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NRL REPORT M-3389

FINAL REPORT ON SEGREGATION IN SMALL STEEL CASTINGS

NAVAL RESEARCH LABORATORY

WASHINGTON, D.C.

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FINAL REPORT ON SEGREGATION IN SMALL STEEL CASTINGS

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CONTENTS

ABSTRACT

Carbon segregation in small castings often occurs near riser necks. Systematic studies were continued to determine effect on segregation of such interrelated factors as size and shape of riser and casting, and design of riser contact.

Results from numerous specimens show quantitatively that intensity of carbon segregation under "neck-down" risers varies directly as the neck length and inversely as the neck diameter. The degree of segregation also increases as the section thickness of the casting increases. Segregation beneath "knock off" riser contacts is minimized by (1) larger neck diameters, (2) shorter necks, (3) use of exothermic materials for "knock off" riser cores, (4) increase in ratio of riser thickness to casting thickness, or (5) any combination of these.

Centerline segregation, resembling that in ingots, was found in long, slender castings, but this segregation relates more to centerline shrinkage than to riser contact design. Centerline segregation is reduced by increasing the taper of castings to provide more complete feeding.

PROBLEM STATUS

This is the final report on this problem. Unless otherwise advised by the Bureau, the problem will be closed one month from the mailing date of this report.

AUTHORIZATION

NRL Problem No. M02-21R

FINAL REPORT ON SEGREGATION IN SMALL STEEL CASTINGS

STATEMENT OF PROBLEM

The occurrence of high-carbon areas near reduced sections in steel castings was first described in an earlier NRL report and in a subsequent publication.[1] It was shown that this type of segregation frequently occurs near blind riser and "knock-off" riser necks. It was concluded that such segregation forms during the late stages of solidification when the dendrites extend across the reduced riser section and allow only the high-carbon interdendritic liquid to flow to the casting. Additional metal may flow from the riser, but in passing through the dendritic network of the neck, it becomes carbon-enriched by the process of selective solidification.

Since these high-carbon areas may be very detrimental to the machinability, weldability, and mechanical properties of the castings in which they occur, additional studies were made to determine how the severity of segregation is influenced by riser size, casting shape, and riser contact design.

EFFECT OF RISER CONTACT DESIGN

A more complete study was made of the 4-inch-diameter, 4-inch-high test castings (used in the previous work) to determine how carbon segregation beneath "knock-off" risers varied quantitatively with neck length, neck diameter, and neck shape. Cores of 4 different thicknesses—1/2, 3/4, 1, and 1-1/2 inches—were used to form the riser necks. Cylindrical and tapered neck openings, as shown in Figure 1, were employed with each core thickness. The test blocks were made as shown in Figure 2 with 4 castings in each flask gated from a central sprue and fed individually by risers 5 inches in diameter and 5 1/2 inches high. Small permeable sand cores were inserted into the completely enclosed risers to permit atmospheric pressure to act on the molten metal within the riser. The use of top blind risers in this manner permitted simultaneous pouring of 4 castings of different neck design with equal amounts of metal flowing through each neck. It also gave assurance that no pipe eliminator, from which carbon might be absorbed, would be placed on the risers. All castings were poured of Navy Class B steel at temperatures between 2900°F and 2950°F. They were annealed at 1650°F for 4 hours, then sectioned and etched with a 10 percent ammonium persulphate solution to delineate the high carbon areas.

Figures 3 through 9 illustrate the effect of varying neck diameter with constant core thickness and neck shape. The neck diameters, the carbon contents at the segregated and

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[1] Bishop, H. F., and Fritz, K. E., "Segregation in Small Steel Castings," NRL Report M-2983, December 1946. Bishop, H. F., and Fritz, K. E., Trans. Am. Foundrymen's Assoc., 55, 412-428, (1947).

normal regions, and the carbon variation (ΔC) between these regions are indicated on the photographs of each casting. The carbon contents were determined from chips made by drilling a 3/8-inch-diameter hole to a depth of approximately 3/16 inch. In Figure 10, carbon segregation is compared with neck diameters for various combinations of core thickness and neck shape. The neck diameters for the castings made with the tapered necks refer to the smallest diameter of the necks, and for this reason they appear to be superior to the cylindrical necks in minimizing carbon segregation. Actually, if the average diameter of the tapered necks were plotted, the curves for the two types would very nearly coincide. The smallest diameter of the tapered necks is used in this report, however, since this nomenclature had been adopted by others.[*]

From Figures 3 through 9, it can be observed that, with the smallest neck diameter in each series, a shrinkage cavity generally appears in the casting below the neck. At somewhat larger neck diameters, the shrinkage cavity is replaced by a region of segregated metal; and as the neck diameter is further increased, the severity of the segregated region decreases. The amount of carbon segregation also decreases as the neck length decreases, the latter being determined by the core thickness. For example, in Figure 10, with a constant neck diameter of 2 inches, the amount of carbon variation in the castings with the cylindrical necks ranges from 0.30 percent with a 1-1/2-inch-thick core to below 0.10 percent with a half-inch-thick core. The curves in Figure 11 show on the one hand, the minimum neck diameters required to make this particular casting sound when various core thicknesses are used and, on the other, the minimum neck diameters necessary to limit the carbon content of the segregated area to within 0.05 percent of the base metal carbon. Thus, with a half-inch-thick core, a sound casting will require only a 3/4-inch-diameter cylindrical neck, but in order to keep the difference in carbon between the base metal and the segregated metal below 0.05 percent, a 2½-inch-diameter neck must be used. Unfortunately, when the neck diameters are increased to the indicated dimensions (upper curves of Figure 11), the risers may no longer be knocked off with a sledge but must be removed by burning.

EXOTHERMIC "KNOCK-OFF" RISER CORES

It was shown in the previous report that less segregation results when the core is thoroughly preheated by large quantities of metal flowing through the neck opening. In other words, the core which forms the riser contact may be considered as a mild chill which changes the temperature gradients from the casting to the riser. By preheating the core, its chilling effect is minimized. It was reasoned, therefore, that less segregation would result if the core were made of an exothermic material so that it could itself supply a large part of the heat necessary to bring it to the interface temperature.

That segregation can be minimized by such means is shown by a comparison of the upper and lower rows of sectioned and etched castings in Figure 12. For example, the carbon variation in a casting fed through a 1½-inch-diameter neck, made in a one-inch-thick core, is reduced from 0.27 to 0.13 percent by substituting an exothermic core for the sand core. An identical test casting fed through a one-inch-diameter neck formed by a 1/2-inch-thick exothermic core was practically free of carbon segregation.

SPECIAL CORES FOR "KNOCK-OFF RISERS"

The special sand core design shown in Figure 13 is a type that has been used frequently in the Naval Research Laboratory foundry to form riser necks on experimental steel castings. The neck diameter is made to any desired size without changing the basic design of the core.

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[*] Steel Founders' Society of America, Research Report No. 6, April 1945.

This core permits short neck lengths to be used without deformation of the core by the pressure of the liquid steel. Bulging of the core when the metal flows against it is a common occurrence when thin cores of uniform thickness are used. The greater thickness of this core at its outer edges not only gives the necessary strength and rigidity to the core but, as can be seen in Figure 14, also allows adequate space between the casting and outer edge of the riser for easy removal of the latter. If the space between the casting and riser is too small, the riser neck cannot be bent enough during the flogging operation to cause it to break.

Less segregation is formed in the castings when this core is used to form riser necks than when the core types of Figure 1 are used. The amount of segregation formed (Figure 15) is relatively low at all neck diameters between 1/2 and 1-1/4 inches. As the neck opening in the core is increased, the neck length necessarily becomes greater but the amount of segregation shows little change.

SEGREGATION IN RELATION TO CASTING DESIGN

Segregation studies were made on cylindrical castings of different shapes. Although these castings had different surface areas, they were selected to contain approximately the same volume as the 4-inch-diameter, 4-inch-high castings. They varied in shape from 8 inches in diameter, 1 inch high to 2½ inches in diameter, 10 inches high and were gated and risered in the same manner as the 4-inch castings. Figures 16 to 31 show how the segregated area in each casting shape is affected by variation in size of the cylindrical necks. In castings where the segregated zone was sufficiently large and concentrated, drillings for carbon analyses were obtained, and the quantitative relation between carbon segregation and neck diameter for each casting shape is plotted in Figure 32. As the casting thickness decreases, the amount of segregation also decreases. In the one-inch-thick castings which were fed through half-inch-long necks, (Figure 16) no appreciable segregation occurred at any contact diameter.

EFFECT OF CASTING SIZE-RISER SIZE RATIO ON SEGREGATION

Since all of the risers on the various castings were 5 inches in diameter, the ratio of riser thickness to casting thickness was different for each design. Thickness in this discussion refers to the diameter of the largest circle which can be inscribed in a cross section through the smallest dimension according to the method of Heuvers.[3] Thus, the thickness of the riser on the 4-inch-diameter casting was 1.25 times the casting thickness, while this same riser on the one-inch-high casting was 5 times the thickness of the casting.

In a discussion of the first paper on segregation it was suggested by Caine[4] that the relation of riser diameter to casting thickness may influence the amount of segregation. That the size of the riser itself may have some influence on the amount of carbon segregation in a casting is indicated in Figure 33. These castings were made in the same manner as were those of Figure 16 with the exception that the riser was reduced to only 4 and 3½ inches in height and diameter respectively. Slightly greater segregation was found in some of the castings made with the 3½-inch-diameter riser. However, because of the greater amount of metal which flowed through it, the neck of the 5-inch-diameter riser was preheated to a greater extent than was the neck of the 3½-inch-diameter riser. In order to eliminate the preheating variable, the 3½-inch-diameter riser on the one-inch-thick castings

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[3] Heuvers, A., Stahl u Eisen, 492, pp. 1249-1256, August 29, 1929.

[4] Cf. footnote 1, page 1.

was increased in height to $11\frac{3}{4}$ inches so that its volume was equal to the volume of the 5-inch-diameter, $5\frac{1}{2}$-inch-high riser. A segregation of 0.04 percent carbon was still found under the long narrow riser. Thus it is concluded that the diameter of the riser probably has only a minor effect on the amount of segregation formed.

CENTERLINE SEGREGATION

Several trends can be observed from the photographs of the various series of castings discussed heretofore. When the neck diameters are too small, gross shrinkage occurs within the castings due to rapid freezing of the neck. With larger neck diameters, gross shrinkage and segregation exist together. As the neck diameters are enlarged still more, gross shrinkage disappears and pronounced segregation is present. And finally, with sufficiently large neck diameters and small neck heights, segregation also disappears. This is in accordance with the evidence presented in the first report: that segregation of this type occurs between the two extremes of feeding conditions. At one extreme gross shrinkage is produced by "underfeeding," and at the other sound homogeneous metal is produced by "overfeeding."

Another observation to be made is that the segregated areas tend to assume the shape of the shrinkage cavities which would form if the neck diameter were reduced. In the chunky castings—such as the 4-inch-diameter, 4-inch-high castings—the shrinkage and segregated areas tend to be of a globular shape, while in the 7-inch-long cylinders the shrinkage voids and the segregated areas are elongated. Where the riser must feed an appreciable distance in narrow sections—such as in the 10-inch-long, $2\frac{1}{2}$-inch-diameter castings (Figures 28 to 31)—some of the shrinkage tends to be of the V-shaped centerline type, and the segregate also assumes this pattern.

