19 January 1938

NRL Report No. M-1420

FR-1420

NAVY DEPARTMENT

BUREAU OF ENGINEERING

Report
on
Steel Casting Design for the Engineer
and Foundryman.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

Number of Pages:	Text - 30	Tables - 7	Plates - 51

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

Prepared by: C.W. Briggs, Metallurgist.

R.A. Gezelius, Associate Metallurgist.

A.R. Donaldson, Assistant Physical Science Aide.

Reviewed by: R.H. Canfield, Senior Physicist, Superintendent,
Division of Physical Metallurgy.

Approved by: H.M. Cooley, Captain, USN, Director.

Distribution:

BuEng.	(10)
BuC&R	(10)

ejh

APPROVED FOR PUBLIC
RELEASE - DISTRIBUTION
UNLIMITED

Table of Contents

ABSTRACT

Steel casting design has been considered from two viewpoints, namely, that of the designing engineer and that of the foundryman. A code or the nucleus of a set of rules is presented for the engineers' guidance and experimental results on padding, external and internal chills, and controlled directional solidification are reported as of possible interest to foundrymen.

Part I

THE DESIGNING ENGINEER AND STEEL CASTING DESIGN

Introduction

It is the plan, in this section, to introduce to the designing engineer the concepts of steel casting design in a logical manner, simplified as much as possible.

It is felt that a discussion of design features at this time is appropriate, as the requirements for new equipment operating under higher pressures and at higher temperatures are calling for new designs. Also, requests for reductions in weight have introduced casting problems which require more tolerant design. These new demands have resulted in reductions in wall thicknesses which have, in some cases, produced wall sections that are but small fractions of those formerly employed.

The reduction of wall thicknesses, to effect weight savings, is causing considerable thought and drawing much attention (among consumers and foundrymen) to the internal condition of castings. Defects that were once hidden by very heavy sections are now brought to light. Also, weight savings have reduced the factor of safety and more concern is being given to the integrity of the castings. Castings that operate under high pressures and temperatures are now required to be absolutely homogeneous, and non-destructive testing methods, especially X-ray and gamma ray inspections, are being frequently used to check on the internal conditions. Thus many things have combined to make the producer and the consumer more conscious of the internal integrity of the casting.

In general, it may be said that most of the defective castings are due to poor design, but as there are no assembled data on design, one can hardly blame the designing engineers for these undesirable conditions.

Difficulties Due to Poor Design

It might be most appropriate to point out to the designer those defects that occur in steel castings because of poor design. Both hot tears and shrinkage cavities are prevalent in poorly designed castings. Hot tears form due to large temperature differences in castings where excessive internal stresses cause members to separate or crack at temperatures slightly below the steels' solidification temperature. Cracks occur at abrupt changes in section and at sharp angles.

Shrinkage cavities are due to insufficient metal to care for metal contraction at the time of casting solidification. They are found in sections that must be fed through smaller sections.

Even though the above discussion may mean little or nothing to the designer it is sufficient to point out, regardless of the terms employed, that internal stresses and contraction phenomena can not be disregarded in the planning of a design from which may be produced a perfect casting. It also should be added that the mechanical properties of the casting will vary with size of section designed. This point will be discussed later at greater length.

Designing to Prevent Hot Tears

There are two ways in which the designer may prevent the possibility of his embryo casting from cracking or being subject to hot tear formation. These are:

(1) Eliminating hot spots that are under stresses.

(2) Eliminating the stresses that would act on the hot spots or other points of stress centralization.

In principle, the above points could be more easily stated by merely emphasizing that all stress should be eliminated, since the high stresses are primarily the cause of hot tear formation. Unfortunately, casting stresses cannot be eliminated, but under certain circumstances they can be controlled. It is not necessary that the details of stress formulation and action be presented here, as the mechanics have been fully described in other publications by the authors (1), (2), (3). It may be pointed out, however, that because of the temperature-contraction relationship, temperature changes are causes of stress formation. Thus, if hot spots are eliminated the excessive temperature changes are eliminated, stresses are thus reduced, and hot tear formation prevented.

Under certain conditions the design cannot be changed to remove the hot spot. In this case the stresses must be relieved in some other manner. That can best be discussed by reverting to illustrations. But first, how is a designer to know what hot spots are and where to look for them?

A member of a steel casting solidifies from the sand faces toward the center of the cavity. The rate of solidification for practical application is about the same whether the section be one inch or four inches thick. Thus, if the rate of skin formation is about the same, it naturally follows that it will take the heavier section longer to completely solidify. If it is considered that the thinner section is integrally connected to the heavier section in the casting, it may be pointed out that the thinner section is completely solidified and is cooling, and therefore contracting, while the heavier section is still solidifying. The temperature gradients so established will result in different rates of contraction and hence the formulation of stress. Cracking will occur at the weakest section, which, of course, will be the hottest section.

Thus, reverting to the question "what are hot spots and where are they found," it may be said that hot spots refer to sections of extra mass and they are found at positions of joining sections. One or two examples may be sufficient to crystallize the statement. In a cast wheel, the solid hub, which is much heavier in section than the arms or the rim, is a section of extra mass and is located at a position of joining sections. Thus the hub may unquestionably be spoken of as a hot spot. In the typically designed valve, the flanges or the seat are sections of heavy mass joined to much thinner wall sections and therefore may be termed hot spots.

The above discussion leads to the statement of the first rule of the code:

<u>RULE:</u> An attempt should be made to design all sections in a casting with a uniform thickness.

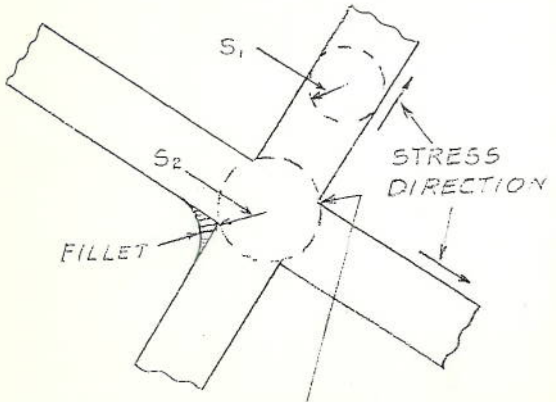
This rule, if followed, reduces the presence of hot spots in a casting to a minimum. These hot spots are responsible for the setting up of temperature gradients, contraction variations, stress formations and their resultant – the deplorable occurrence of hot tears.

It has been suggested previously that the designer will find that under certain conditions the design can not be changed to remove the hot spot. Such a condition necessitates the application of the second plan for the prevention of hot tears by design; namely, eliminating the stresses that would act on the hot spots or other points of stress centralization.

In the first place, what may be considered as points of stress centralization? Stresses acting upon a casting usually concentrate at abrupt changes in section or at sharp corners. These positions are structurally weak and coupled with the fact that they are usually hot spots with low mechanical properties, it is easily seen that they are potential positions of hot tear formation.

For example, two sections, which are an integral part of a casting, are joined together in the shape of an X (Figure 1). By inscribed circles, a method proposed by Heuvers (7), the effective mass can be ascertained.

Figure 1.



Concentration of stress and formation of hot tear.

If, however, liberal fillets replace the sharp corner junctions the stresses will be more evenly distributed and hot tear formation will be less prone to take place.

In the discussion of fillets for the prevention of hot tears, it should be pointed out that the elimination of hot tears must not be the sole consideration since an increase in the radius of the fillet also increases the size of the possible shrinkage cavity. Therefore, judgment as to what constitutes an adequate fillet should be reserved until the section of internal unsoundness due to shrinkage has been thoroughly studied.

Abrupt changes in section may be considered analogous to the case described above in that sharp corners, temperature gradients, and stress concentration are similar. On Plate 1, is illustrated how an abrupt change of section can be altered from a poor design to designs that will reduce the possibilities of hot tear formation to a minimum.

The above explanatory notes lead to the statement of further Rules to the Code.

RULE: It is not desirable to design cast steel structures with abrupt changes in section.

RULE: Sharp corners at adjoining sections are sources of defects, and, if possible, should be eliminated.

The points of stress centralization have been discussed as to their nature and disposition. There is, however, still remaining for discussion that phase pertaining to the elimination of major stresses, which acting on hot spots, result in the formation of hot tears.

It has already been pointed out that if sections throughout the casting are uniform, major stresses will not arise from excessive temperature gradients and, of course, prominent hot spots will not be present within the casting. Under certain conditions it is impossible to design a casting so that prominent hot spots are eliminated, and, since excessive temperature gradients will thus be present, it becomes necessary to relieve the major stresses resulting therefrom by some other means. The foundryman has at his command a method to reduce these stresses by employing mold relieving principles. The designer can also aid toward producing a more stress-free situation by designing an intricate casting in two, three, or more parts, which are finally assembled into one complete casting by joining the various cast parts by welding.

Castings of the weld-assembly design are becoming increasingly popular with design engineers and casting purchasers and are being looked upon quite favorably in the more progressive foundries.

The principles involved in the weld-assembly design are readily discernible to the designing engineer, but for the sake of clarity a simple example will be illustrated.

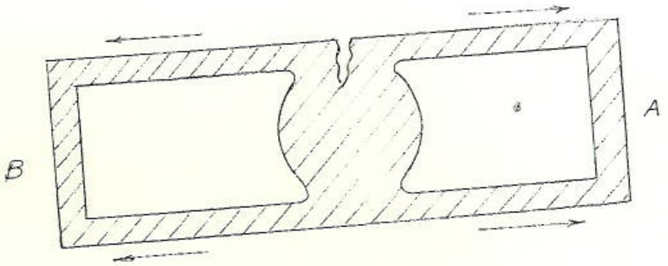


Figure 2.

The above, Figure 2, is a cross section involving two features of poor design; namely, the hot spot and a continuous wall section which would be responsible for hindered contraction stresses set up mainly in the direction of the arrows. A casting so produced would very likely show hot tears in the central section if the foundryman did not take precautionary steps. If, however, the designer eliminated the cross end pieces, A and B, the castings would not be under the major stresses as shown and failure would not be a possibility. The casting could be assembled in the final form by welding previously cast or fabricated sections, A and B, into position.

An actual commercial application of these principles is illustrated in the manufacture of a throttle valve casting. Plate 1 portrays a sketch of the first design of this casting. Considerable trouble was experienced in production and a number of attempts were made before the casting was finally produced without major defects. In Plate 2 the design was altered to the cast-weld-assembly job. All extraneous parts were removed from the base casting, cast separately, and then these parts were welded together to complete the assembly. This casting was produced without defects on the first attempt. It is needless to add that the saving in time and cost of production was considerable.

This principle was extended to the turbine casting as illustrated on Plates 26 to 30.

It is felt that designers should not be alarmed by this type of construction for excellent properties and good homogeneity can be obtained, as has been demonstrated by White, Clark, and Crocker(5).

The above discussion leads to the statement of another rule.

RULE: When a design of a cast steel structure becomes very complicated or intricate, it is suggested that it be broken up into parts so that they may be cast separately and then assembled by welding or bolting.

Designing with a Sine Wave Construction

There is another design feature that should be mentioned in regard to the relief of stresses in an enclosed cast structure. This design calls for the use of members that are slightly waved.

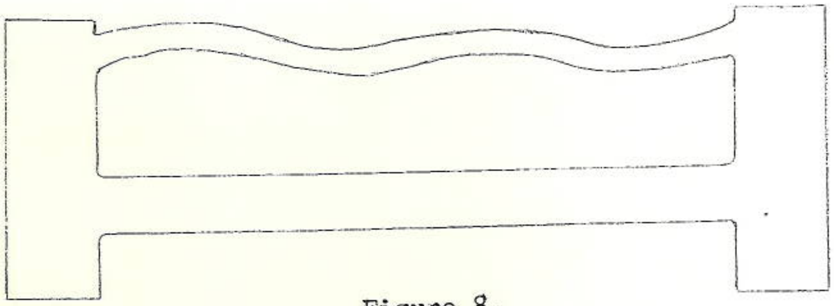


Figure 8.

In the above system, the heavy flanges and two different sizes of connecting members will all cool at different rates, and thus the system will be under considerable internal stress. The small member designed with a wave in it, under the tension stresses of the system, will be pulled toward the shape of a straight member and therefore dissipates the internal stresses without tearing, a condition that could not result if the connecting member were straight.

Whether or not this type of a design is adequate to care for required stiffness needed is not known, and is a point that designers themselves must settle. However, from the foundry viewpoint, such a design is appropriate and very useful as a method of stress reliving in an enclosed system.

Designing to Prevent Contraction Cavities

When liquid steel solidifies it contracts about 3 per cent in volume, and since steel solidifies progressively from the mold surface toward the center of the mold cavity, a pipe or contraction cavity will result unless the section is fed from some reservoir containing liquid steel. If, however, the section is unable to draw liquid metal from other sources because these inlets have completely solidified, then a defect will appear in the unfed section.

Castings with defects of this type, under vibratory stress aided by stress centralization, may develop cracks extending from the cavity to the casting face. If the casting is operating under pressure, leaks may develop.

In general, the problem of removing the possibilities of defects due to contraction results in the elimination of the hot spots in castings. These isolated hot spots are sources of great trouble in the manufacturing of steel castings, and anything that the designer could do toward eliminating them would be greatly appreciated by the foundryman.

A simple illustration will suffice to acquaint the designer with the seriousness of the situation and the possible remedy. The L section, as is shown in the accompanying diagram, Figure 3, is used considerably in practically all castings, such as flanges, connecting and adjoining sections, and the like. If the two arms of the L were of the same thickness,

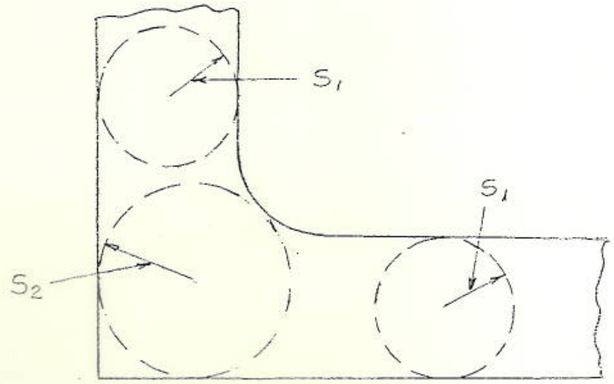


Figure 3.

it may be seen by the method of inscribed circles that where the two legs of the L join, a hot spot will be located. If this hot spot (S_2) can only be fed through the two legs of the L section, one may be certain that when the casting has solidified, since the leg sections solidify first, there will be a cavity somewhere near the center of the inscribed circle, S_2.

If, however, the L section were in a location where the junction could be fed directly by an outside reservoir, instead of attempting to feed through the legs, then the section at S_2 would be sound and contain no cavity.

There are numerous occasions unfortunately when such a joining section can not be fed by an outside reservoir of metal due to its inaccessibility, such as at the bottom of the mold or an internal section of the mold. There is no special problem with joining sections or hot spots that can be fed directly, and design features are not very important as far as safeguards against cavities are concerned; but sections that can not be fed should be considered carefully by the designing engineer.

One of the most difficult features about designing to prevent contraction cavities is to know when and where feed heads may be placed since their position is quite largely a matter of opinion among foundrymen. As a matter of fact, the casting may be molded contrary to any plans that the designer may have had. Thus, the casting may better be designed with the supposition in mind that none of the metal conjunctions or hot spots can be fed from outside reservoirs. With this point in view, experimentation was carried on with joining sections to determine the extent of the contraction cavity with the change in design.

There are only five ways in which sections may joint. These may be exemplified by the following letters of the alphabet: L, T, V, X, and Y. All other modes of connection are merely modifications of the above possibilities. Designs in the forms of these letters have been studied in detail.

Patterns were made of 3 x 3 inch cross-section. The arms were about two feet long and headed at the extreme end. They were poured through the feed heads on the arms. In order that no variations should be overlooked during pouring, studies were made by pouring through one arm, and through two arms at the same time. Molding was according to the dry sand practice and plain carbon basic electric steel was used, poured from a teapot ladle. The sections were all poured in the horizontal position.

It has been stated that in these studies a 3-inch section was used. The reasons for choosing this section were:

(1) A large section would exhibit pronounced defects.

(2) A 3-inch section is not uncommon in structural castings.

(3) With the large section, the conditions of sand and steel would not be so critical and more comparable results could be obtained.

It is felt that the points illustrated in the design charts will be of a comparable order in sections other than those of three inches, and that information obtained on a 3-inch section can be used in the design of other adjoining sections.

The sections were modified by using radii of different sizes in the corners and the effect of the changes was noted. For the purpose of this work it has been assumed that the section studied is located in the casting in such a manner that no feeding is possible except through the arms. Therefore, these arms have been extended about two feet and the only feeding heads provided were those at the end of each arm.

The depth of the section has, of course, no bearing upon the shape of the defect in the plan view as long as the depth is great enough to permit a defect to form. Even if the depth of the section were infinite, the plan view of the defect should, theoretically, remain the same.

After the sections were cast they were radiographed. Castings were radiographed with radium at a distance of 40 inches with a

2 mm source or focal spot in order that the defects would appear in their natural sizes on the film. The defects exhibited in the radiograph were then reduced photographically so that the defect drawn on the small diagrams presented in this report would be shown in their correct proportion. Reproductions of two radiographs are included to illustrate the general characteristics of the defects found (Plates 4 and 5). Plate 3 is a radiograph of a 3 x 3 inch T section and Plate 4 is a radiograph of a section taken from a commercial casting.

It is now suggested that the designer turn to the charts illustrating the various sections. The charts are self-explanatory and from them may be obtained several features of design. See Plates 6 to 21, inclusive.

In discussion of the L section, it may be said that if the outside corner at the junction is maintained, an increasing radius at the inner corner will bring about an increasing size of defect. If the section is uniform throughout, a defect will be found if the inner radius is small. If the inner radius is increased, but a uniform section is maintained, the defect will become smaller until it develops into center line weakness, a condition apt to be found in uniform sections of any length.

Sections of the L type should not have less than 1/2-inch inside radius, and only in a few cases would a 3-inch inside radius be used. The best common practice therefore appears to be one in which radii of 1/2-inch to 1 inch would be used.

The practice of designing the section at the junction slightly smaller than that of the arms appears to give the best results.

The only way in which a T section can be designed without being responsible for a contraction cavity is to core a hole at the center of the junction of the two members. Depressions in the arm of the T, while not eliminating the defect, do reduce it markedly from that found in the common T design.

Since the size of the defect increases with the size of the radius, it is recommended that a radius of 1/2-inch, and not over 1 inch, be used.

It has been suggested from time to time by those writing on the subject of design, that if the leg of the T section were made smaller in section to that of the arm, that the hot spot, and hence the size of the cavity, would be reduced. This is true, as is illustrated in 202, 209, 210, and 211. It should also be pointed out, however, that as the leg section decreases, the temperature differential between the two sections increases, and stresses are formed that may result in the formation of hot tears. Thus, care should be used in designs of this type so as not to incorporate them in enclosed stress active systems.

A uniform section in the shape of a V will not be free from contraction cavities, since a synthetic hot spot is developed at the junction due to the fact that the sand is not able to conduct heat away from the three inside faces as fast as it can from the single outside face. It will be noticed that if the inner radius is increased, as in 305, that the defect will be smaller than in a comparable case such as 302. As in the case of the L design, a slightly reduced section at the junction of the members is necessary for a homogeneous section. In designing V sections, it is suggested that an inner radius not less than 1 inch be used.

The designer will observe that an X section could not be designed that could be made free from a contraction cavity, if the section were fed only through the arms. The defect could, however, be made quite small by designing the section with a cored hole as in 504 and 505.

Much has been said in previous discussions upon casting design concerning offsetting the arms of the X so that the hot spot would be reduced. This is not true if the offset is similar to designs 506, 507, and 508. The defects formed by this type of construction are about the same size as would appear in the usual X type section. A section having one arm completely offset, as in 506, allows the foundryman to use external chills to advantage. Slightly better results could be obtained by spacing the offsets further apart, such as illustrated in 509. Such a design allows the foundryman ample freedom for the placing of external chills. Designs 510, 511, and 512 show how the defect may be decreased in size as the adjoining section is decreased. The same principles apply here as they did in the T section that has previously been discussed.

Unless the cored hole at the center of the hot spot is advantageous to use, it is suggested that the one arm offset similar to 509 be used.

An interesting point encountered in the Y section is that no matter how the features of the design are altered, the defect found was about the same size. Attention is called to 403, 404, 405, and 406. The only design without defect was 408. A triangular hole of this type is able to extend to all the hot spots that are possible in the section. Defects found in sections of commercial casting 409, 410, and 411 are exhibited for sake of comparison. Occasionally there appears a design wherein an area of heavy metal is attached on all sides to members of much smaller thickness and so located that the foundryman has no opportunity to properly feed the heavy portions by means of a conveniently placed feed reservoir. Such a condition is distinctly one of poor design. The heavy section should either be cored or more closely investigated to ascertain if it could not be made lighter.

A study of all these various sections leads to a few general rules:

RULE: In designing unfed joining sections in L or V shapes, it is suggested that all sharp corners at the junction be replaced by radii so that this section becomes slightly smaller than that of the arms.

RULE: In designing sections that joint in an X section, it is suggested that two of the arms be offset considerably.

RULE: In designing any joining sections, it is suggested that all sharp corners at the junctions be replaced by radii. In the case of unfed T and X sections these radii should not be large.

It may be pointed out that in connection with joining sections that it is the custom of designers to use webs, brackets, and ribs between various parts of the casting to impart a certain amount of rigidity or stiffness to the casting. Such stiffing members should be kept to a minimum as they are sources of considerable trouble both as to the formation of hot tears and shrinkage cavities. The placing of brackets across joining sections of course increases the mass effect at the intersection of the adjoining members and the bracket. This undesirable condition may be remedied by the extensive coring of the bracket in the region of the adjoining sections. Such coring will not impair the stiffing features of the bracket and will at the same time allow for better conditions of homogeneity of the adjoining sections.

It is the desire of the authors before leaving this section entirely, to impress upon the designer two things, one of which is that the sections which have been illustrated were not fed, and had it been possible to attach a reservoir of liquid metal to the sections they would have been free from contraction cavities. The foundryman will go to considerable trouble to feed these sections. It is only those that are located in impossible positions that he fails to reach. The second point to be stressed is that even though the designer is unable to design a section which if unfed will be free from contraction cavities, he can design it so that it will have, under the circumstances, the smallest cavity possible. Then with this design the foundryman can apply the tools and knowledge at his command such as the use of padding, external or internal chills to make the section homogeneous.

It is suggested that the designer look over the charts on adjoining sections in the foundryman's portion of this report so that he may see what can be accomplished by chilling unfed sections.

The Effect of Mass Upon the Mechanical Properties of Cast Steel*

The effect of mass upon the mechanical properties of cast steel is a subject that is of practical importance to designing engineers,

---

* Summary of NRL Report No. M-1376 of 1 July 1937.

particularly those engaged in designing power plant equipment where steel castings are being installed in systems subject to greater pressures and higher temperatures than those previously used. Engineers have relied upon data collected on the properties of cast steel, such as that assembled by Lorig and Williams. They realize, as was noted by Lorig and Williams, that such data are rarely complete in that the chemical analyses, size of casting, heat treatment, size of the specimen or the method of testing are not always known. As many of the data are obtained from laboratory heats produced under ideal conditions, the results may not be comparable to those obtained in a commercial casting. In commenting on this condition, Sisco, in his volume of the Alloys of Iron Monographs, pointed out that of all the variables which may affect the mechanical properties of cast steel, and one which is seldom mentioned in the compilation of data, the effect of mass is clearly the most important.

Testing Methods

A study of the previous work on this subject shows that no data have been reported upon the effect of mass on the mechanical properties of cast steels in both the as-cast and annealed conditions. As the designing engineer should have some indication of what may be expected as mechanical properties in various sections, it was deemed advisable to study this effect. It should be noted, however, that these data can refer only to the analyses studied and can only be indicative of the properties of other cast steels produced in similar sections.

In order to study the effect of mass upon the mechanical properties, well-fed coupons were cast horizontally in medium carbon steel and medium manganese steel. The coupons were all 12 inches long and those cast in medium carbon steel were 1/2 x 1/2 inch, 1 x 1 inch, 2 x 2 inches, 3 x 3 inches, 4 x 4 inches, and 8 x 8 inches in cross section. Only the 1 x 1 inch, the 3 x 3 inch and one 8 x 8 inch coupons were cast in medium manganese steel for these tests. Each coupon was top poured through the feed head. The feed heads, along the entire upper faces of the coupons, were large enough to permit the shrinkage cavities to form within them without extending into the coupons. The feed heads were sawed from the coupon prior to heat treating. One coupon of each size was annealed at 900 degrees C. (1650° F.) for the customary time of one hour per inch of section. The coupons were then cut and tensile specimens machined from the locations shown in Figure 4. The specimens were all standard 0.505-inch diameter tensile specimens, except those machined from the 1/2 x 1/2 inch coupon. These specimens were 0.313 inch in diameter with a gauge length of 1.25 inches.

After the tensile tests were obtained, specimens were machined from the threaded portion of the bars for micrographic studies, density measurements and chemical analyses.

In another heat, bars 1/2, 1, 2, and 3 inches in diameter and coupons similar to those mentioned previously were cast from low carbon steel. One-half of the bars and one-half of the coupons were annealed as before. Tensile test bars were machined from the coupons and tested. The bars were tested in the unmachined condition in order that some indication of the actual strength of cast sections might be obtained.

Mass Effect on Medium Carbon Cast Steel

The data obtained from the tensile specimens machined from the medium carbon cast steel at the locations shown in Figure 4 are given in Table I. It will be noted that the yield point in the as-cast condition is listed in only a few instances. The representative stress-strain curve (Figure 5) shows that in the as-cast condition, cast steel has no marked yield point. The yield point must therefore be determined from a stress-strain curve. The data of Table I together with the density data as set forth in Table II are shown diagrammatically in Figure 6.

The most outstanding feature exhibited by the curves is the sharp bends that are found in the tensile, yield and reduction of area curves in the neighborhood of the 2-inch section. In general, all of the mechanical properties in the 8-inch section were lower than those found in the 1/2-inch section. However, the loss was not as great in the annealed state as it was in the as-cast condition. The density curve also shows a drop in value as the mass of the test block increases.

If the properties of any one section are considered, it may be noticed that the lowest results are obtained at the center of the section and the highest in the bottom corners where solidification has proceeded from two faces. The corner results are usually higher than those obtained elsewhere along the bottom where there is only one solidifying face. These conditions are more pronounced, of course, when the steel is tested in the as-cast condition, but they are also noticeable in the heat treated material.

Since the mechanical properties varied to such a considerable degree, it was thought that perhaps segregation of chemical compositions was responsible for a large portion of the difference. Phosphorus and sulphur segregations were studied in the various sections by etching and sulphur prints, but no differences could be ascertained. This was perhaps due to the fact that they were both present in very low amounts in the steel as cast. As the steel was made by the basic process, these analyses were 0.02 per cent for the phosphorus and 0.03 per cent for sulphur. Segregation was also studied by chemical analysis. The centers of each section were analyzed for carbon, manganese, silicon and aluminum and the results are set forth in Table III. The greatest difference appeared in the carbon content where 0.03 per cent was noted. The center of the 1-inch coupon contained 0.27 per cent, while the center of the 8-inch coupon contained 0.24 per cent. The manganese, silicon and aluminum analyses showed that there was practically no segregation of these elements.

The specimens were also studied microscopically in the unetched condition to see if the inclusions had formed an aluminum network which might tend to lower the physical properties in the larger cast sections. No network was evident. The inclusions were, however, slightly larger and fewer in the centers of the heavier sections.

