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PART ONE

(PART TWO contains all figures and tables)

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S Y N O P S I S

The results of a study of the structural behavior and design of hot-metal ladles are offered in this paper. Three 1/5 scale steel model ladles were tested for strains and deflections under static loads, disregarding the temperature effects of the molten metal. The models were: a round riveted ladle, an oval welded ladle, and a round welded ladle, all based on a prototype of 150 ton net capacity.

The test results are given in the form of deflection diagrams, stress diagrams, and tables. The principal stresses as well as horizontal and vertical stress components, as presented, have been evaluated from the measured strains.

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INTRODUCTION

The designation "Hot-Metal Ladle", when used in this report, will mean a vessel, lined with refractory material, used for conveying molten metal from the furnace to the ingot mold. Car ladles and foundry ladles are not considered.

During the extensive growth of the steel industry there has been a consistent trend to increase the capacity of hot metal ladles. Larger furnaces and the convenience of pouring the whole furnace charge into one ladle have combined to make this increase of ladle capacity necessary. At the same time the allowable load on existing ladle cranes and supporting structures is limited, thereby rendering any decrease in dead weight of ladle directly applicable to increased capacity for molten metal. Dependability and safety require careful consideration of ladle design because of this tendency to reduce the dead weight.

The introduction of the welded type ladle*, in 1932, increased the possibilities for decrease in dead weight. In 1938, 206 welded ladles were in use in the U.S.A. While the older riveted types, without spouts, lining and stopper rings, weigh 21 to 27% of the rated capacity, the same percentage for similar welded types is only 16 to 17%. Another expedient to increase capacity is to use an oval shaped ladle, without interference with height clearances and hook distances originally allowed for the round riveted ladles.

Thus, larger ladles are built, new shapes introduced, and the ratio of dead weight to ladle capacity is forced down. This development is continuing, giving significance to the application of more rational and accurate design procedures for hot-metal ladles. Little design information is available in the technical literature. The design procedures used by the different ladle manufacturers apparently have given completely satisfactory ladles. However, these procedures are in general based on assumptions which are not verified by tests.

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* F. L. Lindemuth: "History & Use of Welded Ladles" A.I.M.M.E., Iron & Steel Div., Open Hearth Comm., Open Hearth Proc. 1938, p. 27-32.

A program of experimental and theoretical stress analyses and tests of hot-metal ladles was therefore adopted by the Association of Iron and Steel Engineers as a part of the Standardization Committee's postwar program. In April 1946, the Fritz Engineering Laboratory of Lehigh University undertook the task of investigating the structural behavior of such ladles, initial work starting on June 15, 1946.

The general program was determined at a committee meeting in July 1946. It was decided to test 3 models based on a prototype of 150 ton net capacity. Both riveted and welded construction were considered, and a model of an oval ladle was included. Additional variables were: number and size of stiffener rings, size of trunnions, angle of tilt, amount of load, and distance between the points of support on the trunnion pins. The test program is described in detail under a separate paragraph.

The important problems involving stresses due to temperature differentials caused by the molten metal are not considered in this investigation.

The interest and advice given by Mr. Ingvald Madsen, Research Engineer of AISE; Mr. F. E. Kling, Chairman of the Ladle Design Committee, together with other members of the committee, were essential factors in the planning and execution of the program. The valuable help of Mr. Paul Kaar, Engineer of Tests; and Mr. Kenneth Harpel, Foreman, is acknowledged.

LADLE MODELS

The Ladle Model Design.

The Ladle types chosen for this investigation represent three general types in use in the mills. A summary and comparison of the design of the three models is offered in Table 1. They also reflect different developments in ladle design. Ladle "A" is a round riveted ladle; Ladle "B" is an oval welded ladle, providing increased capacity to meet a fixed distance between lifting hooks; and Ladle "C" is a round welded type with a dished bottom.

All three specimens are based on prototypes of 150 ton net capacity. A survey of actual ladle designs is given in Table 2 for reference. A linear size reduction of 5 to 1 was determined to be most suitable for the models, resulting in both height and top diameter of approximately 30 inches. The side slope was one inch per foot in each model.

The dimensions and material thicknesses are reduced from those of actual ladles approximately in the 5 to 1 ratio, although material availability was to some extent a determining factor. The stresses in the models were checked by methods usual in practice.

Some simplifications were made in the model design, as compared with actual ladles. The slag spout and the pouring device were eliminated. Special joints for facilitating the transport of the ladles were not considered. The additional trunnion pins sometimes used when the ladle is placed in stands for transport on ladle trucks or for lining repair were disregarded. It is believed that the elimination of the slag spout at the lip of the ladle is the only significant deviation of those here mentioned. The test results indicate that the effect of the lip ring on the structural behavior of the ladle is greater than emphasized in present design procedures. The serious discontinuity introduced in this ring by the slag spouts seems therefore to deserve special consideration. Tests with such spounts added on the models were proposed at one step in the development of the test program but were not adopted.

Ladle "A" is given in the drawing, Fig. 1. Photographs of this ladle and its important parts are shown in Figs. 2, 3, 4, and 5. Attention is called to the 1/16" additional plate on the bottom, similar plates on actual ladles being provided to protect against heat radiation during the pouring operation. Ladle "A" was tested with two different size trunnions, also with or without a stiffener band combined with the small pair of trunnions. (Fig 5.) The spacing band is bolted to the trunnions but is not connected with the shell. It is intended to carry the bending and torsional moments introduced by the trunnions, leaving the shell more or less with the hydrostatic loading only.