Segregation in castings of Figures 28 to 31 must be considered as a different manifestation of the same type of segregation as found in the other casting shapes. In the former, much of the segregation occurs independent of the riser neck; it arises from the narrow shape of the casting and the long range of feeding required of its riser. The gross segregation immediately below the riser necks is caused by the restricted neck, but the "chevron-like" segregate along the centerline of the casting occurs even though the riser contact covers the entire top of the casting, as it does in the lower right casting of Figure 31.

The castings in Figures 28 to 31 all contain gross shrinkage because bottom-gating of long narrow castings of this type causes adverse temperature gradients to form within the castings—to the extent that complete feeding is impossible regardless of the size of riser used. When such castings are top-gated (Figures 34 to 37) proper temperature gradients, and hence sound castings, are obtained. The V centerline segregation however still persists.

Because of the small size of these chevrons, it is impossible to determine their carbon content by conventional analyses of drillings. A photomicrograph of one of these chevrons (Figure 38), however, shows a marked difference in carbon between the chevron and the adjacent metal. The extent of segregation is also indicated by hardness measurements. In a casting containing centerline chevrons, it was found that the metal midway between the edge and center had a uniform hardness of 4 Rockwell C, while the hardness along the centerline varied considerably. The dark areas of segregation had hardness values ranging from 8 to 17 Rockwell C while the areas between the segregates had hardness values between -10 and 4 Rockwell C.

The V segregation appears to be analogous to that found under knock-off risers. To account for it on the same basis as the segregation under knock-off risers would require that there be periodic bridging of dendrites, which would allow only higher-carbon liquid to flow into the areas isolated by the dendritic bridges. To determine whether such dendritic bridges form, the casting shown in Figure 39 was made.

The hole at the bottom of the casting was formed by a sand core into which a quartz tube was molded. A tank of dry nitrogen was attached to the tube, and, when the mold was inverted five minutes after pouring, a pressure of 14.5 pounds was applied to aid in the removal of the liquid steel. The nitrogen pressure was applied to simulate the atmospheric pressure which would act on this casting if it were allowed to solidify in the normal manner. Solid bridges, each consisting of several unoriented dendrites, were present, as can be seen in the photograph. Dendritic bridges at temperatures near the solidus temperature are extremely weak and are undoubtedly deformed in the process of inverting and bleeding the mold. Nevertheless, there is evidence of the V shape pointing away from the riser.

Brinson and Duma[5] observed that V centerline shrinkage voids always point away from the riser. To show the similarity between centerline shrinkage and centerline segregation, castings were made in this Laboratory 10 inches long, 2½ inches in diameter at one end, 3 inches in diameter at the other, and fed by full-contact risers 5 inches in diameter (Figure 40). As can be seen, V centerline zones of segregation also always point away from the riser regardless of surface taper, gate locations, or position of the casting. In the top-risered castings the chevrons all point downward, while in the castings fed with the bottom riser they point upward. The chevrons in the casting molded in the horizontal position also point away from the riser.

In their studies, Brinson and Duma[5] found that favorable temperature gradients would eliminate centerline shrinkage. Thus, still more favorable temperature gradients should eliminate centerline segregation. To confirm this, a series of castings was made in which the taper was progressively increased, and the results are shown in Figure 41. The castings were fed by 5-inch-diameter top risers. As the taper is first added to the casting, shrinkage is eliminated but chevrons of segregate are present. With still more taper, segregation also disappears.

SUMMARY AND CONCLUSIONS

Carbon segregation beneath "knock-off" riser contacts can be minimized by: (1) increasing the neck diameter, (2) decreasing the neck height, (3) using exothermic material to make the "knock-off" riser cores, and (4) to a minor extent by increasing the riser diameter.

This form of carbon segregation is more severe in chunky, massive sections than it is in long, slender sections.

Centerline segregation, resembling the V-shaped segregation in ingots, has been found in cast sections which are long and slender. This type of segregation is closely related to centerline shrinkage and does not depend on a reduction in section at the riser contact.

Centerline segregation can be eliminated by increasing the taper on the sections so that more complete feeding is possible.

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[5] Brinson, S. W., and Duma, J. A., Trans. Am. Foundrymen's Assoc., <u>50</u>, 657-765, (1942).

* * *

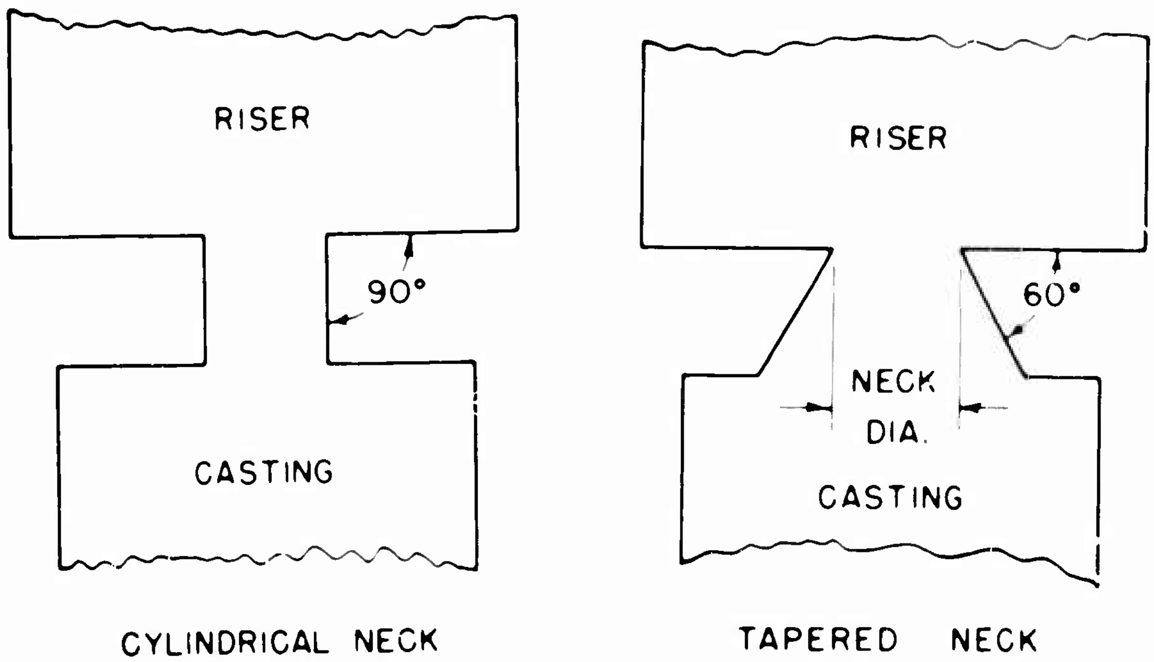


Fig. 1 - Contact neck types used on experimental castings

Fig. 2 - Test castings, as removed from mold, showing gating and risering practice

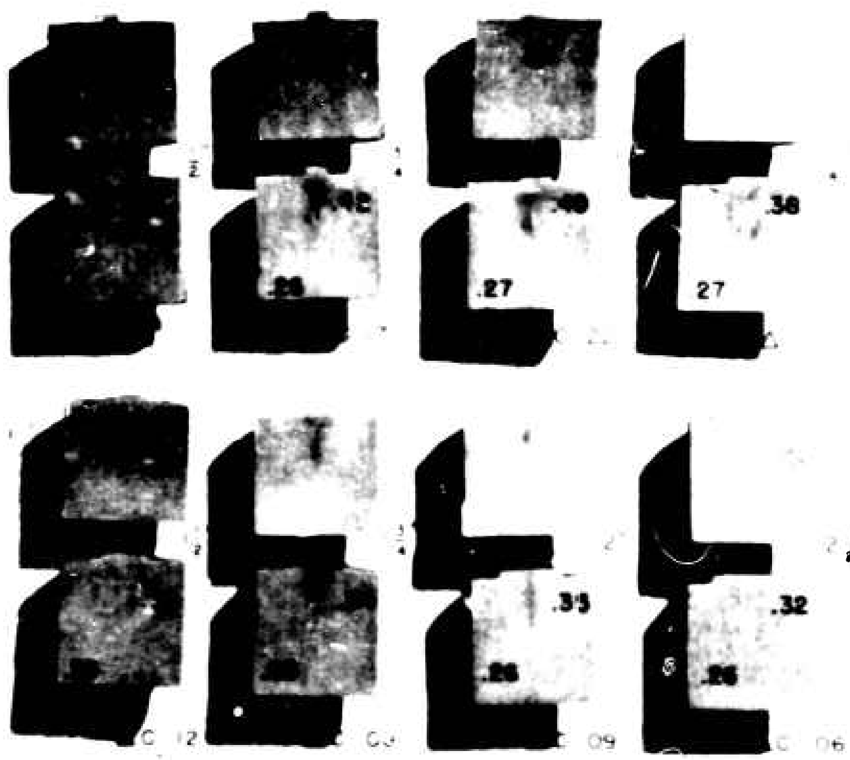


Fig. 3 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 4" - Height, 4" - Neck Length, ½"

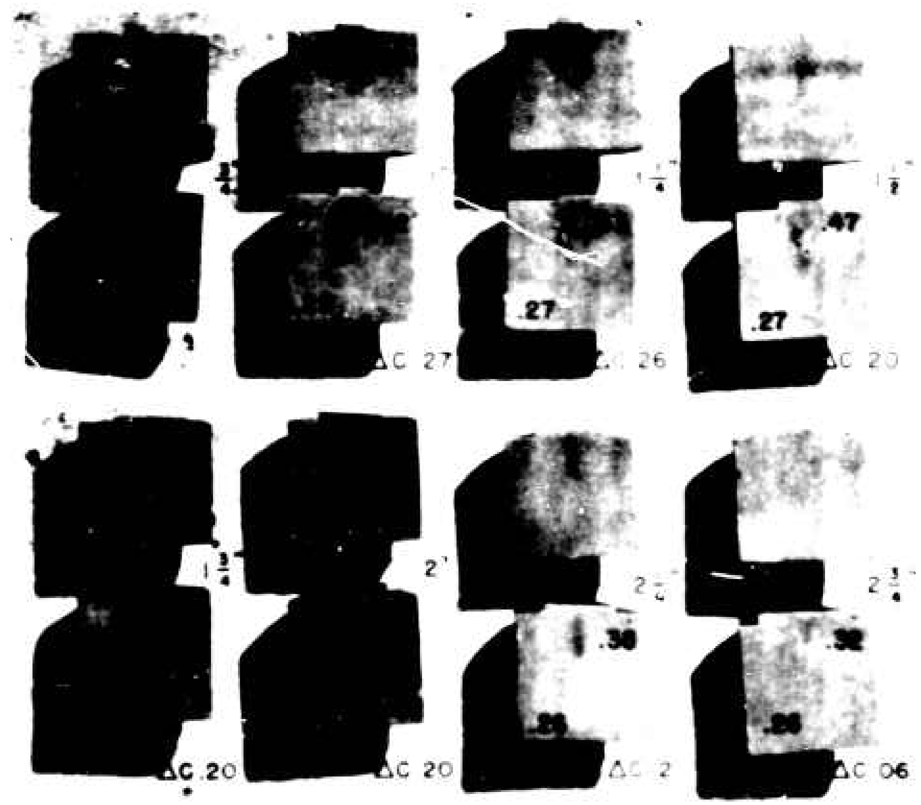


Fig. 4 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 4" - Height, 4" - Neck Length, ¼"

