16 February 1934 Report No. M-1026

NAVY DEPARTMENT

BUREAU OF ENGINEERING

REPORT ON

Solidification Studies
(Part of Steel Casting Research Problem).

NAVAL RESEARCH LABORATORY
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WASHINGTON, D.C.

Number of Pages: Text - 5 Tables - 10 Plates - 3.

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

Date of Tests: January 1932 through January 1934.

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Distribution:
Bu.Eng. (10)
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Bu.Ord. (1)

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APPENDICES

AUTHORIZATION

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

OBJECT

2. The object of this report is to present the data obtained from a study made on the first phase of solidification and rates of skin formation in steel castings. In this phase data are presented on the solidification of a 6 inch sphere and a parallelepiped of corresponding volume but of a 50% greater surface area.

METHODS USED IN TESTING

3. Determinations of the rates at which solidification proceeds in steel castings was thought to be of utmost importance, especially if problems in design were to be considered.

The design of the casting used to obtain such data must satisfy several conditions: (1) the design must be simple so that the data obtained can be reproduced with a fair degree of accuracy; (2) the cross-section of the casting should be such that when the casting is poured, conditions similar to those present in the production of a large casting will be obtained; and (3) the casting must be designed so that it can be easily bled at predetermined times and the formation of the skin thus stopped.

The design chosen for the preliminary work on the problem was a six-inch sphere with a two-inch central down-gate. This design is simple, is easily bled through the top gate, and its thickness of six inches is not uncommon in large steel castings.

The procedure used for the first experiments is given below in detail.

(1) The pattern was molded in standard Downer steel molding sand. A thin coat of an emulsified linseed oil mold wash was sprayed on the surface of the mold and the mold dried at 400° F. for twenty hours. The temperature of the molds at pouring time was about 100° F. The properties of the sand used 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	2.87 lbs/sq.in.

(2) The steel was poured into the sphere through the down-gate that led directly into the top of the sphere. The mold was filled to the top of the down-gate.

(3) The time was noted at the moment the mold was completely filled with steel.

(4) A predetermined time was allowed to elapse and then the mold

was turned upside down allowing the steel that had not solidified to run out of the gate. This operation has been designated bleeding the mold.

(5) The casting was then allowed to cool to room temperature, shaken out of the mold and cut in half, on the diameter at right angles to the pouring gate, on a power saw.

(6) The skin thickness was measured. The accuracy of these measurements was about + 1/64 of an inch. It was impossible to measure closer than this due to the formation of large dendrites on the inner surface of the sphere.

After the initial trials on the six-inch sphere had been carried out, it was recognized that further data would be useful in order that an attempt could be made to correlate the rate of skin formation of solids with identical volumes but varying surface areas. Therefore, several parallelepipeds were designed with the same volume as the six inch sphere but with surface areas 50, 100 and 150% greater than that of the sphere.

In considering the volume of the sphere it was assumed that the total volume of the sphere is active even though a small portion of the sphere does lie within the pouring gate. The metal in the gate probably affects the skin formation of the entire sphere to some extent, but the effect is most marked at the junction of the gate and sphere. This effect is not considered to be of great importance since no measurements are taken near the junction of the gate and the sphere.

The surface area of the sphere was considered to be only the 100 sq.in. exposed to the sand rather than the total surface area (113 sq.in.) of a six-inch sphere. The volume, however, was taken as 113 cu.in. or the total volume of the sphere and not the volume of the sphere minus the portion under the four-inch head.

A parallelepiped 3-5/8" x 3-5/8" x 8-41/64" has the same volume as the six-inch sphere and has a surface area 50% greater than that of the sphere. Other patterns were designed but no data concerning them is presented in this report as a complete study could not be undertaken until the results were obtained on the six-inch sphere and the 3-5/8" x 3-5/8" x 8-41/64" parallelepiped.

About sixty-five determinations were made in the preliminary stages of this study. During this time the procedure was changed as follows:

(1) The pouring gate was increased from two inches to four inches as it was found that the two-inch gate would freeze over before the desired time intervals prior to bleeding had elapsed.

(2) It was found that even after increasing the gate diameter from two to four inches, it was difficult to keep the gate open. Experiments were conducted using thermit on the gate and comparing the thicknesses of such castings with other castings where no thermit was used. The data showed that there were no differences.

