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The Effect of Dynamic Loading on the Stress-Strain Curve of Foam Plastics

Carroll D. Beaman

THE EFFECT OF DYNAMIC LOADING - BEAMAN

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THE EFFECT OF DYNAMIC LOADING ON THE STRESS-STRAIN CURVE OF FOAM PLASTICS

By

Carroll D. Beaman

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

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MASTER OF SCIENCE

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DATE May 28, 1957

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NOMENCLATURE

A	Proportionality constant, dimensionless
α	Stress level parameter, 1/psi
ϵ	Axial unit strain, in./in.
$f_r(\epsilon)$	Relaxed modulus or the slope of the stress-strain curve if the strain were applied at an infinitely slow rate, psi
$f_u(\epsilon)$	Unrelaxed modulus or the slope of the stress-strain curve if the strain were applied in zero time, psi
$g(\epsilon)$	Function of strain, psi
K	Proportionality constant, 1/seconds
M_u	Unrelaxed elastic modulus (i.e., the modulus of elasticity if the stress were applied in zero time), psi
$\phi(T)$	Relaxation coefficient, dimensionless
R	Strain rate, in./in./second
s	Slip, in./in.
σ	Overall stress, psi
σ_b	Stress across the bonds of the material, psi
σ_{bu}	Unrelaxed stress across the bonds of the material (i.e., the stress across the bonds if the strain were applied in zero time), psi
σ_u	Unrelaxed overall stress (i.e., the stress if the strain were applied in zero time), psi
$\Sigma_{A(\epsilon,T,R)}$	Existing stress which is a function of strain, time and strain rate, psi
$\Sigma_{p}(\epsilon,R)$	The relaxable stress at $T = 0$

$\Sigma_R(\epsilon,R)$	Relaxed stress, which is a function of strain and strain rate, psi
t	Time, seconds
T	Time, $T = 0$ at the end of the increasing strain period, seconds
$\tau(\epsilon)$	Relaxation coefficient, seconds
θ	Angle slip band makes with axis of specimen, radians

I. INTRODUCTION

The dynamic properties of materials have received a great deal of attention since about 1935. The mechanical properties of materials at high rates of loading, and in particular, the influence of the rate of loading on the dynamic modulus, has become a subject of growing importance.

Components must now withstand more severe environmental conditions, especially concerning vibration and shock, than ever before. The severe environmental conditions have caused designers to use various methods to protect their designs. As a result of this, the importance of materials used for potting, packing, and cushioning has been increasing. Since these materials are generally used to reduce the effect of dynamic loading, their dynamic properties are very important.

After making a literature review and reading the results of numerous investigations, it appears that there are three phenomena caused by dynamic loading. These are: (1) stress relaxation, (2) wave propagation, and (3) the change of the dynamic modulus with different rates of loading. These are three different phenomena, but they are closely related and interdependent. The stress relaxation and the dynamic modulus are dependent on the rate of loading, and the time duration of the load. If the loading is repeated, the rate of the repetition will also affect these phenomena. The stress relaxation and the dynamic modulus are also affected by shock loading. In shock loading, the effect of the load is not the same at all points of the material at the same time. The effects of the load are propagated in the form of waves from the point of application throughout the material with a finite velocity.

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These phenomena have been studied by others, both theoretically and experimentally, in an effort to use them to predict the effect of the type of loading on the dynamic properties of materials. This investigation was for the same purpose.

II. SCOPE OF INVESTIGATION

This thesis is an investigation of the effect of strain rate on the stress-strain relationship of some of the new foam plastic materials.

The foam plastics are a relatively new product. They are becoming widely used as shock absorbers and potting and packing materials. Despite their wide use in applications involving dynamic loading, very little information is available on their dynamic properties. In many of the applications, the rate of loading is of such a magnitude that the effect of the strain wave propagation is negligible, but high enough that it has a definite effect on the behavior of the stress-strain curve. This is the area of dynamic loading which is investigated in this thesis.

This investigation of the effect of the strain rate on the stress-strain relationship consists of:

(1) Developing a formula to predict the stress-strain curve produced by different rates of loading;

(2) Designing a dynamic test to prove the validity of the developed formula;

(3) Designing and constructing a dynamic test machine to strain the test material at constant rates of strain.

III. LITERATURE REVIEW

The change in the mechanical properties of materials when subjected to dynamic loading has been recognized since before the turn of the century. Many investigators (1)*, (2), (3) have tried to predict the dynamic stress-strain curve by using the results of impact tests. Numerical values are found for the modulus of elasticity, the modulus of rigidity, and Poissons ratio from the tests, and substituted into the appropriate theoretical prediction equations. This method makes a definite division between dynamic and static loading. All loading is dynamic, but varying greatly in degree. Therefore, such a division between dynamic and static loading does not exist.

It has long been recognized that the properties of rubber and rubber-like materials are more time dependent than are those of other materials. The rubber and rubber-like materials have been called visco-elastic. Meyer and Voigt made early attempts to adapt the equations of elastical theory to anelastic materials. Voigt designed an analogous model with a spring and dashpot in parallel to explain the visco-elastic action of materials. Another popular model is the Maxwell model which consists of a spring and dashpot connected in series. Other experimentors (4), (5) have made models using combinations of these two.

Eyring developed his rate theory for the stress relaxation of

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*Numerals in parentheses refer to corresponding items listed under the heading, "LITERATURE CITED".

of materials. Fredrickson and Eyring (6) then gave a molecular explanation of the action within the material during the time of loading and during the time of stress relaxation. This showed the effect of rate of loading on a material's stress-strain characteristics.

Zener (4) first introduced the idea of predicting the stress for a suddenly applied strain. Applying Eyring's Rate Theory and a relationship between the stress, strain, time, the unrelaxed modulus of elasticity, the relaxed modulus of elasticity and the coefficient of relaxation, he formulated his theory for the dynamics of slip bands. The prediction equation which Zener (7) developed gives the stress at any time for an instantly (i.e., in zero time) applied strain.

Dove (8) used this same relationship and modified the equation so as to consider different rates of loading. Dove proposed that each increment of strain should be considered. Then the stress and stress relaxation caused by each increment of strain could be considered. By making this consideration it is possible to use Zener's equation for different rates of loading; i.e., the strain need not be applied in zero time. If small increments of stress and strain are considered, the unrelaxed and relaxed may not be constant, but rather a function of strain. Dove also made this modification in Zener's equation.

Attempts are being made to measure the dynamic as well as the static properties of some materials that are used as shock absorbers and cushioning and potting materials. However, there is still no method of determining the true dynamic properties of material in such a way that they can be used to predict the behavior of a material at different rates of loading.

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IV. THEORETICAL INVESTIGATION

Prediction equations based on impact tests make no allowance for the rate of loading; instead, they divide the types of loading into two distinct types, dynamic (or shock) and static. Such a division does not exist since all loads in practical applications are applied at some finite rate. Consequently, these equations are of little value in the range of dynamic loading where the rate of loading has a definite affect on the dynamic modulus, but the effect of strain wave propagation is negligible.

It appears that a more useful approach to the problem would be to consider all loading as dynamic, but varying greatly in rate. Then the stress would always be a function of strain, strain rate, and time. In some cases some of the terms could be neglected.

According to Zener's*(7) theory of slip bands, the strain can be expressed as:

$$\epsilon = M_u^{-1}\sigma + As \tag{1}$$

where ϵ is strain

M_u is the unrelaxed elastic modulus (i.e., the modulus of elasticity if the stress were applied in zero time)

σ is the overall stress

s is the slip

A is a proportionality constant

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*See page 5, LITERATURE REVIEW.

The interpretation of this equation is that if the strain is instantly increased to the value $M_u^{-1}\sigma$ and the stress held constant, the gradual relaxation of stress within the slip bands causes a gradual increase in the strain. This increase in strain is proportional to the slip as shown in equation (1). However, experimental evidence indicates that the unrelaxed stress-strain curve may not be linear for some materials. Dove (8) introduced the idea of letting the unrelaxed modulus be a function of strain. Substituting $f_u(\epsilon)$ for M_u in the equation (1) gives:

$$\epsilon = f_u(\epsilon)^{-1}\sigma + As \qquad (2)$$

where $f_u(\epsilon)$ is the unrelaxed modulus or the slope of the stress-strain curve if the strain were applied in zero time.

Applying Ering's Rate Theory, the rate of creep or growth of material in the direction of the force may be expressed as a hyperbolic sine function, thus:

$$ds/dt = K \sinh(\alpha\sigma) \qquad (3)$$

where K is a proportionality constant and

α is the stress level parameter.

If a strain were instantly applied and assuming no slip, the stress across the bands would be proportional to the applied stress. If the stress is due to axial loading and the slip band makes an angle θ with the specimen's axis, then without slip:

$$\sigma_B = \cos\theta \sin\theta\, \sigma \qquad (4)$$

where σ_B is the stress across the bonds

If it is assumed that the slip bands have a random orientation, Cos θ

Sin θ can be replaced by its average value, 1/3, or

$$\sigma_B = 1/3\,\sigma \tag{5}$$

Then the general equation for the stress across the bonds, if a constant strain were instantly applied and if the stress relaxation effect caused by the slip were a function of strain, would be

$$\sigma_B = 1/3\sigma - g(\epsilon)\, s \tag{6}$$

where $g(\epsilon)$ is some function of strain.

This equation indicates that the stress across the bonds is proportional to the applied stress minus some function of the strain times the slip.

Solving for the slip and substituting it into equation (2) gives:

$$\epsilon = \frac{\sigma}{f_u(\epsilon)} + \frac{A}{g(\epsilon)}\left(1/3\sigma - \sigma_B\right) \tag{7}$$

or

$$\epsilon = \sigma\left(\frac{1}{f_u(\epsilon)} + \frac{A}{3g(\epsilon)}\right) - \sigma_B\left(\frac{A}{g(\epsilon)}\right) \tag{8}$$

Differentiating equation (6) with respect to time gives:

$$ds/dt = \frac{1}{3\,g(\epsilon)}\frac{d\sigma}{dt} - \frac{1}{g(\epsilon)}\frac{d\sigma_B}{dt} \tag{9}$$

It should be noted that $g(\epsilon)$ is not a function of time. Substituting from equation (3) gives:

$$\frac{d\sigma_B}{dt} = \frac{1}{3}\frac{d\sigma}{dt} - g(\epsilon)\, K \sinh\left(\alpha\sigma\right) \tag{10}$$

If the relaxed modulus $(f_r(\epsilon))$ which is the slope of the stress-strain

curve when the load has been applied at an infinitely low rate, is also a function of strain, then it may be related to the unrelaxed modulus by the following equation:

$$\frac{1}{f_r(\epsilon)} = \frac{1}{f_u(\epsilon)} + \frac{A}{3g(\epsilon)} \tag{11}$$

or

$$\frac{A}{3g(\epsilon)} = \frac{1}{f_r(\epsilon)} - \frac{1}{f_u(\epsilon)} \tag{12}$$

Equation (8) then becomes:

$$\epsilon = \sigma\left[\frac{1}{f_r(\epsilon)}\right] - 3\sigma_B\left[\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)\ f_r(\epsilon)}\right] \tag{13}$$

If a strain is instantly applied and maintained constant, the relationship between the change of bond stress and the change of the applied stress with respect to time can be found by differentiating equation (13) with respect to time. Differentiating equation (13) with respect to time gives:

$$\frac{d\epsilon}{dt} = 0 = \frac{1}{f_r(\epsilon)}\frac{d\sigma}{dt} - 3\left[\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)\ f_r(\epsilon)}\right]\frac{d\sigma_B}{dt} \tag{14}$$

or

$$\frac{d\sigma}{dt} = 3\left[\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)}\right]\frac{d\sigma_B}{dt} \tag{15}$$

Substituting this result into equation (10) gives:

$$\frac{d\sigma_B}{dt} = \frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)}\ \frac{d\sigma_B}{dt} - g(\epsilon)\ K\ \mathrm{Sin}\ (\alpha\sigma) \tag{16}$$

and

$$\frac{d\sigma_B}{dt} = -\frac{f_u(\epsilon)}{f_r(\epsilon)} g(\epsilon)\, K \,\mathrm{Sinh}\,(\alpha\sigma) \tag{17}$$

The relaxation coefficient $\tau(\epsilon)$ can be defined as:

$$\tau(\epsilon) = \frac{f_u(\epsilon)\, g(\epsilon)\, K}{f_r(\epsilon)}\alpha \tag{18}$$

In this case the relaxation coefficient is a function of strain. Substituting into equation (17) gives:

$$\frac{d\sigma_B}{dt} = -\frac{1}{\tau(\epsilon)\alpha}\mathrm{Sinh}\,(\alpha\sigma) \tag{19}$$

If a stress is applied instantaneously the average stress across the bonds is equal to $1/3\sigma_u$, providing no slip has occured. Integrating equation (15) and using this boundary condition gives:

$$\sigma = 3\left[\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)}\right]\sigma_B + \left[\frac{f_r(\epsilon)}{f_u(\epsilon)}\right]\sigma_u \tag{20}$$

where σ_u is the unrelaxed applied stress.

