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METALLURGY DIVISION

STEEL CASTINGS SECTION

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CONVECTION CURRENTS
IN GRAY CAST IRON

By

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ABSTRACT

Experimental evidence is presented showing that convection currents exist in molten iron while the iron is solidifying in the mold. Bleeding experiments have revealed a consistent tendency for walls of gray iron castings to solidify more repidly at the bottom than at the top. Cooling curves were obtained by inserting thermocouples into various positions in bottom poured test castings. From these curves it is possible to trace the flow of hot metal from the bottom to the top of the castings. From temperature measurements on a variety of test castings it was possible to conclude that convection currents are of sufficient magnitude and act long enough in gray cast iron to cause bottom poured castings to freeze from the bottom toward the top. This mode of freezing is dependent on pouring temperatures and size of casting.

Authorization

1. Research on gray cast iron was authorized by BuShips ltr. to NRL, Q/P Castings (334) dated 25 October, 1943; Subj: Gray Cast Iron - Authorization of Investigation (BP1R).

Statement of Problem

2. The objective of the experimental work described in this report was to determine the occurrence or absence of convection currents in solidifying gray iron castings and, if present, to evaluate their effects upon the solidification characteristics of gray cast iron.

Known Facts and Theoretical Considerations

3. In physics textbooks, convection currents are defined as the transfer of heat by moving masses of matter, as by currents in gases and liquids caused by differences in temperature and therefore in density. Although it is logical to expect convection currents in all liquids there has been little positive proof of their existence, magnitude, or importance in liquid metals. Gray noticed the influence of convection currents from observations of segregation, shrinkage, and temperature when he studied the side feeding of steel castings.1/ He claimed that convection currents occur most markedly when bottom gating was practiced. The hottest steel was present at the bottom of the mold when pouring was completed but rose to the top as soon as turbulence ceased. Short heads and short castings were influenced very little by these currents and likewise the influence was not great in top poured castings. Gray concluded that in castings with a thickness less than three inches there was no time for convection currents to occur before preliminary growth of the columnar wall was finished. Gray, however, did not take pouring temperatures into consideration which undoubtedly have a great influence on convection currents.

4. Fifield and Schaum observed the solidification characteristics of gray iron by bleeding cylinders at selected time intervals after pouring and measuring internal metal temperatures with thermocouples.2/ They concluded that gray iron solidifies by forming interlacing dendrites which extend from the surface to the center of the casting and entrap large quantities of metal with lower freezing temperatures during the early stages of solidification. In gray cast iron the contraction in volume

caused by the solidification of the entrapped metal is compensated by the expansion which occurs as a result of graphitization.

5. Steel foundrymen have developed a number of fundamental practices such as directional solidification and bottom risering. When attempts were made to apply these steel foundry practices to cast iron, the results were unsuccessful. Cast iron and steel do not have the same solidification characteristics and physical properties at high temperatures.

Method of Procedure

6. Gray iron for the experimental castings described in this report was melted in a clay graphite crucible contained in an Ajax high frequency lift coil type induction furnace. The charge was composed of charcoal pig iron, scrap, Armco iron, Mexican graphite, and ferro-alloys. All the iron was superheated to 2850°F, inoculated with 0.50 percent silicon as 50 percent ferrosilicon, and poured five to ten minutes later. Molds were rammed with synthetic sand and were allowed to air dry at least one day. Ladle temperatures were read with an immersion type thermocouple. Cooling data within the casting were obtained by inserting platinum-platinum, rhodium couples into quartz tubes which extended into the mold cavity. An automatic high speed Brown temperature recorder provided a continuous record of temperature changes within the casting. Macro-examination of the solidification characteristics was afforded by bleeding partially solidified castings. Bleeding is the process in which a casting is poured, allowed to set a short interval of time, and then drained of all remaining liquid metal.

Description of Experiments

7. Many of the solidification characteristics of cast iron have heretofore been theorized from observations of completely solidified castings. Such examinations were usually made by sectioning with saw cuts. However, such a technique was inadequate for development of a fundamental understanding of the mechanism or dynamics of solidification. In the gray iron solidification research of Fifield and Schaum 2/ best observations were obtained by arresting the process of solidification by bleeding methods. Similar bleeding techniques were therefore adopted for the studies described in this report. The length of the time interval naturally influences the extent to which the process of solidification or skin formation has proceeded. The rate of solidification is dependent on many variables such as degree of superheat above the liquidus at the time of pouring, chemical composition, mold material, inoculation, etc.

8. In the first bleeding experiments, simple blocks, two inches thick, six inches long and eight inches high were top poured, permitted to set from two to five minutes, and then inverted to allow the remaining liquid metal to run out of the solid shell which had formed. Plate 1 shows one of these blocks which was sectioned transversely through the center of the larger face. This iron contained 2.82% C - 2.10% Si - 0.61% Mn - 0.056% S - 0.173% P, and was poured at 2534°F, a temperature which is 300°F above the liquidus, and was bled two minutes after pouring. The pronounced taper of the walls from 3/4 inches at the bottom to 3/8 inches near the top was typical of all such blocks. It was felt that this taper could only be partially attributed to end effect of the bottom surface. However, the chilling effect at the open top, which was radiating heat rapidly to the atmosphere, should have overcome the initial advantage of top pouring which placed the hottest metal in the top of the casting. The fact that the top metal remained the hottest for two minutes, as evidenced by the walls of the bled casting, in spite of the radiant heat less at the top, led to the conjecture that convection currents may have a strong influence on the solidification characteristics of cast iron. More definite evidence of this phenomenon is presented later in this report.

