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SUBJECT

Progress Report on

The Strength and Ductility of Steel Castings

at Hot Tearing Temperatures -

1250 - 1400 degrees Centigrade

FR-1479

by

C. W. Briggs

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NAVAL RESEARCH LABORATORY

BELLEVUE, D. C.

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NAVY DEPARTMENT
BUREAU OF ENGINEERING

Progress Report on

The Strength and Ductility of Steel Castings at Hot Tearing Temperatures - 1250 - 1400 degrees Centigrade

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
WASHINGTON, D.C.

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TABLE OF CONTENTS

APPENDICES

ABSTRACT

Equipment has been devised and constructed to test cast steel at temperatures (1250° C. to 1400° C.) near the solidification temperature of steel. This equipment consists of a small type tensile machine operating against a calibrated spring attached to the mold.

A test bar has been developed which shows a uniform temperature throughout its gage length.

Preliminary testing has established the nature of existent variations in results and the shape and trend of tensile strength and ductility (elongation) curves.

AUTHORIZATION

1. The studies in steel castings were originally authorized by the Bureau of Engineering letter P/Castings (6-19-Ds) of 13 July 1928.

STATEMENT OF PROBLEM

2. The object of this report is to present information concerning the progress attained on the studies of the strength and ductility of steel castings at temperatures slightly below the solidification temperature of the steel.

KNOWN FACTS BEARING ON THE PROBLEM

3. Some of the most serious defects found in steel castings are cracks. In some cases the cracks are quite large and will extend many feet in length, while at other times they are found to be short in length of perhaps only an inch or two and are present as a very fine network. These cracks are caused by hindered contraction. By that it is meant that either the mold or the casting is so shaped that it does not allow the metal to contract normally. Because of this resistance to normal contraction large internal stresses are developed which concentrate at hot spots or other structurally weak sections with the result that the metal strength is exceeded and the casting cracks.

4. Because these cracks have a very irregular and jagged appearance, and as the fracture face is quite oxidized and shows a heat effect, these cracks are known as hot tears.

5. From various practical considerations and from certain experimental observations it has been somewhat established that hot tearing takes place in the neighborhood of 1350 degrees Centigrade.

6. Though the cracking temperature was somewhat tentatively known, there were many other points on which steel founders needed information. These points may be stated as follows:

(1) What is the strength and ductility of cast steel at hot tearing temperatures?

(2) Do carbon or alloy contents have any influence on the mechanical properties of cast steel at these high temperatures?

(3) Is there a minimum point in strength and ductility through which cast steel passes upon cooling from its solidification temperature to room temperature?

7. It was with the view of answering some of these questions that the research on the strength and ductility of cast steel at temperatures from 1250 to 1400 degrees Centigrade was undertaken.

METHODS USED IN RESEARCH

8. First of all, in order that experimental results be comparable to actual manufacturing conditions, it was necessary to test the steel, while it was cooling, shortly after it had solidified. It seemed fairly evident that any results obtained on cast bars that were allowed to cool to room temperature before testing them at the high temperature would not tell the actual story of hot tear conditions. This seems especially true when it is considered that the properties of the casting are evaluated in terms of the "as cast" or Widmanstatten structure, whereas bars cooled to room temperature and then reheated, go through two phase changes, which produce a different structure not comparable to steel which has not traversed a phase change.

9. Thus, in view of the above considerations, it was necessary that a method of testing be devised that would allow the cast steel to be studied as it cooled from its solidifying temperature. In this regard, it was necessary to provide a mold to hold the molten steel, an accurate testing machine, and clamps to hold the specimen in the machine.

10. After three years of study and planning, machine construction, testing, redesigning, reconstruction and further testing, four testing machines with mold assembly were prepared.

11. The details of the machine and mold design are shown in Plates 1 to 4, inclusive.

12. A bed plate was provided with a 1/2 H.P. motor securely fastened to one end. The motor is so constructed that its speed of operation is constant, whether operating with or without a load. This allows all testing to be carried on at a uniform and constant rate of speed.

13. A yoke is securely mounted to the bed plate against which is placed the mold flask. These flasks are sturdily constructed out of 5-inch channel iron so that it will not deform or give during the testing operation. After the flask is placed in position, it is bolted to the bed plate.

14. A revolution counter was also set up on the bed plate. In this manner, it was possible to record the movement of the pulling screw. The complete operating assembly is shown in Plate 1.

15. The bar design is molded in green sand. A follow-board

is used, thus preventing the bar from being split along its length. In this manner, a very accurate mold could be made. At the pulling end of the bar, a cavity for a sand core was formed. A core was used at this end of the flask so that it could move out of the flask as the bolt moved during testing. In this way, there was no portion of the mold that would be resisting the movement of the cast steel bar under test.

16. Two steel bolts with ground ends were allowed to enter the mold cavity about 2 inches. Their purpose was to fasten the cast steel into the testing machine. The molten steel flowed into the mold cavity and around the bolts, and upon solidification, securely gripped the bolts.

17. The test bar was designed so that it would be 2 square inches in cross-sectional area with a corresponding gage length of 6-11/32 inches, in accordance with the standard ratio of gage length to bar diameter.

18. Considerable experimental study was given to designing the test bar so that along the entire gage length the temperature was uniform. Of course, there was a temperature gradient existing from the mold-metal interface to the center of the bar. This condition, however, is natural to all steel castings, so it became merely one of the conditions of the test. Thus, all temperatures mentioned in this study, unless otherwise designated, refer to the temperature of the center of the test bar. This temperature was uniform throughout the gage length. The large ends of the bar took care of the chilling conditions exerted by the bolts. Details of the bar design and the position of the tying-in bolts are shown in Plate 2.

19. The details regarding the size of the flask used and the method in which the bolt is connected to the pulling mechanism are shown in Plate 3. A coupling on the end of a four pitch screw is used to hold the bolt, and by this means the flask is placed in line. The coupling is constructed with a slide movement on the screw. In setting up the apparatus, the coupling is set to a line on the screw so that the screw will move 1/8 of an inch before it picks up the coupling. This was done so that there would be no tension on the bar, which was contracting during cooling, before the testing took place. In other words, the test bar was allowed to contract freely up until the time of testing.

20. The bolt on the recording end of the flask was held in position by a guide washer.

21. Plate 4 shows the mold assembled and details of the recording end of the flask. A flat silicon-manganese steel spring

extends from one side of the flask to the other. The bolt is fastened to the spring, just slightly more than finger tight, but not sufficient to cause the spring to deflect. The spring is 7/8 inches thick and 2 inches wide and is carefully calibrated at regular intervals. The spring deflection is recorded by an Ames dial gage reading to 10,000ths inches. This dial is held securely in place by a yoke which is bolted to the flask.