Fig. 5 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 4" - Height, 4" - Neck Length, 1"

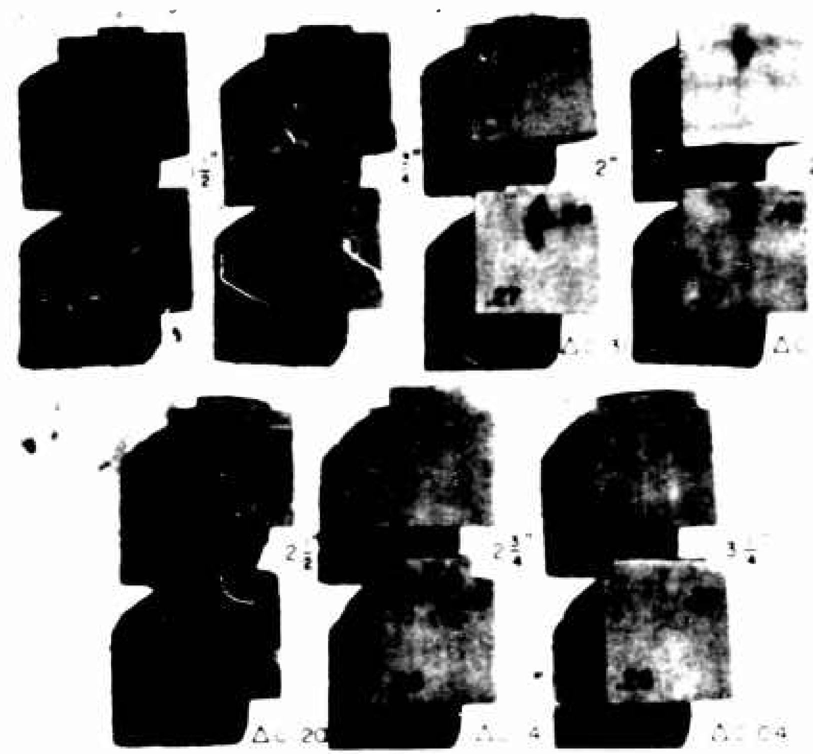


Fig. 6 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 4" - Height, 4" - Neck Length, $1\frac{1}{2}$"

Fig. 7 - Degree of segregation for a given size and shape of casting with varying diameters of tapered neck. Carbon contents and neck diameters as indicated.

Fixed casting dimensions: Diameter, 4 - Height, 4 - Neck Length, ½

Fig. 8 - Degree of segregation for a given size and shape of casting with varying diameters of tapered neck. Carbon contents and neck diameters as indicated.

Fixed casting dimensions: Diameter, 4 - Height, 4 - Neck Length, ¾

Fig. 9 - Degree of segregation for a given size and shape of casting with varying diameters of tapered neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 4" - Height, 4" - Neck Length, 1"

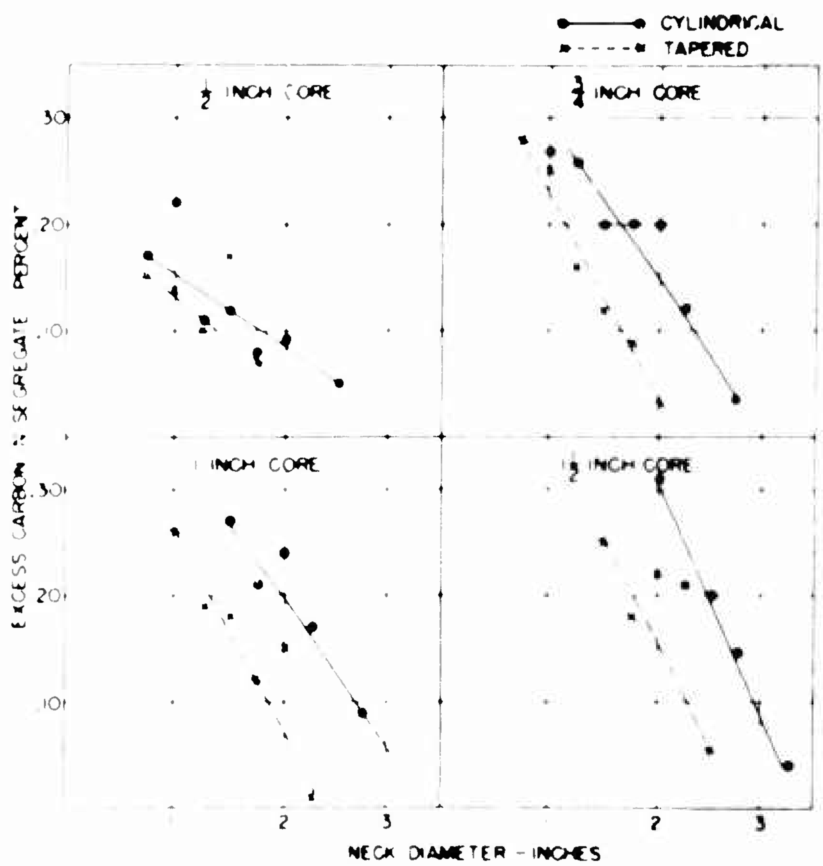


Fig. 10 - Relation of segregation to neck type, core thickness (neck length), and neck diameter in 4-inch-diameter cylinders

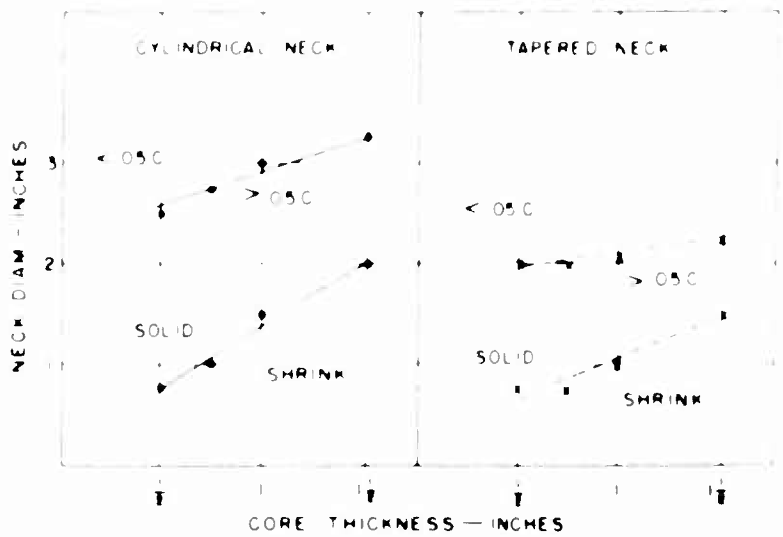


Fig. 11 - Relation of core thickness and neck diameter required on 4-inch-diameter cylinders to (1) produce sound castings and (2) keep segregation less than 0.05 percent carbon

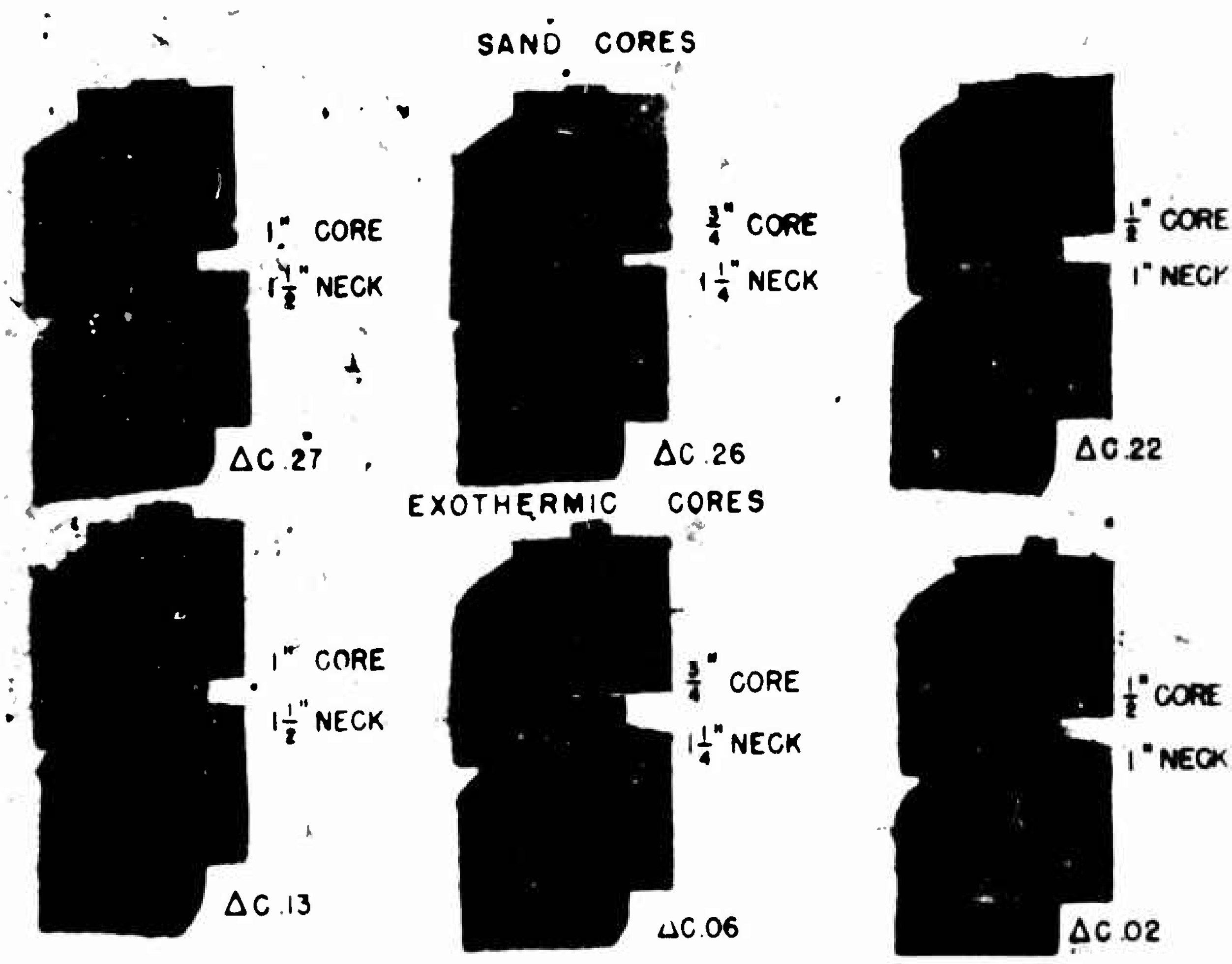


Fig. 12 - Sectioned casting showing how segregation can be reduced by the use of exothermic cores