It appears from the above study that there are three conditions that bear upon the mechanical properties as affected by mass. These are: (a) the density, (b) the carbon segregation, and (c) the microstructure. It is difficult to ascertain from the data which of these is the most important. As the section increases, the density drops, the carbon content drops and the grain size increases. In regard to the tensile strength and yield point values, the microstructure and the carbon segregation are probably the most important in causing the lower values. The density and the microstructure are responsible for the lower ductility found in the heavier sections. From this it appears that the microstructure is the dominant controlling factor.

The properties listed at the center of the section are the poorest ones present in this section. The average properties over the entire section are better than those exhibited by the center, due to the preponderance of material having better properties, such as those exhibited by the corners and edges.

The Mass Effect in Medium Manganese Steel

The effect of mass upon the mechanical properties of the medium manganese steel studied (Figure 7) is similar to that found in the medium carbon steel. In each case the mechanical properties at the center of the test coupon decrease as the mass of the section increases. The variation in the tensile strength is, however, considerably greater in the manganese steel than it is in the plain carbon steel. The tensile strength in the plain carbon steel in the center of the 8-inch coupon is 5000 pounds per square inch less than that in the 1-inch coupon, a crop of 6.5 per cent. In the medium manganese steel the decrease in similar coupons is 10,400 pounds per square inch, a change of 10.5 per cent. It should be noted that the change in the tensile strength of the manganese steel decreases gradually and rather uniformly with an increase in mass, whereas the tensile strength of the plain carbon steel decreases rapidly at first and then at a decreasing rate as the mass increases.

The other tensile properties of the medium manganese steel also decrease gradually and at a more uniform rate than in the plain carbon steels.

The tensile properties of various sections of the 8-inch coupon vary in a manner similar to that found in the plain carbon steel. Table IV indicates that the best tensile properties are found in the lower corner and the bottom of the test coupon. The top of the coupon, immediately under the head, exhibits the poorest properties and the properties then increase gradually toward the bottom of the coupon. The Izod impact strength, however, increases as the mass of the section increases and is greater at the center of the 8-inch coupon than it is in the corner of the coupon.

Chemical analyses were obtained from the center of the 1-inch and 3-inch sections and from the top, center, bottom and corner of the 8-inch section in order that the amount of segregation could be determined (Table V). Segregation of carbon can be seen in that the carbon content at the center of the coupon decreases as the mass of the section increases. The carbon content at the center of the 8-inch section is the same as that at the center of the 1-inch coupon. There is slight segregation of manganese but no segregation of silicon or aluminum.

This segregation of carbon and manganese will probably account for the decrease in tensile strength as the mass is increased.

Comparison of Coupons and Bars Cast to Size

One of the points upon which designers have desired information is the comparison of the mechanical properties of cast steel sections and the properties exhibited by the well fed coupon. This point was investigated and the results are set forth in Table VI. In this experiment, bars were cast in the horizontal position while coupons were cast similar to those used previously. From the center of these as-cast and annealed coupons, standard tensile bars were machined and tested. These

Table VI

The Comparison of the Mechanical Properties of Well Fed Test Coupons and Bars Cast to Size

Carbon 0.21 Manganese 0.60 Silicon 0.31

Section	Gauge Length	Yield Point		Tensile Strength		Per Cent Elongation		Per Cent Red. of Area	
		As Cast	Annealed	As Cast	Annealed	A.C.	Ann.	A.C.	Ann.
½" Coupon	Standard Tensile Spec.	......	44,600	69,800	70,700	29	34	40	50
1" "		......	42,500	69,000	69,700	28	33	38	48
2" "		......	41,750	67,000	69,000	20	32	23	44
3" "		......	40.750	64,500	67,750	18	32	24	40
½" Dia. Bar	2"	......	43,000	69,000	69,500	11	20	13	25
1" " "	4"	58,500	40,000	67,100	64,600	12	16	12	30
2" " "	8"	54,200	39,200	61,800	64,000	8	13	8	23
3" " "	12"	......	39,500	......	63,550	.	14	.	13

specimens likewise showed the effect of mass on the mechanical properties.

The bars were tested in the condition they came from the sand mold except that one set was annealed before testing. The bars were not machined nor were the cast surfaces removed.

The yield and the tensile strengths were nearly the same in both bars and specimens machined from the coupons. The ductility, however, was much lower in the case of the bars. This is undoubtedly due to the rough surface of the bars. The decrease in ductility with increasing mass is much greater with the bars than it is with the coupons.

These data point out that while the strength properties in cast sections are nearly the same as those represented by the coupon, the ductility properties are much lower and should be borne in mind by the designer. The interesting point is that the ductility results are rather erratic and would depend a great deal on the surface of the casting, and probably on the size of the axial weakness.

The purpose in presenting data on bars cast to size is to inform design engineers of the properties of castings that may have sections similar to those tested. It is requested that the data obtained on the machined test specimen be not directly compared to the data resulting from testing the cast bars, since the latter is a notable variation from the standard test bar and will not give comparable results. The machined specimen taken from the coupon gives an indication of the best properties of the metal. The data obtained from testing the cast bars give an indication of the properties of an actual cast section. It is well known that a rough surface will result in lower ductility values being presented, but it should also be pointed out that most castings are used in commercial installations with the cast surfaces exposed and that the actual mechanical properties of that section as it stands in the installation are more along the lines of the data as presented for the cast bars than they are according to the data collected from the coupon. Thus, the properties are reported as an indication of what the section will withstand and it is not at all a test of the most favorable properties of the steel, nor a direct comparison of two types of test specimens.

The above section on the effect of mass on the mechanical properties of cast steel can be summarized as follows:

(1) There is a loss in strength and ductility, as measured at the center of the section, as the mass increases.

(2) In the carbon steel studied the loss is pronounced for the first two inches of cross section, after which it tapers off gradually. In the manganese steel there is no decided knee to the curve.

(3) There is a decrease in density and carbon content, and an increase in Izod impact value as the mass increases.

(4) Microstructure, carbon segregation and density values are responsible for the decrease of mechanical properties as the mass increases.

(5) Segregations of silicon, aluminum, phosphorus and sulphur were small and had no apparent effect as to producing low mechanical properties.

(6) The mechanical properties of sections as represented by cast bars show that strengths are quite similar to the optimum values as recorded by the machined test specimens, but that the ductility is much lower.

The above discussion in regard to mass effect leads to the following statement:

RULE: In a general way it may be said that the effect increasing mass has on the mechanical properties is not pronounced and probably is amply covered by the present factor of safety.

SUGGESTED RULES FOR STEEL CASTING DESIGN

1. An attempt should be made to design all sections in a casting with a uniform thickness.
2. It is not desirable to design cast steel structures with abrupt changes in section.
3. Sharp corners at adjoining sections are sources of defects, and, if possible, should be eliminated.
4. When a design of a cast steel structure becomes very complicated or intricate it is suggested that it be broken up into parts, so that they may be cast separately and then assembled by welding.
5. In designing unfed joining sections in L or V shapes, it is suggested that all sharp corners at the junction be replaced by radii so that this section becomes slightly smaller than that of the arms.
6. In designing sections that join in an X section, it is suggested that two of the arms be offset considerably.
7. In designing any joining sections, it is suggested that all sharp corners at the junctions be replaced by radii. In the case of unfed T and X sections, these radii should not be large.
8. In a general way it may be said that the effect increasing mass has on the mechanical properties is not pronounced and probably is amply covered by the present factor of safety.

Part II

THE FOUNDRYMAN AND STEEL CASTING DESIGN

Introduction

In discussing the question of design from the foundry viewpoint, only the shape and size of the mold cavity will be considered. The composition of the mold may, of course, effect the soundness of the casting by producing hot tears, porous spots, or sand inclusions. This is in itself a most comprehensive subject, but one which is controlled largely by the type of materials available locally and the sand treating and sand testing equipment at hand. What may be expedient for one foundry may be entirely out of the question for another concern. The mold, therefore, will be considered merely as a medium in which a cavity similar to the finished casting may be produced.

It has been stated previously that the defects that may be attributed to the design of the casting are shrinkage cavities and hot tears. It should be noted that while many hot tears are due to mold composition and the manner of molding, a large portion of the hot tears found in castings are inherent in the casting design and cannot be eliminated by mold relieving.

Shrinkage cavities are produced by the contraction of the metal upon solidifying and, theoretically, they can be eliminated only in one manner, i.e., by "controlled directional solidification." Foundrymen have for many years used "directional solidification" and "progressive solidification" as synonymous terms. To the authors, however, each of these terms has a specific meaning and, for the purpose of this discussion, it may be well to define them.

Progressive Solidification. Any liquid metal cooling in a cavity formed in a refractory or metal mold will solidify *progressively* from the mold-metal interface toward the center of the cavity. Thus *progressive solidification* is present in every casting produced.

Directional Solidification. In addition to the *progressive solidification* from the mold-metal interface toward the center of the cavity, solidification will proceed *along* the cast member in the direction of the increasing temperature gradients produced in pouring the casting. These temperature gradients *along* the cast member appear in both the metal and the mold and are determined by the shape of the mold cavity and the method of gating and heading. They are, therefore, *controllable*, whereas the foundryman has no control over the direction of the temperature gradients producing *progressive solidification*. If this analysis is followed to its logical conclusion it is evident that all shrinkage cavities in castings are the result of adverse temperature gradients, or *uncontrolled directional solidification*. Only when the temperature gradients within the metal and the mold are such that the "feed heads" are the last portions of the casting to solidify, and thus can furnish liquid metal to fill the voids formed during solidification, can a "sound" casting be produced. As in most castings, desirable temperature gradients can be produced by using tapered sections, proper methods of gating and heading, and properly placed chills; it follows that <u>controlled directional solidification</u> is the governing factor in the elimination of cavities due to shrinkage.

<u>Controlled Directional Solidification in the Foundry.</u>

In the section devoted to "design for the engineer" it was emphasized that designing engineers should endeavor to maintain uniform cross-sections throughout the casting. The paragraph above on directional solidification appears to be a direct contradiction of the first statement as it advocates the use of tapered sections in producing "sound" castings. This apparent contradiction has been placed in this discussion for the reason that the designer cannot know how the foundryman will produce his casting, and any tapering of sections that he may provide might produce temperature gradients opposing those that the foundryman finds essential to secure a good casting. If, however, the designer maintains fairly uniform cross-sections throughout the casting the foundryman can much more easily produce the temperature gradients he desires.

An illustration of how temperature gradients produced by tapered sections can insure correct solidification is given in the sketch of the turbine casing casting shown in Figure 9. If this casting is poured

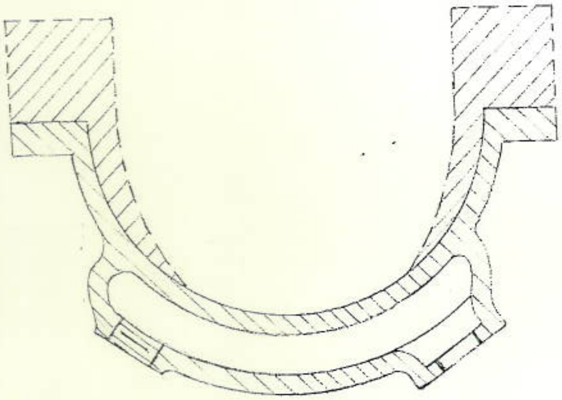


Figure 9.

flange-up, the sections tapered as shown and a collapsible ~~rotten~~ core used to forestall hot tears, it is comparatively easy to produce a sound casting. It should be noted that the padding on the cylinder bore is brought down below the steam chamber so that the steam chamber can be fed directly. The casting was poured through the head so that the last metal to enter the mold (hot metal) was in the head. Now, if external chills are placed around the ports of the steam chamber, it can readily be seen that solidification proceeds from the lower portion of the casting toward the heads. This

The fed gates were entered on each side
just below the heads and in this way an excellent
temperature gradient was established in both metal and sand

direction of solidification has been controlled by producing favorable temperature gradients with tapered sections and this casting becomes a comparatively easy one to produce without defects.

Some objection may be raised to the excessive amount of machining required on the bore of the cylinder. This is merely a question of economics. Four of these castings were produced; each one was declared acceptable after a complete gamma-ray inspection. The loss of one casting, produced without the precaution of padding, would have cost more than the total extra machining charges on all four castings.

In many castings, particularly small and medium sized castings, the temperature gradients can be controlled by proper gating and pouring methods. These principles have been very well presented by the late George Batty, and it would be superfluous to discuss them here.

Models as an Aid to Foundry Practice.

In many cases slight changes in design will enable the foundryman to produce sound castings even when it is almost physically impossible to make a casting without defects from the original design. It is, at times, difficult to obtain the consent of the costumer for even slight changes in design. This is particularly true if the casting is complicated and rather difficult to visualize from blue-prints. It may then be advantageous to prepare a model of the original design at an appropriate scale and use this model to point out the difficulties connected with the design and the modifications required to remove or elevate them.

This method of attack has been used to advantage by the Norfolk Navy Yard in the production of turbine castings. The models shown in this report (Plates 24 and 25) to illustrate their advantages were prepared at the direction of Mr. S. W. Brinson, Master Molder of the Norfolk Navy Yard. Photographs of a completed casting prepared after the design had been modified are shown in Plates 26, 27, and 28. If the photographs of the models and the castings are compared, it will be noted that while the changes are minor in character, as far as the engineering usefulness of the casting is concerned every effort has been made to obtain directional solidification and to simplify the production of the casting. It may be appropriate to point out a few of the changes that were made.

(A) The base casting was separated at (A) and the high pressure end was cast separately. This facilitated the production greatly.

(B) The thickness of the gland supporting web was increased and the cored "pockets" eliminated by changing the shape of the web.

(C) The bolt bosses were tapered from top to bottom to facilitate feeding.

(D) The thickness of the steam belt was increased and an opening provided for core anchorage. This opening was later closed by a plate welded on.

(E) The radius at the junction of the flange and web was increased to eliminate a sharp change in section and permit feeding of the sections at the bottom.

(F) The thickness of the web was increased and a larger radius provided to insure proper feeding.

(G) This outlet was cast separately and welded on.

(H) The wall thickness of the steam belt was increased and the outlet was cast separately and welded on. As the castings were to be used as a "right" and a "left" two openings were made to secure proper core anchorage. One of these openings was sealed by a welded cap, the other was welded to the outlet case separately. This permitted the use of identical cores for both the "right" and "left" castings.

(I) The web was cast separately and welded on to the main casting. This web, if cast integrally, would very probably have caused hot tears, which would have had to be repaired by welding after considerable chipping.

(J) The walls of the by-pass valve were brought straight down to the casing to eliminate sharp changes in direction of section and permit better feeding. The outlet was cast separately and welded on.

In addition to the changes listed above, padding was provided to insure proper feeding. This extra metal was removed from the casting in the chipping and cleaning operation. These castings were cast flange-up in a manner similar to that mentioned previously. The castings were radiographed and were found to be exceptionally free from defects.

In this particular case the use of a model of the casting as originally designed not only resulted in changes in design which facilitated production, but it also reduced the cost of pattern construction considerably.

Radiography in the Foundry.

If several castings are to be prepared from one pattern, radiographic tests become a distinct aid to the foundryman. In the case of the turbine castings mentioned above, one casting of each type was prepared and examined thoroughly before production was started on the remainder of the order. In this case, due to the changes in design, no changes were required. In the production of other castings, however, defects have been found in the first casting which were eliminated from all succeeding castings by slight changes in the pattern to facilitate directional solidification.

Chilling of Steel Castings

Proper chilling is also an important factor in the production of sound castings. There still are sections of castings which it is impossible to feed and in these cases the foundryman's only expedient in the production of sound castings is the chill. There have been many arguments concerning the use of external and internal chills. The authors prefer the use of external chills for several reasons. The size of the chill employed is important when either external or internal chills are used, as the effect of the chill may prevent feeding if too large, and fail to accomplish anything if too small. With internal chills other factors arise. The chill must fuse into the cast matrix if a perfectly sound casting is to be obtained. The chill must be absolutely clean and dry if blow-holes or porous spots are to be eliminated. In green sand practice the chills can easily be inserted just prior to closing the mold and the cleanliness of the chill is comparatively easy to control. This is not always true in dry sand practice, for if the chills must be inserted into the green mold, the fumes from the organic binders leave a deposit on the chills when the mold is dried, which invariably causes trouble in the finished casting.

The effect of internal chills of various sizes upon cast sections was studied by the authors in a very simple experiment. Ordinary well-fed coupons with cross-sections of 1 inch and 3 inches were molded in dry sand. After the molds were dried, chills 3/32, 1/8, 1/4, 3/8, 1/2 and 5/8 inches in diameter, respectively, were inserted in the mold. These chills had previously been cleaned in an acid, then in a caustic bath, and nickel-plated to insure cleanliness. The molds were bottom-poured so that the steel would rise evenly over the entire chill.

This experiment, of course, indicates the effect of chills only upon metal that rises over the chill. A chill placed so that a large quantity of metal would run past it before the mold was filled, would have an entirely different effect upon the metal as the chill would heat up slowly and a portion of it might be erroded. In these circumstances a considerably larger chill would be required to accomplish the same purpose.

If the photomicrographs of the etched sections of some of these chilled coupons are examined, several interesting points may be noted. The 5/8-inch diameter chill did not "fuse in" in either the 1-inch or 3-inch section. The mechanical bond in the 1-inch section was so poor that upon deep etching the acid penetrated the crack and enlarged it. (Figure 9.) It should also be noted that the chilled envelope that first formed on the chill cracked as the chill was heated and expanded. The dense chilled area extends across the entire section and therefore no feeding took place below the chill. A small secondary pipe may be seen about mid-way between the chill and the bottom of the casting. A radiograph of this section is shown on Plate 30.

The 5/8-inch chill placed in the 3-inch section (Figure 10) also failed to fuse in, but the mechanical bond was considerably better than that found in the 1-inch section. A slight crack was also formed in this case. The area of dense chilled material is about the same size as that found in the 1-inch section. In this case the chilled area is surrounded by a ring of porous dendritic material which is a semi-circular line similar to what is commonly called "axial weakness."

The 1/2-inch diameter chills also failed to fuse in properly in either section (Figure 8, Figure 12) and the effect, while slightly less in magnitude, is similar to that of the 5/8-inch chill.

The 3/8-inch rod was the largest chill that showed any indication of fusion with the cast material in the 3-inch section. The photomicrograph of this section is shown in Figure 11. In this case the chilled area is quite small. An indication of a small circumferential crack may be seen just above the chill. A photomicrograph of the fusion zone in this section is shown in Figure 14. The unfused chill-cast metal interface of the 1/2-inch chill in the 1-inch section (Figure 15) is also shown for comparison.

The ordinary horse-shoe nail chill cast into a 3-inch section is shown in Figure 13. In this case also the chill is welded to the cast material but, again, the chilling action has been slight for the chilled area is very small. The large internal stresses brought about by chilling may be imagined by noting the diagonal cracks appearing in the head of the horse-shoe nail. These cracks have, of course, been enlarged by the deep etching treatment but they were visible in the rough-ground unetched specimen. Similar cracks are visible in the chills shown in Figures 8 and 20.

The 1/8-inch diameter rod was the largest chill that showed good fusion in the 1-inch cast section. The chilled area is also quite small in this case (Figure 16). The horse-shoe nail did not fuse into the 1-inch section at all (Figure 17). The 1/4-inch chill indicated partial fusion only (Figure 18). A porous area and a secondary pipe are visible below the chill in the etched section and also in the radiograph (Plate 34).

The two sizes of coil chills used seemed to fuse in very well. The small coil (3/32" diameter wire) used in the 1-inch section chilled but a small area of metal. The outline of this chilled area is visible in the etched cross-section of the casting (Figure 19). The chilled area produced by the larger coil chill in the 3-inch section is not as well defined. This section is shown in Figure 20. In spite of the precautions taken this chill must have collected some dirt or water as there are porous areas above, as well as below the chill.

As the coupons containing these chills were available, test specimens were machined from them in such a manner that the chill passed through the center of the test specimen normal to the direction of testing. The data obtained on machined specimens of this type cannot be correlated for as the size of the chill increases, the area of cast metal present in the cross-section of the specimen decreases rapidly. In the specimens containing the larger chills the central portion of the test bars was practically all "chill," whereas in other specimens very little chill metal was present. The only point worthy of note indicated by these data was the fact that, provided the chill was actually fused in, the mechanical properties were not seriously affected.

The advantages in favor of the use of external chills are: (1) that fusion between the chill and the casting is not important in considering the size of the chill, (2) cleanliness is not as important, as the gases evolved can escape through the sand, and (3) in many cases the chills can be used more than once. External chills have the disadvantage that for some applications they must be cast, or machined, to fit the surface they are to chill, and of course, have the same difficulty as internal chills in that the choice of the proper size is most important.

The effect of external chills of various sizes has been studied qualitatively in a few of the adjoining sections mentioned previously. It should be noted again that these sections have not been fed except through the arms and that, therefore, they are typical only of the inaccessible junctions found in actual castings. It will be noted that in the case of the T-section with unusually large radii, some of the cylindrical chills employed are not those that might be used in actual foundry practice. They were included in the study in order that a comparison of the results might be made with those obtained with the T-section having smaller radii. The other unusual shapes were used so that the effect of the amount of surface in contact with the casting might be noted.

The cross-sectional area of the chill, the perimeter of the chill in contact with the casting (noted as the "effective perimeter"), and the cross-sectional area of the defect are given in each case. This method of illustration was chosen as it was deemed to be the easiest manner to visualize the effect of the chill upon the sections.

Chilled L-Sections

The effect of chills upon the defects found in unfed L-sections is shown on Plate 36. A 1/2-inch diameter external chill placed at the radius of the inner corner reduces the size of the defect considerably. A chill 1-inch in diameter, or a small triangular chill with about the same cross-sectional area, produced a sound section.

Chilled T-Sections

It is difficult to produce sound T-sections by the use of external chills alone. Eight different sizes of chills were used on T-section 202 and while each type produced a smaller defect than that present in the original casting, only one of the modifications produced a sound casting. The types of chills used are shown on Plates 37, 38, 39, 40, and 41. Chills 1/2, 1, 1-1/2, and 2 inches in diameter, respectively, were placed at the radii of the section. As the size of the chill at the radius was increased, the size of the defect decreased until a critical size of chill was reached.

The increase in chill diameter from 1-1/2 to 2 inches also increased the size of the radius and this apparently counteracted the effect of the larger chill, as the size of the defect obtained is approximately the same in each case.

Two triangular chills were also used. The smaller of the two had a volume approximately equal to that of the 1-inch diameter chill with, of course, a much larger area in contact with the casting. This increase of the area in contact with the casting did not affect the size of the defect, as the result obtained with the 1-inch diameter is approximately the same as that obtained when the triangular chill is used.

It has been noted that chills placed at the radii of a T-section tend to move the defect toward the top of the T. A plate chill placed across the top of the T has the opposite effect. This type of chill will decrease the size of the defect and move the defect down into the leg of the T (202-7). If a combination of these two types of chills, i.e., 1-inch diameter chills at the radii plus a plate across the top, is used, it is possible to produce a sound section (202-8).

If the leg of the T is smaller than the top of the T, a plate chill across the top is in many cases all that is required to produce a sound junction (210-1).

In T-sections, excessive fillets are a liability to the foundryman, as it is very difficult to produce a sound section. This is illustrated by a series of studies with chills of various sizes with pattern 204. As in the T-section previously mentioned, an increase in the size of the chill tends to reduce the size of the defect. The size of the defect does not decrease as rapidly as in the previous case. Even a chill 4 inches in diameter does not reduce the defect to a size comparable to that obtained with a chill 2 inches in diameter in the T-section previously discussed.

When a very large chill that fits the entire radius is used (204-5), the defect, while of a different shape, is as large as that found in the casting made without chills. It was suggested by a foundryman who visited this Laboratory that the defect shown in this section was much larger than one could expect and he mentioned the possibility that radiography had introduced considerable error. This casting was, therefore, sectioned on the center line and the defect revealed was compared with the original radiograph. The outlines of the defect on the radiograph and on the casting coincided perfectly. Calculations on the amount of liquid steel involved in producing a defect of this size have indicated that with such a large chill it is theoretically possible to have a defect even larger than that found.

The minimum defect in this type of T-section was obtained when 4-inch diameter chills were used at the radii and a plate chill was placed across the top of the T.

The X-sections (Plates 42, 43, and 44) were the most difficult sections to chill properly. In fact, it was not possible to produce a sound X-section by chilling alone. An increase in the size of the chill again produced a smaller defect. The best results were obtained with the large triangular chill (502-4). An increase in the radii at the corners of the casting, as in the case of the T-section (202-4), produced a larger, rather than a smaller defect (503-1). In this case it appears that the 1/2-inch radius is preferable to the 1-inch radius.

The staggered X-section, unfed and unchilled, presents an elongated defect. Chilling this section with 1-inch diameter bars divides the defect into two smaller defects. Using chills larger in diameter increases, rather than decreases, the size of the defects produced. It would seem, therefore, as suggested in the section on design, that staggered section with some distance between the arms would be preferred (see 509, 510, 511, 512 on Plates 18 and 19). These sections could be chilled as T-sections and produced without defects if feeding was not possible.

Sections in the form of a Y are not encountered as frequently as some of the other types. They are, like the X-sections, very difficult to produce without defects unless they can be fed directly. The results of various chilling methods are shown on Plates 45 and 46. The test result obtained is indicated in casting 402-5.

A summary of the effect of external chills upon the sections studied is presented in Table VII. It is interesting to note that in the castings studied the diameter of the chill was very important when an increase in this diameter meant an increase in the radius at the corner of the casting. For instance, in the T-section 202 a radius of approximately 3/4 of an inch appears to be the critical radius. An increase from a 1-inch diameter chill (1/2-inch radius) to a 1-1/2 inch diameter chill (3/4-inch radius) decreased the cross-sectional area of the defect from 0.8 to 0.3 square inches. If, however, the diameter of the chill is increased to 2 inches (1-inch radius) the cross-sectional area of the defect becomes 0.4 square inches. The same thing may be noted with the X-section. In this case an increase in the diameter of the chill from 1 inch to 2 inches increases the cross-sectional area of the defect from 0.6 to 0.9 square inches.

Another interesting fact is that the location of the chill is as important as the size of the chill. For instance casting 202-6 is chilled with two triangular chills having a total cross-sectional area of 5.38 square inches and a total effective perimeter of 7.6 inches. The defect obtained has a cross-sectional area of 0.5 square inches. Casting 202-8, however, is sound, and total cross-sectional area and effective perimeter of the chills are 5.31 square inches and 5.56 inches, respectively.

The effective perimeter and the cross-sectional area of the chill both govern the chilling effect of a particular chill, but the latter is the more important. The heat conductivity of steel is great enough so that the cross-sectional area must be quite large in proportion to the effective perimeter before the efficiency of the chill is impaired. This is illustrated by results obtained on castings 202-2, 202-5, 502-2, 502-3, 502-5, 402-4, and 402-5. It will be noted that in each case where the 1-inch diameter chill and the small triangular chill are used the size of the defect is approximately the same even though the effective perimeter of the triangular chill is over twice that of the 1-inch diameter chill. However, when the plate chill with a 1/2-inch radius is substituted for the 1-inch diameter chill, the cross-sectional area is increased considerably while the effective perimeter remains the same. The change in the size of the defect is very slight, indicating that plate chills of this type are very inefficient and not a great deal better than a 1-inch diameter bar.

