth in Fig. 2. In this study, a Pt and Pt-Rd thermocouple was placed at the center of the sphere, another at the mold-metal interface and a third on the radius of the sphere midway between the other two. The temperatures indicated by these thermocouples were all read on one millivoltmeter at intervals of 45 seconds. The temperature of the sand surrounding the sphere was also noted at several points. The data show that there is a difference of 350°F between the center of the sphere and the mold metal interface during the first 20 minutes of cooling of the casting. This variation in temperature decreases after solidification of the sphere is completed. The magnitude of the temperature gradient that exists within the metal is also pointed out by the data.

Crystallization

21. It is not the purpose of this report to enter into a discussion of the macro and micro structures of cast steel, the dentritic formation, or the zones of chill, columnar, and equiaxed structure, but it would seem advisable, however, to enumerate some of the phases of crystallization.

22. The first contact between molten steel and the mold wall will immediately cool down a surface layer of steel to such low temperatures that in accordance with the results of the well known investigations by Tammann and Miers numerous nuclei will be formed. How many nuclei will be formed in a given mass is evidently a problem in probability. Examination of sections of cast steel of the same composition and cast at the same time in similar molds will show that the number of crystals does not vary widely.

23. The distribution of the nuclei is not entirely a random one. The first nuclei, those that originate in contact with the walls of the mold,

are probably very numerous, but comparatively few of them grow to such a size as to penetrate far into the mass. The separation of the first crystals from the liquid undoubtedly occur under metastable conditions, the crystals which had already formed bringing about further crystallization by contact. As cooling proceeds, a stage is reached at which fresh nuclei appear spontaneously in the liquid preceding the advancing solid zone. Thus it is seen that the number and arrangement of the nuclei are responsible for the form and dimensions of the crystal grains, and going back one step further, the number and arrangement of the nuclei depend upon the temperature distribution in the casting.

24. The temperature distribution is defined at every point either (1) by the temperature gradient, indicative of the direction of the maximum heat flow, or (2) by the direction at right angles to this, that is, the isotherm which intersects this point.

METHODS USED IN TESTING

25. The methods used in obtaining the data are identical with those used in the study of the three-inch, six inch and nine-inch diameter spheres, as reported previously in the Naval Research Laboratory Reports Nos. M-1026 of 16 February 1934 and M 1108 of 2 January 1935.

26. The design of the castings used to obtain data on the progress of solidification must be simple so that the data can be reproduced with a fair degree of accuracy. The design chosen for the preliminary work on this problem was a six-inch diameter sphere with a two-inch diameter central downgate. This design is simple, is easily bled through the top gate and its thickness of six inches is not uncommon in large steel castings.

27. The pattern was molded in Downer sand, the properties of which in the dried state are:

Permeability	87 cc/min.
Compression strength	93.5 lbs./sq.in.
Shear strength	29.5 lbs./sq.in.
Tensile strength	2.9 lbs./sq.in.

28. A thin coating of an emulsified linseed oil mold wash was sprayed on the surface of the molds and the molds dried at 400°F for twenty hours. The temperature of the molds at pouring time was about 100°F. The steel was poured into the sphere through the down-gate until the down-gate was full. The time was noted at the moment the mold was full, a predetermined period of time was allowed to elapse and then the mold was turned over so that the steel that had not solidified could run out of the mold. The casting was then cooled, shaken out of the mold, and cut in half on the diameter perpendicular to the down-gate. The thickness of the skin was then measured, the accuracy of the measurements being about ± 1/64 of an inch. It was impossible to measure closer than this due to the irregularity of the inner surface.

29. The lower halves of the spheres were weighed and the weights reported on the entire sphere by doubling the weight obtained.

36. The effect of pouring temperature on the rate of solidification was shown by pouring several six-inch diameter and nine-inch diameter spheres at a comparatively high temperature (2940°F), holding the heat for some time and pouring the remaining spheres at a lower temperature (2620°F).

37. The influence of mold material on the rate of solidification was noted by pouring alternately spheres molded in the usual dried sand and spheres molded in a typical synthetic green sand.

38. A pattern was prepared in which three cylinders of two-inch diameter, four-inch diameter and six-inch diameter and three, three and three and one-half inches in height, respectively, were joined together. This casting was poured with the large end up and bled at various times so that the effect that the sections of different size had upon each other might be noted.

39. The readings of thickness of skin obtained at an interval of five seconds after pouring were as close to a zero time interval as could be obtained. It required this much time to move the ladle away and overturn the mold.

EXPERIMENTAL DATA

40. In the study of the rate of solidification by bleeding various sizes and spheres and parallelepipeds 388 determinations were made which established 38 points. These determinations were averaged and the data is presented in Table 1 and shown graphically in Figs. 3 and 4.

41. In order that a study could be made of the effect of the size of a casting on the rate of skin formation, a series of spheres of different diameters were bled at various time intervals. If the volume of the six-inch sphere is considered as unity, the volumes of the other spheres compare as follows:

9 inch sphere	382 cu.in.	3.44
6 " "	113 " "	1.00
4.5 " "	48 " "	0.43
3 " "	14 " "	0.12

42. It will be noticed that the volumes differ considerably and that the rate of skin formation apparently increases as the volume of the sphere decreases.

43. In the second phase of the investigation it was planned to study shapes that have the same volume for varying surface areas. The volume of the six-inch sphere was chosen as constant and parallelepipeds were selected giving the same volume with 35, 60, 110% greater surface area.

44. An explanation is necessary concerning these data. It was found that on taking linear measurements the sides of the parallelepipeds were thinner than the corresponding values obtained for the six-inch spheres, but that the corners were considerably thicker due to the well known "corner effect" of solidification. This variation in the thickness made it practically impossible for an average thickness to be obtained; thus it was calculated from the volume of steel solidified.

45. It can be seen from Fig. 4, where the calculated average linear thickness is plotted against time, that the greater the surface area the faster is the rate of skin formation. The differences obtained are, however, small and in the case of the parallelepiped with 35% greater surface area the increase in rate is nearly negligible. This is in line with the preliminary results as reported in an earlier paper of this series (11).

46. It should be noted, Table 2, that even though the linear rate of skin formation varies with the volume of the spheres and also to a slight degree with the surface area of solids with identical volumes, the velocity of solidification is a constant. That is, at any definite time after pouring the weight of steel solidified, or the volume of steel solidified, per square inch of mold surface is the same. These data are shown graphically in Fig. 5. Using this curve, it was possible to predict with a fair degree of accuracy the skin thickness and weight of a 4.5-inch diameter sphere bled 3.5 minutes after pouring.

47. It has been pointed out that there are three phases in the solidification of a casting: (1) almost instantaneous freezing, (2) very rapid freezing, and (3) very slow freezing. These transitions are shown in Fig. 6, where the rate of solidification in cubic inches per minute is plotted against time. It should be noted that the initial rate of solidification (due to chilling by the mold) is very high but decreases very rapidly to a second phase of solidification that is rapid but which in turn decreases to a very slow rate of freezing.

48. The number of measurements required to obtain sufficient data to determine the rate of skin formation on the various solids listed above necessitated numerous different heats of steel. As it was impossible to obtain steel of the same analysis each time, it was decided to vary the carbon, manganese, and silicon contents within the usually allowable limits of cast carbon steel in order to detect the influence of the composition on the rate of skin formation. It was found that the differences, if any, were all within the limit of error in measurement.

49. The difficulty of taking measurements of a high degree of accuracy should be appreciated for the inner surface of the bled casting varies from extreme unevenness in the case of castings poured at high temperatures to smooth inner surfaces in castings poured at low temperatures.

50. As each mold was poured a temperature reading was made with an optical pyrometer of the molten steel entering the mold. Thus a study at any one bleeding time consisted of a range of castings poured from high super-heat temperatures to low super-heat temperatures. All these values were averaged to give the point for a definite bleeding time. In this way a fair average was obtained.