Ladle "B" is detailed in Fig. 6, and photographs of important features are shown in Figs. 7, 8, and 9. The oval shape of this ladle is obtained by inserting a straight middle section of six inches width in the sides. The curved parts of the cross section consist of two semicircles. This shape is often inaccurately referred to as "elliptical" but is designated herein as "oval". Ladle "B" has a flat bottom with a reinforcing plate as in the case of Ladle "A". The lower stiffener ring is wider than the top ring, giving a vertical face to the trunnion assembly without major change in ring sections. The lip ring is stiffened by means of a series of small triangular plates welded between it and the shell. The trunnion pins on all ladles were made long enough to permit study of the effect of hook spreading, as required by the test program.

Ladle "C", finally, is detailed in Fig. 10, and special features are pictured in Figs. 11, 12, and 13. The bottom is dished and has no reinforcing plate, but is thicker than in the other two ladles. The reinforcing rings are of equal size and comparatively small, but there is a heavier middle section of the shell between the rings. The trunnions are built up of plates with no ribs of the type used on ladles "A" and "B".

The Model Material

Carbon structural steel is suitable for use in hot metal ladles; hence, Light Gage Structural Quality Flat Hot-Rolled Carbon Steel conforming to ASTM Specification A245-44T, grade C, was specified for the thin plates. Other parts were to meet A.S.T.M. Specifications A-7 for structural steel. A series of tensile test coupons were taken in the shop and the results of the tests are given in Fig. 14 and in Table 3. In the stress computations, a modulus of elasticity of 29,500,000 lbs. per sq. in. was used.

The Ladle Model Fabrication

A tolerance of $\pm$ 1/32 inch was initially specified for the manufacturing of the models. The shop could not, however, guarantee to hold the dimensions within this range without additional expense. The requirement was therefore changed to "as close as possible". Measured dimensions indicate that the actual accuracy lies within 1/8".

The models were stress-relieved after the fabrication. Fig. 15 shows the stress-relieving temperature record.

Before testing, the ladles were lined with fire-clay. It was decided to use "half" lining, simulating the condition for a worn-down fire-brick lining in the actual ladles. The thickness of the fire-clay was therefore made approximately 3/4" on the sides and 1" on the bottom. The lining was applied wet with ample time allowed for its hardening. While the clay was still plastic, it was cut through with a knife in a pattern, which, after the hardening and shrinkage of the clay had taken place, divided the lining into simulated bricks.

TEST PROCEDURE

Loading Agent

The actual ladles are loaded with molten metal weighing approximately 430 lbs. per cu. ft. Since, for the purpose of experimental stress analysis, it is undesirable to load the models in the laboratory with hot liquid metal, some substitute had to be found. Amount of load was one of the test variables. This could be obtained in two ways:

1. By completely filling the ladles with several liquids of different specific gravities or

2. By using different amounts of one particular liquid, which is the average weight of molten steel. In this case the change in load would alter the stress distribution.

As the first of these solutions seemed most satisfactory from a theoretical point of view, the use of several liquids with different specific gravities was proposed: Water, carbon tetrachloride, sodium silicate, mercury, etc. Also, granular materials were considered, among which were sand, iron shot and lead shot.

Serious inconveniences result in the case of some of these loading agents. The granular materials will not give a true substitution of a fluid. Some of the liquids mentioned are difficult to handle, others are expensive.

The selection finally narrowed to the use of water and mercury. If a partial load of mercury, weighing the same as a full load of water, would give very nearly the same stresses and deflections as the water, then a series of tests with various percentages of mercury load could be made. The tests did not show this to be the case. A comparison of bottom deflection on one of the models for equal weights of water and of mercury is shown on the diagrams, Fig 16. The diagrams A, B, C, and D give the deflections on a vertical section through the center of the bottom and 12 1/2°, 30°, 60°, and 90° apart from the vertical section through the trunnion pin centers, respectively. The difference in deflections under the two types of loading is due to the difference in the relation between the outward pressure on the side wall as compared with the downward pressure on the bottom of the ladle. A comparison of stresses for the same two loadings is obtainable from columns b and c on the stress table for Ladle B, Table 6. However, the small magnitude of the stresses and corresponding large possible errors at such low stress levels obscure any relation that may exist.

In spite of the divergence between partial and full loading, and in view of the very small stresses to be expected from full water load, mercury was chosen as loading agent for all tests. Since some parts of the ladle might reach their maximum stress at less than full load of liquid mercury, steps of approximately 25%, 50%, 75%, and 100% of the weight of full load were applied, "full load" referring to an amount of mercury reaching 3" below the lip of the ladle.

General Test Arrangement

The general test arrangement is shown in Figs. 17 and 18. A supporting frame is erected to carry the specimen during test operation. The usual hooks have been replaced by eye-bars, Fig 19. These function in the same manner as the hooks and were easier to fabricate. The eye-bars are movable along the top beam of the frame, providing a means of varying the hook distance.

The frame also supports a wooden plug covered by a tight fitting rubber casing to prevent leakage of mercury. Fig 18. The plug fits into its corresponding ladle model and is shaped so as to leave approximately 1/2" free space all around. Fig 17. The plug will then displace 93% of the mercury volume otherwise required for full mercury load, yet provide a fully equivalent full load condition at a considerable saving of investment in mercury. Intermediate loads are obtained by lowering the ladle by means of the nuts on top of the eye-bars, or by using a fraction of the mercury volume required for full load. The upward flotation force imposed upon the wooden plug is resisted by the top beam of the test frame.