Internal chills were used in an attempt to produce sound sections in cases where external chills could not do so. These attempts were not satisfactory, as in most cases the location of the chill was shown clearly on the radiograph by lack of fusion, dirt, or gas around the chill. Typical radiographs showing the type of defects encountered are shown on Plates 47 and 48. It should be noted that the type of defect is the same whether one coil chill or four are used, so that "over-chilling" cannot be responsible. A longitudinal view of two coil chills is shown on Plate 49. In this case practically every turn of the coils may be seen. The use of solid internal chills presented the same difficulties and it appeared that, for the same volume of chilling material, as good results could be obtained with solid chills as with the coil variety.

It is the opinion of the authors that if chills similar to those mentioned above are used on sections less than 3 inches in thickness, the results would be similar. The effect of these chills upon defects present, of course, will increase as the size of the section decreases.

Summary of Part II

The first requirement in the production of a sound casting is a design to which the principles of "controlled directional solidification" may be applied. If this is not possible with the design as originally produced, a few slight changes may be required. Models of the original design at a suitable scale are very helpful to both the designer and foundryman, as the changes required can then be pointed out. These models are sometimes a distinct aid in convincing the designer or consumer that the alterations desired are reasonable and not injurious to the proper use of the casting.

After the foundryman has obtained a workable design he can use the tools at his command, such as tapered sections, proper gating and heading, chills, relieving blocks, etc., to preclude the possibility of shrinkage cavities and hot tears. These foundry arts have been used to advantage on poorly designed castings, but they cannot be expected to cure all the evils found in designs produced with little or no thought to foundry problems.

BIBLIOGRAPHY

1. Briggs, C. and Gezelius, R., Report No. M-1075, 26 September 1934.
2. Briggs, C. and Gezelius, R., Report No. M-1229, 13 January 1936.
3. Briggs, C., Report No. M-1355, 20 April 1937.
4. White, Clark, and Crocker, Am. Soc. of Mechanical Engineers, Vol. 58, November 1936.
5. Lorig and Williams, Am. Foundrymen's Association - American Society for Testing Materials, "Symposium on Steel Castings," 1932.
6. Batty, G., Trans. Am. Foundrymen's Association, Vol. 6, p. 237, February 1935.
7. Heuvers, A., Stahle und Eisen, 1929, No. 35.

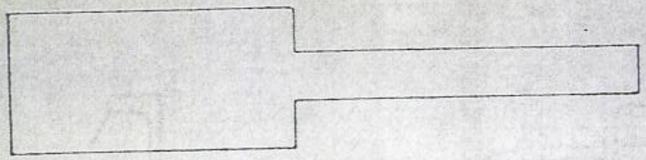
Table VII

Casting Number	Corner Radius in Inches	Types of Chills Used	Inches Effective Perimeter	Total Cross-Sectional Area in Square Inches	Area of Defect in Sq.In.
L Sections					
102	0.50	None	–	–	2.8
102-1	0.50	1/2-inch diameter	0.25	0.20	0.1
102-2	0.50	1-inch diameter	0.78	0.78	None
102-3	0.50	Small triangle	1.87	0.70	None
T Sections					
202	0.50	None	–	–	3.6
202-1	0.50	1/2-inch diameter	0.50	0.40	2.1
202-2	0.50	1-inch diameter	1.56	1.56	0.8
202-3	0.75	1-1/2 inch diameter	2.36	3.54	0.3
202-4	1.00	2-inch diameter	3.14	6.28	0.4
202-5	0.50	Small triangles	3.74	1.40	0.9
202-6	0.50	Large triangles	7.60	5.38	0.5
202-7	0.50	1-inch plate	4.00	3.75	0.6
202-8	0.50	1-inch diameter plus 1-inch plate	5.56	5.31	None
204	3.00	None	–	–	4.1
204-1	3.00	1-inch diameter	0.25	1.56	3.0
204-2	3.00	1-1/2 inch diameter	0.38	3.54	2.7
204-3	3.00	2-inch diameter	0.50	6.28	1.3
204-4	3.00	3-inch diameter	1.0	7.07	1.1
204-5	3.00	Semi-circular (3-inch radius)	9.42	28.27	4.1
204-6	3.00	3-inch diameter plus plate	5.00	10.82	0.2

Table VII (Continued)

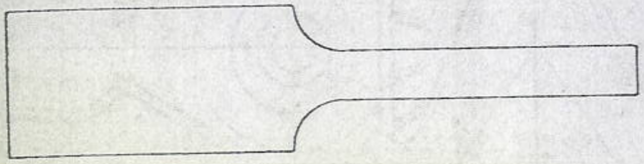
Casting Number	Corner Radius in Inches	Types of Chills Used	Inches Effective Perimeter	Total Cross-Sectional Area in Square Inches	Area of Defect in Sq. In.
X Sections					
502	0.50	None	-	-	6.4
502-1	0.50	1/2-inch diameter	1.00	0.80	2.1
502-2	0.50	1-inch diameter	3.12	3.12	0.6
502-3	0.50	Small triangles	7.48	2.80	0.7
502-4	0.50	Large triangles	15.2	10.76	0.2
502-5	0.50	1-inch plates	3.12	15.57	0.5
503-1	1.00	2-inch diameter	6.28	12.56	0.9
506	0.50	None	-	-	5.0
506-1	0.50	1-inch diameter	3.12	3.12	1.2
Y Sections					
402	-	None	-	-	2.7
402-1	-	1- 1-inch diameter	0.78	0.78	2.1
402-2	-	3- 1-inch diameter	2.34	2.34	1.6
402-3	-	1-inch diameter plus 2-inch diameter	3.92	7.06	1.0
402-4	-	1-inch diameter plus chill plates	9.05	8.78	0.2
402-5	-	1-inch plates	9.05	11.89	0.1

1



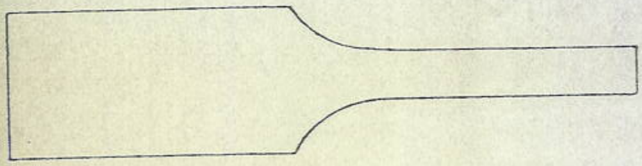
Poor design.

2



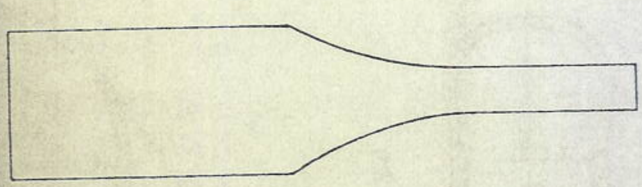
Not recommended.

3



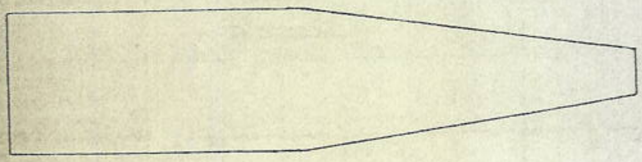
Fair.

4



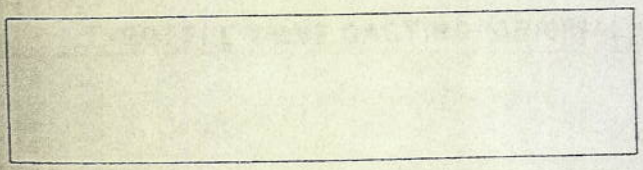
Good.

5



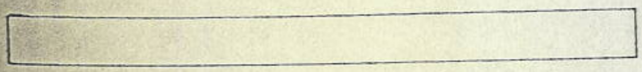
Best, and in some cases, better than 6.

6 A



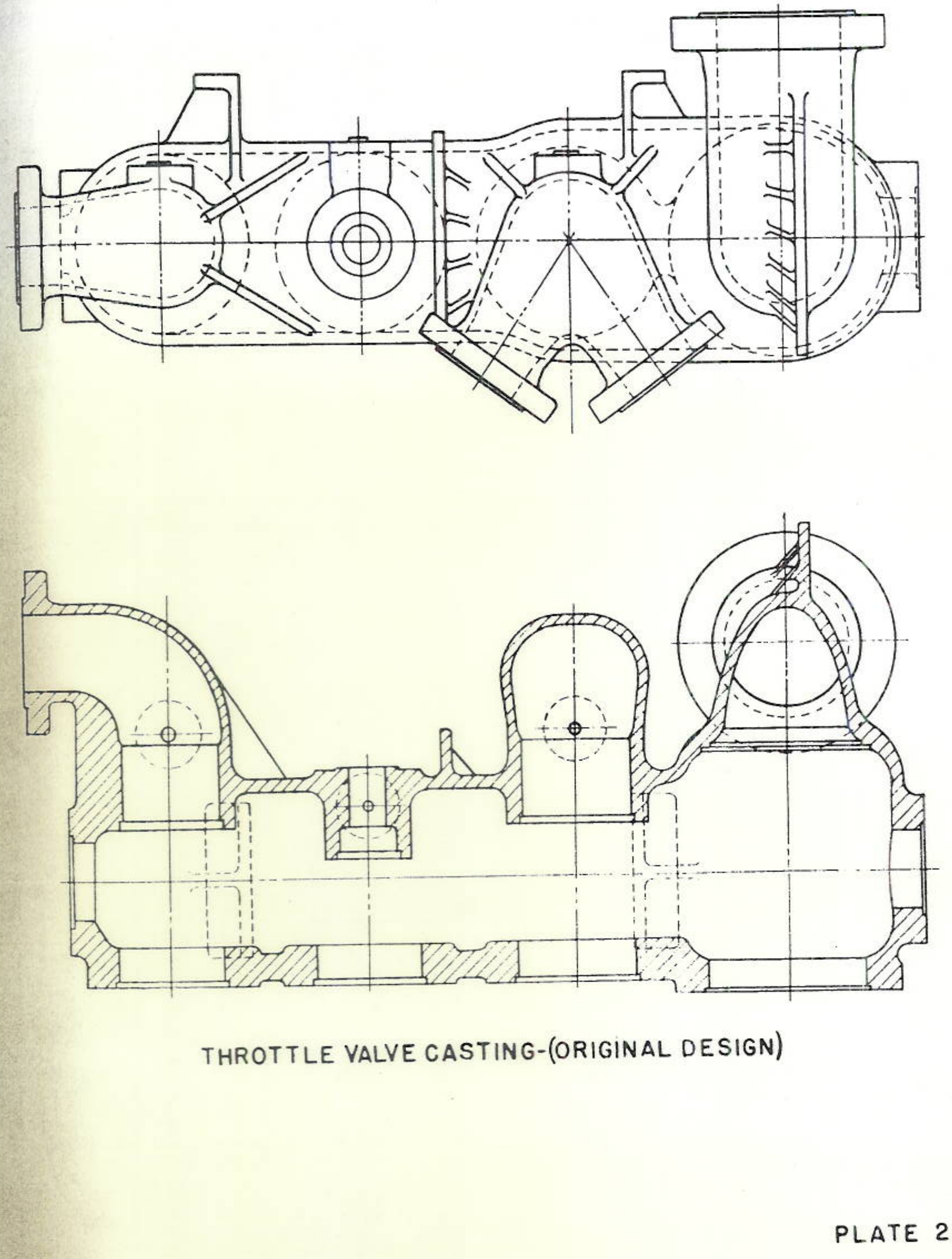
No change of section. Recommended design.

6 B



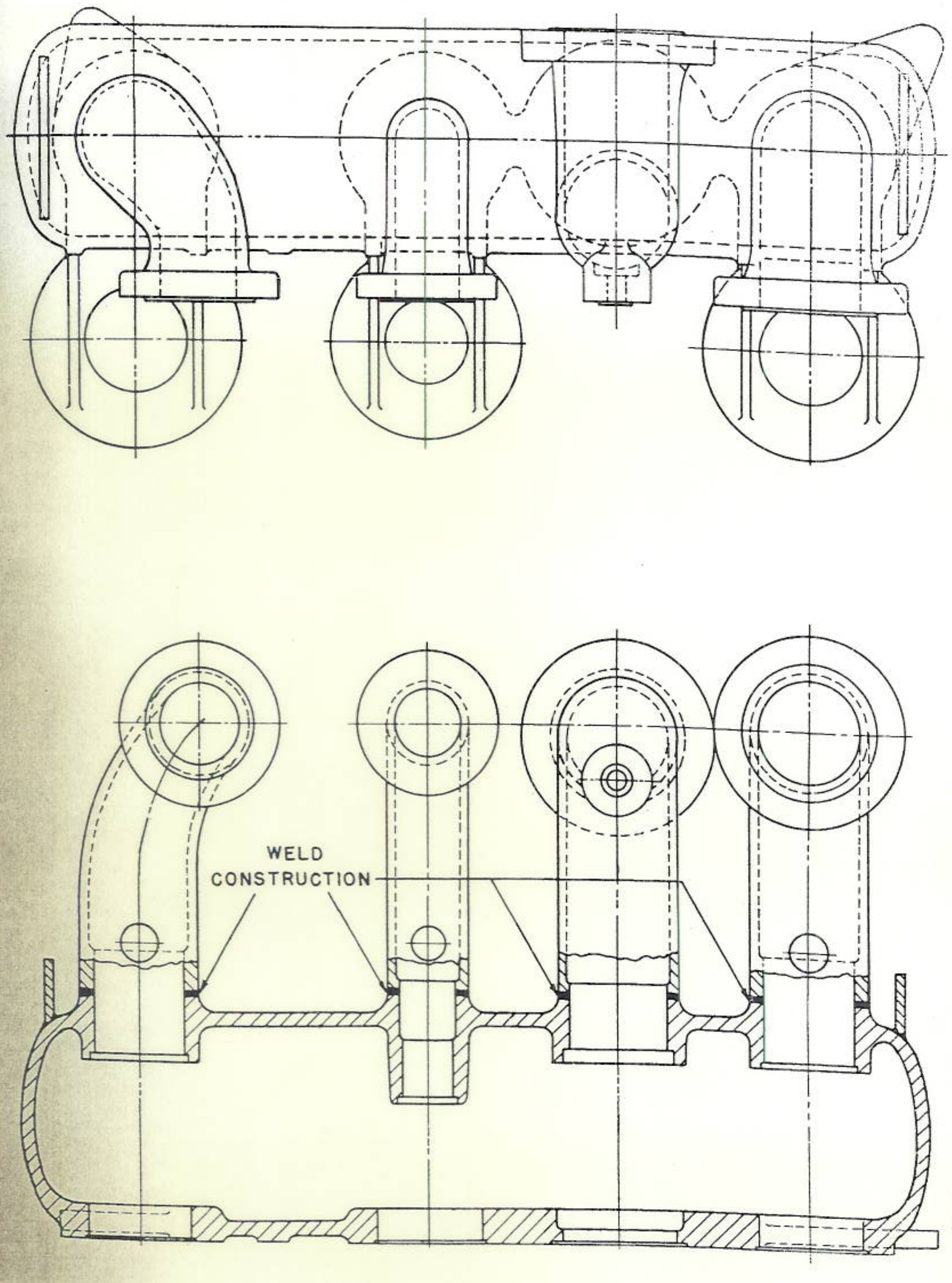
No change of section. Recommended design.

PLATE 1



THROTTLE VALVE CASTING-(ORIGINAL DESIGN)

PLATE 2



THROTTLE VALVE-(CAST WELDED CONSTRUCTION)

PLATE 3

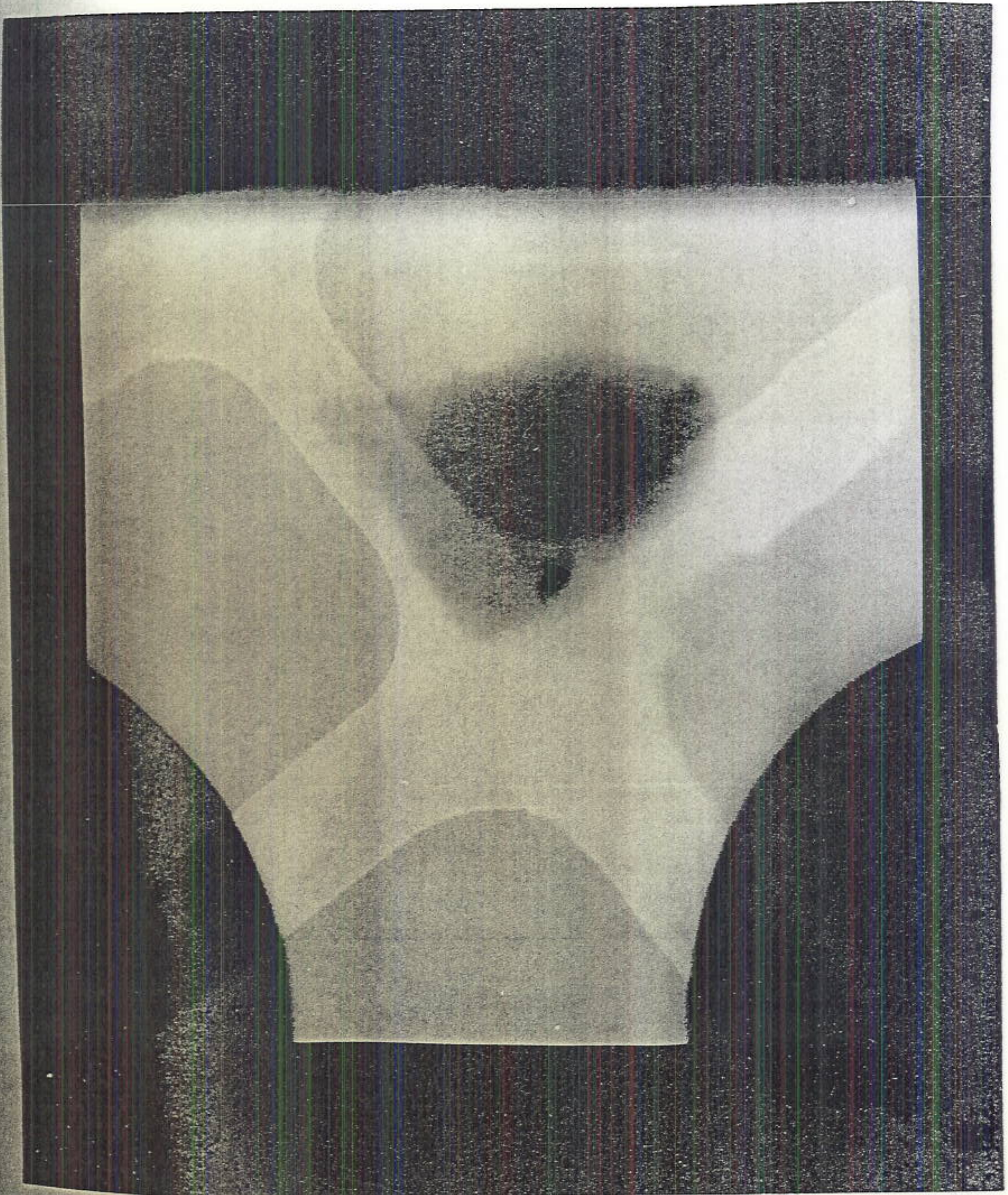
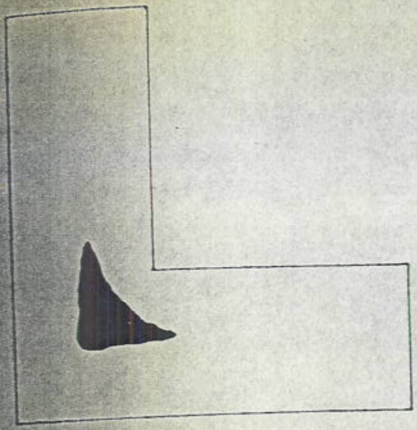


Plate 4

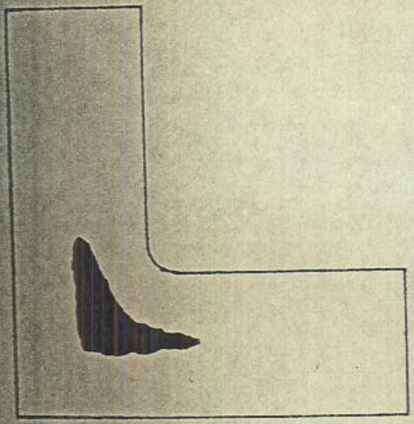
Plate 5



101

Square corners - no radii.
Section 3" x 3".
Poor design - also possibility of
hot tears at sharp corner
junction.

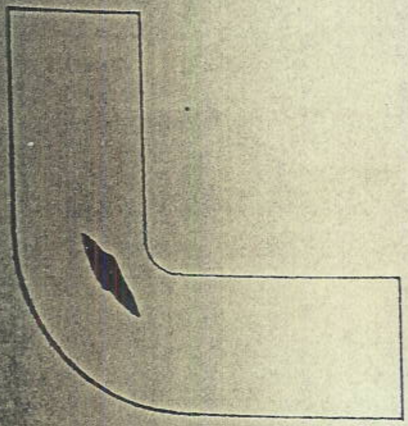
AREA OF DEFECT - 2.05 square inches.



102

Inner corner - 1/2" radius.
Radius slightly increases the
size of defect.

AREA OF DEFECT - 2.8 square inches.

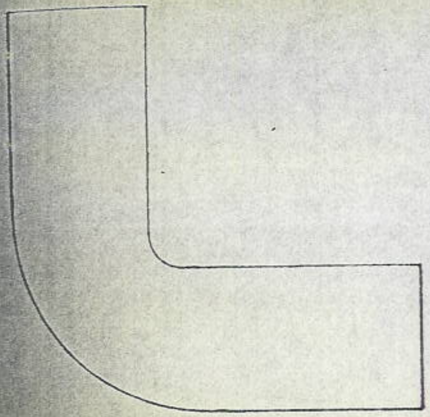


103

Inner corner - 1/2" radius.
Outer corner - 3-1/2" radius.
Uniform section shows a small defect.
Design better than 102.

AREA OF DEFECT - 0.6 square inches.

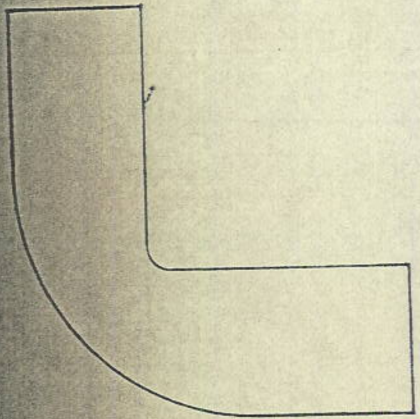
PLATE 6



104

Inner corner - 1/2" radius.
Outer corner - 4-1/2" radius.
Section at the junction is slightly smaller than the arms.
No defect.
Best design.

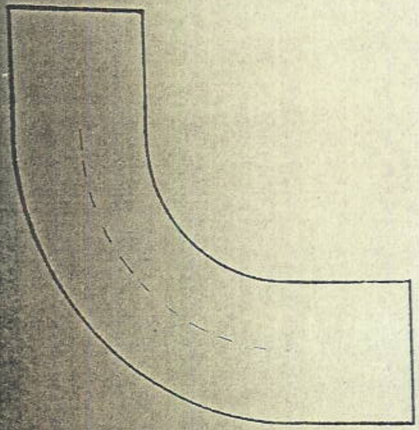
NO DEFECT.



105

Inner corner - 1/2" radius.
Outer corner - 5-1/2" radius.
Very much smaller junction than arm sections.
Drastic design not needed for complete soundness.

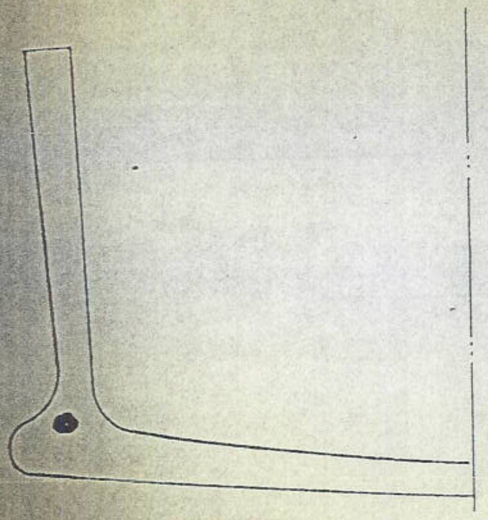
NO DEFECT.



106

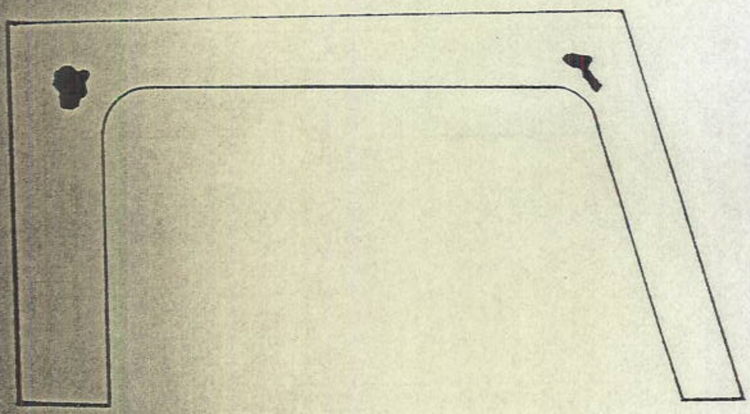
Inner corner - 3" radius.
Outer corner - 6" radius.
Uniform section with large radius - development of center line weakness which can be remedied by foundryman.
Good design.

PLATE 7



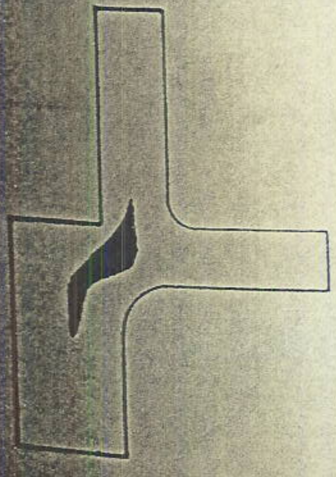
107

Section of a 14" Bitt casting.
Defective - a poor design.
To remedy -
Maintain uniform section or core out hole at position of defect.



108

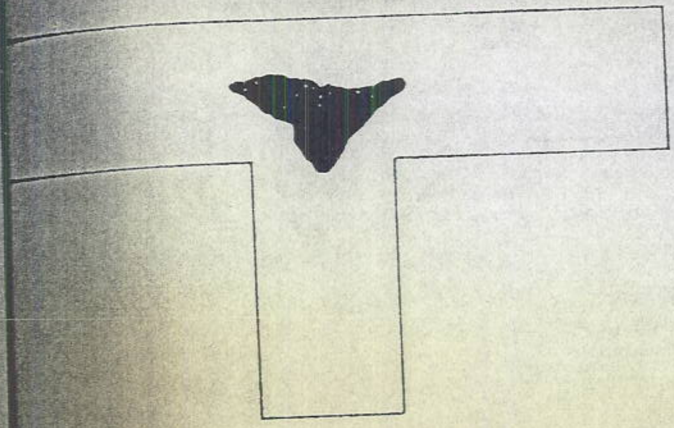
Double "L" from stern post casting.
Defective - poor design.
To remedy -
Eliminate corners.



109

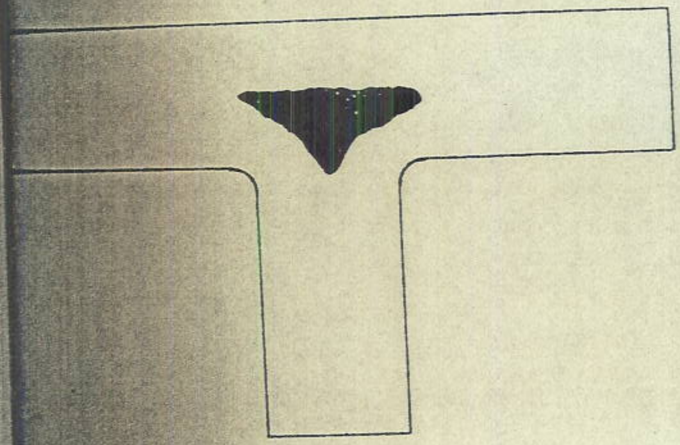
Double "L" from stern post casting.
Poor design.
Study also sections X and Y.
To remedy -
Make sections uniform and core out hot spot center.