51. The ideal situation of filling the mold instantly could not be attained, of course. Two things were done to overcome this. First, an attempt was made to pour the molds at the same pouring speed, and secondly, to take the measurements always on the horizontal diameter; in this manner the error due to the time required to pour the mold was at a minimum.

52. It has been stated that the variation in molding materials would result in little more than a perceptible change in the velocity of solidification. The extent of this variation was the object of a study wherein both dry and green sand molds were used. The molds (six-inch spheres) were poured alternately and all bled at a time interval of two minutes. The averages obtained were:

Mold type	Skin thickness inches	Weight lbs.
Green sand	0.75	18.8
Dry sand	0.74	18.3

53. The results are within the limit of error of measurement. The data tend to show that the rate of solidification is practically the same in either of the common types of green or dry sand. This might be expected as the rate of heat transference of these two sands is not appreciably different, Fig. 8, Fig. 9. The rate of heat transference in sands of different types can vary greatly, as is shown in Figs. 7 and 10. The Chamotte, a European molding material, has a very high rate of heat transference due primarily to the rapid heat transference by radiation through the large air spaces between the grains. The permeability of this molding material is 2,000 cc/min. or greater in the green state. The cement-bonded sand has unusually low heat conductivity due to its low permeability and the more or less refractory cement used as a bonding material. More detailed information on this subject appeared in an earlier publication (12).

54. It has been pointed out previously that the pouring temperature of each mold was taken with an optical pyrometer and that in this way a study of the effect of temperature on the rate of skin formation could be attained. A typical condition found is reported as follows:

Sphere	Bleeding Time Minutes	Thickness Inches	Weight Pounds	Internal Cavity Vol.-C.C.	Temp. Degrees F.
9 inch	6	1.35	67.2	2130	2940
9 inch	6	1.50	73.2	1850	2620
6 inch	3	1.01	21.4	615	2930
6 inch	3	1.07	22.4	525	2630

This type of data leads to the general curve, as shown in Fig. 1.

55. A further study of the effect of shape and size of molds on the rate of skin formation was made. These results, obtained by bleeding the mold composed of three cylinders, are shown in Fig. 11. The object of this experiment was to determine whether or not the linear rate of solidification of one cylinder would be changed by being connected to a larger cylinder. The volumes, surface areas, and ratio of surface area to volume of each cylinder are given below:

Cylinder	Volume	Area	Area Volume
2" dia. by 3"	9.42 cu.in.	21.98 sq.in.	2.20
4" " " 3"	37.68 " "	47.06 " "	1.25
6" " " 3 1/2"	98.94 " "	81.65 " "	0.82

56. It should be noted that even though the volume of each section is considerably different and the ratio of surface area to volume decreases rapidly, the castings that were bled at 5 seconds, 1 minute, and 2 minutes show no differences in linear solidification in the three sections. After 2 minutes this is no longer true, as the "corner effect", due to the heat being conducted away from one corner more rapidly than the other, has overshadowed the solidification perpendicular to the cylinder walls.

57. It should also be noted that even on the casting overturned as soon as possible after pouring (5 seconds) each small corner of sand at the base of the cylinders has been overheated so that the steel envelope is very thin at these points. Also, the center corners of the cylinder are already thicker than the walls of the cylinder. Both of these effects could have been minimized by increasing the radius of the corner.

CALCULATIONS

58. The solidification of ingots has been studied theoretically by Saito (10), Fields (4), Lightfoot (6c), (6d), and Schwartz (7). These investigators have calculated, among other things, the velocity of solidification in an ingot. In general, they have all arrived at somewhat the same formula, which tends to show that the velocity of solidification is a parabolic function.

59. Saito used a very complicated formula in his calculations and obtained some very good results, which were excellently substantiated by Heggie (8), with studies on the solidification of steric acid. Field's formula gives the solidification thickness as:

$$D = K \sqrt{t} \quad ; \text{with } K = 0.88$$

Where D is the total distance through which solidification has progress in time t, and K is a constant of solidification.

60. The formula used by Lightfoot was the same as that of Fields except for the value of K,

$$D = K \sqrt{t} \quad ; \text{where } K = 0.34.$$

61. A slight difference is recorded by Schwartz, who gives the following formula:

$$D = 1/2 \frac{q}{\sqrt{t}}$$

where q is a constant of solidification.

62. After performing a series of experiments on the bleeding of ingots, Nelson (5) attempted to fit his data to the formula developed by Fields and found that the data corresponded very well in the early stages of solidification, but that as solidification proceeded his data deviated further from the theoretical curve.

63. Just how the theoretical data would compare with the experimental data obtained in the study of steel cast into sand molds was of interest. The manifested differences of the two methods would undoubtedly result in a modi-

fied value for K, the solidification constant.

64. Several attempts were made to fit the general curve $D = K \sqrt{t}$ to the experimental data. It was found, however, that this equation could be used successfully only on the lower portion of the curve. The data appear to fall upon a hyperbolic rather than a parabolic curve, but a fairly good fit can be obtained using the general equation $D = K_1 t^{.4} + K_2 t$ where K_1 and K_2 are constants, depending upon the shape of the mold, etc. The equations that were found to represent the cases studied with a fair degree of accuracy are shown graphically in Figs. 12, 13, 14, and given below.

9-inch sphere - $D = .342 t^{.4} + .125t$
6 " " - $D = .346 t^{.4} + .172t$
3 " " - $D = .309 t^{.4} + .428t$

65. It should be noted that the constant of first term of the equation which controls the lower portion of the curve, and therefore indicates the chilling action of the sand, is practically the same in each case. The constant of the second term of the equation which controls the upper, straighter portion of the curve, and therefore represents the solidification due to the heat conducted away by the mold, decreases as the volume of the casting increases.

66. Previous investigators have attempted to obtain theoretically an equation that would represent the rate of skin formation with respect to time. The authors believe that although it is possible to obtain a general equation to represent this phenomenon, the constants used will vary for each particular case studied. They also believe that the velocity of solidification, that is, the volume of steel solidified per square inch of mold area, is practically constant under ordinary working conditions. Therefore, further study of this phenomenon should result in information very useful to both the foundryman and the designer in the planning of future castings.

CONCLUSIONS

67. The following conclusions are presented:

(a) The rate of skin formation increases as the volume of the steel casting decreases.

(b) The greater the surface area of a steel casting, the faster is the rate of skin formation.

(c) The velocity of solidification is a constant; that is, at any definite time after pouring the volume of steel solidified per square inch of mold surface is the same.

(d) Variations in the ordinarily used molding materials results in little more than a perceptible change in the velocity of solidification.

(e) The degree of super-heat modifies the rate at which the skin forms.

(f) Calculations of the rate of skin formation can be made and predicated in various sizes of sphere castings.

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TABLE 1.

Thickness of Skin Formation in Inches

Time	3" dia.	4.5" dia.	6" dia.	9" dia.	3-5/8"x 3-5/8"x 8"	2-1/4"x 6-1/4"x 8"	1-25/64"x 10-5/32"x 8"
5 sec.	0.15	–	0.14	0.14	0.13	0.14	0.15
30 "	0.45	0.40	0.37	–	0.35	0.38	0.41
45 "	–	–	–	–	–	–	0.50
1 min.	0.75	0.54	0.50	0.48	0.49	0.53	0.57
1-1/2		0.67	–	–	–	0.64	
2 min.			0.76	–	0.76	0.82	
3 "		1.55 at 3-1/2 min.	1.00	0.90	1.04		
4 "			1.29	–	1.40		
5 "			1.54	–			
6 "			1.80	1.34			
9 "				1.93			
12 "				2.48			
15 "				3.00			

TABLE 2.

Volume of Steel Solidified per Square Inch of Surface Area.

