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THE EFFECT OF MOISTURE CONTENT ON THE  
ACTION OF SEA COAL IN MOLDING SANDS

by

Robert J. Endres

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A

Thesis

Submitted to the Faculty of the  
University of Missouri School of Mines and Metallurgy  
in partial fulfillment of the requirements for the  
Degree of  
Master of Science in Metallurgical Engineering  
Rolla, Missouri  
1964

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## ABSTRACT

An assumption was made that an increase in moisture content in the sand would result in an increase in the amount of volatile matter retained in a sand, clay, water, and sea coal mixture which had been subjected to the heat of molten iron. Because of a lack of positive evidence to support this assumption, it was concluded that the volatile matter retained within the sample is independent of the moisture content.

It was also shown that the volatile products do not travel back through the sand, away from the mold-metal interface. Rather, the volatiles escape from the sand and are present as a thin film of gas between the metal and the mold.

## ACKNOWLEDGEMENT

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## I. INTRODUCTION

Sea coal is the name given to very finely ground bituminous coal prepared especially for use in the foundry industry as an addition to the molding sand in grey iron and malleable iron foundries. Sea coal is characterized by having a low ash content, a high volatile content, and a low sulfur content. Representative proximate analyses show the sea coal to contain 0.75 to 2.25% water, 32.0 to 38.0% volatiles, 50.0 to 58.0% fixed carbon, 0.70 to 1.0% sulfur, and 3.0 to 8.0% ash. Because sea coal is a gas former and because most non-ferrous metals are gas absorbers, the use of sea coal is not practical in non-ferrous foundry operations.

Sea coal has been used in the foundry industry for over two hundred years. It was considered a necessary evil and was used only because it prevented sand burning onto the casting and gave the casting a smoother and cleaner surface finish. In addition, it was found as the years went by, that the use of sea coal in the molding sand would help to eliminate pinholes, rat-tails, buckles, and other expansion defects; control shrinkage; resist metal penetration; and help to give better dimensional tolerance in the casting. The foundrymen did not know why sea coal would perform all of the services mentioned above and, at the present time, all aspects of the action of sea coal in the mold are not fully understood.

One facet of the problem which seems to have been overlooked by most investigators concerns the volatile products of the coal and the products of combustion after the coal has been subjected to the heat

of the molten metal. Toriello and Wallace,<sup>(25)</sup> in an investigation of the enlargement of grey iron castings due to mold wall movement and subsequent enlargement of the mold cavity, noticed that their molds, after the castings had been removed, contained three distinct layers of discoloration. The zone closest to the mold cavity was silvery grey and was due to the coke remaining from the sea coal. The next zone was a charcoal grey color and supposedly contained the recondensed heavier volatiles. The farthest zone from the casting was lighter in color and supposedly contained the lighter volatiles from the sea coal.

As this was the only reference to the recondensation of the combustion products which could be found, it was decided that a study of the volatile content of the sand as a function of distance from the mold-metal interface would be useful. In particular, the study was concerned with the effects of the moisture content of the sand on the distance through which the volatile products will travel before recondensing in the sand.

It was felt that a study of this type would be of value, not only because it sheds additional light on the overall problem of the effects of adding sea coal to a molding sand, but also because it may give a keener insight into the action of the sand during the critical pouring and cooling periods.

## II. REVIEW OF LITERATURE

Most of the investigation in this field has been conducted in one of two aspects of the problem. These two areas of endeavor have been to determine the effect of sea coal additions on the physical properties of a clay, sand, and water mixture; and to determine and explain the reactions taking place when the sea coal in the molding sand is acted upon by the heat of the molten metal. These two areas, while they may appear to be quite independent of each other, are actually very closely related since the properties of the sand will often determine the effect of the heat upon the sea coal. Likewise, the product left after the coal has burned during pouring will often have a serious effect upon the properties of the recycled sand. However, these areas will be discussed separately for ease of explanation, and will be drawn together only when it is deemed necessary to more fully explain some facet of the complicated series of reactions which may take place in a molding sand to which sea coal has been added.

Two of the most important properties of a clay, sand, and water mixture are the green compressive strength and the permeability. The green compressive strength must be sufficient for the sand to withstand the weight and metallostatic pressure of the liquid metal. The permeability of the molding material must be sufficient to allow the gases, generated by the heat of the molten metal striking the mold, to escape through the sand in order to prevent porosity, blow holes, or any other number of gas-caused defects in the casting. Both of these properties are greatly affected by the addition of sea coal to the molding sand.

Both Morrison<sup>(15)</sup> and Zirzow<sup>(28)</sup> have stated that the slightest addition of sea coal to the molding sand will sharply reduce its permeability. This is due to the fact that sea coal, being very fine, will clog up the pores between the sand grains. Also the ash in the sea coal will gradually accumulate in the sand as it is recycled. As the ash is also very fine, it will also act to fill up the voids and reduce the permeability.

Schauss<sup>(23)</sup> has studied the effects of a variation of fineness of the sea coal on the permeability of the sand. He found that sand which had a permeability number of 70 when sea coal with an AFS fineness number of 95 was used, would have a permeability number of 58 with AFS fineness number 120 sea coal, 48 with AFS fineness number 140, and 40 when sea coal with an AFS fineness number of 165 was added. In each case the weight per cent of sea coal in the mix was the same. When presented graphically, these data showed that the permeability decreased almost linearly as the size of the grains of sea coal decreased.

Saunders and Saunders<sup>(22)</sup> showed that the permeability of a sand containing sea coal was markedly affected by an increase in temperature. They showed that the permeability dropped sharply in the temperature range from 150-200 C, depending upon the per cent of sea coal present. This drop in permeability was explained by the fact that the volatile content of the sea coal was being driven off in this temperature range in the absence of air. This created a back pressure and lowered the permeability. At higher temperatures the permeability decreased, but less rapidly. The further decrease is due to the swelling of the coal and sand grains which fills the voids and reduces the permeability. These investigators also found that the sea coal would reduce the

permeability at room temperature even after the volatiles had been driven off. This would seem to agree with Morrison<sup>(15)</sup> and Zirzow<sup>(28)</sup> who stated that the fineness of the ash and carbon act to reduce the permeability at room temperature.

Most investigators have agreed that the addition of sea coal will increase the strength of molding sand at room temperature. Zirzow<sup>(28)</sup> has explained this phenomenon by the fact that, for some reason, the sea coal allows better distribution of the clay around the sand grains. He goes on to explain that the clay is probably thinned out, which causes it to more nearly approach its maximum efficiency for causing the sand grains to adhere to each other.

Parkes<sup>(16)</sup> states that the addition of 5% very fine sea coal increased the strength of his sand from 110 psi to 175 psi. Parkes brings up an important point when he states that these figures may not mean much, as the addition of sea coal necessitates an increase in the amount of water needed to temper the mixture. Thus, the addition of sea coal may increase the strength; but what percentage of this increase is due to the sea coal and what percentage is due to the increase in moisture is not readily known.

Parkes sheds additional light on the problem by stating that the addition of sea coal will have little or no effect upon the strength unless the grading of the sea coal is very much different from that of the sand. This seems reasonable if, according to Zirzow,<sup>(28)</sup> the sea coal is to mix with the clay and surround the sand grains rather than to act similar to the sand grains, which the coal would certainly do unless it was very much smaller than the sand.

Schauss<sup>(23)</sup> has investigated the question of how the size of the sea coal affects the strength at room temperature. He found that a sea coal of fineness number 95 gave his sand a dry compressive strength of about 31 psi, fineness number 120 gave a strength of about 42 psi, 140 gave about 48 psi, and a sea coal with an AFS fineness number of 165 gave the sand a dry compressive strength of about 65 psi. Schauss presented these data graphically and showed that the dry compressive strength increased almost linearly as the size of the sea coal decreased.

Hird<sup>(9)</sup> used a different approach to the problem of strength in sands to which sea coal had been added. He milled sand which showed an increase in strength after each use which could not have come from the clay bond. Examination showed each sand grain to be covered with carbon. This rough carbon deposit, combined with a small per cent of distilled tar, gave a bond which was partly frictional and partly glutinous. Hird believed this bond to be responsible for the increase in strength after sea coal had been added.

There has not been so much work done on the hot strengths of molding sands as has been done on the strengths at room temperature. Parkes<sup>(16)</sup> reported that the strength of a synthetic sand with 5% sea coal remained constant at 175 psi up to 400°C, then fell to 140 psi at 700°C. Parkes explained this by the fact that sea coal partially liquifies in this range. As the temperature rises, the amount of liquid increases and the strength decreases. Parkes added that any liquid formed in the mold wall would decompose. This decomposition would increase the viscosity of the liquid while the amount decreased, tending to offset the reduction in strength. Parkes concluded that the

amount of sea coal and the rate of heating are the important factors in determining the amount of reduction in strength. This agrees with the work of Sanders,<sup>(20)</sup> who showed that the hot strength of an AFS standard test sand at 950° F is reduced from 80 psi with no sea coal to 65 psi with 4% sea coal.

Another aspect of the effect of sea coal on the properties of molding sands is the effect of sea coal on the expansion and contraction of the sand at elevated temperatures. Several investigators have found that the addition of sea coal controls sand expansion and contraction during the pouring and cooling cycles. Dietert and Valtier<sup>(7)</sup> stated that sand without sea coal had an expansion of 0.016 inches per inch while the same sand with 12% sea coal had an expansion of only 0.007 inches per inch. The contraction of the sand without sea coal was 0.0134 inches per inch and with 12% sea coal was only 0.0055 inches per inch. Dietert and Valtier showed that the reduction in both expansion and contraction of the sand increases as the amount of sea coal present increases, the reduction increasing very rapidly from 8 to 12% sea coal.

Roberts and Woodliff<sup>(19)</sup> showed that sea coal acts to decrease the expansion and contraction of the sand not only during the pouring cycle, but throughout the solidification period of the casting as well. Using 7% sea coal with a natural Tennessee sand, they showed that the effect of the sea coal increased as the number of minutes after pouring increased. Roberts and Woodliff also showed that a coarser grade of sea coal, because it does not burn so quickly as a finer grade, will remain an active expansion control element over a longer period of time.

No investigator has offered a definite theory as to how sea coal acts to reduce both expansion and contraction. However, it has been suggested that sea coal acts as a buffer between the expansion of the sand grains and the contraction or shrinkage of the clay. This buffering action of the sea coal is important in that it reduces scabs, rat-tails, and buckles, which are all common defects caused by thermal instability of the molding sand.

Dietert and Dietert<sup>(6)</sup> and other investigators have found that the addition of sea coal will increase the hot deformation rate of the sand up to 6% sea coal. Above 6% the deformation decreases. Dietert and Valtier<sup>(8)</sup> have shown that the addition of sea coal will reduce the flowability of the sand due to an increase in green strength and the low flowability of the coal.

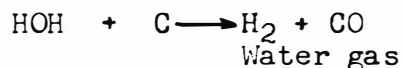
The second of the two most popular areas of investigation has been the study of what actually happens when the sea coal is subjected to the heat of the molten metal. In these studies, investigators have attempted to theorize the mechanics of the process and to use these theories to explain why sea coal is effective in producing a better surface finish and in preventing the sand from burning onto the casting.

The first problem for the investigators to solve was the exact effect of the molten metal upon the sea coal during pouring of the mold. Although many investigators have explained this action very well, Aptekar<sup>(1)</sup> has presented one of the most complete and detailed explanations.