(3) The use of thermit was later discarded, however, for the more favorable method of filling the pouring top to a certain level with molten steel. A spillway of a definite depth is cut in the pouring top and the pouring of the casting is continued until the

steel runs out of the spillway. When it is time to bleed the casting the mold is turned over, the pouring top breaks off and the steel remaining in the fluid state runs out.

(4) Studies were first made on spheres and parallelepipeds separately but a lack of correlation between the results made it necessary to cast them from the same heat.

(5) The plan of study called for bleeding the castings at 0, 1, 2, 3 and 4 minutes. Thus at the stated times and in the order named a sphere and a parallelepiped were bled. After several attempts to make the results of several heats correlate and attempts to get some sort of a ratio between times this method of testing was abandoned as the data did not lend itself to correlation.

(6) It was decided to reverse the bleeding times. In that manner the molds to be bled in 4 minutes were poured first, and so on. The result was that all the molds were bled at about the same time. The operation of bleeding was handled nicely but the results obtained did not lend themselves to correlation any better than those that had been obtained in the previous plan of study.

(7) The previous experiments showed that the only plan remaining was to make an entire heat of castings that were all to be bled at the same time interval. This proved to be the correct solution.

The procedure used in collecting the data appearing in this report is as follows:

(1) The use of dry sand molds.

(2) Pouring through a 4 inch down-gate.

(3) Filling the pouring top to a definite level.

(4) Devoting a single heat to a definite bleeding time.

(5) Recording the pouring temperature of each mold with an optical pyrometer.

(6) Obtaining the fluidity of the steel at various intervals during the pouring of a heat.

To make the data complete the temperature at which the molds were poured and the fluidity of the steel poured were recorded. It is believed that the optical temperature readings are fairly accurate, or at least comparable, as all readings were taken with the same instrument by one observer.

The fluidity of the steel was obtained by using a modification of the Bureau of Standards' fluidity mold. This mold is described in detail by C.M. Saeger, Jr., and A.I. Krynitsky in the Transactions of the American Foundrymen's Association (1932) Vol. 40, p.125. The modification made at the Laboratory consisted of increasing the diameter of the smaller end of the horn gate from 1/4 to 1/2 inch.

The fluidity molds were prepared of green sand a few hours prior to pouring. These molds are poured from a teapot ladle and a slow pouring speed was maintained. The results obtained with this mold are not as accurate as is desired and too much stress should not be given to the fluidity data collected.

A temperature study of a six-inch sphere was made wherein a Pt and Pt-Rd thermocouple registered the metal temperature. This thermocouple was protected by a small quartz tube. The hot junction was placed at the center of the sphere. Other thermocouples registered the temperature of the sand at distances of 1/8 inch and 1 inch from the mold-metal interface.

DISCUSSION OF RESULTS

4. The data obtained in the temperature study of the six-inch sphere are shown graphically on Plate 1. It will be noted that, according to these temperature readings, the sphere has solidified completely in about nine minutes.

The data obtained by bleeding the castings at 0, 1/2, 1, 2, 3 and 4 minutes after pouring are given in Tables 1, 2, 3, 4 and 5. The averages of these readings are summarized in Table 6 and plotted on Plates 2 and 3. The lapsed time shown in these tables is the time between the pouring of the first parallelepiped or sphere in the heat and the pouring of the remainder of the molds.

The bleeding time of zero minutes refers to turning over a mold as soon as the pouring is completed. That is, the skin formed is the result of only filling the mold.

The weights taken on the spheres and parallelepipeds are accurate to only ± 5%. The graphical presentation of the data on Plate 3 indicates the general trend of solidification.

The rate of skin formation, linearly, is a straight line function except for the first one-half minute where it appears that the chilling of the mold was responsible for a faster rate. It is also evident that an increase of 50% in the surface area does not cause a very pronounced change in the linear rate of skin formation.

It should be noted that although the increase in surface area does not cause an increase in the linear rate of skin formation, the actual weight of steel solidified is greater in the parallelepiped than in the sphere by an amount roughly proportional to the increase in area.

It will be noticed that in obtaining the averages used in preparing the curves, no regard was given to the composition of the steel, the actual fluidity data as measured by the fluidity mold, or the temperature of the steel as poured. The right to disregard this data in compiling the averages is based on other evidence furnished by the data. For example, a study of Table 8 shows a variation in the carbon content whereas the skin thickness remains practically constant. The fluidity and temperature readings in this set are very uniform. It would appear, therefore, that the chemical analyses (the usual constituents analyzed for in plain carbon steel) are of insufficient importance to bring about a major change in the rate of skin formation. This point is substantiated further by data obtained at other bleeding times such as at one minute in heats 78 and 86, etc.