22. About an hour's time is required to make the mold and to set it up ready for testing.

23. In general, the process of testing is one that by the use of a variable speed motor, gears and screw, one bolt is moved forward while the other is tied down to a calibrated spring. The resulting tension brought about by pulling against the spring is recorded in inches of deflection on the Ames dial. When the tension becomes too great, the bar breaks and the spring returns to zero deflection.

24. The number of revolutions of movement required by the screw before the bar breaks is recorded on the revolution counter. Since the movement of the bolt is in effect an elongation of the test bar prior to its breaking, a record of the ductility (elongation) is obtained.

25. The assembly of the mold and views of the equipment are shown in the photographs of Plates 5 and 6. Figure 1, Plate 5, shows the drag in place against the yoke; also both bolts are in place and the core is set. In Figure 2 the cope has been placed, the spring and yoke added to the flask and the camera-recording apparatus installed. The pulling end of the equipment is shown in Figure 3 and the recording end of the flask is pictured in Figure 4. The Ames dial, the revolution counter, and a stop watch are shown. Figure 5, Plate 6, is an illustration of the mold and equipment fully shielded reading for casting.

26. The gate arrangement employed is that of a straight down gate with a small runner that leads into an open riser. A step gate leads from the riser into the bar. It was necessary to bring the steel into the bar flowing as quietly as possible. The open riser was used for the purpose of cutting down the swirl of metal from the down gate and prevent the steel from spurting into the bar cavity. The step gate in connection with the open riser was provided to prevent slag from entering the bar cavity.

27. Numerous types of gates were experimentally studied before the above arrangement was worked out. For example, the horn gate allowed the metal to enter the mold cavity with such a swirling action that only a steel shell was formed. It is absolutely necessary that the test bars be completely filled and that the amount and size

of contraction cavities be kept to a minimum. For this reason, steel with a very low degree of super heat is used and extreme care is given to the gate arrangement so that the bar will be completely filled.

28. Since the bar is not fed by an outside reservoir, a small amount of center line porosity is found. This is a natural condition of the test, since it is impossible to care for solidification contraction by feeding means.

29. The gate enters the test bar near the recording bolt where movement of the test bar is very slight.

30. It has been previously stated that four sets of equipment were constructed. This was to allow for testing of the same steel at four different temperatures.

31. It was found that thermocouples placed in the bar being tested caused conditions of stress concentration, so that the bars would often break at the position where the thermocouple entered the bar. It was thus decided to set up a fifth mold, under the same test conditions, but without the pulling mechanism, for temperature control. Into this mold two or three platinum-platinum rhodenium thermocouples were placed. The couples extended into the center of the mold cavity. The temperature recording set-up is shown in Figure 6, Plate 6. Synchronized telechron motors operate cameras which take readings every 10 seconds.

32. Since the mold conditions are practically the same in all tests and since the same degree of super-heat is desired for concurrent tests, it follows that the cooling curve of the test bar is practically identical with the previous run.

33. Stop watches are set in motion at the moment the molds are filled. The motors on the test machines are started by the operator according to prearranged times which represent the desired temperatures on the cooling curve.

34. The steel is melted in a 100 pound high frequency induction furnace. Final additions are made with ferro-manganese and ferro-silicon, and just before the steel is tapped into a pre-heated hand ladle, aluminum is added (2 pounds per ton of steel). The tapping temperature is about 2800° F. Figure 7 of Plate 6 shows addition of the aluminum and the beginning of tapping. In the picture of Figure 8, Plate 7, the steel is being poured into the test bar. The operator is setting in motion the stop watch at the moment the mold is filled. Figure 9 is an illustration of pouring the temperature bar. In Figure 10, the operator starts the movie camera and then the motor at the prearranged time as shown by the stop watch.

shown in Figure 11, Plate 8. The arrangement of the gate and run-over basin is clearly shown. In Figure 12, the test bars are more closely examined to show the nature of the ragged type of fracture that exists. Another view of the fracture in the cross-sectional plane is shown in Figure 13. Since the surface is quite rough and jagged, a well-defined photograph is difficult to obtain. A predominate radial structure is shown. A small center line cavity may be seen in some of the specimens.

DATA OBTAINED

36. After considerable experimental investigation, a test bar was designed so that a uniform cooling temperature was maintained along the entire 6-11/32 gage lengh of the bar. The temperature study was made by inserting thermocouples into the center of the bar. The skin temperature of the test bar was also obtained. The temperatures recorded are shown on Plate 9. It may be noted that the variations that exist in temperature are not of a very high order. The skin temperature is more than a 100 degrees below that recorded at the center of the test bar during the first minute and a half of cooling. These temperatures equalize in the neighborhood of 900 degrees Centigrade.

37. Under the plan of testing, the test bar is broken at a pre-determined time which is correlated with actual temperature conditions. The time-stress relation is recorded by a movie camera and subsequently the results are calculated and plotted as shown in Plate 10. The results so presented were obtained on a cast steel of 0.30 per cent carbon tested at approximately 2 minutes after pouring. This corresponds to a temperature of about 1395 degrees Centigrade. The strength time curve shows that the testing time to failure was less than one second. The other curve shows the type of a stress-strain curve that is obtained by plotting the strength against the elongation in inches per inch.

38. In this particular case, the data shows that at 1395 degrees Centigrade the steel had a strength of 875 pounds per square inch. The ductility, however, is very low since the elongation is only 0.75 per cent.

39. The deviation of values that exist when a number of bars are tested at the same temperature may be relatively small or large, depending to a large extent upon the condition of the test bar.

40. Bars that have been poured in such a manner that they contain cavities and slag particles will show considerable deviation.

41. Four bars that were tested at 2 minutes (1395° C.) after pouring showed the following values:

1	800 lbs. per sq.in.	0.98%
2	885 " " " "	0.75
3	875 " " " "	0.98
4	755 " " " "	1.07

42. This series shows only a deviation of 130 pounds per square inch in tensile strength. If, however, this value is figured in percent deviation, or 16 percent, it may be looked upon to be a considerable error. However, this is about the best that can be obtained.

43. If there is a cavity present in the bar, the bar will cool faster and at any one testing time, such a bar will show higher strengths than are recorded for a completely homogeneous bar. This condition may be observed by reviewing the following data:

	Tensile Strength Lbs.per Sq. In.	Elongation %	Condition of bar
1	1020	1.05	Solid
2	1150	1.40	Cavity
3	1030	1.81	Solid
4	1605	2.61	Large Cavity

44. The smallest figures cannot in all cases be taken as depicting the true results, for in some cases included slag droplets are found near the surface of the bar in such a manner as to act as a notch effect upon the bar. In such cases, the values obtained are always of a low order. Thus, considerable care must be exercised in the casting of the test bars and in the study of the fracture to ascertain whether the results are in line with data from other sources. This may be difficult to do if, in the testing of the series of four bars, each bar is tested at a different temperature.

