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WATERTOWN ARSENAL NO. 111/7

FIRST REPORT ON TENSION TESTS UNDER PRESSURE
FOR THE WATERTOWN ARSENAL

A950284

P. W. Bridgman
Harvard University

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Report No. 111/7
Watertown Arsenal
Purchase Order No. 20491

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PLASTIC PROPERTIES OF STEEL
~~First Report on~~ Tension Tests under Pressure for
the Watertown Arsenal.

FOREWORD 9 Rept. no. 1

This is the first of a series of reports upon the plastic behavior of steels submitted under contract by Professor P. W. Bridgman of Harvard University, to the Watertown Arsenal.

One of the outstanding problems in metals concerns the influence of prior deformation upon the plastic properties. Professor Bridgman is particularly able to investigate this field. He has developed a technique, using high pressures, for obtaining prior strains of any arbitrarily large magnitude. His experiments therefore provide an unusually severe test which any theory regarding plastic deformation must meet. Conversely, they are fruitful in stimulating ideas concerning plastic flow and rupture.

C. Zener
Physicist

APPROVED:

H. H. ZORNIG
Colonel, Ordnance Dept.
Director of Laboratory

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Outline of Results.

1. The linear relation between true stress and $\log A_0/A$ continues to hold up to values of A_0/A at least equal to 20.
2. The stronger the steel the greater the slope of the line of true stress versus $\log A_0/A$, that is, the greater the rate of strain hardening. This result is somewhat rough, but indicates the general trend.
3. The strength of steels at atmospheric pressure may be greatly increased, with no loss in ductility, by a previous stretching under hydrostatic pressure.
4. Fractures may occur in material supported by hydrostatic pressure under conditions incompatible with currently accepted conditions of rupture, thus indicating the necessity for a reformulation of the general conditions which produce rupture.

First Report on Tension Tests under Pressure for
the Watertown Arsenal

The primary purpose of these tests was to determine the relation between true stress and extensional strain produced by simple tensile stress for several grades of steel of known composition and heat treatment over a range of strain considerably greater than that possible with the usual methods of producing strain. In order to do this advantage was taken of a recent discovery that if the tensile specimen is immersed in a fluid medium in which there is a hydrostatic pressure of 300,000 lb/in² or more, the ductility of the steel is so greatly increased that rupture may not occur until the reduction of area is close to 100 per cent. In one case a reduction of area of 99.7 per cent has been observed, which means an elongation at the neck of 300 fold.

The apparatus and the experimental method were the same as that used and described in a recent Progress Report of the N.D.R.C. No. A-95, and reference is made to that report for experimental details. In rough outline the tension specimen is first exposed to a pressure of the order of 300,000 lb/in². Tension is then applied to it in addition to the pressure, and the extension measured as a function of the tension. During the application of tension the hydrostatic pressure rises, but this is by a comparatively small amount and is only an incident accompa-

nying the tension necessitated by the design of the apparatus. Tension is increased until the specimen ruptures, or to a predetermined maximum. If the specimen is not ruptured, tension is then removed, then the hydrostatic pressure is removed, and then the specimen removed from the apparatus and the permanent changes of dimensions measured.

In the work for the N.D.R.C. the chief emphasis was laid on comparing the curves of extension versus load at atmospheric pressure and under hydrostatic pressure. To this end, only two samples of each grade of steel were usually tested, one at atmospheric pressure and one under high pressure. The two samples were often carried to rupture; in the case of the high pressure sample this meant such extreme reductions of area because of the greatly increased ductility that the total load could not be measured with sufficient accuracy to give the true stress with satisfactory percentage accuracy.

In the work reported here, several samples were pulled under pressure, and the pullings were stopped at reductions of area distributed over the range between the reduction at which fracture occurs at atmospheric pressure and a reduction between perhaps 90 and 95 per cent, but in no case so high as to diminish to an unsatisfactory amount the accuracy with which the true stress can be calculated from the load. After release of pressure

the reduction of area is measured. Each sample in this way gives a single point on the true stress versus strain curve, the point corresponding to its maximum extension. It would have been possible to dispense with the measurements on several specimens and use the measurements on a single sample to give the complete stress-strain curve up to the maximum extension if it were possible to convert the measured curves of total load versus over-all extension into curves of total load versus reduction of area. Now this is possible approximately as was shown in the N.D.R.C. report, because reduction of area is approximately a linear function of over-all extension. There does not seem to be any theoretical reason for this linear relation, however, which at best is only approximate. In fact, it can be shown not to be valid for an indefinite extrapolation to 100 per cent reduction of area. In view of the uncertainties, it was therefore felt best to go through the extra labor of actually determining several intermediate points on the curves.

The dimensions of the test pieces are shown in Figure 1.

Six series of measurements were made, on straight carbon steels of two compositions. Five series were made on a 1045 steel of various heat treatments, and one series on a 1020 steel in the annealed condition. The heat treatment of these steels are given in Table I. The results are collected into Tables II giving the essential data, and

which is self explanatory. It is to be understood that each line in the table is obtained from a complete curve of extension versus load.

The results are plotted in Figs. 2-7. Each experimental point for extension under high pressure gives the final stress and the final natural strain, of a particular specimen obtained in the high pressure chamber. The natural strain is defined, as usual, to be the natural logarithm of the ratio of original to final cross sectional area. In general it would seem that the true stress rises linearly with the strain over a range of 3 or more, that is, up to extensions of well over 20 fold. It seems difficult to believe, however, that the linear relation can continue for indefinitely high strains because this would imply an infinite strength at infinite extension. Furthermore, if one assumes a smooth analytical connection between the strain hardening curves for extension and compression, then the linear relation cannot hold for too small extensions because the flow strength is raised by compression as well as by extension. The points for the samples tested at atmospheric pressure lie nearly on the line with the high pressure samples, but nevertheless lie below the lines in all cases and by an amount which on the average is too great to attribute to experimental error. This is in line with the previous observation that pressure increases the yield strength as well as the ductility. The

increase observed in the yield strength brought about by the pressures used here was between 10 and 15 per cent on the average.