Equation (20) can be rewritten:

$$\sigma = \sigma_u\left[\frac{f_r(\epsilon)}{f_u(\epsilon)} + 3\left(\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)}\right)\frac{\sigma_B}{\sigma_u}\right] \tag{21}$$

If only the case of a high stress level is considered, i. e.,

$$\sigma_B \ll \frac{1}{\alpha}, \tag{22}$$

equation (19) can be integrated using this inequality from time equal zero to time equal t. This gives:

$$\sigma_B(t) = \sigma_{Bi}\, e^{-t/\tau(\epsilon)} \tag{23}$$

or

$$\sigma_B(t) = 1/3\,\sigma_u\, e^{-t/\tau(\epsilon)} . \tag{24}$$

When this is substituted into equation (21) it becomes:

$$\sigma = \sigma_u \left[\frac{f_r(\epsilon)}{f_u(\epsilon)} + \left(\frac{f_u(\epsilon) - f_r(\epsilon)}{f_u(\epsilon)} \right) \left(e^{-t/\tau(\epsilon)} \right) \right] \tag{25}$$

or

$$\sigma = \epsilon f_r(\epsilon) + \epsilon \left[f_u(\epsilon) - f_r(\epsilon) \right] e^{-t/\tau(\epsilon)} . \tag{26}$$

Equation (26) can be interpreted as follows: the stress at any time is equal to the stress that would result if the strain were applied at an infinitely slow rate ($t = \infty$) plus the amount of relaxable stress which has not occured at the time t. One of the conditions in the derivation of this formula was that the strain was applied instantly. This formula is not suitable for practical applications or for checking experimentally because of this condition. Therefore, it is necessary to formulate an equation considering the time required for strain application if the concept of relaxable stress and a relaxed modulus is to have any practical applications.

In formulating a different equation using the concept of a relaxed modulus and a relaxable stress, the term $\Sigma_A(\epsilon,T,R)$ will be defined as the stress existing at any time T. It will be a function of the strain, ϵ, time elapsed after the strain is applied, T, and the rate of strain, R. It will be expressed as the sum of the relaxed stress, $\Sigma_R(\epsilon,R)$ and $\Sigma_D(\epsilon,R)\phi(T)$, the amount of the relaxable stress which has not relaxed. The formula for existing stress is:

$$\Sigma_A(\epsilon,T,R) = \Sigma_R(\epsilon,R) + \Sigma_D(\epsilon,R)\phi(T) \tag{27}$$

which is the prediction equation for the existing stress at any time (T) as a function of strain, time, and rate of strain.

V. EXPERIMENTAL INVESTIGATION

The purpose of the experimental investigation was to find the effect of different rates of loading on the foam plastics and to check the validity of the prediction equation

$$\Sigma_A(\epsilon,T,R) = \Sigma_R(\epsilon,R) + \Sigma_D(\epsilon,R)\phi(T). \tag{27}$$

The experimental investigation consisted of two parts. The first part was the preliminary investigaton. It consisted of testing specimens to check:

(a) the equipment and instrumentation,

(b) the sensitivity of the stress-strain relationship of different types of foam plastics to the rate of strain,

(c) the variation of the stress-strain curve among specimens, and

(d) the repeatability of the recoverable types of foam plastics' stress-strain curve upon reapplication of the load.

The second part of the investigation consisted of a number of runs at different rates of strain. Several runs were made on each specimen of a recoverable type of foam plastic.

The results of this part of the investigation were used to determine the functions $\Sigma_D(\epsilon,R)$, $\Sigma_R(\epsilon,R)$, and $\phi(T)$. The function $\Sigma_D(\epsilon,R)$ was found by measuring the relaxable stress at the same strains with different rates of strain. The function $\Sigma_R(\epsilon,R)$ was found by measuring the stress after it had had sufficient time to relax after being strained at different rates to various strains. It would take an infinite amount of time ($T = \infty$) for the stress to completely relax; however, it was

determined the relaxed stress at any strain was practically zero and negligible compared to the other terms. The coefficient of relaxation, ϕ (T), was found by fitting the function to the stress relaxation curve.

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VI. APPARATUS

The test equipment is shown in Figures 1, 2, and 5. The test equipment was designed to strain specimens of foam plastic over a wide range of constant strain rates to different values of strain, and then to hold the strain constant. The rates of compression could be varied from approximately 0.001 in./sec. by turning the flywheel manually, to approximately 40 in./sec.; however, about 15 in./sec. was the highest speed normally used.

A variable speed motor (Part Number 16, Figure 1) was used to bring the flywheel (#15) up to speed. When the flywheel attained some predetermined speed, the pull-out wire (#13) was pulled out of the clutch (#14). The spring loaded tooth in the clutch was forced outward and engaged the single tooth in the flywheel. The flywheel turning the clutch also caused the cam shaft (#12) and the cam (#11) to turn. The cam in turn drove the compression rod (#10). The compression rod, by means of the cradle shown in Figure 2, pulled the compression plate (#3) toward the end plate (#1) causing the specimen (#2) to be compressed.

The compression plate (#3) in Figure 2 was pulled by the two transducers (#17) which were made of brass shim stock with SR-4 strain gages mounted on them. These gages measure the strain of the brass shim stock which is produced by the resistance of the specimen to compression and the forces necessary to accelerate the compression plate. The effect of the strain produced by the acceleration of the compression plate can be measured at each speed by running the machine without a specimen in place.

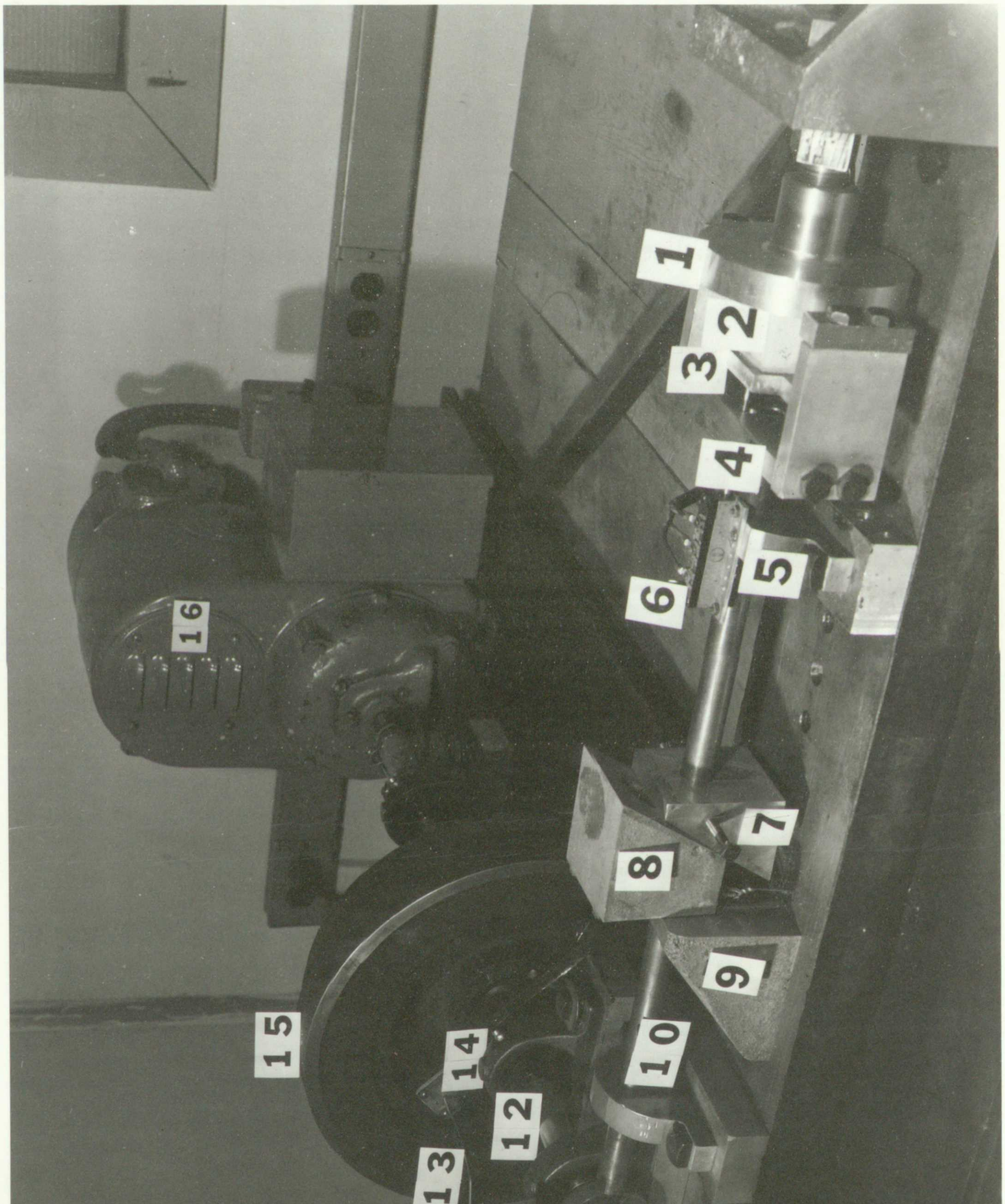

Figure 1. Testing Machine.

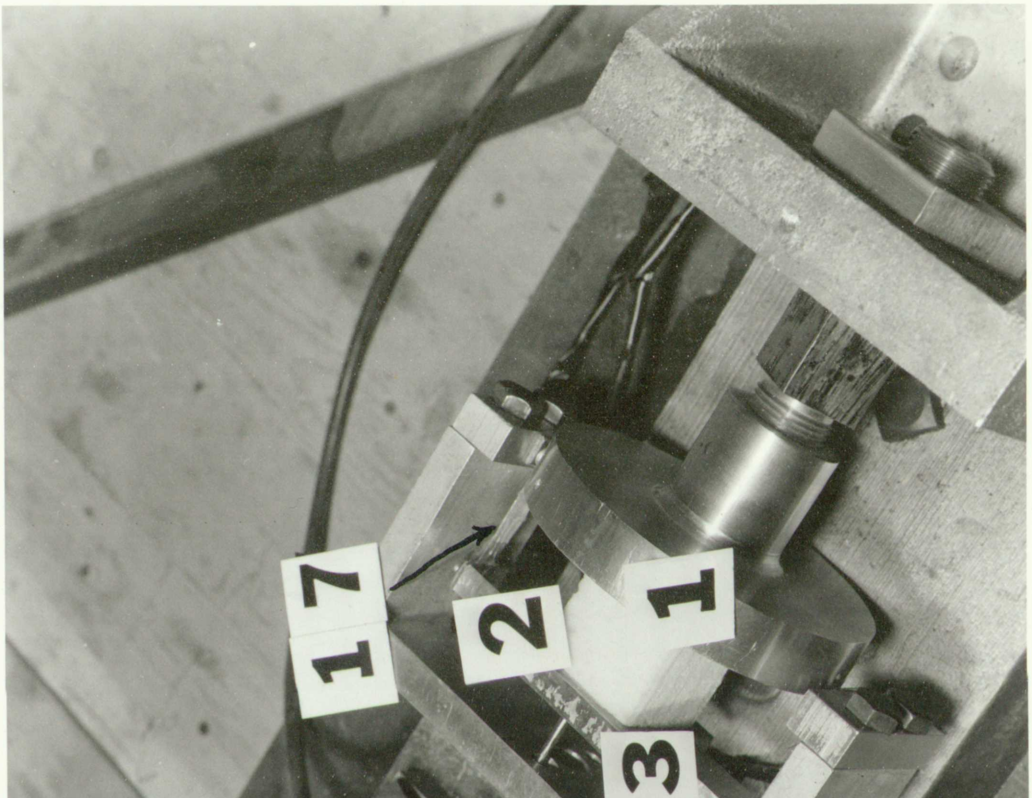

Figure 2. Cradle of Test Machine.

By using two strain gages the average value of the load on the specimen is measured.

Wedges (#7, #8, #9) were used to hold the strain constant at the maximum value obtained. Part number (#8) wedges between part number (#9) which was attached to the 6 in. channel iron mounting plate and part number (#7) which was fastened to the compression rod with two set screws. At low speeds, the wedge (#8) was pulled down by weights which were hung from the wedge. However, at high speeds, it was necessary to either pull the wedge down by means of a spring, or to force it down manually.

The two SR-4 strain gages on the transducers were connected to two inactive strain gages to form a Wheatstone bridge circuit, as shown schematically in Figure 3. Since the strain in the two strain gages mounted on the transducers is proportional to the load on the specimen, the unbalance of the strain gage bridge is proportional to the load on the specimen. The strain gage bridge was calibrated by removing the cradle and loading the compression plate with dead weights. A resistor was then placed in parallel with one of the strain gages and the displacement on the scope was measured. Calibration was checked periodically during the test by putting this resistor in parallel with the strain gage.