45. The actual collection of data of various carbon and alloy steels has not progressed far. From the present information available it is evident that considerable repetition must be undertaken before final values can be reported.

46. An indication of preliminary results may be obtained by studying Plate 11. From the data presented, it may be concluded that there are no outstanding differences in the strength or ductility characteristic as the carbon content of the steel is increased from 0.08 to 0.24 percent carbon. This statement is necessary in view of the fact that a 0.27 percent carbon steel varies widely from the 0.24 percent carbon steel curves. In fact, the 0.08 percent carbon curves fall between the 0.24 and 0.27 percent carbon curves.

47. The present strength curves show a very steep increase between 1400 and 1440 degrees Centigrade. Below this temperature, the

strength-temperature relation is one of nearly a straight line. There appears to be no outstanding decrease in strength at temperatures of approximately 1300 degrees Centigrade.

48. The ductility values appear to vary considerably. This condition may be corrected in further testing. It seems, however, that the ductility of cast steel above 1300 degrees Centigrade is very low and that at temperatures below 1300 degrees it increases rapidly.

49. In order for a steel casting to crack, it is necessary that stresses be formed. Since hindered contraction stresses are not possible until solidification is complete, it appears that a hundred degrees of cooling would be necessary in order to develop sufficient stress by means of hindered contraction.

SUMMARY

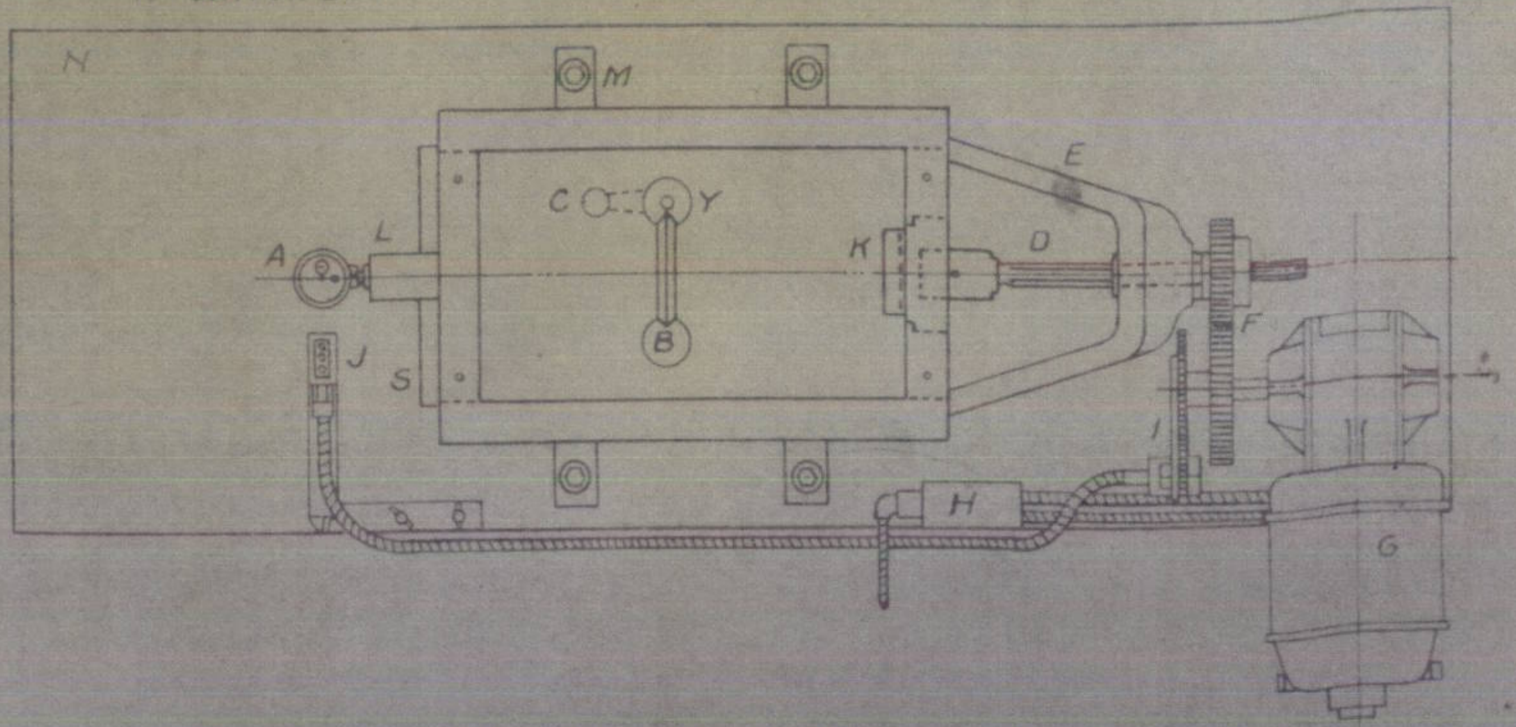
50. Equipment has been devised and constructed to test cast steel at temperatures (1250° C. to 1400° C.) near the solidification temperature of steel. This equipment consists of a small type tensile machine operating against a calibrated spring attached to the mold.

51. A test bar has been developed which shows a uniform temperature throughout its gage length.

52. Preliminary testing has established the nature of existent variations in results and the shape and trend of tensile strength and ductility (elongation) curves.