Temperature data are of importance in that they show the pouring range over which the data was collected. Other than that it does not appear to be significant as it is impossible to correlate temperature with the fluidity data obtained. Nor does a drop in temperature necessarily mean an increase in skin thickness. In some cases the rate of increase in thickness with temperature drop is very pronounced while in others it is not apparent. This can be noted in Table 9, and by reviewing Table 8. In these cases the fluidity is also uniform.

It would thus appear that even though temperature variations are noted, an average of the thickness data can rightfully be made without taking them into account.

It has been pointed out that no regard was given to the actual f uidity data as measured by the fluidity mold in compiling the averages for the different bleeding times. This statement does not infer that fluidity is not a factor in the rate of skin formation. Reference is made only to a correlation of the individual fluidity measurements with those of skin thickness measured at the same time and temperature. Observation of any of the tables will show this to be true. Perhaps, however, the general change found in the fluidity as shown by test length is not of sufficient magnitude to attempt a correlation. In Table 10 data are given showing a fairly large change in the magnitude of the fluidity and an accompanying change in the skin thickness. From this table it also appears that when the fluidity was high the skin thickness remained constant and was not of the same magnitude as that obtained by lower measured fluidity. This is not as significant, however, as it would seem, since constant skin thicknesses have been obtained with a low measured fluidity.

This table also points to the observed fact that the steel analysis is not of major importance for, as can be seen, the carbon analysis is uniform while there is considerable variation in the skin thicknesses obtained.

CONCLUSION

5. Conclusions as to the results exhibited in this report are not presented as this portion consists of only the first phase in the studies on solidification and the rates of skin formation. Further information is necessary before any definite conclusions can be formulated.

TABLE I

Bled after 0 minutes.

6-inch spheres.

Heat #:	Analysis:	Thickness: inches :	Weight: pounds:	Lapsed time : Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
87	C 0.18	.137	4.0	0 : 24	3	2900
87	Mn 0.68	.129	3.9	1 : 12	3	2860
87	Si 0.24	.133	4.2	3 : 50	2.5	2760
87		.156	4.8	4 : 40	1	2740

3-5/8 inch Parallelepiped.

Heat #:	Analysis:	Thickness: inches :	Weight: pounds:	Lapsed time : Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
87	C 0.18	.148	5.4	0	3	2910
87	Mn 0.68	.129	5.5	0 : 48	3	2880
87	Si 0.24	.144	5.8	3 : 36	2.5	2770
87		.141	5.7	4 : 23	1	2750
		.148	6.0	5 : 34	0	2720

Average for Spheres	.140	4.2
" " Parallelepipeds	.142	5.9

TABLE II

Bled after 1/2 minute.

6 inch Spheres.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity inches :	Temperature °Fahr.
89	C .18	.360	9.5	0 : 15	6	2860
"	Mn .69	.378	10.0	0 : 54	5	2835
"	Si .39	.368	9.9	2 : 43	4.5	2790
"		.378	10.0	5 : 52	2.5	2720

3-5/8 inch Parallelepiped.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity inches :	Temperature °Fahr.
89	C 0.18	.340	13.4	0	6	2875
89	Mn 0.69	.332	12.8	0 : 35	5	2845
89	Si 0.39	.307	12.0	2 : 34	4.5	2795
89		.325	13.0	3 : 59	3	2775
89		.309	12.5	5 : 34	2.5	2725

Average -

6 inch Spheres	.371	9.9
3-5/8 " Parallelepiped	.323	12.7

TABLE III

Bled after 1 minute.

6 inch Spheres.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min. Sec.:	Fluidity : inches :	Temperature °Fahr.
77	C 0.18	.488	12.4	0 : 28	4	2880
77	Mn 0.68	.515	12.8	3 : 40	3.5	2790
77	Si 0.19	.550	13.4	4 : 30	3.0	2760
78	C 0.34	.500	12.8	0 : 16	5.5	2910
78	Mn 0.63	.535	13.2	4 : 14	4.5	2815
78	Si 0.30	.553	13.5	5 : 08	4	2800
83	C 0.30	.456	11.0	0 : 20	5.5	3010
83	Mn 0.62	.481	11.6	3 : 09	4.0	2940
83	Si 0.37	.488	11.9	3 : 49	4.0	2920
86	C 0.18	.500	13.2	0 : 25	6.5	2960
86	Mn 0.48	.469	11.9	0 : 55	4.0	2940
86	Si 0.18	.500	13.0	3 : 15	3.0	2860
86		.507	12.6	5 : 00	2.5	2820
86		.507	13.5	6 : 04	2.5	2790

3-5/8 inch Parallelepipeds.