The voltage divider was used to vary the amount of current through the bridge. The balancing potentiometer was placed in the circuit to obtain zero initial output. All leads were shielded to keep stray pickup and noise out of the circuit. A battery was used as a voltage supply.

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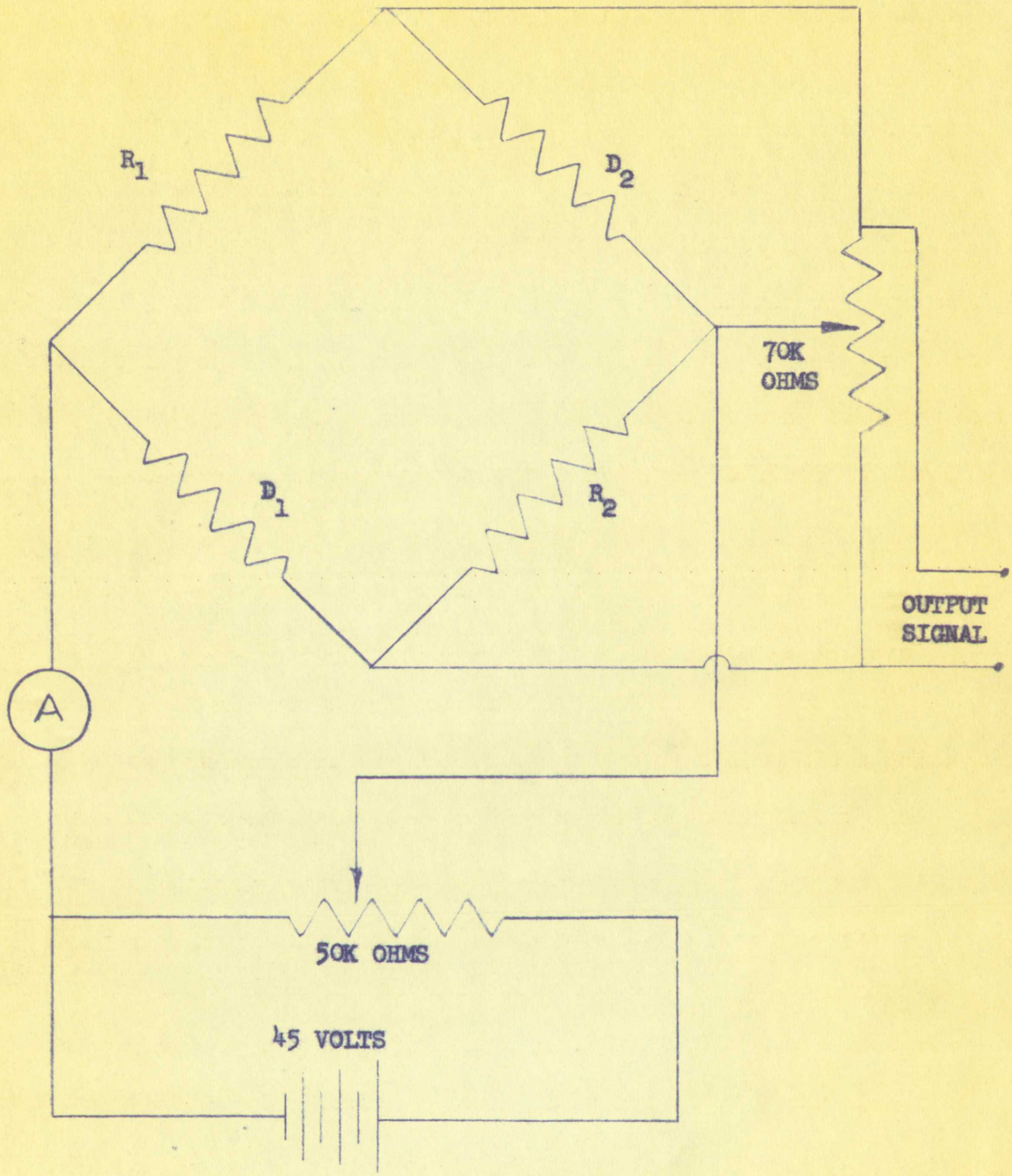


D_1 and D_2 - Dummy strain gages, SR-4, Type 2C.

R_1 and R_2 - Active strain gages, SR-4, Type 2C.

Figure 3. Strain Gage Schematic.

A Bourns displacement gage, Model 108 (#6) was mounted on the second compression rod guide (#5) and attached directly to the compression plate (#3). This gave the true displacement of one end of the specimen. The circuit for the Bourns gage is shown schematically in Figure 4. The 10K voltage divider is in the circuit to control the current through the gage.

The Bourns displacement gage was calibrated by measuring the output at different displacements as measured by a dial indicator. The dial indicator was a Starrette No. 196A and the scale was broken into 1/1000 inch increments. The gage was found to be linear throughout its entire range of measurement and the output was proportional to the current through the gage.

With the Hewlett-Packard Oscilloscope, Model 130A, it was possible to trace stress vs. strain, stress vs. time, or strain vs. time. By using a DuMont Electronic Switch, Type 330, it was possible to put two traces on the Hewlett-Packard Oscilloscope simultaneously. However, it was necessary to amplify the strain gage signals before putting them through the electronic switch. This was accomplished by using the vertical amplifier of a General Electric Oscilloscope, Type ST-2B. This set up is shown in Figure 5 and the schematic is shown as Figure 6.

Using the electronic switch, it was possible to display stress-time and strain-time on the Hewlett-Packard Oscilloscope simultaneously. The stress and strain signal were put on the vertical places and the triggered sweep produced the horizontal displacement giving the stress-time and strain-time relationships. A 35mm DuMont Oscillograph Camera, Type 296, was used to record these traces. With these two relationships recorded, it was also possible to plot the stress-strain curve.

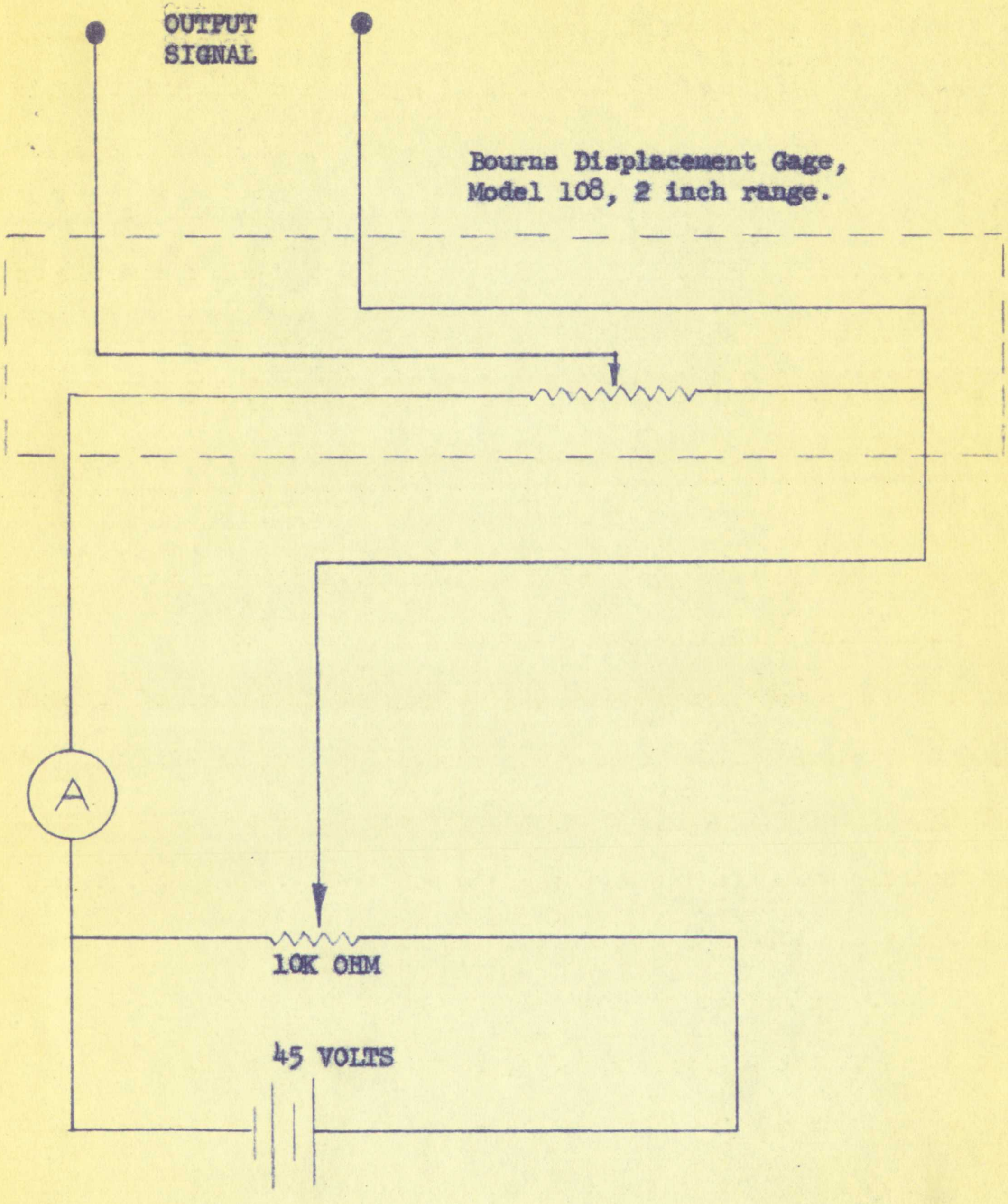


Figure 4. Bourns Displacement Gage Schematic.

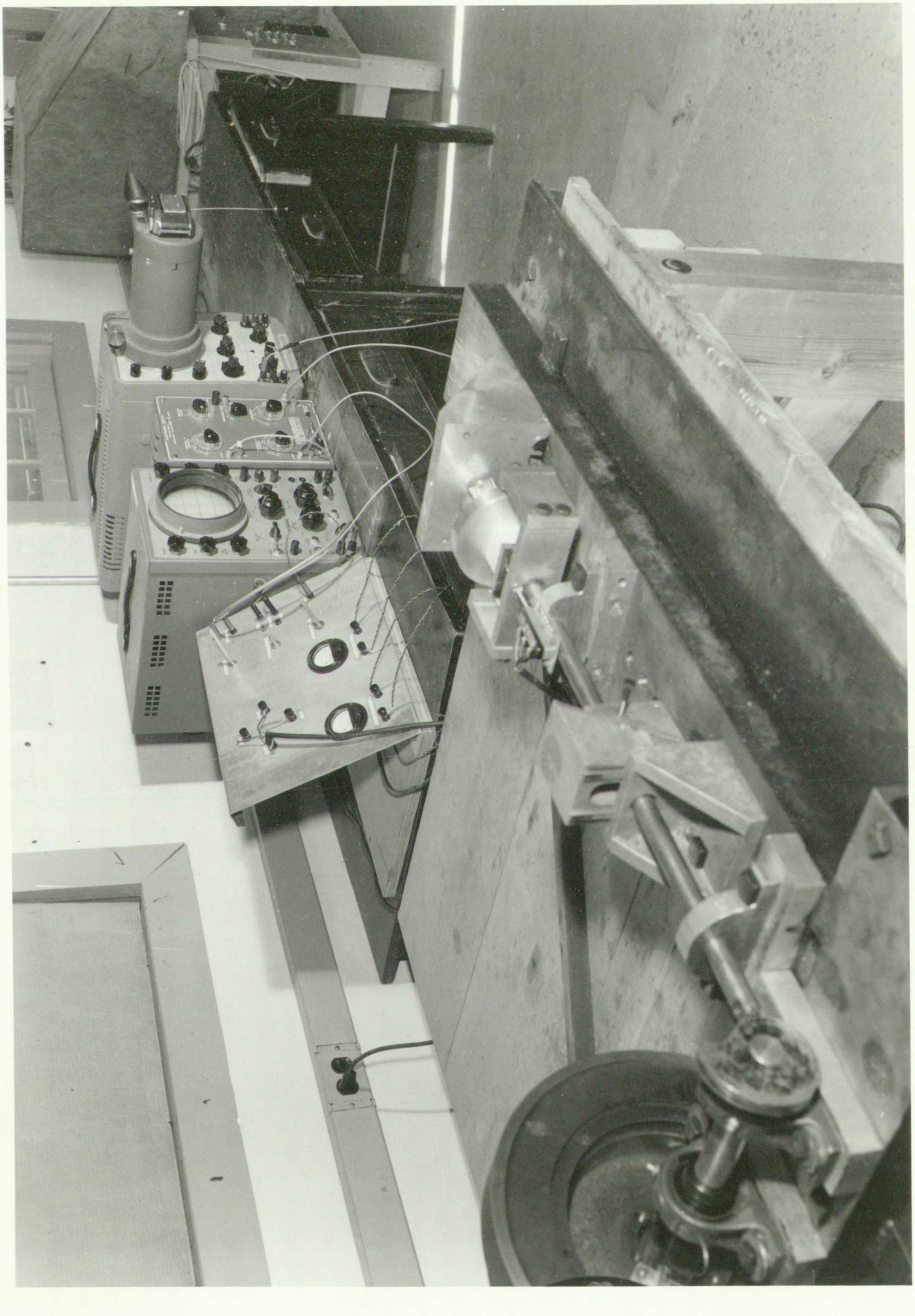


Figure 5. Test Setup for Displaying Both Stress and Strain vs. Time.