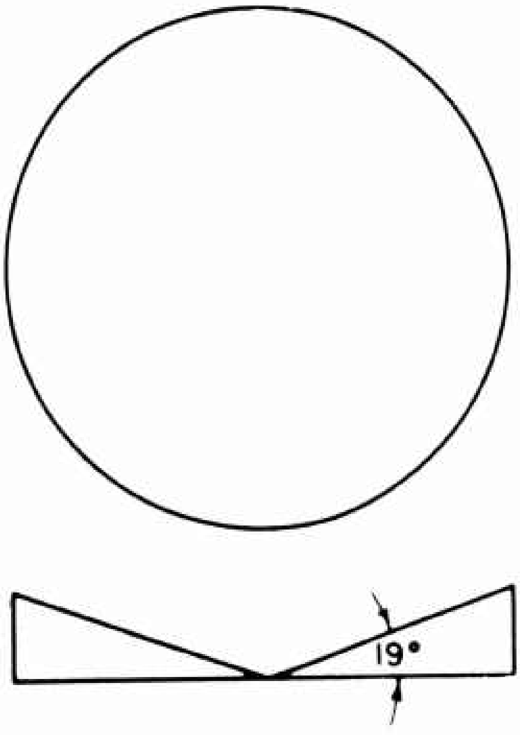


Fig. 13 - Special core used to form "knock-off" riser contacts. Core diameter and diameter of open.ug can be made to any desired size

Fig. 14 - Section through casting and riser made with the special core shown in Figure 13

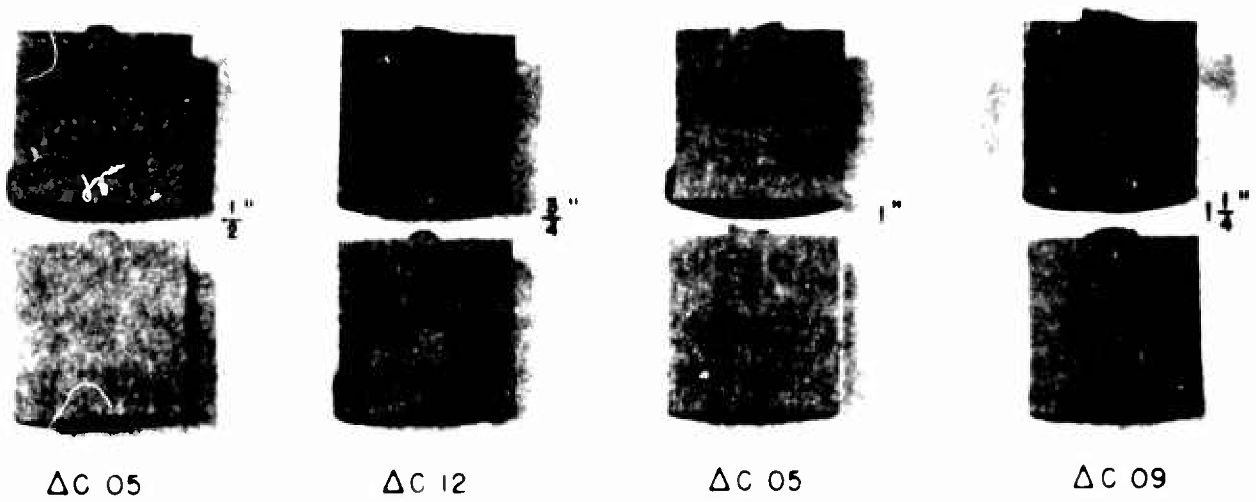
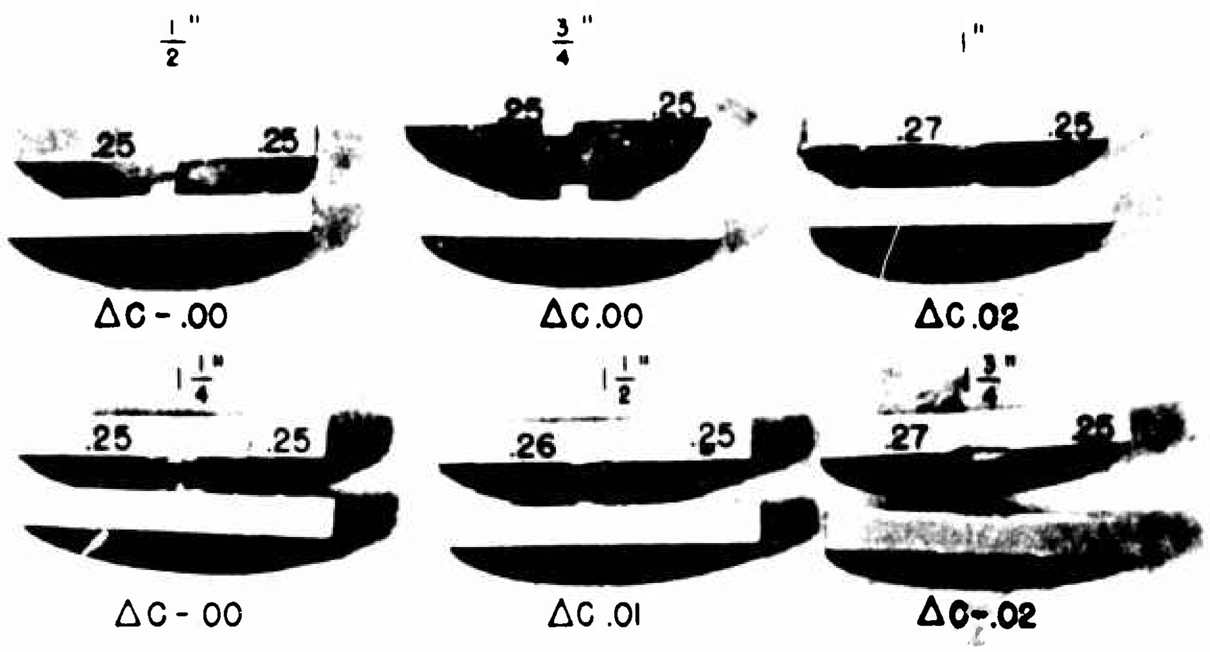


Fig. 15 - Sectioned and etched castings made with special core—neck diameters and carbon contents as indicated



Fixed casting dimensions:
Diameter, 8"
Height, 1"
Neck Length, ½"

Fig. 16 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated

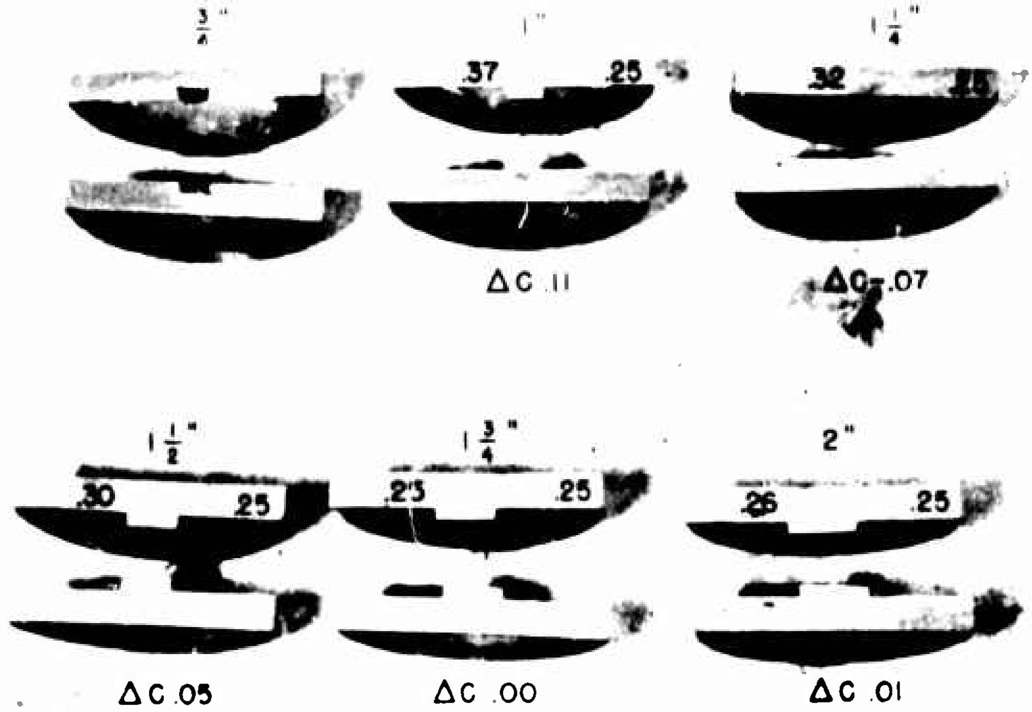


Fig. 17 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 8" - Height, 1" - Neck Length, 3/4"

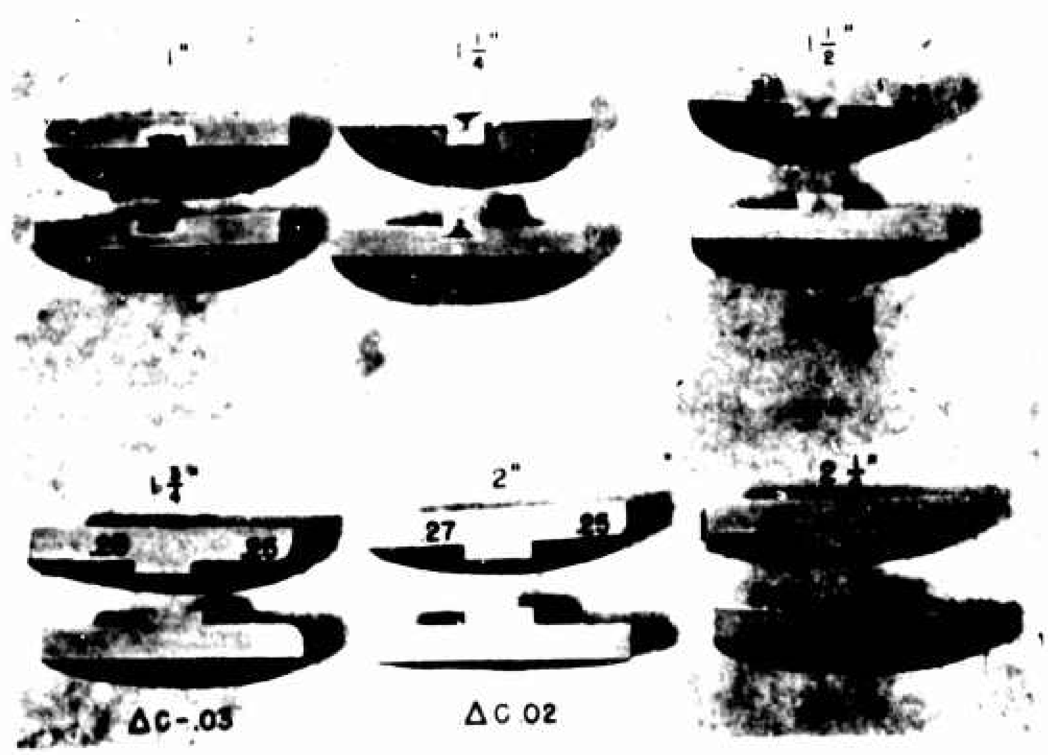


Fig. 18 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 8" - Height, 1" - Neck Length, 1"