In general the slope of the stress-strain curve is greater for higher absolute values of the stress. That is, the stronger a steel, the greater the amount by which it is hardened by a definite amount of extensional strain. That this is roughly the case is shown by Table IV and Figure 8 giving the slopes of the stress-strain curves versus the intercepts on the stress axis.

In addition to the tests under pressure, a series of tensile tests were made at atmospheric pressure on the samples that had been pulled under pressure. For these tests the pressure samples were filed down at the neck with a round file of circular section to an isthmus of the appearance indicated in Figure 1. They were then pulled at atmospheric pressure in a specially constructed small testing machine, usually to fracture. The maximum load, the load at fracture, and the diameters at the narrowest part before and after fracture were observed. In addition measurements were made of the extension during the complete loading process, but the significance of these is not clear because the stretch was confined to such a small region because of the contour of the isthmus.

The results are given in Table III and are also

plotted on the same diagrams, Figs. 2-7, that give the results of the tests under pressure. In the Figures, the observation on the same specimen after pulling under high pressure and at atmospheric pressure are joined by dashed lines. In the tables the arrangement under each series is in the order of the previous reduction of area under pressure. Several general results emerge from an examination of Tables II and III.

Even if the initial strain under pressure has been very much beyond the strain at which fracture occurs in virgin material at atmospheric pressure, the material has not lost its power of supporting still further reduction of area at atmospheric pressure. In fact, the additional ductility after exposure to pressure may be greater than the ductility of the virgin material, so that the stretching under pressure constitutes an absolute improvement. Examples of this are the first members of the A_3 and the A_2 series, which after stretching under pressure to very nearly the extent which produces fracture in the virgin specimen, are so improved in properties that they will support an additional strain of more than the amount which fractures the virgin material. In general the amount of additional strain which can be supported after exposure to pressure is in the inverse order of the amount of previous strain under pressure. There is only one exception to this, in the first and second members of

the A_3 series, and here the failure is by only a small amount. Apparent exceptions in the A' and B series are to be ruled out because the specimen was not pushed to fracture. If the previous stretching under pressure was by an extreme amount, the possibility of further plastic stretch at atmospheric pressure may be almost entirely lost, as shown by the last members of the A' and B series.

Along with the additional ductility there is an increase of the true stress at fracture produced by stretching under pressure as compared with that of the virgin material at atmospheric pressure. Without exception the triangles in the diagrams (stress-strain at fracture following stretch under high pressure) lie at higher stresses than the crosses (stress-strain relation at fracture in virgin material). The triangles in general do not lie on the stress-strain line of the high pressure samples. That is, when a sample is pulled under pressure and then restored to atmospheric pressure the nature of the material has been drastically changed. In the greater number of cases the triangles lie below the stress-strain line and below the corresponding circles (final stress-strain relation at high pressure), which means that when restored to atmospheric pressure the sample will not support as great a maximum stress as that which it previously experienced under pressure. This is not surprising. But there are numerous exceptions in which the triangles lie

above the stress-line and above the corresponding circles. The most striking example of this is afforded by the A_2 series. Here is a specimen which after exposure to treatment has retained an additional ductility equal to that of the virgin material but which supports a maximum true stress of more than twice that of the virgin material.

It was thought that there might be some relaxation of the additional acquired strength with time. For this reason the time of the pulling at atmospheric pressure after the treatment under pressure was systematically varied in the A_1 series. In addition the times of all the pullings are given in the table and noted on the diagram. In general there seems no correlation between the stresses and the times. The conclusion is therefore indicated that this constitutes a permanent alteration in the mechanical properties of the material.

There seems to be for each material a degree of pulling under pressure that gives an optimum enhancement of the properties when returned to atmospheric pressure. For most of the series the extreme pulling is beyond the optimum.

Two general comments may be made on these results. In the first place, the absolute amount of strain which a material has experienced does not alone determine its properties, but the manner of stretching is also important. This observation is of importance for the general under-

standing of plasticity. In the second place, now that it has been established that such very great enhancements of mechanical properties are possible by cold working, it would seem that a serious effort should be made to discover some method by which such effects could be produced in an industrially feasible way.

Table I

Type of Heat treatment of Steel

| <u>Designation</u> | <u>steel</u> | <u>heat treatment</u> |
|--------------------|--------------|---|
| A ¹ | 1045 | quenched into water from 1575° F and drawn to 400°-500° F |
| A ₁ | 1045 | as received |
| A ₂ | 1045 | quenched into water from 1575° F and drawn to 800° F |
| A ₃ | 1045 | quenched into salt at 800° F from 1575° F |
| A ₄ | 1045 | quenched into salt at 1100° F from 1575° F |
| B | 1020 | dead soft |

Table II

Stress-Strain data for Specimens Pulled at High Pressure

| Designation | Hydrostatic Pressure lb/in ² | Stress range A ₀ /A | Maximum Strain loge A ₀ /A | True Stress at Max Strain | Engin. Stress at Max Strain | Stress lb/in ² | Engin. Stress at Max Load | Fracture or not |
|--------------------|---|--------------------------------|---------------------------------------|---------------------------|-----------------------------|---------------------------|---------------------------|-----------------|
| A ¹ III | 295.000 375.000 | 2.45 | 0.896 | 324.000 | 133.000 | 194.000 | n.f. | |
| A ¹ V | 300.000 395.000 | 3.98 | 1.381 | 387.000 | 97.000 | 189.000 | n.f. | |
| A ¹ IV | 305.000 400.000 | 7.29 | 1.987 | 468.000 | 65.000 | 194.000 | n.f. | |
| A ¹ II | 300.000 415.000 | 23.8 | 3.169 | 622.000 | 26.000 | 195.000 | n.f. | |
| A ¹ I | Atmos | 2.67 | 0.982 | 320.000 | 120.000 | 169.000 | f. | |
| <hr/> | | | | | | | | |
| A ₁ III | 280.000 410.000 | 2.43 | 0.888 | 211.000 | 87.000 | 113.000 | n.f. | |
| A ₁ V | 250.000 390.000 | 4.05 | 1.399 | 266.000 | 66.000 | 112.000 | n.f. | |
| A ₁ IV | 245.000 405.000 | 7.44 | 2.069 | 331.000 | 45.000 | 113.000 | n.f. | |