9. The next series of bleeding experiments was made on cylinders two and one-half inches in diameter and eight inches high. Since cylinders have greater strength to resist compressive forces, observations were not obscured by collapsing walls, as may be the case with rectangular blocks.

10. These cylinders were top and bottom poured and top and bottom bled so that pouring and bleeding variables could be correlated with solidification characteristics. Bottom bleeding was made possible by pouring a two and one-half inch diameter cylinder attached to and centered over a plate three and one-half inches in diameter and one and one-half inches deep. The cylinder was torn from the plate by lifting the cope from the drag so that the remaining liquid iron could drain through the bottom.

11. Plate 2 is a photograph of one of these cylinders, bottom poured at 2612°F and bottom bled three minutes and nineteen seconds later. A Brown high-speed temperature recorder with a platinum-platinum, rhodium thermocouple in a quartz protection tube was used to measure the temperature in the center of a duplicate cylinder. This iron had a liquidus at 2295°F and was bled near the end of the liquidus isothermal hold. The metal contained 3.00% C - 1.72% Si -

0.63% Mn - 0.026% S and 0.007% P. The same pronounced taper is apparent in this casting. The wall measured one inch in thickness at the bottom and three-eighths of an inch at the top.

12. The influence of end effects, pouring method, and bleeding technique are shown in Plate 3. Proceeding from left to right, No. 1 casting was top poured and top bled, No. 2 was top poured and bottom bled, No. 3 was bottom poured and top bled, and No. 4 was bottom poured and bottom bled.

13. All four castings show the same tendency of the wall to taper from thick at the bottom to thin at the top in spite of the different methods of pouring and bleeding. The walls of the top poured cylinders naturally showed a more marked taper since the hottest metal was mechanically placed at the top. The relative importance of convection currents on the solidification of iron is apparent in the bottom poured cylinders. The degrees of wall taper of the four castings are not comparable since the castings were poured from different heats under varying conditions.

14. Although there were indications of convection currents in these small cylinders, larger castings were considered to be more suitable for making such observations. It was planned to substantiate the evidence obtained by bleeding experiments with measurements of temperatures with thermocouples placed in the mold cavity. A larger mass of metal was considered necessary to retard the temperature changes sufficiently to permit accurate observation and recording of data so a cylindrical test casting four inches in diameter and twenty-four inches high was adopted. The cylinder was poured in a vertical position and the metal was introduced at the bottom by a special gating system that minimized turbulence in the casting. The top of the cylinder was closed by a cope. Platinum-platinum, rhodium thermocouples in quartz protection tubes were located at the longitudinal centerline of the cylinder four inches from the top, seven inches from the top, and three inches from the bottom. A Brown high speed temperature recorder was used for obtaining a continuous record of the thermocouple temperatures. The cooling curves obtained from these thermocouples are shown in Plate 4. The metal was poured at 2650°F and contained 2.65% C - 2.23% Si - 0.51% Mn - 0.048% S - 0.118% P. Since the casting was bottom poured, the hottest point in the casting immediately after pouring was at the bottom. Thermocouple No. 3 (located three inches from the bottom) indicated 2560°F about ten seconds after pouring was completed, whereas couple No. 1 (located four inches from the top) showed only 2420°F. However, within approximately one minute

the top and bottom of the casting had reached the same temperature and a few seconds later the top became the hottest and maintained this relative position until the metal passed through the liquidus. After passing through the liquidus, cast iron acts essentially as a solid and the end effect of the sand conducting away the heat caused the top couple to cool below the temperature of couple No. 2. This observed reversal of the hottest metal going from the bottom of the casting to the top within a minute after pouring seems to be direct evidence of convection currents acting in the liquid metal.

15. To prove that this temperature reversal was not an end effect, this type of experiment was repeated with some modification. The casting was enlarged to a cylinder measuring six inches in diameter and 32 inches high. Two arms were welded on the outside of one of the flasks so that the casting and mold could be lifted and rotated 180° whenever desired. This arrangement is shown in the photograph of Plate 5. By rotating the mold during the solidification process, the presence or influence of convection currents could be observed more than once in the casting. Four thermocouples were used in this test. They were located two inches from the top, five inches from the top, three inches from the bottom, and six inches from the bottom. The metal was poured at 2650°F and contained 2.76% C - 1.92% Si - 0.45% Mn - 0.024% S - 0.092% P. The cooling curves are shown in Plate 6. Consistent with previous experiments, the hottest metal was initially at the bottom of the casting, but within 30 seconds the top of the casting had become the hottest. As soon as this condition became well established, the casting was rotated 180° and in 20 seconds the hot metal, which had been put at the bottom mechanically by rotation, had flowed by convection back to the top of the casting. After the iron had passed through the liquidus, the mold was rotated two more times but there was no evidence of convection currents nor any change in the relative temperature conditions in the casting. Below the liquidus cast iron acts essentially as a solid because the remaining liquid metal is isolated in the many small voids existing between the solid dendrites.