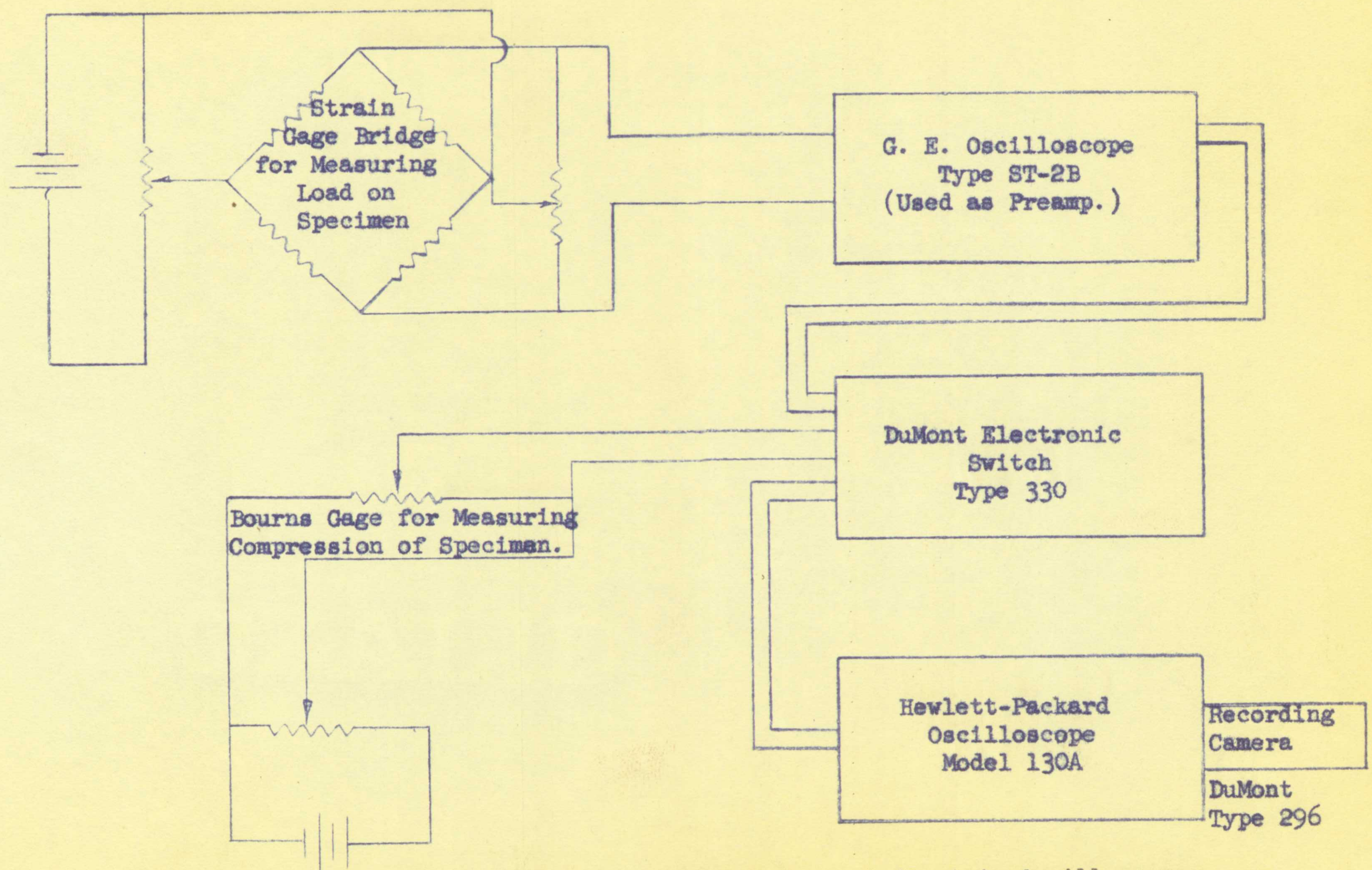


Figure 6. Schematic of Test Setup Using General Electric Oscilloscope, Electronic Switch and Hewlett-Packard Oscilloscope.

During some runs the stress-strain trace was put on the Hewlett-Packard Oscilloscope and a Hathaway Oscillograph, Type S-14C, was used to measure the strain-time relationship. For timing lines an oscillator was used to produce a 60 cycle signal which was put on one galvonometer. It was possible to derive the stress-time relationship from the stress-strain and the strain-time relationships. A schematic of this arrangement appears in Figure 7.

A strobatac was used to determine the speed of the flywheel. However, the actual rate of strain was found from the strain-time curves.

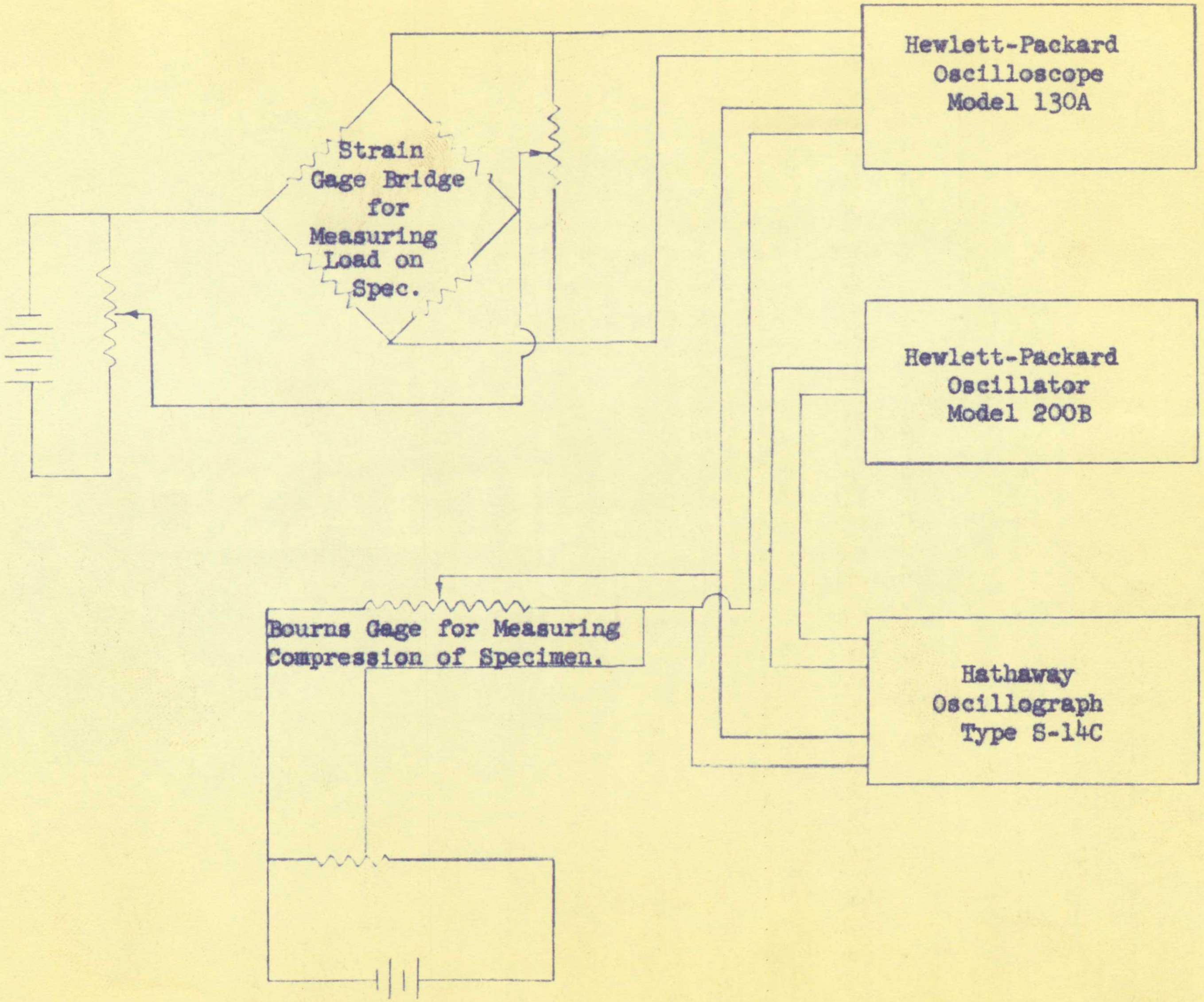


Figure 7. Schematic of Test Setup Using Hewlett-Packard Oscilloscope, Hathaway Oscillograph and Hewlett-Packard Oscillator.

VII. RESULTS

While checking the equipment and instrumentation, the limitations on the specimen size were checked. The limiting factor for specimens was the load required to compress them. About the smallest sample that could be tested was one that required at least one pound of force to strain it to the desired value. With 50 milliamperes flowing through the strain gage bridge, one pound of force gave an oscilloscope trace displacement of 1.4 cm. when SR-4, Type C-2, strain gages were used on the transducers. This sensitivity could be approximately doubled by using type C-10 strain gages. Greater sensitivity could be gained by using the General Electric Oscilloscope amplifier as a preamplifier; however, this introduced an objectionable amount of noise. Also, it is not desirable to have more than 10 or 15 milliamperes flowing through the bridge since the heat dissipation of the brass shim stock on which the gages are mounted is small. Use of a small current increases the life of the strain gages.

The largest specimen that could be tested was one that was not physically more than 4 in. in diameter and did not require more than about 250 pounds force to compress it to the desired strain.

Several types of specimens were tested during the preliminary tests to determine the sensitivity of their stress-strain curves to rate of strain. Two types of rigid foam plastics that were tested were Emerson and Cummings Ecco Foam (10 lb./ft.^{3} density and 6 lb./ft.^{3} density). The one inch cube shown in Figure 9 is the 10 lb./ft.^{3} density specimen and the $1\frac{1}{2}$ inch cube is the 6 lb./ft.^{3} density specimen. The modulus

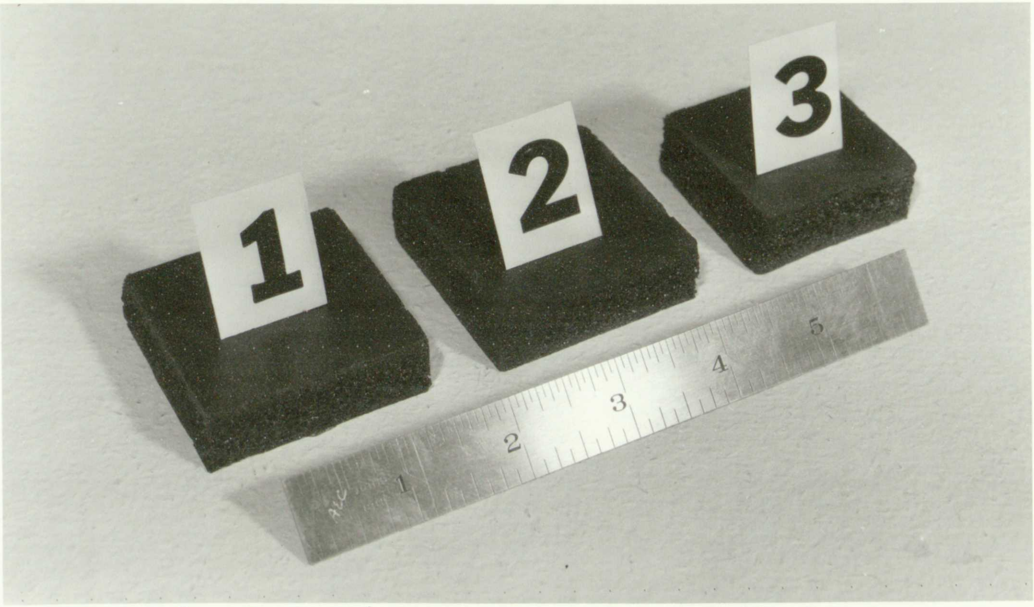


Figure 8. Nopco F-4 Recoverable Foam Plastic Specimens.