Aptekar stated that there was a release of a large volume of steam from the moisture in the sand upon the introduction of the iron. As



the temperature of the sand goes quickly above 840 F, the combined water of the clay and sea coal begin to distill off and the sea coal softens. The lighter volatile components of the sea coal decompose and form water gas with the steam being driven off according to the following equation:



Aptekar goes on to state that dehydration and shrinkage of the clay take place rapidly. The sea coal, which is a swollen, frothy mass by this time, flows into the cracks in the clay. The mold face is deformed due to the shrinkage of the clay and the expansion of the sand grains. As the temperature continues to rise, the heavier hydrocarbons are driven off and the sea coal is present as a boiling tarry mass. This tarry mass fills in the cracks caused by the expansion of the sand grains and shrinkage of clay. The evolution of the heavier hydrocarbons continues until only coke or carbon is left. As the silica expansion continues, the coke acts as a binder and shrinks to make up for the expansion of the sand.

Zirzow<sup>(26)</sup> has published a theory which agrees quite well with Aptekar's ideas. Zirzow adds some personal observations which help to support his theory. He states that a person observing a mold during the pouring cycle sees first steam coming off, then a blue flame caused by the burning of the water gas, and finally, dark gases which are evolved due to the distillation of the heavier hydrocarbons. As a result of his observation, Zirzow concludes that there are four complete reactions taking place at the mold-metal interface.

1. Evaporation of the tempering water.
2. Distillation of the volatile matter in the sea coal.
3. Formation of coal tar or viscous ingredients.
4. Formation of the coke.

Most investigators agree, more or less, with the ideas presented above. These theories have been applied in an effort to explain how the addition of sea coal can help to alleviate or eliminate some of the defects which have been mentioned above.

According to Meader,<sup>(14)</sup> there are three distinct theories as to how sea coal helps to produce a good surface finish. The first of these states that the molten metal vaporizes the sea coal. The resulting gas is rich in carbon and deposits a layer of soot on the interface between the metal and the mold. This layer of soot serves to prevent the metal from wetting the sand grains, which it must do in order to react with them and form a rough surface.

Another theory is that the molten metal vaporizes the sea coal, which forms an envelope of gas between the metal and the mold. Theoretically, the envelope of gas prevents the metal from actually coming into contact with the grains of sand. Thus, a good surface finish is effected.

Meader goes on to state that the most widely accepted theory is the formation of a reducing gas during the destructive distillation of the sea coal. The iron in the mold will oxidize in the presence of air. The ferrous oxide then attacks the sand grains to form a thin, glassy slag which adheres to the casting and causes a poor surface finish. The presence of a reducing gas in the mold will prevent the formation of iron oxide, thus preventing slag formation and insuring a smoother, cleaner surface on the casting.

Investigators are divided as to which of these theories is responsible for the effectiveness of sea coal in producing a better surface finish. No investigator really adheres to one theory and disproves the other two. It is possible that all three explain accurately the action of sea coal.

Silk<sup>(24)</sup> has stated that fine sea coal flashes quickly and deposits a carbon film between the metal and the sand. This soot fills the voids in the sand and provides a smoother surface against which the metal may lie.

Hird<sup>(9)</sup> agrees with Silk and states that the sea coal along the side of the mold cavity will volatilize. Carbon from the escaping gases is deposited in the form of soot on the upper sides and top, giving extra protection to the sand.

Reichert and Woolley<sup>(18)</sup> argue that the sand grains expand and cause the permeability to decrease as the sand becomes hotter. The coal also begins to expand and these expansions cause the permeability of the sand to be reduced to very low values. At the same time, the volatile matter of the coal comes off as the destructive distillation of the coal begins. As the permeability of the sand behind the sea coal has been drastically reduced, these gases have no place to go except out along the face of the mold where they must act as a film between the metal and the mold.

As was pointed out by Meader,<sup>(14)</sup> the most widely accepted theory is that a reducing gas is formed in the mold during the distillation of the coal. As has already been stated, the reducing gas prevents the formation of iron oxide which reacts with the silica to produce slag.

Jones and Grim<sup>(12)</sup> have used this theory to explain how sea coal prevents the formation of pin holes in malleable iron castings. Jones and Grim contend that pin holes result from water vapor which combines with iron according to the equation:



The oxide is present in a layer of scale because of its slow rate of diffusion. The atomic hydrogen readily diffuses into the iron and raises its hydrogen content. The hydrogen then combines with the oxide to form a bubble of water vapor which grows as more hydrogen diffuses into the bubble. As the metal solidifies and the growth of the bubble slows down, the bubble is sealed off and a pinhole is formed.

Jones and Grim further state that sea coal, although it is a heavy gas producer, decreases the ease with which pinholes are formed. This is due to the fact that the carbon in the coal has a greater affinity for the oxygen than the iron. Thus, carbon monoxide will be formed rather than the iron oxide and the formation of pinholes is reduced.

Besides improving the surface finish by reducing metal penetration, and reducing expansion defects such as rat-tails, scabs, and buckles, sea coal has also been credited with reducing shrinkage defects such as piping. Sanders and Sigerfoos<sup>(21)</sup> have done a good deal of work in this area and have concluded that sea coal increases the stability of the mold-metal interface. They discount the theory that the gas pressure from the sea coal, after the metal has entered the mold, tends to counteract the pressure of the metal and thus stabilize the mold. They argue that a permeability of 73 to 115, such as that of the sands which they tested, would make this theory infeasible.

A more acceptable theory, according to Sanders and Sigerfoos, is that sea coal cokes and expands upon heating. This expansion is the force which tends to counteract the movement of the sand due to the pressure of the metal and, thus, reduces shrinkage.

In addition to the studies done on the more theoretical aspects of the use of sea coal, a good deal of attention has been given to the problem of when to add the sea coal, whether to add it to the heap sand or a special facing sand, exactly how the sea coal should be added, and, finally, how much sea coal should be used in a typical situation.

Zirzow<sup>(27)</sup> has studied the problem of when the sea coal should be added during the reconditioning cycle. According to this investigator, a foundryman has four choices as to when he might add sea coal to his sand. One choice is to add the sea coal to the rebonding mixture. However, as Zirzow points out, this choice is not advisable because of the adverse effect upon the bond and permeability of the clay and sea coal balling up and causing segregation.

The foundryman's second choice is to add the sea coal by itself during the milling of the green sand. This choice again presents the danger of segregation with its resulting loss in bond strength and permeability.

The two remaining choices are to add the sea coal either with facing or with the burned sand at the mill. Zirzow states that these methods are best and are the ones with which most uniform results are obtained.

Morrison<sup>(15)</sup> also believes that the foundryman has several choices. He eliminates adding sea coal to facing sand, but agrees that adding the sea coal to the burned sand at the mill gives the best distribution.

Schauss<sup>(23)</sup> concludes from his investigation of the problem that it is common for foundries to shake out the castings and heap the sand into long, low piles to which are added the bond and sea coal. In some cases the bond and sea coal are added to the top of the molds before dumping.

If a continuous mill is used, Schauss believes that the sea coal may be added to the stream of sand either before it enters the mill or at the point where the sand enters the mill.

There has been some discussion as to exactly how the sea coal should be added. Schauss<sup>(23)</sup> is of the opinion that when sea coal is added to the muller, the dry materials are added into the mill, then the water. Investigators in the Pontiac Motor Division<sup>(17)</sup> believe that a slurry could be used to deliver sea coal to the sand. The slurry contains bentonite, 5-8% sea coal and 3-4% water. This slurry holds up to 1-1/4 lb. sea coal per gallon.

None of the other investigators mentioned using a slurry, so it is assumed that the sea coal was added dry as Schauss did. However, Dietert<sup>(4)</sup> states that the sea coal may be coated with a thin film of a neutral hydrocarbon which will help to avoid dusting.

Most of the investigators failed to mention whether a special facing sand should be made, or the sea coal added directly to the heap sand. It would seem likely that adding sea coal to the heap sand would not be so economical as making a facing sand. The sea coal would eventually make its way into the heap sand. However, the making of a

special facing sand would perhaps encounter additional materials handling problems of which this author is unaware.

The amount of sea coal to be added is one problem which has been given much attention. According to Zirzow,<sup>(28)</sup> there are five factors which should be considered when determining the amount of sea coal to be used. The first factor is the amount of burned core sand. The burned core sand increases the volume of the sand grains and necessitates the use of additional sea coal.

The second factor is the condition of the castings when shaken out of the mold. Because of a greater danger of oxidation at higher temperatures, castings dumped at red heat require more sea coal than those dumped at black heat.

The casting area and cross section is the third factor. A greater surface area means that more sea coal will be converted to ash. A larger cross section means that there will be greater heat penetration of the sand.

The fourth factor is the pouring temperature. A higher pouring temperature requires more sea coal and a 50°F change will produce a marked effect on the surface finish of the casting.

Finally, the permeability of the sand is a factor. Zirzow claims that higher permeability allows better heat dissipation. A high permeability means a larger number of interconnecting voids are present in the sand.

Silk<sup>(24)</sup> offers more quantitative data on the subject of the effect of casting thickness on the amount of sea coal to be used. Silk contends that 6% sea coal should be used for castings 3/16" - 1/4" in thickness,

8% for thicknesses of 1/4" - 5/8", 10% for 5/8" - 1 1/2" thicknesses, 12.5% for 1 1/2" - 2 1/2" thicknesses, and 15% sea coal for castings over 2 1/2" thick. Silk cautions against using over 15% sea coal because of the resulting ash contamination of the sand. This warning brings up another important question. What are the harmful effects of using sea coal, especially of using too much sea coal?

One of the most undesirable properties of the sea coal is its effect in sharply reducing the permeability of the sand to which it has been added. However, as this has been discussed under the general topic of the effect of sea coal on the properties of the molding sand, no further mention will be made of it here. Likewise, the fact that sea coal reduces the hot strength and flowability of the sand and necessitates a greater amount of clay and tempering moisture will be mentioned here only to show that these are some of the objections to the use of sea coal which have been raised by the various investigators.

The most serious objections to the use of sea coal are the defects which result from using too much sea coal. Zirzow<sup>(28)</sup> has compiled a list of results from the improper use of sea coal, all of which result from using too much. Zirzow lists rat-tails, cold shuts, misruns, dirt, drops, and surface checks as defects caused by excessive sea coal. This list of possible defects is substantiated by similar lists by such investigators as Clark<sup>(2)</sup> and Morrison<sup>(15)</sup>

Reichert and Woolley<sup>(18)</sup> and Jones<sup>(11)</sup> have contributed to the study of why excessive sea coal causes veining in castings. Jones contends that veining is due to coking of the sea coal. As the coal is exposed to heat, free water is immediately driven off. Volatile matter is



driven off, the coal breaks open, and gas escapes through the fissures. The high boiling point volatiles are finally driven off through a mass of boiling liquid pitches. Gas, breaking through the carbonaceous material, forms thin skins of coke or carbon. The physical size increases due to expanding gases in a plastic mass. The whole mass begins to shrink when the last gases escape, and when it has lost plasticity, shrinking stops. Coke then has sufficient strength to resist erosion by the iron.

Reichert and Woolley<sup>(18)</sup> reported that a "grape vine" effect was produced on the surface of their castings when 5% sea coal was used. They caution that their results do not indicate that veining will occur whenever 5% sea coal is used because the effect of the sea coal varies with the temperature of the iron, character of the sand, and type of casting produced.

Kiley<sup>(13)</sup> stated that he was forced to reduce the ratio of sea coal in his facing sand from a 1 to 8 ratio by volume to a 1 to 11 ratio, for if a ratio of 1 to 8 was used, veining occurred on the surface of the casting.

The final objection to the use of sea coal, as mentioned by Clark<sup>(2)</sup> and others, is the difficulty of controlling sea coal additions properly. It appears that the only control is to keep a record of the weight of sea coal added per ton of metal poured and to refer to these records periodically.

In view of the many objections to the use of sea coal, there has been a considerable amount of research done in comparing sea coal to other additives such as pitch, wood flour, cereal, and silica flour.