PLATE 8



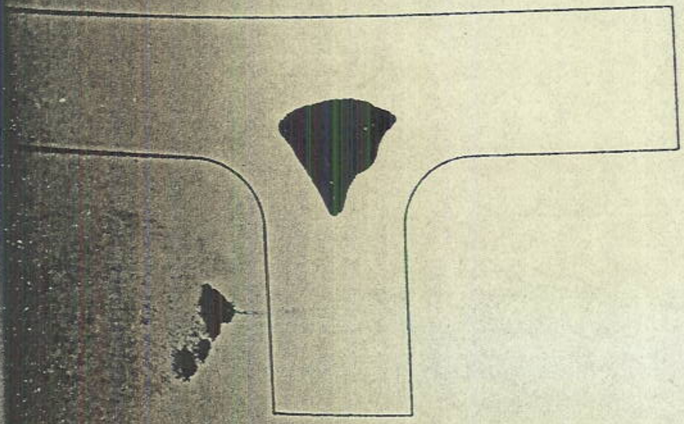
Section 3" x 3".
Square corners - no radii.
Very poor design.

AREA OF DEFECT - 3.5 square inches.



Inner corners - 1/2" radii.

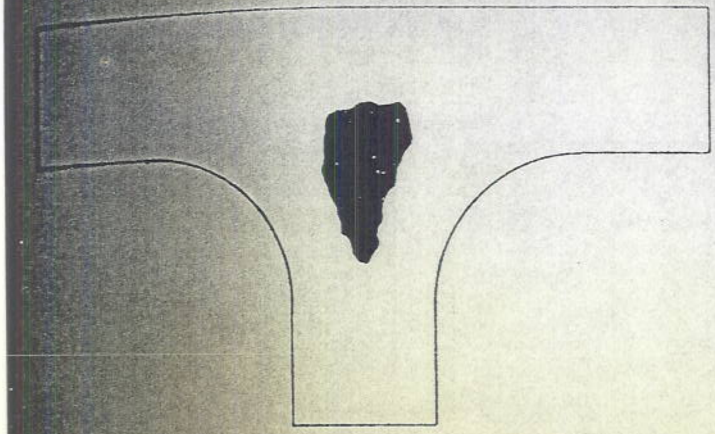
AREA OF DEFECT - 3.6 square inches.



Inner corners - 1-1/2" radii.
Defect slightly larger than 202.

AREA OF DEFECT - 3.8 square inches.

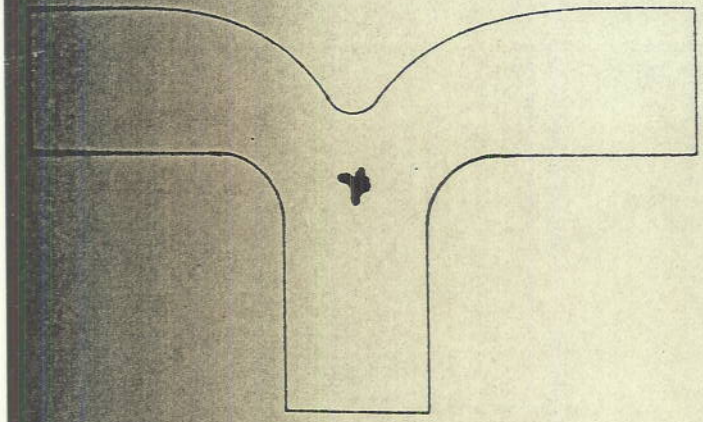
PLATE 9



204

Inner corners - 3" radii.

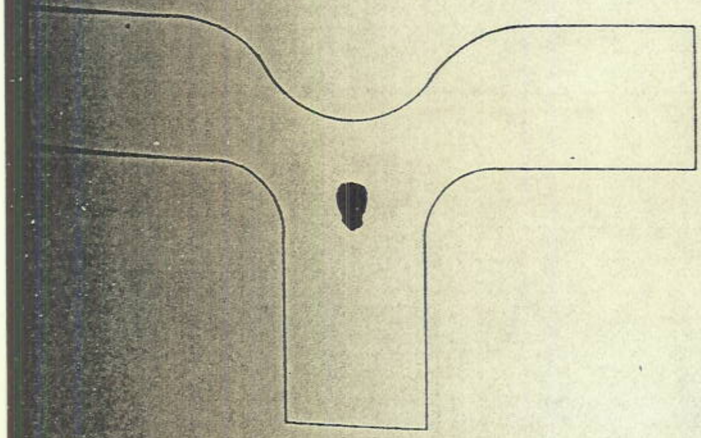
AREA OF DEFECT - 4.1 square inches.



205

Inner corners - 1-1/2" radii.
Outside - 5" radius - V-shaped.
Design much better than 203.

AREA OF DEFECT - 0.3 square inches.

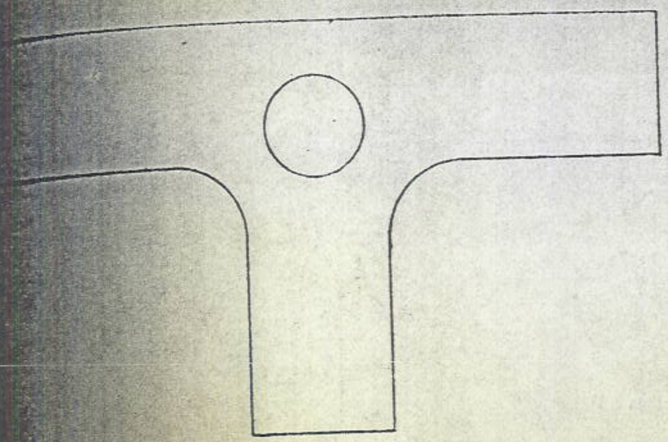


206

Inner corners - 1-1/2" radii.
Outside - 2" radius - U-shaped.
Defect larger than 205.

AREA OF DEFECT - 0.6 square inches.

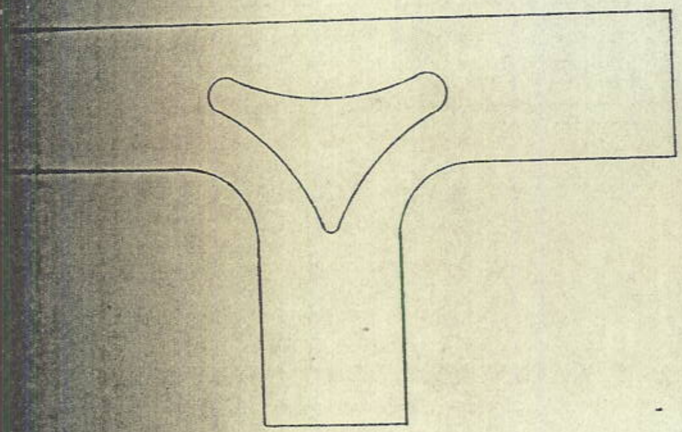
PLATE 10



207

Inner corners - 1-1/2" radii.
Cored 2" diameter hole.

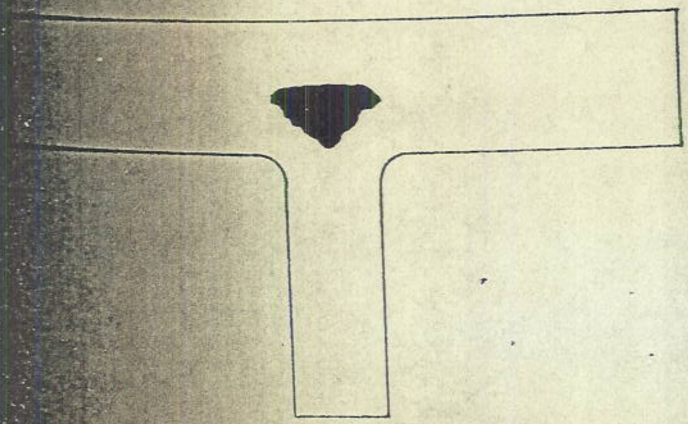
No defect.
The best design.



208

Inner corners - 1-1/2" radii.
Cored hole.

No defect.
Design not as practical as 207.

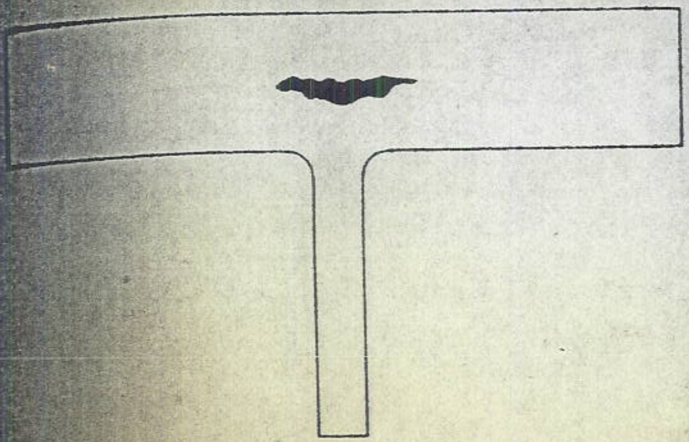


209

Sections: Arms - 3" x 3"
Leg - 2" x 3"

Inner corners - 1/2" radii.
Compare with 202.

AREA OF DEFECT - 1.8 square inches.

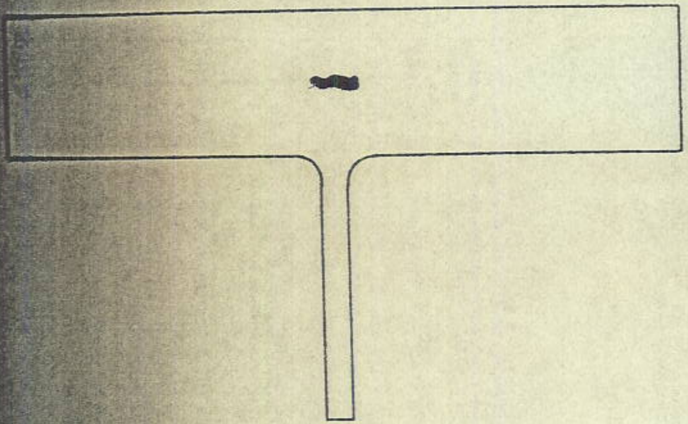


210

Sections: Arms - 3" x 3"
Leg - 1" x 3"

Inner corners - 1/2" radii.

AREA OF DEFECT - 1.0 square inches.

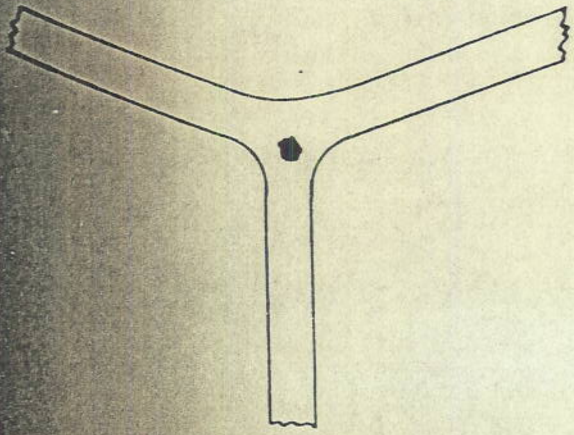


211

Sections: Arms - 3" x 3"
Leg - 1/2" x 3"

Inner corners - 1/2" radii.

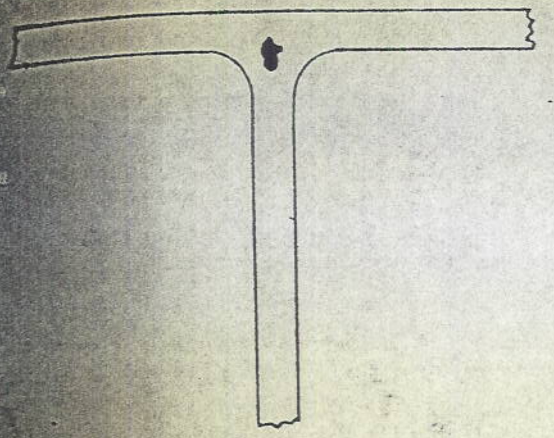
AREA OF DEFECT - 0.2 square inches.



212

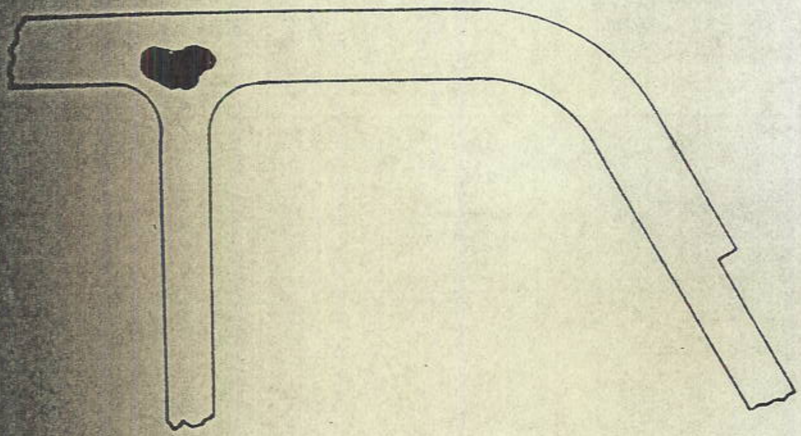
Section of an upper stem casting. Use cored hole in design to illiminate defect.

PLATE 12



213

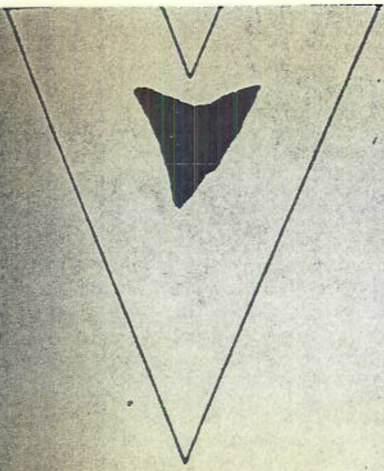
Section from a structural casting.
Remedy same as 212.



214

Section from a stem casting.
To reduce size of defect use
dip in arm at intersection
as 205.

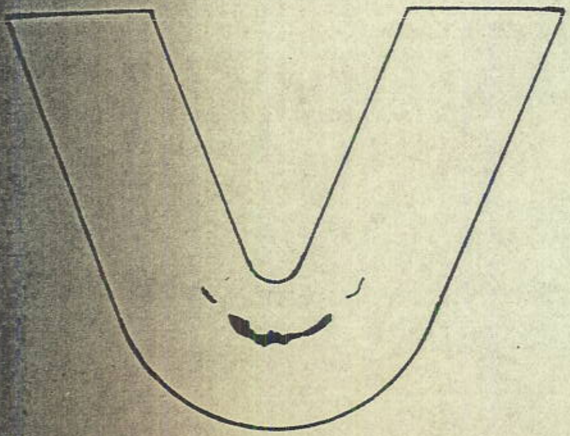
PLATE 13



301

Members intersect at 45 degrees.
Section - 3" x 3".
No radii - sharp corners.

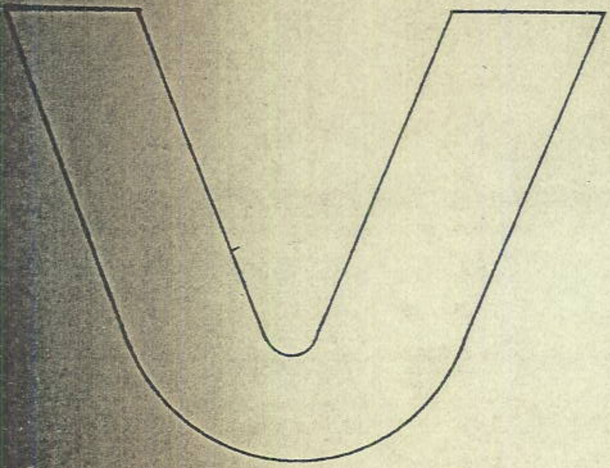
AREA OF DEFECT - 3.3 square inches.



302

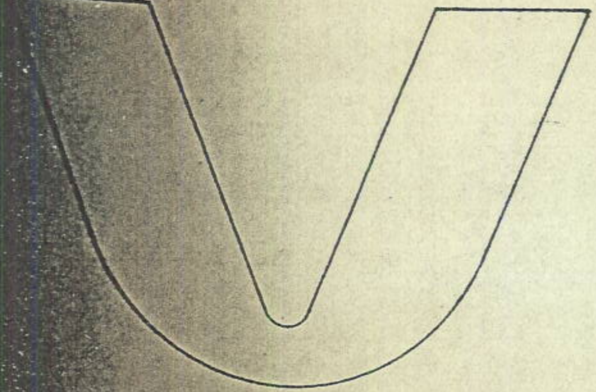
Inner radius - 1/2 inch.
Outer radius - 3-1/2 inches.
Uniform section.
Defect due to poor conduction.of sand from the inner face.

AREA OF DEFECT - 0.3 square inches.



303

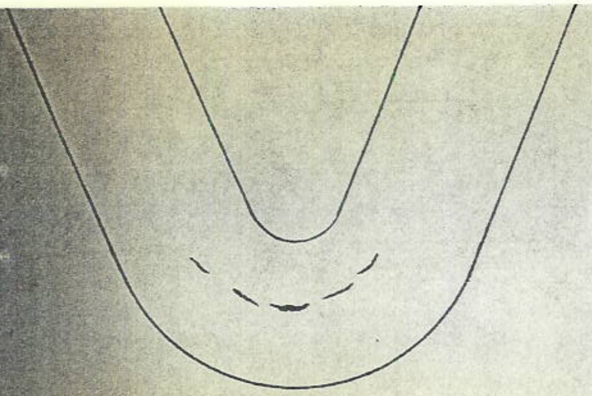
Inner radius - 1/2 inch.
Outer radius - 4 inches.
No defect.
Best design.



304

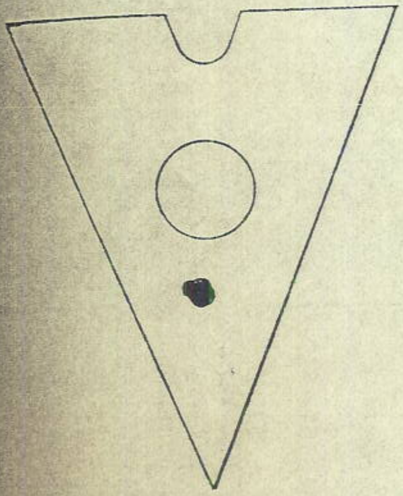
Inner radius - 1/2 inch.
Outer radius - 4-1/2 inches.
No defect.
Design not as good as 303.

PLATE 14



305

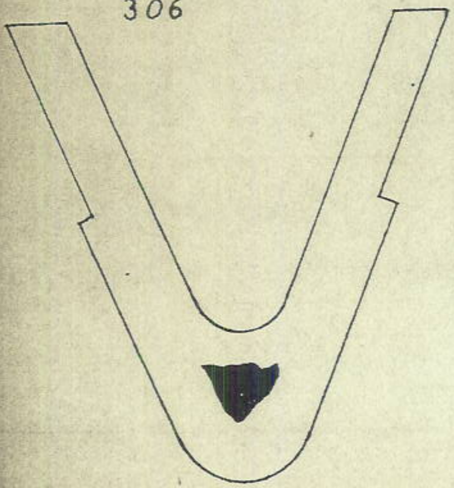
Inner radius - 1 inch.
Outer radius - 4 inches.
Uniform section - compare with 302.



306

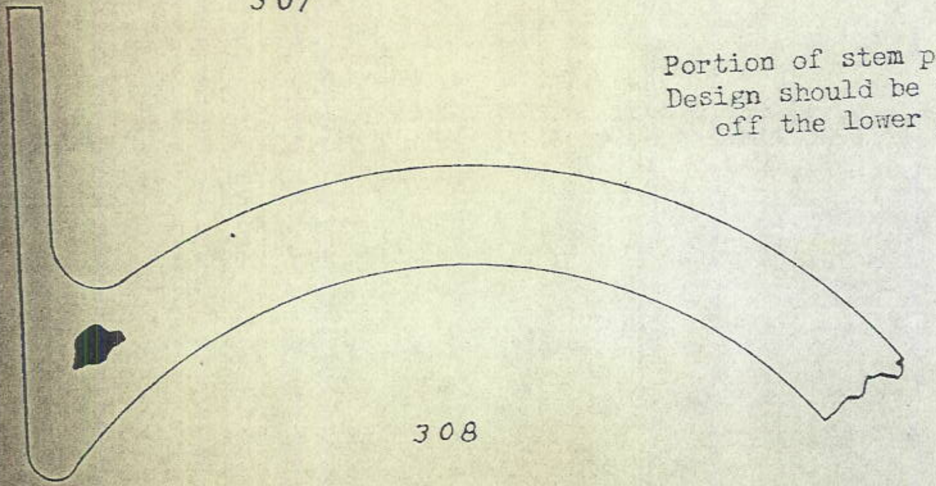
Inner radius - 1/2 inch.
Cored 2-inch diameter hole.

AREA OF DEFECT - 0.3 square inch.



307

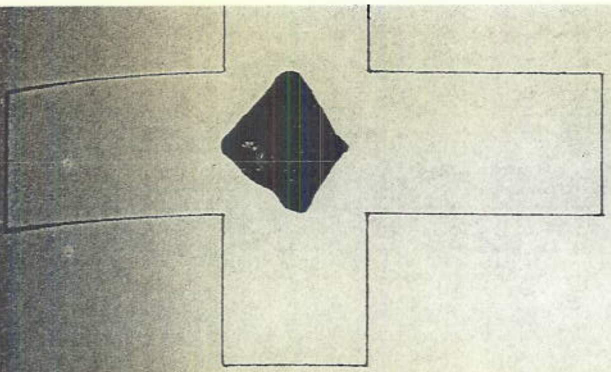
Portion of lower stem casting.
Section could not be fed except
through the arms.
Design very poor.



308

Portion of stem post casting.
Design should be modified to take
off the lower portion of the "Y".

PLATE 15

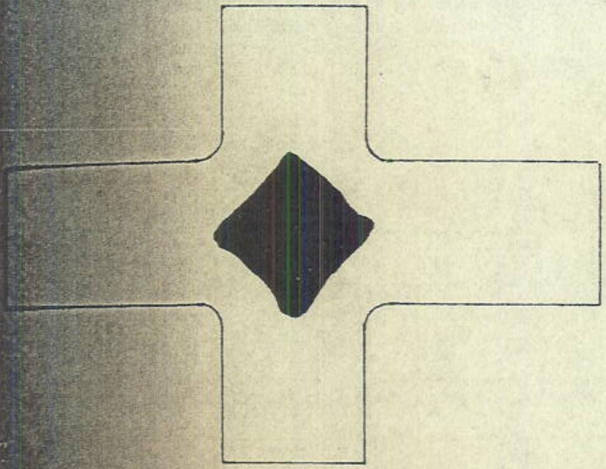


501

Section 3" x 3".

Sharp corners - no radii.

AREA OF DEFECT - 5.5 square inches.

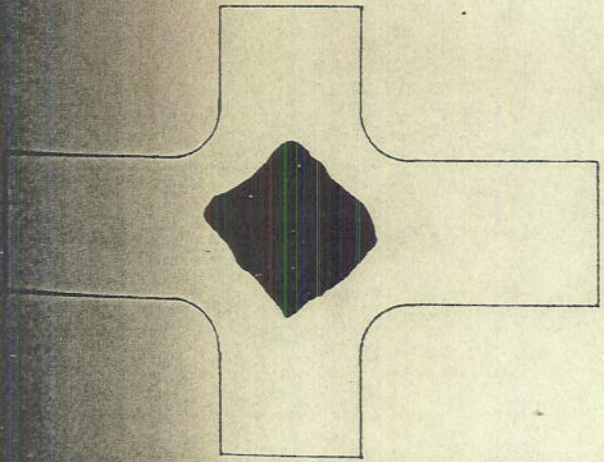


502

All radii 1/2 inch.

Defect slightly larger than 502.

AREA OF DEFECT - 6.4 square inches.

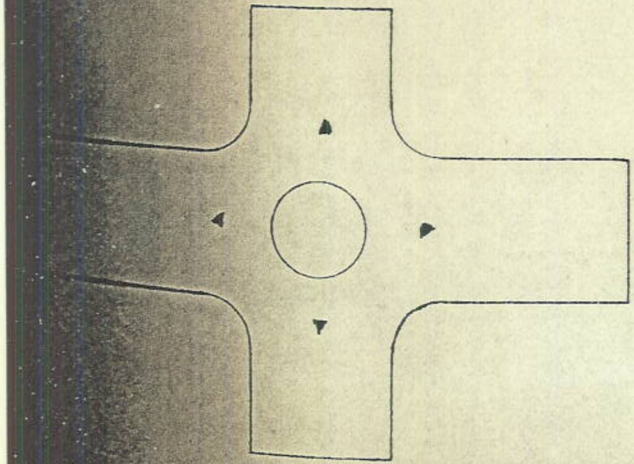


503

All radii 1 inch.

Defect slightly larger than 503.

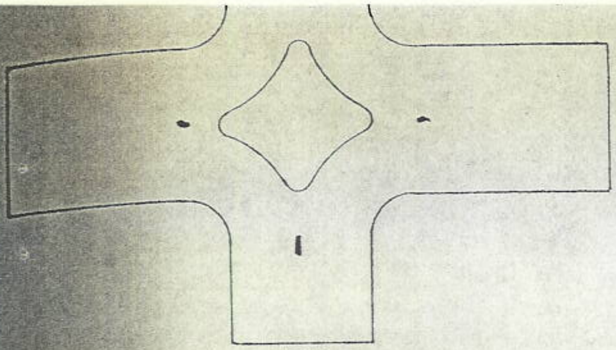
AREA OF DEFECT - 8.1 square inches.



504

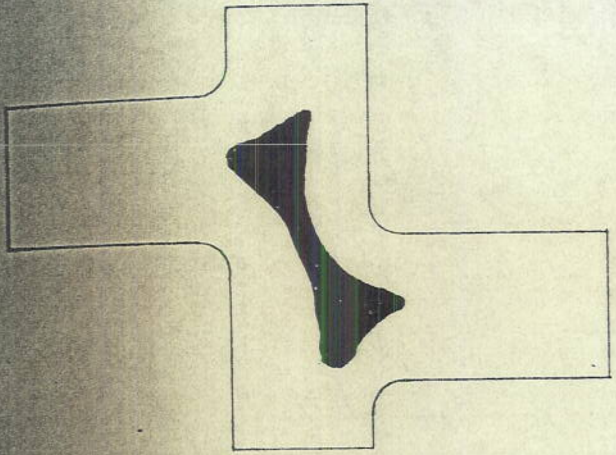
All radii 1 inch.
Two-inch diameter cored hole.
Four very small cavities at the
head of each arm.

PLATE 16



505

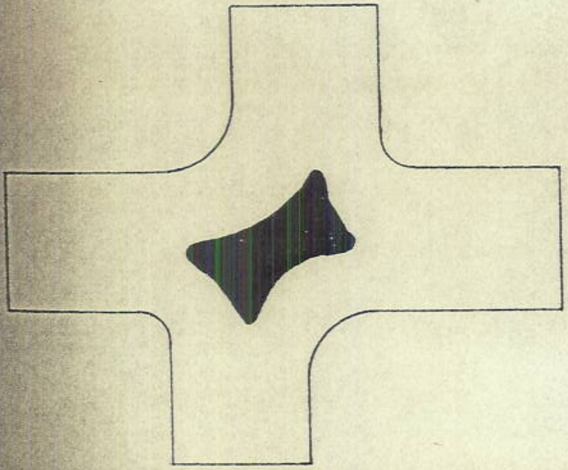
All radii 1 inch.
Cored rectangular hole cavities
smaller than those of 504.