	3"dia.sphere		4.5"dia.sphere		6"dia.sphere		9"dia.sphere		3-5/8" x 3-5/8"x8-5/8" Parallelepiped		2-1/4" x 6-1/4" x 8" Parallelepiped		1-25/64" x 10-5/32" x 8" Parallelepiped			
Time	Lbs.Steel Solidified	Lbs./sq.in. of surface area	Lbs.Steel Solidified	Lbs./sq.in. of surface area	Lbs.Steel Solidified	Lbs./sq.in. of surface area	Lbs. Steel Solidified	Lbs./sq.in. of surface area	Lbs.Steel Solidified	Lbs./sq.in. of surface area	Lbs. Steel Solidified	Lbs./sq.in. of surface area	Lbs.Steel Solidified	Lbs./sq.in. of surface area	Avg.Lbs./sq.in. of surface area	Cu.in.solidified /sq.in. of surface area
5 sec.	1.0	.037	-	-	4.2	.038	9.8	.038	5.7	.038	6.2	.038	8.6	.038	.038	.134
30 "	2.6	.093	6.0	.094	10.4	.092	-	-	14.1	.093	15.3	.092	21.1	.094	.093	.329
1 min.	3.5	.123	7.7	.121	13.4	.119	31.1	.122	18.3	.122	19.8	.121	27.6	.123	.121	.427
1-1/2"			8.8	.138	-	-	-	-	-		22.6	.137			.138	.488
2 "					18.5	.164	-	-	24.8	.163	26.9	.165			.164	.579
3 "					22.5	.199	52.7	.207	30.9	.204					.204	.721
4 "					26.1	.228	-	-	34.8	.232					.230	.813
5 "					27.3	.243	-	-							.243	.859
6 "					30.0	.265	70.6	.277							.271	.957
9 "							87.9	.354							.354	1.251
12 "							99.6	.391							.391	1.382
15 "							104.0	.408							.408	1.442

TABLE 3.

2-1/4 x 6-1/4 x 8 inch Parallelepipeds bled at 4.0 seconds.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Pouring Speed Sec.	Bleeding Time Sec.	Temp. °F
123	C 0.32	0.14	6.2	0:00	9	3.5	2900
123	Mn 0.83	0.14	"	1:30	10	3.5	2860
"	Si 0.46	0.13	"	2:45	6	3.0	2845
"		0.14	"	3:50	8	4.0	2800
"		0.14	"	5:50	5	3.5	2760
"		0.14	"	6:40	3	3.5	2650
Average		0.14	6.2				
1-25/64 x 10-5/32 x 8 inch Parallelepipeds							
123	C 0.32	0.13	8.6	0:40	4	3.5	2890
"	Mn 0.83	0.13	"	2:15	5	4.0	2855
"	Si 0.46	0.15	"	3:30	8	3.5	2830
"		0.15	"	4:30	6.5	3.0	2790
"		0.14	"	5:30	5.5	3.5	2775
Average		0.14	8.6				

TABLE 4.

2-1/4 x 6-1/4 x 8 inch Parallelepipeds bled at 1/2 minute.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Pouring Speed Sec.	Temp. °F
127	C 0.20	0.32	15.5	0:46	6-9 sec.	2860
"	Mn 0.70	0.34	15.0	1:52	"	2820
"	Si 0.20	0.34	14.9	2:18	"	2790
"		0.35	15.5	3:15	"	2730
"		0.34	15.4	3:42	"	2680
Average		0.338	15.3			

1-25/64 x 10-5/32 x 8 inch Parallelepipeds

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Pouring Speed Sec.	Temp. °F
127	C 0.20	0.30	20.5	0:30	6-9 sec.	2870
"	Mn 0.70	0.32	21.0	0:58	"	2850
"	Si 0.20	0.35	21.7	2:05	"	2800
"		0.35	21.4	3:02	"	2740
"		0.35	20.9	3:26	"	2710
Average		0.334	21.1			

TABLE 5.

1-25/64 x 10-5/32 x 8 inch Parallelepipeds bled after 3/4 minute.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Bleeding Time Sec.	Temp. °F
136	C 0.35	0.40	24.8	2:10	6-9	2880
"	Mn 0.74	0.41	23.8	3:10	"	2870
"	Si 0.27	0.41	24.9	3:25	"	2860
"		0.40	25.7	3:40	"	2850
Average		0.405	24.8			

TABLE 6.

2-1/4 x 6-1/4 x 8 inch Parallelepipeds bled at 1 minute.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Pouring Speed Sec.	Temp °F
132	C 0.20	0.46	20.2	0:00	6-9	2880
"	Mn 0.55	0.45	19.8	0:30	"	2870
"	Si 0.31	0.45	19.4	0:50	"	2860
"		0.44	19.0	1:11	"	2850
"		0.48	20.8	1:30	"	2850
Average		0.455	19.8			
1-25/64 x 10-5/32 x 8 inch Parallelpipeds						
136	C 0.35	0.46	28.5	1:10	6-9	2920
"	Mn 0.74	0.48	26.7	1:27	"	2910
"	Si 0.27	0.46	27.0	1:47	"	2900
"		0.49	27.8	4:42	"	2830
"		0.49	28.1	4:57	"	2820
"		0.49	27.4	5:13	"	2810
Average		0.48	27.6			

TABLE 7.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec	Temp °F.
130	C 0.44	0.57	22.4	0:00	2890
"	Mn 1.04	0.56	22.4	0:17	2870
"	Si 0.50	0.57	23.0	0:40	2860
"	S 0.02	0.58	22.4	0:58	2850
"	Phos 0.02	0.57	23.2	1:21	2830
"		0.57	22.2	1:57	2830
Average		0.57	22.6		

TABLE 8.

2-1/4 x 6-1/4 x 8 inch Parallelepipeds bled at 2 min.

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Temp. °F
134	C 0.35	0.66	26.8	1:05	2880
"	Mn 0.65	0.66	26.0	1:20	2860
"	Si 0.44	0.69	26.8	1:34	2850
"		0.70	26.3	1:47	2830
"		0.69	27.3	2:00	2810
"		0.74	27.8	5:40	2680
"		0.73	27.3	5:55	2670
Average		0.696	26.9		

TABLE 9.

6-inch Spheres Bled after 2 min.*

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Mold	Temp. °F
142	C 0.24	0.75	18.4	0	dry sand	2900
"	Mn 0.74	0.71	18.8	0:38	"	2875
"	Si 0.34	0.72	19.0	1:11	"	2850
"		0.75	19.5	3:40	"	2800
"		0.79	18.7	4:10	"	2785
"		0.73	19.2	4:32	"	2760
Average		0.74	19.0			
142	C 0.24	0.74	19.3	0:20	green sand	2890
"	Mn 0.74	0.75	17.8	0:56	"	2860
"	Si 0.34	0.74	18.1	1:25	"	2840
"		0.75	17.2	3:54	"	2800
"		0.78	18.0	4:21	"	2770
"		0.75	17.5	4:44	"	2750
Average		0.75	18.5			
*Grand Average		0.76	18.5			

*This data, when averaged with that previously obtained on 6-inch spheres bled at 2 minutes (See Table 4, Report M-1026, 16 Feb. 1934), gives the above grand average.

TABLE 10.

6-inch Spheres Bled after 5 Minutes

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Temp. °F
98	C 0.32	1.51	27.5	0:00	2930
"	Mn 0.64	1.53	27.3	2:52	2835
"	Si 0.36	1.55	27.4	3:22	2805
"		1.59	27.0	4:43	2760
101	C 0.45	1.55	-	0:00	2890
"	Mn 0.50	1.53	-	0:36	2870
"		1.51	-	3:06	2830
"		1.50	-	3:37	2800
"		1.58	-	4:41	2780
Average		1.54	27.3		

TABLE 11.

6-inch Spheres Bled after 6 Minutes

Heat No.	Analysis	Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Temp. °F
98	C 0.32	1.77	-	0:47	2900
"	Si 0.64	1.83	30.0	5:00	2750
101	C 0.45	1.76	-	0:19	2880
"	Mn 0.50	1.80	-	0:59	2865
"		1.84	-	3:54	2780
"		1.82	-	4:27	2745
Average		1.80	30.0		

TABLE 12.

4-1/2-inch Spheres Bled at 1/2, 1, 1-1/2, 3-1/2 Minutes.