Dietert and Barlow<sup>(5)</sup> showed that the hot deformation rate of sand in the range between 500 and 1500°F is increased by the addition of wood flour and cereal. It is reduced by the addition of sea coal, pitch, and silica flour. At 2000°F wood flour, pitch, sea coal, and cereal all greatly increase the hot deformation rate. Sea coal, however, imparts by far the greatest increase.

Johnston<sup>(10)</sup> showed that sea coal reduces the hot deformation rate at 1200 F, while cereal and wood flour increase the rate of deformation. Johnston claims that this is due to the fact that the sea coal won't burn out to leave voids in the sand at this low temperature. However, at 2400°F sea coal produces a hot deformation of 0.646 inches per inch which easily accommodates expansion at that temperature.

Johnston also studied the effect of various additives on the hot compressive strength at 2000°F. No additives produced a strength of 430 psi, adding only 2% wood flour reduced strength to 192 psi, 5% sea coal decreases strength to 205 psi, and 2% cereal yields 390 psi.

On the subject of reducing porosity in grey iron castings, Dawson and Smith<sup>(3)</sup> state that the addition of 6% sea coal will suppress pinholes, but will increase the hydrogen pickup by the metal. Pitch will also suppress the pinholes and doesn't increase hydrogen pickup.

Finally, on the practical and economics side, Sanders<sup>(20)</sup> reports that small additions of wood flour will replace a greater weight of sea coal. Moreover, the wood flour is much cleaner to handle than the sea coal.

## III. LABORATORY WORK

A. Preparation of the mixes.

Each batch of sand was to contain, on a dry basis, 8.0% sea coal, 7.0% Southern bentonite, and 85% pure silica sand. The dry constituents were weighed out and charged into a Simpson mixer. A pre-calculated weight of water was added to the dry mix and the batch was mulled for five minutes. The amount of water added in each case was varied so as to produce a series of mixes containing from 1.0% to 5.0% water. The variation in moisture content between two successive mixes was 0.5%. After mixing, each batch was sealed in a glass jar until needed.

B. Preparation of standard samples.

Standard specimens were made from each mix using AFS standard sand ramming equipment. To make a specimen, a quantity of sand was rammed three times. Each ram consisted of a fourteen pound weight falling two inches and compressing the sand within a steel cylinder whose inside diameter was  $2.000" \pm 0.001"$ . Thus, the finished sample was a right circular cylinder with a diameter equal to that of the steel cylinder. A specimen was considered acceptable if the height of the specimen was  $2.00" \pm 1/32"$ . Two specimens were made from each batch whose moisture was an integral per cent (1.0%, 2.0%; etc.). One standard specimen was made from each mix whose moisture was 1.5%, 2.5%; etc. The duplicate samples were used to check the reproducibility of the results.

### C. Preparation of the sand molds.

The molds into which the standard specimens would be placed were made using the heap sand available in the foundry. The pattern used in each mold was of wax and had been made by pouring molten paraffin wax into the same cylinder used in making the standard specimens. After removal of the wax pattern from the steel cylinder, it was sectioned longitudinally. This produced a split pattern which facilitated the molding operation.

Using the pattern described above, the sand mold contained a cavity two inches in diameter and four inches in length. The molds were so constructed that the longer axis of the mold cavity was horizontal. An illustration of the specimen in the mold cavity may be found in Figure 1 on the following page.

### D. Pouring the molds.

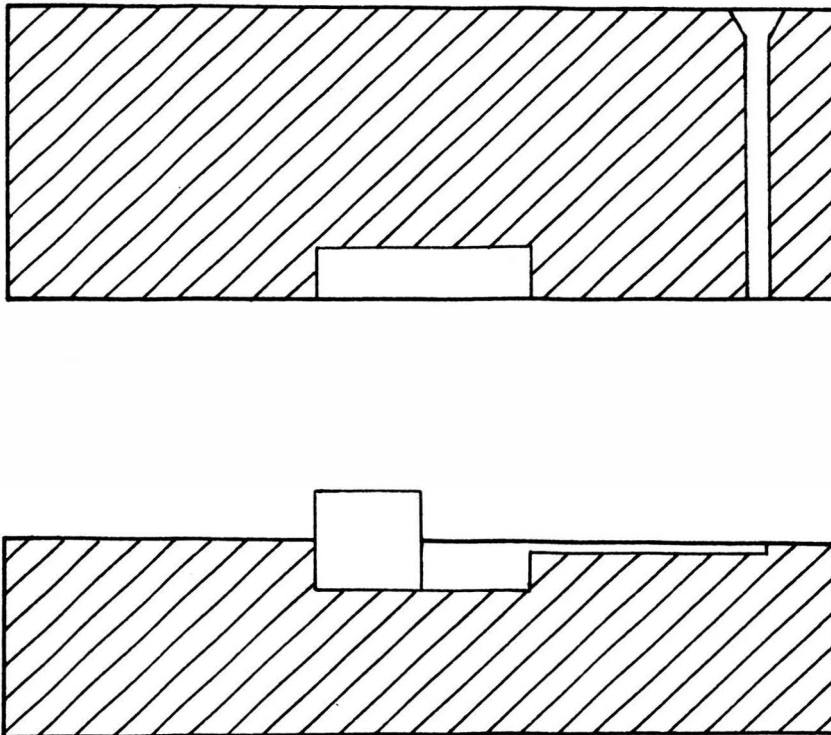
Once the required number of molds had been made, grey iron was melted in an Ajax induction furnace and heated to a temperature of 2600 - 2700° F.

Immediately before pouring, the mold was opened and the standard specimen was placed in the cavity in a horizontal position at that end of the cavity opposite the gate. This arrangement allowed the molten metal to flow into the mold cavity and lie against the one base of the standard specimen. Thus, the specimen was heated only on one end and a temperature gradient developed within the specimen.

### E. Testing for volatile content.

After the castings had cooled, each specimen was removed from the mold and sectioned longitudinally with a hacksaw blade. One half

*FIGURE 1. SECTION OF MOLD SHOWING  
SPECIMEN IN MOLD CAVITY*



*DRAWING NOT TO SCALE*

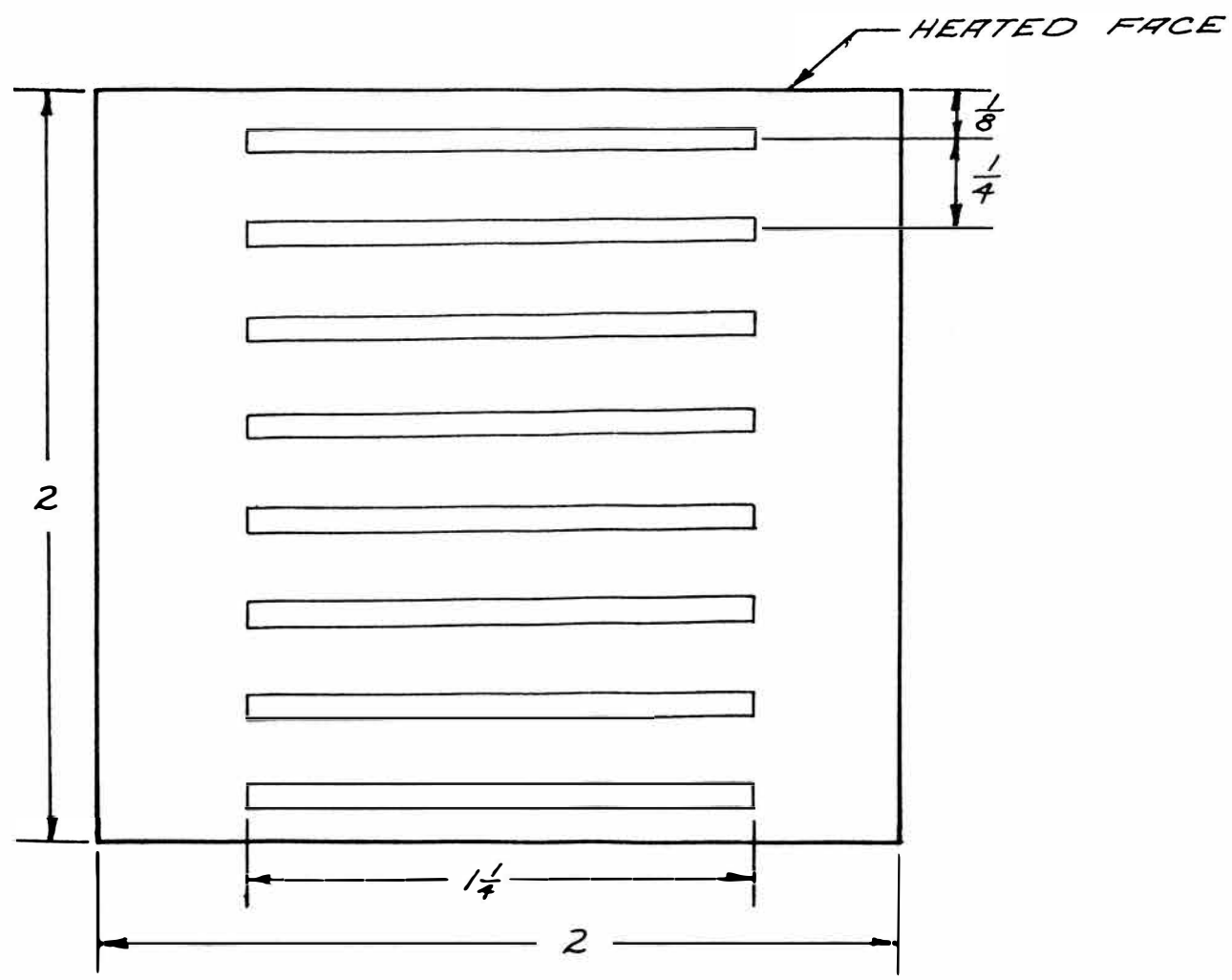
of the sectioned sample was then used to test for the volatile content at specific distances from the end against which the metal had lain.

Samples were taken from the sectioned cylinder at distances of  $1/8"$ ,  $3/8"$ ,  $5/8"$ ,  $7/8"$ ,  $1-1/8"$ ,  $1-3/8"$ ,  $1-5/8"$ , and  $1-7/8"$  from the heated end. Each sample was then dried in an oven for one hour at  $110^{\circ}\text{F}$ . This temperature was chosen in preference to one more nearly approaching the boiling point of water to insure little or no volatilization of constituents other than water during the drying period.

After drying, each sample was weighed and the weight recorded. The sample was placed into a boat and the boat was placed in a tube furnace at a temperature of  $950^{\circ}\text{C}$ . To avoid burning the coal, argon flowed through the furnace to maintain a neutral atmosphere with the furnace. After being held in this inert atmosphere for seven minutes, the boat was removed from the hot zone of the furnace and allowed to stay in a much cooler zone of the furnace for four minutes. This brought the temperature of the sample down low enough to eliminate the danger of burning the sample when the boat was taken out of the furnace and the sample was exposed to the atmosphere.

After the sample was removed from the furnace, it was reweighed and the final weight recorded. The loss in weight was calculated for each sample and expressed as a per cent of the original weight. An illustration of the specimen, showing the positions from which the samples were removed, can be found in Figure 2. on the following page.

FIGURE 2. HEATED SPECIMEN SHOWING POSITION OF SAMPLE REMOVAL



ALL CUTS  $\frac{1}{32}$ " -  $\frac{1}{16}$ "

SCALE 2" = 1"

F. Testing for losses not due to volatile content.

The testing described above was carried out on the assumption that the weight loss corresponds to the volatile content of the sand. However, there were reasons to believe that the loss of other constituents in the sand may have added to the loss in weight. To determine the loss in weight due to constituents other than the sea coal, a batch was made without sea coal. The sand and clay in this batch were present in the same ratio as in the batches containing sea coal.