The volume of the ladle models at all levels were calibrated with water before testing. After multiplying these volumes by the specific gravity of mercury, a graph was plotted of the load as a function of distance between the mercury level and the lip of the ladle. This distance was measured by means of a simple electric depth gage as indicated on the drawing, Fig. 17.

Tests in the tilted position are included in the program. To this end, the support of the wooden plug was arranged as shown in Fig. 20. A series of bolts designed for the full force of flotation was placed along the arc of a circle with the radius point on the center line through the trunnion pins. The ladle models were tilted in a manner similar to that normally used in the mills.

Strain Measurements

The strains were obtained by means of SR-4 bonded electric strain gages of the types shown in Fig. 21. The gage locations and the types used are shown in Figs. 22, 23, and 24 for the three ladle models. All of the models are symmetrical about two mutually perpendicular vertical planes. For tests in the normal (not tilted) position, the load is also symmetrical about the same two planes. All four quadrants were assumed to behave identically, and the measurements were taken in only one quadrant. For testing in the tilted position, the loading is symmetrical about one plane only, and measurements in two quadrants are required. To avoid the mounting of gages on more than one quadrant, the stress distribution over one half of the ladle was obtained by tilting the ladle alternately in each of the two possible directions.

On the shell, three way rosette gages of type AR-1 or AR-4 were used. The data obtained from these gages allow the evaluation of the principal stresses and their directions. On the planes of symmetry the directions of the principal stresses are known to be horizontal and vertical. Type AX-5 two way gages were therefore used at such location. On the thin rings, the stress is essentially uni-directional and type A-1 or the narrower A-12 gage was therefore used, depending on the space available. The choice of gage types is shown on Figs. 22, 23, and 24.

Strain gages were mounted at identical locations on the outside and the inside of the ladle. The average direct stress (membrane stress) and the bending moment at a gage location can then be evaluated from the skin stresses obtained from the outside and inside gages.

The strain readings were measured by means of a Baldwin-Southwark Type K Indicator Box. Fig. 25. The change in electric resistance of the gages during a change of load is converted to micro-inches (millionths of an inch) per inch strain on the scale of the indicator box. Temperature compensating gages were used. It was assumed that the temperature inside and outside the shell was the same. The gage readings before and after loading were taken within as short a time interval as practicable in order to reduce the effect of temperature gradients through the shell to the inside gages. The temperature of the loading agent was checked for each separate test to disclose the existence of such gradients. A brief study of the temperature effect and the reading dependability of the operator indicated an accuracy of $\pm$ 5 micro-inches with corresponding maximum expected errors in evaluated stress of approximately $\pm$ 150 lbs. per sq. in.

A system of switch boxes manufactured at the laboratory (Fig. 25.) provided rapid and dependable selection of measuring gages and the corresponding compensating gages. The leads from the inside gages were carried through small drilled holes in the ladle shell to the outside, as may be seen in Fig. 26. The inside strain gages were protected against attack from moisture in the clay lining and from possible leakage of mercury or water used for loading or calibration by means of a cover of wax. A detail of a cross section through the ladle and the wooden plug is shown in Fig. 27.

Mohr's Circle as well as numerical methods was used in the calculation of stresses on basis of the measured strains. The horizontal and vertical stress components, the principal stresses, and their directions were computed. The test results are presented and discussed under a separate paragraph.

Deflection Measurements.

The deflection measurements were obtained by means of a series of 1/1000inch dial gages. As in the case of strain measurements the symmetry of the ladles permitted the measurements to be taken in one quadrant only. Figures 22, 23, and 24 show the general location of the points where the deflections were measured. The points fall on four vertical lines, namely 12 1/2°, 30°, 60°, and 90° from the vertical section through the trunnions. The test set-up did not allow deflection measurements at 0° due to interference with the trunnion pins. On the four vertical lines mentioned, the deflections were measured on a series of points along the side and bottom, including points on the lip ring and the two stiffener rings.

The set-up for a deflection test is shown on Fig. 28. The dials are supported by means of a comparatively rigid plywood bracket,which rests on radially orientated knife-edges fitting in slots on the lip of the ladle. These slots are carefully made to coincide with the direction of diameters of the ladle cross section. The bracket is further secured against any horizontal motion at the center point of the ladle bottom, in a way allowing free vertical movement and the measurement of the vertical deflection at that point. The basic readings were then taken on the dials shown in Fig. 28, while the readings obtained from a few control dials on the opposite leg of the bracket unveiled possible shifting-over of the bracket in its own plane.

The lip of the ladle deflects horizontally during loading. The bracket, resting on the lip, will tend to deform in the direction of this deflection due to friction between the knife-edges and the greased slots in the ladle lip ring. This effect was minimized, however, by means of an aluminum ring connecting the two legs of the bracket. On this ring were mounted two SR-4 strain gages at points 90° apart. Any change in the distance between the two top points of the bracket changed the shape of the ring, thus introducing measurable strains at the gage-points, which permit corrections to be applied to the readings for change in shape of the plywood bracket.

The temperature was checked during all deflection tests, and corrections were applied to the readings for over-all expansion or contraction of the ladle.

Fig. 20 also shows the details of the fixtures for the dials, and the location of the points where readings were taken. The test procedure was as follows: The bracket was placed resting in the slots on the particular vertical line in question, and the bottom center point was secured. The dial points were brought to contact with the ladle, allowing sufficient travel of the dial points in both directions. The dial scales were turned to zero, the readings on the two SR-4 gages on the ring taken, and load applied. The readings were taken on the two SR-4 gages, on the deflection dials on the side and bottom, and on the control dials on the opposite side. The measurement was then completed, and the bracket could be moved to the next vertical line for repeating of the process.

