

LABORATORY

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INVENTORY

NOV 27 1958



REPORT NO. 112/25

⑭ WA-112/25

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HIGH SPEED TESTING.

A Critique of the Measurements of the Stress-Strain Relation
at High Speeds,

⑫ 3φ

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by

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HIGH SPEED TESTING

A Critique of the Measurements of the Stress-Strain Relation
at High Speeds

OBJECT

To interpret the results of previous experiments on the effect of speed of testing upon the stress-strain relation.

REFERENCE

The references to this report are submitted as Appendix B.

CONCLUSIONS

1. The stress variation in a tensile specimen being tested at velocities higher than 100 fps is so great that the measured stress-strain curve, or any quantities derived therefrom, have little or no significance. (Fig. 1)
2. Valuable information regarding the relation between stress and strain at high rates of deformation may be obtained by extrapolating the results obtained from lower rates by standard testing machines. (Fig. 6)
3. In all materials the strain-hardening curve rises with increasing rates of deformation. (Fig. 2)
4. In many steels, perhaps in all, the yield stress is equal to the tensile stress at rates of strain applicable to ordnance problems. (Fig. 6)
6. The equality of the yield and tensile strength at high rates of deformation is responsible for the shear type of failure peculiar to high rates of strain.
7. The upper yield point is so sensitive to the surface finish, the shape

of the specimen, and its eccentricity in loading, that its measurement gives little indication as to how the material will behave under service conditions.

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"The off-chance that a future generation may discover a significance
in our utterances is scarcely an excuse for making meaningless noises."

--Eddington

INTRODUCTION

Ordnance materiel is subjected often in service to impulsive loads. The response of the material may be more readily calculated, the more is known regarding the relation between stress and strain at high rates of deformation. Such calculations will permit a more judicious choice of material for any particular ordnance application.

In certain of these applications, it is only necessary that the material have a sufficiently high yield strength. In other cases the shape of the stress-strain curve is of paramount importance, for it determines the speed of propagation of the elastic or plastic deformation. Lacking this basic information upon the stress-strain relations at high rate of deformation, the Ordnance Department has based acceptance specifications, either upon the quasi-static properties obtained by the usual testing machines, or upon performance tests. The first procedure may lead to a poor selection of material for service conditions, while the second procedure is costly. Since, during armor penetration, the rate of deformation is extremely high, the quasi-static properties are of little significance. In order to understand the mechanism by which armor penetration occurs, it is of primary importance to determine the effect of speed upon the stress-strain relations of the material used for armor.

As if in response to the needs of the Ordnance Department, several laboratories have recently undertaken high speed testing. In their pre-occupation with the experimental difficulties of such testing, these laboratories have neglected to analyze carefully the theory of their experiments. In this paper a theoretical analysis of the tensile test at high speeds is presented. This analysis indicates that measurements made at high speeds (above 100fps) cannot give load-elongation curves nor any

quantities derivable therefrom, such as energy of rupture. Useful information relative to high rates of deformation can be obtained, however, with the usual types of testing machines by extrapolating the results to higher rates of strain. An examination was made of the literature on the effect of speed in this lower range, and the results are presented in this report.

DISCUSSION

a. Theoretical Analysis of High Speed Tensile Tests

In the quasi-static tension test, one measures the force applied to the specimen as a function of the elongation. This force divided by the original cross-sectional area is called, incorrectly, "stress." In the dynamic tensile test one attempts to measure these same quantities. Often the vibrations of the apparatus and the specimen are of such magnitude that a precise determination of the force is not possible.¹ The presence of this error is readily observable, however, for the vibrations are recorded by the stress-measuring device. There is another source of error, the presence of which is not obvious to the experimenter. Two forces are actually applied to the specimen; one at the moving end and another at the stationary end. The difference in these forces is equal to the force necessary to accelerate the mass of the material between the two ends, and will be present as long as one end of the bar is accelerated. Since this difference in force exists, the "stress" is not uniform along the specimen. If this difference is of the same order of magnitude as the load applied, the lack of uniformity of the "stress" over the gage length is so great that the measurement of the stress at either end has little or no significance.

The analysis of the stress difference at the two ends is given in

Appendix A. Fig. 1 illustrates this stress difference in the particular case where the velocity of the head of the machine increases linearly with time, until a strain of 0.1 is reached. If the final velocity is reached at a smaller strain, the stress difference will of course be greater. The results indicate that in testing steels at velocities greater than 100 fps, the error introduced in this manner may be a large percentage of the measured "stress."

The rate of strain may be increased by decreasing the gauge length as well as by increasing the speed of testing. Decreasing the gauge length, however, increases the possibility of stress concentrations, increases the uncertainty of the extrapolation to larger sizes, and increases the experimental difficulties. In order to obtain results applicable to material deformed at high speeds, it is advisable and perhaps necessary to extrapolate from lower strain rates.

b. Interpretation of the Literature

In one respect all metals react similarly to an increase in testing speed; the stress-strain curve in the plastic region is raised as the speed is increased and the magnitude of the rise increases with increasing stress.² (Fig. 2) Iron and steels, which exhibit a drop in load at the yield point, behave in a characteristic manner. The yield point (lower) increases with increasing rate of strain faster than the tensile strength.³⁻¹¹ This behavior is illustrated by data obtained by Winlock and Leiter³ and presented in Fig. 3. The data presented in this figure were obtained from a steel containing .05% carbon, annealed, and having a grain count of 90 per square inch at 100 magnification. (A. S. T. M. No. 7)

The lower yield point is used as the criterion for the beginning of plastic deformation, rather than the upper yield point, since the latter is dependent upon the surface condition, and shape of the specimen, and upon any slight eccentricity in loading. The lower yield point appears to be

characteristic of the metal itself. Experiments have been performed in which the upper yield point was raised as high as, or higher than, the tensile strength, even in quasi-static tests. The effect of speed on materials with upper and lower yield is presented schematically in Fig. 4. The stress-strain relation for such materials can be considered as made up of two curves essentially independent of rate of strain joined by horizontal lines. The first part of the total stress-strain curve is elastic; in the second part, inhomogeneous deformation occurs; and in the third part, the material undergoes homogeneous deformation accompanied by work hardening and sensible reduction of area. In this figure the slight effect of speed beyond the lower yield point is neglected. As the speed is increased, the horizontal portion of the stress-strain curve rises, and the amount of strain at this lower yield point increases.

During the second part of the deformation, the strain occurs by the formation and spreading of Lüder bands. In each Lüder band the strain is equal to the yield point elongation. Only after all of the specimen has been traversed by Lüder bands does it deform homogeneously. From Fig. 4 it appears that a critical strain ^{ϵ_{cr}} exists, above which the specimen will fail by shear along the first and only Lüder band formed, and homogeneous deformation will not occur. The usefulness of the schematic diagram in Fig. 4 for tension suggests that a similar one be constructed for pure shear. Such a diagram is presented as Fig. 5. This diagram illustrates the approximate behavior in shear of the same steel to which Fig. 4 pertains. Since in pure shear, the static stress-strain curve does not pass through a maximum as does the force-elongation curve for tension, a critical rate of shear beyond which all deformation is confined to a single band does not necessarily exist. The yield point elongation, and hence the elongation associated with each Lüder band, increase rapidly with increasing rate of strain. When, however, this yield point elongation is so

large that the temperature rise of the material in the band is several hundred degrees centigrade, the "static" stress-strain curve will be lowered. In this case the deformation to fracture may likewise be confined to a narrow band.

An indirect substantiation of this conclusion may be found in the work of Itihara.¹⁴ He found that by raising the rate of strain, by a factor of 4×10^4 over that in the quasi-static tests, the yield point was doubled, while the maximum stress remained essentially unchanged. The details of the stress-strain curve were obscured, however, by vibrations. The curves in Figs. 3, 4, and 5 refer specifically to a single type of steel tested by Winlock and Leiter.³ The general features of these curves will apply to any steel with a lower yield point. In particular the lower yield stress approaches the tensile strength at high rates of deformation. In an attempt to find those factors which influence the rise of the lower yield point with rate of strain an extensive search was made in the literature of the effect of speed on the tensile test. Most of the investigators recorded only the upper yield point. Fig. 6 shows all the data in which the lower yield strengths, as well as the tensile strengths, were reported as a function of the rate of strain.