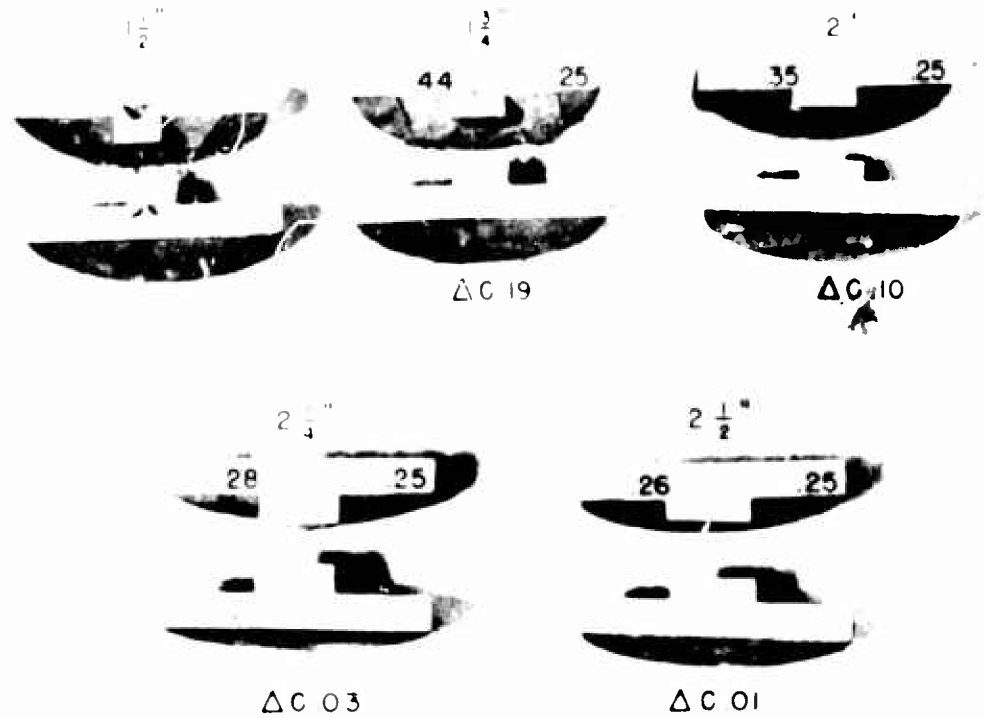


Fig. 19 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 8" - Height, 1" - Neck Length, 1"

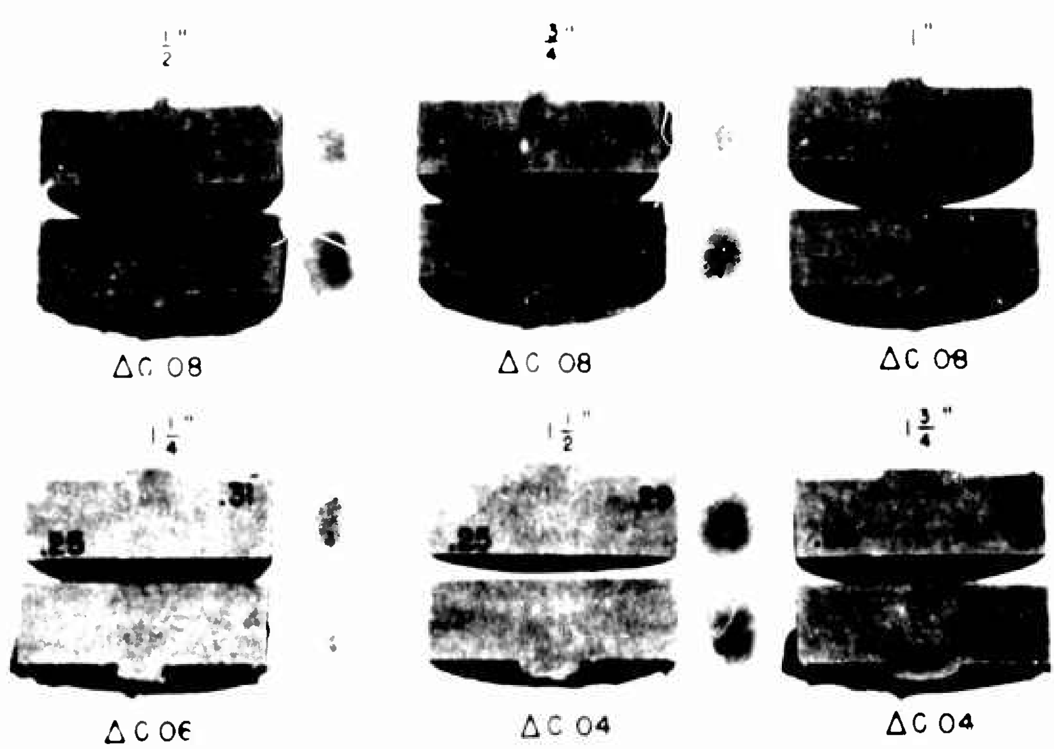


Fig. 20 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 6" - Height, 2" - Neck Length, "

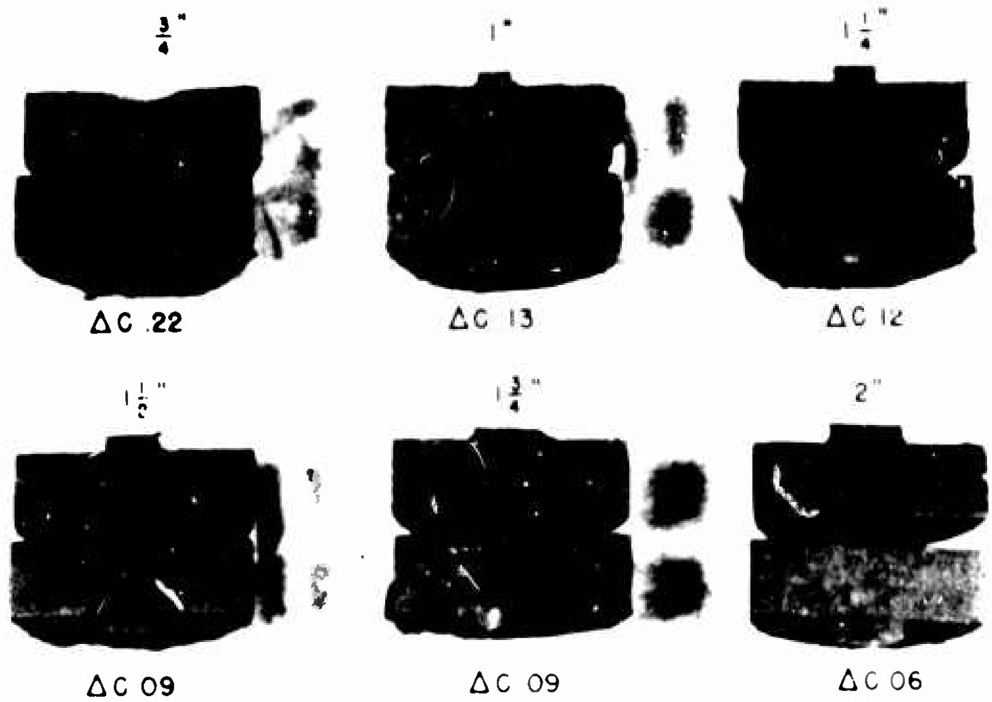


Fig. 21 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 6" - Height, 2" - Neck Length, 3/4"

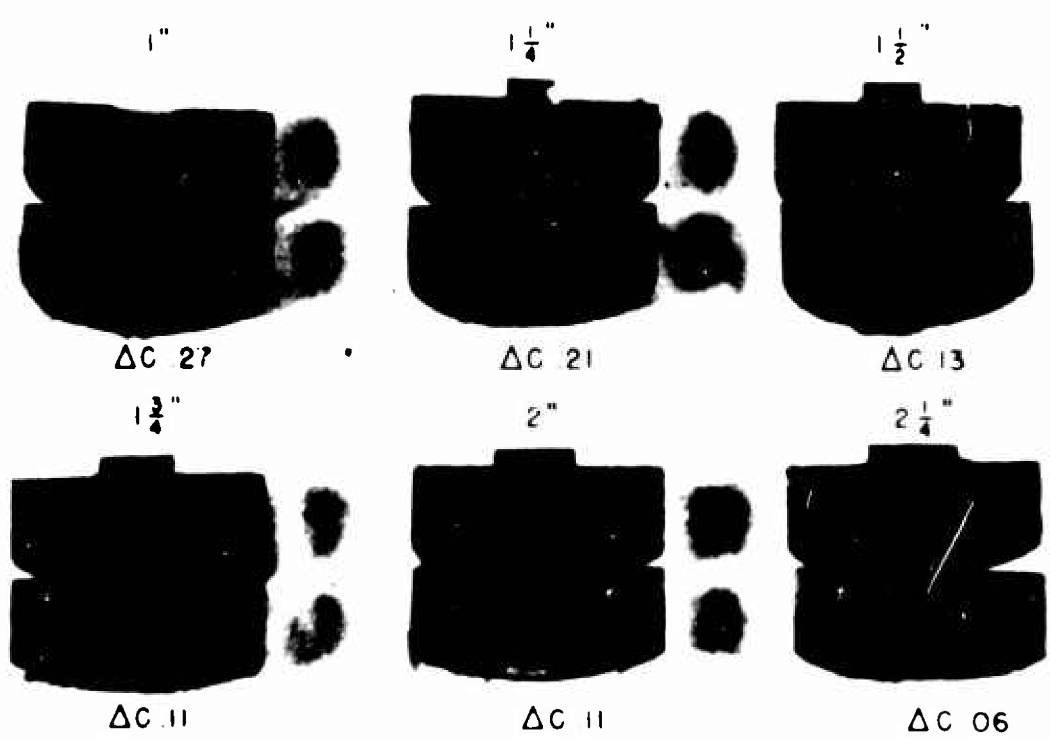


Fig. 22 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions: Diameter, 6" - Height, 2" - Neck Length, 1"

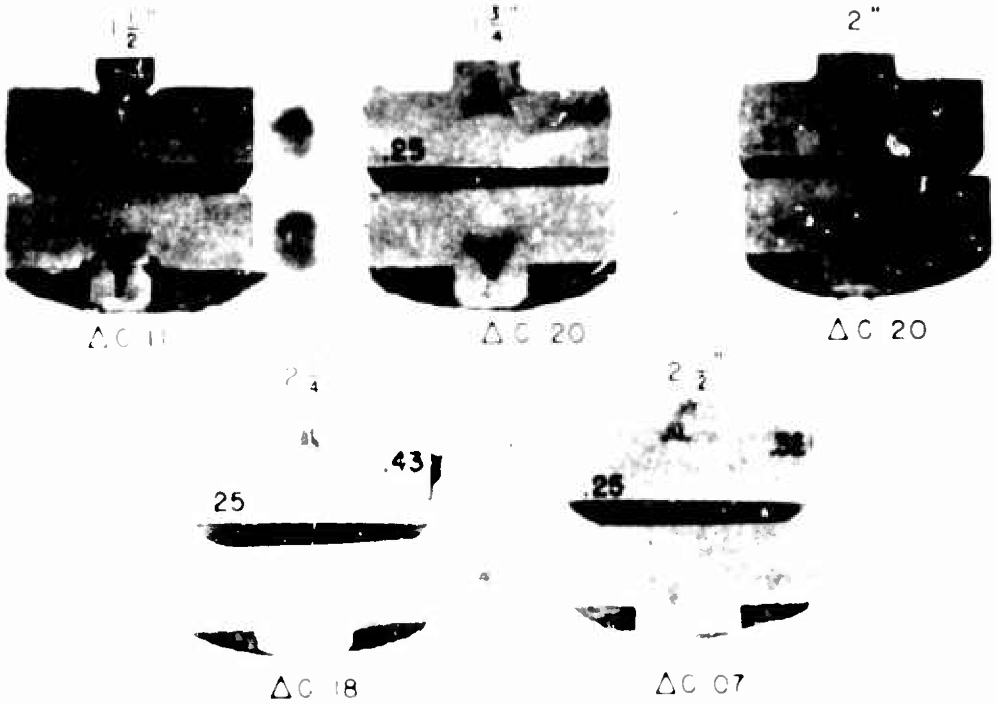


Fig. 23 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Fixed casting dimensions Diameter, 6" - Height, 2" - Neck Length, $1\frac{1}{4}$"