Table II (Cont'd)

| | | | | | | | |
|---------------------|--------------------|-------|-------|--------------|---------|---------|------|
| A ₁ VII | 235.000 300.000 | 8.15 | 2.098 | 324.000 | 40.000 | 114.000 | n.f. |
| A ₁ VIII | 250.000 405.000 | 9.95 | 2.297 | 355.000 | 36.000 | 115.000 | n.f. |
| A ₁ II | 235.000 400.000 | 15.44 | 2.736 | 384.000 | 25.000 | 109.000 | n.f. |
| A ₁ VI | 255.000 430.000 | 32.4 | 3.478 | not accurate | | 111.000 | n.f. |
| A ₁ I | Atmos | 2.18 | 0.779 | 176.000 | 81.000 | 99.000 | f. |
| A ₃ IV | 240.000 340.000 | 2.20 | 0.788 | 209.000 | 95.000 | 131.000 | n.f. |
| A ₃ V | 275.000 390.000 | 4.02 | 1.391 | 289.000 | 72.000 | 136.000 | n.f. |
| A ₃ III | 270.000 405.000 | 15.67 | 2.751 | 415.000 | 26.000 | 131.000 | n.f. |
| A ₃ II | Atmos | 2.52 | 0.924 | 215.000 | 91.000 | 114.000 | f. |
| A ₂ III | 280.000 350.000 | 2.12 | 0.751 | 324.000 | 153.000 | 210.000 | n.f. |

Table II (Cont'd)

| | | | | | | | |
|--------------------|---------|-------|-------|---------|---------|---------|------|
| A ₂ IV | 250.000 | 5.12 | 1.633 | 457.000 | 89.000 | 205.000 | n.f. |
| | 345.000 | | | | | | |
| A ₂ II | 280.000 | 28.2 | 3.339 | 656.000 | 23.000 | 210.000 | n.f. |
| A ₂ I | 400.000 | 2.42 | 0.884 | 306.000 | 126.000 | 183.000 | f. |
| | Atmos | | | | | | |
| A ₄ III | 250.000 | 2.16 | 0.770 | 202.000 | 93.000 | 115.000 | n.f. |
| | 350.000 | | | | | | |
| A ₄ IV | 260.000 | 4.43 | 1.488 | 270.000 | 61.000 | 115.000 | n.f. |
| | 395.000 | | | | | | |
| A ₄ II | 255.000 | 14.16 | 2.650 | 385.000 | 27.000 | 114.000 | n.f. |
| A ₄ I | 405.000 | 2.43 | 0.888 | 191.000 | 78.000 | 105.000 | f. |
| | Atmos | | | | | | |
| B VI | 255.000 | 3.88 | 1.356 | 171.000 | 44.000 | 68.000 | n.f. |
| | 410.000 | | | | | | |
| B VII | 255.000 | 5.53 | 1.710 | 185.000 | 33.000 | 69.000 | n.f. |
| | 425.000 | | | | | | |
| B IX | 240.000 | 9.72 | 2.274 | 225.000 | 23.000 | 70.000 | n.f. |
| | 420.000 | | | | | | |

Table II (Cont'd)

| | | | | | | | |
|--------|--------------------|------|-------|---------|--------|--------|------|
| B VIII | 230.000 420.000 | 18.2 | 2.901 | 286.000 | 16.000 | 69.000 | n.f. |
| B V | Atmos | 2.50 | 0.916 | 112.000 | 45.000 | 56.000 | f. |
| B X | Atmos | 2.54 | 0.932 | 114.000 | 45.000 | 59.000 | f. |

Table III

Stress-Strain Data for Specimens Pulled at Atmospheric Pressure after Prior Strain at High Pressure.

| Designation | Max. Strain at Atms. Pressure $(A_0/A)_a, \ln(A_0/A)_a$ | Previous max. strain at high pressure $(A_0/A)_p, \ln(A_0/A)_p$ | Over-all max. strain $\Delta_0/A, \ln(A_0/A)$ |
|--------------------|--|--|--|
| A ₃ IV | 2.56 0.940 | 2.20 0.788 | 5.63 1.728 |
| A ₃ V | 2.73 1.004 | 4.02 1.391 | 11.0 2.395 |
| A ₃ III | 1.99 0.688 | 15.67 2.751 | 31.2 3.439 |
| A ₂ III | 2.52 0.924 | 2.12 0.751 | 5.35 1.675 |
| A ₂ IV | 1.875 0.628 | 5.12 1.633 | 9.61 2.261 |
| A ₂ II | 1.076 0.072 | 23.2 3.339 | 30.5 3.411 |
| A ₄ III | 2.08 0.732 | 2.16 0.770 | 4.50 1.502 |
| A ₄ IV | 1.85 0.615 | 4.43 1.488 | 8.19 2.103 |
| A ₄ II | 1.77 0.573 | 14.16 2.650 | 25.0 3.223 |

Table III (Cont'd)

| | | | | | |
|---------------------|---------|---------|---------|----------|------------------|
| A ¹ III | 324.000 | 262.000 | 303.000 | 5 days | n.f. |
| A ¹ V | 519.000 | 314.000 | 327.000 | 3 days | f. |
| A ¹ IV | 430.000 | 374.000 | 340.000 | 4 days | f. |
| A ¹ II | 423.000 | 419.000 | 419.000 | 6 days | f. |
| <hr/> | | | | | |
| A ₁ VII | 298.000 | 166.000 | 221.000 | 15 days | f. |
| A ₁ VIII | 321.000 | 199.000 | 218.000 | 23 hours | f. |
| A ₁ VI | 359.000 | 257.000 | 313.000 | 76 min. | 2 pullings f. |
| <hr/> | | | | | |
| B VI | 210.000 | 130.000 | 149.000 | 4 days | f. |
| B VII | 162.000 | 131.000 | 147.000 | 2 days | n.f. |
| B IX | 187.000 | 140.000 | 168.000 | 1 day | n.f. |
| B VIII | 204.000 | 204.000 | 204.000 | 1 day | f. |