In all cases the ratio (lower yield stress/tensile strength) approaches an asymptote at low rates of strain, and varies nearly logarithmically at higher rates of strain. The ratio is dependent upon the carbon content, decreasing as the carbon content increases. For a given carbon content the ratio is larger, the smaller the grain size. The absolute magnitude of the ratio as well as its dependence upon rate of strain should be dependent upon the microstructure, as well as upon carbon content, but a detailed study of the effect of these variables is lacking. The values of this ratio obtained from the tensile impact machine are consistent with the extrapolation of the data obtained from the standard testing machines. 9, 10

Although the unit of rate of strain used in Fig. 6, namely sec^{-1} is the most logical unit, it is one for which few have any physical grasp. In order to give the rates more concrete expression, an interpretation of these units is presented along the top margin in terms of the rate at which the head of a one-inch gauge length specimen must move to produce the appropriate rate of strain.

c. Application to Ordnance Materiel

The relevance of high speed tests to ordnance problems can best be seen by indicating in Fig. 6 the range of strain rate associated with each type of test, together with the range of strain rate associated with each type of ordnance problem. The order of magnitude of the rate of strain at which the material of the breech of a gun is deformed during firing is obtained by dividing the maximum elastic strain of about .002 by the time interval of .001 secs. This rate of strain lies considerably below that in impact testing, considerably above that obtained in standard tests, and is the middle of the range of strain rates at which the lower yield stress becomes equal to the tensile strength.

The raising of the lower yield stress at high rates of strain may have important implications. The yield strength at these high rates of strain may best be determined by measuring the tensile strength at the rate of strain obtained by the usual testing methods. In particular, if the material in a gun barrel behaves as the material in Fig. 3, the yield stress under firing conditions is at least as large as the tensile strength as measured in standard machines.

The order of magnitude of the rate of strain of an armor plate during penetration is given by the reciprocal of the time required for a projectile to traverse the distance of one calibre. This rate varies from a minimum of about 10^3 for 12"-projectiles to a maximum of about 10^5 for calibre .30 bullets. The lower end of this range envelops the strain rates obtained in plugging experiments with velocities in the neighborhood of 10 fps. This

overlapping suggests the relevance of observations upon plugging to the problem of armor penetration. A report upon this subject is being prepared. An extrapolation of the curves in Fig. 6 to the rate of strain pertinent to armor penetration suggests that steels with as much as .58% carbon and of varying microstructure will behave quite differently from low carbon steels. It is possible that the yield strength in .58% carbon steels will be below the tensile strength, while in .20% carbon steels the stress-strain curve will be flat for high strain rates.

The existence of such large yield point strains in shear is of particular significance in armor penetration. In certain types of penetration the projectile pushes out a plug. The deformation of the plate is confined to the immediate vicinity of the nearly cylindrical surface of the plug. In this region the plate becomes very hot, certainly above the transformation temperature of the steel. This concentration of strain lowers the ability of the plate to resist penetration. Since the increase of the yield to tensile ratio with rate of strain is affected by carbon content and microstructure, the resistance to plugging by different steels may be varied over a wide range.

APPENDIX A

In this appendix the calculation is carried out for the difference in stress at the two ends of a tensile specimen during a high speed test.

The difference between the forces acting at the two ends is equal to the sum of the products of all the elements of mass in the gauge length and their respective accelerations.

$$\Delta f = \sum \delta m_k a_k \quad (1)$$

During the entire test the right member of Eq. (1) is given very nearly by the relation

$$\sum \delta m_k a_k = \frac{1}{2} \rho A \ell a \quad (2)$$

where ρ , A and ℓ refer to the original density, cross-sectional area, and gauge length, respectively, and where a refers to the accelerations of the moving end. Thus, before necking, the acceleration varies linearly along the specimen from 0 to a . Here the mean acceleration is $\frac{1}{2}a$.

After the onset of necking, half the specimen has practically no acceleration, the other half has nearly the acceleration a . Again the mean acceleration is given nearly by $\frac{1}{2}a$.

After substituting Eq. (2) into Eq. (1), and dividing the resulting equation by A , one obtains for the stress difference

$$\Delta S = \frac{1}{2} \rho \ell a \quad (3)$$

If it is assumed that the moving end of the specimen has acquired the velocity v by the time the specimen has elongated a distance $\Delta \ell$, then the maximum value of ΔS during this elongation will be a minimum if it is a constant. This constant is given in terms of v and by the equation.

$$a = v^2 / 2 \Delta \ell \quad (4)$$

The substitution of the relation into Eq. (3) gives the final equation

$$\Delta S = 1/4 (\rho / \Delta \ell) v^2 \quad (5)$$

In the above equation, all quantities must, of course, be expressed in a consistent set of units. The corresponding equation for iron or steel in which S is expressed in units of psi, and v in units of ft/sec,

$$\Delta S = 0.027 (\lambda / \Delta \lambda) v^2 \text{ in psi} \quad (6)$$

This equation is plotted in Fig. 1 for the typical case of $\lambda = 0.1$.