16. Some interesting observations of the shrinkage pattern were made by sawing from the center a one inch thick slab parallel to the longitudinal axis. Plate 7 shows the upper six inches and lower ten inches of the slab. The position of the thermocouples and ingate may be noticed on the outer edge of the slab. The upper six inches of the casting reveals the original tucking or sinking

of the metal at the top of the cylinder during the initial stages of solidification. The pattern of this sink is outlined clearly by sand which adhered to the molten iron when original contact was made at the time of pouring. When the casting was rotated 180°, liquid iron broke through the hottest and weakest point at the center of this sink and refilled the cavity created by shrinkage. The appearance of the lower ten inches of the slab might possibly be attributed to the effects of shrinkage and other internal forces acting during subsequent rotations of the casting.

17. A similar experiment was made with an iron of higher carbon equivalent in order to allow more time in which to manipulate the casting before reaching the liquidus temperature. The metal was poured at 2450°F and contained 3.99% C - 1.72% Si - 0.67% Mn - 0.019% S - 0.157% P. Plate 8 shows the cooling curves. Since the liquidus of this iron was 2100°F, sufficient time was available for rotating the casting 180° three times to observe the effect of convection currents with each reversal before they ceased to act. As expected, the bottom of the casting was initially the hottest, 2400°F, and the top the coldest, 2305°F. At approximately two minutes the top became the hottest. Two and one-half minutes after pouring, when this condition became thoroughly established, the casting was rotated 180°. Another temperature reversal then took place at approximately three minutes (elapsed time after pouring). Rotation was made a second time at four and three quarters' minutes, and temperature reversal was completed for the third time at five and three quarters' minutes. The third rotation followed at eight and one-half minutes and the temperatures crossed at the liquidus, nine minutes after pouring.

18. This experiment shows conclusively that hot metal flows from the bottom of a casting to the top by the mechanism of convection currents.

19. Since observations thus far had been limited to cylinders with diameters ranging from two and one-half inches to six inches, an experiment was made to establish the minimum cross-section in which convection currents could cause temperature reversal.

20. Four cylinders were bottom poured simultaneously from the same runner gate at 2600°F (370°F above the liquidus). These cylinders were ten inches high and one inch, one and one-half inches, two inches, and two and one-half inches in diameter. Thermocouples were placed one and one-half inches from the bottom and three inches

from the top of each cylinder. A carbonaceous anti-piping compound was put on top of all cylinders upon completion of pouring. The metal contained 3.03% C - 2.19% Si - 0.38% Mn - 0.041% S - 0.148% P.

21. Plate 9 is a plot of the cooling curves which were obtained. The one inch diameter cylinder passed through the liquidus before convection currents were able to act sufficiently to equalize the temperature gradient existing between the metal at the top and bottom of the cylinder.

22. The cooling rate in the one and one-half inch diameter cylinder was slow enough to allow convection currents to raise the temperature of the colder metal in the top of the cylinder until it exceeded the temperature of the metal in the bottom. Curve 2B shows the initial temperature at the bottom to be 2410°F compared to 2320°F at the top (Curve 2T). Within 20 seconds the temperature at top and bottom was the same and thereafter the top metal remained the hottest.

23. The two inch and two and one-half inch cylinder had a temperature reversal about 25 seconds after pouring.

24. As previously observed, temperature reversal must take place before the liquidus is reached. Of interest also is the depression of the solidus by supercooling. Curve 1T shows a solidus at approximately 2005°F while curves 3T, 4T, and 4B indicate the more true value of 2090°F.

25. Convection currents are not only influenced by the cross section but also by the height of the casting. Observations of the effect of height were made by bottom pouring simultaneously four cylinders measuring three inches in diameter and three, four, six, and eight inches high, respectively. As in the preceding experiments, cooling curves were obtained from thermocouples placed one inch from the top and bottom of all castings, which were completely enclosed in sand. In the three, four, and six inch high cylinders, the top couples read the hottest at all times. In the short cylinders the metal at the top and bottom are probably initially at the same temperature because of turbulence during pouring. Convection currents very rapidly establish a hot top before the relatively sluggish thermocouples can indicate the original temperature distribution. In the eight inch high cylinder the bottom couple was the hottest for only about 20 seconds before reversal took place. Although only one inch of metal separated the two thermocouples in the three inch high cylinder, the top couple showed a maximum of 30°F above the

bottom couple for the first 30 seconds after pouring.

26. Still another variable, the effect of pouring temperature, must be considered in predicting the action of convection currents. If a casting is bottom poured at a low temperature, it may pass through the liquidus before convection can bring about temperature reversal and solidification will proceed from the top downward. Observations of the effect of pouring temperature were made by bottom pouring three duplicate cylinders at three different temperatures from the same ladle of metal. The cylinders were three inches in diameter and ten inches high with thermocouples placed one and one-half inches from the bottom and three inches from the top. After the liquidus of the metal was determined to be 2210°F, the three cylinders were poured at 2560°F, 2460°F, and 2310°F. The cooling curves revealed that convection currents were able to effect temperature reversal in the first two castings before the metal cooled to the liquidus but in the cylinder poured at 2310°F (only 100°F above the liquidus) the metal at the top remained 10°F colder than the bottom throughout solidification.