Table III

Stress-Strain Data for Specimens Pulled at Atmospheric Pressure
after Prior Strain at High Pressure

| Designation | True Stress at Max. Strain | Stress lb/in ² Engin. Stress at Max. Strain | Engin. Stress at Max. Load | Time Between Fullings | Fracture or not |
|--------------------|-------------------------------|--|-------------------------------|--------------------------|--------------------|
| A ₃ IV | 360.000 | 147.000 | 216.000 | 12 days | f. |
| A ₃ V | 391.000 | 143.000 | 233.000 | 11 days | f. |
| A ₃ III | 395.000 | 202.000 | 283.000 | 12 days | f. |
| A ₂ III | 559.000 | 221.000 | 289.000 | 17 days | f. |
| A ₂ IV | 650.000 | 347.000 | 347.000 | 15 days | f. |
| A ₂ II | 430.000 | 401.000 | 419.000 | 18 days | f. |
| A ₄ III | 294.000 | 140.000 | 190.000 | 8 days | f. |
| A ₄ IV | 288.000 | 156.000 | 220.000 | 7 days | f. |
| A ₄ II | 350.000 | 197.000 | 258.000 | 8 days | f. |

Table III (Cont'd)

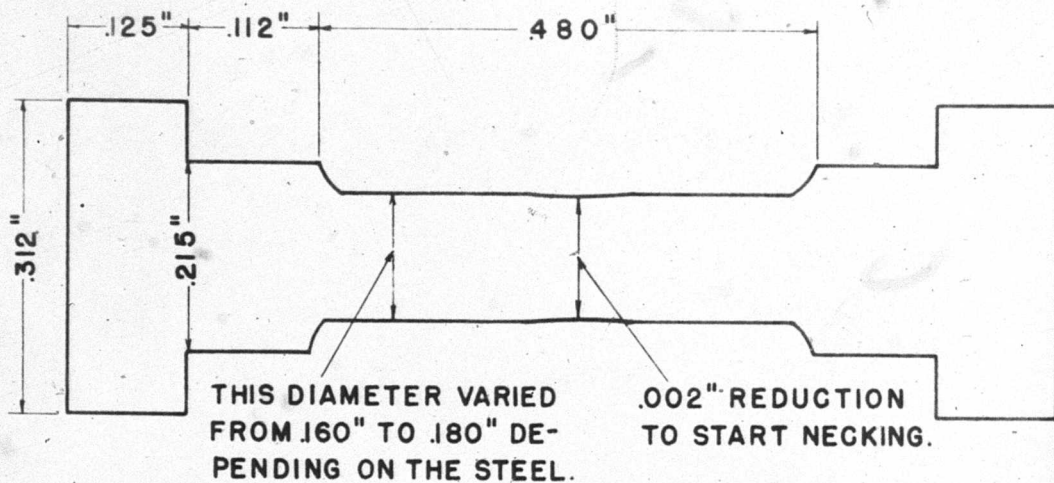
| | | | | | | |
|---------------------|-------|-------|------|-------|------|-------|
| A ¹ III | 1.24 | 0.215 | 2.45 | 0.896 | 3.04 | 1.111 |
| A ¹ V | 1.65 | 0.501 | 3.98 | 1.381 | 6.56 | 1.882 |
| A ¹ IV | 1.27 | 0.239 | 7.29 | 1.987 | 9.25 | 2.226 |
| A ¹ II | 1.008 | 0.008 | 23.8 | 3.169 | 24.0 | 3.177 |
| <hr/> | | | | | | |
| A ₁ VII | 1.79 | 0.582 | 8.15 | 2.098 | 14.6 | 2.680 |
| A ₁ VIII | 1.62 | 0.482 | 9.95 | 2.297 | 16.1 | 2.779 |
| A ₁ VI | 1.25 | 0.223 | 32.4 | 3.478 | 40.5 | 3.701 |
| <hr/> | | | | | | |
| B VI | 1.61 | 0.476 | 3.88 | 1.356 | 6.25 | 1.832 |
| B VII | 1.24 | 0.215 | 5.53 | 1.710 | 6.86 | 1.925 |
| B IX | 1.24 | 0.215 | 9.72 | 2.274 | 12.1 | 2.489 |
| B VIII | 1.00 | 0.000 | 18.2 | 2.901 | 18.2 | 2.901 |

Table IV

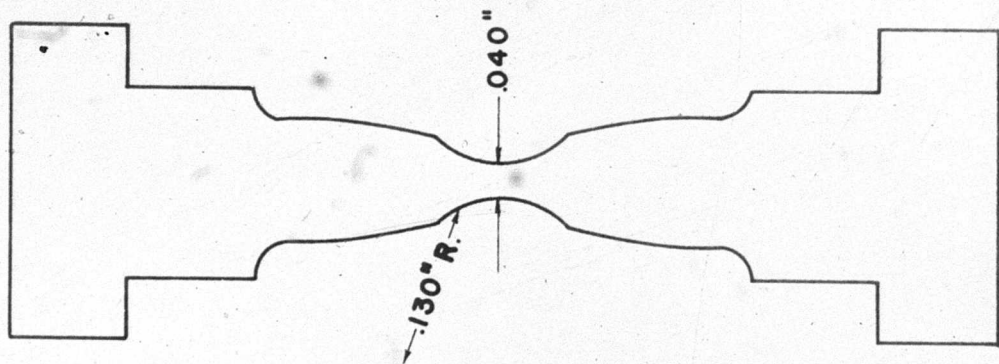
Relation between Rate of Strain Hardening and
Intercept on Stress Axis

| Series | Intercept on Stress Axis | Slope |
|----------------|-----------------------------|--------------------|
| | lb/in ² | lb/in ² |
| B | 65.000 | 75.000 |
| A ₁ | 134.000 | 94.000 |
| A ₄ | 127.000 | 97.000 |
| A ₃ | 128.000 | 110.000 |
| A ₁ | 200.000 | 133.000 |
| A ₂ | 238.000 | 129.000 |

FIGURE 1



SAMPLE FOR STRETCHING UNDER PRESSURE



PRESSURE SAMPLE ALTERED FOR PULLING AT ATMOSPHERIC PRESSURE.