Several samples from this additional mix were dried in the same manner as described above. After drying, the samples were tested in the tube furnace, again, as described above. It was found that the loss in weight from these samples was fairly consistent and equal to 0.738% of the weight of the sample. While no definite reason can be given for this additional weight loss, it is assumed that the loss is due to moisture not driven off during the drying period and to moisture which is chemically combined with the clay. It should be noted that the reasons for this additional loss are not of great importance with respect to the problem. What is of importance is that the value of 0.738% was then used as a correction factor for the data obtained when testing for volatile content. It is felt that the corrected weight loss is due only to a loss of volatiles in the sand sample. The data for this determination are found in Table 1 on page 26.

G. Testing for volatile content of the sea coal.

Four samples of sea coal were tested for volatile content, using the same procedure as outlined above. The average volatile content of the sea coal was found to be 39.30%. As the sea coal constituted 8.0%



of each mix, it was calculated that the mixture of sand, clay, sea coal and water contained 3.14% volatiles before being subjected to the heat of the molten metal. This value was used to determine the change in volatile content due to the heating of the sample. The data for this determination are found in Table II on page 27.

TABLE I - DATA AND RESULTS FOR THE DETERMINATION OF WEIGHT LOSS  
NOT DUE TO THE VOLATILE CONTENT OF THE SEA COAL

Original Weight	Final Weight	Weight Loss	Per Cent Loss
0.941 gm.	0.934 gm.	0.007 gm.	0.744%
0.820 gm.	0.814 gm.	0.006 gm.	0.732%
0.813 gm.	0.807 gm.	0.006 gm.	0.738%

Average Weight Loss = 0.738%

TABLE II - DATA AND RESULTS FOR THE DETERMINATION OF THE VOLATILE  
CONTENT OF THE SEA COAL

Original Weight	Final Weight	Weight Loss	Volatile Content
0.673 gm.	0.406 gm.	0.266 gm.	39.5%
0.720 gm.	0.438 gm.	0.282 gm.	39.2%
0.288 gm.	0.174 gm.	0.114 gm.	39.5%
0.489 gm.	0.298 gm.	0.191 gm.	39.0%

Average Volatile Content = 39.3%

#### IV. DISCUSSION OF RESULTS

The results obtained from the laboratory work can be seen in Table III on page 34. The same data has been presented graphically in Figures 3 through 15 immediately following this discussion.

For ease of explanation the experimental results may be categorized under two topics. The first category concerns results dealing with the change in volatile content within each sample.

The graphs of the variation in volatile content as a function of distance from the heated face show that virtually all of the volatile matter in every sample had been driven off in that zone which was  $1/8$ " from the specimen-metal interface. This was expected, as this zone was exposed to the intense heat of the molten metal with very little protective cover.

The same graphs show that there is a rather large decrease in volatile content  $3/8$ " from the heated face. The magnitude of the loss in volatile content at  $3/8$ " was smaller than that of the loss at the  $1/8$ " level. This is understandable in view of the fact that the heat would not be expected to be so intense further away from the casting.

All samples showed that a loss of volatiles had occurred  $5/8$ " from the heated face, although this loss was quite a bit smaller than the loss in zones closer to the casting.

As was expected, each sample showed that the magnitude of the loss in volatile content in that region  $7/8$ " from the heated face was also quite small.

It is evident from the graphs that little or no volatile matter was lost at a distance of 1-1/8" from the heated face. Furthermore, it was found that there was no loss of volatiles in any of the zones further away from the heat. Thus, it was concluded that the heat of the molten metal affected only that portion of the sample lying within 7/8" of the source of heat. Also, the effect of the heat was slight in those areas which were not within 3/8" of the specimen-metal interface.

Thus, in summary, the results showed that there was a very large decrease in volatile content (virtually 100% of the original volatile content) near the casting. The loss in volatile content became less as the distance from the casting increased until, at about 1-1/8" from the source of heat, the heat had no effect upon the volatile content of the sand.

Very closely connected with the problem of determining the effects of the heat upon the volatilization process is the problem of determining how the volatile products recondensed in the specimen. Upon examination of the data and the graphs, it was evident that there was little or no recondensation of the volatile matter within the specimens. It almost goes without saying that little recondensation is to be expected within 7/8" of the heated face, as the results show that volatiles were being driven off in this entire section of the sample. Thus, an examination of the data for that portion of each specimen from 1-1/8" to 1-7/8" will be sufficient to determine whether or not there was any substantial amount of recondensation taking place within the specimen.

Such an examination of the volatile contents of these zones showed that there is no evidence of substantial recondensation of volatiles in any of these zones. In some samples, one or more of the zones may have a volatile content higher than that of the sample before being heated. However, in virtually all cases, the volatile content was only slightly higher than that of the original sand. In view of this fact, it was decided that the deviations from the volatile content of the unheated sand were due to experimental error rather than any recondensation of volatiles. Proof of this assumption is given by the fact that there were negative deviations from the original volatile content as well as positive deviations in all except a few of the specimens.

It is possible that there may have been a very small amount of recondensation in one or more of these zones. However, this recondensation seems to be so slight that it is negligible and adds little to an explanation of the action of the sea coal in the sand.

The question of volatilization and recondensation within each sample was approached from a more quantitative standpoint. The weight of volatiles which was volatilized during pouring was calculated for each specimen containing an integral per cent moisture. The weight of volatiles which was recondensed was also calculated for these specimens. The results of these calculations, which can be found in Table IV on page 35, verify what can be seen from observing the graphs. The amount of volatiles recondensed in each case was insignificant when compared to the amount which was volatilized.

The second topic of discussion concerns the influence of an increase in water content upon the volatilization and recondensation processes taking place in the sand. In dealing first with the recondensation, it can be seen from the graphs that an increase in water content seems to have had little or no effect upon the deviations of the volatile contents in the recondensation zones from that of the unheated sand. The volatile contents of the zones from 1-1/8" to 1-7/8" seem to lie in the region of the volatile content of the unheated sand regardless of the moisture content of the sand.

The effect of the moisture content upon the action of the sea coal in those zones from 3/8" to 1-1/8" is not so easily seen from a visual examination of the graphs. Thus, it was necessary to plot the volatile contents of these zones as a function of the water content of the sand. In these graphs, shown in Figures 12 through 15, an attempt was made to derive a linear relationship between the volatile content and the moisture content. To do this, the method of least squares was used to find the equation of the straight line which best represents the points. This equation was then used to plot the line shown on each graph.

Once a linear relationship has been assumed, two aspects of the resultant straight line are important. The position of the line on the graph is important as it gives a semi-quantitative measure of the average magnitude of the loss in volatile content at each specific distance from the heated face. The position helps to more clearly show how the volatile content in the heated sample increases as the

distance from the source of heat increases. This is equivalent to a smaller loss of volatiles during the period in which the sand was being subjected to the heat of the molten metal. This same relationship was seen in studying the graphs discussed above, but is, perhaps, seen more clearly here. In general, at  $3/8$ " from the source of heat, most of the samples had a volatile content on the order of 0.90%, corresponding to a loss of 2.24% during pouring of the mold. The average volatile content at  $5/8$ " was about 2.75%, which is a loss of 0.29% during pouring. At  $7/8$ " the average volatile content retained in the samples was about 3.05%, corresponding to a loss of 0.09%. At  $1-1/8$ " from the heated face, the average volatile content was seen to be about 3.10%, which corresponds to a loss of only 0.04% volatiles during pouring of the mold.

The second important aspect of each line was the slope of the line. This is perhaps of even more importance than the position of the line. As mentioned previously, the position of the line merely confirms the relationship between the volatile content and distance from the heat that had been seen from an examination of the graphs of the variation in volatile content within each sample. However, the slope of the line is the only indication of the effect of the water content on the volatilization process.

An examination of the four graphs showed that the slope of the line is very close to zero for each of the zones in which volatilization took place. As the retained volatile content in the  $1/8$ " zone was equal to zero for virtually all of the samples, no graph could be



drawn for this zone. The slope is negative for the  $3/8$ " and  $5/8$ " zones and is positive for the  $7/8$ " and  $1-1/8$ " zones. However, in no case was the slope of the line of large enough magnitude to prove without a doubt that the retained volatile content either increases or decreases as the moisture increases. This lack of positive evidence seems to indicate that the moisture content has little or no effect upon the per cent volatile content in the volatilization zones of the sample after it has been subjected to the heat of the molten metal.

These observations were verified by the calculated results shown in Table IV. The results show that there is no significant change in either the amount volatilized or the amount recondensed as the moisture content of the sample increased.

TABLE III - RESULTS OF DETERMINATION OF VOLATILE CONTENT WITHIN SAMPLE

Sample No.	%H <sub>2</sub> O	Per Cent Volatile Content							
		1/8"	3/8"	5/8"	7/8"	1-1/8"	1-3/8"	1-5/8"	1-7/8"
1	1.0	0.00	0.73	3.05	2.90	3.21	3.23	3.13	3.07
1A	1.0	0.00	0.66	3.07	2.87	3.02	2.95	3.03	3.04
2	1.5	0.00	0.99	3.03	2.82	3.43	3.65	3.42	3.38
3	2.0	0.17	1.23	2.57	3.16	3.15	3.20	3.18	3.16
3A	2.0	0.00	0.79	3.06	2.81	2.73	2.68	2.93	2.69
4	2.5	0.00	1.14	2.74	3.14	3.05	3.47	3.11	3.06
5	3.0	0.00	0.61	2.76	3.04	3.24	3.40	3.17	3.03
5A	3.0	0.00	0.97	2.70	3.02	3.04	3.21	2.93	2.84
6	3.5	0.03	0.96	3.18	3.23	2.77	3.43	2.84	2.74
7	4.0	0.00	1.02	2.84	3.22	2.94	2.81	3.14	3.21
7A	4.0	0.00	0.97	2.88	3.11	3.13	2.95	2.91	3.08
8	4.5	0.05	0.88	2.74	3.15	3.27	3.62	3.54	3.36
9	5.0	0.00	0.81	2.58	2.61	3.08	2.77	3.52	3.21
9A	5.0	0.00	0.78	2.73	2.73	3.05	3.11	3.37	3.33

All values for per cent volatile content have been corrected by subtracting 0.738% from the original weight loss.

TABLE IV. PRODUCTS VOLATILIZED AND RECONDENSED WITHIN EACH SAMPLE

<u>Per Cent Moisture</u>	<u>Weight Volatilized</u>	<u>Weight Recondensed</u>
1.0	1.2 gm.	0.0 gm.
2.0	1.3 gm.	0.0 gm.
3.0	1.1 gm.	0.0 gm.
4.0	1.1 gm.	0.0 gm.
5.0	1.2 gm.	0.1 gm.