77	C 0.18	.372	15.7	0	4	2900
77	Mn 0.68	.391	15.4	3 : 22	3.5	2795
77	Si 0.19	.488	17.1	4 : 13	3.0	2770
78	C 0.34	.475	17.4	0	5.5	2920
78	Mn 0.63	.475	17.5	3 : 53	4.5	2820
78	Si 0.30	.475	17.4	4 : 47	4.0	2800
83	C 0.30	.407	15.1	0	5.5	3020
83	Mn 0.62	.425	15.8	2 : 21	4.0	2945
83	Si 0.37	.454	16.2	3 : 32	4.0	2930
86	C 0.18	.452	15.4	0	6.5	2970
86	Mn 0.48	.435	14.6	0 : 40	4.0	2950
86	Si 0.18	.452	15.4	3 : 03	3.0	2875
86		.376	14.8	4 : 42	2.5	2825
86		.450	15.5	5 : 49	2.5	2800

Average -

6 inch Spheres	.503	12.6
3-5/8 " Parallelepiped	.437	15.9

TABLE IV

Bled after 2 minutes.

6 inch Spheres.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
43	C 0.38	.84				
58	C 0.20	.75				
59	C 0.14	.72				
60	C 0.16	.84				
62	C 0.48	.868		0 : 50	3	
62		.810		1 : 15	3	
62		.878		7 : 00	0	
63	C 0.21	.718	17.5	0 : 50	6.7	
63	Mn 0.50					
63	Si 0.21	.797	18.2	1 : 12	6.5	
65	C 0.25	.718	17.2	5 : 00	3.5	
66	C 0.40	.718	17.4	1 : 15	7.0	
66	Mn 0.51	.704	16.0	1 : 55	8.5	
66	Si 0.35	.706	16.8	4 : 34	6.5	
66		.715	16.2	5 : 38	5.5	
67	C 0.30	.735	17.4	0 : 58	6.0	
	Mn 0.88	.765	17.9	1 : 32	5.7	
	Si 0.50	.797	18.4	4 : 43	4.0	
		.875		5 : 33	3.5	

3-5/8 inch Parallelepipeds.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
52	C 0.52	.625				
52	C 0.52	.625				
54	C 0.26	.563				
57	C 0.18	.625				
57	C 0.18	.596				
59	C 0.14	.688				
61	C 0.38	.686				
62	C 0.48	.720	22.0	0	3	
62		.756	22.5	1 : 35	3	
62		.742	22.1	1 : 55	3	
62		.738	22.0	7 : 00	0	
63	C 0.21	.576		0	6.7	
63	Mn 0.50	.644		1 : 32	6.5	
63	Si 0.21	.650		1 : 51	6.5	
63		.782		8 : 19	0	
64	C 0.20	.632	24.4	0	6.2	
64	Mn 0.34	.587	22.4	1 : 49	6	
65	C 0.25	.689	22.9	0	7.25	
		.656	22.6	0 : 50	7.25	
66	C 0.40	.623	21.4	0	6.0	
	Mn 0.51	.625	21.5	0 : 48	6.5	
	Si 0.35	.656	21.7	1 : 36	8	
67	C 0.30	.545	21.1	0	6	
	Mn 0.88	.546	21.2	0 : 43	6	
67	Si 0.50	.642	23.5	1 : 17	5.75	
		.626	22.5	4 : 30	4.0	

Averages - 6 inch Spheres .773 18.1
3-5/8 " Parallelepiped .650 22.2

TABLE V

Bled after 3 minutes.