Three corrections were applied to the deflection readings. The first compensates for the shifting of the bracket in its own plane during loading, as mentioned above. The readings on the control dials were made equal to the readings on the corresponding dials on the measuring side by re-adjusting the bracket, thus sharing the total horizontal changes of the top and bottom ladle diameters equally between the two sides.

The second correction eliminates errors due to change in shape of the plywood bracket and applies to the side deflection only. The readings from the two SR-4 gages on the aluminum ring attached to the top of the bracket yield, as mentioned, a means of evaluating the change in distance between the two top points of the bracket. As this change was usually only a few thousandths of one inch, the correction was linearly reduced from the value at the lip ring to zero at the bottom of the bracket, thus neglecting bending curvature of the vertical members of the bracket.

The third correction to the deflection readings applies to the bottom plate only. From the deflection diagrams it is seen that the side deflection is essentially a rotation around the joint of the ladle side and bottom. Due to the 1:12 slope of the side, a horizontal lip deflection will be accompanied with a vertical component equal to one twelfth of the horizontal deflection. The plywood bracket, resting on the lip ring, follows this vertical movement, which causes an error in the bottom deflection readings. The latter are therefore all corrected with 1/12 of the horizontal lip deflection, the sign of the correction depending on the direction of the lip deflection.

The lip ring also shows an additional deflection as may be expected by regarding the ladle as a simple beam between the trunnion supports. This deflection will show up as a difference in recorded deflection of the bottom center point when recorded with the bracket resting on different points on the lip ring. Generally, no corrections are applied to the deflection data for this effect, which in most of the tests was small. Correction is applied, however, to the deflection diagram Fig. 16, by using the average of the four recorded bottom center deflections.

The deflection test data are given in diagrams later in this report.

Whitewash.

One quadrant of the ladle was painted with slaked lime whitewash before testing, as shown on Fig. 29, to give a warning as to appreciable yielding of any part of the ladle during loading. No such yielding was observed.

T E S T   P R O G R A M

The types of measurements called for in the program are already described in detail under "Test Procedure".

The variations in the ladle structure are discussed under "Ladle Models" and summarized in Table 1. These are again listed below with a supplementary discussion where necessary.

1. Type of construction: riveted or welded.
2. Ladle shape: round or oval.
3. Bottom shape: flat or dished.
4. Stiffener band effect.
   (On Ladle "A". Tests, entry Nos. 1 and 2 in Table 4)
5. Trunnion assembly size.
   (Ladle "A". Entry Nos. 2 and 6 in Table 4)
6. Number of stiffener rings.
   (On Ladle "C". Entry Nos. 24, 29, and 30 in Table 4)

   The ladle was first tested with both stiffener rings. The lower stiffener ring was then ground off and a new strain test was performed. Finally a test under the same conditions was carried out with both stiffener rings removed.

The further variables, together with the last three tests mentioned above, are given in Table 4, a survey of the test program as it was carried out. The table yields information on the type of measurement taken in each test for each ladle. The further variables listed in this table are:

7. Load distribution

   The effect of different distributions of loads having the same total weight has been discussed in connection with choice of loading agent. A comparison of the results of the tests under entry numbers 9 & 10 in the table will yield information on this effect for the Ladle "B". Entry numbers 19 & 28 are similar tests for Ladle "C".

8. Amount of Load

The effect of this variable is investigated in the following test series, listed in Table 4:

Ladle "A" : Entry Nos. 3, 4, 5. and 6.
Ladle "B" : Entry Nos. 11, 12, 13, and 14.
Ladle "C" : Entry Nos. 20, and 21.

9. Hook Distance

By "hook distance" is meant the horizontal distance from the inside of the shell at the trunnion pin center-line to the center of the supporting hook. The effect of variation of this distance is studied through the following tests, listed in Table 4:

Ladle "A" : Entry Nos. 6, and 7.
Ladle "B" : Entry Nos. 13, 15, 16, and 17.
Ladle "C" : Entry Nos. 21, 22, and 23 for strain, 24 and 25 for deflections.

One test was made with the ladle supported in the stands, as shown in Fig. 7. This condition is essentially equivalent to a smaller hook distance than can be obtained by support in the hooks. The test is listed as entry No. 18 in the table. Only 91% of full load could be applied, and the test is not directly comparable to any other.

10. Tilt Angle

Ladle "C" was tested in tilted positions, 6° and 20° from the normal position. (Entry Nos. 26 & 27.) The percentages of full normal position load in these two cases were 98% and 82% respectively, corresponding in each case to a 3" distance between the mercury surface and the lowest point on the lip ring. As previously discussed, two alternately directed tilt tests were necessary for each tilt angle to obtain the complete strain distribution by means of gages on only one quadrant.

11. Lining

The program included an investigation of the effect of lining on the stress distribution, to which end the tests entry Nos. 8 and 10 were performed. No appreciable effect was found, and the lining might have been eliminated in later tests. However, to avoid alteration in wooden plugs or purchase of extra mercury it was desirable to use a lining in all tests. The fire-clay also formed a smooth support for the outer rubber casing, thus decreasing the danger of puncture under the high mercury pressure.

Attention is again called to the most significant limitation in the scope of this investigation, namely, the disregard of temperature gradients resulting from proximity to molten metal during operation. The applicability of any results of this investigation should be judged with this limitation in mind.

The ladles were tested in the order B, C, and A. For each ladle, the tests were arranged in the order which should be expected to give increasing stresses. Possible yielding of any parts of the ladle would then affect the other tests as little as possible.