APPENDIX B

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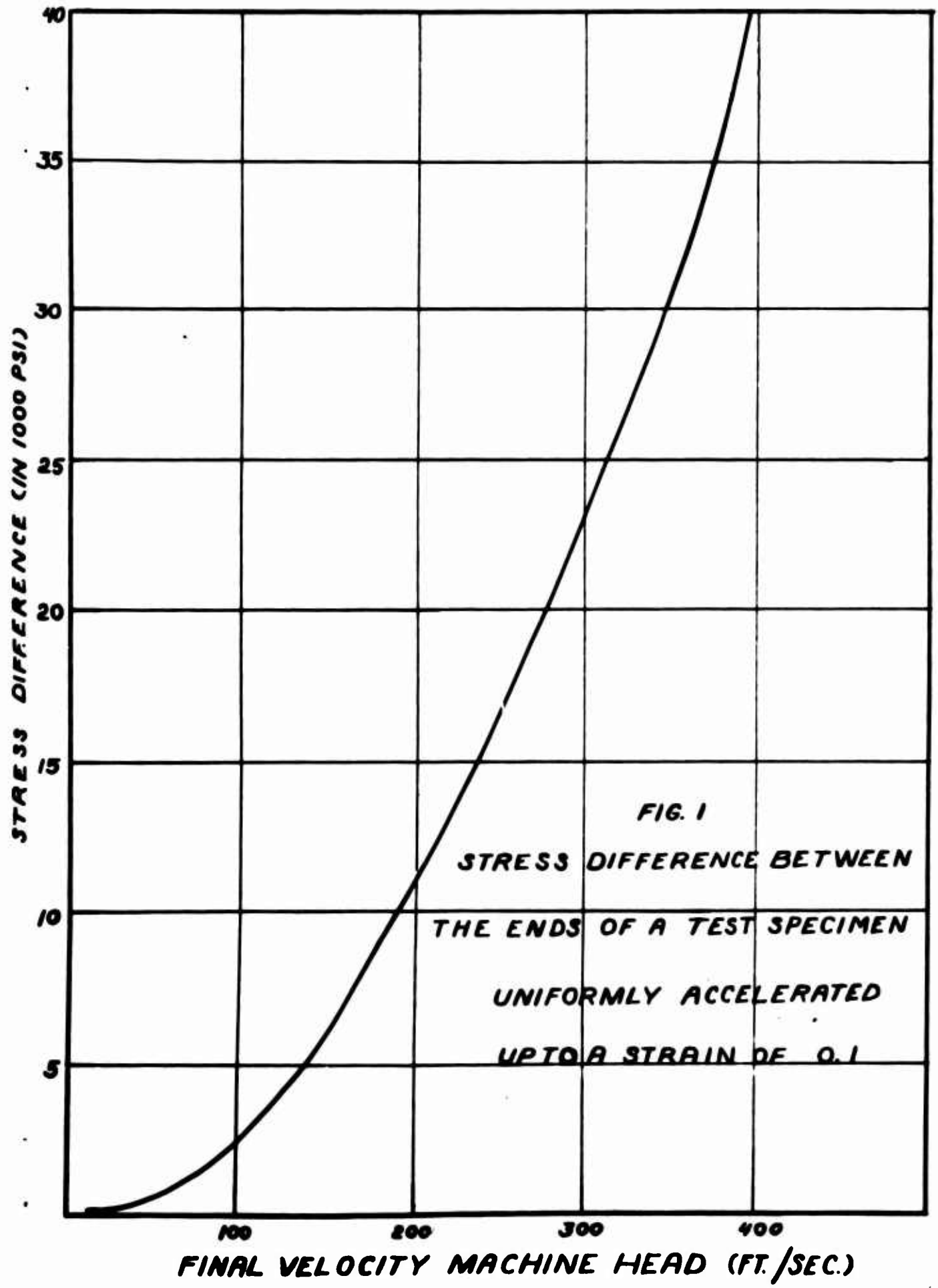
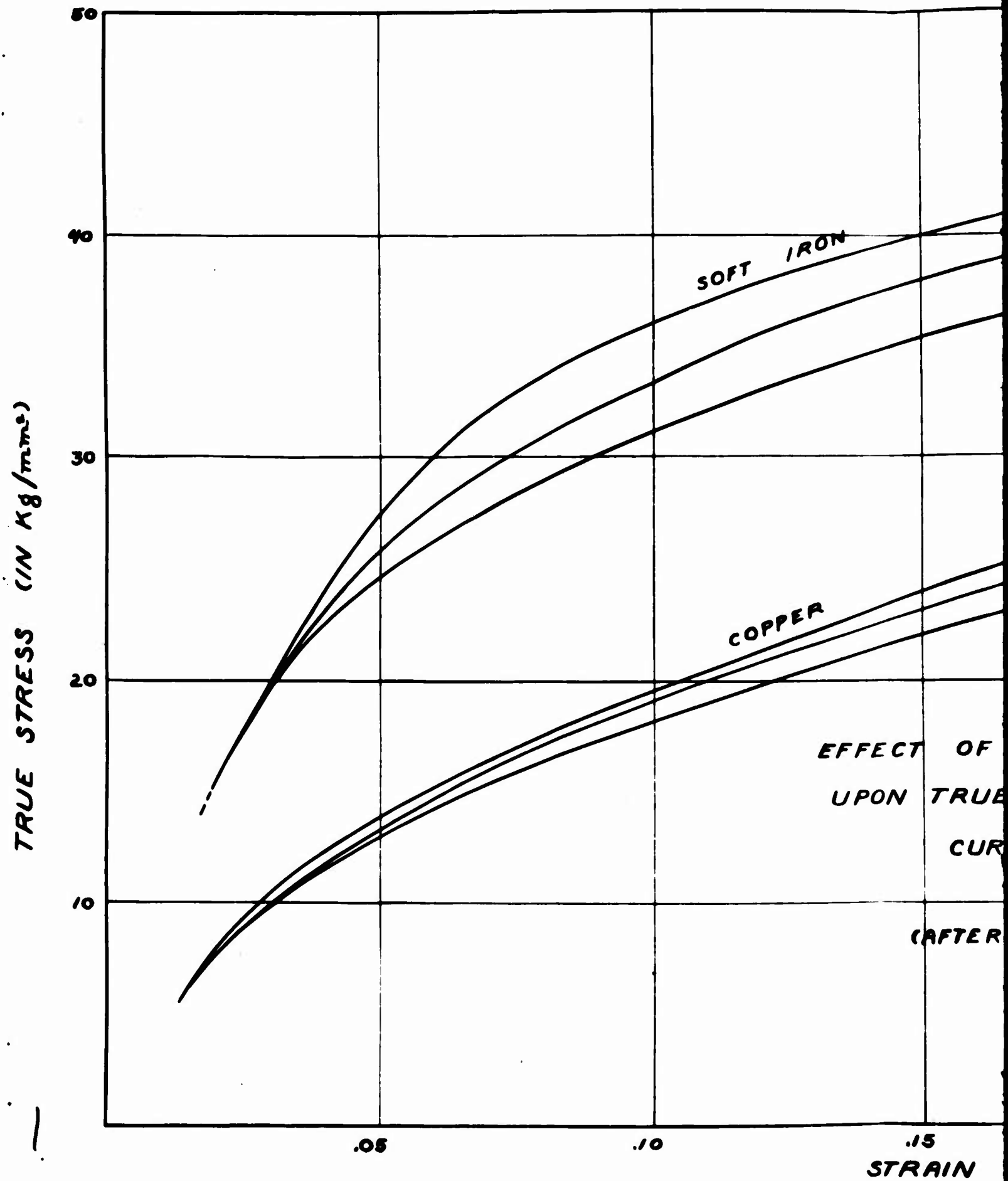