DIMENSIONS OF THE TEST PIECES

FIGURE 2

STRESS-STRAIN CURVE FOR A3 SERIES
(1045 STEEL QUENCHED INTO SALT AT 800°F FROM 1575°F)

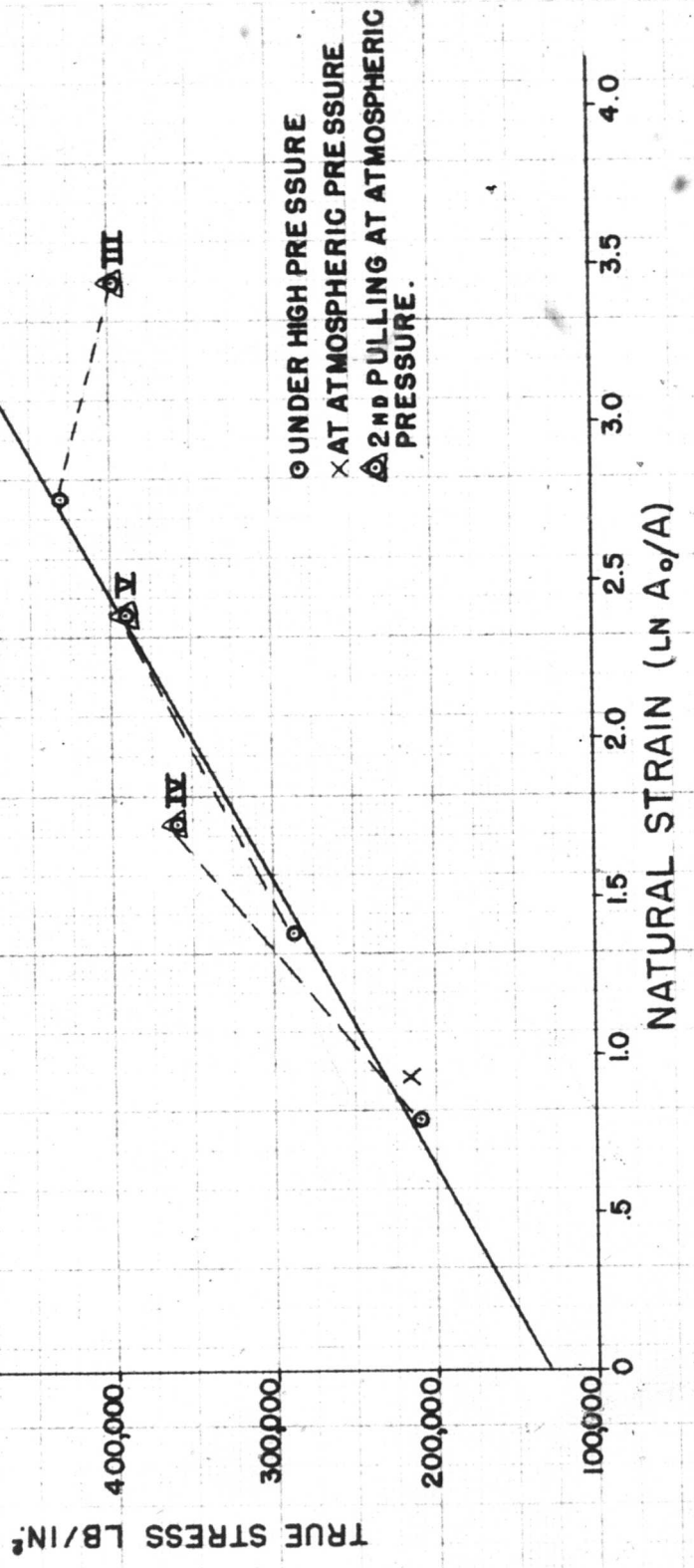
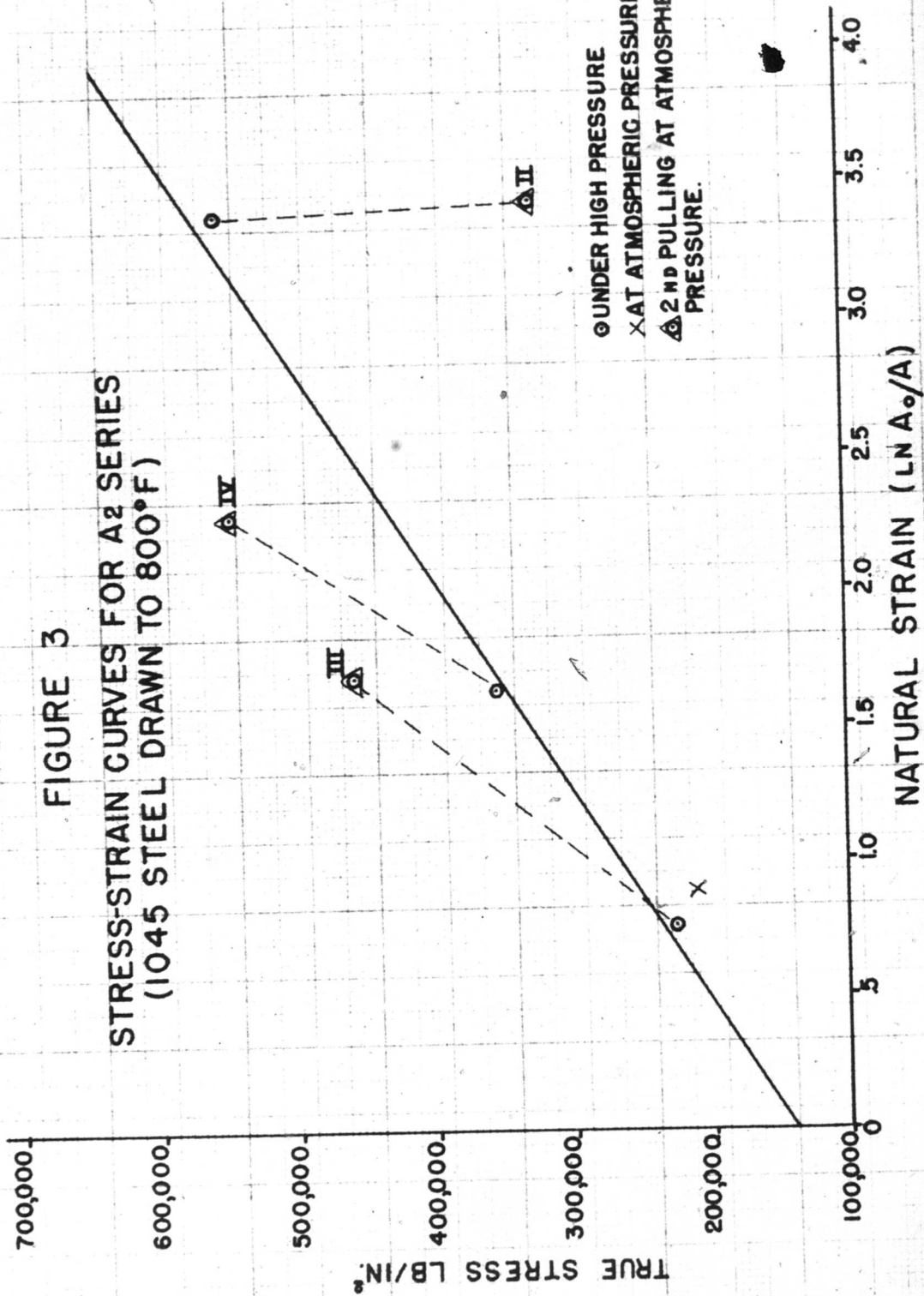