Heat No.	Analysis		Thickness Inches	Weight Lbs.	Lapsed Time Min:Sec.	Temp. °F
Bled at 1/2 min.			0.39	5.6	0:00	2910
144	C	0.34	0.31	6.3	0:21	2905
"	Mn	0.78	0.49	6.5	3:44	2760
"			0.41	5.6	4:01	2750
Average			0.40	6.0		
Bled at 1 min.						
144	C	0.34	0.53	8.0	1:08	2840
"	Mn	0.78	0.52	7.3	1:26	2820
"			0.52	8.0	4:54	2730
"			0.55	7.5	5:09	2720
Average			0.54	7.7		
Bled at 1-1/2 min.						
144	C	0.34	0.65	8.4	1:42	2810
"	Mn	0.78	0.67	8.6	1:58	2800
"			0.68	9.1	5.23	2700
"			0.68	9.1	5.37	2690
Average			0.67	8.8		
Bled at 3-1/2 min.						
146	C	0.35	1.51	13.1	1:24	2840
"	Mn	0.70	1.55	--	1:57	2820
"			1.59	--	2:13	2800
Average			1.55	13.1		

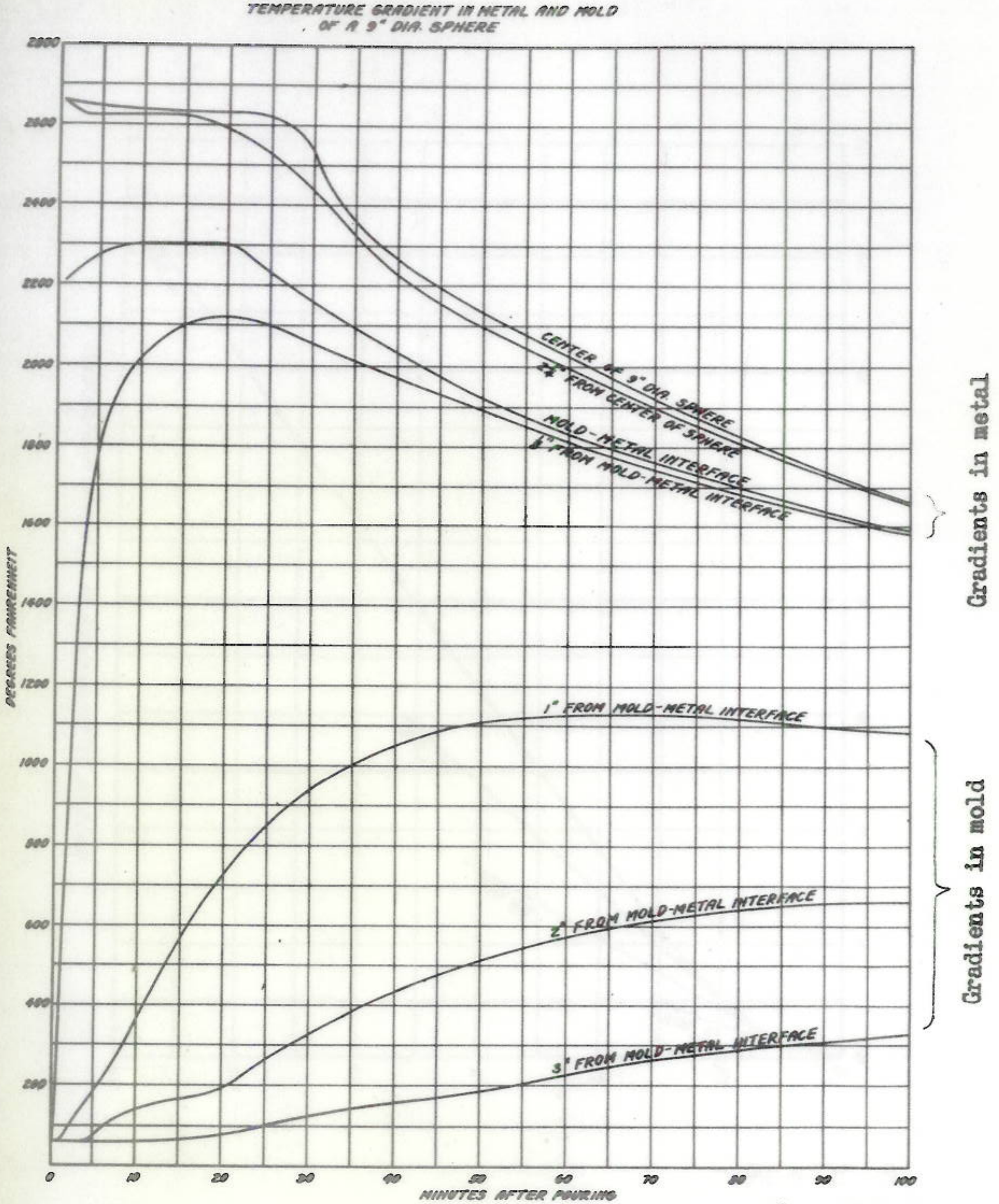

TEMPERATURE GRADIENT IN METAL AND MOLD
OF A 9" DIA. SPHERE
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
DEGREES FAHRENHEIT
0
10
20
30
40
50
60
70
80
90
100
MINUTES AFTER POURING
CENTER OF 9" DIA. SPHERE
2¼" FROM CENTER OF SPHERE
MOLD-METAL INTERFACE
½" FROM MOLD-METAL INTERFACE
1" FROM MOLD-METAL INTERFACE
2" FROM MOLD-METAL INTERFACE
3" FROM MOLD-METAL INTERFACE
Gradients in metal
Gradients in mold