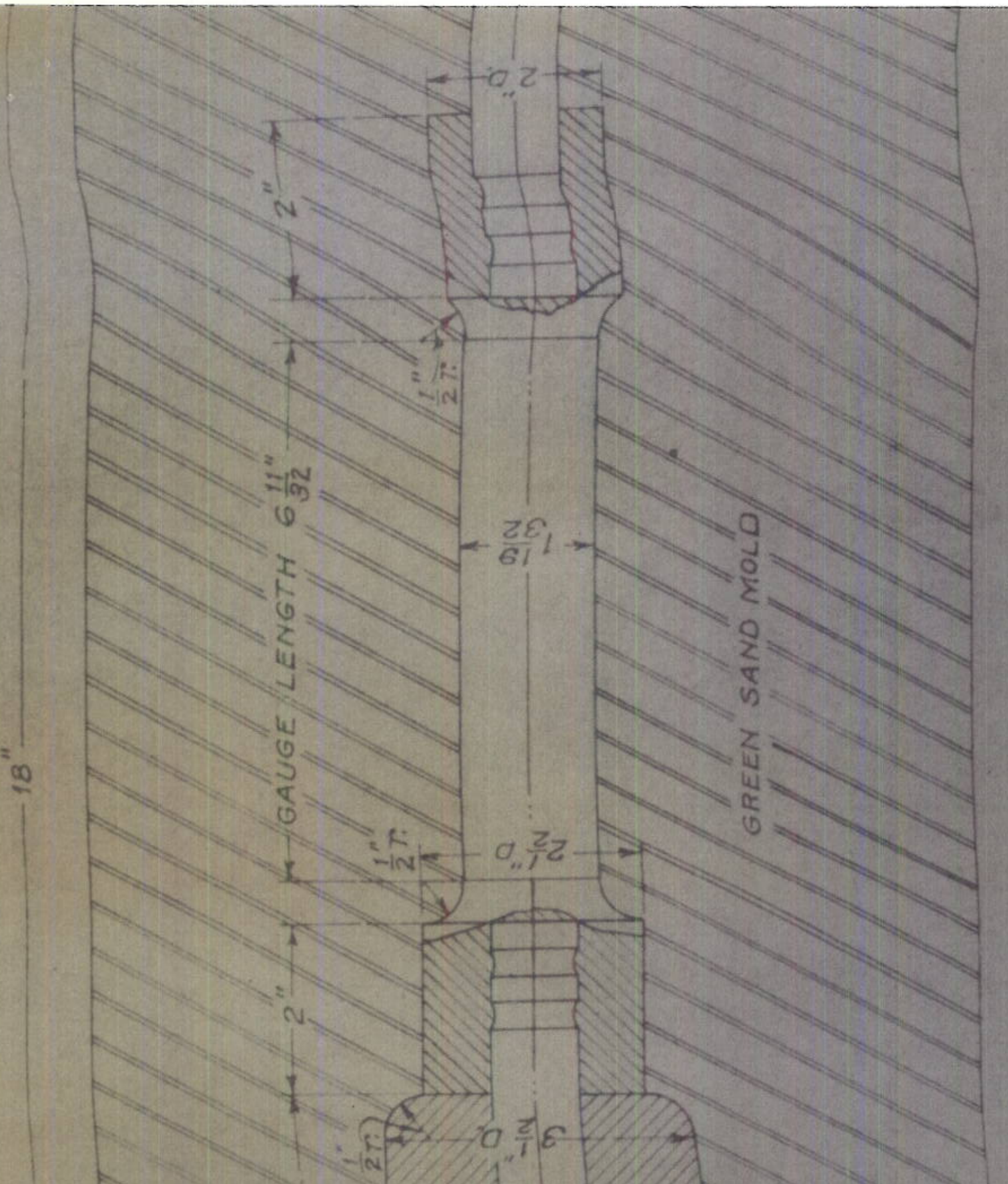
LEGEND-

A-AMES DIAL
B-OVERFLOW BASIN
C-DOWN GATE
D-PULLING SCREW, 4 PITCH
E-YOKE FOR SCREW
F-PULLING GEARS, RATIO-15:1
G-$\frac{1}{2}$ H.P., VAR. SPEED MOTOR
H-SWITCH BOX
I-SPEEDOMETER SPROCKET
J-REVOLUTION COUNTER
K-TIN PLATE FOR HOLDING CORE IN PLACE
L-GAGE YOKE
M-CLAMPS
N-BED PLATE
S-CALIBRATED SPRING
Y-RISER