FIG. 1
STRESS DIFFERENCE BETWEEN
THE ENDS OF A TEST SPECIMEN
UNIFORMLY ACCELERATED
UPTO A STRAIN OF 0.1



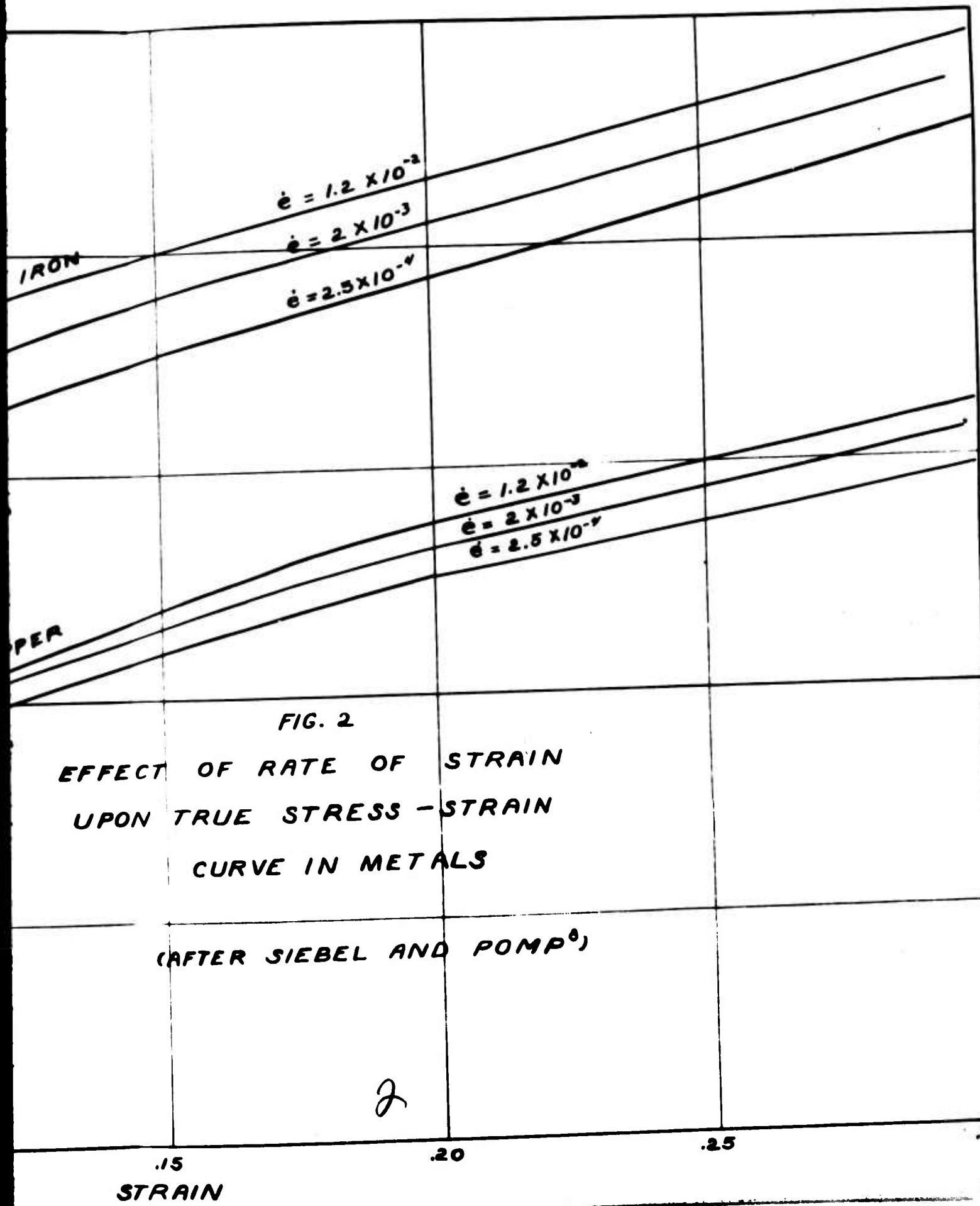
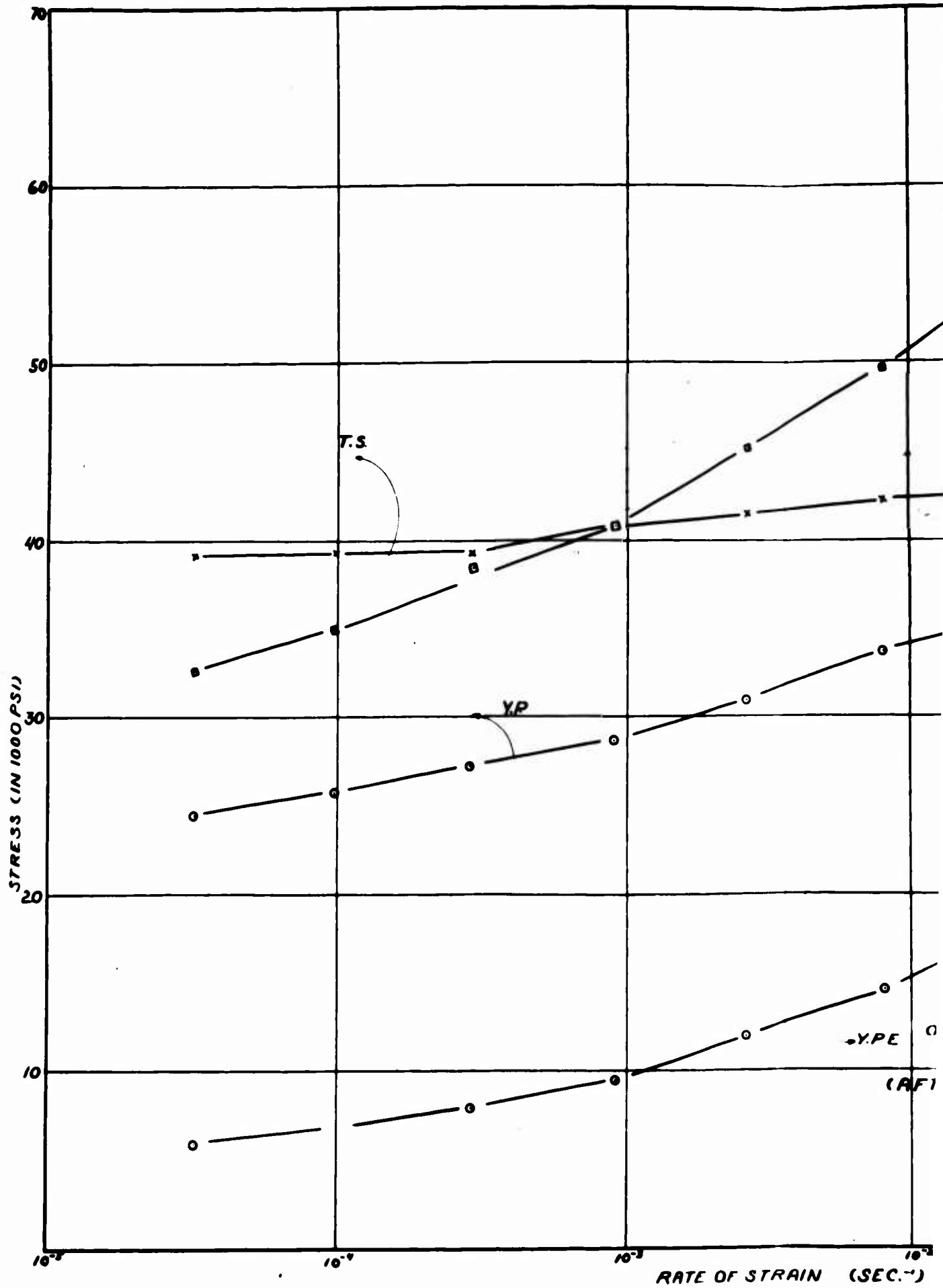


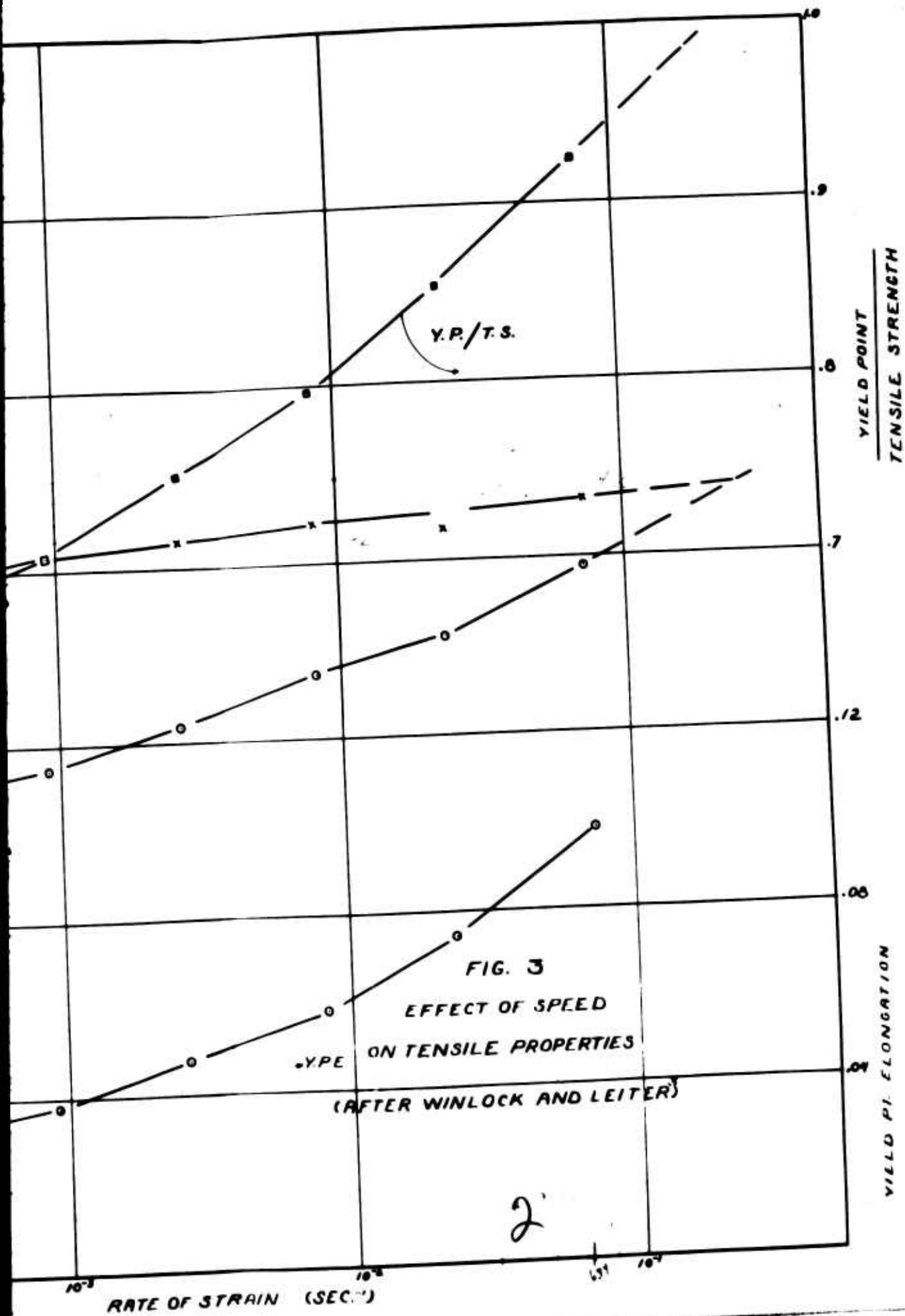
FIG. 2

EFFECT OF RATE OF STRAIN
UPON TRUE STRESS - STRAIN
CURVE IN METALS

(AFTER SIEBEL AND POMP⁶)