PLATE 2

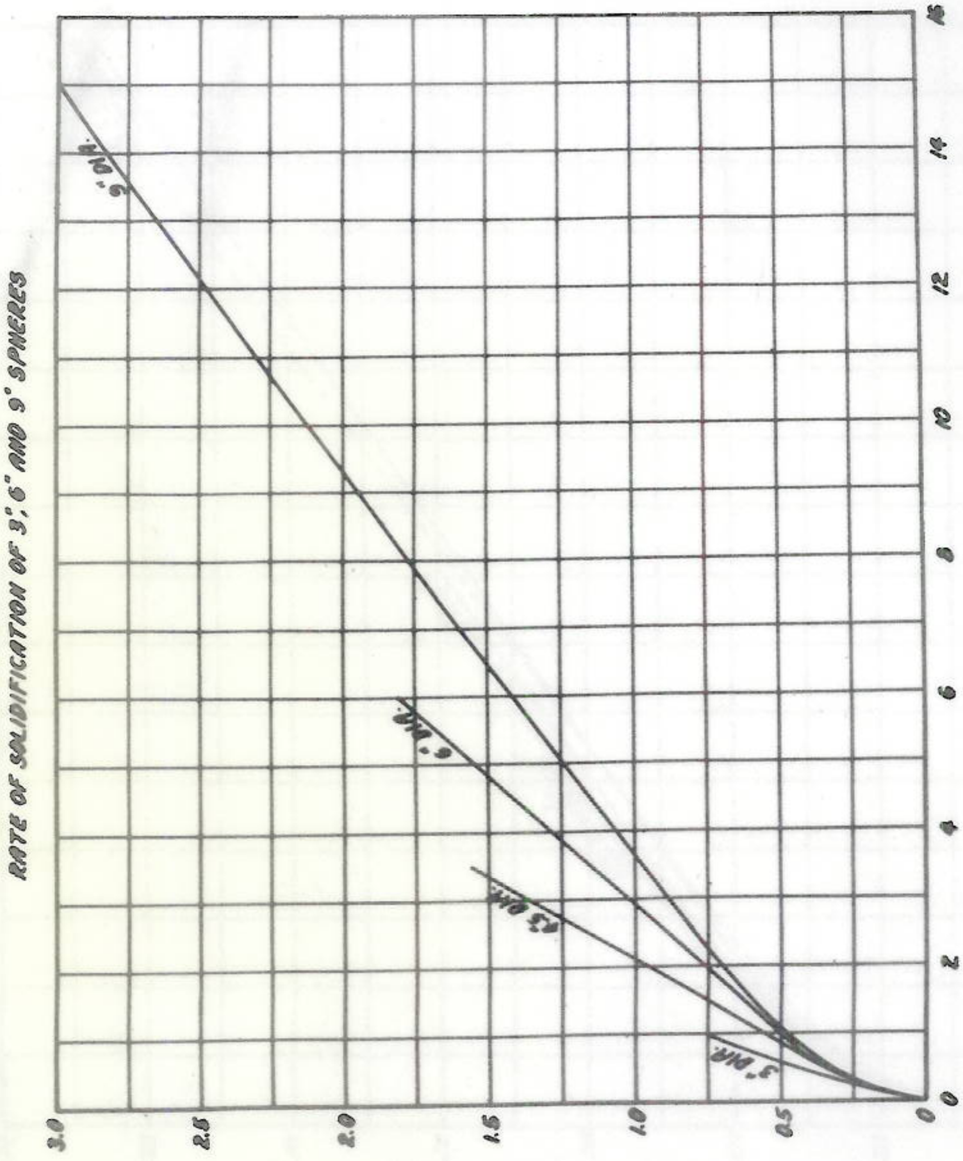

RATE OF SOLIDIFICATION OF 3", 6" AND 9" SPHERES
9" DIA.
6" DIA.
4.5" DIA.
3" DIA.
0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8
10
12
14
16