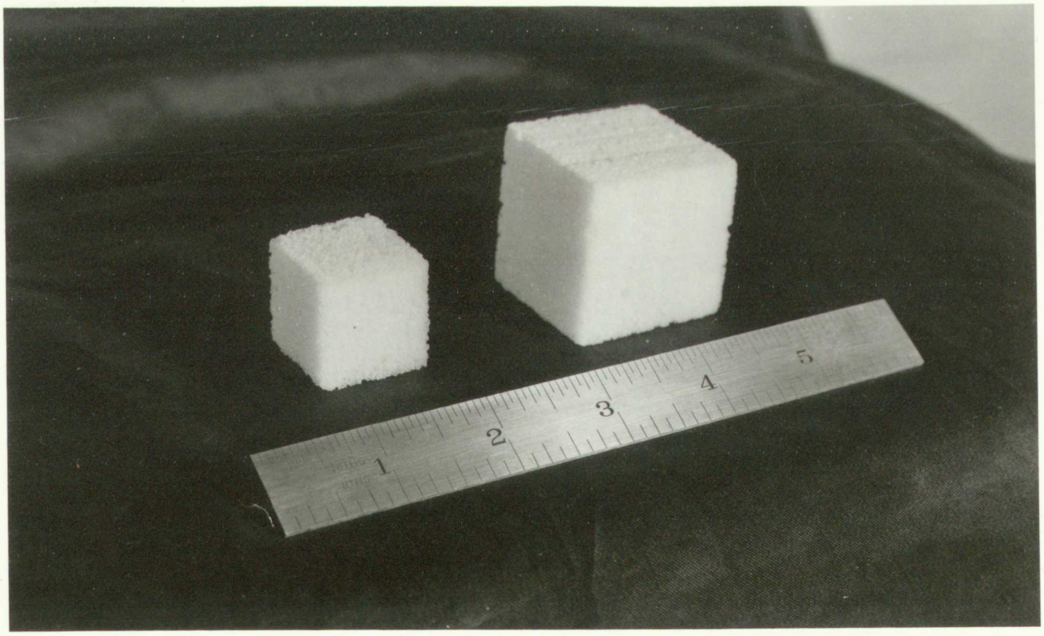
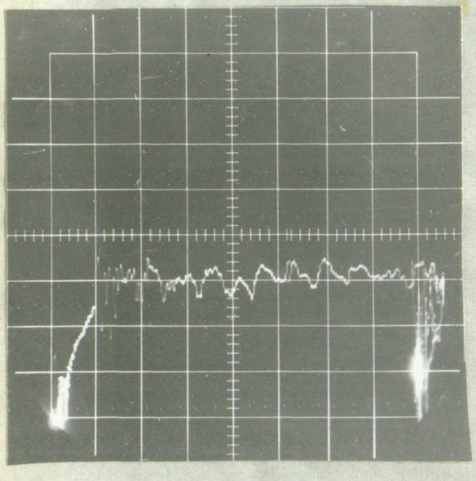


Figure 9. Emerson and Cummings Ecco Foam Plastic Specimens, 1" Cube, 10 lb./ft^3 Density, $\frac{1}{2}$" Cube, 6 lb./ft^3 Density.

or the slope of the stress-strain curve of both of these types of foam plastic showed a definite sensitivity to rate of strain as can be seen in Figures 10 and 11. Although the stress-strain curves of these foam plastics were sensitive to rate of strain, they were not as sensitive as some of the recoverable types. The variation of the stress-strain curve among different specimens of the two types of rigid foam plastic tested was very small as can be seen in Figures 12 and 13.

It was decided to use the recoverable types of foam plastic for the major portion of the tests since stress relaxation and the effect of rate of strain on the stress-strain curve were much easier to measure. Also, to test rigid foam plastics would have required more specimens since one would be expended during each test. The recoverable type plastics could be tested over and over. The variation was more among supposedly identical specimens of the recoverable types of foam plastics than had been found for the rigid foam plastic. This can be seen from the stress-time pictures shown in Figure 14 which were taken on different specimens strained at the same rate to the same strain. However, the repeatability of the recoverable foam plastics upon reapplication of the load was excellent as shown in Figures 15 and 16.

The results of tests on the recoverable type foam plastics are shown in Figures 17 through 22. The specimens of the material tested were of Nopco F-4; See Figure 8. Specimen #1 was two inches square and 0.625 inches high. The material was uncured. Specimen #2 was two inches square and 0.625 inches high. The material had been cured for two hours at 55°C. Specimen #3 was 1.75 inches square, 0.625 inches high and had been cured 60 hours at 55°C.

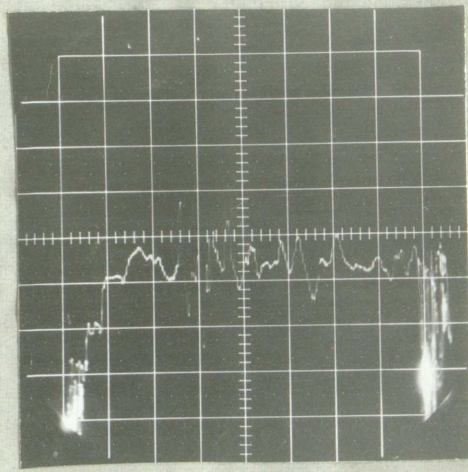


Run Number 203

Strain Rate - 5.0 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm

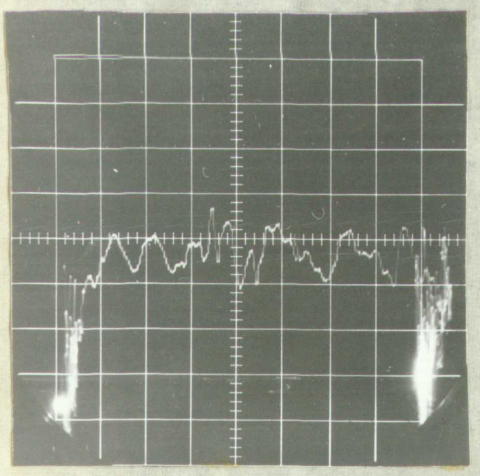


Run Number 205

Strain Rate - 7.5 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm

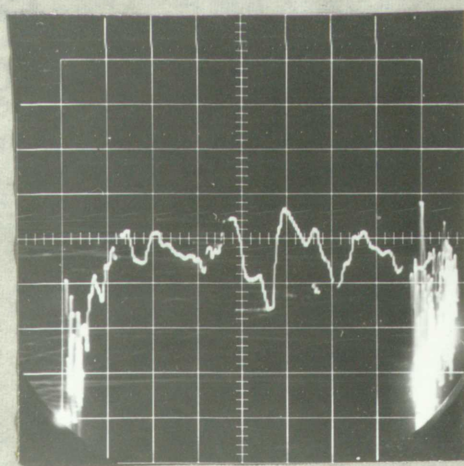


Run Number 206

Strain Rate - 10.0 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm



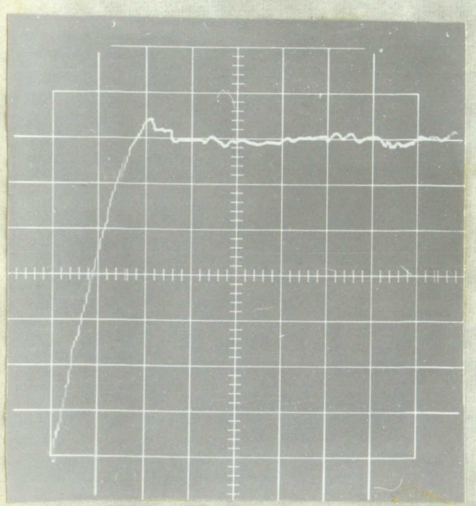
Run Number 209

Strain Rate - 12.5 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm

Figure 10. Stress-Strain Curves at Different Strain Rates for Emerson and Cummings Ecco Foam Plastic, 10 lb./ft^3 Density.

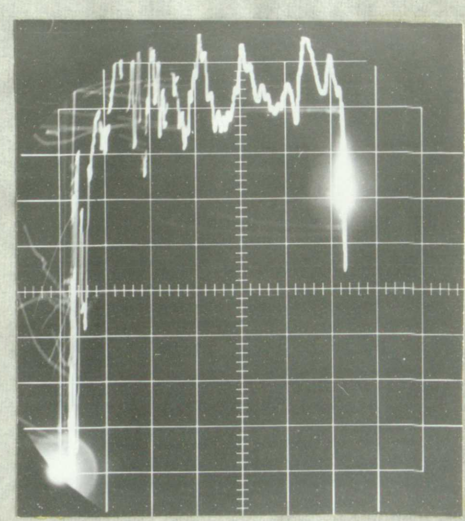


Run Number 211

Strain Rate - 0.05 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 5 millivolts/cm



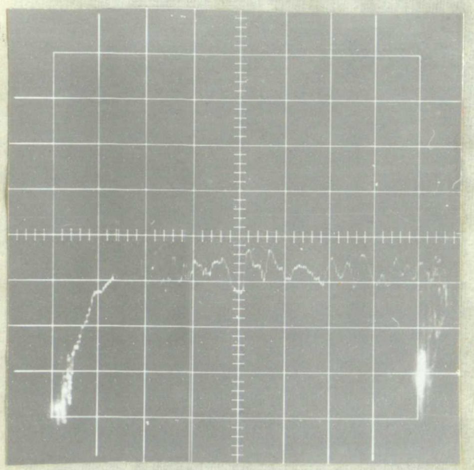
Run Number 214

Strain Rate - 10.0 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 5 millivolts/cm

Figure 11. Stress-Strain Curves at Different Strain Rates for Emerson and Cummings Ecco Foam Plastic, 6 lb./ft^3 Density.

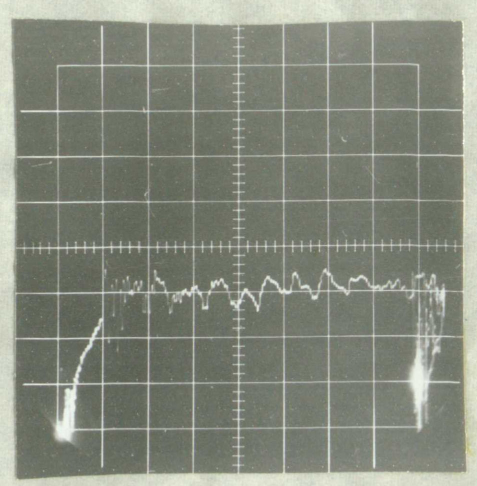


Run Number 202

Strain Rate - 5.0 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 5 millivolts/cm



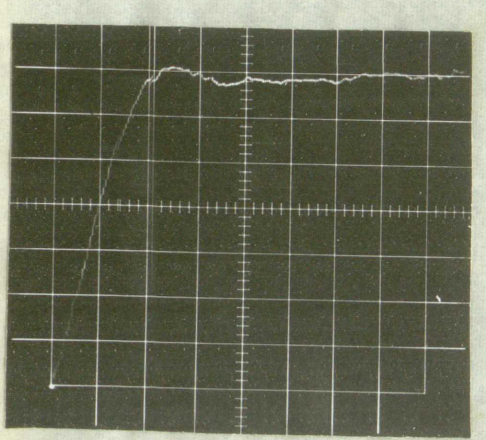
Run Number 203

Strain Rate - 5.0 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm

Figure 12. Stress-Strain Curves at the Same Strain Rates for Emerson and Cummings Ecco Foam Plastic, 10 lb./ft^3 Density.

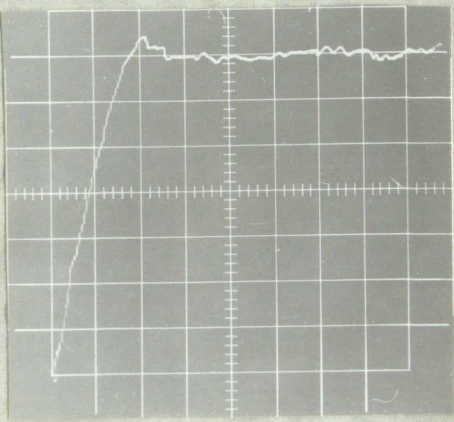


Run Number 210

Strain Rate - 0.05 in./in./sec.

Vertical Sensitivity of

Oscilloscope - 10 millivolts/cm



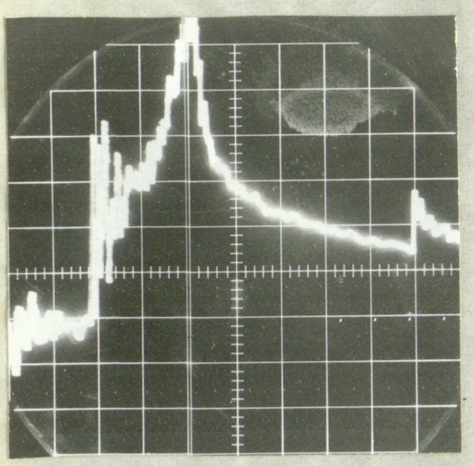
Run Number 211

Strain Rate - 0.05 in./in./sec.

Vertical Sensitivity of

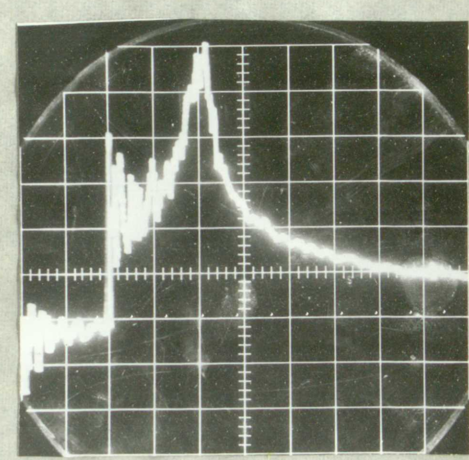
Oscilloscope - 10 millivolts/cm

Figure 13. Stress-Strain Curves at the Same Strain Rate for Emerson and Cummings Ecco Foam Plastic, 6 lb./ft^3 Density.