FIGURE 3. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 1.0% WATER

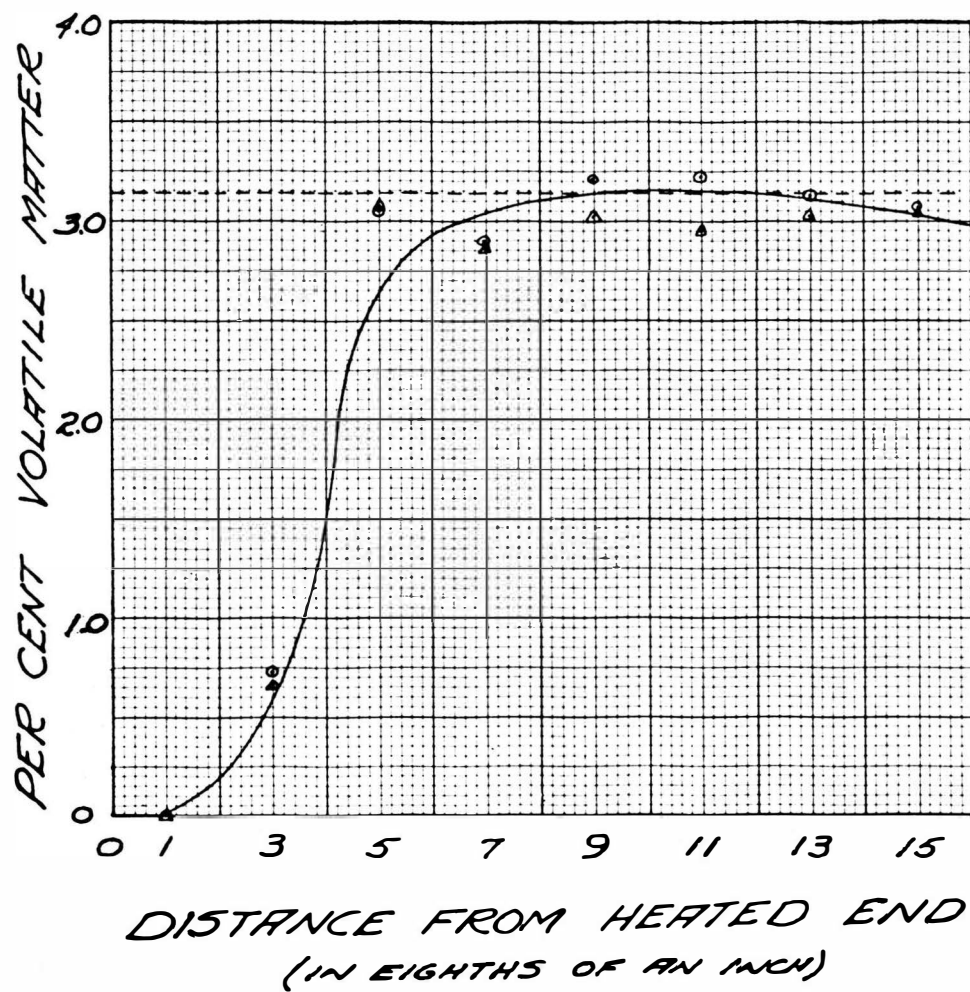


FIGURE 4. VARIATION IN VOLATILE  
CONTENT WITHIN A SAMPLE CONTAINING  
1.5% WATER

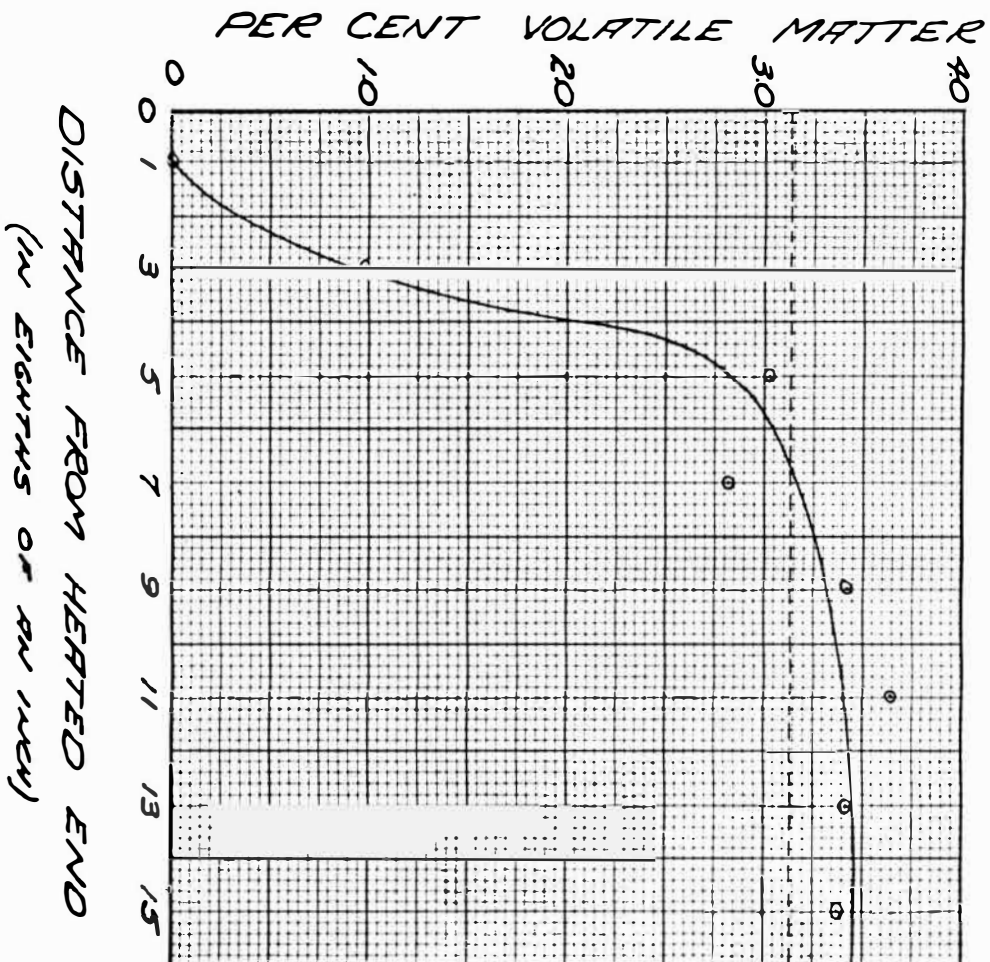


FIGURE 5. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 2.0% WATER

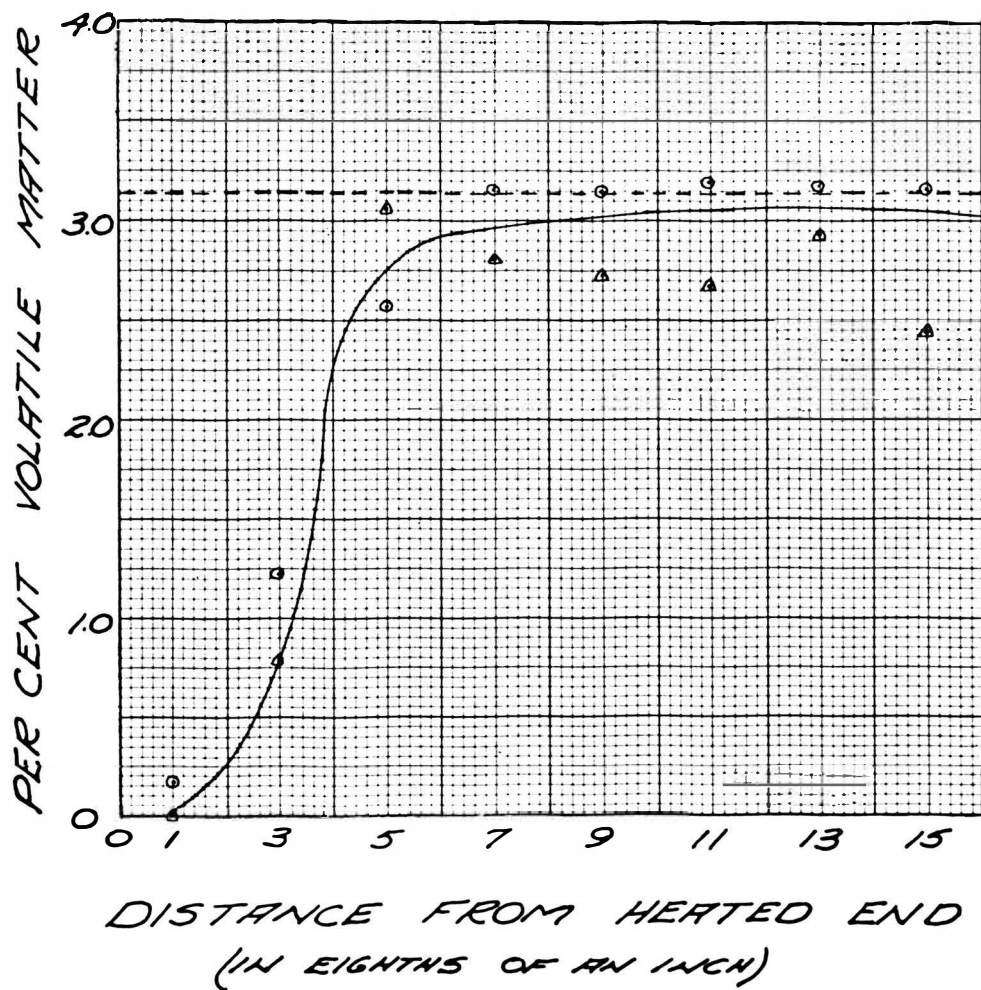