PLATE 3

RATE OF SOLIDIFICATION OF STEEL
IN DRIED DOWNER SAND MOLDS

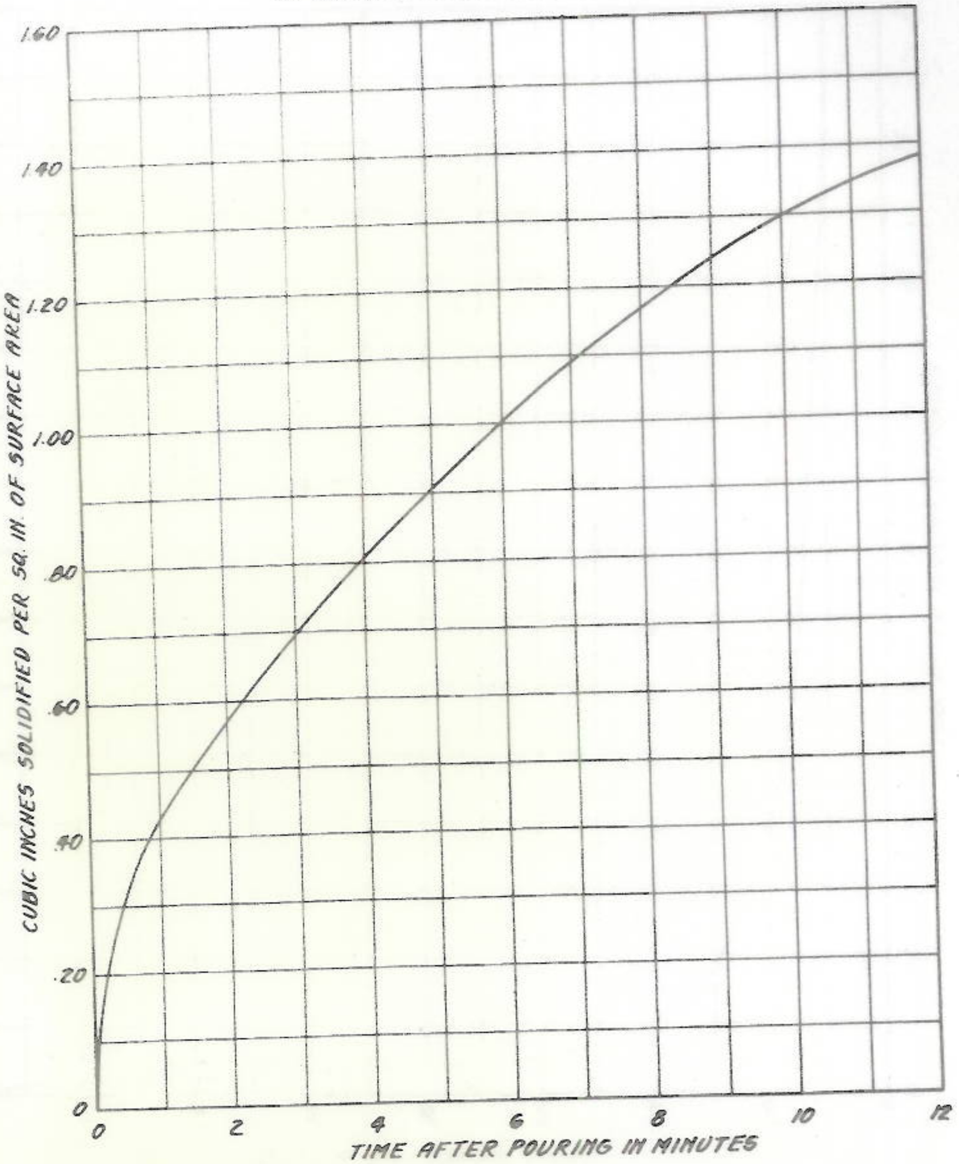


PLATE 5

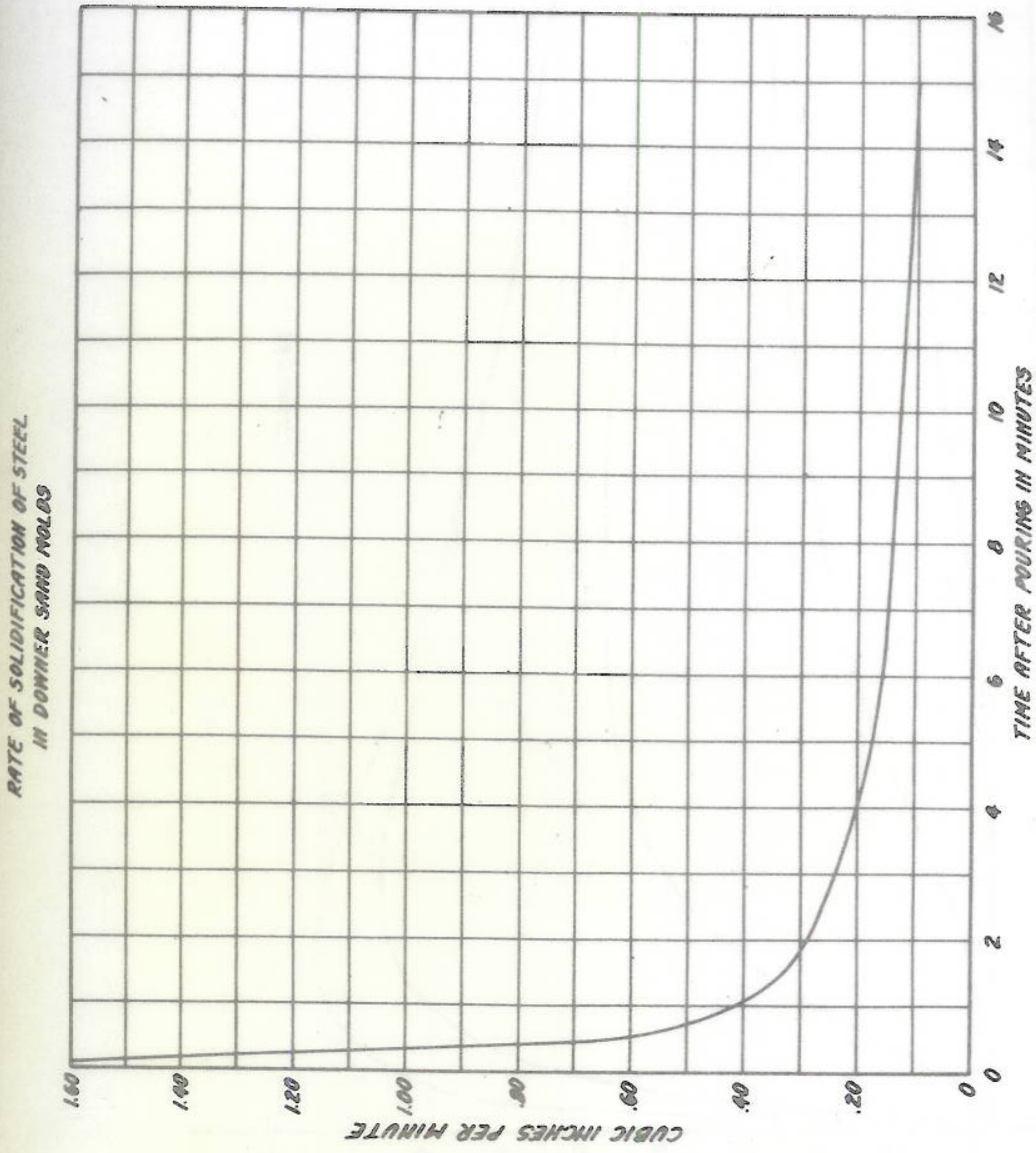

RATE OF SOLIDIFICATION OF STEEL
IN DOWNER SAND MOLDS
CUBIC INCHES PER MINUTE
1.60
1.40
1.20
1.00
.80
.60
.40
.20
0
TIME AFTER POURING IN MINUTES
0
2
4
6
8
10
12
14
16

PLATE 6

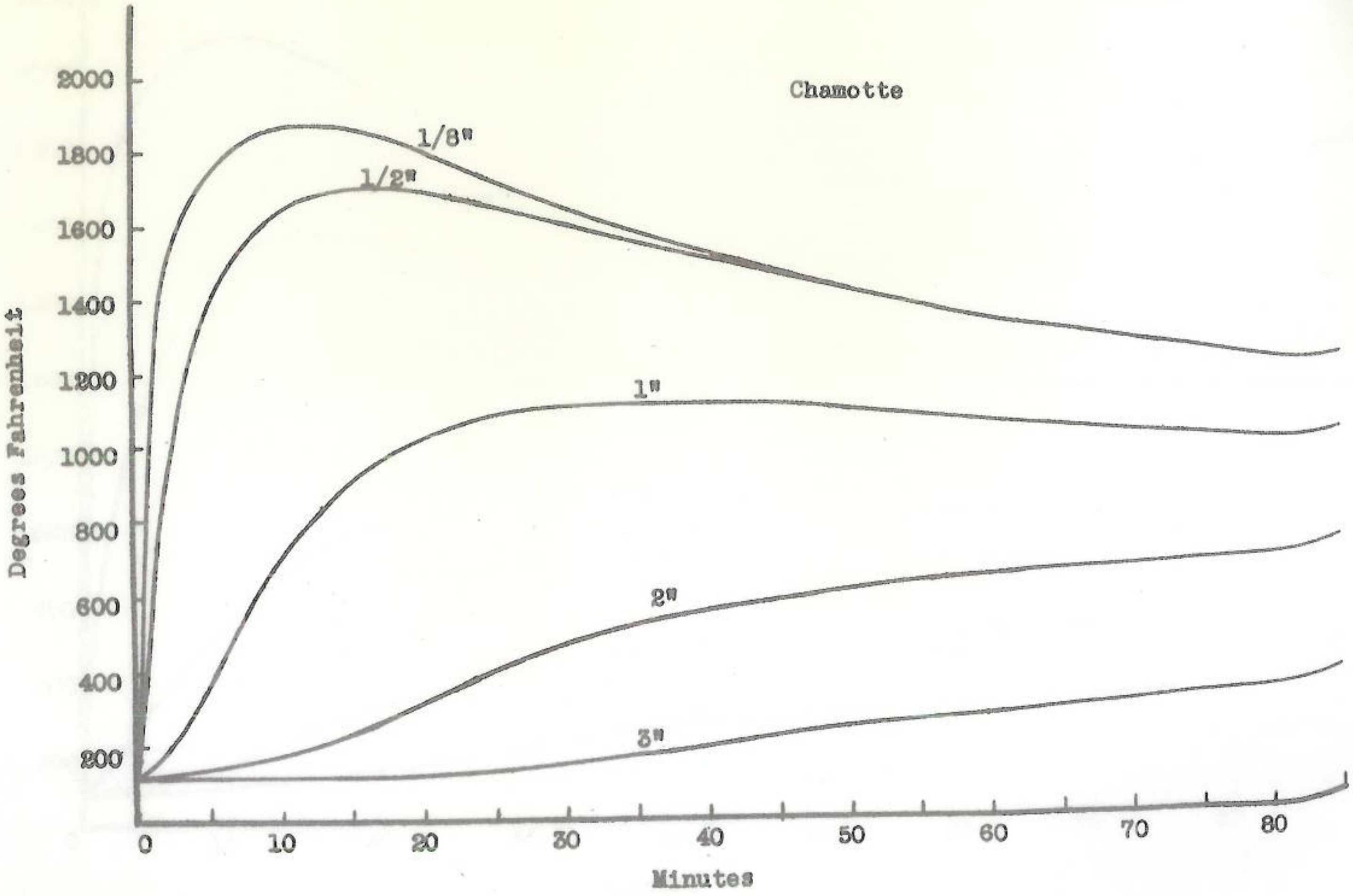

Chamotte
1/8"
1/2"
1"
2"
3"
Degrees Fahrenheit
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
Minutes