506

All radii 1/2 inch.
One arm completely offset.
Area of defect about the same as 502.

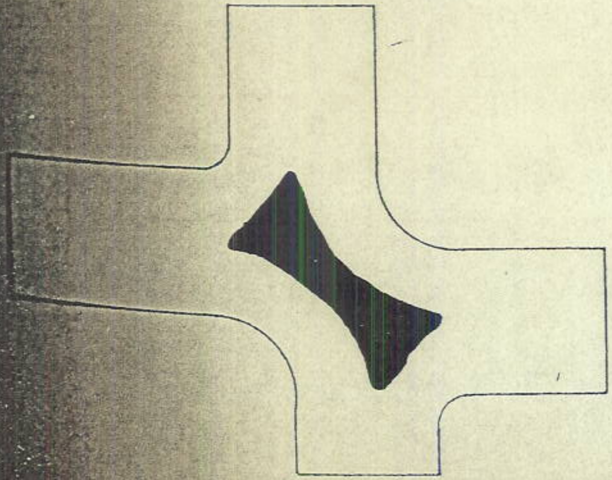
AREA OF DEFECT - 5.5 square inches.



507

Two radii 1/2 inch.
Two radii 1-1/2 inches.
One arm 1/2 offset.

AREA OF DEFECT - 5.3 square inches.

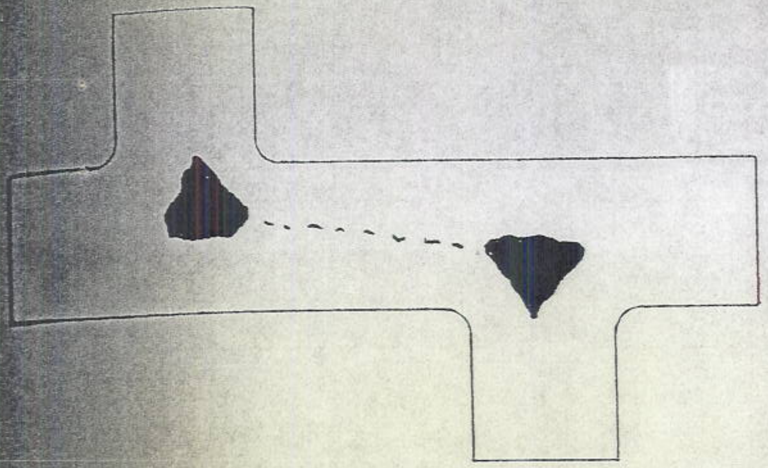


508

Two radii 1/2 inch.
Two radii 1-1/2 inches.
Both arms 1/2 offset.

AREA OF DEFECT - 5.9 square inches.

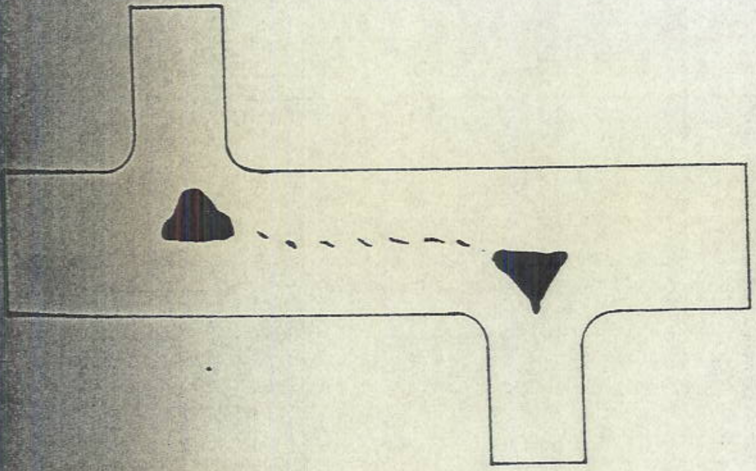
PLATE 17



509

All sections 3" x 3".
All radii 1/2 inch.
Center lines of offsets are
8 inches apart.

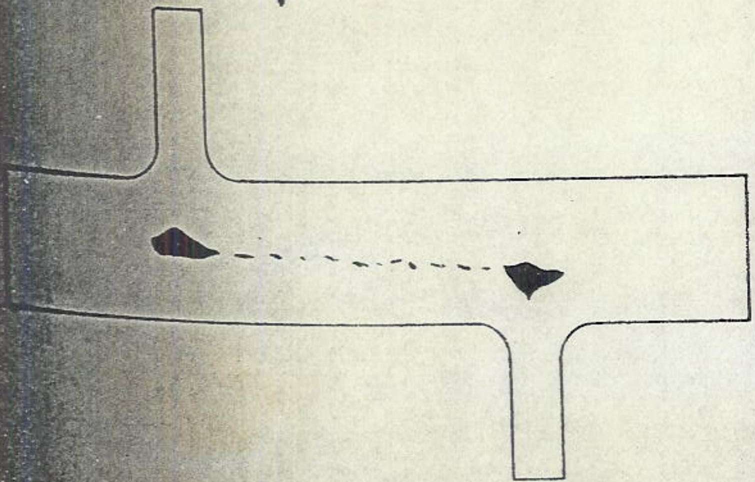
TOTAL AREA OF DEFECTS - 4.3 square inches.



510

Offset sections 2" x 3".
All radii 1/2 inch.

TOTAL AREA OF DEFECTS - 2.0 square inches.

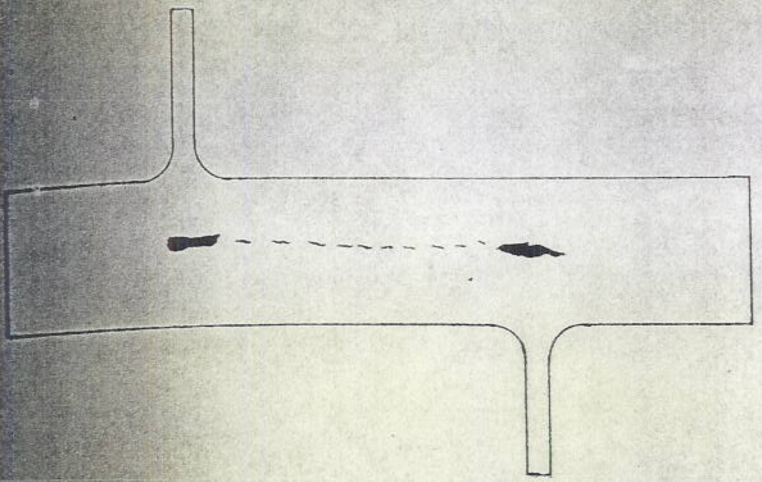


511

Offset sections 1" x 3".
All radii 1/2 inch.

TOTAL AREA OF DEFECTS - 0.9 square inches.

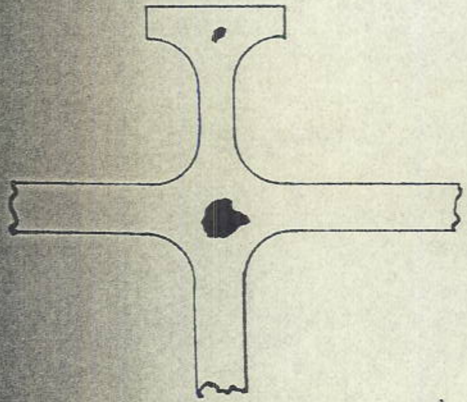
PLATE 18



512

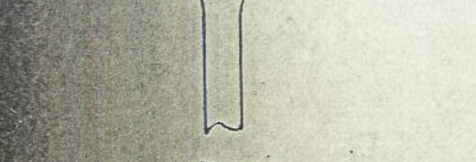
Offset sections 1/2" x 3".
All radii 1/2 inch.

TOTAL AREA OF DEFECTS - 0.4 square inch.



513

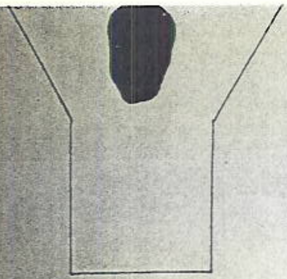
Section taken from a stern post casting.



514

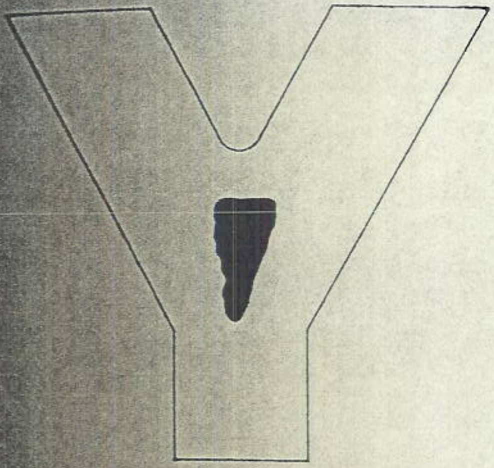
Showing defect found in a portion of a structural casting with arm offset.

PLATE 19



401

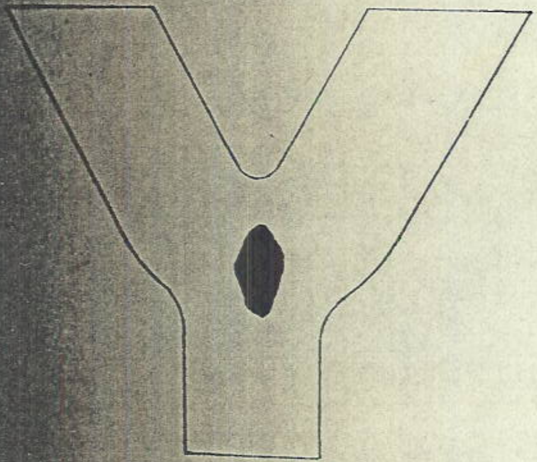
AREA OF DEFECT - 2.7 square inches.



402

Inner radius - 1/2 inch.
Outer radii - 3 inches.

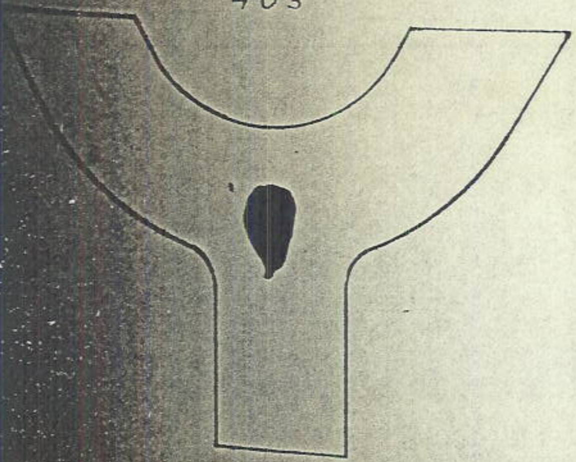
AREA OF DEFECT - 2.7 square inches.



403

Inner radius - 1/2 inch.
Outer radius - 3-1/2 inches.
Lower radii - 1 inch.
Defect smaller than 401, 402.

AREA OF DEFECT - 1.9 square inches.

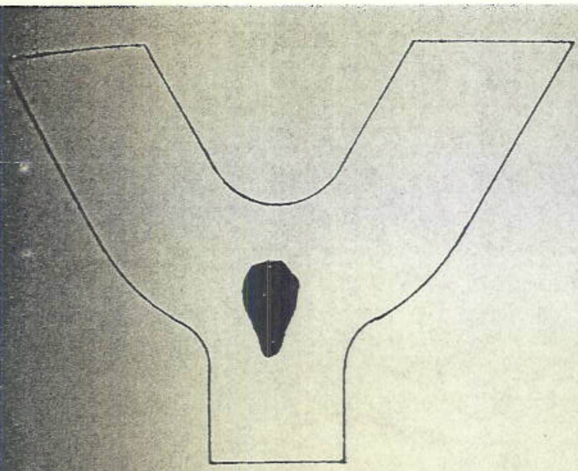


404

Inner radius - 3 inches.
Outer radius - 6 inches.
Lower radii - 1 inch.
Defect similar to 403.

AREA OF DEFECT - 1.9 square inches.

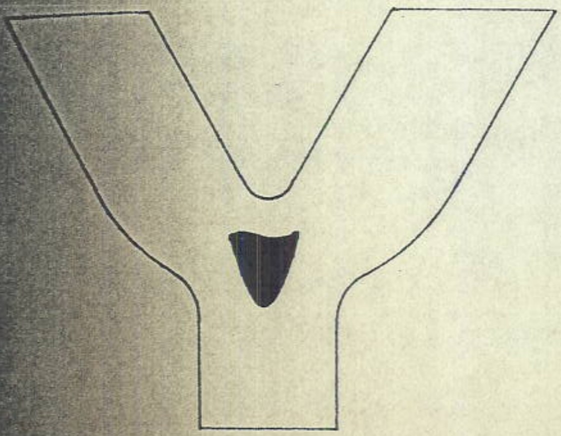
PLATE 20



405

Inner radius - 1-1/2 inches.
Outer radius - 4-1/2 inches.
Lower radii - 1 inch.
Defect the same size as 403.

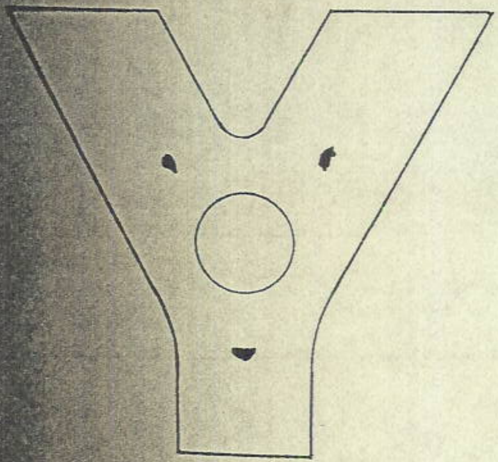
AREA OF DEFECT - 1.9 square inches.



406

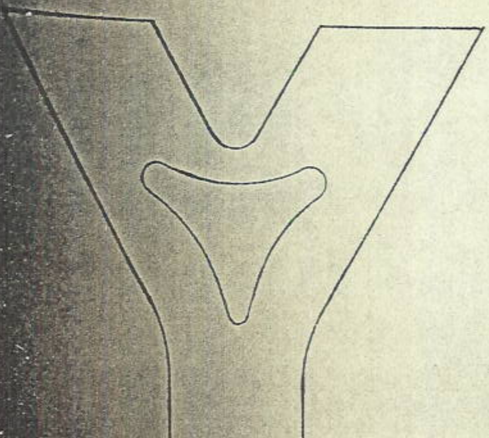
Inner radius - 1/2 inch.
Outer radius - 4-1/2 inches.
Lower radii - 1 inch.
Defect nearly the same size as 403.

AREA OF DEFECT - 1.8 square inches.



407

Same as 402, except with cored hole 2 inches in diameter.

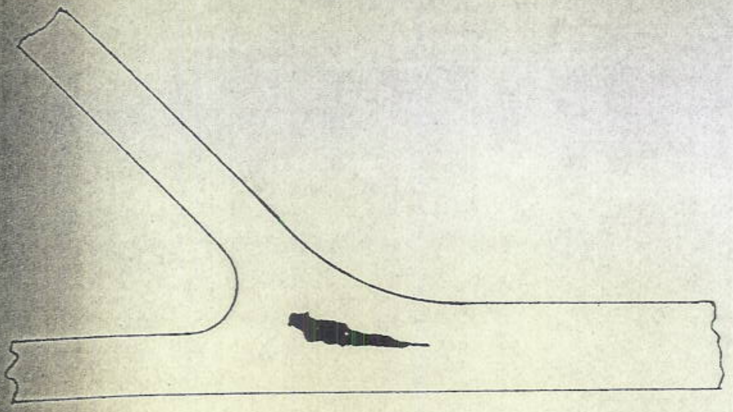


408

Same as 402, except with cored triangular hole.

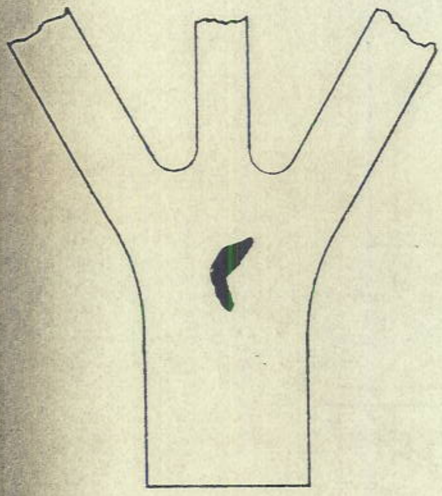
NO DEFECT.

PLATE 21



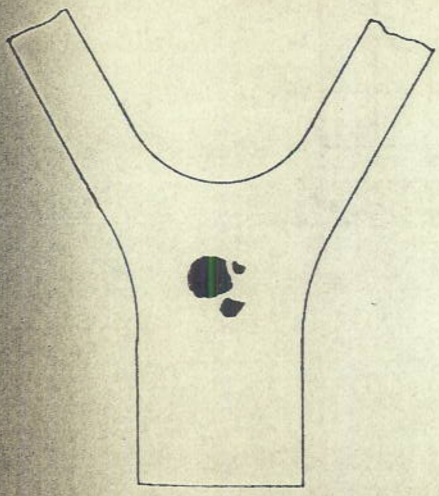
409

Portion from the upper stem structural casting showing type of defect found.



410

Section of the lower stem casting showing double "Y" and type of defect encountered.



411

Section of a structural casting showing type of defect found.

PLATE 22

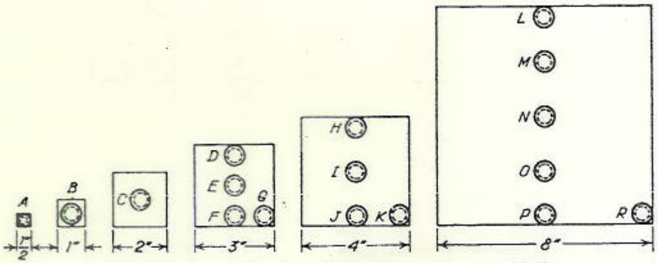


Fig. 4—Location of Test Bars in the Carbon Cast Steel Blocks.

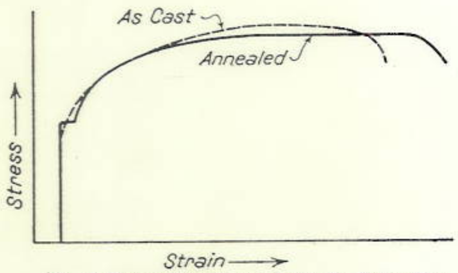


Fig. 5—Typical Stress-Strain Curves for Carbon Cast Steel.

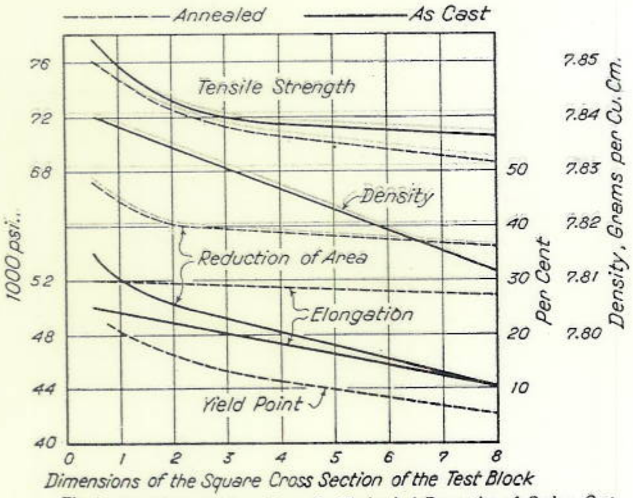


Fig. 6—The Effect of Mass Upon the Mechanical Properties of Carbon Cast Steel at the Center of the Test Block.

PLATE 23

Table I

The Effect of Mass Upon the Mechanical Properties of Medium Carbon Cast Steel

Specimen		Yield Point Lbs. Per Sq. In.		Tensile Strength Lbs. Per Sq. In.		Per Cent Elongation		Per Cent Reduction in Area	
		As Cast	Annealed	As Cast	Annealed	As Cast	Annealed	As Cast	Annealed
Center ½" Block	A	38,200	49,000	77,600	75,450	25	30	35	47
Center 1" Block	B	......	48,000	75,500	75,000	25	28	30	46
Center 2" Block	C	......	46,750	73,000	74,500	21	30	26	40
Top 3" Block	D	......	44,750	71,750	71,500	18	28	19	35
Center 3" Block	E	......	45,200	72,300	72,000	20	29	23	39
Bottom 3" Block	F	......	45,000	74,000	72,400	21	28	26	40
Lower Corner 3" Block	G	......	45,250	73,500	73,250	23	29	30	42
Top 4" Block	H	......	45,250	71,000	70,000	15	29	21	43
Center 4" Block	I	......	44,500	71,200	70,500	19	29	23	39
Bottom 4" Block	J	......	45,750	73,250	72,250	22	30	21	46
Lower Corner 4" Block	K	......	45,500	73,700	73,000	25	30	33	46
Top 8" Block	L	......	41,750	70,000	70,125	8	26	9	40
Center of upper half 8" Block	M	......	43,000	71,000	68,250	9	26	9	40
Center 8" Block	N	33,500	42,000	70,500	68,500	9	27	10	36
Center of lower half 8" Block	O	......	41,750	74,250	68,750	16	28	18	41
Bottom 8" Block	P	......	43,750	76,100	70,750	18	29	21	44
Lower Corner 8" Block	R	......	43,500	76,750	72,125	22	29	30	44

Table II

The Effect of Mass Upon the Density of Cast Steel

Location of Specimen	Density
Center 1-Inch Coupon	7.8379
Center 3-Inch Coupon	7.8306
Top 8-Inch Coupon	7.8106
Center 8-Inch Coupon	7.8114
Bottom 8-Inch Coupon	7.8122
Lower Corner 8-Inch Coupon	7.8175

Table III

Chemical Analyses of Sections of Medium Carbon Steel

Location of Specimen	Per Cent			
	Carbon	Manganese	Silicon	Aluminum
Center 1" Coupon	0.270	0.634	0.212	0.035
Top 8" "	0.265	0.634	0.229	0.028
Center 8" "	0.243	0.623	0.228	0.040
Corner 8" "	0.268	0.637	0.230	0.032

PLATE 24

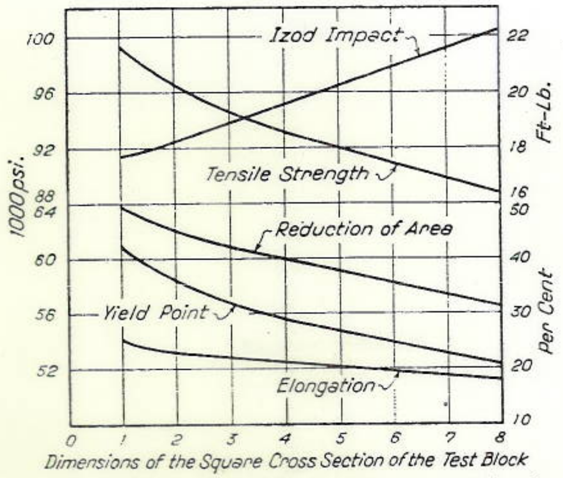


Fig. 7—Effect of Mass Upon the Mechanical Properties of Medium Manganese Steel at the Center of the Test Block.

Table IV

The Effect of Mass Upon the Mechanical Properties of Medium Manganese Cast Steel

Specimen			Heat Treatment Degrees Fahr.		Lbs. Per Sq. In. Yield Point	Tensile Strength	Per Cent Elongation	Reduction of Area	Ft.-Lbs. Izod
Center	1"	Coupon	Annealed	1650—1 hr.	60,750	99,000	25	49	17.7
"	3"	"	"	1650—3 hr.	56,750	94,750	22	42	18.6
"	8"	"	"	1650—8 hr.	52,250	88,625	18	31	22.3
Top	8"	"	"	1650—8 hr.	52,750	88,125	18	31	....
Bottom	8"	"	"	1650—8 hr.	56,000	95,000	23	41	....
Corner	8"	"	"	1650—8 hr.	56.000	95,000	24	50	19.2
Midpoint	8"	"	"	1650—8 hr.	55.750	92,250	21	35	....
*C-4			"	1650—1 hr.	61.375	91.375	20	52	....
*C-5			"	1850—1 hr.	56,000	88,650	20	50	....
*D-3			"	2050—1 hr.	58,625	99,125	22	46	14.6
*D-4			"	2250—1 hr.	60.000	99,675	17	36	....
*D-6			"	1850—15 min.	60,650	96,125	22	42	....
*E-4			"	2050— 5 min.	60,750	96,875	22	41	16.3
*E-5			"	2250— 5 min.	......	99,650	18	40	....
*F4			"	1650—1 hr. 1525—1 hr.	68,250	96,375	22	48	....
*F5			Merten's Treatment		51,500	90,000	25	50	....

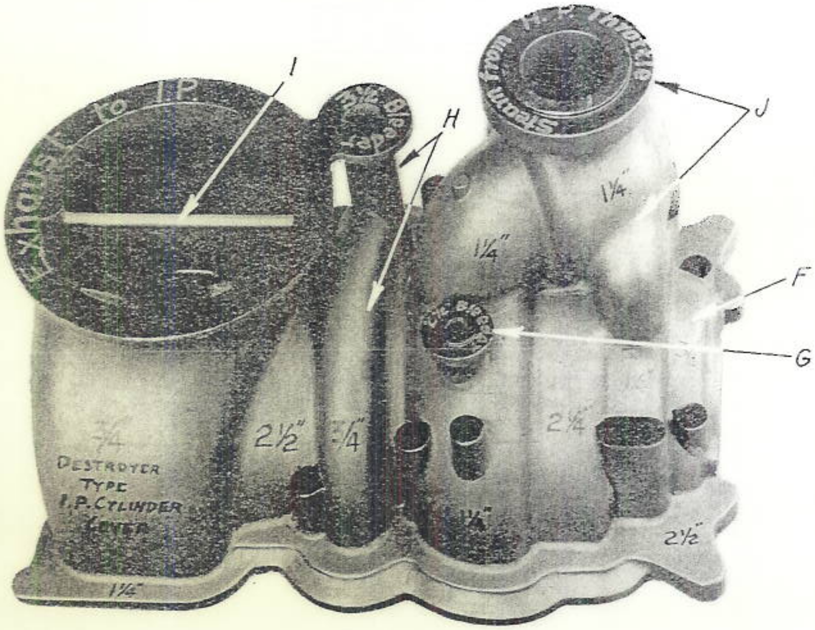
*Specimens previously annealed in coupon at 1650 degrees Fahr. for 8 hours.

Table V

Chemical Analyses of Sections of Medium Manganese Steel

Location of Specimen			Per Cent Carbon	Manganese	Silicon	Aluminum
Center	1"	Coupon	0.340	1.46	0.322	0.057
Center	3"	"	0.323	1.46	0.320	.....
Top	8"	"	0.320	1.46	0.319	.....
Center	8"	"	0.297	1.41	0.312	0.056
Bottom	8"	"	0.333	1.47	0.322	.....
Corner	8"	"	0.342	1.48	0.321	.....