FIGURE 6. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 2.5% WATER

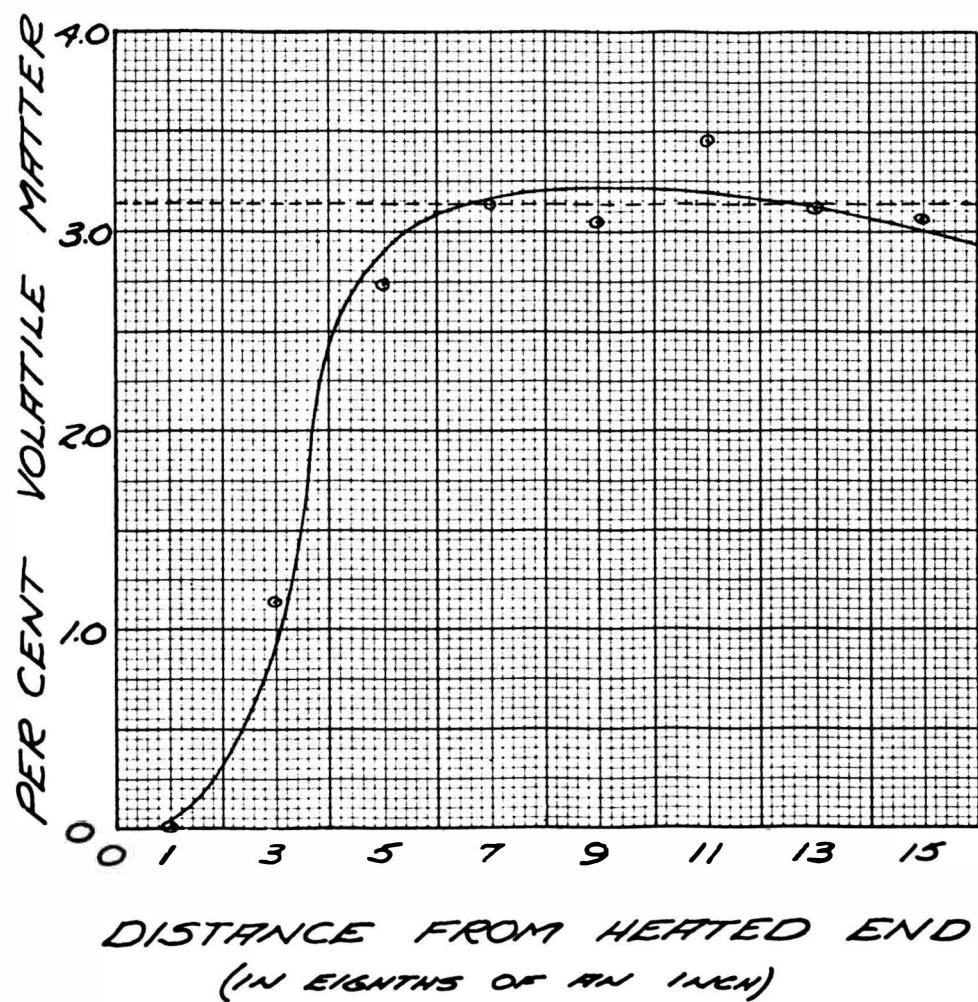


FIGURE 7. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 3.0% WATER

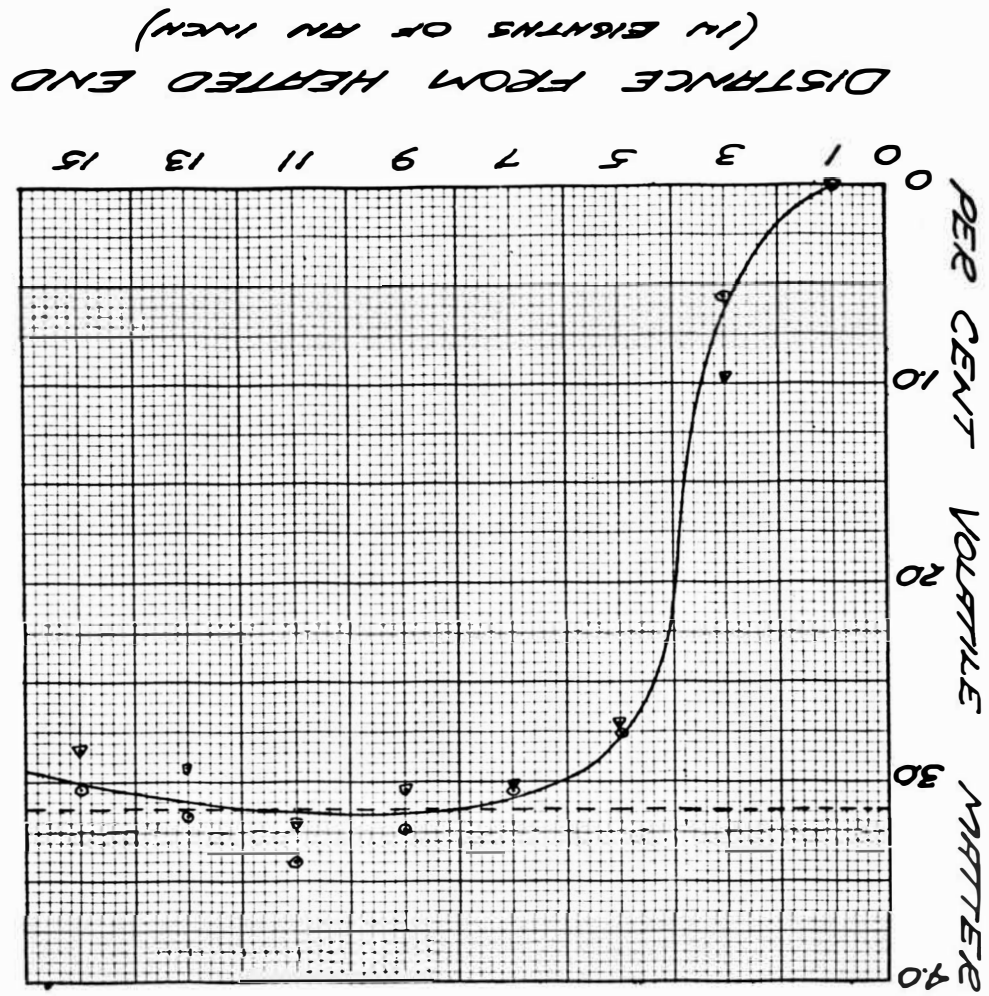




FIGURE 8. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 3.5% WATER

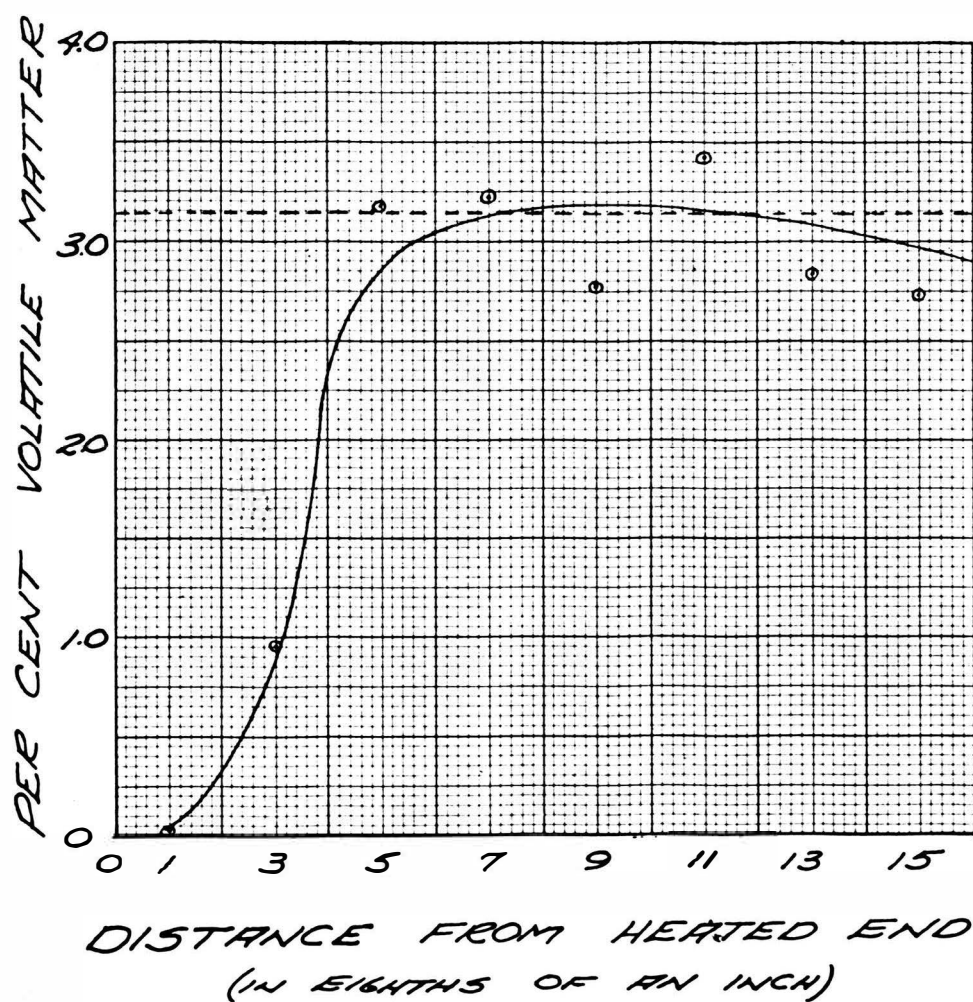


FIGURE 9. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 4.0% WATER