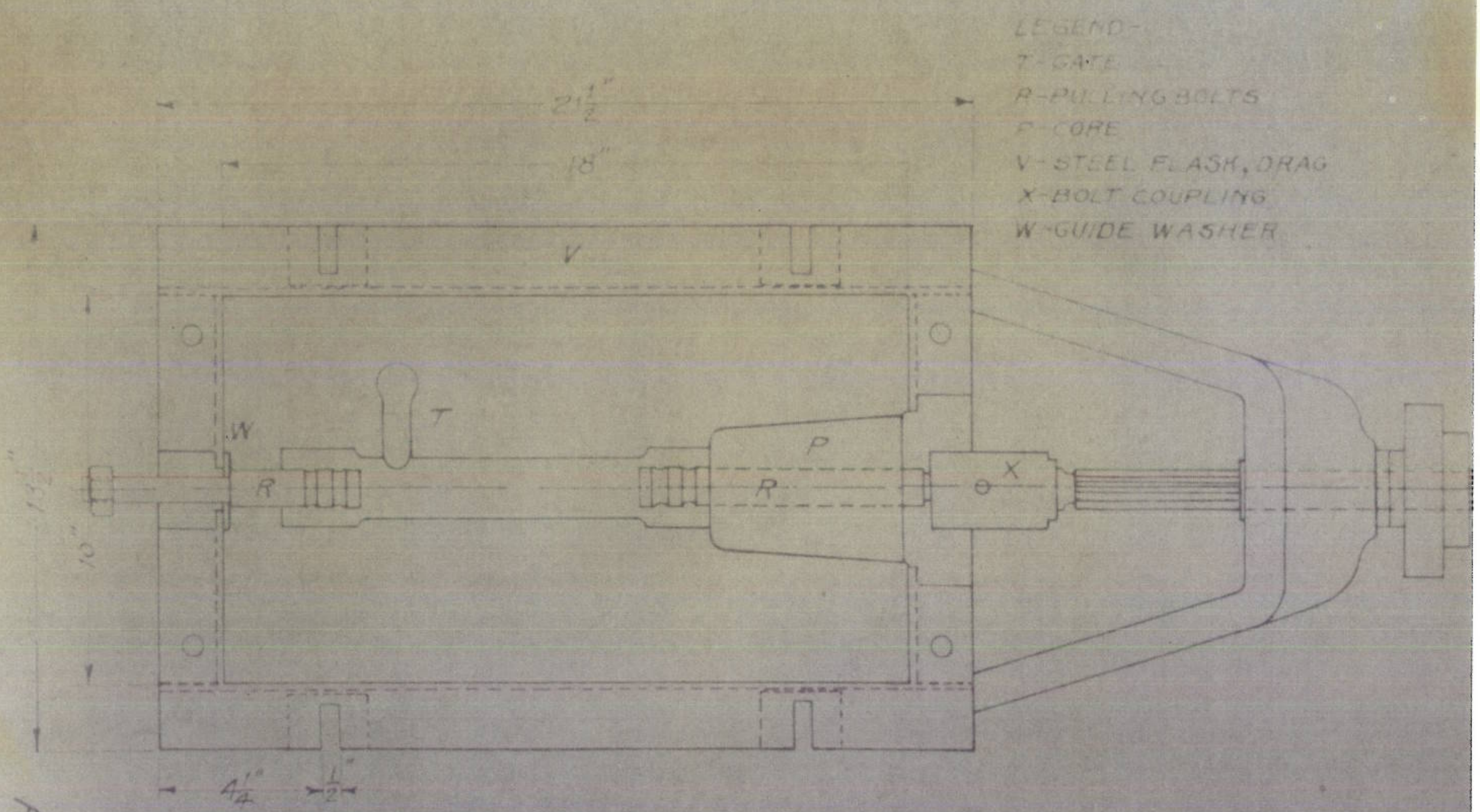
COMPLETE OPERATING ASSEMBLY

PLATE 1



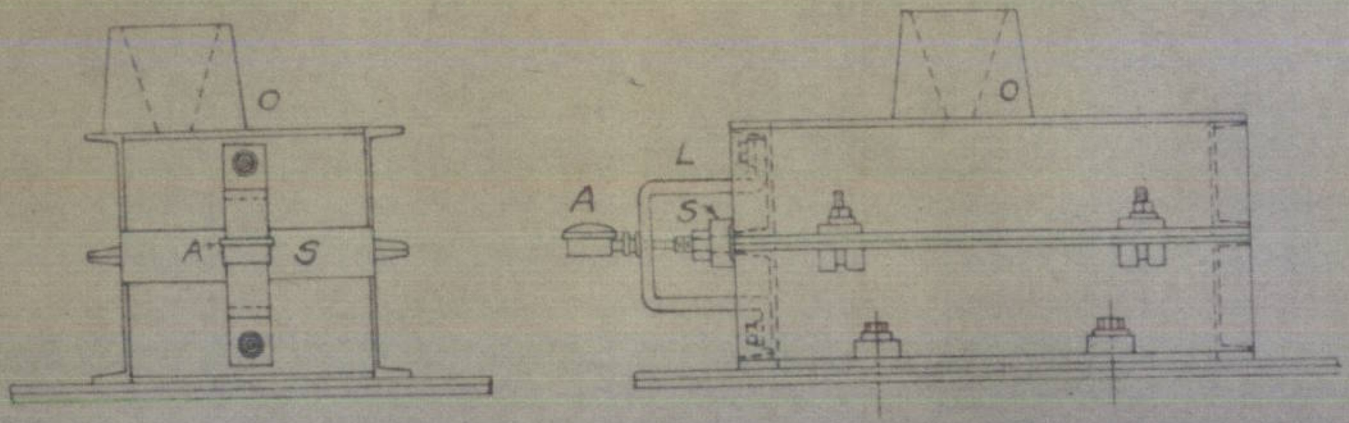
TEST BAR DETAIL

PLATE 2



DETAILS OF DRAG, YOKE, & PULLING GEAR

PLATE 3



MOLD ASSEMBLY

LEGEND-
A-AMES DIAL
L-HEAVY STEEL YOKE
S-CALIBRATED SPRING
O-RUNNER

PLATE 4

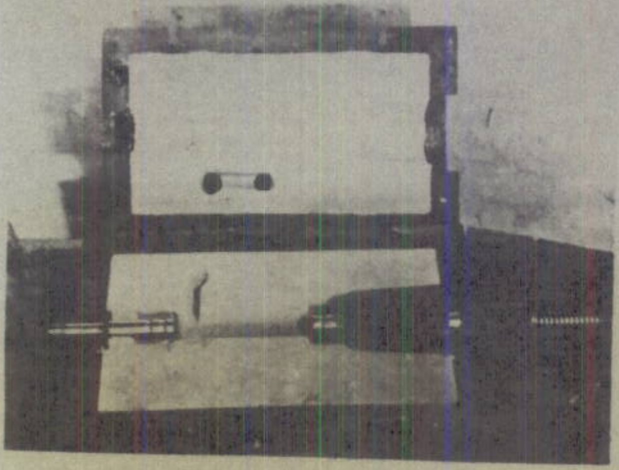


FIG. 1 - OPEN MOLD, SHOWING CORE IN PLACE.

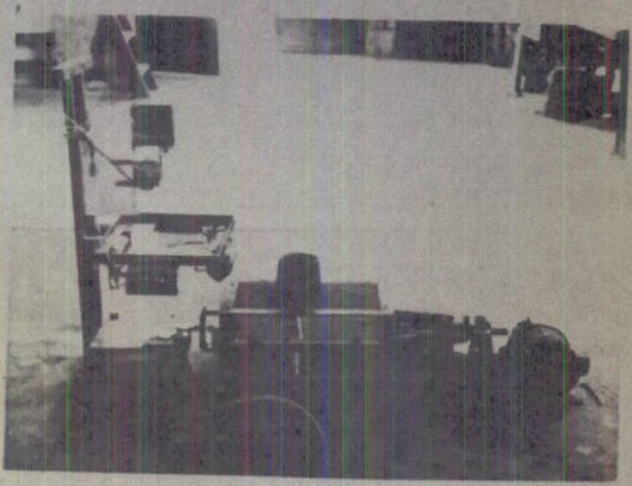


FIG. 2 - GENERAL VIEW OF OPERATING ASSEMBLY

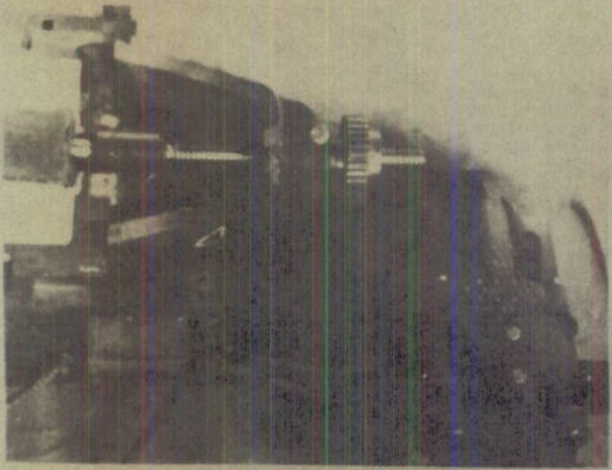


FIG. 3 - MOTOR, GEAR UNIT AND PULLING SCREW.

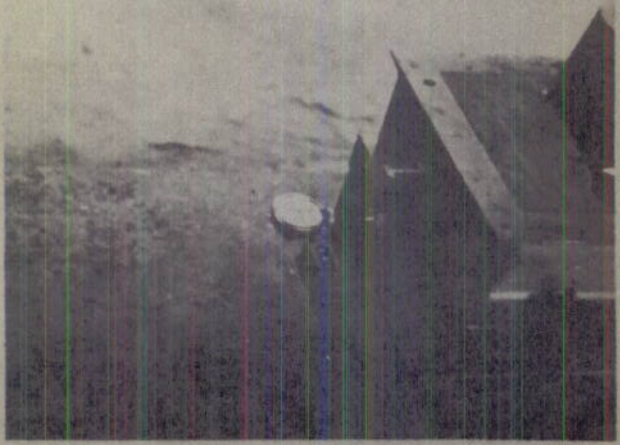


FIG. 4 - CALIBRATED SPRING, AMES DIAL AND REVOLUTION COUNTER.