6 inch Spheres.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
70	C 0.33	1.01	22.2	1 : 11	5.5	2920
70	Mn 0.66	1.00	21.5	4 : 25	4.5	2850
70	Si 0.35	1.03	22.2	4 : 50	4.25	2830
75	C 0.42	0.98	21.2	0 : 55	5.5	2890
75	Si 0.40	1.04	23.2	4 : 25	6.0	2770
79	C 0.19	0.975	22.5	0 : 26	3.5	2910
79	Si 0.33	1.005	23.1	4 : 18	1.0	2810
88	C 0.18	1.00	21.4	0 : 13	6	2955
88	Mn 0.64	1.00	21.1	0 : 50	5.5	2940
88	Si 0.19	1.00	21.6	3 : 05	4.5	2860
88		.985	21.4	4 : 28	4.5	2810
88		.982	21.4	5 : 44	4	2770

3-5/8 inch Parallelepipeds.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity : inches :	Temperature °Fahr.
70	C 0.33	0.84	27.0	0 : 38	4.5	2940
70	Mn 0.66	0.83	26.2	4 : 10	6.25	2850
70	Si 0.35	0.85	26.9	4 : 40	5.0	2840
75	C 0.42	0.815	26.0	0 : 55	5.0	2900
75	Mn 0.90	0.954	25.8	4 : 25	6.0	2780
79	C 0.19	0.855	26.2	0	3.5	2920
79	Mn 0.80	0.850	25.8	3 : 58	1.0	2820
79	Si 0.33	0.890	26.5	5 : 10	1.0	2800
88	C 0.18	.790	24.4	0	6	2970
88	Mn 0.64	.832	24.3	0 : 28	5.5	2955
88	Si 0.19	.863	24.8	2 : 49	4.5	2870
88		.835	24.4	4 : 09	4.5	2830
88		.790	24.2	5 : 36	4.0	2785

Averages -

6 inch Spheres	1.000	21.9
3-5/8 " Parallelepipeds	.846	25.5

TABLE VI

Bled after 4 minutes.

6 inch Spheres

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity inches :	Temperature °Fahr.
68	C 0.35	1.36	22.6	1 : 06	9.0	2900
68	Mn 0.72	1.45	26.7	5 : 12	5.5	2650
69	C 0.38	1.24	24.8	1 : 05	9.5	2860
	Mn 0.53	1.32	25.3	4 : 15	4.5	2780
82	C 0.38	1.20	24.5	0 : 12	16	2960
82	Mn 0.77	1.22	24.6	4 : 08		2830
82	Si 0.36	1.21	24.8	4 : 53	16	2820

3-5/8 inch Parallelepipeds.

Heat #:	Analysis :	Thickness: inches :	Weight: pounds:	Lapsed time Min.Sec.:	Fluidity inches :	Temperature °Fahr.
68	C 0.35	1.12	28.0	0	9.5	2930
68	Si 0.24	1.07	26.8	0 : 48	9.0	2900
68	Mn 0.72	1.26	29.9	4 : 55	5.5	2650
69	Si 0.28	1.18	29.0	0 : 48	9.0	2890
82	C 0.38	1.06	28.2	0	16.	2960
82	Si 0.36	1.17	28.7	3 : 50		2830
82	Mn 0.77	1.06	28.0	4 : 35	16	2820

Averages -

6 inch Spheres	1.260	24.6
3-5/8 " Parallelepipeds	1.130	28.6

TABLE VII

Averages obtained by bleeding.

Time Minutes	No. of Heats	No. Determinations	Thickness inches Average	Weight pounds Average
6 inch Spheres.				
0	1	5	.140	4.2
1/2	1	4	.371	9.9
1	4	14	.503	12.6
2	7	18	.773	18.1
3	4	12	1.000	21.9
4	3	7	1.260	24.6
3-5/8 inch Parallelepipeds.				
0	1	5	.143	5.9
1/2	1	5	.323	12.7
1	4	14	.437	15.9
2	7	26	.650	22.2
3	4	13	.846	25.5
4	3	7	1.130	28.6

TABLE VIII

Study in the Variation of Carbon Contents.

6 Inch Spheres. Time of Bleeding 3 minutes.

Carbon content	Heat #	Thickness inches	Fluidity inches	Temperature °Fahr.
0.18	88	1.00	6	2955
0.18	88	1.00	5.5	2940
0.18	88	1.00	4.5	2860
0.18	88	.98	4.5	2810
0.18	88	.98	4.0	2770
0.33	70	1.01	5.5	2920
0.33	70	1.00	5.0	2850
0.33	70	1.03	4.25	2820
0.42	75	.98	5.5	2890
0.42	75	1.04	5	2770

TABLE IX

Temperature - Thickness Relationships.

6 inch Spheres. Bleeding time 1 minute.