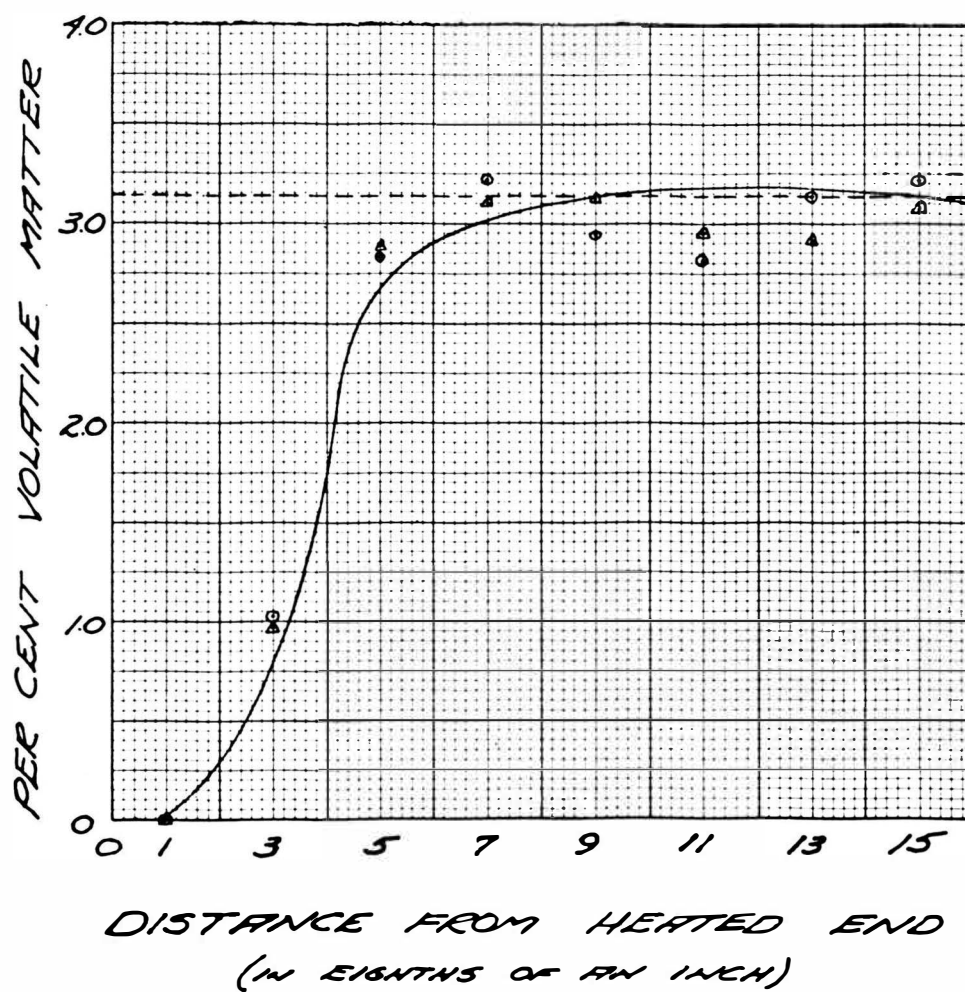


FIGURE 10. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 4.5% WATER

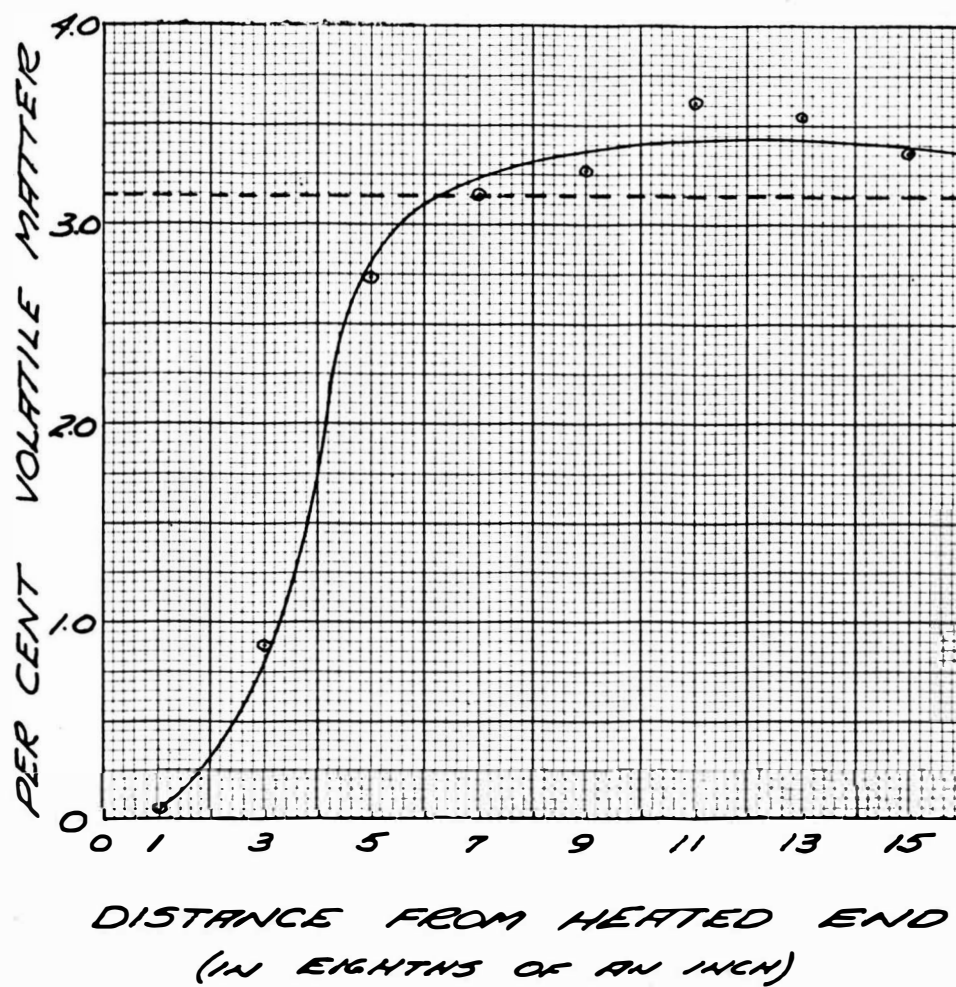


FIGURE 11. VARIATION IN VOLATILE CONTENT WITHIN A SAMPLE CONTAINING 5.0% WATER

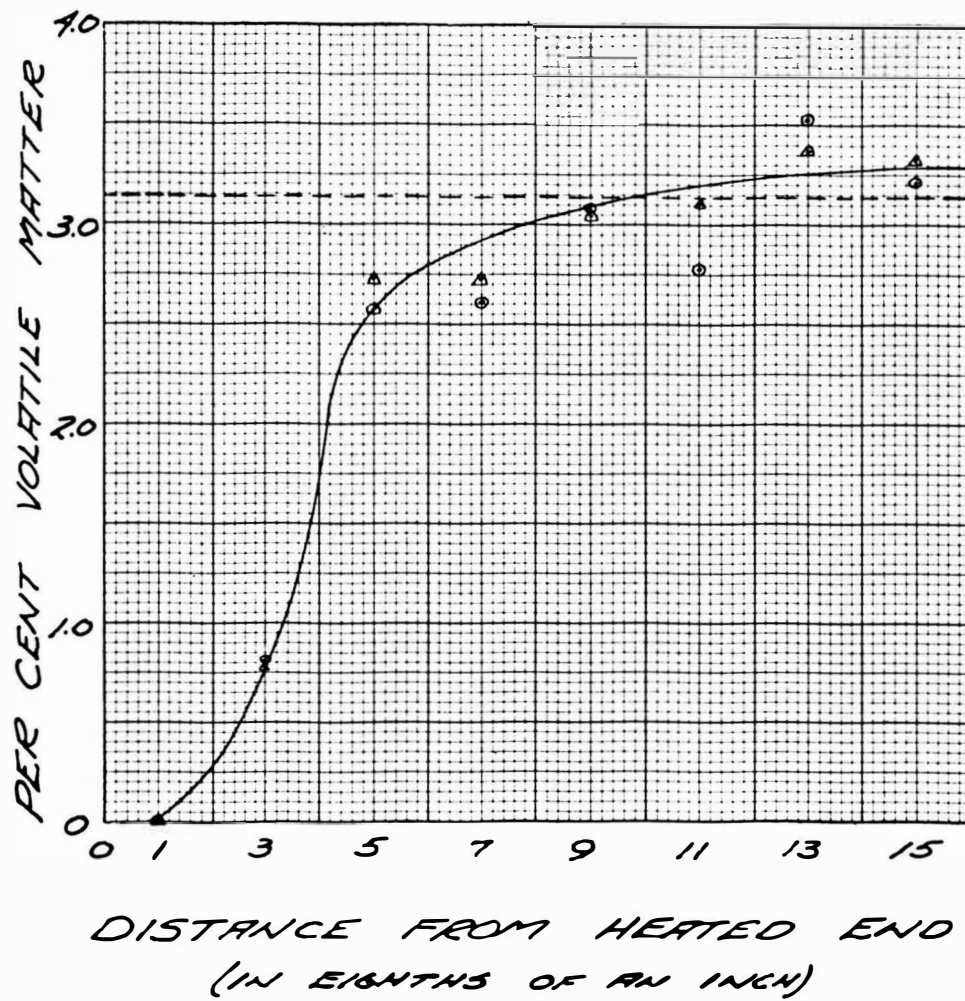
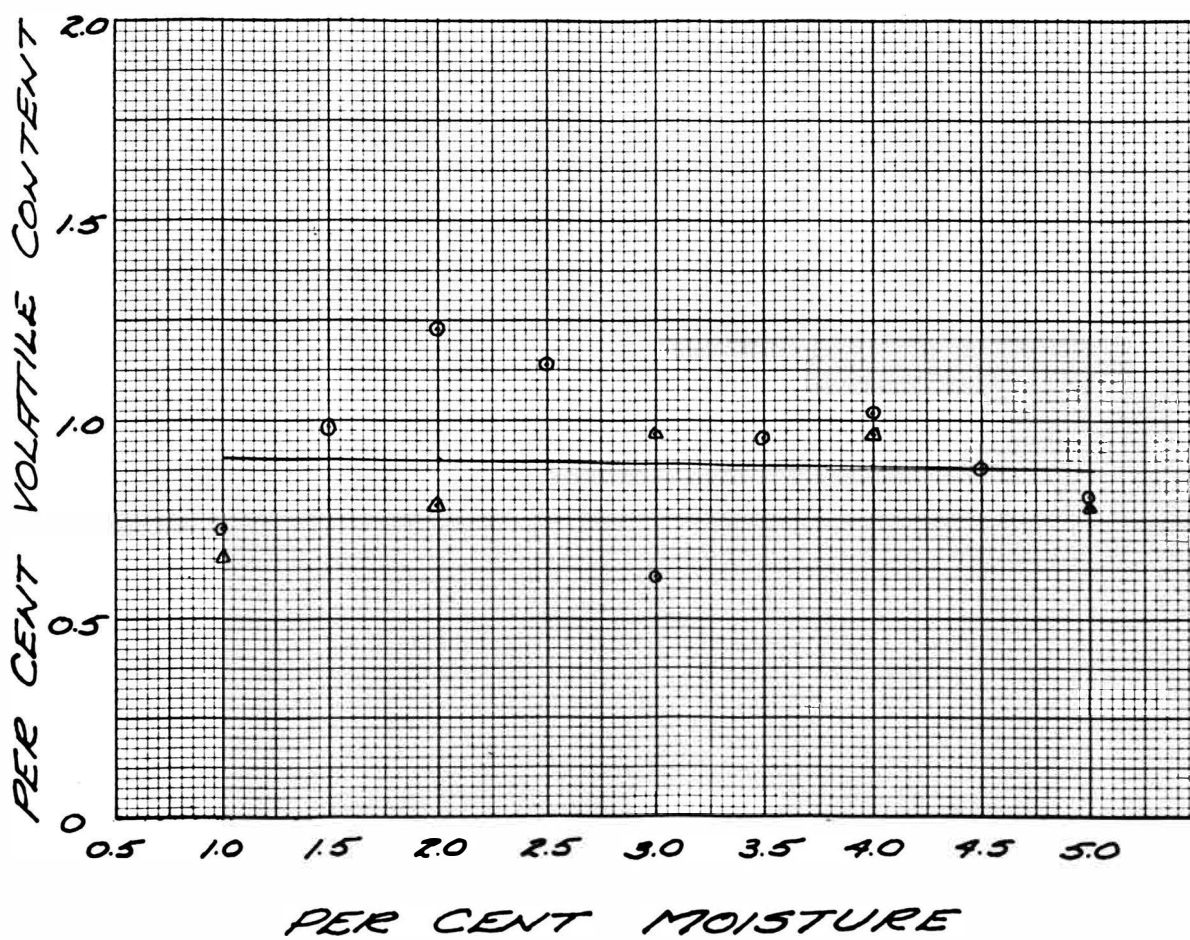
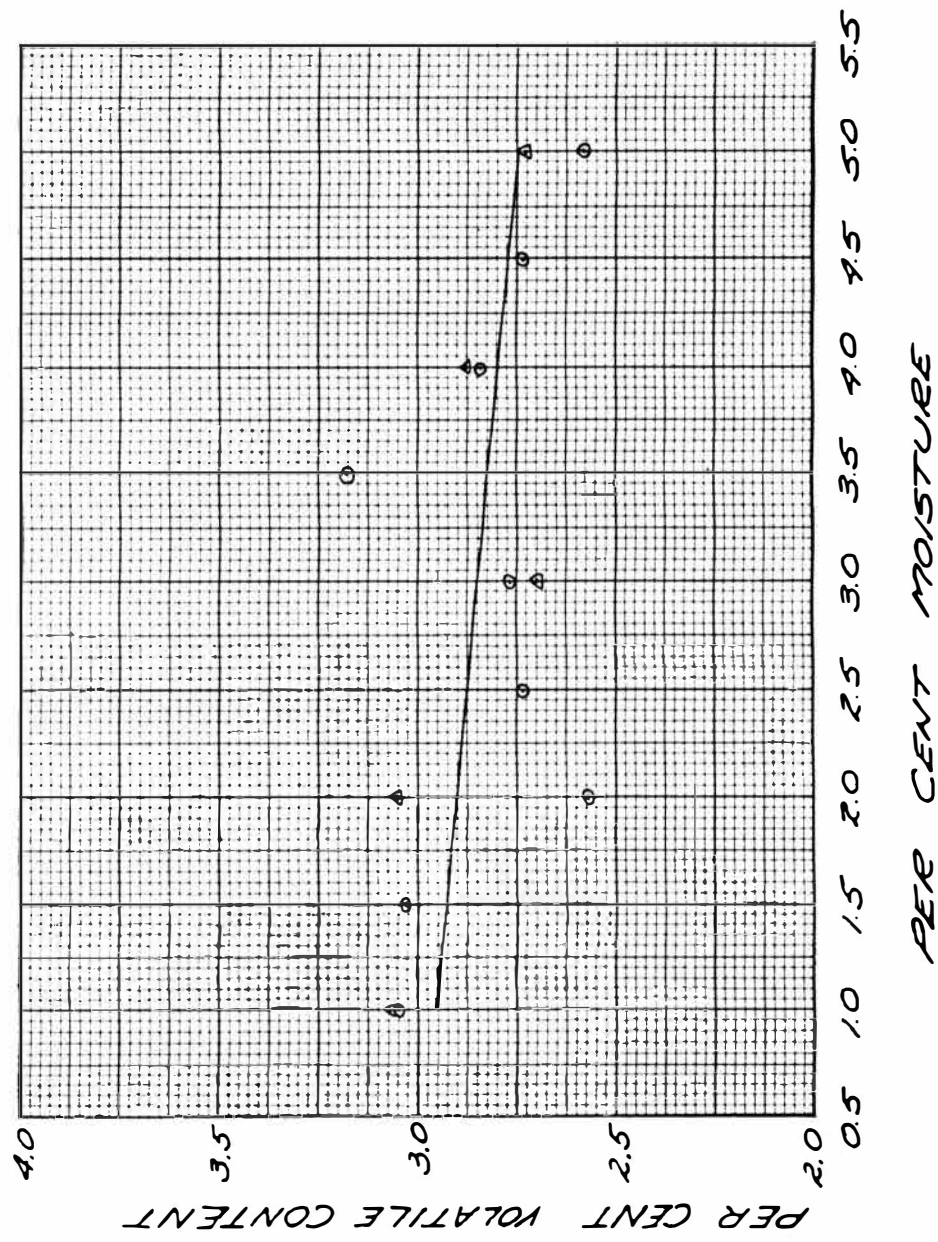