PRESENTATION OF THE TEST RESULTS

The test data obtained in this investigation are given in Tables 5 to 7 and deflection and stress diagrams, in Figs. 30 to 55.

Table 4 offers a survey of all tests, listing the variables and the measurements taken in each case. References are given in Table 4 to the columns in Tables 5 to 7, listing the experimental stresses obtained in each test. The last three columns in Table 4 also give the figure numbers referring to diagrams plotted from the deflection and strain test results.

Deflection Diagrams.

The deflection data are presented graphically in Figs. 30 to 38. A table giving the variables for each of these diagrams is placed in front of Fig. 30.

The deflection data are generally plotted on both horizontal and vertical cross sections. The horizontal sections, as per example shown on Fig. 30, are taken at the lip ring, the top stiffener and at the lower stiffener. Only one half of each cross section is shown. The data, obtained in one quadrant only as described earlier, are plotted for both quadrants as shown, to give a better picture of the behavior of the ladles. Fig 31 is one of the deflection diagrams showing the deformation of vertical sections. These sections correspond to the four positions of the plywood deflection bracket, as described under "Deflection Measurements" on p. 9.

The scale used in plotting the deflections varies from one diagram to the other, and the diagrams are therefore not directly comparable.

Stress Tables

The key to the designation system for the strain gage locations used in the stress tables is given in Figs. 22, 23 and 24 for Ladles "A", "B" and "C" respectively. Thus the designation C4 indicates that the gage is located on the intersection of the vertical line C with the horizontal level 4.

The strain gages mounted on the trunnion assemblies of Ladles "B" and "C" are designated by double letters or double numbers. On Table 7B, the location "A-B 3-4", as an example, refers to the gage shown on Fig. 24 between the A and B lines at a level between 3 and 4.

The stress tables (Tables 5, 6 and 7) generally give the horizontal and vertical stress components (σ_x and σ_y), the principal stresses (σ_1 and σ_2) and their direction (α). σ_1 is always taken as the algebraic larger of the two principal stresses. The angle α is measured clockwise from the x-axis to the direction of σ_1. A negative α therefore means that the direction of σ_1 is obtained by a counter-clockwise rotation from the x-axis. σ_2, of course, is directed normal to the σ_1 direction. In determining α, both the inner and outer surfaces are seen from the outside of the ladle. The inner surface is thus imagined as seen through the ladle wall. In cases when the horizontal and vertical stress components were found to be equal, the indeterminacy of the principal directions is indicated in the tables with the letter α in place of a numerical value.

On axes of symmetry the principal directions are known to coincide with the x and y directions. For gages on these axes, σ_x and σ_y are therefore identical with the principal stresses, the algebraic larger being σ_1 and the other being σ_2.

On the narrow rings, the vertical stress component σ_y is assumed to be zero. Then the horizontal stress component σ_x is identical with one of the principal stresses, the other being zero.

Tensile stress is taken as positive, negative stress values indicating compression. The letters "o" and "i" on top of the stress columns refer to outside and inside ladle wall surfaces, respectively.

For some tests, stress values on the lip ring larger than the yield point of the material will be found in the tables. In these cases, the actual stress is equal to the yield point of the steel, and may be found from Table 3, CONTROL COUPON SUMMARY. The value in the stress tables is evaluated from the measured strain by multiplying this with Young's Modulus, 29,500 ksi. The fictitious stress ($E\epsilon$) thus obtained merely indicates the amount of yielding which has taken place in each test.

Stress Diagrams

While all deflection data are presented in form of diagrams, the same would hardly be practicable for the stress data. The number of stress diagrams is therefore limited to give the outside and inside horizontal stresses at the levels of the lip ring, top stiffener and lower stiffener for representative tests.

A survey of the stress diagrams, Figs. 40 to 55, is given on the page in front of Fig. 40.

As for the deflection diagrams, only one half of each cross section is shown. The stress diagrams are drawn in full lines in the quadrant on which the measurements are taken, and repeated in dotted lines on the other quadrant shown. On Figs. 53 and 54, showing the stresses on the ladle in tilted position, the whole cross section has to be shown, due to dissymmetry of the stress distribution.

Fig. 48 shows the vertical stress component, plotted on vertical cross sections through the ladle. Fig. 55 gives the average of the outside and inside horizontal surface stresses, plotted on a perspective view of a vertical section through the ladle.

The stress scale used varies from one diagram to the other, which should be taken into account if the results are mutually compared.

DISCUSSION OF TEST RESULTS

General Deformation Behavior.

The deflection diagrams, Figs. 30 to 38, throw light upon the structural behavior of the ladles under various conditions of loading.

The deflection tests as a whole show an appreciable divergence from the deformation which might be anticipated from at least some of the present design assumptions. The most important difference is probably the overall inward rotation of the ladle side at the trunnions and overall outward rotation midway between the trunnions. This difference is demonstrated in Fig. 39, showing an exaggerated picture of both the anticipated and actual types of deflection. The irregularity superposed on the straight-line side rotation is due to the trunnion bending moment. This effect is actually smaller than shown in Fig. 39, and decreases rapidly with increasing distance from the trunnions. Thus, on Ladle "A" in Fig. 31, the "trunnion effect" is easily distinguished at the A-line near the trunnions, and shows up also 30° from the trunnions at the B-line. Lines C and D, however, show no such effect.

A similar picture is obtained in Fig. 33, where the trunnion effect on the deflection is especially pronounced on the curve representing the maximum hook distance, which is the case of maximum trunnion bending moment.