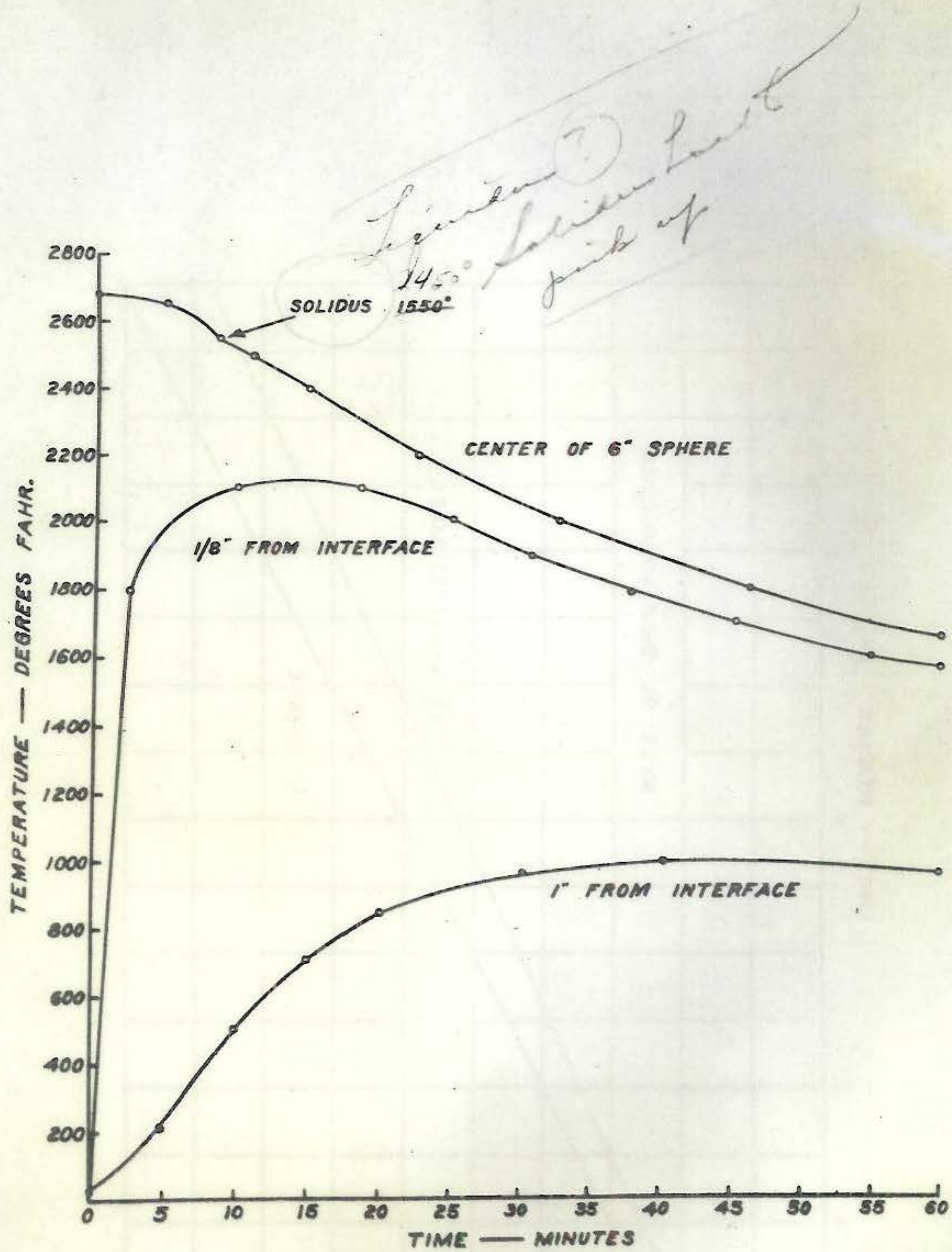
Heat #	Thickness inches	Temperature °Fahr.	Fluidity inches	Carbon content
86	.500	2960	6.5	0.18
86	.469	2940	4.0	0.18
86	.500	2860	3.0	0.18
86	.507	2820	2.5	0.18
86	.507	2790	2.5	0.18
78	.500	2910	5.5	0.34
78	.535	2815	4.5	0.34
78	.553	2800	4.0	0.34
83	.456	3010	5.5	0.30
83	.481	2940	4.0	0.30
83	.488	2920	4.0	0.30
77	.488	2880	4.0	0.18
77	.515	2790	3.5	0.18
77	.550	2760	3.0	0.18

TABLE X

A Study of Fluidity - Thickness Correlations.

6 inch Spheres. Bleeding time 4 minutes.