PLATE 5

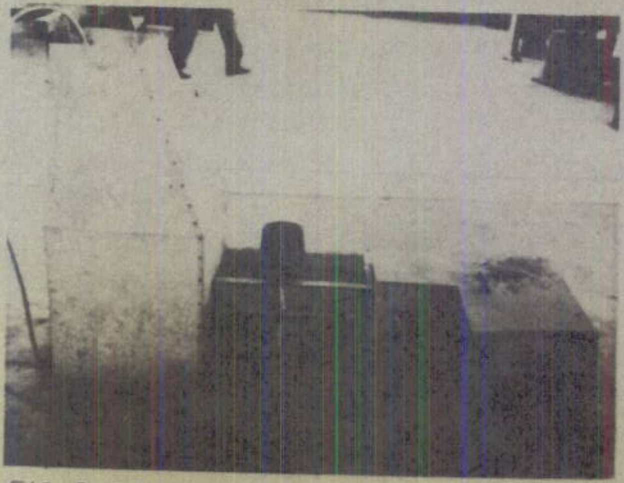


FIG. 5 - OPERATING ASSEMBLY SHIELDED FOR PROTECTION, PREPARATORY TO CASTING.

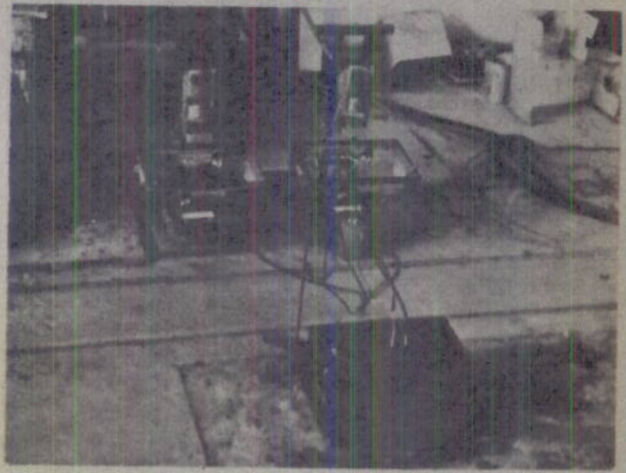


FIG. 6 - TEMPERATURE CONTROL BAR.


FIG. 7 - ADDING ALUMINUM AS METAL IS POURED INTO LADLE

PLATE 6

FIG. 8 – CASTING TEST BAR. MEN IN BACKGROUND SKIMMING THE METAL AND SETTING STOP WATCH.

FIG. 9–CASTING THE TEMPERATURE BAR.

FIG. 10– OPERATOR READY TO START TESTING.

PLATE 7

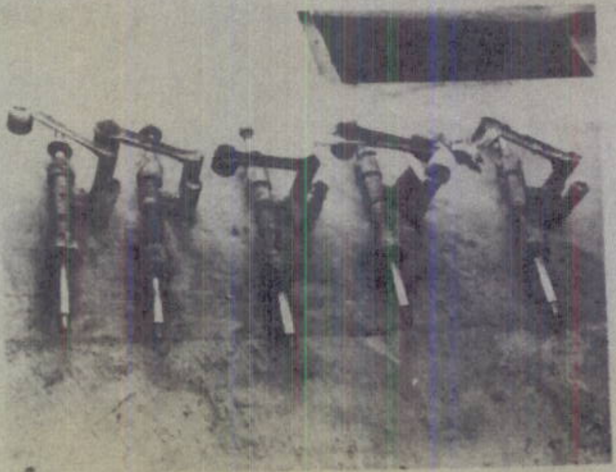


FIG. 11-TEST BARS AND TEMPERATURE BAR AFTER TESTING.

FIG. 12- SAME AS 11 WITH GATES REMOVED

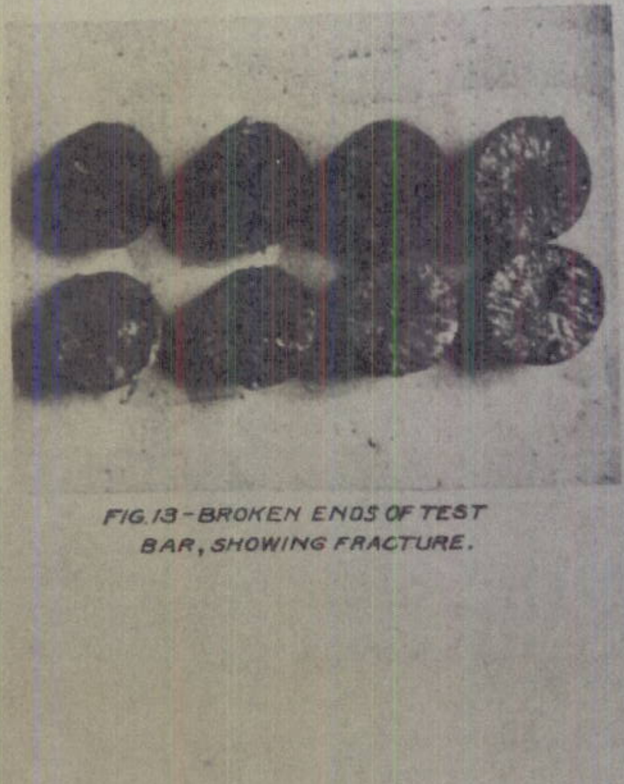


FIG. 13-BROKEN ENDS OF TEST BAR, SHOWING FRACTURE.

PLATE 8

FIG. 11-TEST BARS AND TEMPERATURE BAR AFTER TESTING.