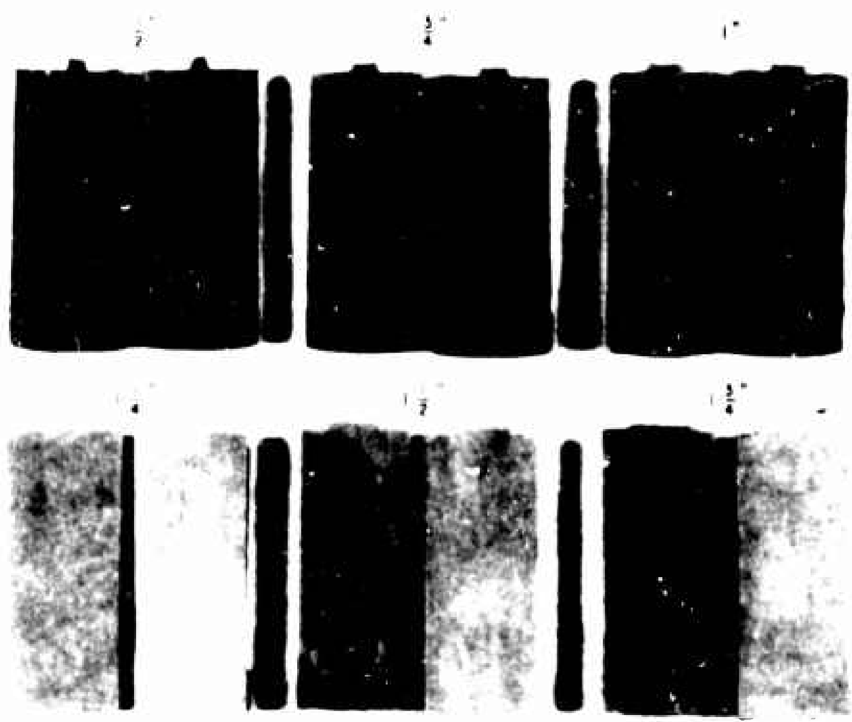


Fig. 24 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions Diameter, 3" - Height, 7" - Neck Length, $\frac{1}{2}$"

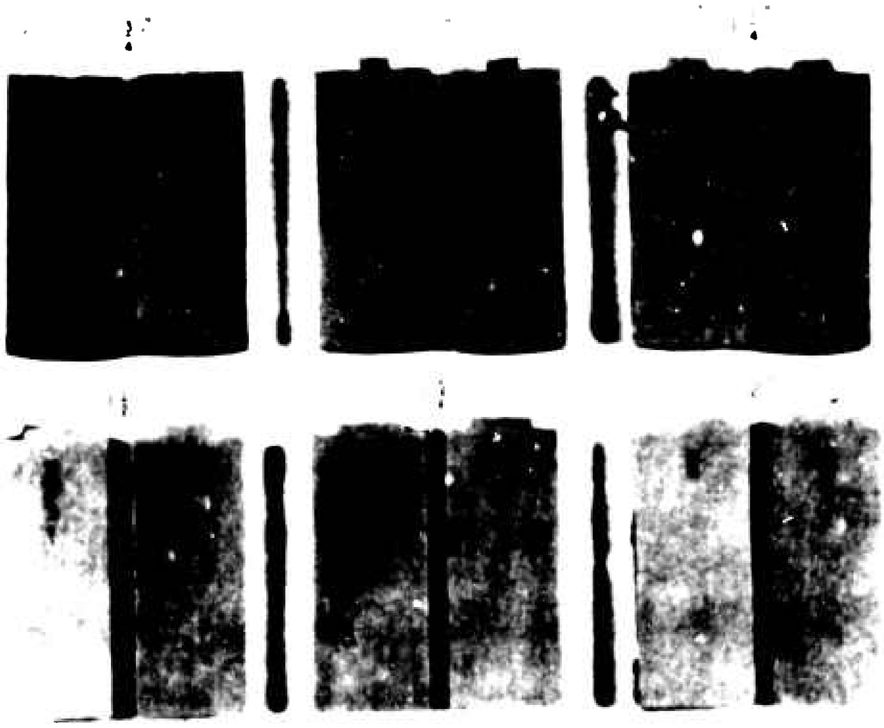


Fig. 25 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, 3" - Height, 7" - Neck Length, $\frac{3}{4}$

Fig. 26 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, 3" - Height, 7" - Neck Length, 1"

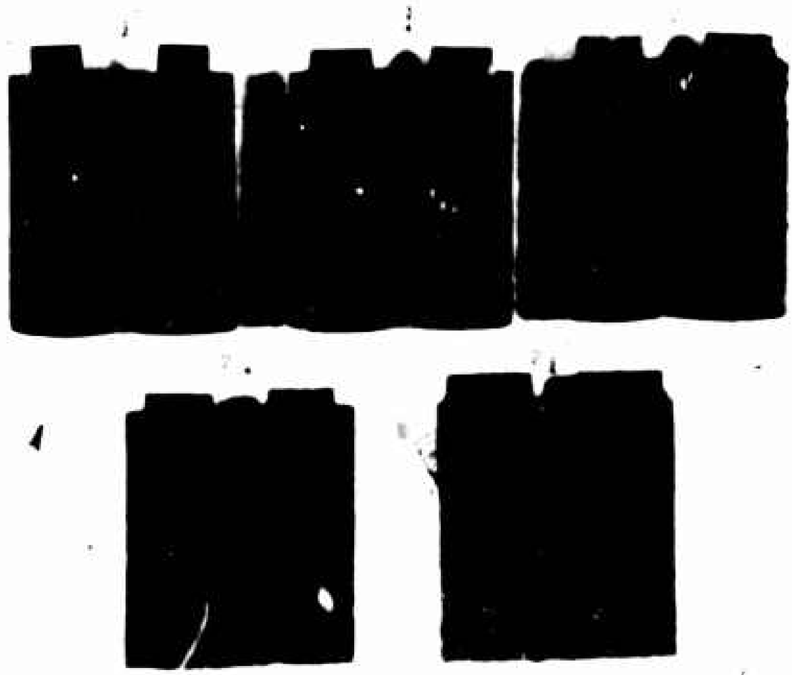


Fig. 27 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions. Diameter, 3" - Height, 7" - Neck Length, 1½"

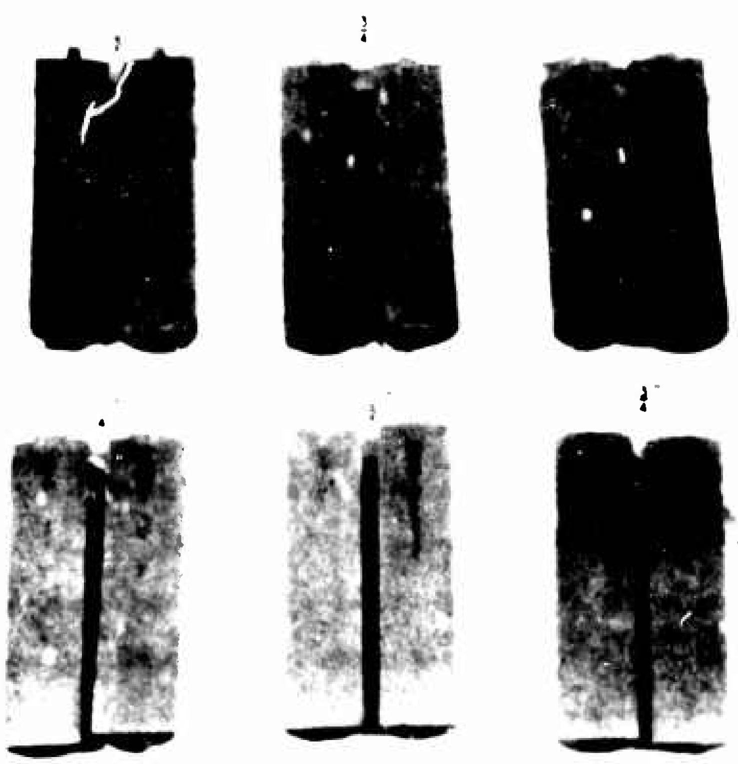


Fig. 28 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions. Diameter, 2½ - Height, 10 - Neck Length, ½

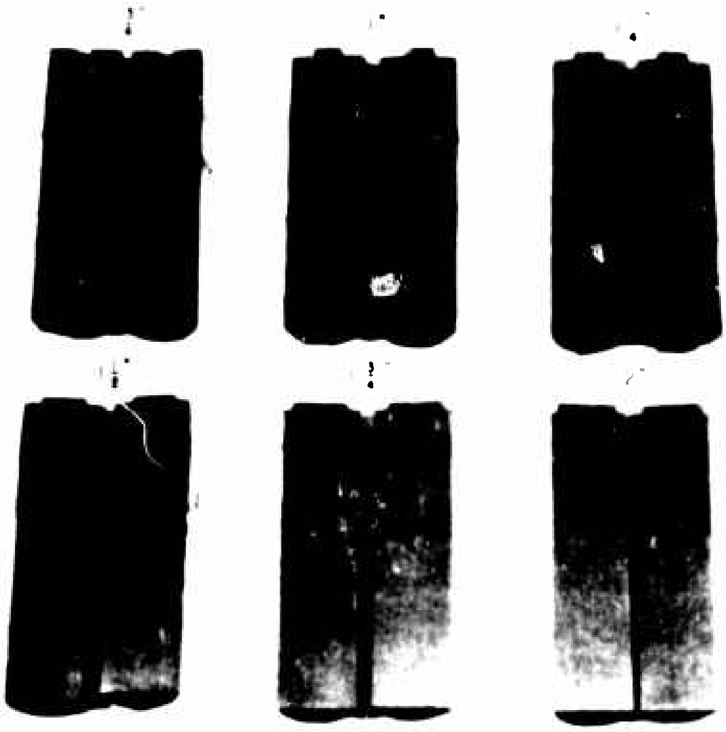


Fig. 29 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, 2"; Height, 10"; Neck Length, ¾"