Run Number 410

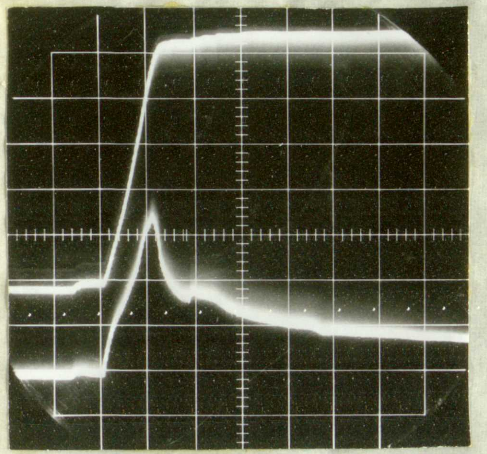
Strain Rate - 7.5 in./in./sec



Run Number 417

Strain Rate - 7.5 in./in./sec.

Figure 14. Stress-Time Curves for the Same Size Nopco Recoverable Foam Plastic Specimens Strained at the Same Strain Rate to the Same Strain.



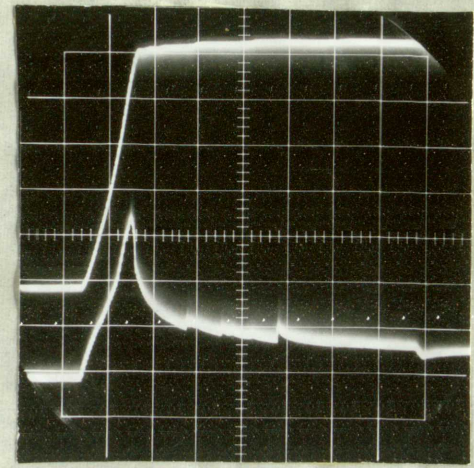
Run Number 633

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 2 sec./cm



Run Number 636

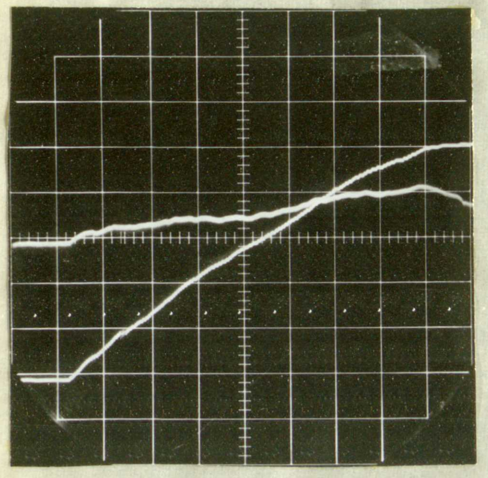
Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 2 sec./cm

Figure 15. Stress-Time and Strain-Time Curves for the Compression of Specimen #1 at Approximately the Same Rate. Two Different Runs.



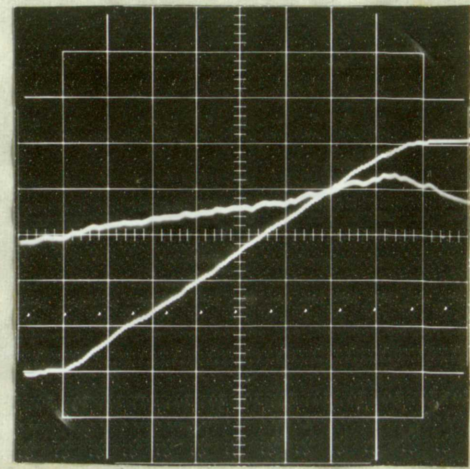
Run Number 658

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./ cm



Run Number 667

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm

Figure 16. Stress-Time and Strain-Time Curves for the Compression of Specimen #2 at Approximately the Same Rate. Two Different Runs.

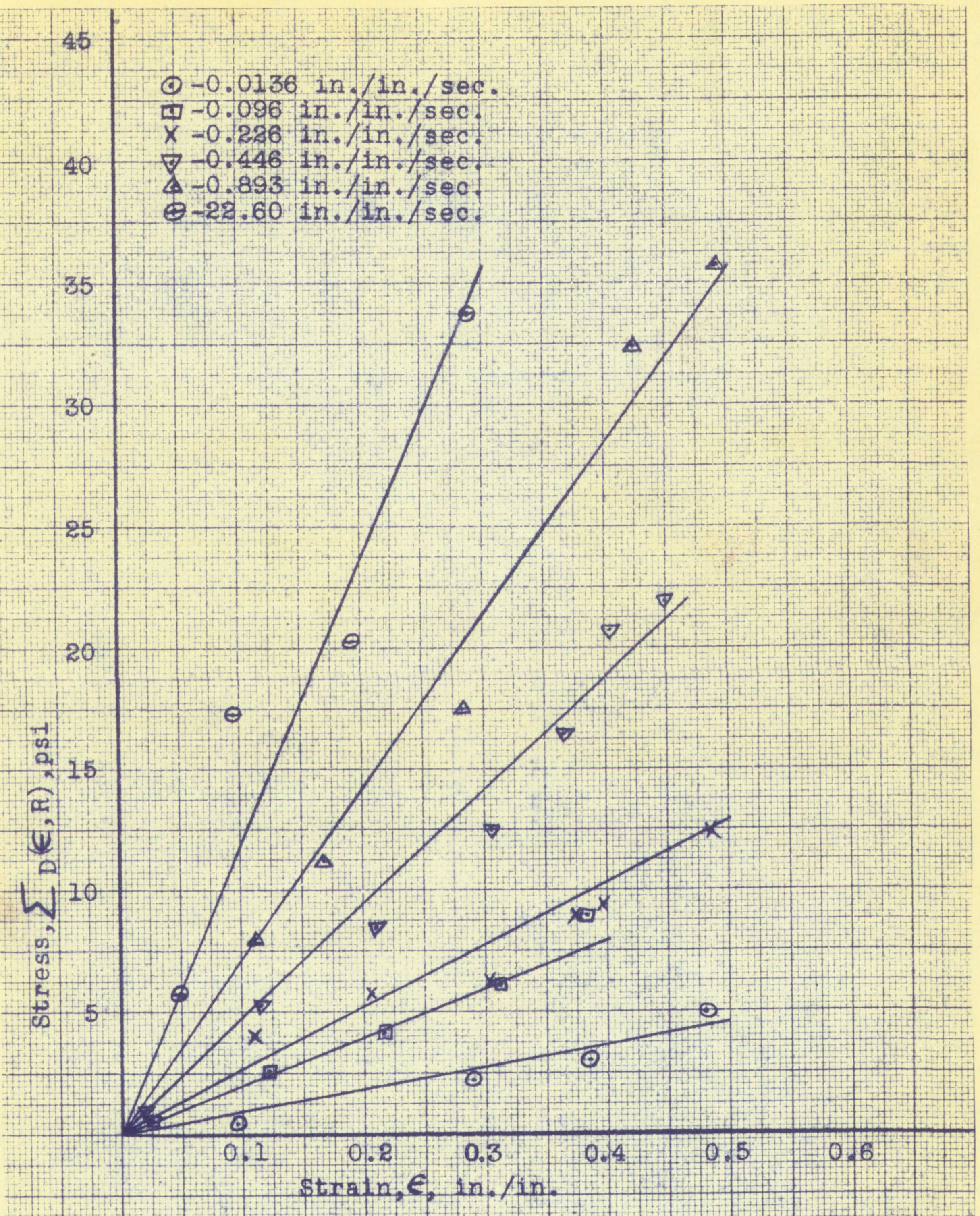


Figure 17. Stress vs. Strain Curves at Different Strain Rates for Specimen #1.

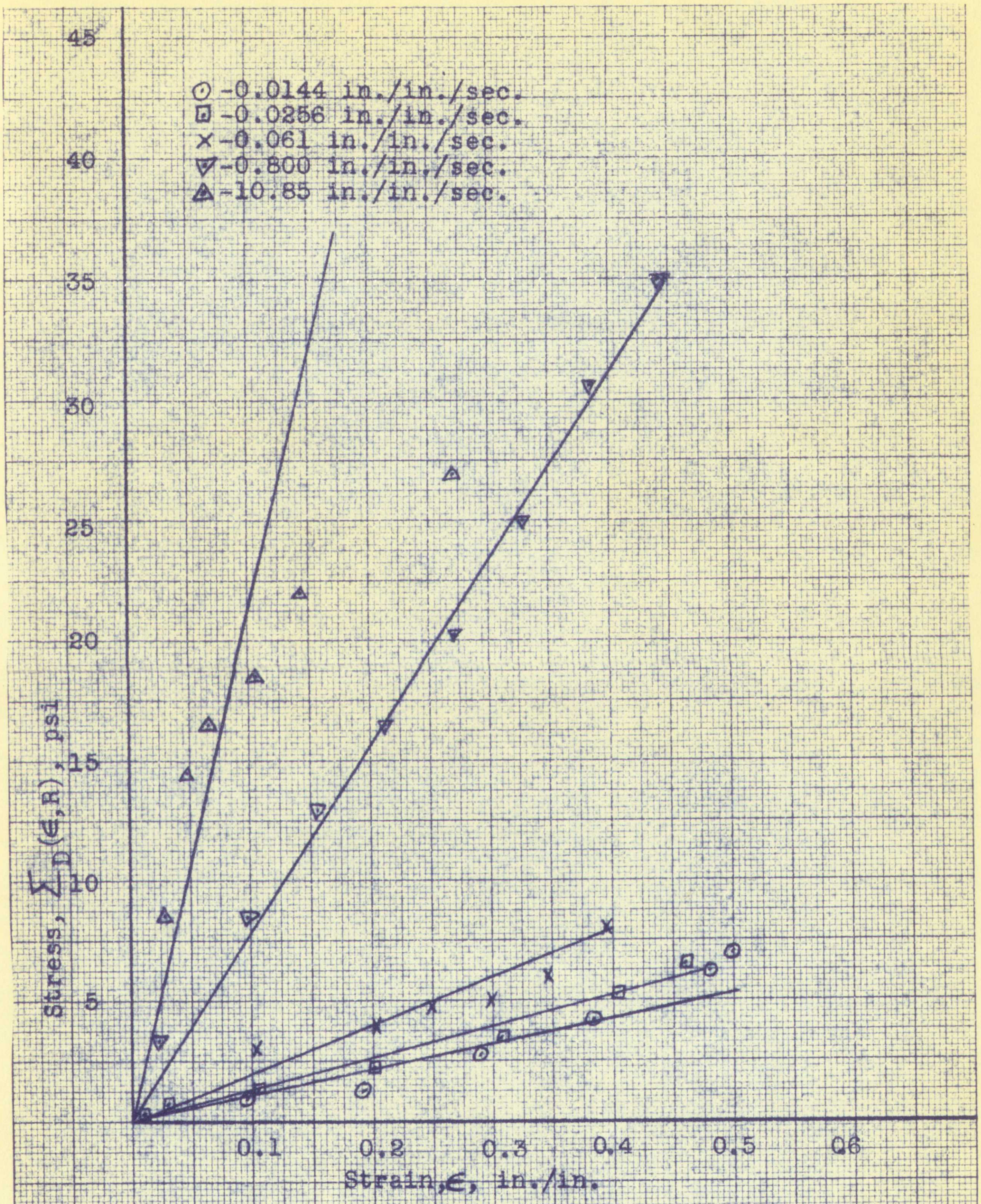


Figure 18. Stress vs. Strain Curves at Different Strain Rates for Specimen #8.