Heat No.	Thickness inches	Fluidity inches	Temperature °Fahr.	Carbon content
68	1.36	9.0	2900	0.36
68	1.45	5.5	2650	0.36
69	1.24	9.5	2860	0.38
69	1.32	4.5	2780	0.38
82	1.20	16	2960	0.38
	1.22	–	2830	0.38
	1.21	[illegible]	2820	0.38



SOLIDUS 1550°
CENTER OF 6" SPHERE
1/8" FROM INTERFACE
1" FROM INTERFACE
TEMPERATURE — DEGREES FAHR.
TIME — MINUTES
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
5
10
15
20
25
30
35
40
45
50
55
60

PLATE 1

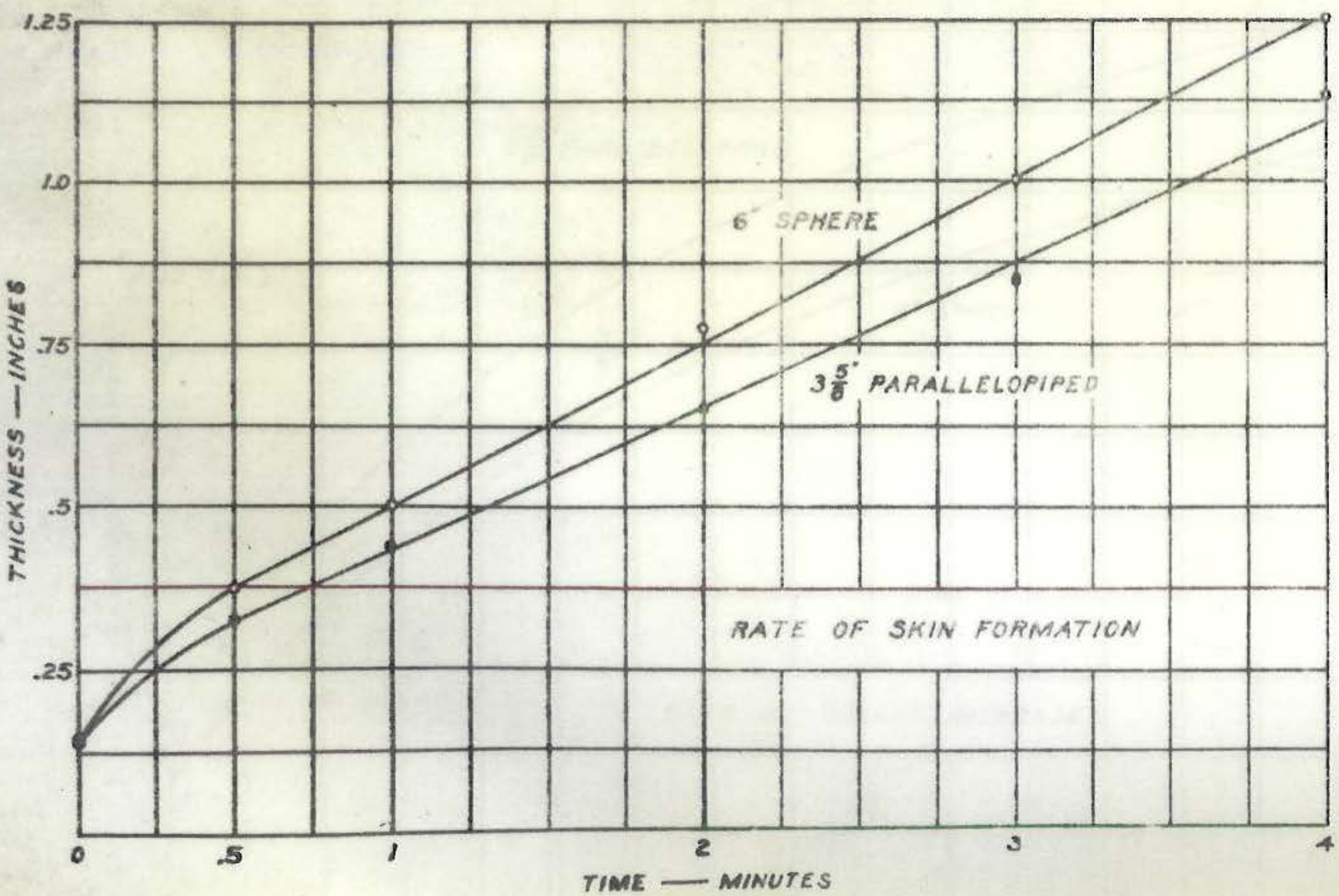

1.25
1.0
.75
.5
.25
THICKNESS — INCHES
0
.5
1
2
3
4
TIME — MINUTES
6" SPHERE
3 5/8" PARALLELOPIPED
RATE OF SKIN FORMATION