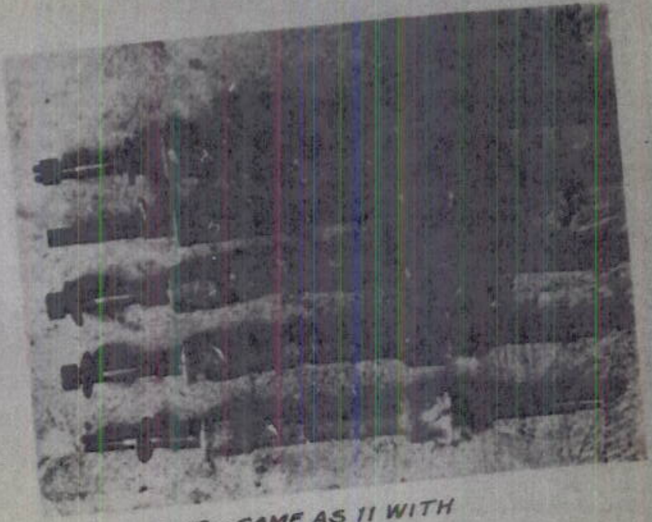


FIG. 12- SAME AS 11 WITH GATES REMOVED

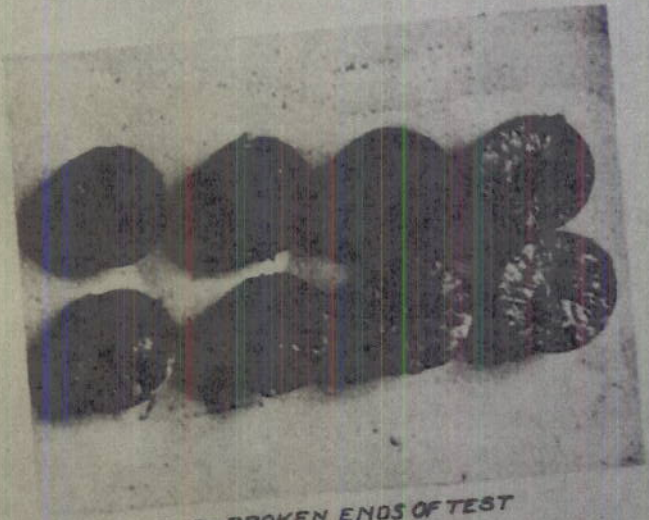
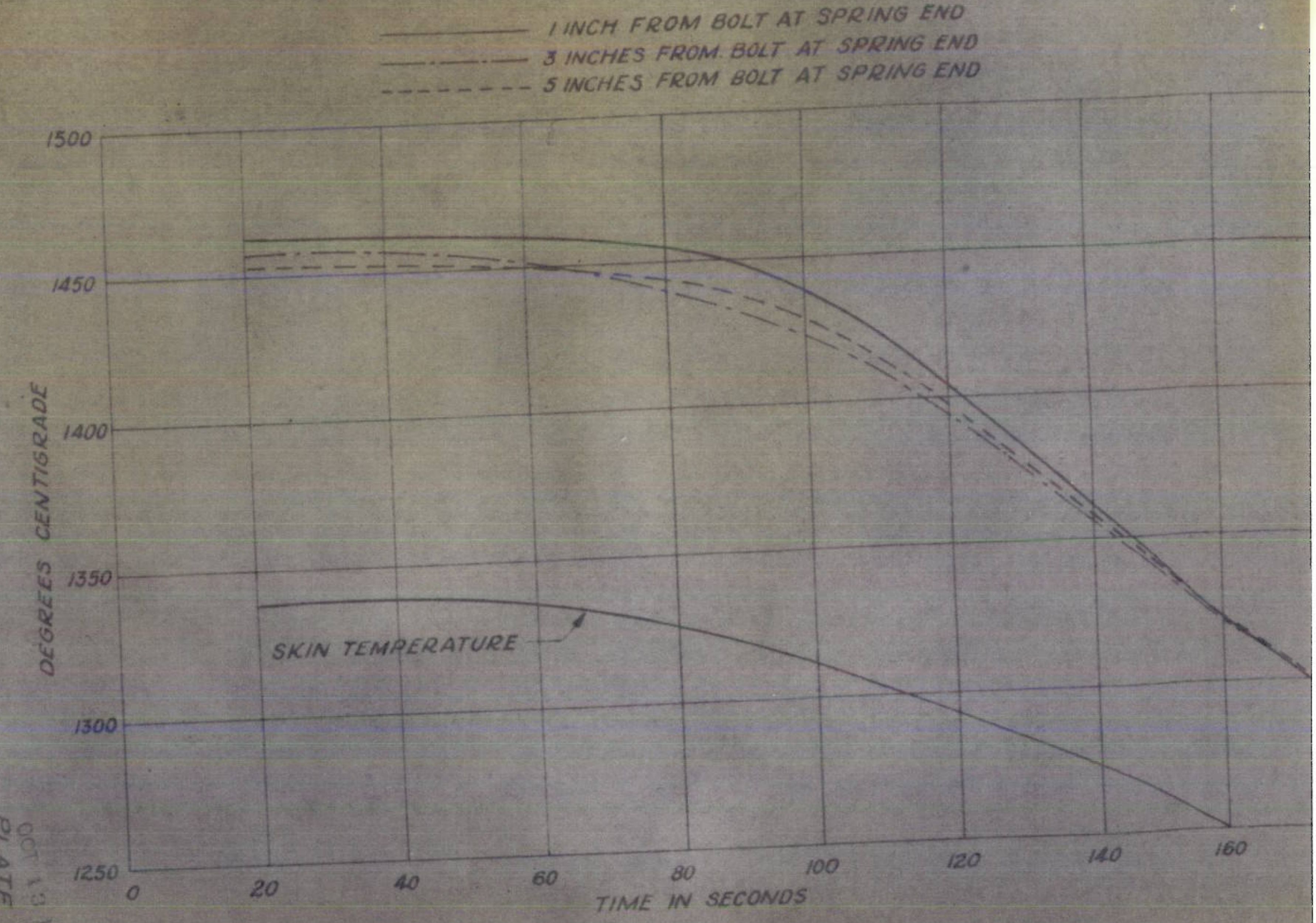


FIG. 13 - BROKEN ENDS OF TEST BAR, SHOWING FRACTURE.