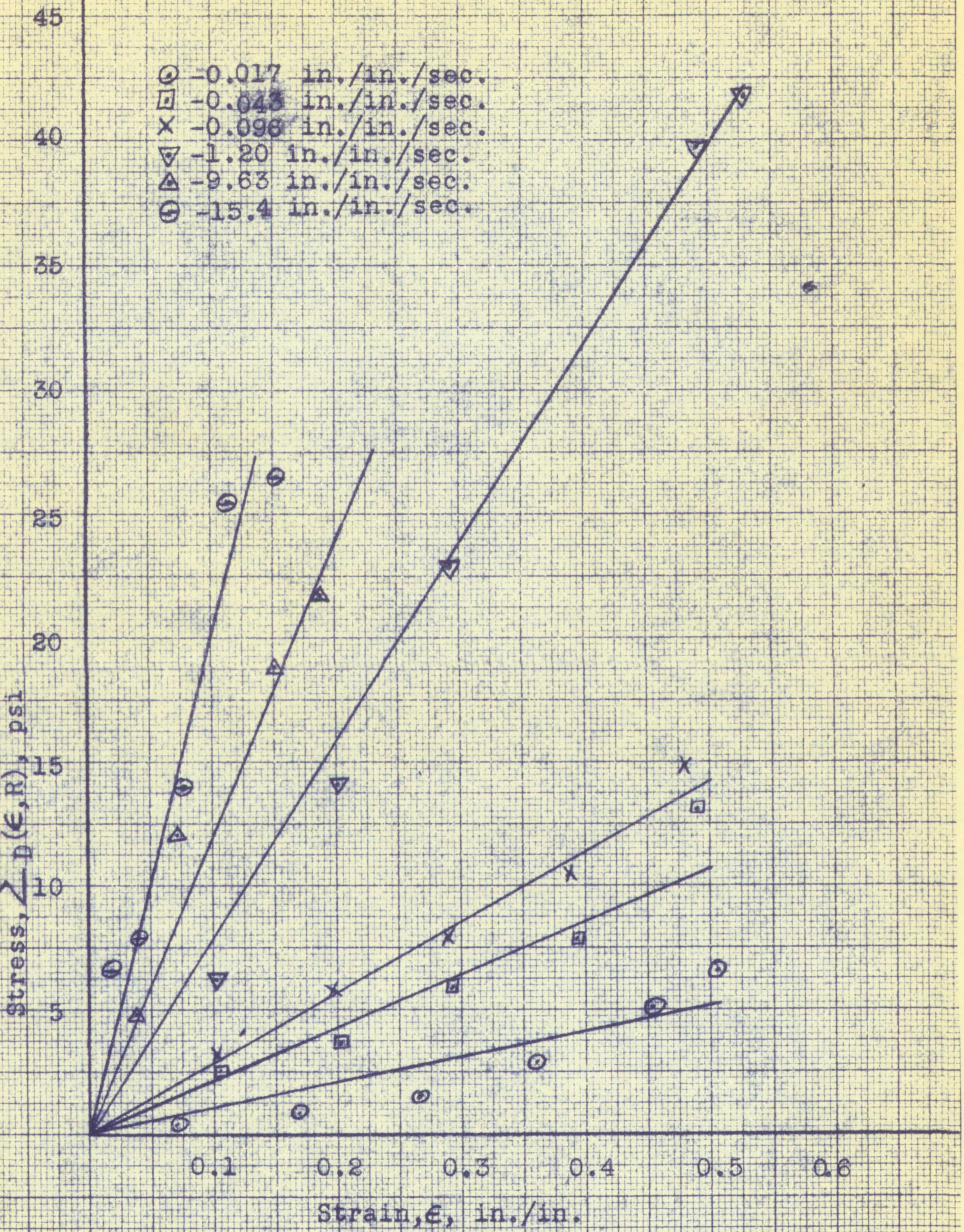


Figure 19. Stress vs. Strain Curves at Different Strain Rates for Specimen #3

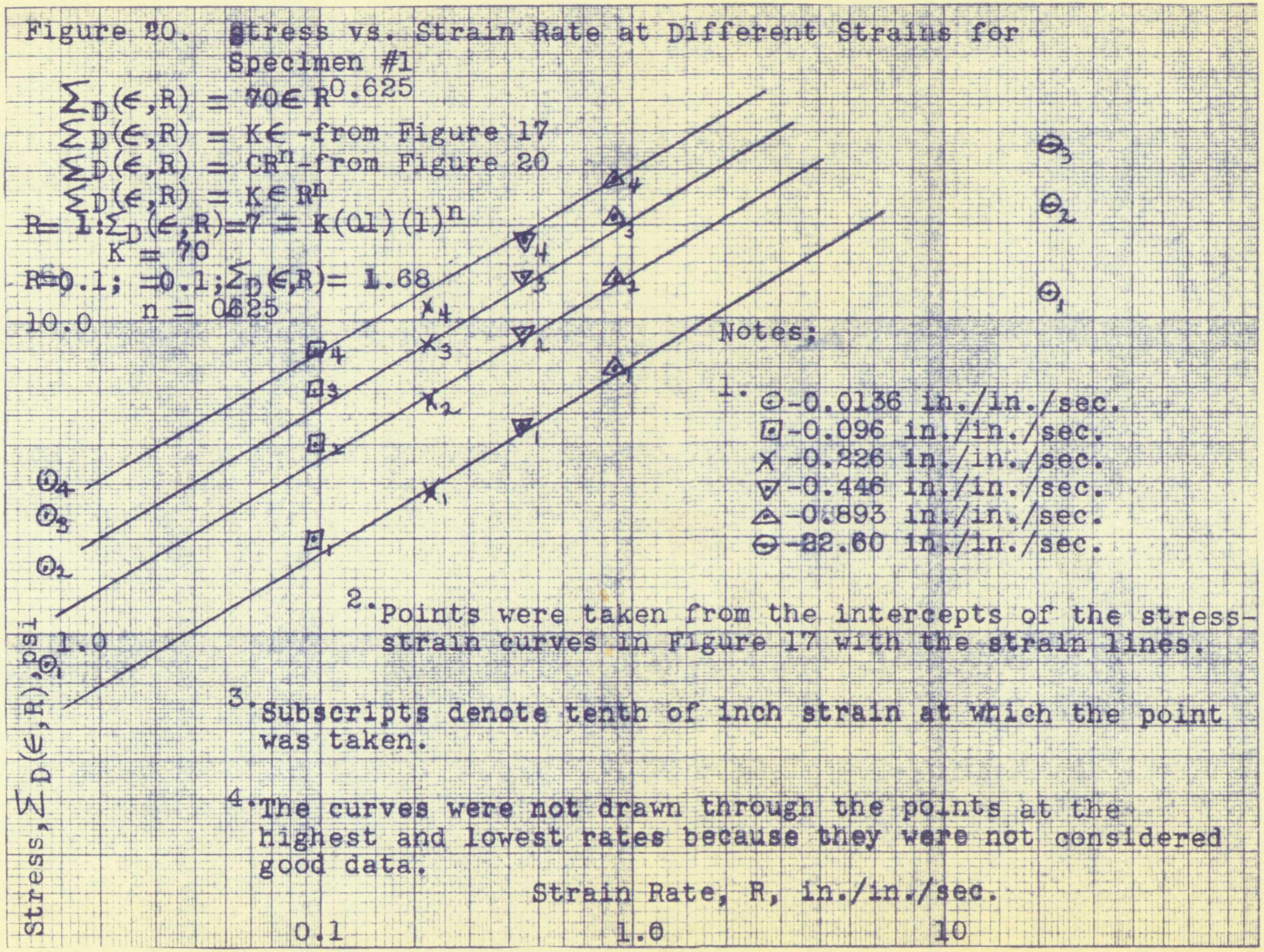


Figure 20. Stress vs. Strain Rate at Different Strains for Specimen #1

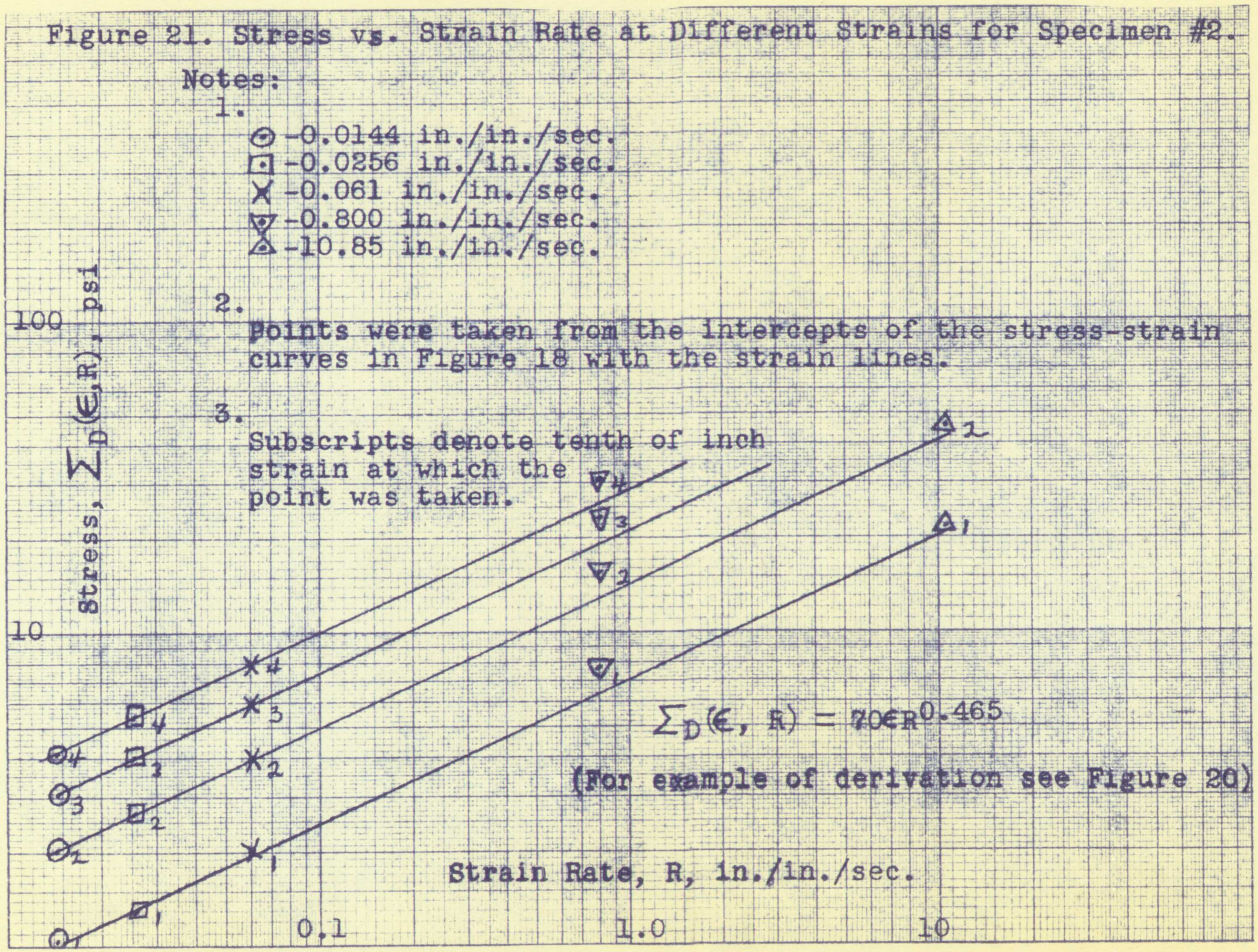
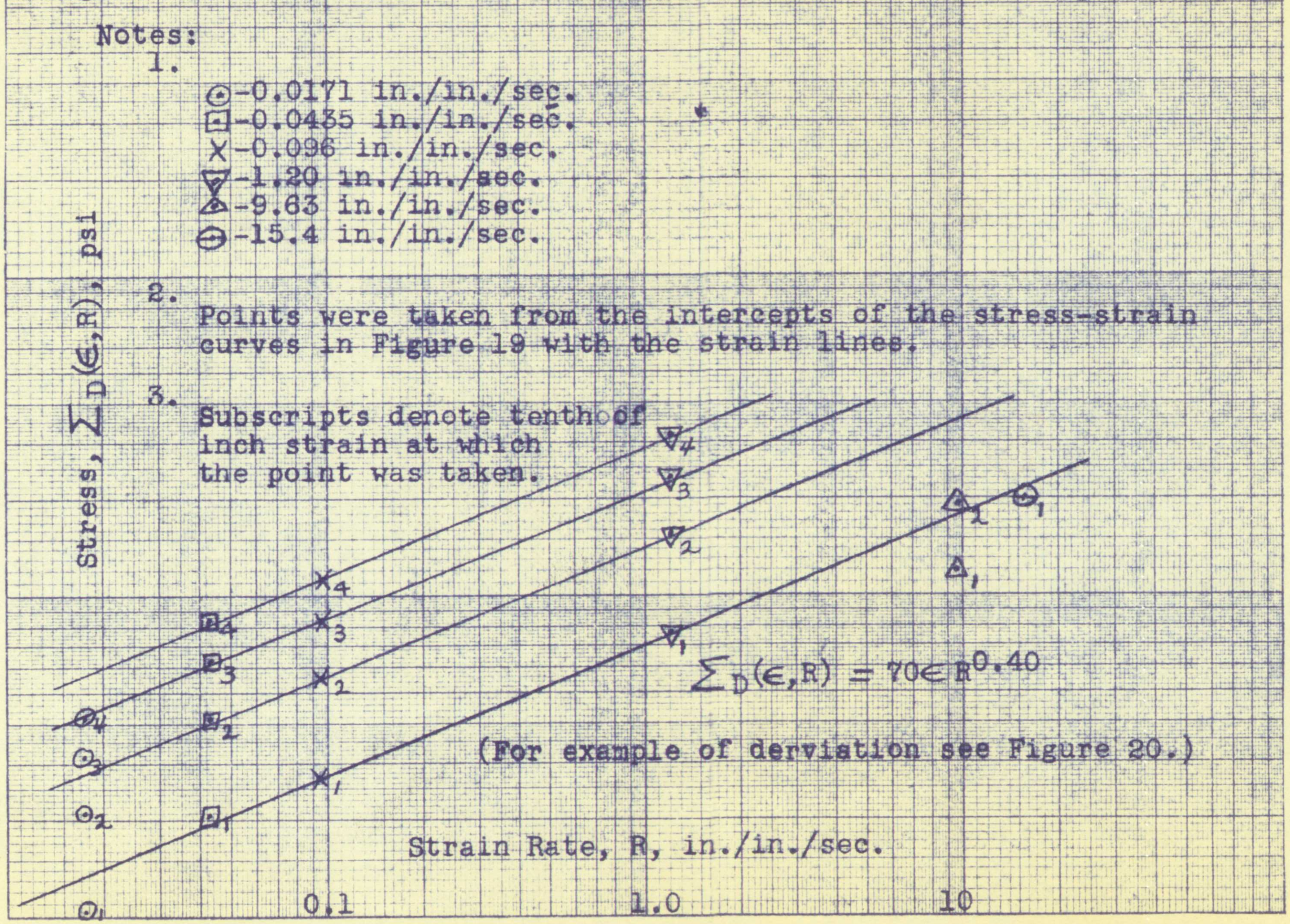


Figure 21. Stress vs. Strain Rate at Different Strains for Specimen #2.