2





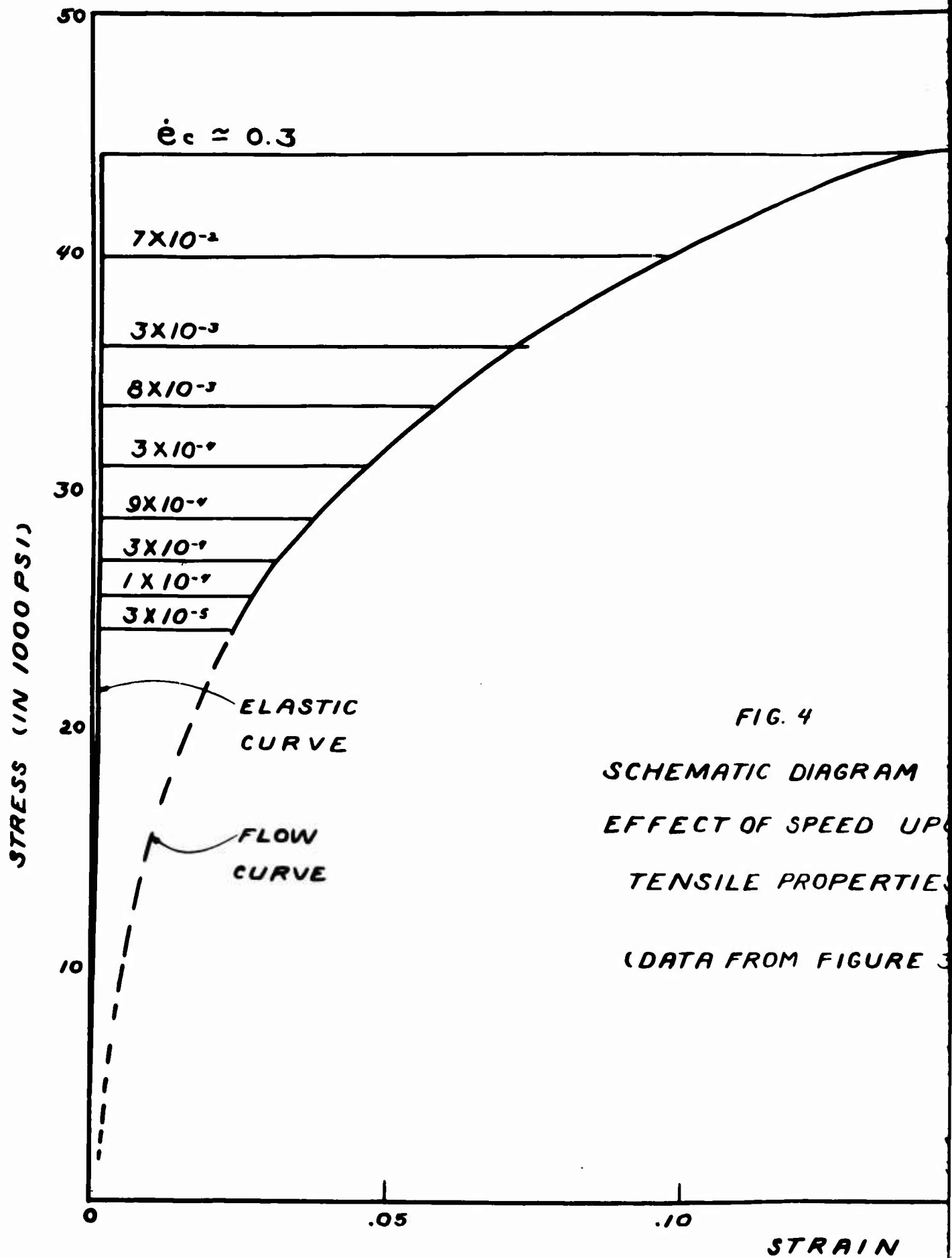


FIG. 4
 SCHEMATIC DIAGRAM
 EFFECT OF SPEED UP
 TENSILE PROPERTIES
 (DATA FROM FIGURE 3)

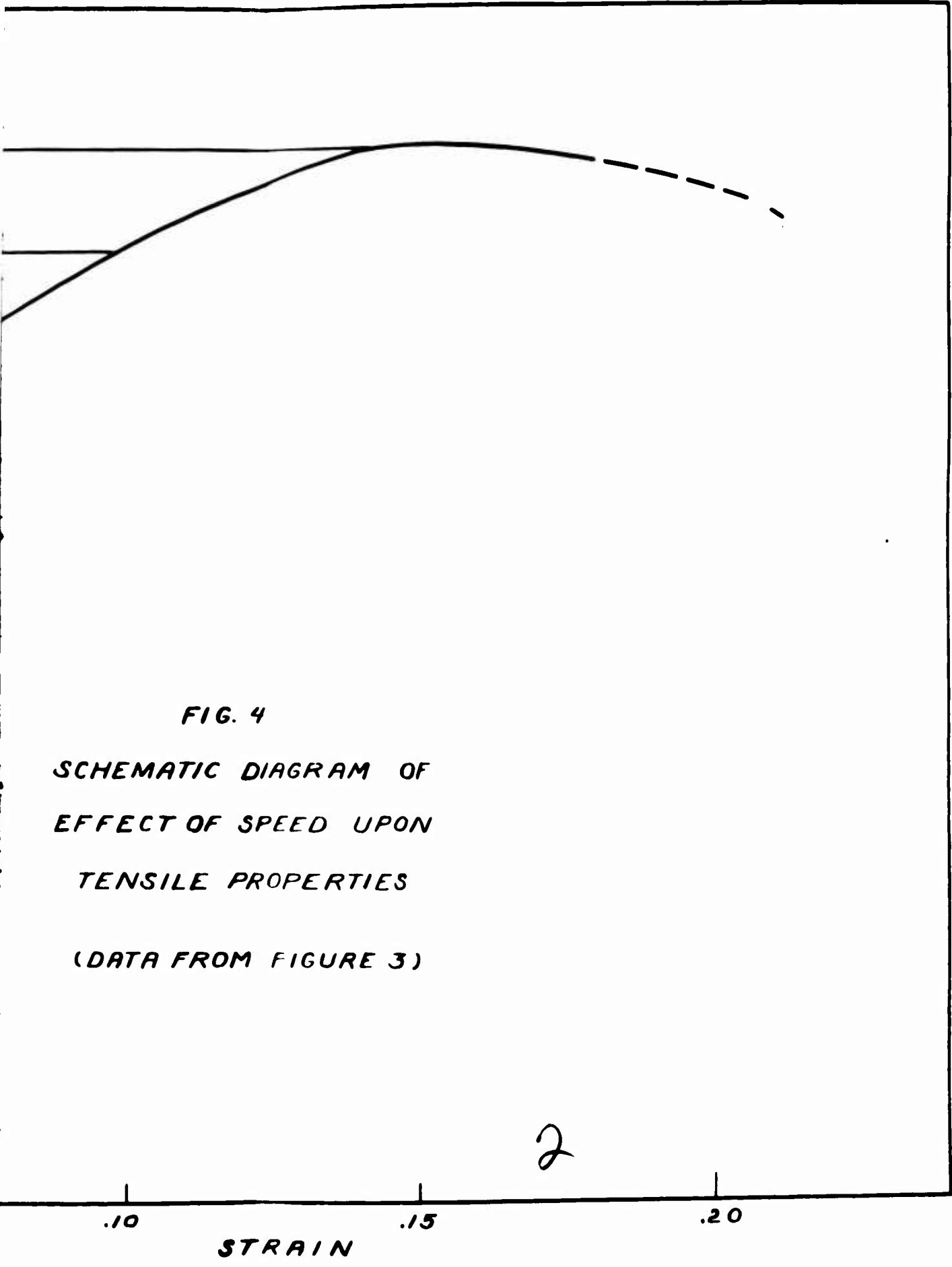


FIG. 4

**SCHEMATIC DIAGRAM OF
EFFECT OF SPEED UPON
TENSILE PROPERTIES**

(DATA FROM FIGURE 3)