PLATE 7

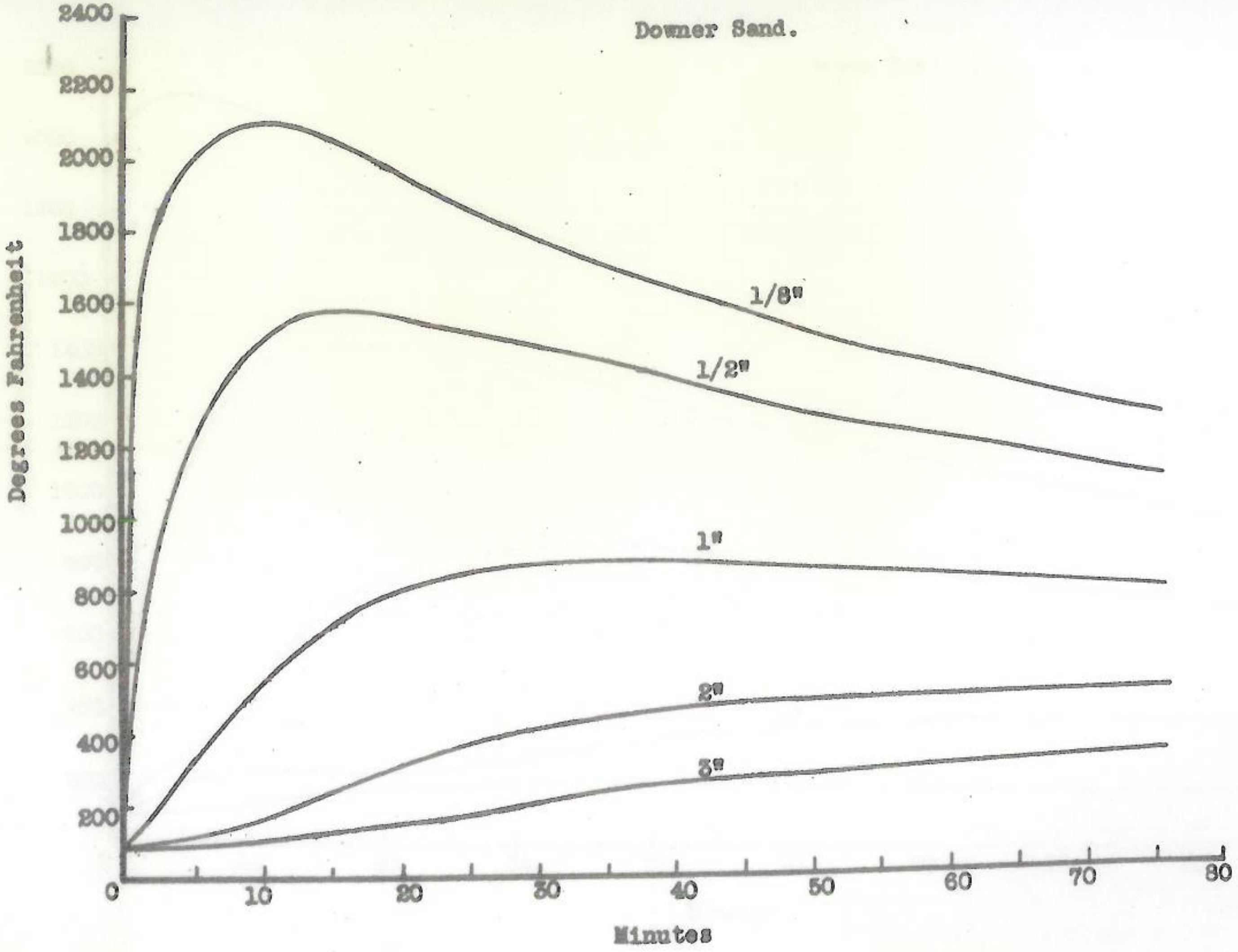

Downer Sand.
Degrees Fahrenheit
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
Minutes
1/8"
1/2"
1"
2"
3"

PLATE 8

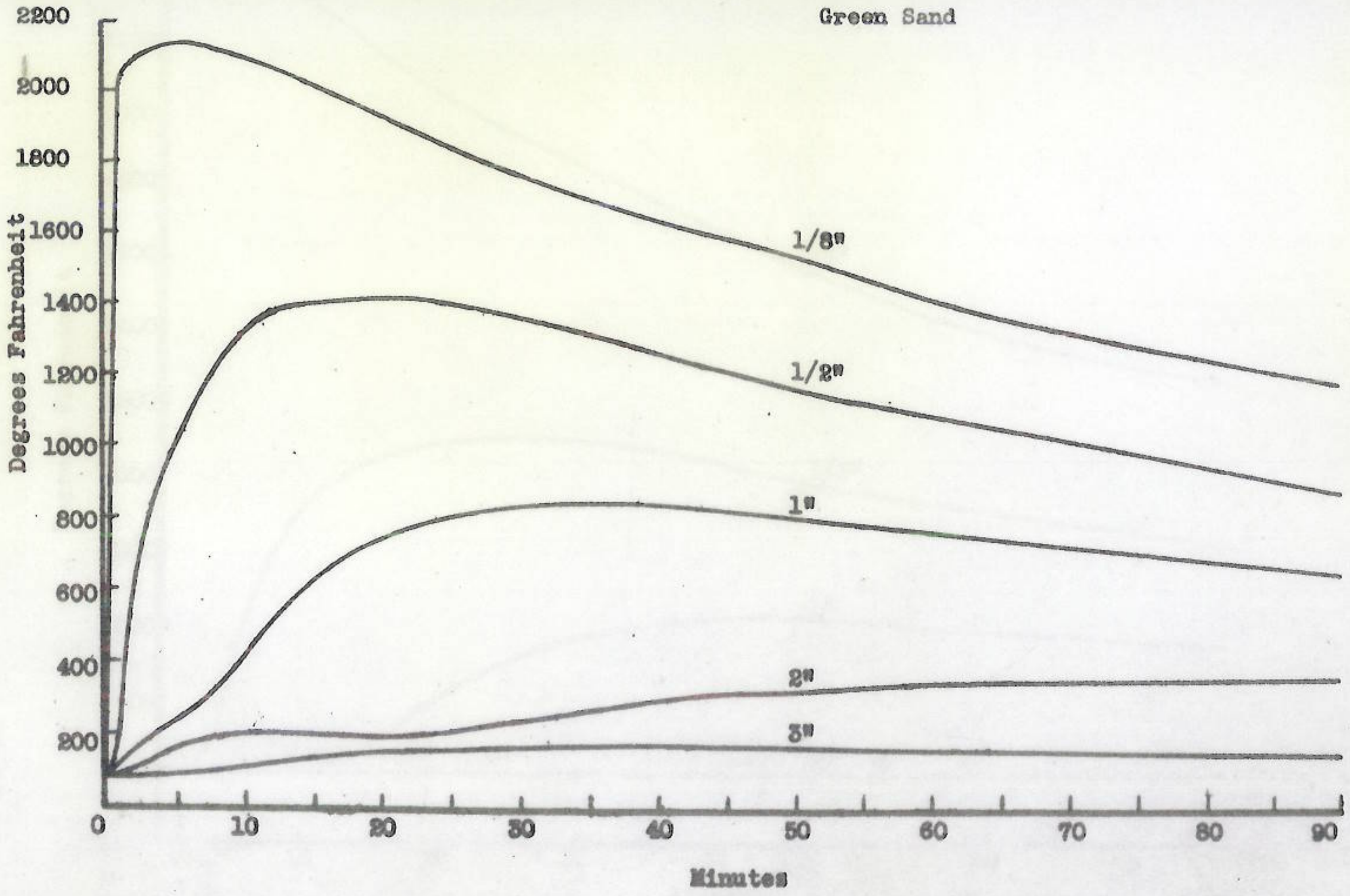

Green Sand
Degrees Fahrenheit
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
90
Minutes
1/8"
1/2"
1"
2"
3"