PLATE 8



TEMPERATURE DISTRIBUTION ALONG TEST BAR

PLATE 9

TYPICAL STRENGTH-TIME CURVE AND STRESS-STRAIN CURVE OBTAINED IN TESTING

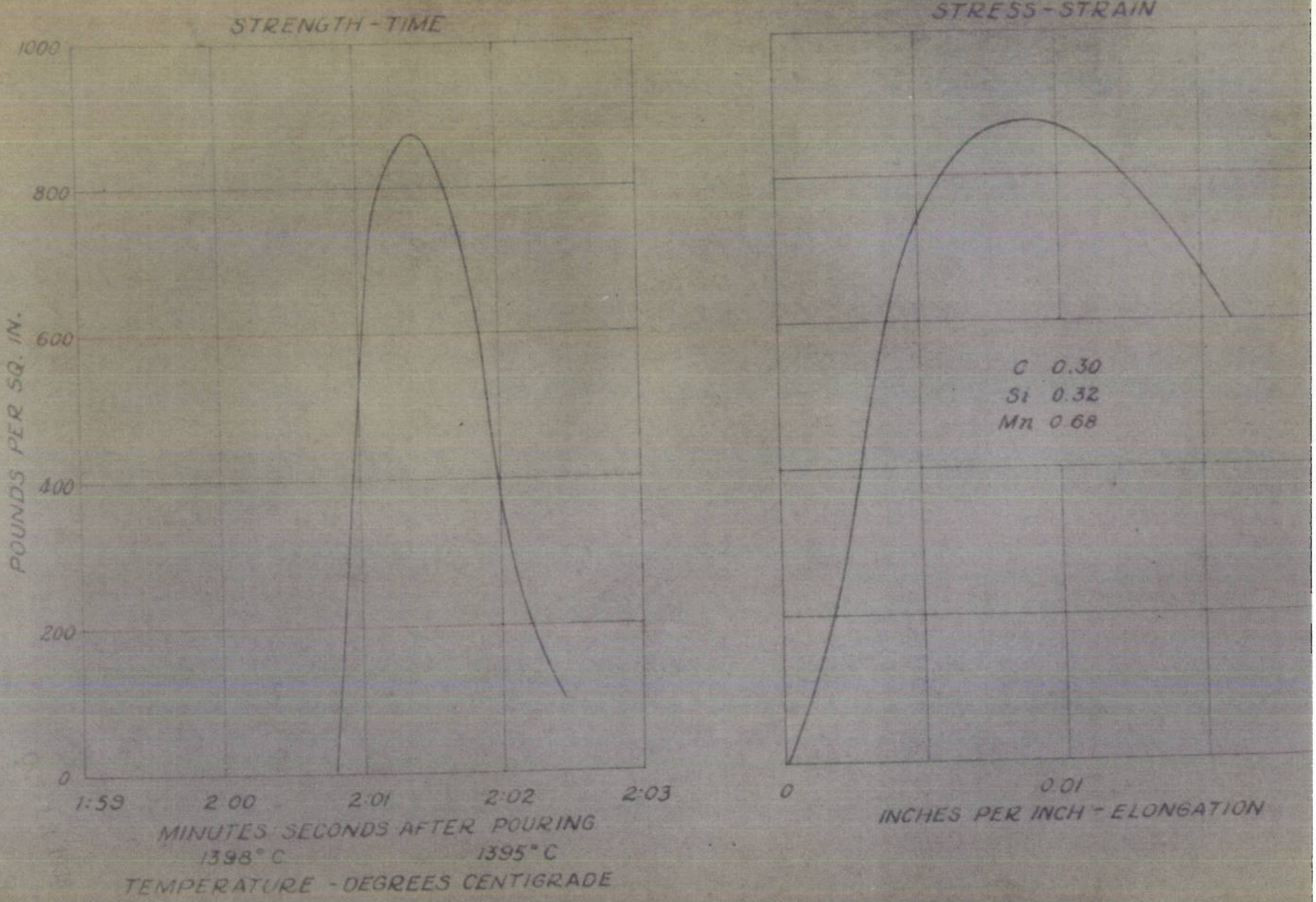


PLATE 10

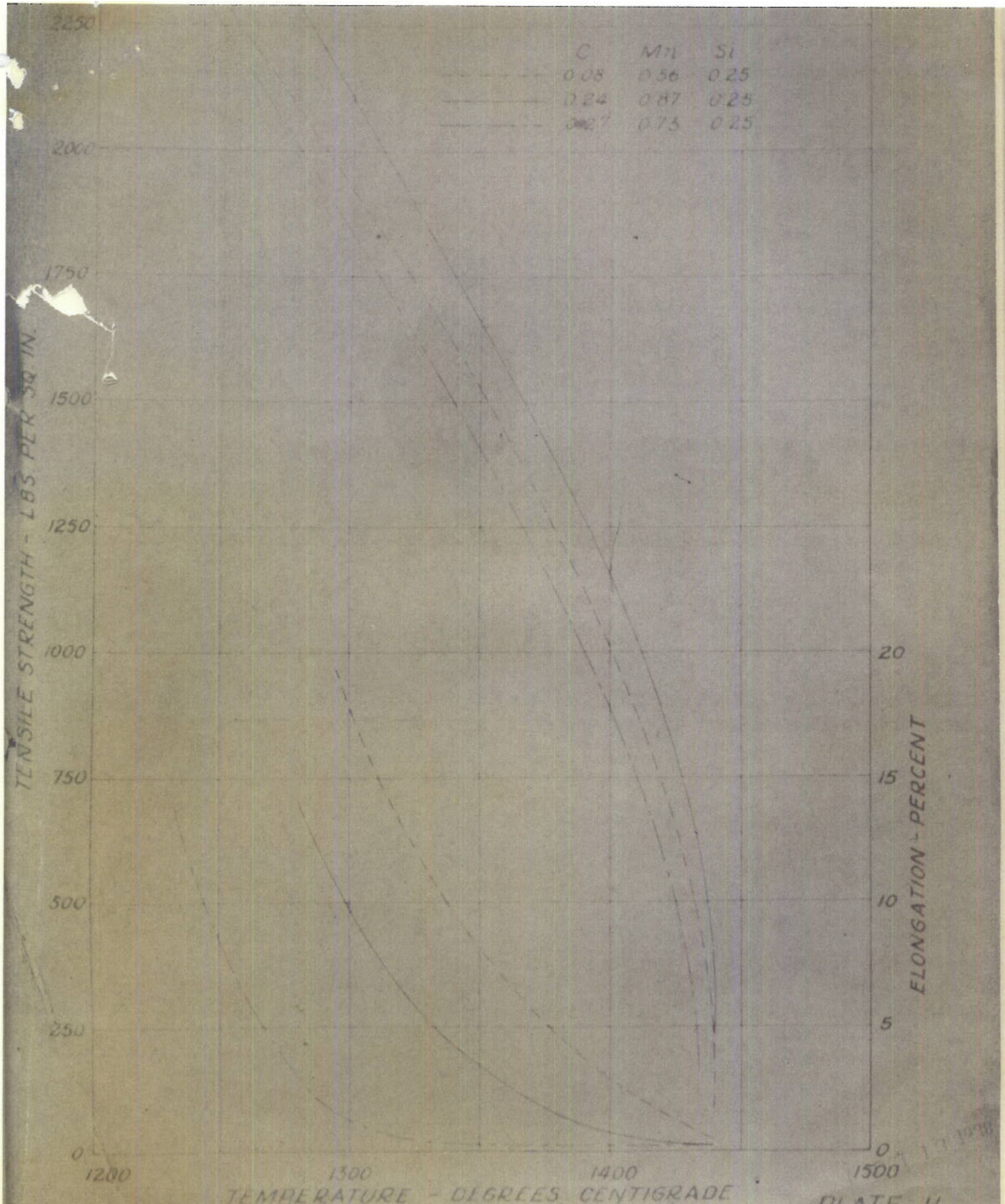

C Mn Si
0.08 0.56 0.25
0.24 0.87 0.25
0.27 0.75 0.25
TENSILE STRENGTH - LBS PER SQ IN.
2250
2000
1750
1500
1250
1000
750
500
250
0
ELONGATION - PERCENT
20
15
10
5
0
1200
1300
1400
1500
TEMPERATURE - DEGREES CENTIGRADE

PLATE II