FIGURE 3

STRESS-STRAIN CURVES FOR A2 SERIES
(1045 STEEL DRAWN TO 800°F)



○ UNDER HIGH PRESSURE
× AT ATMOSPHERIC PRESSURE
△ 2ND PULLING AT ATMOSPHERIC PRESSURE.

NATURAL STRAIN (LN A₀/A)

FIGURE 4

STRESS-STRAIN CURVES FOR A4 SERIES
(1045 STEEL QUENCHED INTO SALT AT 1100°F FROM 1575°F)

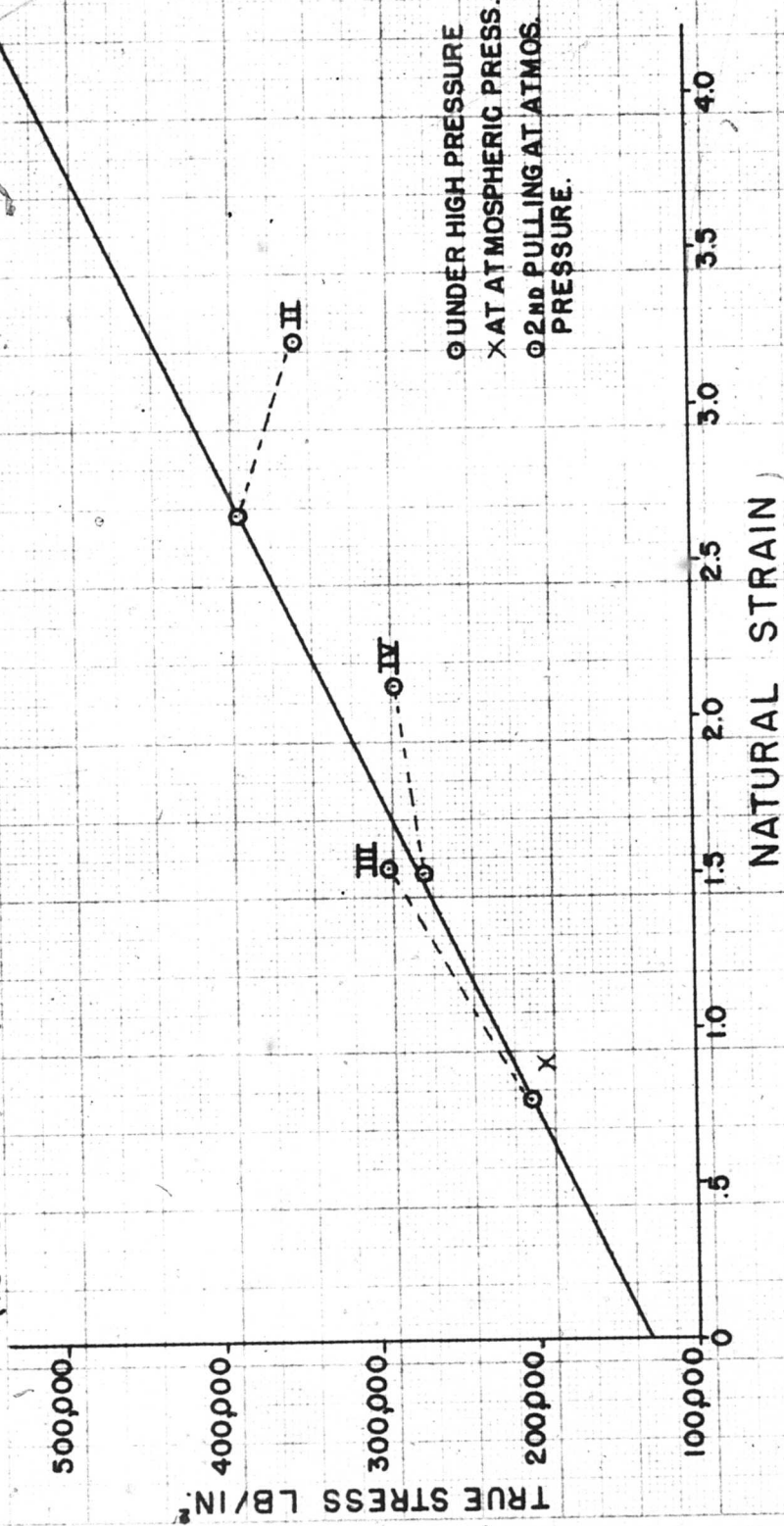


FIGURE 5

STRESS-STRAIN CURVE FOR A SERIES
(1045 STEEL DRAWN AT 400°-500°F)