FIGURE 12. VARIATION IN VOLATILE CONTENT WITH MOISTURE CONTENT  
3/8 INCHES FROM HEATED END



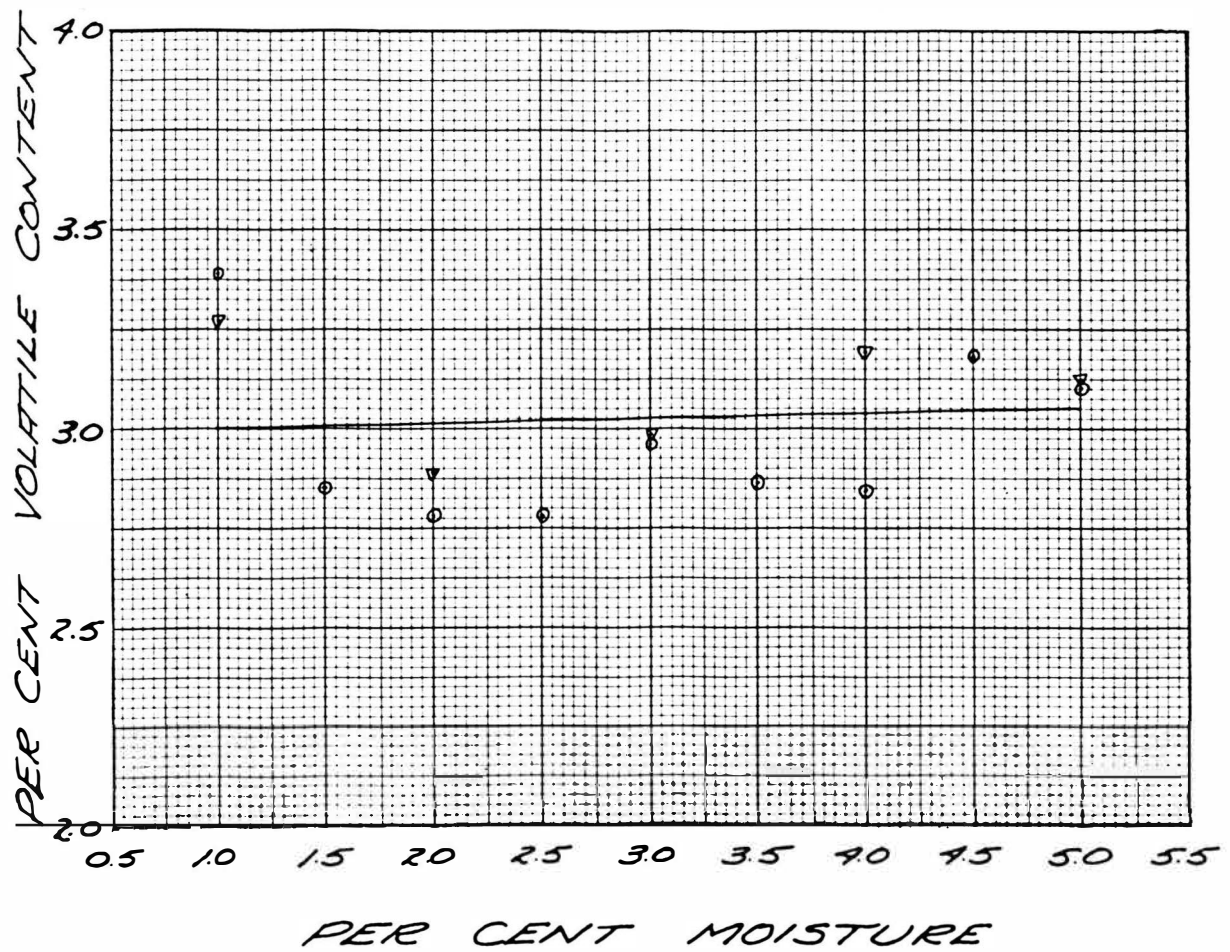
$$Y = 0.902 - 0.0024X$$

FIGURE 13. VARIATION IN VOLATILE  
CONTENT WITH MOISTURE CONTENT  
5/8 INCHES FROM HEATED END



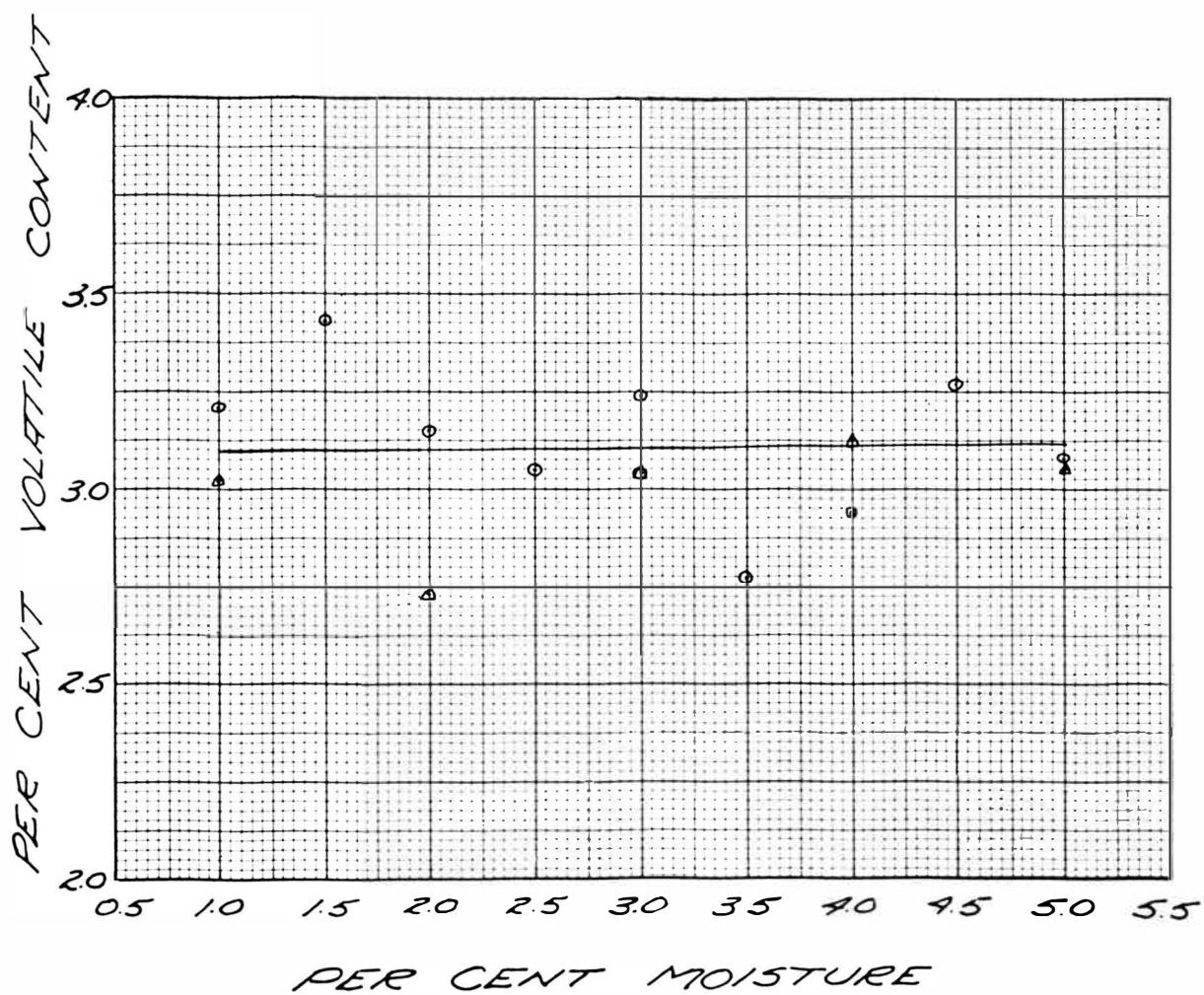
$$Y = 3.02 - 0.0569X$$

FIGURE 14. VARIATION IN VOLATILE CONTENT WITH MOISTURE CONTENT  
7/8 INCHES FROM HEATED END



$$Y = 2.94 + 0.0136 X$$

FIGURE 15. VARIATION IN VOLATILE CONTENT WITH MOISTURE CONTENT 9/8 INCHES FROM HEATED END



$$Y = 3.09 + 0.0068 X$$



## V. CONCLUSIONS

Even before the actual laboratory investigation was begun, the basic assumption was made that an increase in moisture content would probably result in an increase in the amount of volatile matter retained in the specimen during pouring and cooling of the casting. This assumption was based on the idea that a higher moisture content should result in a greater cooling effect within the sample. It was expected that a greater cooling effect would tend to restrict the volatilization of the sea coal and, at the same time, help to keep the sand at a temperature low enough to induce recondensation of any volatile matter driven off from that portion of the specimen nearest the heat of the molten metal.

If, as assumed, the amount of volatile content in the heated sample increased as the moisture increased, a plot of the volatile content as a function of water content, for each specific position within the sample, would have a positive slope. In addition, if the increase in volatile content was significant, the slope of such a plot would be expected to be quite large. However, such a plot made from the experimental data was found to have either a small negative slope or a positive slope of very small magnitude. The failure of these graphs to have a large and positive slope was taken as proof that the original assumption was in error. An increase in moisture content does not result in an increase in the amount of volatiles retained in the heated specimen.

The failure of any of the graphs to show a large and negative slope was likewise taken as proof that an increase in moisture content does not result in a decrease in the amount of volatiles in the

specimen after it has been heated. It was not expected that there would be such a relationship between moisture and volatile content.

As an increase in water content caused neither an increase nor a decrease in the volatiles remaining in the sand, it is concluded that the amount of moisture present has no effect upon the volatilization and recondensation of the volatile matter in the sea coal. Although, as stated previously, the increased water content was expected to have a greater cooling effect within the sand, the conclusion that the water has little or no effect on the volatile content can be easily explained. If the temperatures to which the sand was subjected were relatively low, the cooling effect of the water would be expected to be of great significance. However, it should be remembered that the iron was poured into the mold at a temperature of 2600 - 2700°F. As the pouring temperature was so much greater than the boiling point of water, it is understandable that the water content would contribute only an insignificant amount of cooling in the sand. In order to exhibit a substantial cooling effect in the sand, water would have to be present in such a great quantity that it would make the use of such a sand as a molding material impossible.

The second basic assumption under which the experiment was carried out was that the volatile products which were driven off from those zones nearest the heat would diffuse through the specimen, in a direction away from the heated face, and, at some point where a sufficiently low temperature prevailed, the volatiles would recondense within the specimen. However, from the experimental data, it was shown that there was little recondensation of volatiles within

the specimen, even in those areas which were rather far from the heated face. If, as must be concluded from the data, there was no significant pick up of volatiles within the specimen, what happens to the volatile products driven off during the pouring?

The answer to this question has been given by Reichart and Woolley.<sup>(18)</sup> These investigators have argued that the expansion of the sand grains causes the permeability of the sand to decrease in that range of temperature during which the destructive distillation of the coal is taking place. This fact has been verified by several other investigators. Because of this drastic reduction in permeability, the volatile products can not proceed through the sand away from the source of heat. Thus, the volatile products are forced out along the face of the mold and act as a film of gas between the mold and the casting.

The fact that there was no condensation evident in any of the specimens proves that the volatile matter did not travel away from the mold-metal interface. As there is no other means of escape except along the sides of the mold cavity, it must be concluded that Reichart and Woolley were correct and that the escaping gases do form a thin film between the metal and the mold. Whether or not this thin film of gas has any significance in the explanation of the action of sea coal in improving the surface finish of the castings is still uncertain. However, it is safe to assume that the film is present and could possibly act to improve the surface finish.

Thus, the laboratory investigation has served to shed some light on the explanation of the action of sea coal in the molding sand

during pouring and, at the same time, has added to a solution of the more practical problem - how the foundryman can control the additions of sea coal to the molding sand. In the more theoretical sense, there is evidence to prove that the volatile products are present along the edges of the mold cavity and help to improve the surface finish of the casting. On the more practical side, the foundryman may feel relatively safe in assuming that any day to day variation in the moisture content of his molding sand has no bearing upon the amount of sea coal to be added. And he may be assured that a change in moisture will call for neither an increase nor a decrease in the amount of sea coal to be added to achieve the desired properties in his castings.

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