27. In the preceding experiments the occurrence of convection currents was clearly shown. Within certain limitations of section size, they are able to function until the iron has passed through the liquidus, after which its pseudo-solid structure of bridging dendrites prevents their occurrence. The period of time during which convection currents can act is ordinarily much longer for gray iron than for steel because the former is usually poured with more superheat above the liquidus temperature. Within reasonable limitations gray iron castings will solidify from the bottom upward independent of any gating system. Risers placed on top of iron castings can be smaller and function more efficiently because of the upward flow of heat from the casting to the riser by convection currents.

Summary and Conclusions

The major points established in this paper are:

1. Convection currents are of sufficient magnitude and act long enough in gray iron castings, bottom poured with 370°F superheat, to cause the hottest metal to flow from bottom to top in sections as small as one and one-half inches diameter and as much as ten inches high. When the diameter is increased to three inches with the same height, only 250°F superheat is required to effect temperature reversal.

2. In castings three inches in diameter and less than eight inches high, the top becomes hottest in less time than can be observed with thermocouples and solidification proceeds from the bottom upward.

3. For castings gated and risered so as to benefit from convection currents, the pouring temperature of the metal must be sufficiently high to allow convection currents to take effect before cooling below the liquidus temperature.

4. When the temperature of gray cast iron has dropped below the liquidus, the metal acts essentially as a solid and convection currents cease to act.

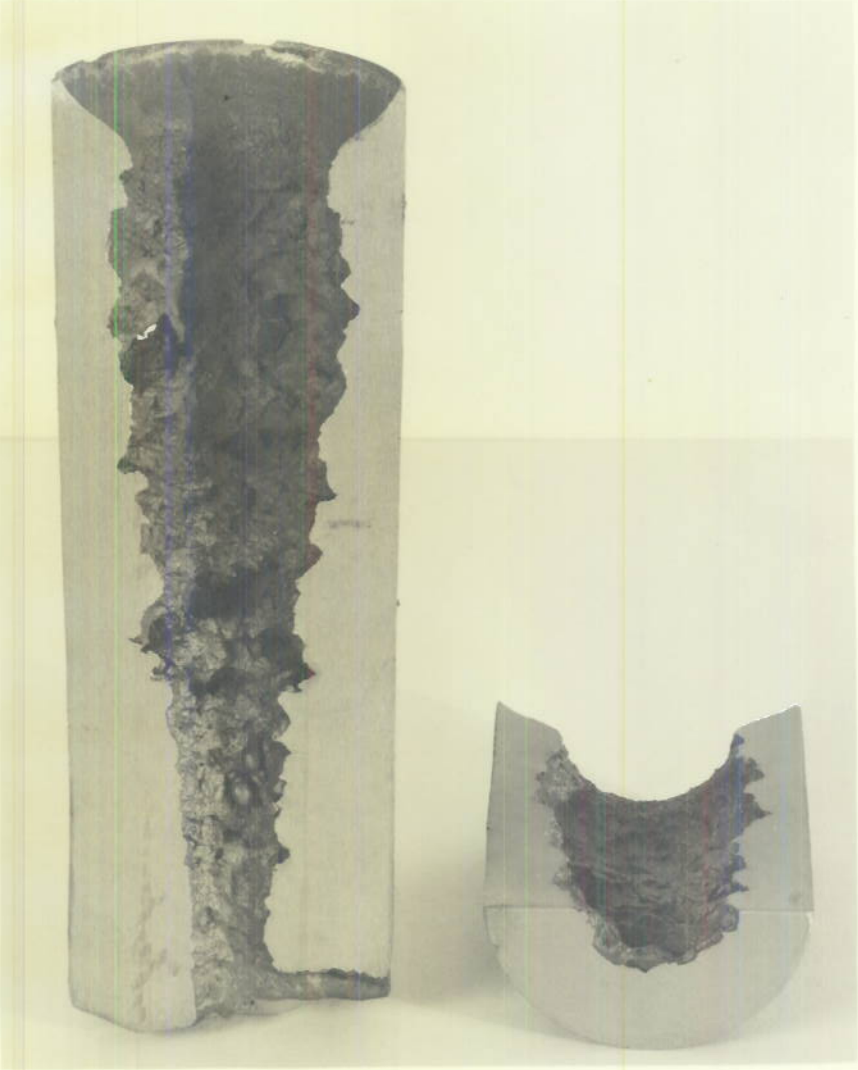
5. When the convection currents are sufficiently active in castings to cause the top of the casting to become hottest, top risers should be used. In such cases side risers are not desirable because directional solidification toward the riser will not be obtained.