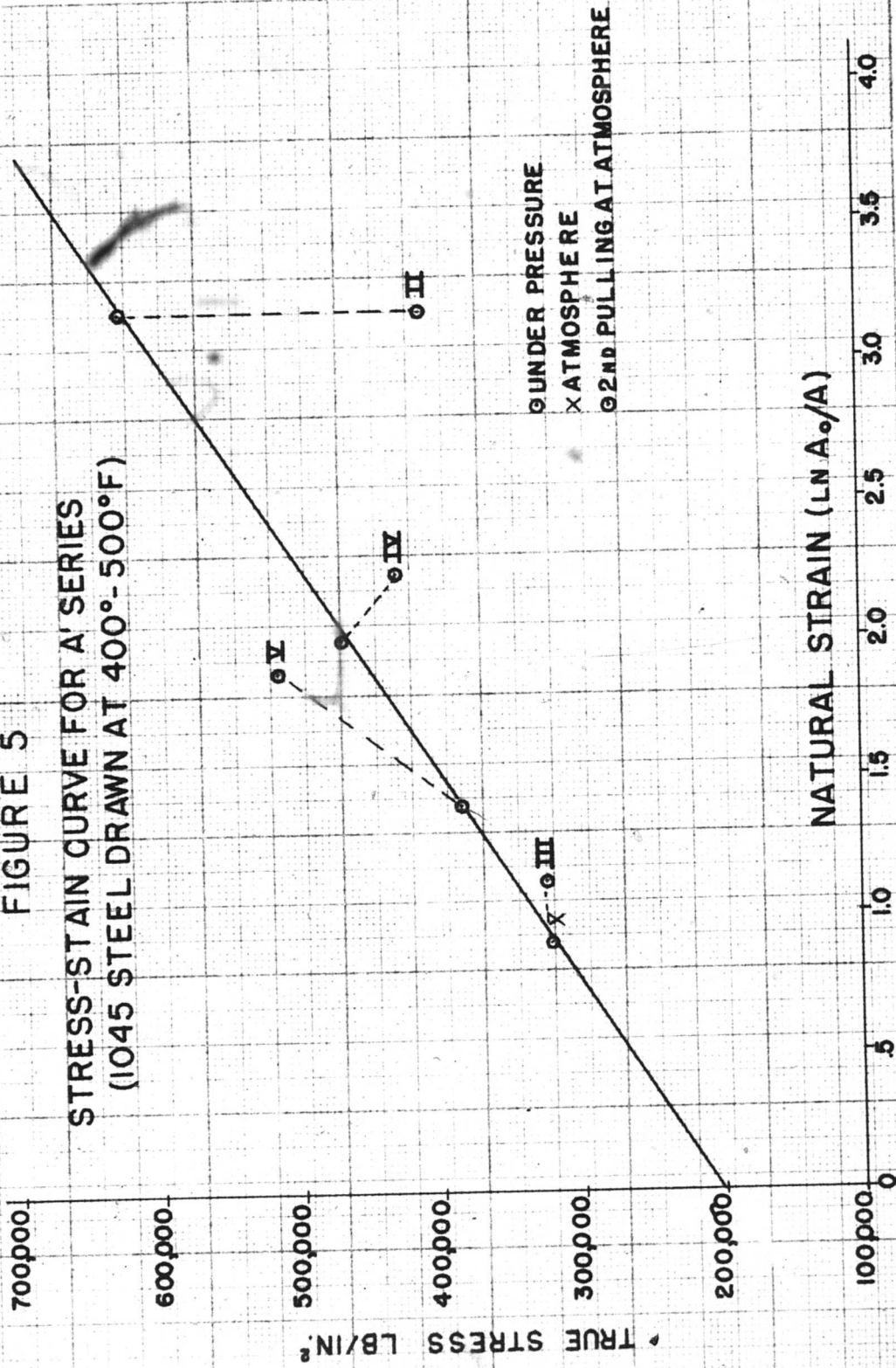


FIGURE 6
 STRESS-STRAIN CURVE FOR A1 SERIES
 (1045 STEEL AS RECEIVED)