PLATE 9

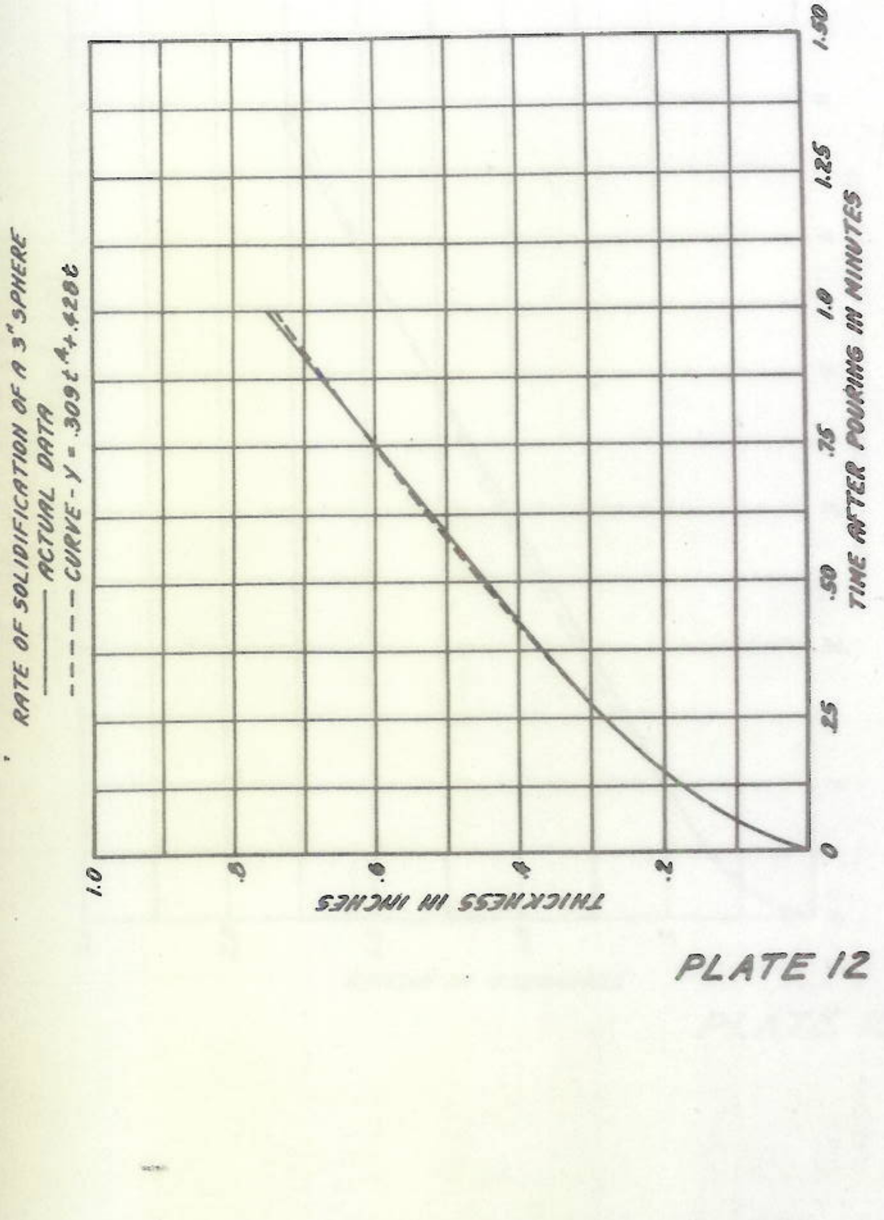
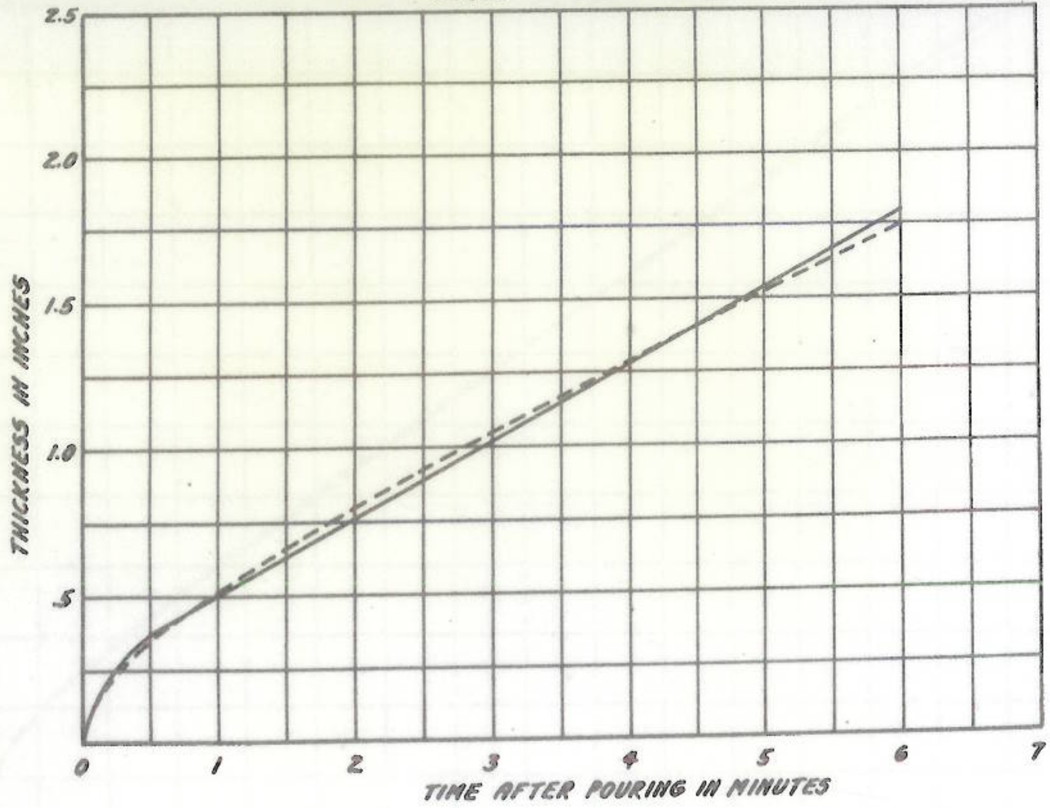

RATE OF SOLIDIFICATION OF A 3" SPHERE
——— ACTUAL DATA
- - - - CURVE - $y = .309t^{.4} + .428t$
THICKNESS IN INCHES
1.0
.8
.6
.4
.2
TIME AFTER POURING IN MINUTES
0
.25
.50
.75
1.0
1.25
1.50

PLATE 12

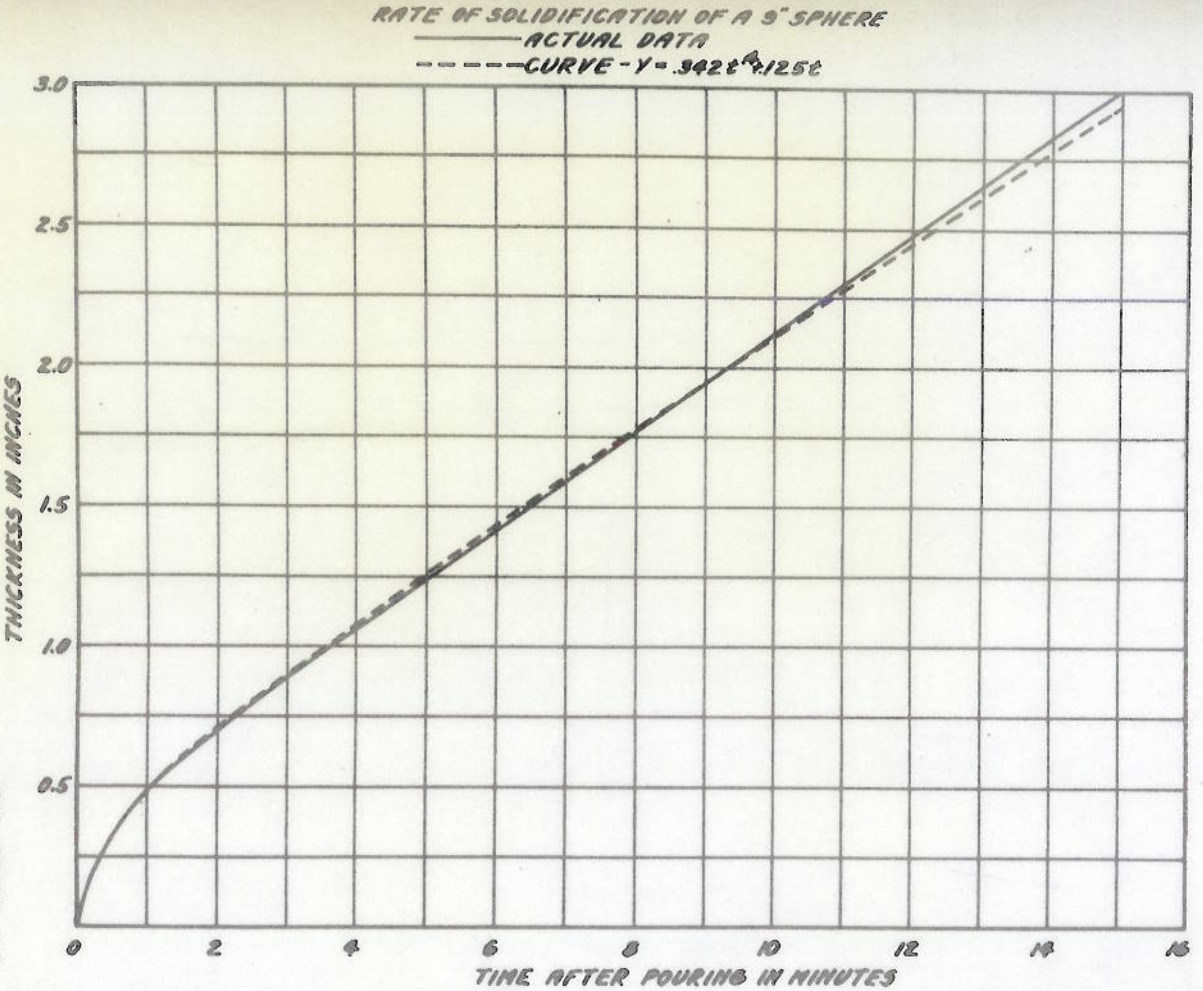


RATE OF SOLIDIFICATION OF A 6" SPHERE

——— ACTUAL DATA

- - - - - CURVE – $Y = .346t^{.4} + .172t$

PLATE 13



RATE OF SOLIDIFICATION OF A 9" SPHERE

PLATE 14

Plate 11

Rate of Skin Formation in Joined Cylinders.