Bibliography

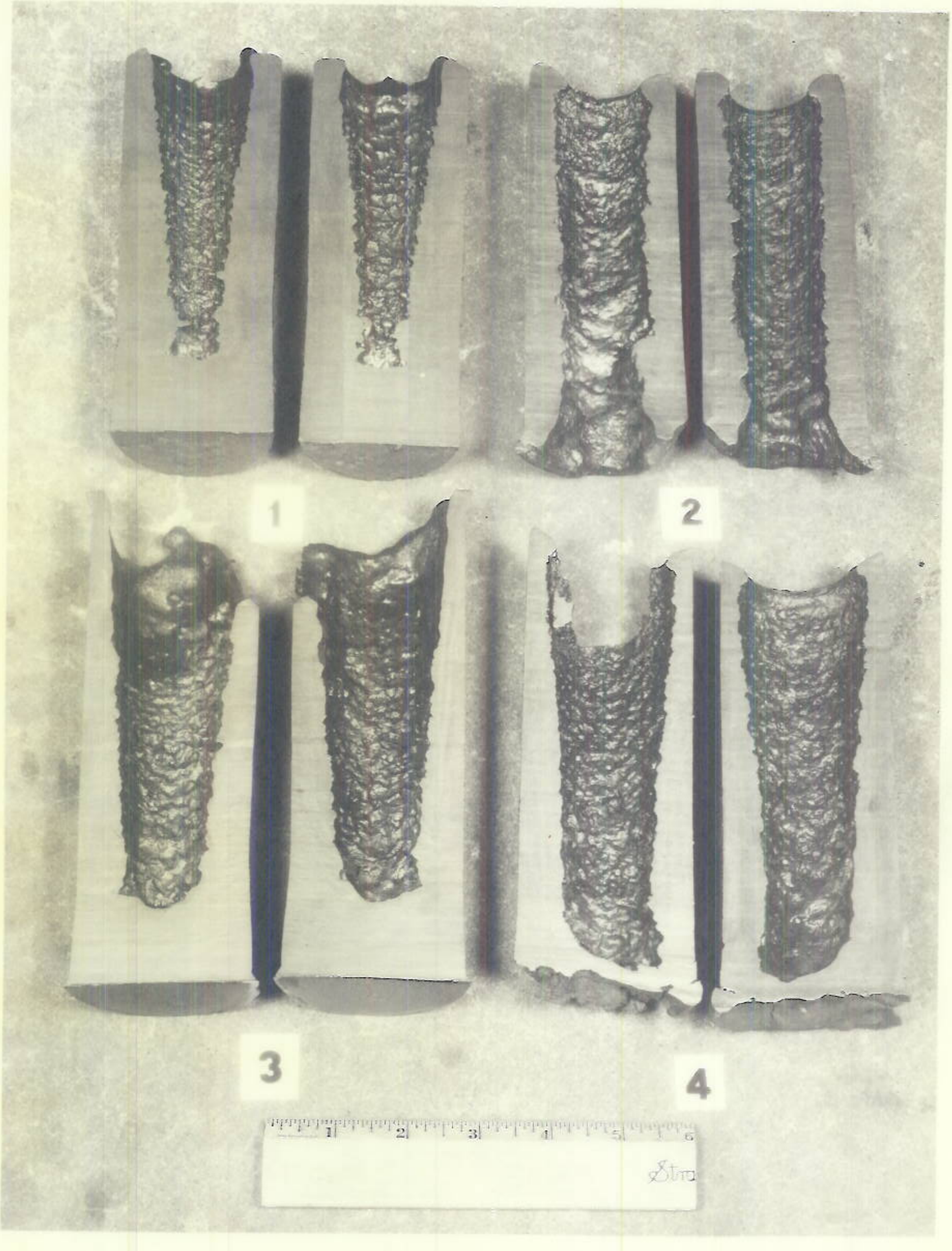
1. B. Gray, The Side Feeding of Steel Castings, Paper No. 10/1944 of the Steel Castings Research Committee, The Iron and Steel Institute.

2. J. E. Fifield and J. H. Schaum, Solidification Characteristics of Gray Cast Iron, Naval Research Laboratory Report No. M-2993.

TAPER OF WALL THICKNESS SHOWN IN A
CASTING TOP BLED TWO MINUTES
AFTER POURING



TAPER OF WALL THICKNESS SHOWN
IN A BOTTOM POURED,
BOTTOM BLED TEST CASTING



TAPER OF WALL THICKNESS SHOWN
IN FOUR TEST CASTINGS
NO. 1 - TOP POURED AND TOP BLED
NO. 2 - TOP POURED AND BOTTOM BLED
NO. 3 - BOTTOM POURED AND TOP BLED
NO. 4 - BOTTOM POURED AND BOTTOM BLED