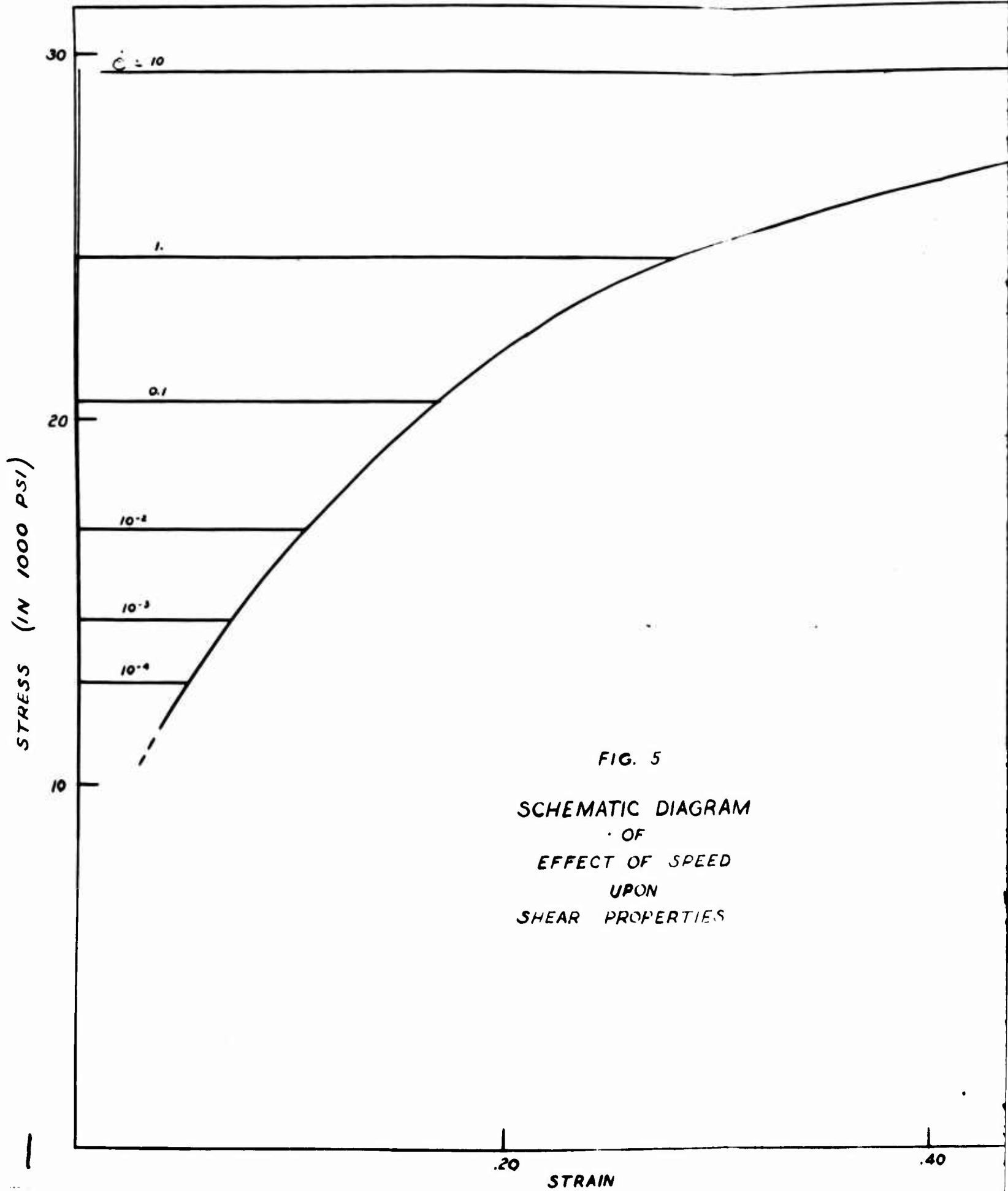
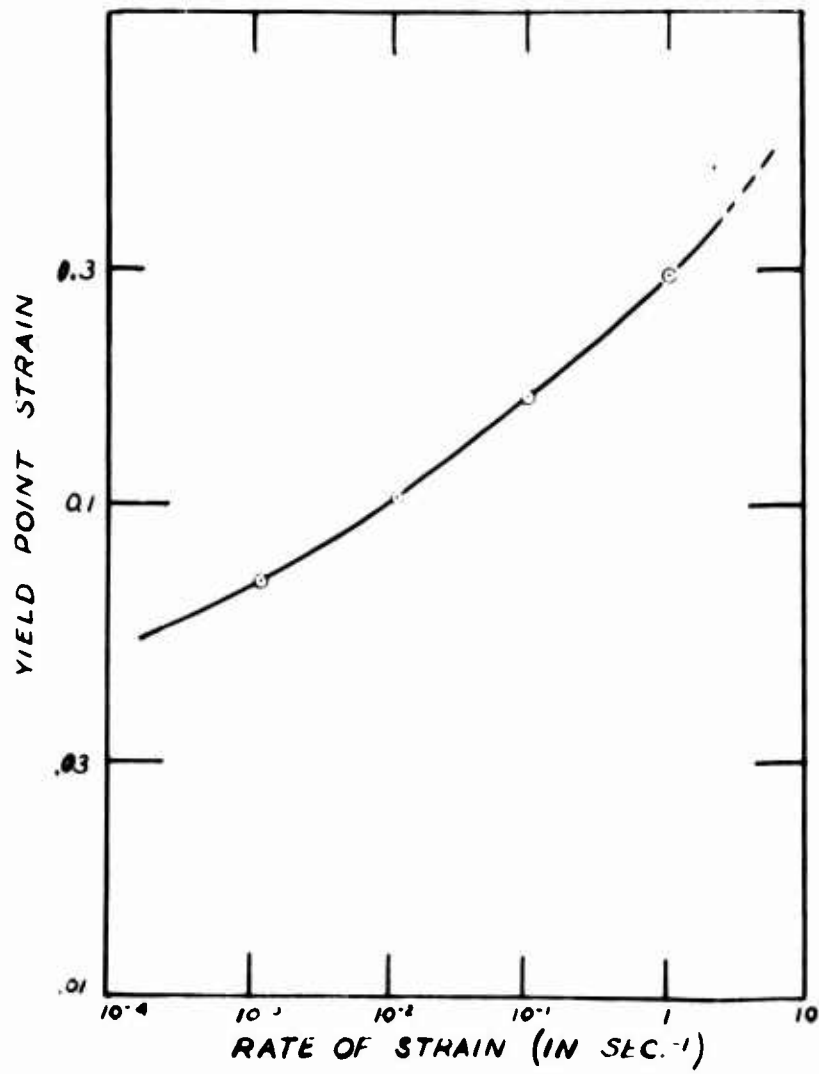