Two similar diagrams for Ladle "B", Figs. 34 and 36, do not show such a regular behavior. The deflections on these diagrams are plotted to a much larger scale. Line A in Fig. 36 shows larger deviation from a simple rotation than do the other three lines in that figure, which is probably due to the trunnion effect. The deflection curves on this diagram are based, however, on only four measured deflections.

Ladle "C", with a heavy plate on the middle section, would be expected to resist local bending effectively. In Fig. 38, the trunnion effect is not distinguishable. The side deflections of this ladle follow curves rather than straight lines as in the case of Ladle "A", but the general behavior is the same as for Ladle "A" and "B": The side moves inward over its whole height at the trunnions and moves outward in the same manner midway between the trunnions. On this deflection is superposed the more or less pronounced local deflection due to the trunnion bending moment.

The point of zero horizontal side deflection, between the region of inward deflection and the region of outward deflection, are generally located between 40° and 50°

from the trunnions at all levels. This statement is verified for Ladle "A" by Figs. 30 and 32 and for Ladles "B" and "C" by Figs. 35 and 37 respectively. Thus, along the sides, 40° to 50° from the trunnions, are vertical lines that do not deflect horizontally.

A horizontal cross section through the ladle, originally circular, deform under load into an oval shape as shown in Figs. 30 and 32 for Ladle "A". The same behavior is found for Ladle "B" in Fig. 35 and for Ladle "C" in Fig. 37. The amount of decrease in diameter at the trunnions is of the same order as the increase in diameter midway between the trunnions. In accordance with the way the sides deform, as discussed above, the deflections are largest at the lip ring and smallest at the lower stiffener.

As an average under equivalent conditions, the magnitude of the horizontal deflections of the side is about three times as large for the riveted Ladle "A" as for either of the welded Ladles "B" or "C".

The flat bottom of Ladle "A", Figs. 31 and 33, deflects into the shape expected for a uniformly loaded circular plate with partially fixed edge. The behavior of the flat oval bottom of Ladle "B", Fig. 34, is similar to that of Ladle "A". Ladle "C" has a dished bottom, and the deflection picture, Fig. 38, is quite different. The maximum deflection does not occur at the centre of the bottom, but along a circle about one third of the way in from the center. This bottom resists the load mainly by means of membrane stresses in the plane of the bottom plate. The deflection is only about one sixth or one seventh of that which the flat bottoms of Ladles "A" and "B" develop under similar loads.

Factors Affecting the Deflections.

Effect of Stiffener Band.

Fig. 30 and 31 show the influence of the stiffener band (see Fig. 5) on the deformation of Ladle "A" under load. While the effect in the trunnion region is small, the stiffener band decreases the deflection appreciably at the lines 60° and 90° from the trunnions. The effect of the stiffener band on the bottom deflection is small (Fig. 31).

Effect of Trunnion Width.

By comparing Figs. 30 and 31 with Figs. 32 and 33, the effect of the width of the trunnion assembly may be found. The 16" wide trunnion assemblies give side deflections approximately 75% of those obtained with the 8" assemblies. The reduction in bottom deflection is smaller.

Effect of Variable Load and Hook Distance.

Figs. 32 and 33 offer a comparison for Ladle "A" between deflections under half load and full load, and also between 2.50" and 7.50" hook distance for full load. Both an increase of load and of hook distance will increase the horizontal deflections of the sides. The bottom deflection also increases with the loading, but shows little response to an increase of the hook distance (Fig. 33). While the side deflections roughly double with doubling of the load, the bottom deflections increase less rapidly. This may be expected, as membrane stresses develop rapidly in the bottom when the deflections become larger than the plate thickness. Closer proportionality between load and deflection should therefore be expected for the dished bottom on Ladle "C", where bending is a minor effect. Fig. 38 bears out this assumption.

The effect of load increase on the deformation of the bottom of Ladle "B" is given in Fig. 34. The relation between load and deflection follows the same pattern as for Ladle "A". Some information as to the side behavior under load increase may be obtained by comparing Fig. 34 (6250 lbs. load) and Fig. 36 (4970 lbs. load). The trend seems to be the same as discussed for Ladle "A".

Figs. 35 and 36 present the relation between side deflection and hook distance for Ladle "B". Corresponding measurements for the bottom of this ladle were not taken, but it is reasonable to assume no effect on the bottom, as shown in Figs. 33 and 38 for the other two ladles.

Finally, Figs. 37 and 38 give the deflections of Ladle "C" under variable load and hook distance. As already mentioned, the dished bottom deflects differently from the flat one, the only resemblance being the insensibility to variation in hook distance. The side deflections increase with both load and hook distance. For this ladle, the deflections are very nearly proportional to the amount of load.

General Stress Distribution.

Tables 5 to 7 and Figs. 40 to 55 give the stresses calculated from experimentally determined strains. To obtain a picture of the general distribution of stress in the ladles under load, first the horizontal and vertical stress components are considered separately.

Figures 40 and 41 may be taken as examples of the distribtuion of horizontal stress along the outside and inside surfaces of the ladles at the levels of the three rings or stiffeners. The distribution is consistent with the previously discussed results of the deflection tests. In the trunnion region of each of the rings or stiffeners there is a compressive stress on the outside surface and a tensile stress on the inside surface. This indicates that there are moments acting in these regions, tending to decrease the curvature of the rings. In the region halfway between the trunnions the stresses are reversed, indicating a tendency towards increasing curvature of the rings.

This general stress distribtuion is the same on all three levels shown in Figs. 40 and 41. The stresses are largest on the lip ring and smallest on the lower stiffener, as should be expected from the deflection diagrams. Also the irregularity of the deflection curves caused by the trunnion bending moment has its parallel in the stress diagrams, as may be seen in Fig. 40, the diagrams for the top and lower stiffener.