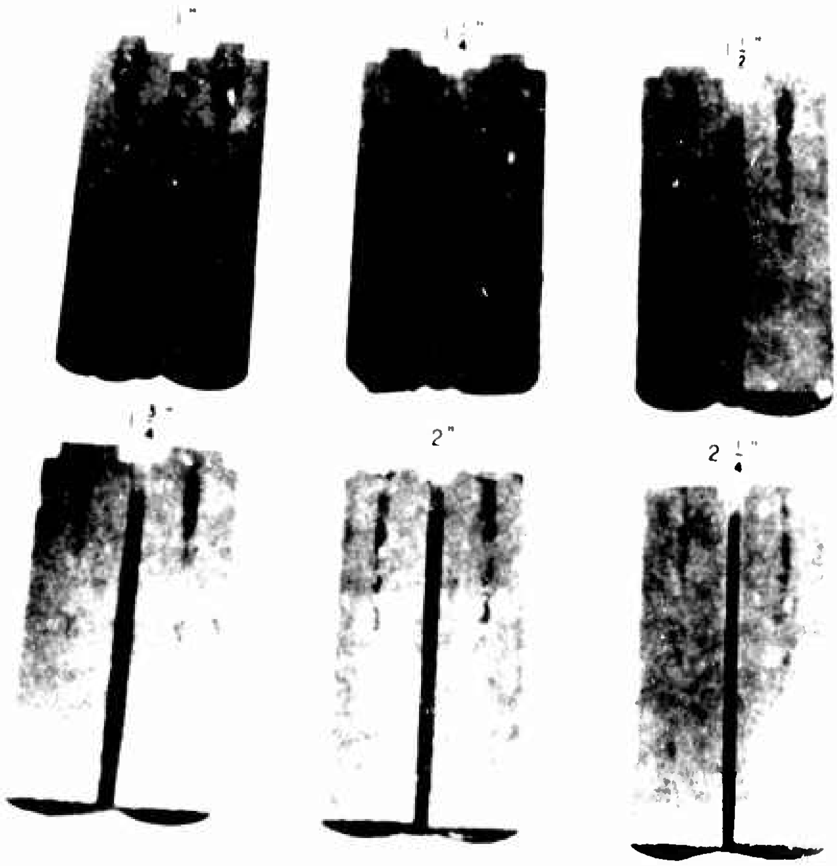
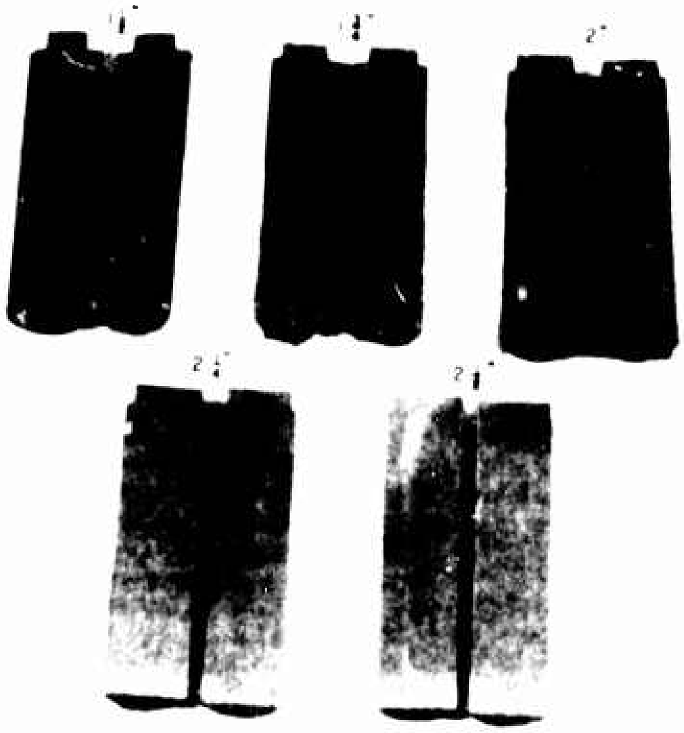


Fig. 30 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, 2½" - Height, 10" - Neck Length, 1"

Fig. 31 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Neck diameters as indicated.

Fixed casting dimensions
Diameter, 2½" - Height, 10" - Neck Length, 1½"



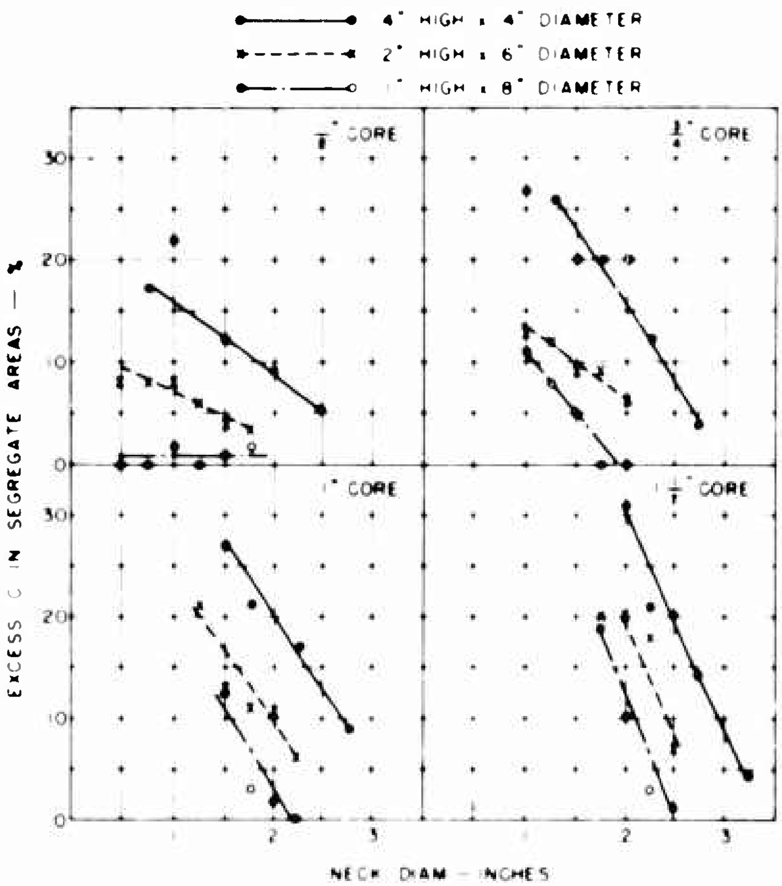


Fig. 32 - Relation between carbon segregation and neck diameter in castings of different thicknesses but of equal volumes. All castings fed by 5-inch-diameter riser

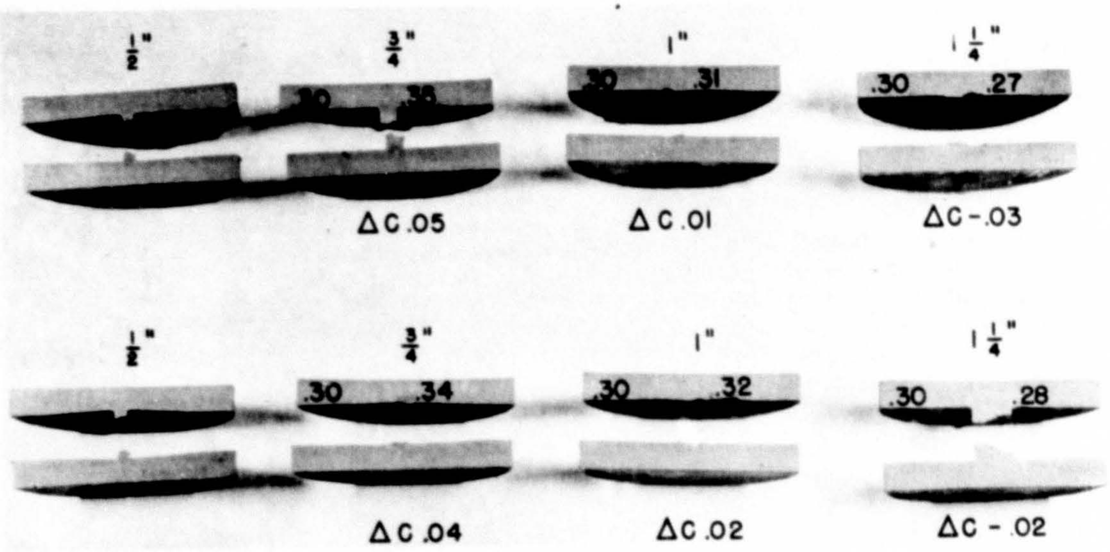


Fig. 33 - Degree of segregation for a given size and shape of casting with varying diameters of cylindrical neck. Carbon contents and neck diameters as indicated. Castings in bottom row gated over core. Fixed casting dimensions: Diameter 8" - Height, 1" - Neck Length, ½" — Fixed riser dimensions: Diameter, 3½" - Height, 4"

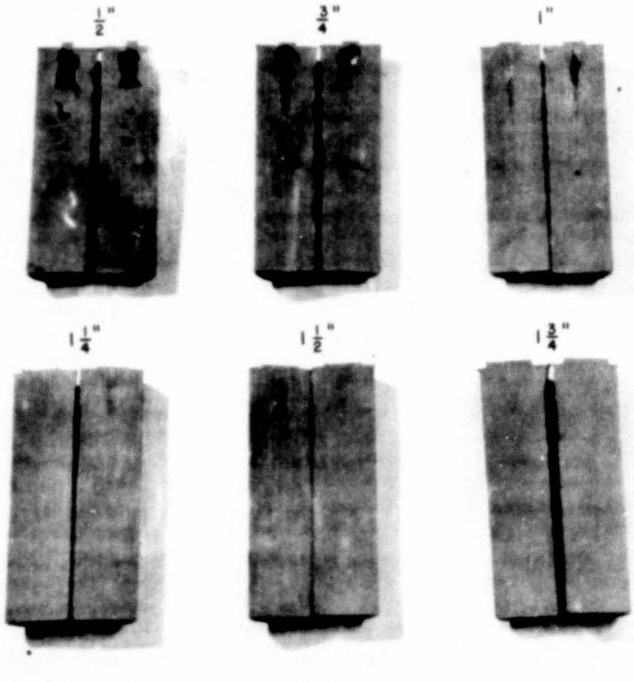


Fig. 34 - Degree of segregation for a given size and shape of top-gated casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, 2½" - Height, 10" - Neck Length, ½"

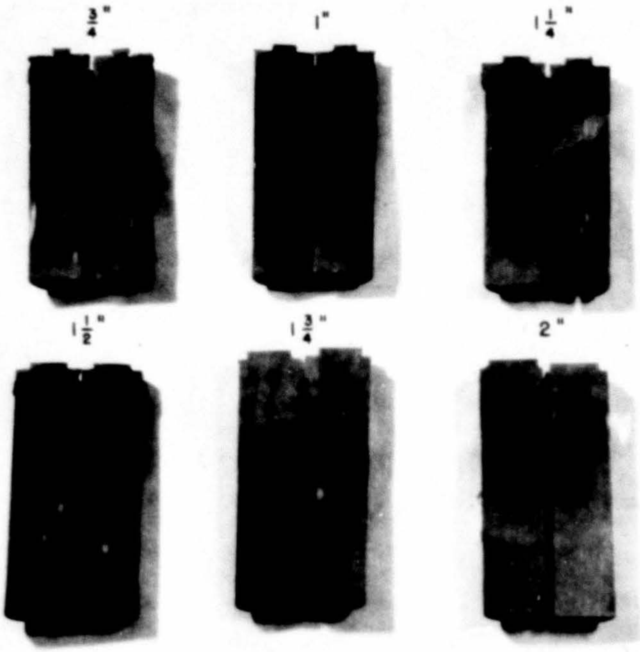


Fig. 35 - Degree of segregation for a given size and shape of top-gated casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, $2\frac{1}{2}''$ - Height, 10" - Neck Length, $\frac{3}{4}''$