FIG. 5
 SCHEMATIC DIAGRAM
 OF
 EFFECT OF SPEED
 UPON
 SHEAR PROPERTIES



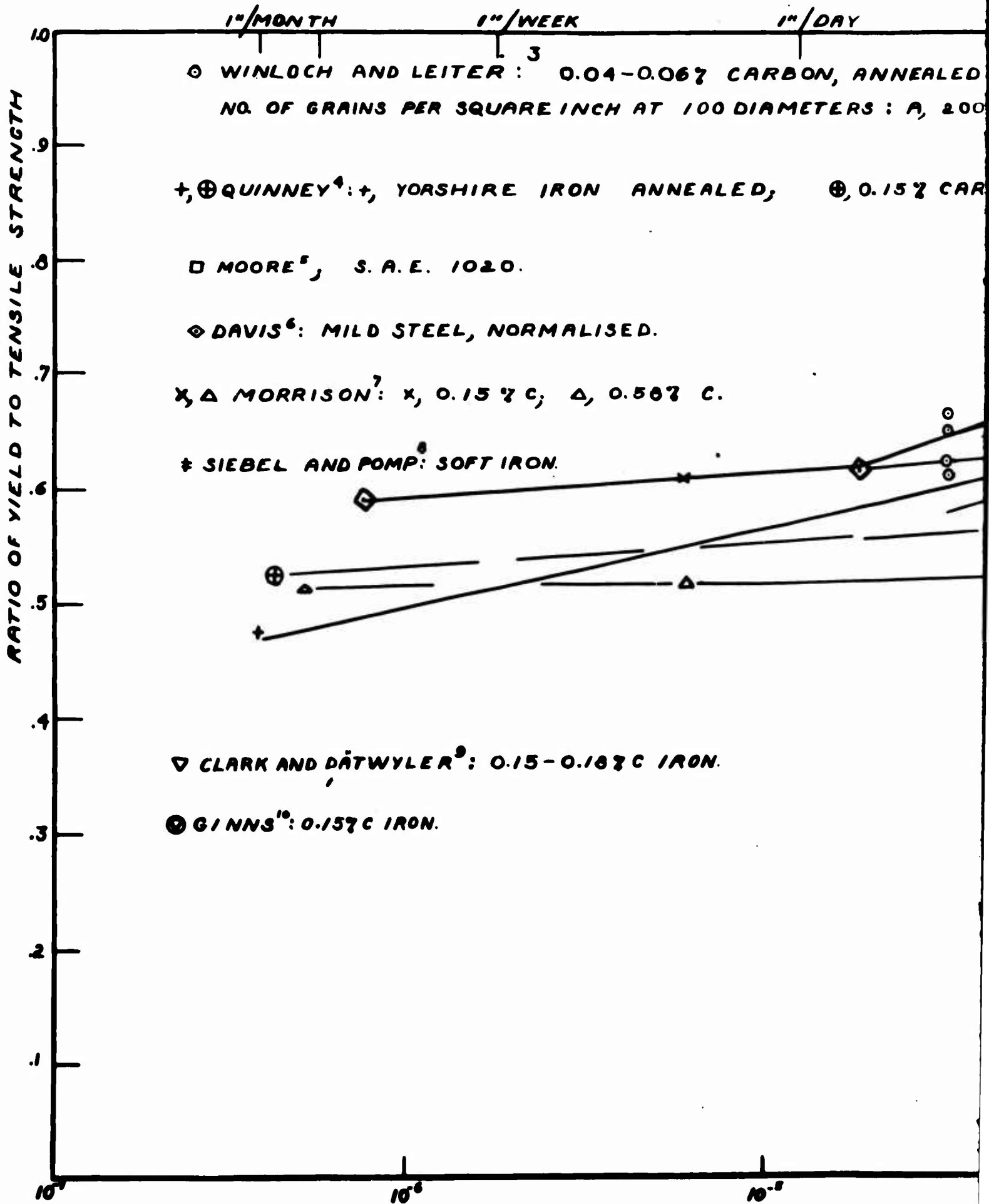
2



3

.50

1.0

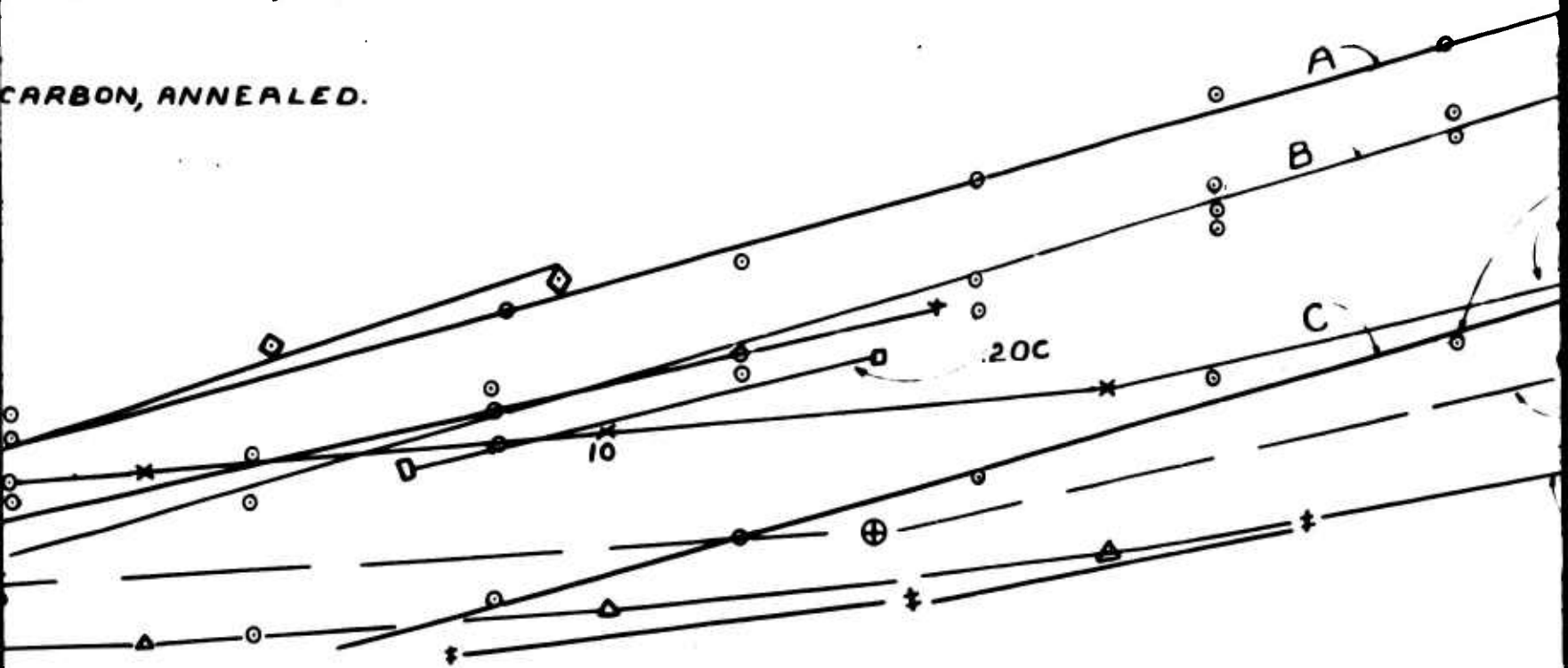


1" / HOUR

1" / MIN.

LED.
200, B, 84-107, C, 20.

CARBON, ANNEALED.



STANDARD TENSILE MACHINES

2

10^{-3}

10^{-2}

10^{-1}

SPEED OF HEAD FOR ONE INCH GUA

1"/SEC.

1"/SEC.