PLATE 25


I
H
J
F
G
Exhaust to I.P.
3/4" Bleeder
Steam from H.P. Throttle
1¼"
1¼"
2½"
3/4"
2¼"
1¼"
2½"
1¼"
3/4
DESTROYER TYPE I.P. CYLINDER COVER

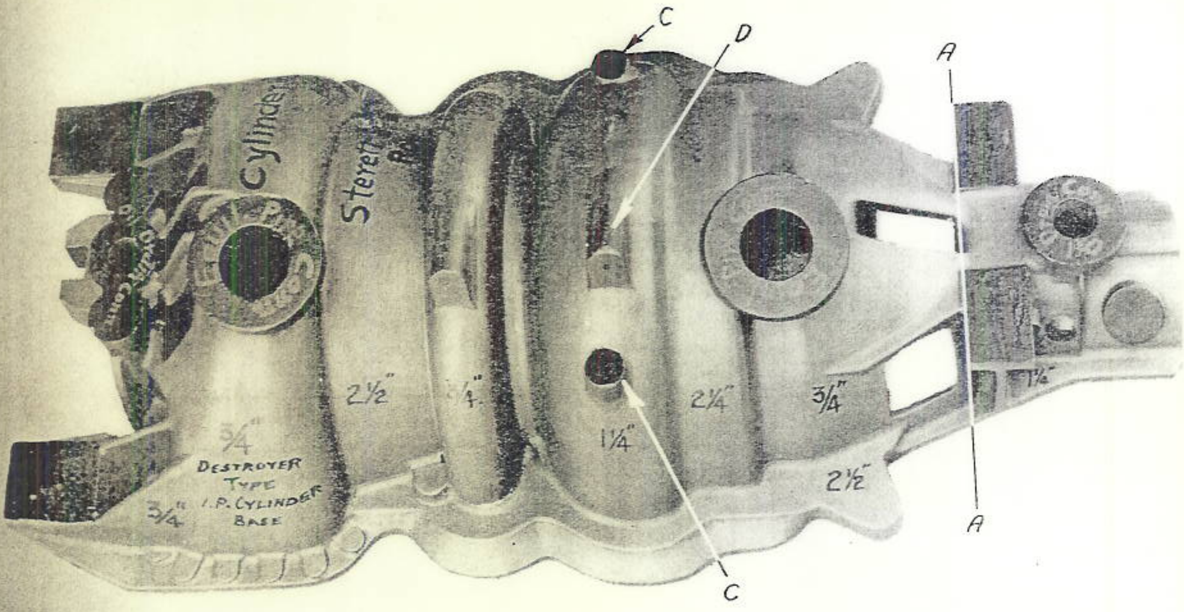

C
D
A
A
C
Cylinder
Sterett
2½"
3/4"
1¼"
2¼"
3/4"
2½"
1¼"
3/4"
DESTROYER TYPE I.P. CYLINDER BASE
3/4"

PLATE 26

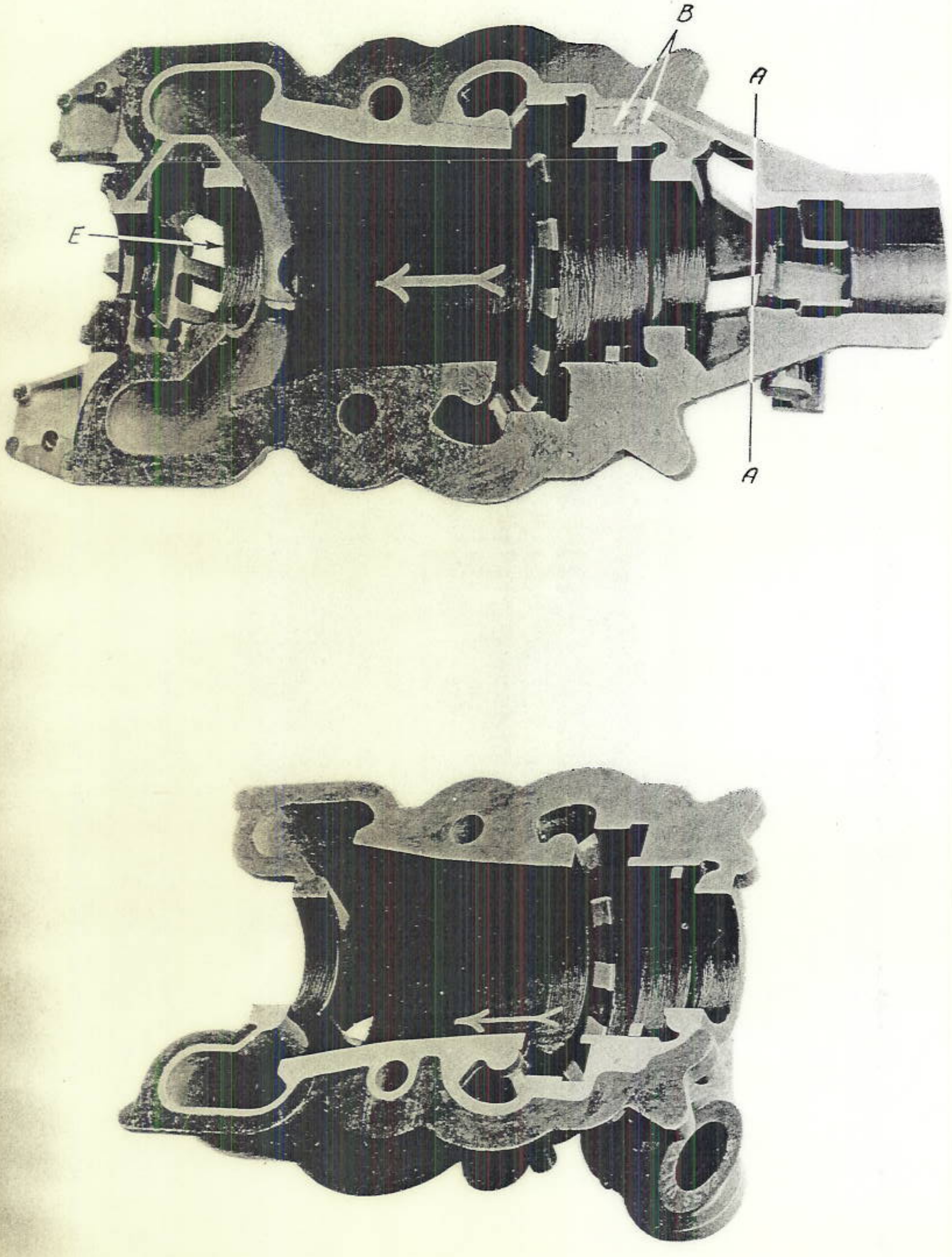


PLATE 27

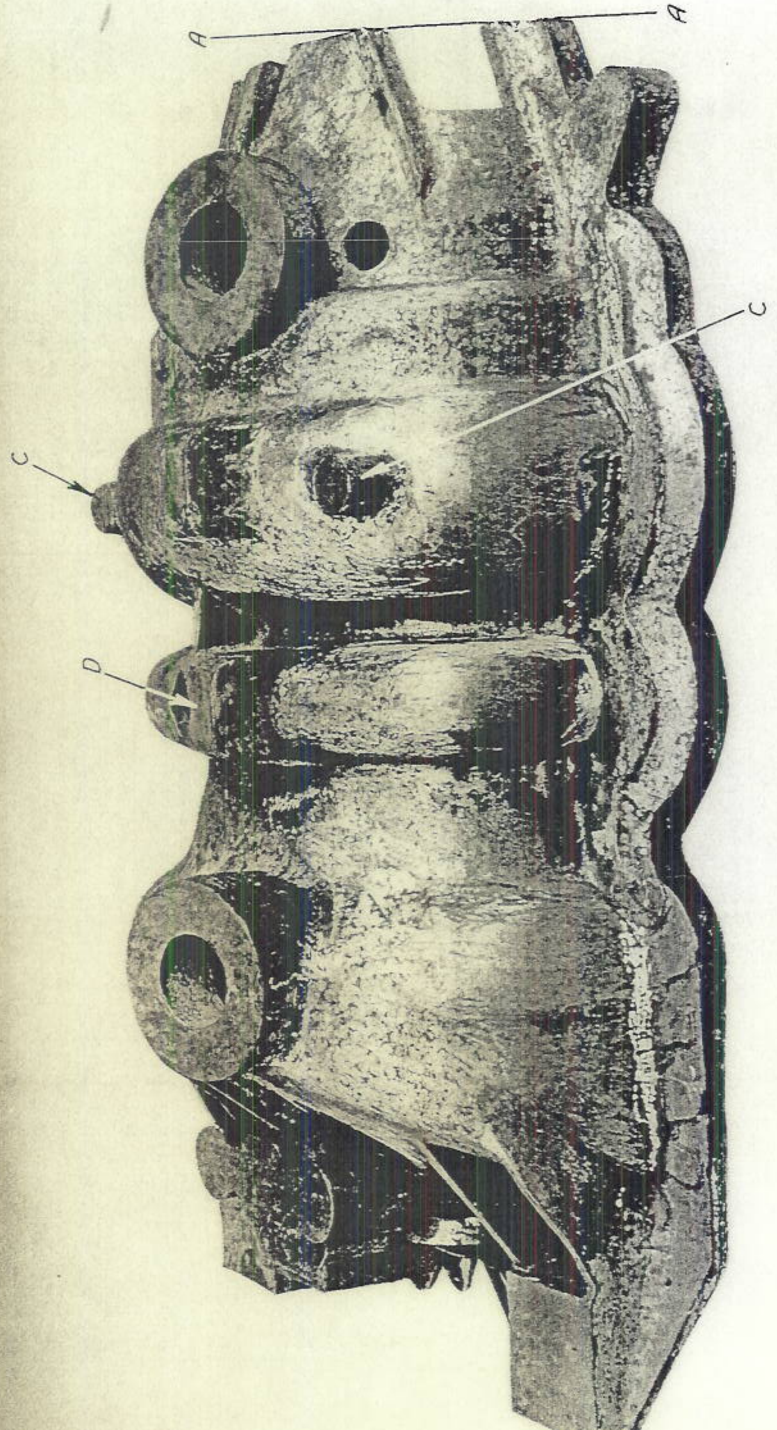


PLATE 28

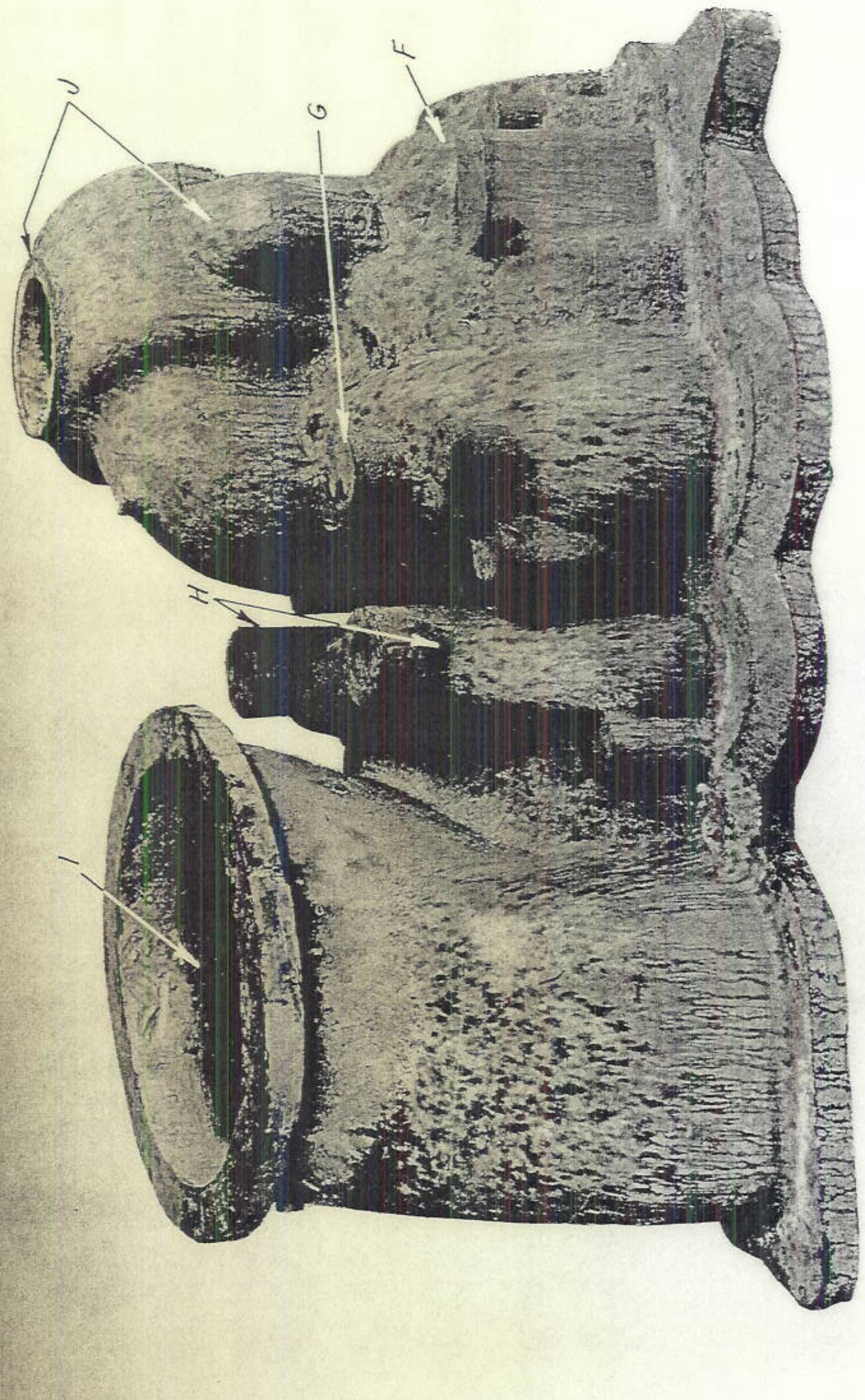


PLATE 29

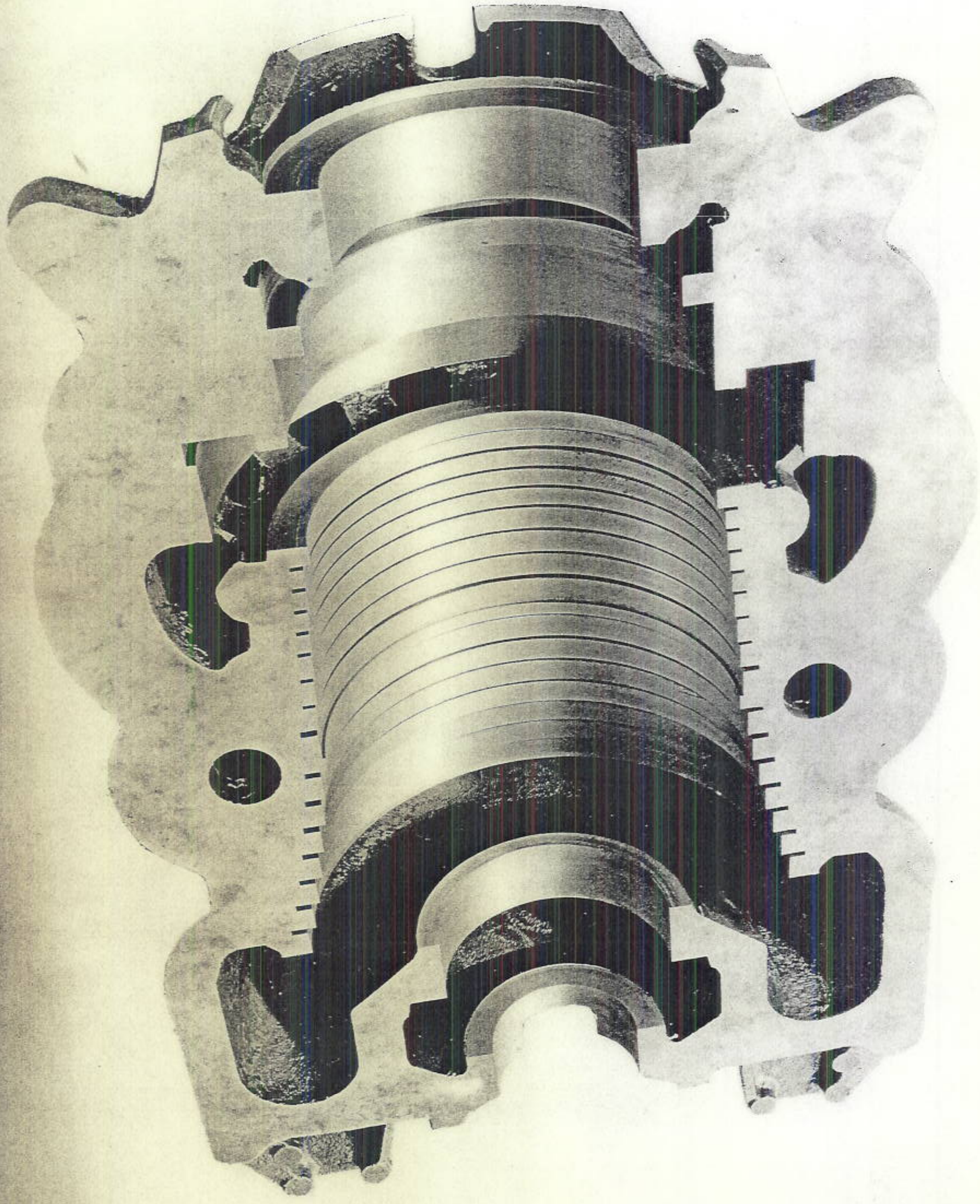


PLATE 30

FIG. 9

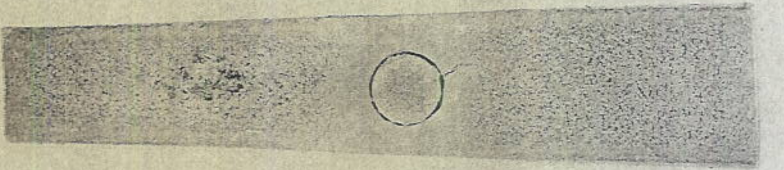


FIG. 10

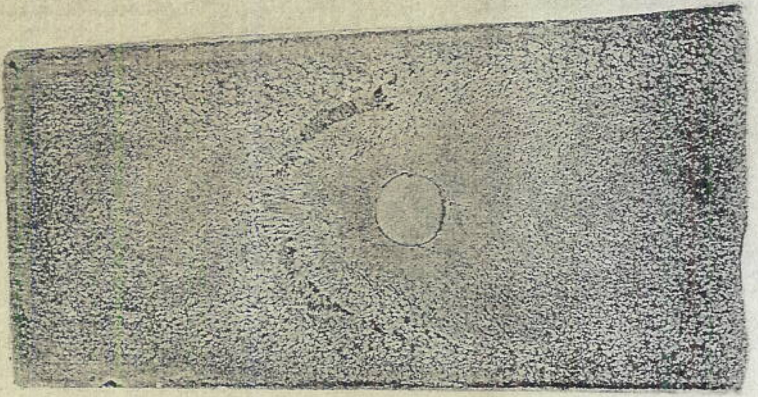


FIG. 11

PLATE 31

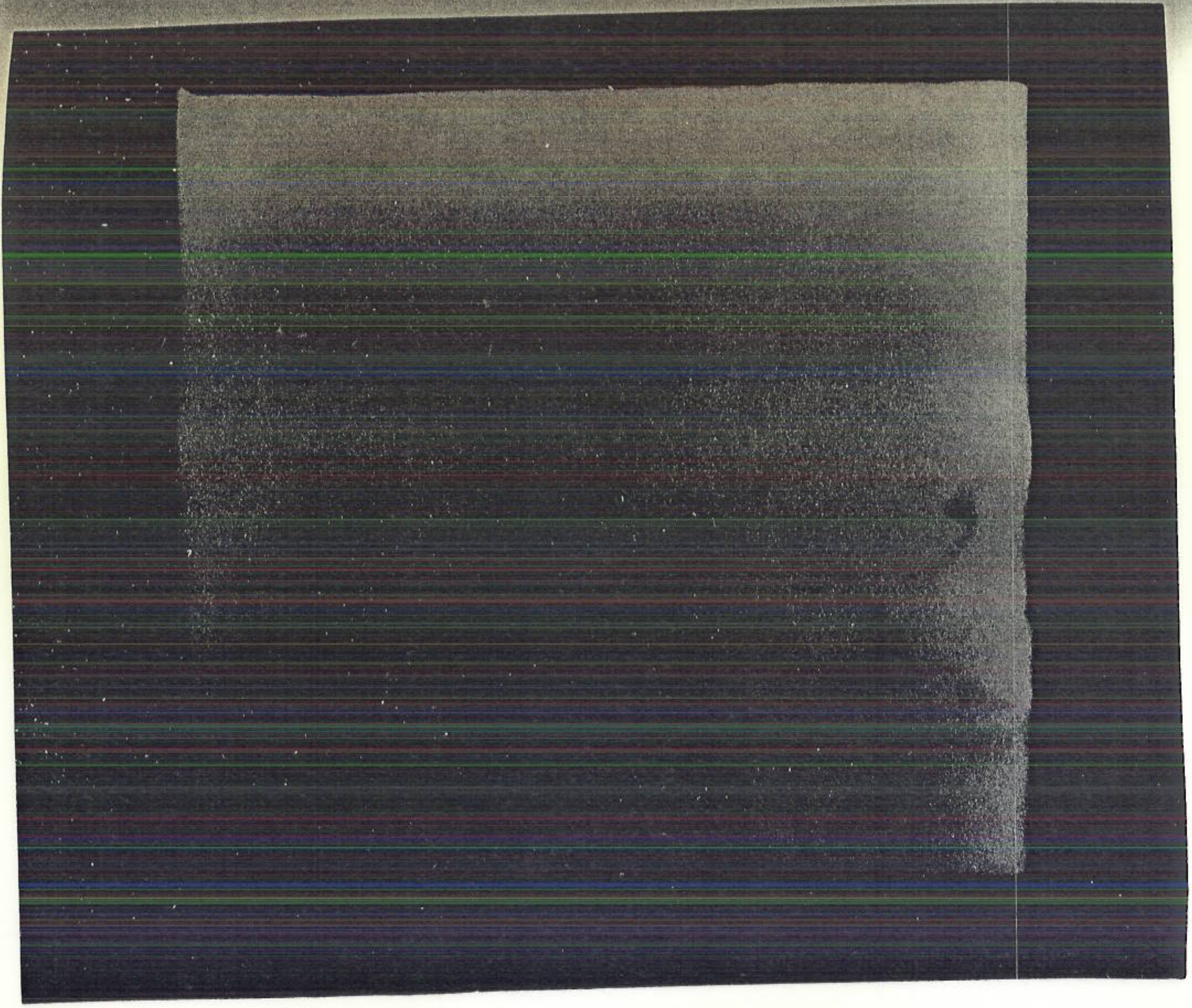


Plate 32

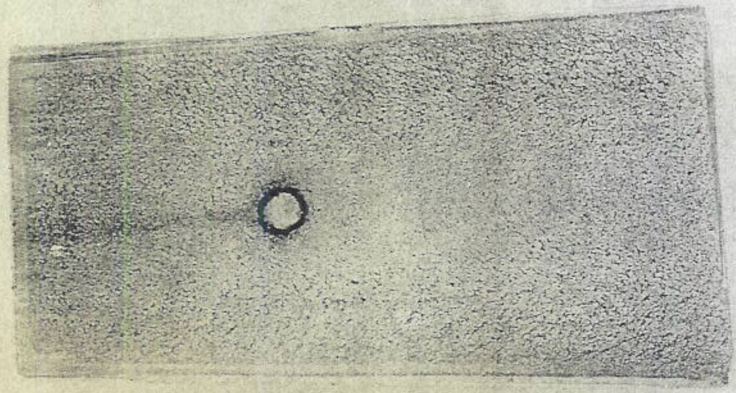


FIG. 12

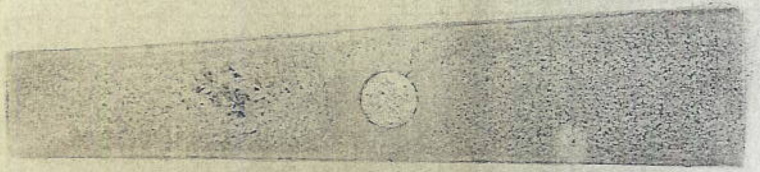


FIG. 13

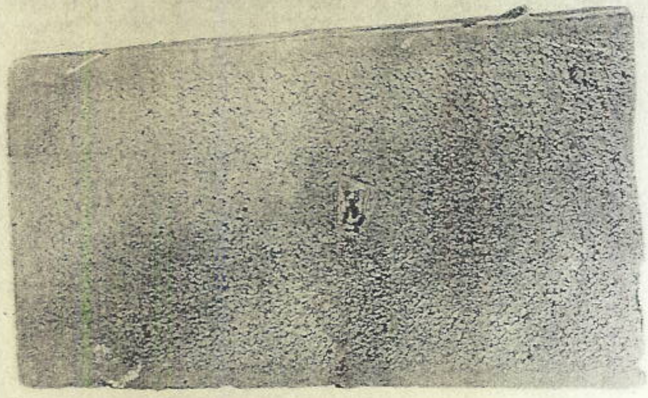
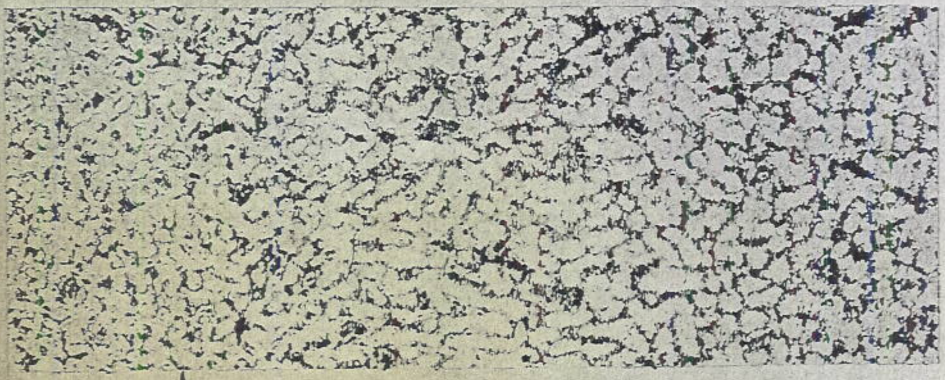