The highest stress values are measured on the lip ring above the trunnion. Yielding occurred at this point in some tests, as indicated in the stress diagrams. In the stress tables, as explained earlier, the product of the measured strain and the modulus of elasticity is given for these cases.

The vertical stress components given in the stress tables are generally not plotted. Fig. 48, however, shows a plot of these stresses for Ladle "B". The stresses in general are small, but rise to a considerable amount around the side-bottom joint. These high stresses are similar to the discontinuity stresses produced near the heads of pressure vessels. Yielding has probably taken place at this location, at least on Ladles "A" and "B" with flat bottoms.

The vertical stress components are also high near the trunnions. The highest value is measured near the bottom directly below the trunnions.

Fig. 48 presents a typical distribution of the vertical stress components. The stresses obtained at the lowest gage line (Line 8) of Ladle "A" are considerably lower than those shown for Ladle "B". Because of rivet heads near the bottom joint on Ladle "A", the strain gages were mounted two inches farther from the knuckle than on Ladles "B" and "C". The high discontinuity stresses occur only in a narrow region on both sides of the juncture, and were therefore not registered on Ladle "A" (Table 5). On Ladle "C" the lowest gages were mounted close to the juncture. Nevertheless, only smaller stresses are obtained (Table 7). This is an indication that the dished bottom shape considerably reduces the discontinuity stresses, as pointed out both experimentally and theoretically in research on the design of pressure vessels.

A few strain gages were mounted on the ladle bottoms. Line 9 in Tables 5 to 7 refers to the gage locations nearest the bottom edge shown on the top view of the ladles in Figs. 22 to 24. Line 10 refers to the gages closer to the center of the bottom. High stresses, indicating severe bending moments as well as direct tension forces, are measured at these locations on Ladles "A" and "B", especially closer to the bottom center (Tables 5 and 6). On Ladle "C" these stresses are very much smaller (Table 7). Also, a comparison of the algebraic sum and the algebraic difference of the outside and inside stresses at each of these locations on Ladle "C" indicates that bending in this case is less important and that the direct tensile forces are governing. This was predicted by the deflection diagrams for the bottom of Ladle "C".

The algebraic average of the corresponding stresses at the outside and inside surfaces will give the average direct stress or membrane stress for the location and direction in question, and will thus be a measure of the total tensile force per unit width of material. Fig. 55 shows the horizontal membrane stress calculated in this manner for a vertical cross section through Ladle "C". As an oversimplification, the ladle may be regarded as a vertically loaded deep beam. The top part of the cross section is in compression, and the lower part in tension. The horizontal liquid pressure is carried by tension forces in the rings. This simple picture is complicated by the discontinuity stresses at the bottom edge, which cause compressive horizontal membrane stresses in that region.

Tables 5 to 7 also give the magnitude and direction of the principal stresses at all gage points. At least one of the two principal stresses is always equal to or larger than either σ_x or σ_y. The largest horizontal and vertical stresses are found, however, where these stresses coincide with the principal stresses. The stress diagrams for the lip ring and for the outside surface at the top and lower stiffener show the only principal stress different from zero at these locations. Also the high stresses in the bottom plate are either identical to or very close to the principal stresses.

The shear stress at any gage point in any direction may be calculated from the principal stresses by the formula

$$\tau_\theta = 1/2(\sigma_1 - \sigma_2) \sin 2\theta$$

where σ_1 and σ_2 are taken from Tables 5 to 7. α is the angle to the direction of σ_1, as given in Tables 5 to 7, and θ is the direction in which the shear stress is sought.

Factors Affecting the Measured Stresses.

Effect of Variable Load.

The effect of load on the stresses is investigated for all three ladle models. The results for Ladle "A" are listed in columns c and d of Table 5, and are shown graphically in Figs. 40 and 41. A comparison of the diagrams a and b in these figures shows that the horizontal surface stresses are approximately doubled during a doubling of the load. Table 5 shows less consistency in increase of the stresses on the shell.

Table 6, columns d, e, f and g, gives the stresses from similar tests on Ladle "B". Figs. 44 and 45 are plots of the stresses for half and full load. The results are similar to those obtained for Ladle "A". A study of the stresses obtained in this series of four tests leaves the impression that the measurements are satisfactorily consistent.

Columns a, b and c of Table 7, and Figs. 49 and 50 present the results of the tests with variable load for Ladle "C". Again, the general behavior is found to be as described for Ladle "A".

Effect of Variable Hook Distance.

The hook distance is also a test variable for all the ladle models. For Ladle "A", the results are given in columns d and e of Table 5 and in Figs. 40 and 41. The stresses are found to increase rather consistently with the hook distance at all gage locations on the rings. The effect on the stresses in the side shell is smaller and less consistent. The bottom stresses are very little influenced by variation of hook distance.

For Ladle "B", the similar test series is reported in columns f, h, i and j of Table 6 and in Figs. 46 and 47. The results from these four tests point out a linear relationship between the stresses and the hook distance. All the ring stresses agree approximately with the expression

$$s = c(\text{hook distance} + 2.25 \text{ in.})$$

where c is a different constant for each strain gage location. The stresses obtained from the gages on the trunnion assembly show a similar relationship. For the side shell the effect is smaller and less consistent. The bottom plate is practically unaffected by variation of hook distance.

Columns c, d and e in Table 7 and Figs. 49 and 50 show similar results for Ladle "C". The ring stresses may be expressed in the same way as for Ladle "B". The bottom stresses are practically unchanged. The stresses on the trunnion assembly and on the shell are also approximately linear functions of the hook distance, but the changes are smaller than for the rings.