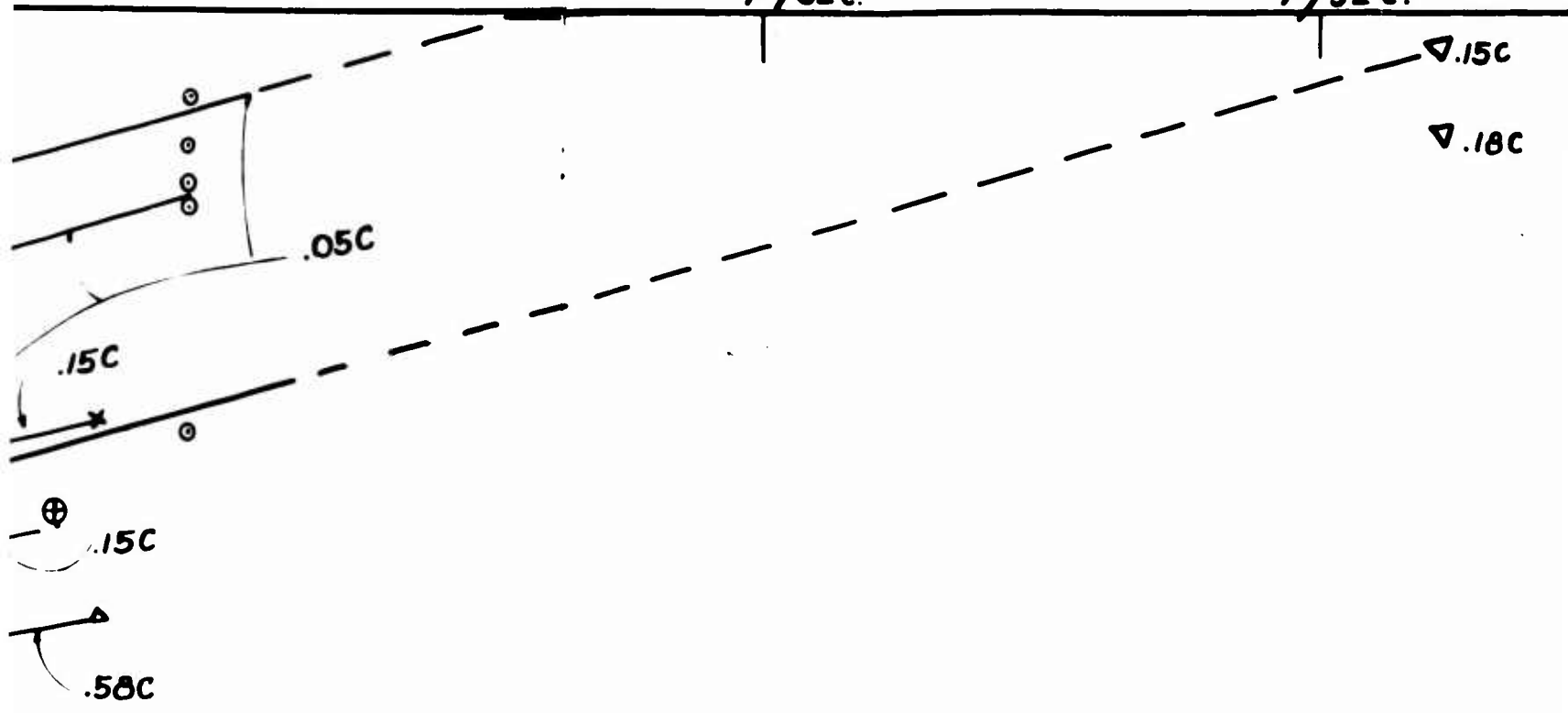


FIGURE 6

EFFECT OF SPEED
ON
RELATION BETWEEN
YIELD POINT
AND
TENSILE STRENGTH

3

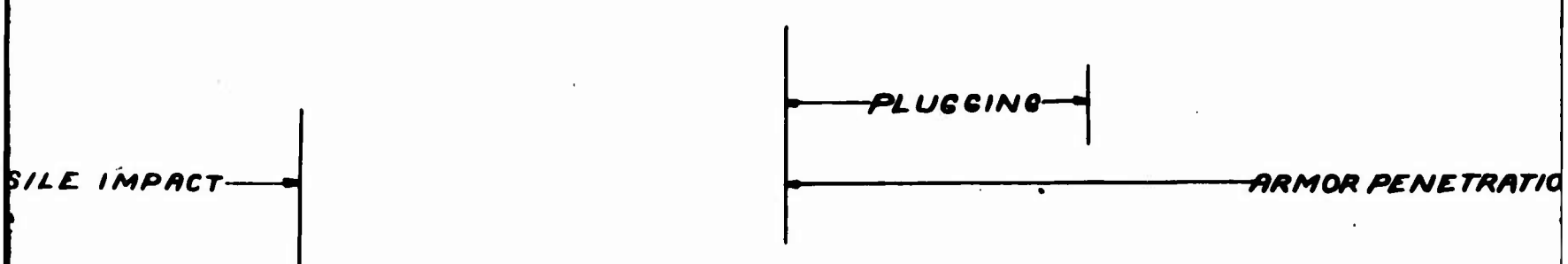
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1 10
RATE OF STRAIN (SEC.-1)

UARGE LENGTH

10'/SEC. 100'/SEC. 1000'/SEC.

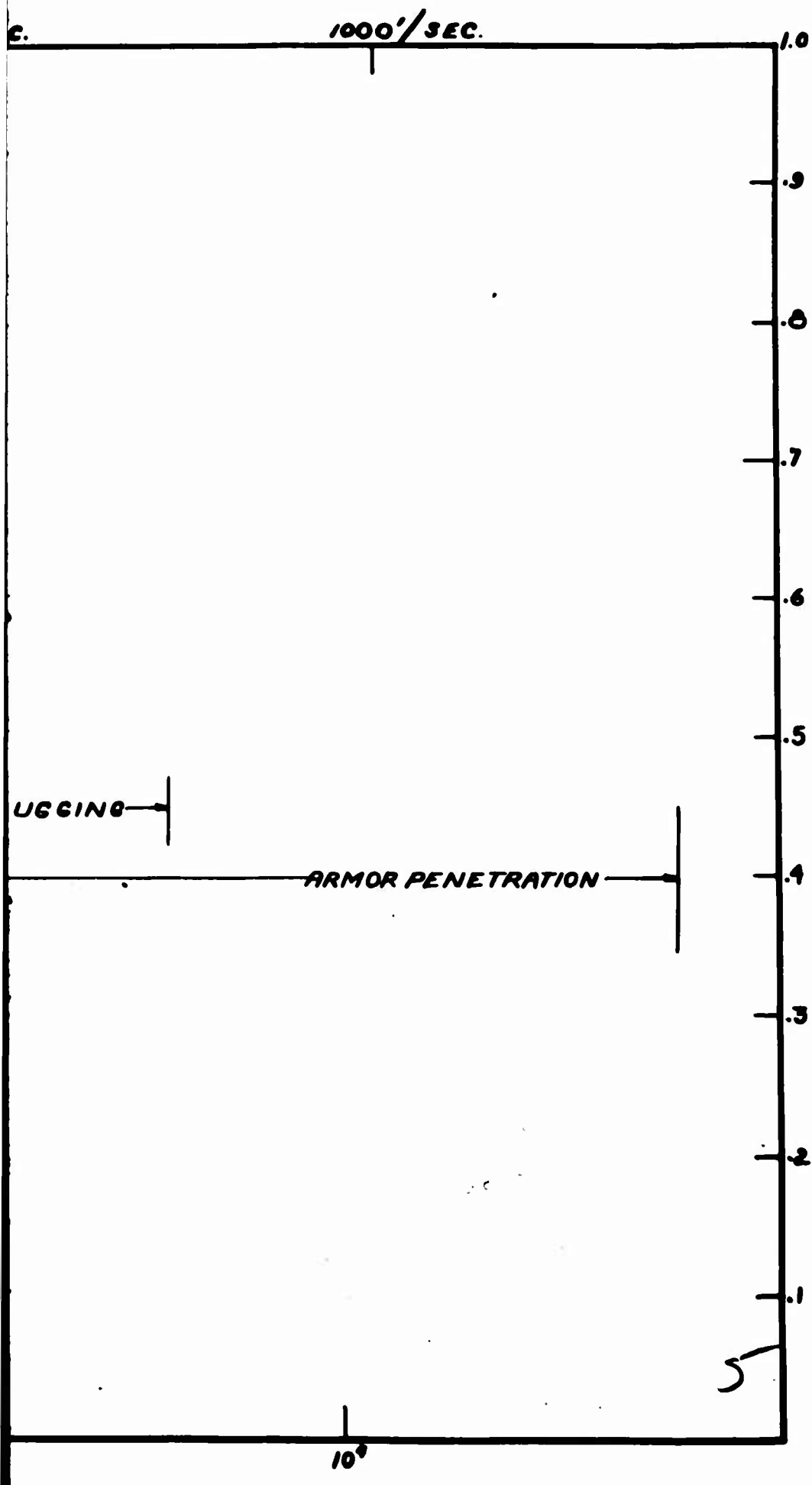
C .15C BC



4
10²

10³

10⁴



1000'/SEC.

1.0

.9

.8

.7

.6

.5

.4

.3

.2

.1

5

10^9

UGGING

ARMOR PENETRATION

C.