FIG. 14

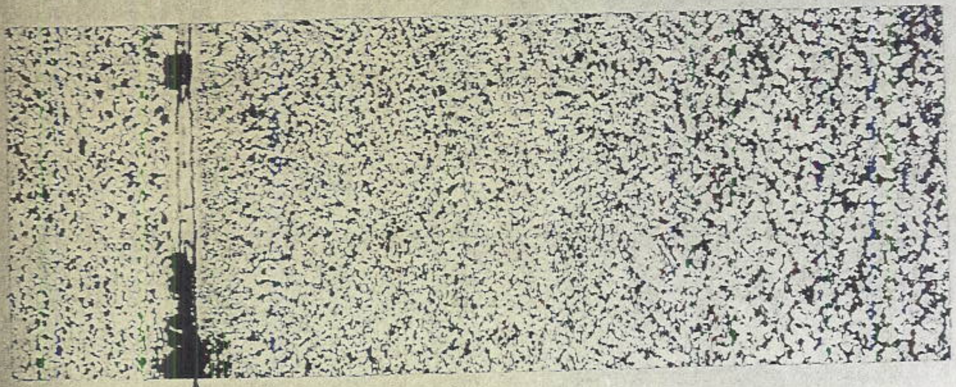
PLATE 33



CHILL-CAST METAL INTERFACE

FIG. 15

FUSION ZONE OF 3/8 INCH DIAMETER CHILL IN 3 INCH CAST STEEL SECTION
. X 25



CHILL-CAST METAL INTERFACE

FIG. 16

FUSION ZONE OF 1/2 INCH DIAMETER CHILL IN 1 INCH CAST STEEL SECTION

FIG. 17

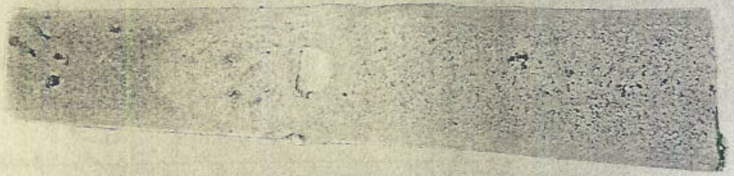


FIG. 18

FIG. 19

PLATE 35

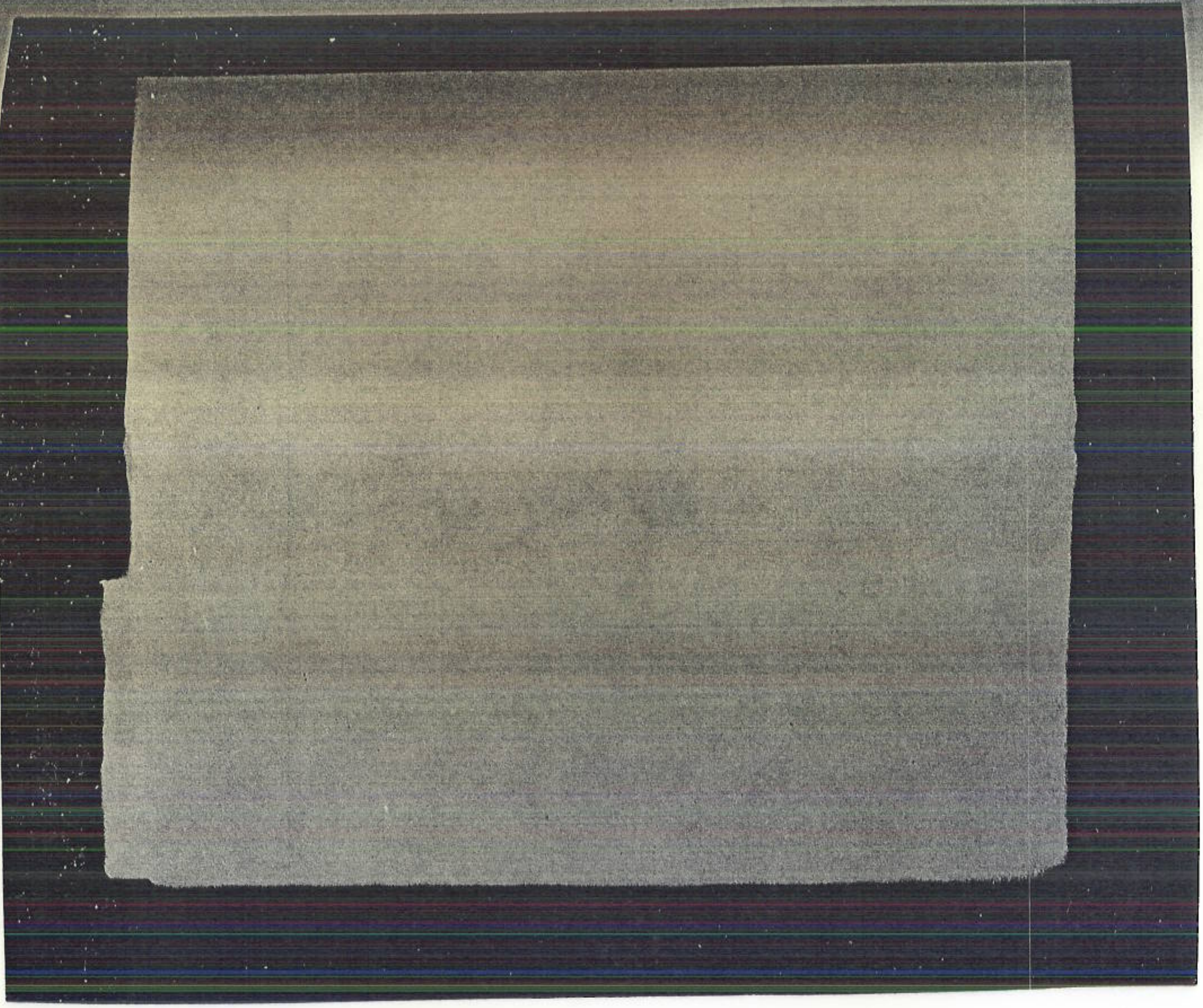


Plate 36

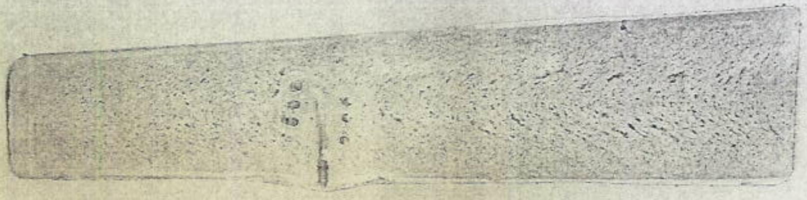
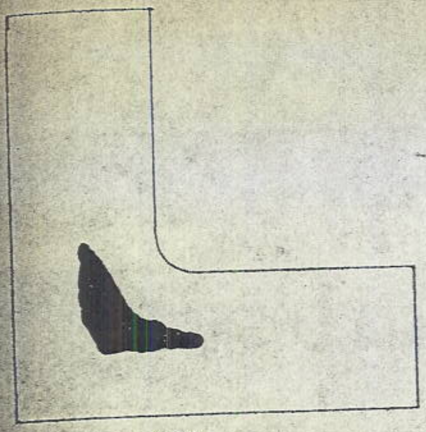


FIG. 20

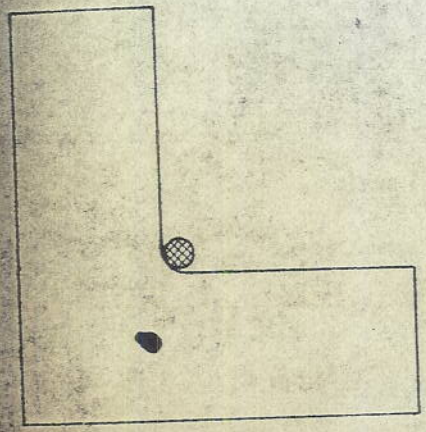
FIG. 21



102

Standard section.

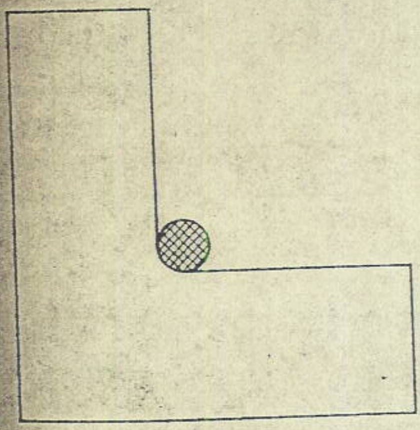
AREA OF DEFECT - 2.8 square inches.



102-1

1/2" diameter chill.
Cross-sectional area - 0.20 square inches.
Effective perimeter - 0.25 inches.

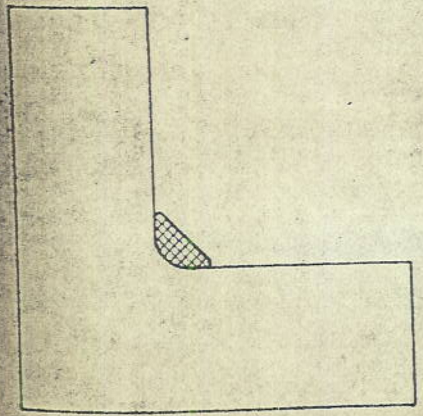
AREA OF DEFECT - 0.1 square inches.



102-2

One inch diameter chill.
Cross-sectional area - 0.78 square inches.
Effective perimeter - 0.78 inches.

NO DEFECT.

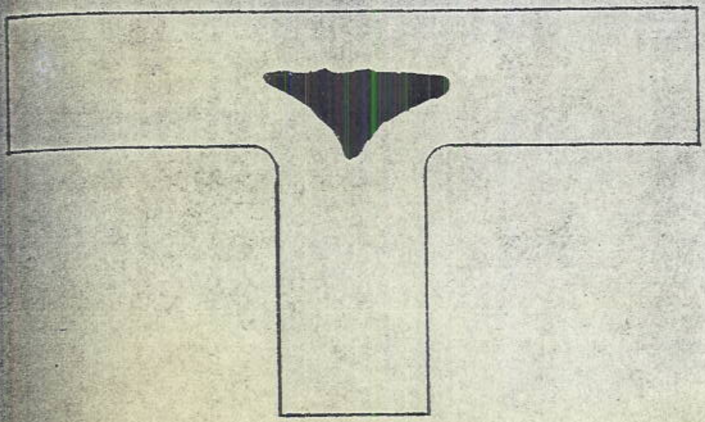


102-3

Small triangular chill.
Cross=sectional area - 0.70 square inches.
Effective perimeter - 1.87 inches.

NO DEFECT.

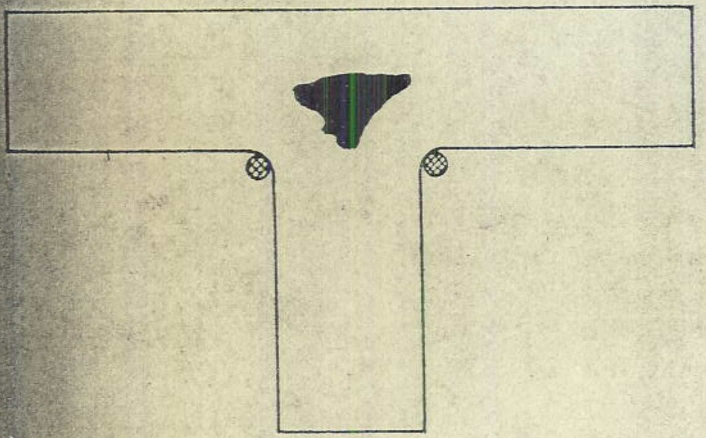
PLATE 38



202

Standard section.

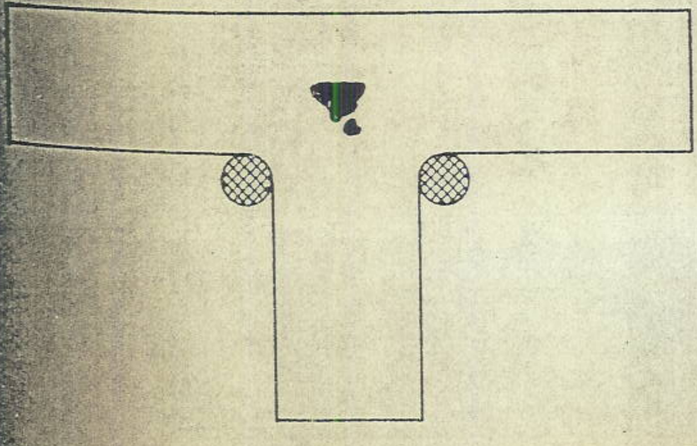
AREA OF DEFECT - 3.6 square inches.



202-1

1/2-inch diameter chills.
Total cross-sectional area - 0.40 square inches.
Total effective perimeter - 0.50 inches.

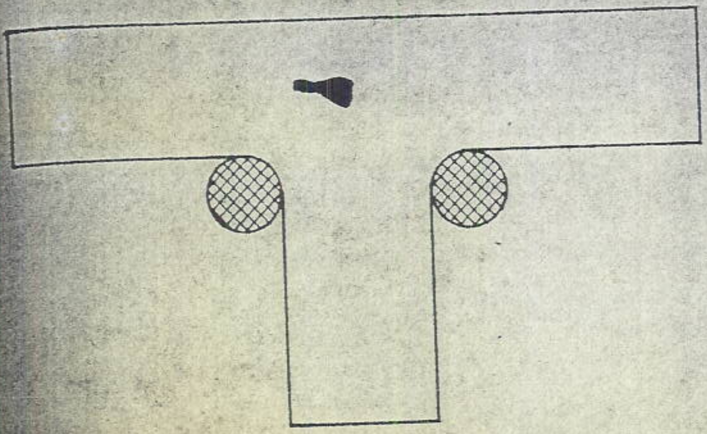
AREA OF DEFECT - 2.1 square inches.



202-2

1-inch diameter chills.
Total cross-sectional area - 1.56 square inches.
Total effective perimeter - 1.56 inches.

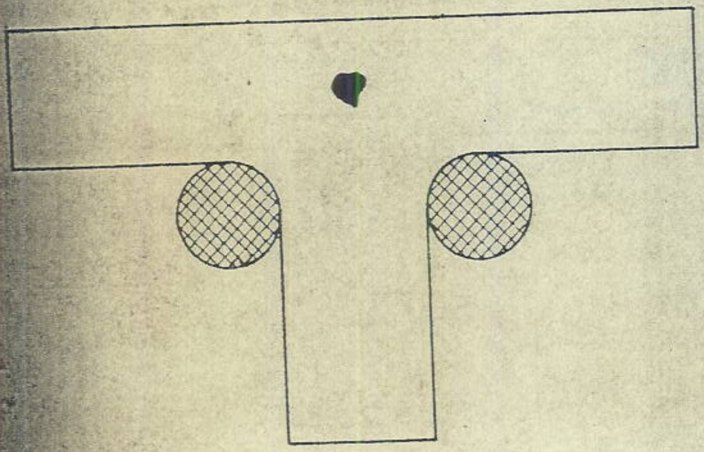
AREA OF DEFECT - 0.8 square inches.



202-3

1-1/2" diameter chills.
Total cross-sectional area - 3.54 square inches.
Total effective perimeter - 2.36 inches.

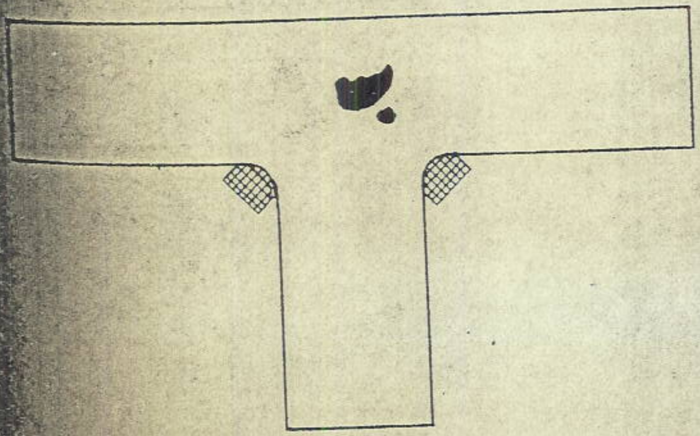
AREA OF DEFECT - 0.3 square inches.



202-4

2-inch diameter chills.
Total cross-sectional area - 6.28 square inches.
Total effective perimeter - 3.14 inches.

AREA OF DEFECT - 0.4 square inches.

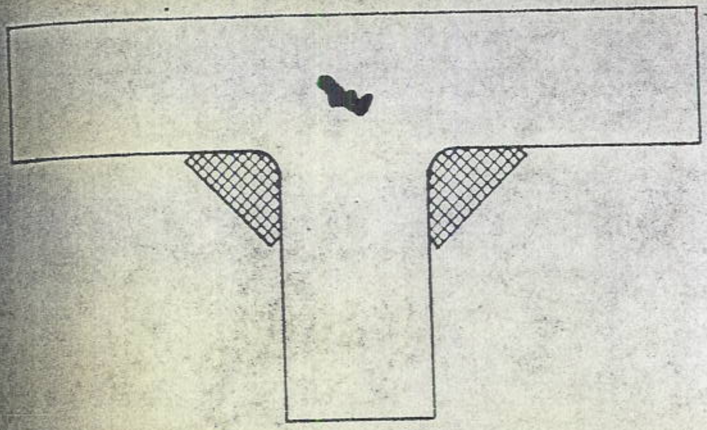


202-5

Small triangular chills.
Total cross-sectional area - 0.70 square inches.
Total effective perimeter - 1.87 inches.

AREA OF DEFECT - 0.9 square inches.

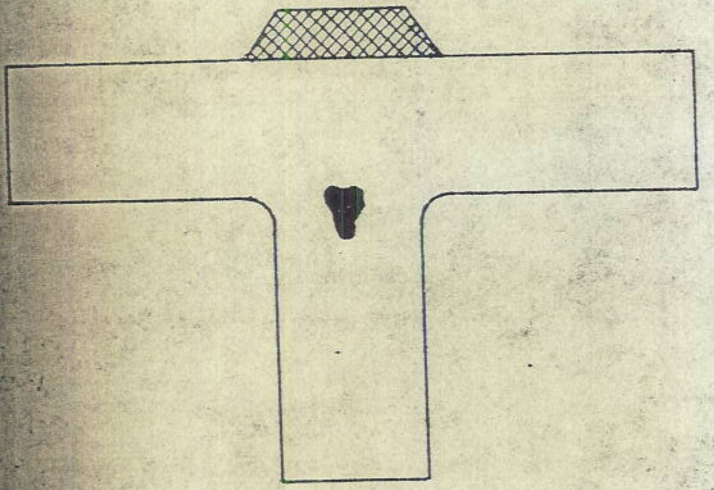
PLATE 40



202-6

Large triangular chill.
Total cross-sectional area - 5.38 square inches.
Total effective perimeter - 7.6 inches.

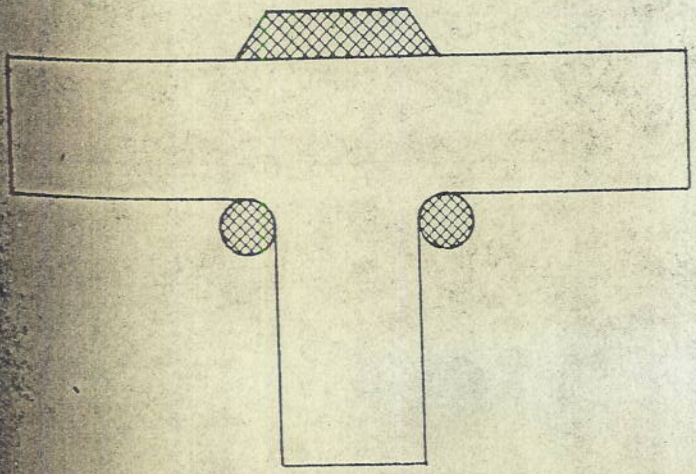
AREA OF DEFECT - 0.5 square inches.



202-7

1" Plate chill (4" to 2-1/2").
Cross-sectional area - 3.75 square inches.
Effective perimeter - 4.0 inches.

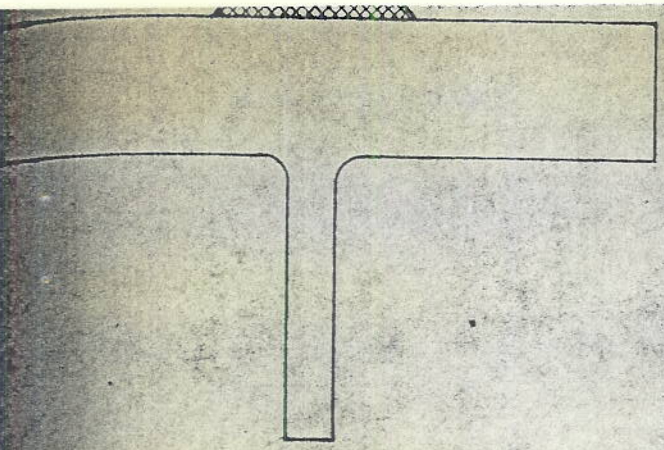
AREA OF DEFECT - 0.6 square inches.



202-8

1" Diameter chills plus 1" plate chill.
Total cross-sectional area - 5.31 square inches.
Total effective perimeter - 5.56 inches.

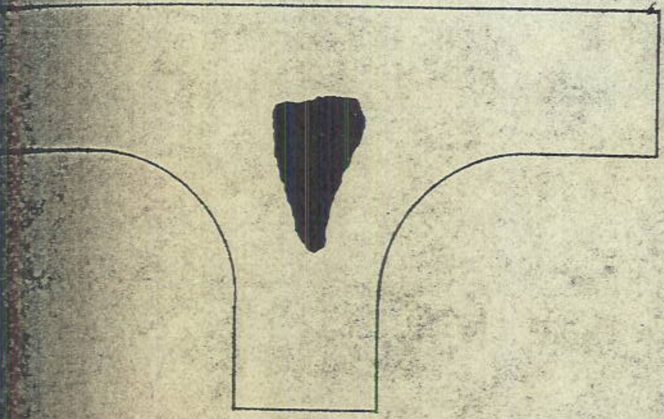
NO DEFECT.



210-1

1" Plate chill (4" to 2-1/2").
Cross-sectional area - 3.75 square inches.
Effective perimeter - 4.0 inches.

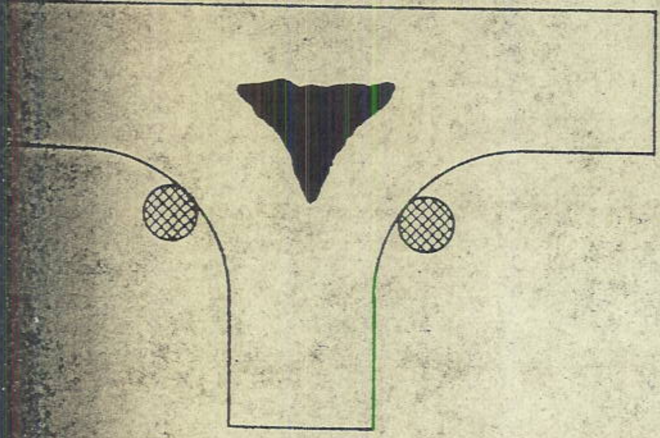
NO DEFECT.



204

Standard section.

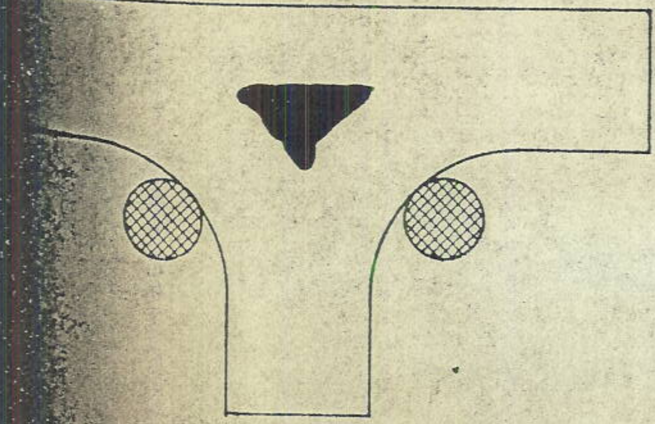
AREA OF DEFECT - 4.1 square inches.



204-1

1-inch Diameter chills.
Total cross-sectional area - 1.56 square inches.
Total effective perimeter - 0.25 inches.

AREA OF DEFECT - 3.9 square inches.

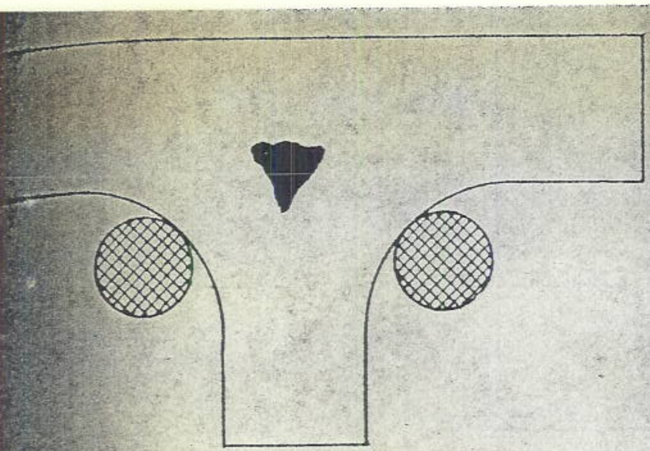


204-2

1-1/2 inch Diameter chills.
Total cross-sectional area - 3.54 square inches.
Total effective perimeter - 0.38 inches.

AREA OF DEFECT - 2.7 square inches.

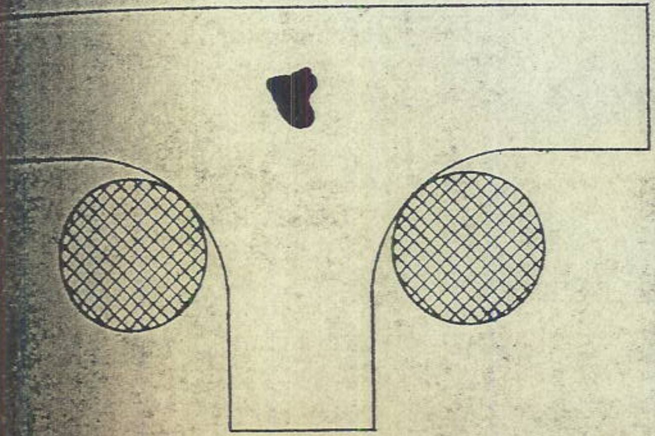
PLATE 42



204-3

2-inch Diameter chills.
Total cross-sectional area – 6.28 square inches.
Total effective perimeter – 0.50 inches.

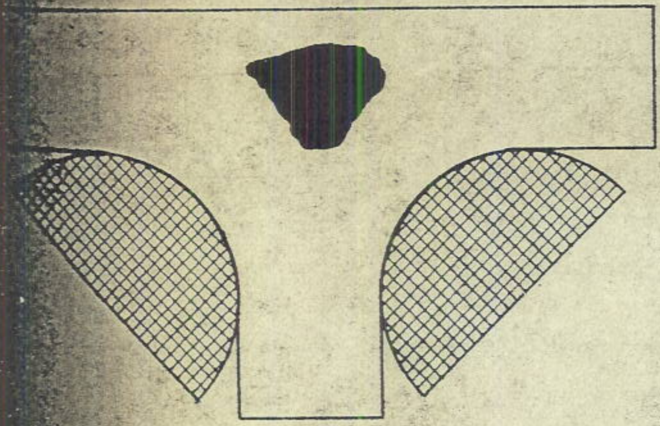
AREA OF DEFECT – 1.3 square inches.



204-4

3-inch Diameter chills.
Total cross-sectional area – 7.07 square inches.
Total effective perimeter – 1.0 inches.

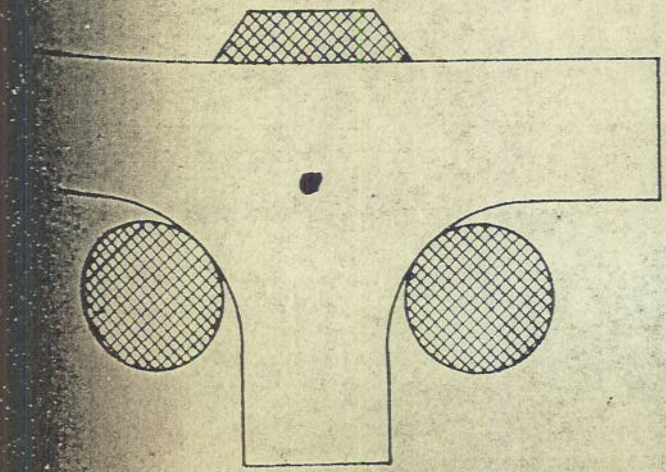
AREA OF DEFECT – 1.1 square inches.



204-5

Semi-circular chill (3" radius).
Total cross-sectional area – 28.27 square inches.
Total effective perimeter – 9.42 inches.

AREA OF DEFECT – 4.1 square inches.