PLATE 3

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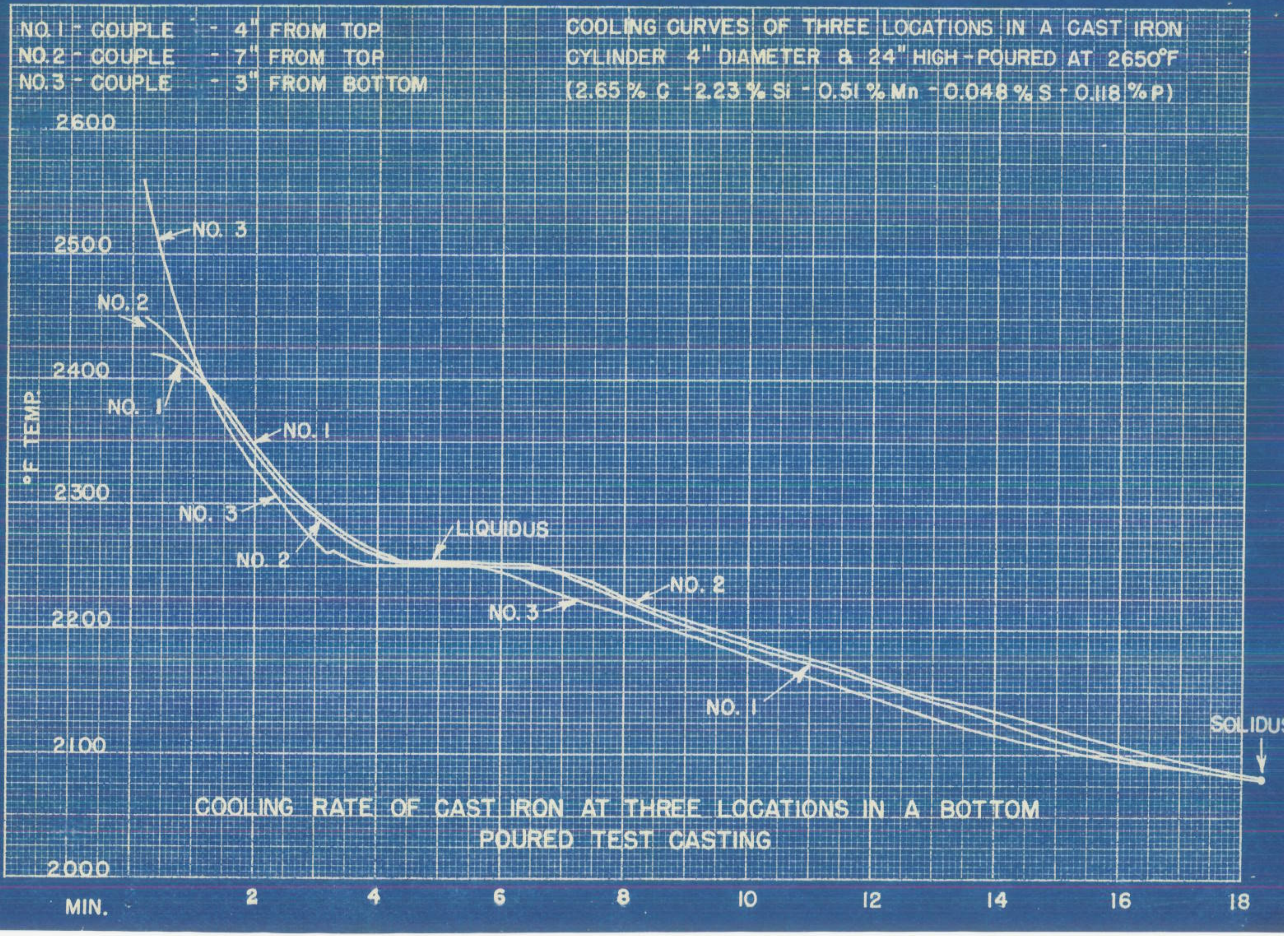
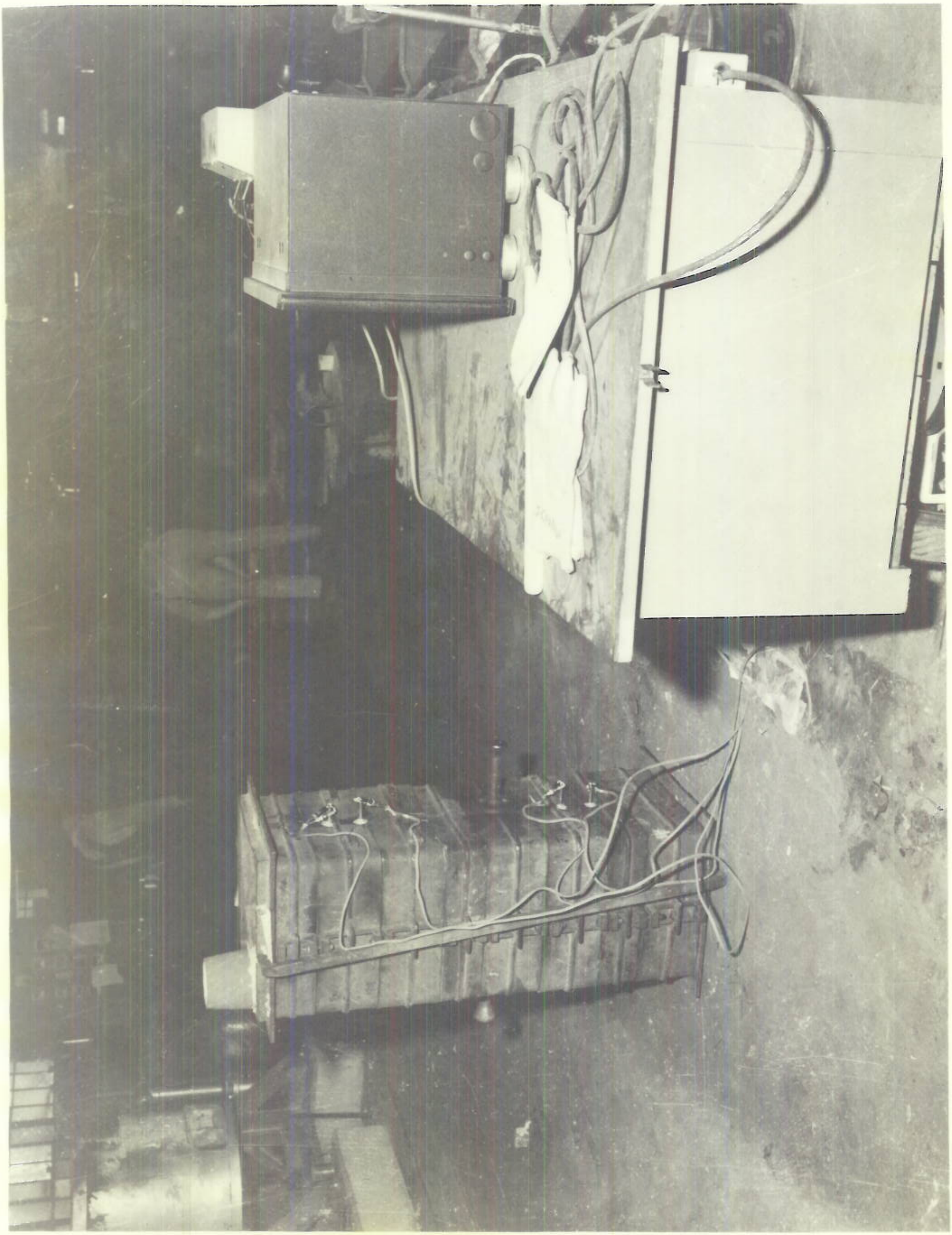