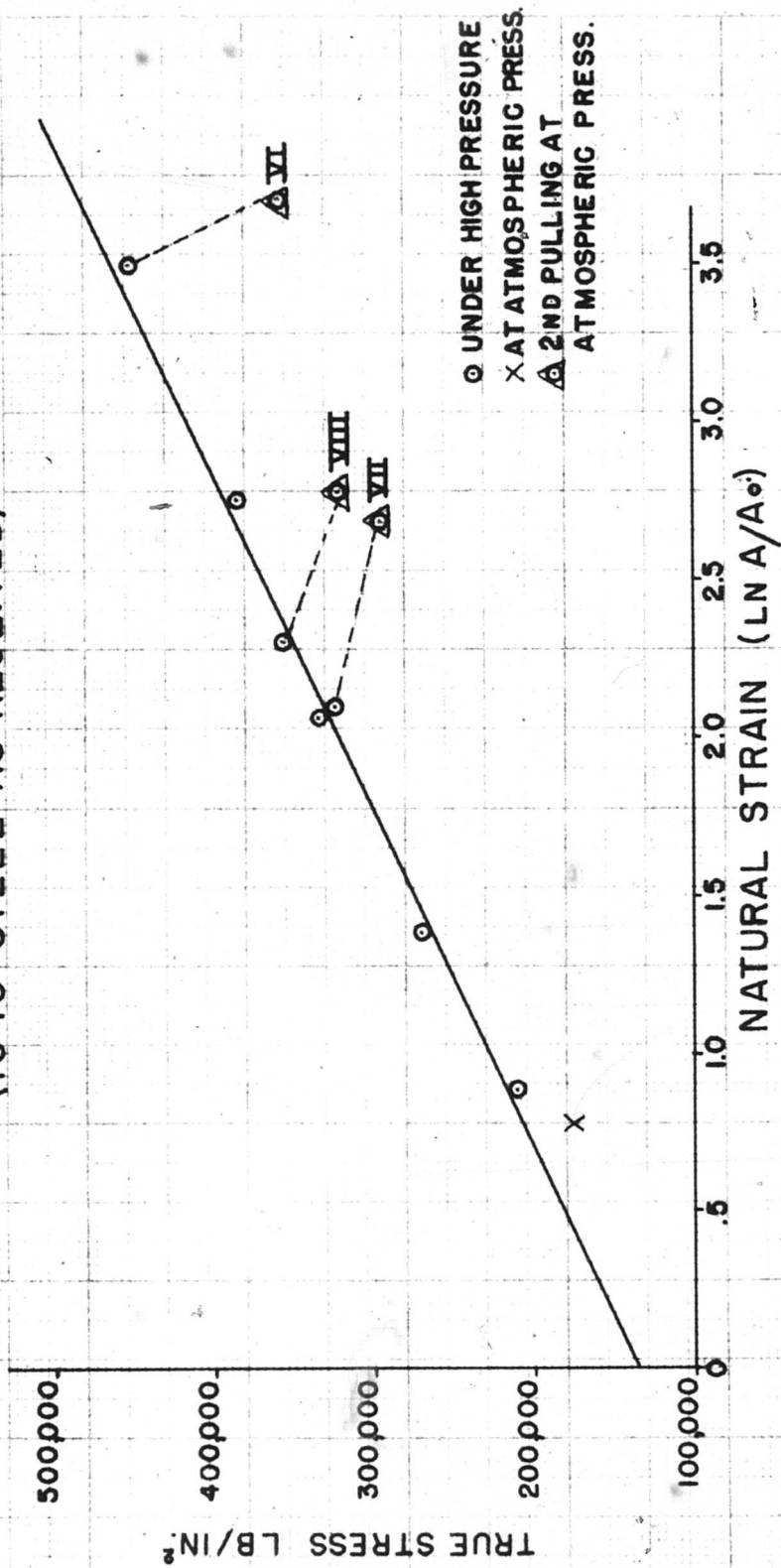
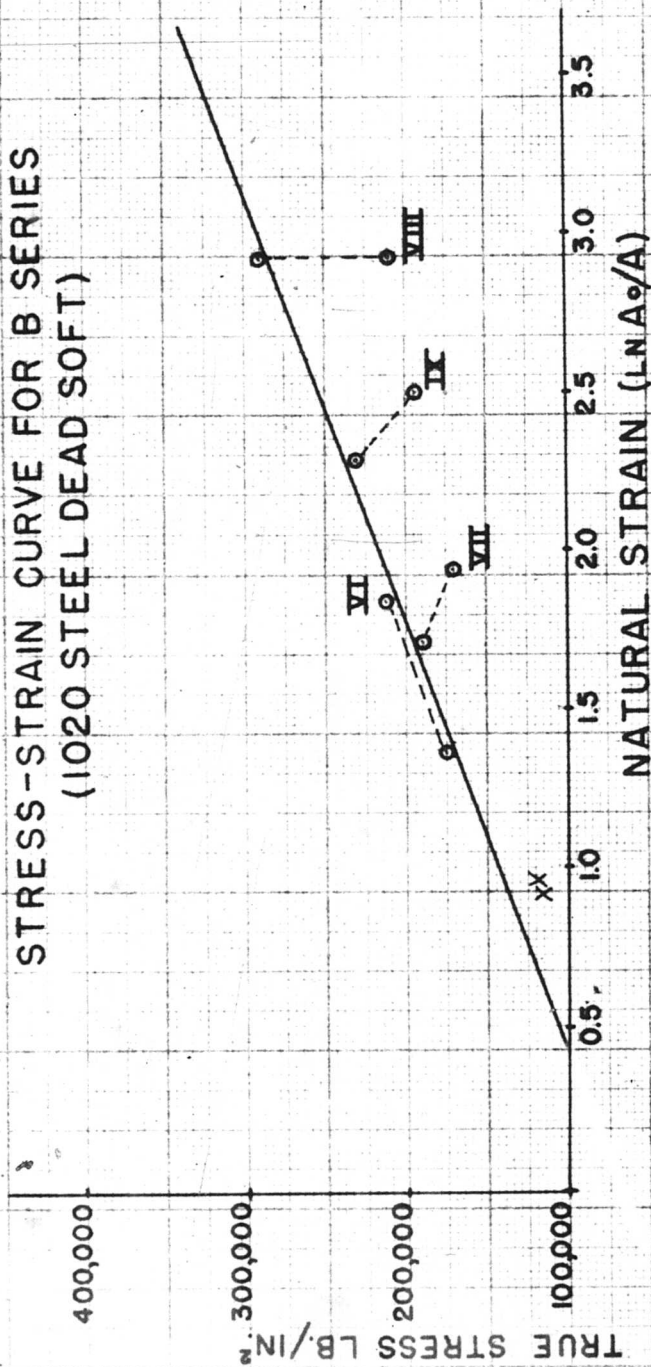


FIGURE 7

STRESS-STRAIN CURVE FOR B SERIES
(1020 STEEL DEAD SOFT)



⊙ UNDER PRESSURE
X ATMOSPHERE
⊙ 2ND PULLING AT
ATMOSPHERE.

FIGURE 8
VARIATION OF RATE OF STRAIN
HARDENING WITH INTERCEPT ON
STRESS AXIS