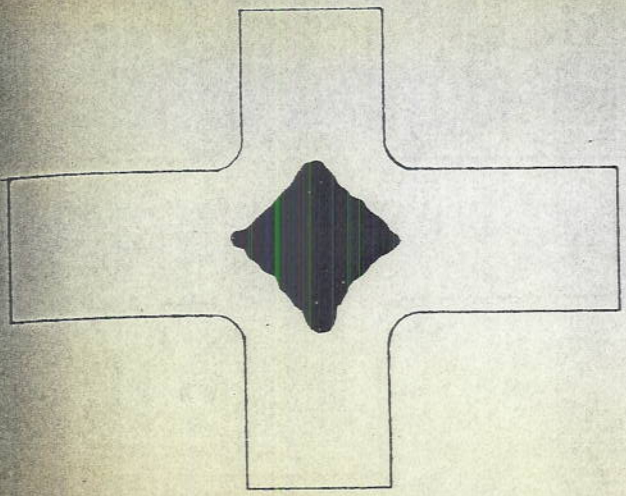


204-6

3-inch Diameter chills plus 1-inch plate chill.
Total cross-sectional area – 10.82 square inches.
Total effective perimeter – 5.0 inches.

AREA OF DEFECT – 0.20 square inches.

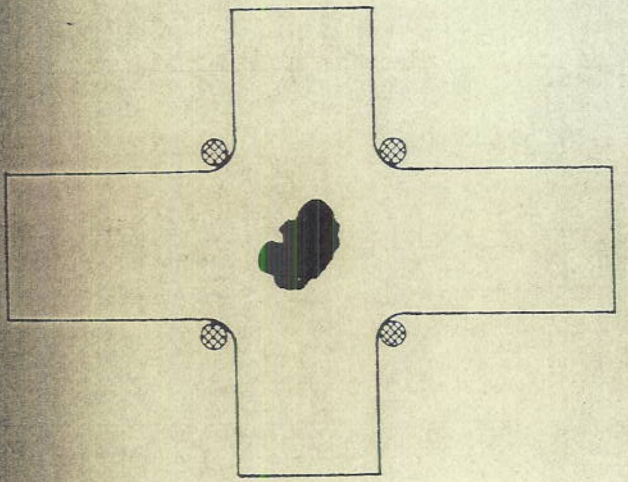
PLATE 43



502

Standard section.

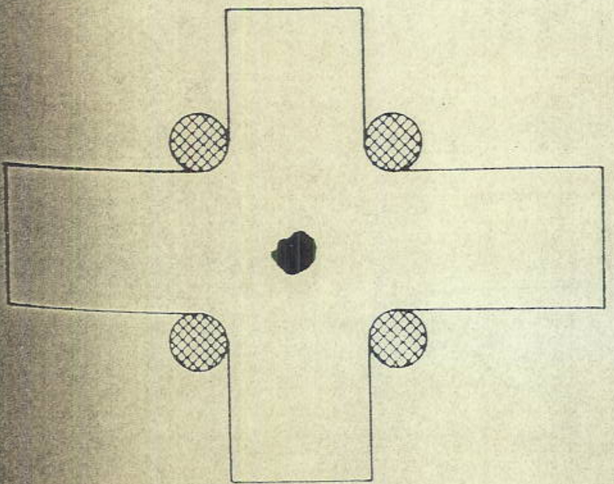
AREA OF DEFECT - 6.4 square inches.



502-1

1/2-inch Diameter chill.
Total cross-sectional area - 0.80 square inches.
Total effective perimeter - 1.00 inches.

AREA OF DEFECT - 2.1 square inches.

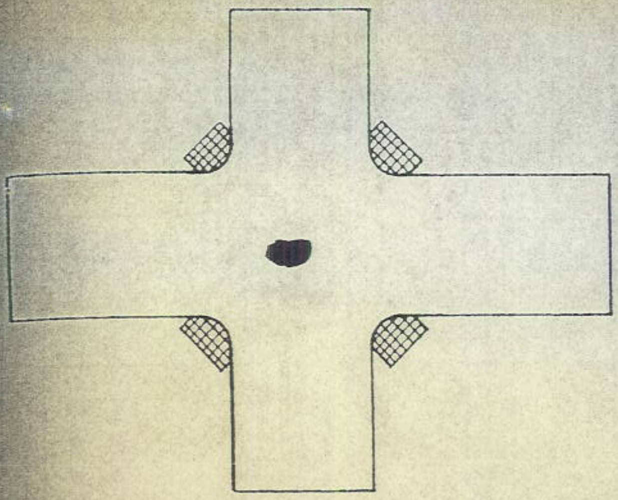


502-2

1-inch Diameter chills.
Total cross-sectional area - 3.12 square inches.
Total effective perimeter - 3.12 inches.

AREA OF DEFECT - 0.60 square inches.

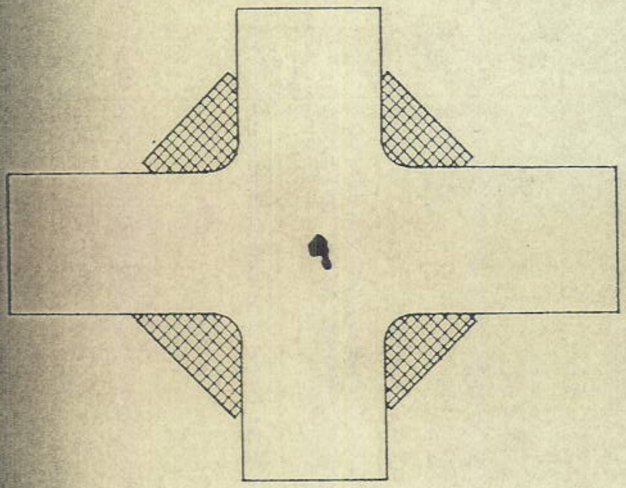
PLATE 44



502-3

Small triangular chills.
Total cross-sectional area - 2.80 square inches.
Total effective perimeter - 7.48 inches.

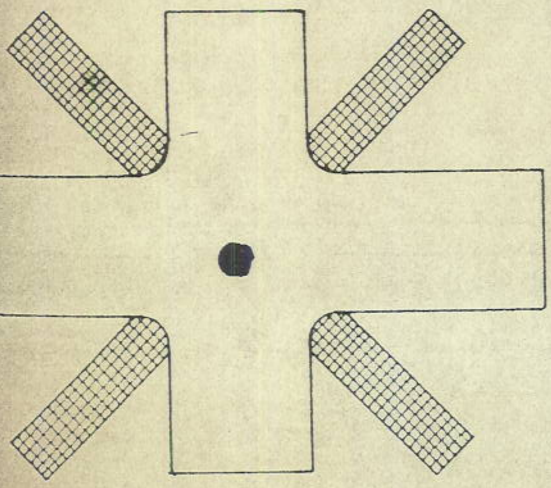
AREA OF DEFECT - 0.7 square inches.



502-4

Large triangular chills.
Total cross-sectional area - 10.76 square inches.
Total effective perimeter - 15.2 inches.

AREA OF DEFECT - 0.2 square inches.

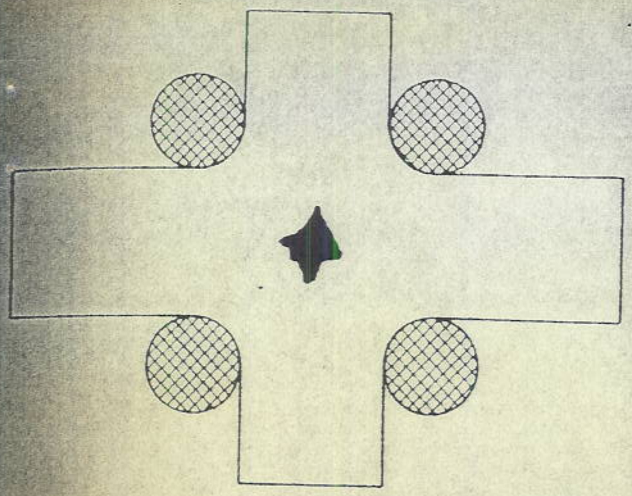


502-5

Plate chills (1" x 4" - 1/2" radius).
Total cross-sectional area - 15.57 square inches.
Total effective perimeter - 3.12 inches.

AREA OF DEFECT - 0.5 square inch.

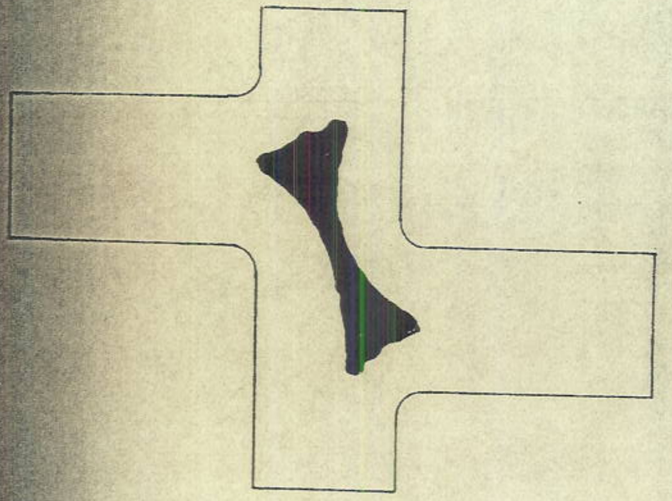
PLATE 45



503-1

2-inch Diameter chills.
Total cross-sectional area - 12.56 square inches.
Total effective perimeter - 6.28 inches.

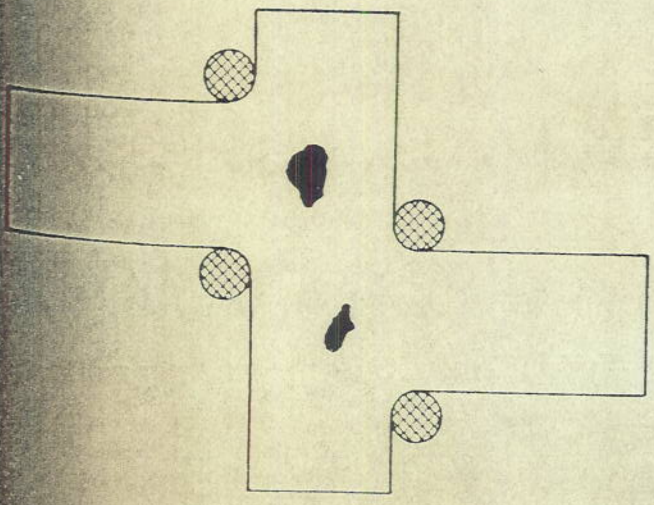
AREA OF DEFECT - 0.9 square inch.



506

Standard section.

AREA OF DEFECT - 5.0 square inches.

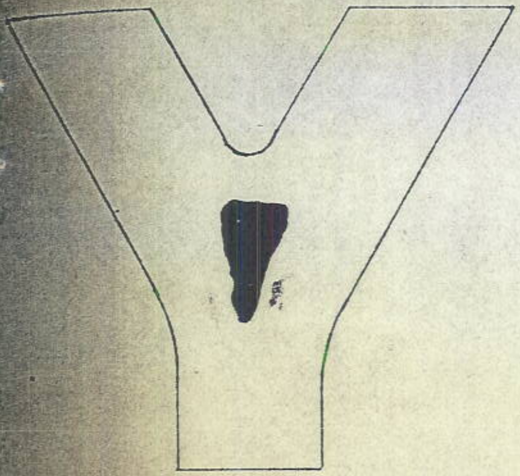


506-1

1-inch Diameter chills.
Total cross-sectional area - 3.12 square inches.
Total effective perimeter - 3.12 inches.

AREA OF DEFECT - 1.2 square inches.

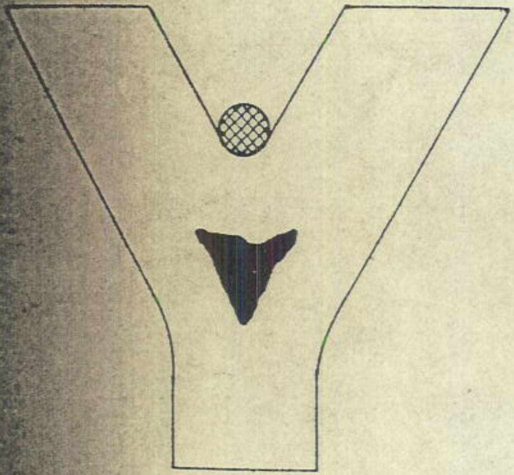
PLATE 46



402

Standard section.

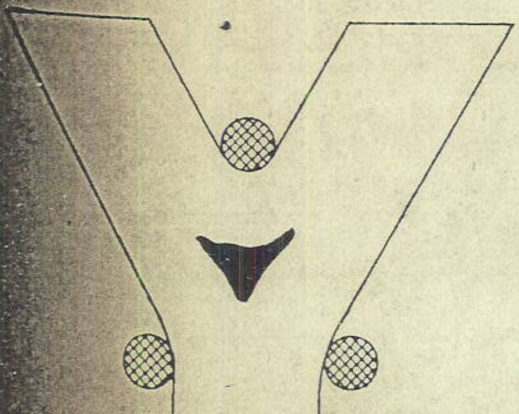
AREA OF DEFECT - 2.7 square inches.



402-1

1-inch Diameter chill.
Cross-sectional area - 0.78 square inches.
Effective perimeter - 0.78 inches.

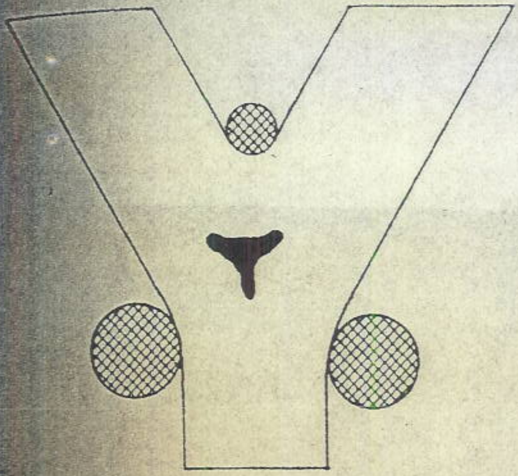
AREA OF DEFECT - 2.1 square inches.



402-2

1-inch Diameter chills.
Total cross-sectional area - 2.34 square inches.
Total effective perimeter - 2.34 inches.

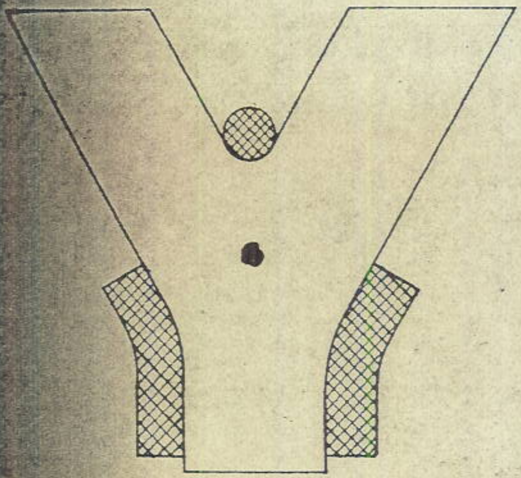
AREA OF DEFECT - 1.6 square inches.



402-3

1-inch Diameter chill plus 2-inch diameter chills.
Total cross-sectional area - 7.06 square inches.
Total effective perimeter - 3.92 inches.

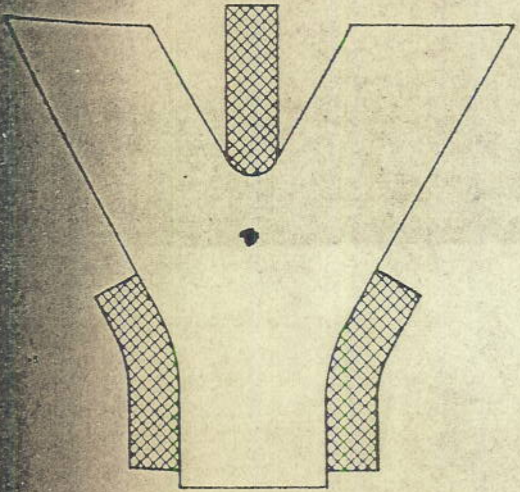
AREA OF DEFECT - 1.0 square inches.



402-4

1-inch Diameter chill plus 1-inch chill plates.
Total cross-sectional area - 8.78 square inches.
Total effective perimeter - 9.05 inches.

AREA OF DEFECT - 0.2 square inches.



402-5

1-inch Chill plates.
Total cross-sectional area - 11.89 square inches.
Total effective perimeter - 9.05 inches.

AREA OF DEFECT - 0.1 square inches.

PLATE 48

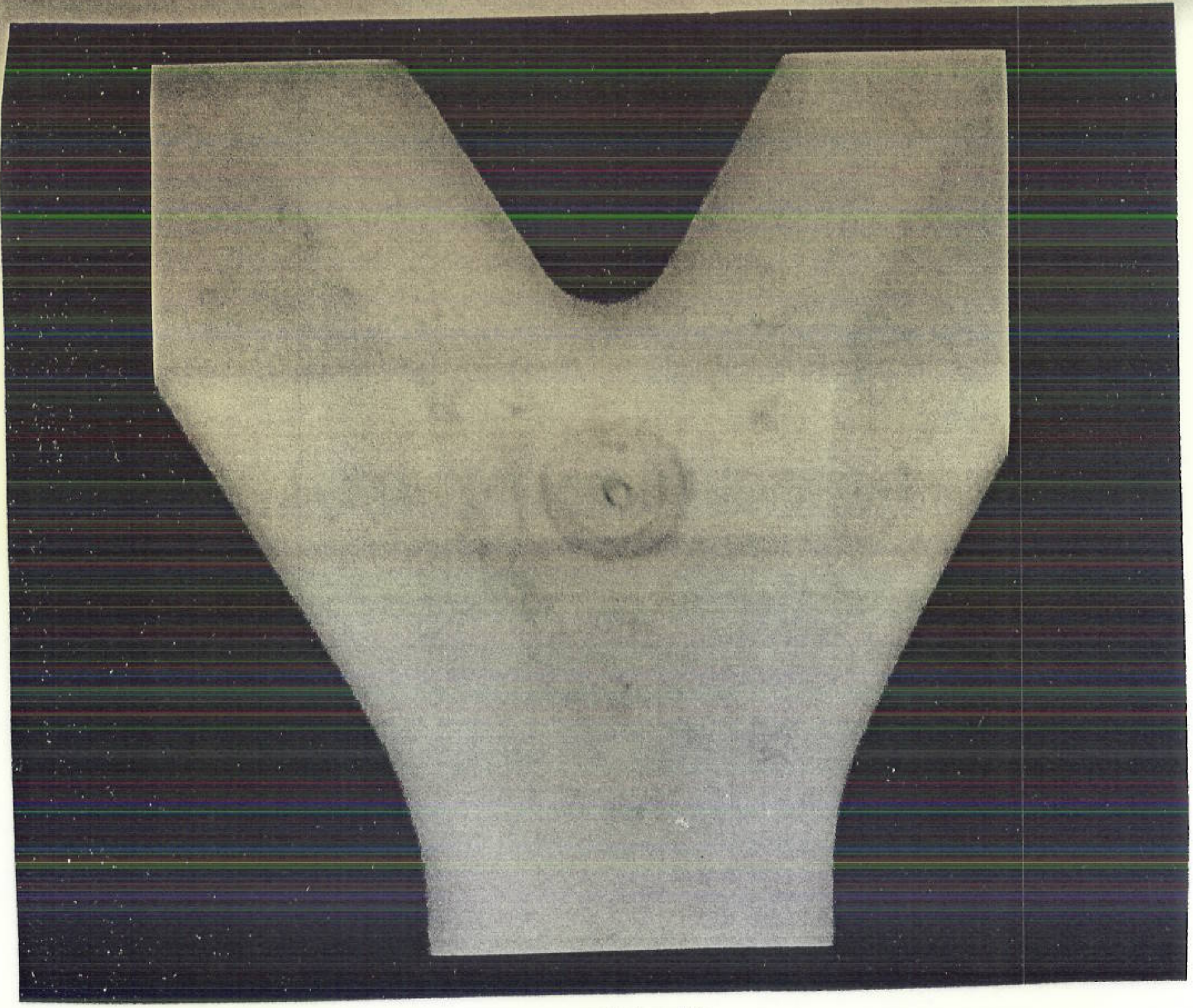


Plate 49

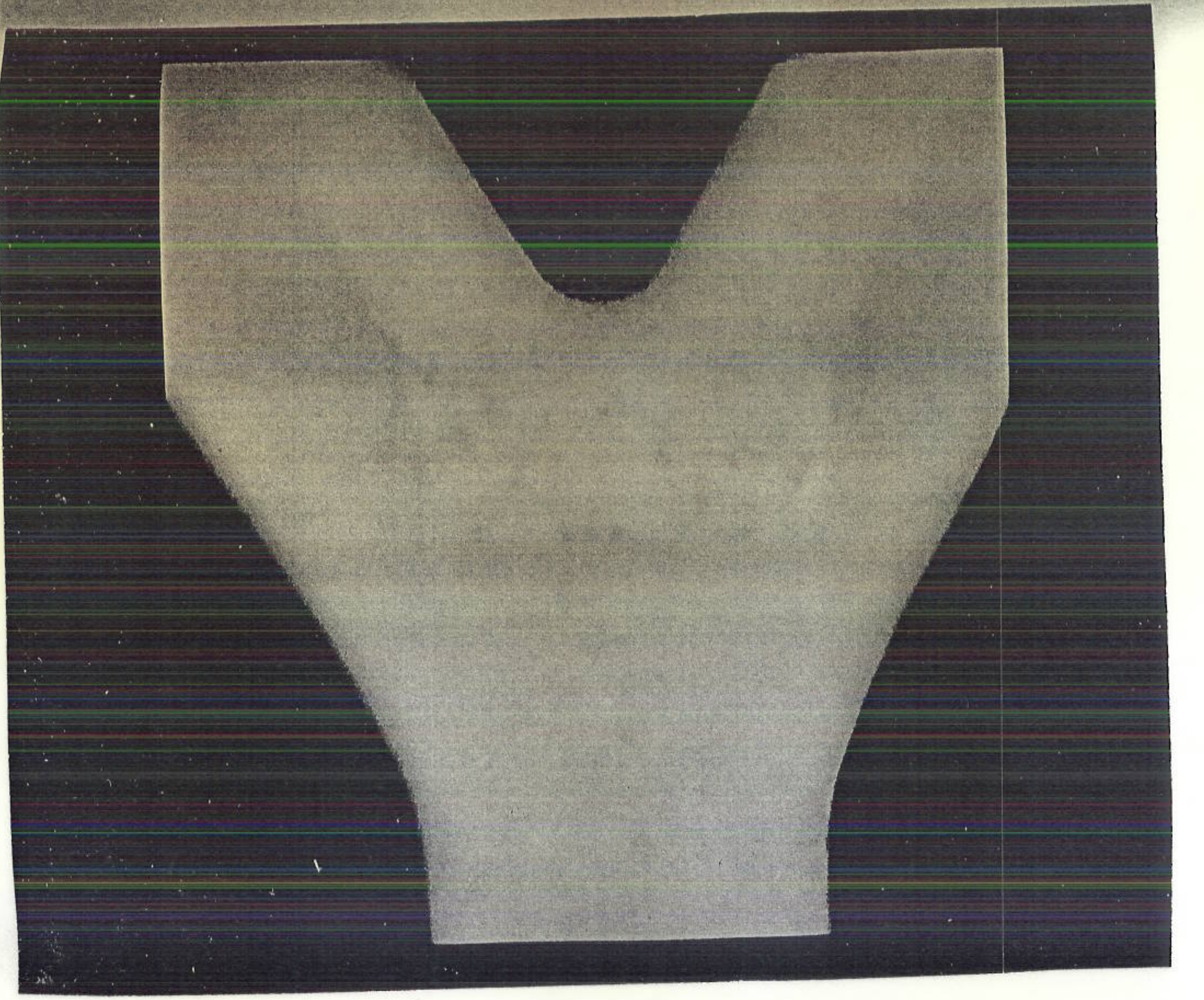


Plate 50

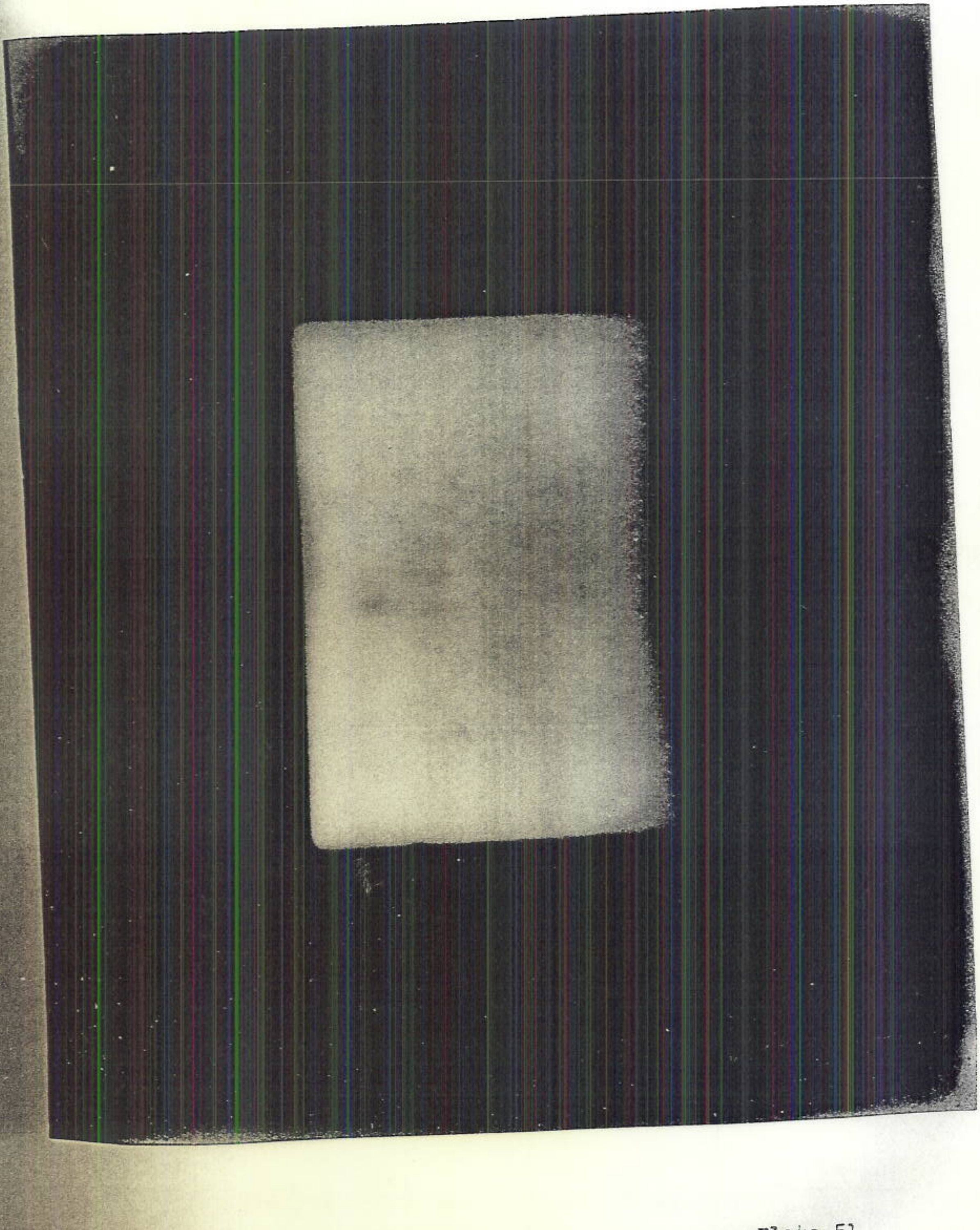


Plate 51