COOLING CURVES OF THREE LOCATIONS IN A CAST IRON
CYLINDER 4" DIAMETER & 24" HIGH - POURED AT 2650°F
(2.65 % C - 2.23 % Si - 0.51 % Mn - 0.048 % S - 0.118 % P)

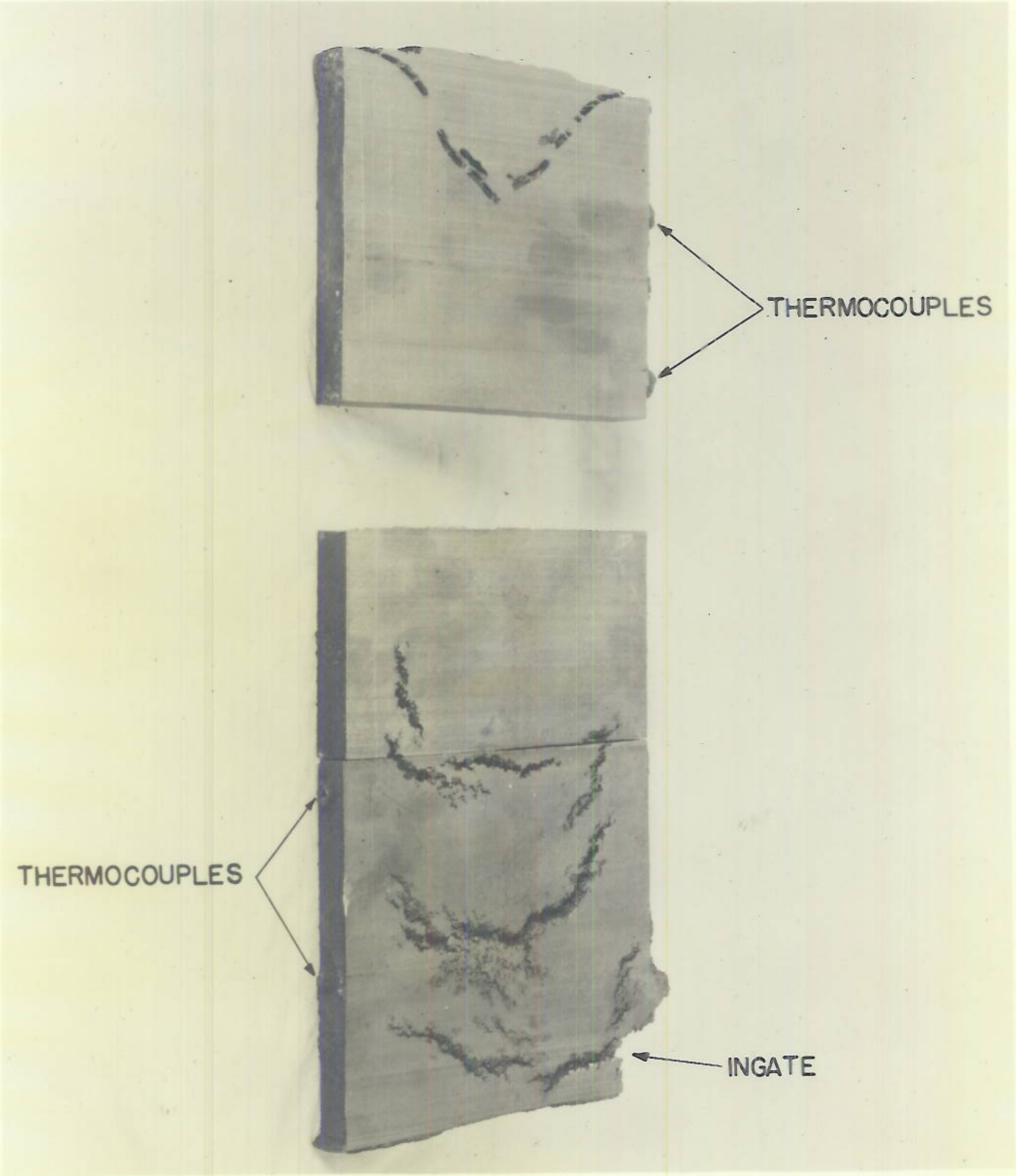
COOLING RATE OF CAST IRON AT THREE LOCATIONS IN A BOTTOM
POURED TEST CASTING

PLATE 4

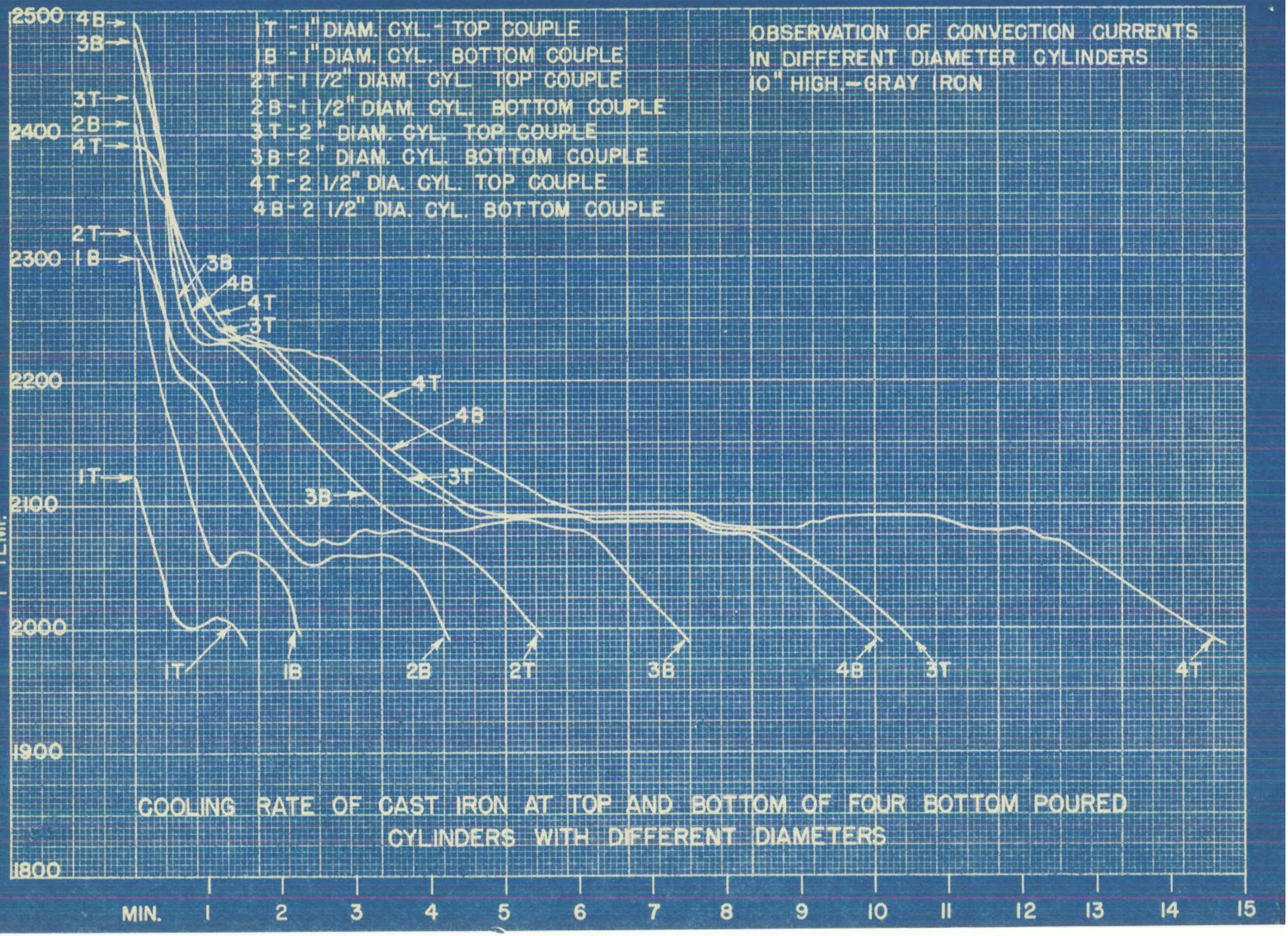


VIEW OF EQUIPMENT USED FOR
INVESTIGATING CONVECTION CURRENTS

PLATE 5



CENTER SLICE OF TEST CASTING WHICH HAS BEEN ROTATED 180° BEFORE REACHING THE LIQUIDUS



COOLING RATE OF CAST IRON AT TOP AND BOTTOM OF FOUR BOTTOM POURED CYLINDERS WITH DIFFERENT DIAMETERS

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PLATE 9