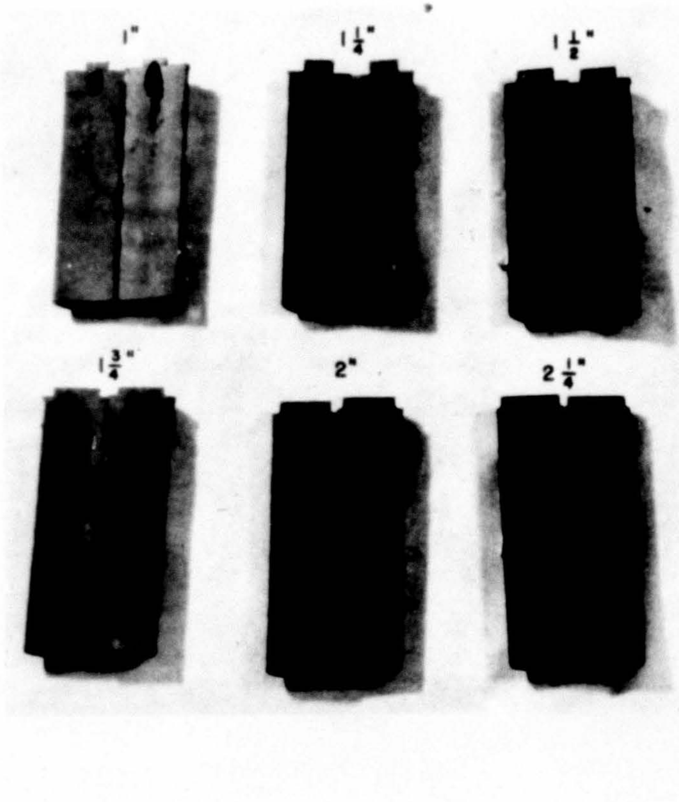


Fig. 36 - Degree of segregation for a given size and shape of top-gated casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, $2\frac{1}{2}''$ - Height, 10" - Neck Length, 1"

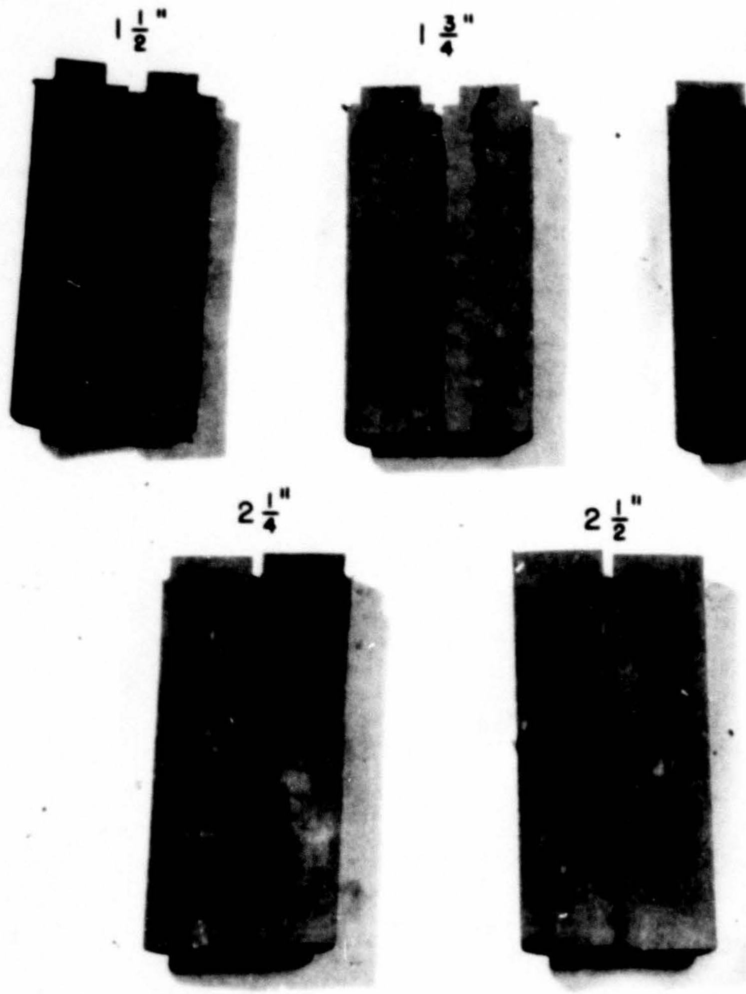


Fig. 37 - Degree of segregation for a given size and shape of top-gated casting with varying diameters of cylindrical neck. Neck diameters as indicated. Fixed casting dimensions: Diameter, $2\frac{1}{2}''$ - Height, 10" - Neck Length, $1\frac{1}{2}''$

Fig. 38 - Photomicrograph through a V segregate (35x)

Fig. 39 - Section of a casting bled near the end of solidification

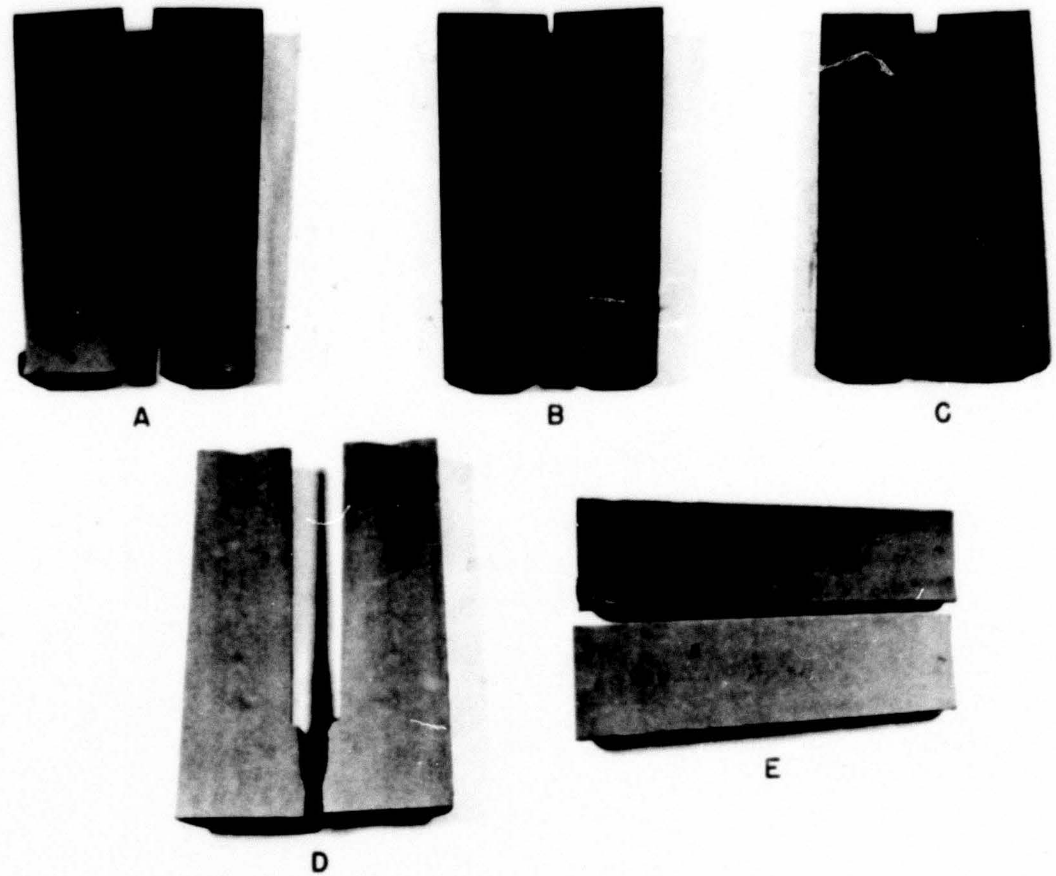


Fig. 40 - Sectioned and etched castings showing that orientation of V segregation is dependent only upon the riser position

(A) Top riser, bottom gate
(B) Top riser, top gate
(C) Inverse-taper top riser, top gate
(D) Bottom riser, gate into riser
(E) Casting made in horizontal position, riser on large end

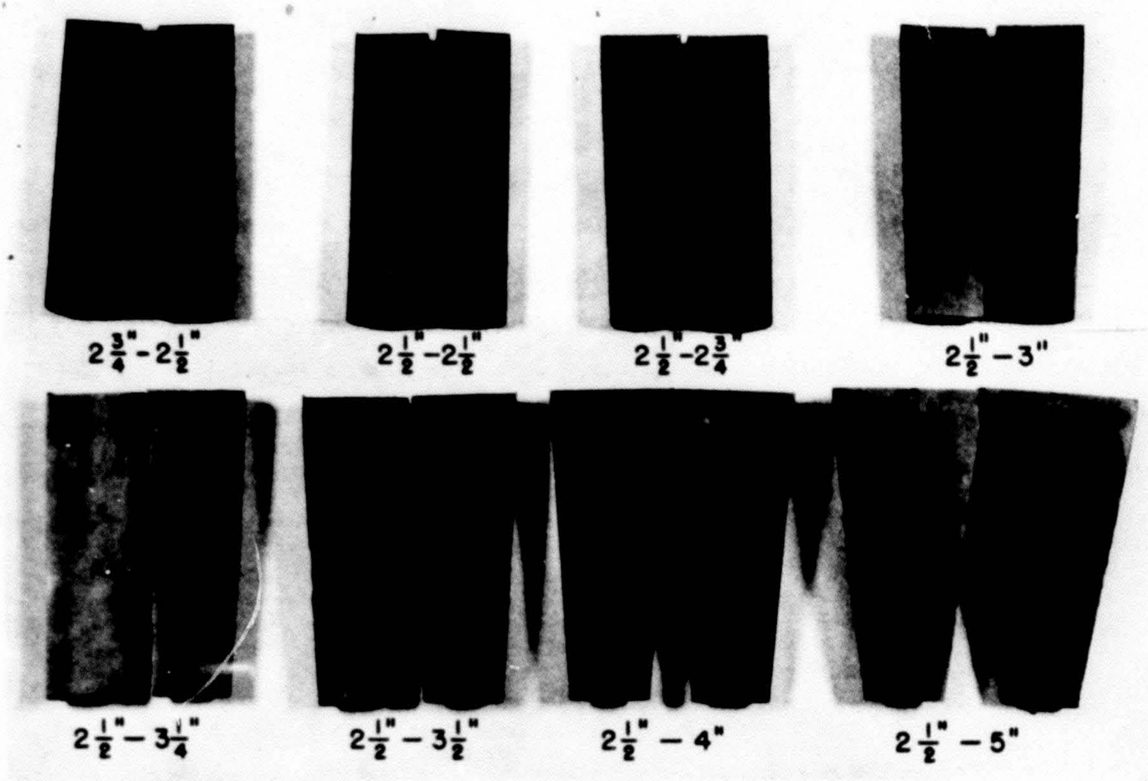


Fig. 41 - Sectioned and etched tapered castings ten inches long, bottom-gated, and with bottom and top diameters as indicated, showing how shrinkage and segregation are influenced by taper

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