Ladle "B" was also tested in supports as shown in Fig. 7. The stresses are given in Table 6, column k. The condition essentially corresponds to the use of a small hook distance, and the stresses fall in line with those obtained with hook distance as the variable (Columns f, h, i and j.)

Effect of Structural Variables.

Under this heading may be gathered the investigation of the effect of the stiffener band and of different trunnion widths on Ladle "A", and the effect of the number of rings on Ladle "C".

The data used in plotting Figs. 42 and 43 are taken from columns a, b and d in Table 5. The diagrams show the effect of the stiffener band and the trunnion width. As may be expected, the stress distributions are different in the three cases. In general, however, the wide trunnion assemblies give the lowest stresses and the narrow trunnion assemblies without the stiffener band give the highest stresses.

The stresses on Ladle "C" with both stiffeners, with only the top stiffener and with neither stiffener are listed in Table 7, columns c, k and l, respectively. The data for the rings are plotted in Figs. 51 and 52. It is seen that both stiffeners add to the strength of the ladle, although the effect of the lower stiffener is comparatively small. The top stiffener seems desirable, in spite of the heavy middle section of the shell on this ladle.

Effect of Tilting.

The effect of tilting on the stresses in Ladle "C" is shown in columns c, f, g, h and i of Table 7 and in Figs. 53 and 54. It should be noted that the load for column c is somewhat smaller than "full load", and the stresses are therefore not directly comparable. The results show that tilting of the ladle up to 20° has no appreciable effect on the stress. For tilting angles exceeding 20° the load would rapidly decrease. It may therefore be concluded that tilting does not appreciably increase the stresses, except at the local region where the tilting force is applied.

Effect of Distribution of Load.

Comparative tests with equal weights of water load and mercury load were performed on Ladles "B" (Table 6, columns a and b) and on Ladle "C" (Table 7, columns a and j). These tests were primarily of interest in planning the test procedure, and are not called for in the test program. The stresses obtained are small and difficult to compare. Still it may be concluded that the two types of loading produce different stress distributions. The water load gives higher stresses in the side wall, and the mercury load causes higher bottom stresses.

Effect of Lining.

Columns a and c in Table 6 give the stresses for Ladle "B" loaded with 450 lbs. of water, without and with the fire-clay lining, respectively. Again, most of the stresses are so small that a comparison is difficult. It is also uncertain whether a particular difference in stress is due to the weight of the lining, or due to a changed distribution of the loading on the shell because of the presence of the lining. No definite conclusions as to the effect of the lining may be drawn from these tests.

SUMMARY AND CONCLUSIONS

Three ladle models, having one-fifth the capacity of 150 ton net prototypes, were tested for deflections and strains under various conditions. Ladle "A" was a round riveted ladle, Ladle "B" an oval welded ladle and Ladle "C" a round welded ladle.

The following conclusions may be drawn from the deflection tests:

1) The round ladles tend to take an oval shape, and the oval ladle becomes more oval under load.

2) Because of this behavior, the deflections increase with the distance from the bottom of the ladles, following a straight or slightly curved line, except for local trunnion effects.

3) The maximum inward deflections at each level occur along vertical lines through the trunnions. The largest outward deflections occur along vertical lines halfway between the trunnions. Lines 40° to 50° from vertical planes through the trunnions show no horizontal deflections.

4) The flat bottoms have deflections expected of uniformly loaded plates with partially restrained edges. The dished bottom has maximum deflection on a circle with a diameter one third that of the outside diameter.

5) The magnitudes of the horizontal side deflections of the round riveted ladle and the oval welded ladle are approximately equal and about three times the deflections of the round welded ladle with a heavy middle section in the shell.

6) The maximum vertical deflections of the flat circular and the flat oval bottom plates are approximately equal and are six to seven times larger than the maximum deflection of the circular dished bottom.

7) The stiffener band on Ladle "A" decreases the side deflections.

8) The 16" wide trunnion assemblies on Ladle "A" give approximately 75% of the side deflections obtained with the 8" assemblies. Bottom deflections are reduced less.

9) For all ladles, side deflections increase at about the same rate as the load, as do the deflections of

the dished bottom, while the flat bottom deflections increase less rapidly.

10) Side deflections increase with the hook distance. Bottom deflections are not affected by change in hook distance.

The following conclusions may be drawn from the strain tests:

1) The stress distribution is consistent with the deflections discussed above: Of the three rings, the lip ring is most highly stressed and the lower stiffener is least stressed. On each ring, largest stresses generally occur at the trunnion line and halfway between the trunnions.

2) High discontinuity stresses are observed at the juncture of the side and the bottom, especially on the flat bottoms.

3) The dished bottom shows smaller stresses than observed on the flat bottoms.

4) The stresses in the side of the ladles increase linearly with the hook distance, while the bottom stresses are practically unchanged.

5) The wide trunnion assemblies on Ladle "A" give slightly smaller stresses than the narrow trunnion assemblies.

6) The stiffener band on Ladle "A" slightly reduces the stresses.

7) On Ladle "C", both stiffeners add to the strength of the ladle. The top stiffener is considerably more effective than the lower stiffener.

8) Tilting of a ladle with full load will not appreciably increase the stresses.

The test results show an appreciable difference between the actual structural behavior of the ladles and the assumptions made in present design procedures insofar as they are known to the authors. Attempts have therefore been made to develop a new method of analysis consistent with the experimental data, but no final conclusions have been reached within the time available on this project. Further theoretical study of the analysis and design problem is therefore recommended.