PLATE 2

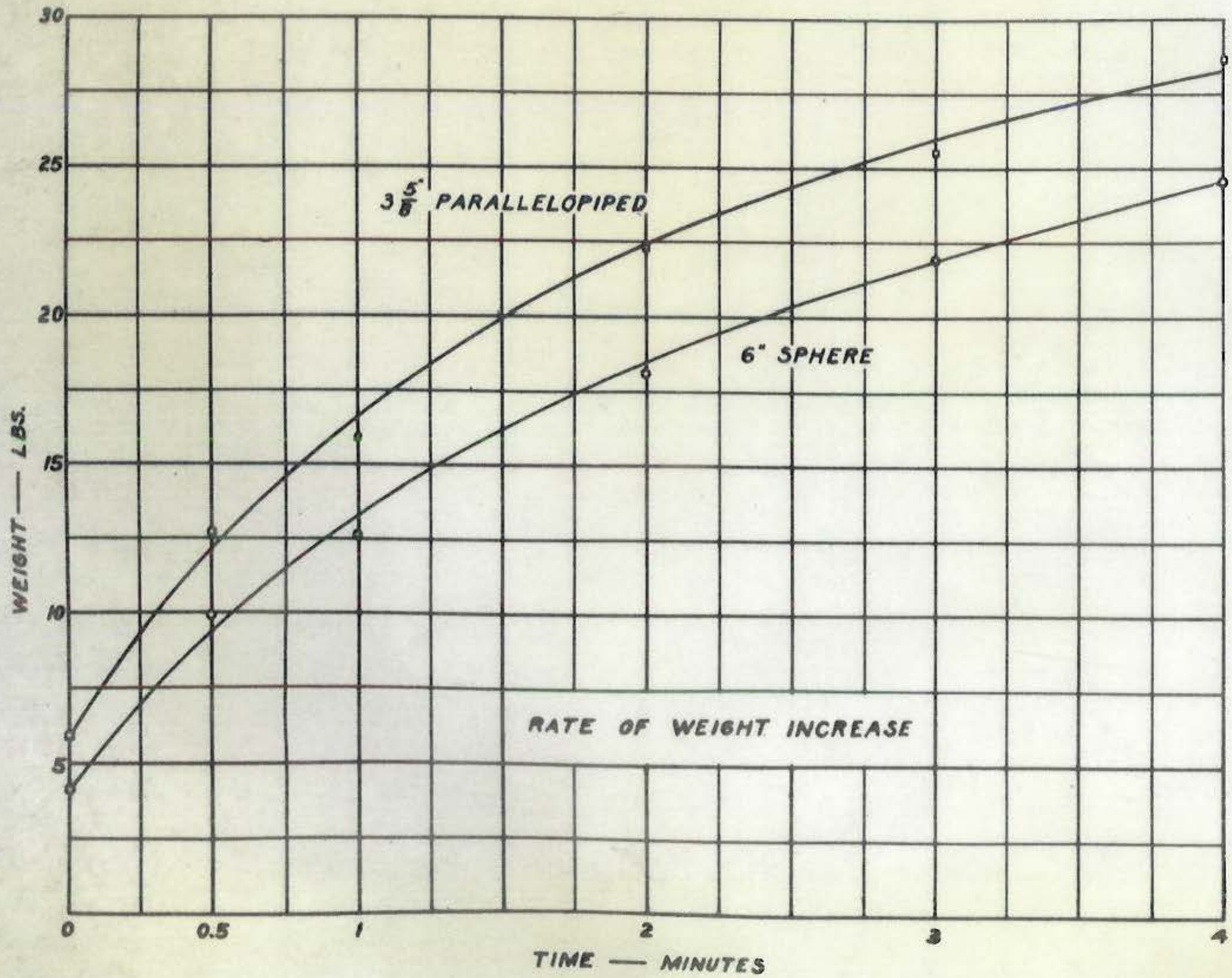

30
25
20
15
10
5
WEIGHT — LBS.
3 5/8" PARALLELOPIPED
6" SPHERE
RATE OF WEIGHT INCREASE
0
0.5
1
2
3
4
TIME — MINUTES

PLATE 3