Figure 22. Stress vs. Strain Rate at Different Strains for Specimen #3.



Figures 17, 19, and 21 show the stress-strain curves at different rates of strain for each specimen. Figures 18, 20, and 22 show stress plotted against strain rate at different strain levels. These figures are plotted from data taken from Figures 17, 19, and 21. Figure 23 is the stress relaxation curve of each specimen. Photographs of the stress-time and strain-time curves from which these data were taken can be identified in the appendix by the run numbers.

Attempts were made to measure the relaxed stress by measuring the stress after long periods of time; however, it was found to be negligible compared to the stress at the lowest rates tested. When attempts were made to measure the relaxed stress which resulted from slowly straining the specimen after periods of time, five minutes and greater, the signals were so small that they were camouflaged by the drift in the amplifiers. Therefore, the functions of the relaxed stress in the prediction equation were omitted.

Since the relaxed stress was found to be negligible, the entire stress was considered relaxable. It was found that the relaxable stress at $T \doteq 0$, which is shown in Figures 17 through 22, could be expressed by the following equations:

Specimen #1

$$\Sigma_D(\epsilon, R) \doteq 70 \epsilon R^{0.625} \qquad (28)$$

Specimen #2

$$\Sigma_D(\epsilon, R) \doteq 70 \epsilon R^{0.465} \qquad (29)$$

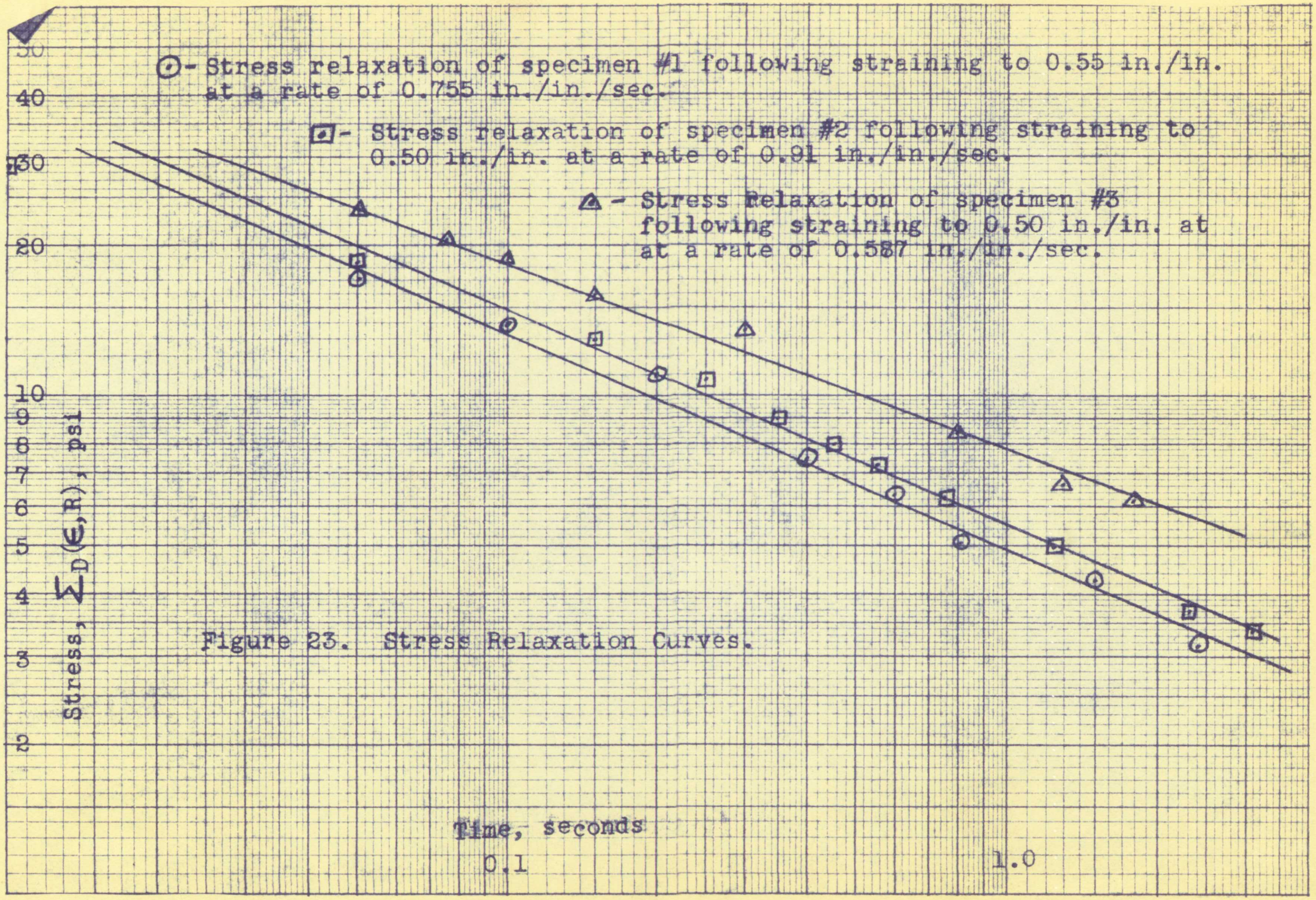


Figure 23. Stress Relaxation Curves.

Specimen #3

$$\sum_D(\epsilon,R) = 70\epsilon R^{0.40} \tag{30}$$

where ϵ is in units of in./in.,

R is in units of in./in./sec., and

$\sum_D(\epsilon,R)$ is in units of psi.

The stress relaxation of each specimen is shown in Figure 23. From these data, the stress relaxation factor for each specimen was found to be:

Specimen #1

$$\phi(T) = 1-0.8T^{0.25} \tag{31}$$

Specimen #2

$$\phi(T) = 1-0.8T^{0.22} \tag{32}$$

Specimen #3

$$\phi(T) = 1-0.8T^{0.20} \tag{33}$$

where T is the time in seconds which has elapsed since ϵ equal $\epsilon_{max.}$, i.e., the time since the end of the increasing strain period; the time during which has been constant.

Equations (31), (32) and (33) were derived assuming the stress relaxation independent of strain and rate of strain.

The prediction equation (27) was reduced to two functions, the relaxable stress and the relaxation factor since the functions of the relaxed stress were found to be negligible. The relaxable stress

functions are given in equations (28), (29) and (30), and the stress relaxation factor for each specimen is given in equations (31), (32) and (33). The prediction equation for the stress of each specimen as a function of strain, strain rate, and time is gained by combining these two functions. Hence:

$$\Sigma_A(\epsilon, R, T) = \Sigma_D(\epsilon, R)\phi(T) \tag{27}$$

Specimen #1

$$\Sigma_A(\epsilon, R, T) = 70\,\epsilon R^{0.625}(1-0.8T^{0.25}) \tag{34}$$

Specimen #2

$$\Sigma_A(\epsilon, R, T) = 70\,\epsilon R^{0.465}(1-0.8T^{0.22}) \tag{35}$$

Specimen #3

$$\Sigma_A(\ , R, T) = 70\,\epsilon R^{0.40}(1-0.8T^{0.20}) \tag{36}$$

It should be noted that time T is the time during which the strain is held constant following the application of the strain at constant rate.

When the rate of strain was held constant, the stress-time curve was a straight line as shown in run Number 667 in the appendix. However, the material was found to be so sensitive to rate of strain that a small variation in the rate changes the stress considerably. It was attempted to take into consideration this sensitivity when drawing the stress-strain curves for the different rates shown in Figures 17, 19 and 21.

As an example, equations (34), (35) and (36) have been used to predict the stress at various values of strain and for different strain

rates. These predicted curves are compared to the experimental curves for the same rates in Figures 24, 25 and 26. Figure 27 is stress plotted against time for both the experimental and the theoretical results. The scope of the investigation limited the study of the stress relaxation to one strain rate for each specimen.

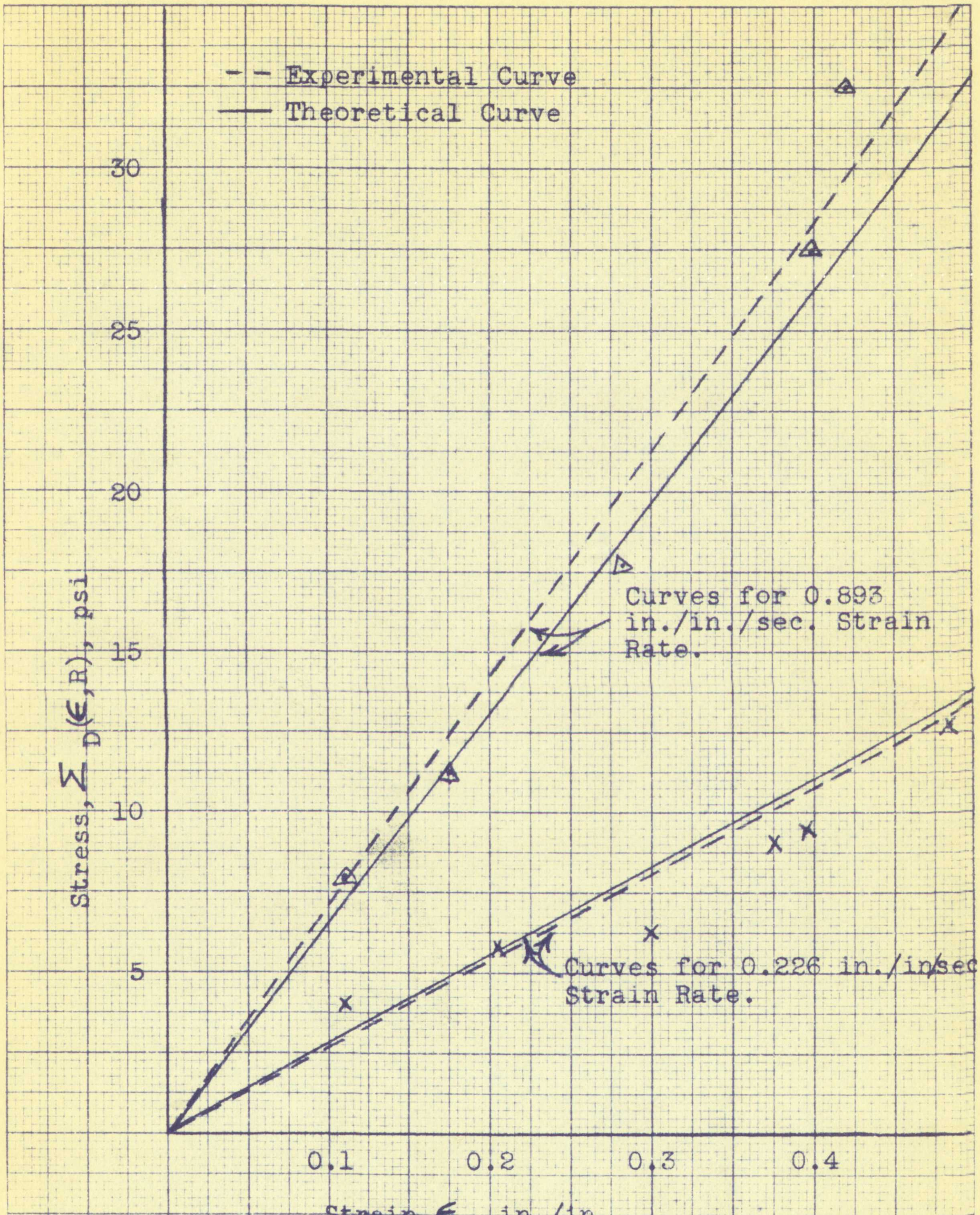


Figure 24. Experimental and Theoretical Stress-Strain Curves for Specimen #1 at 0.893 and 0.226 in./in./sec. Strain Rates.

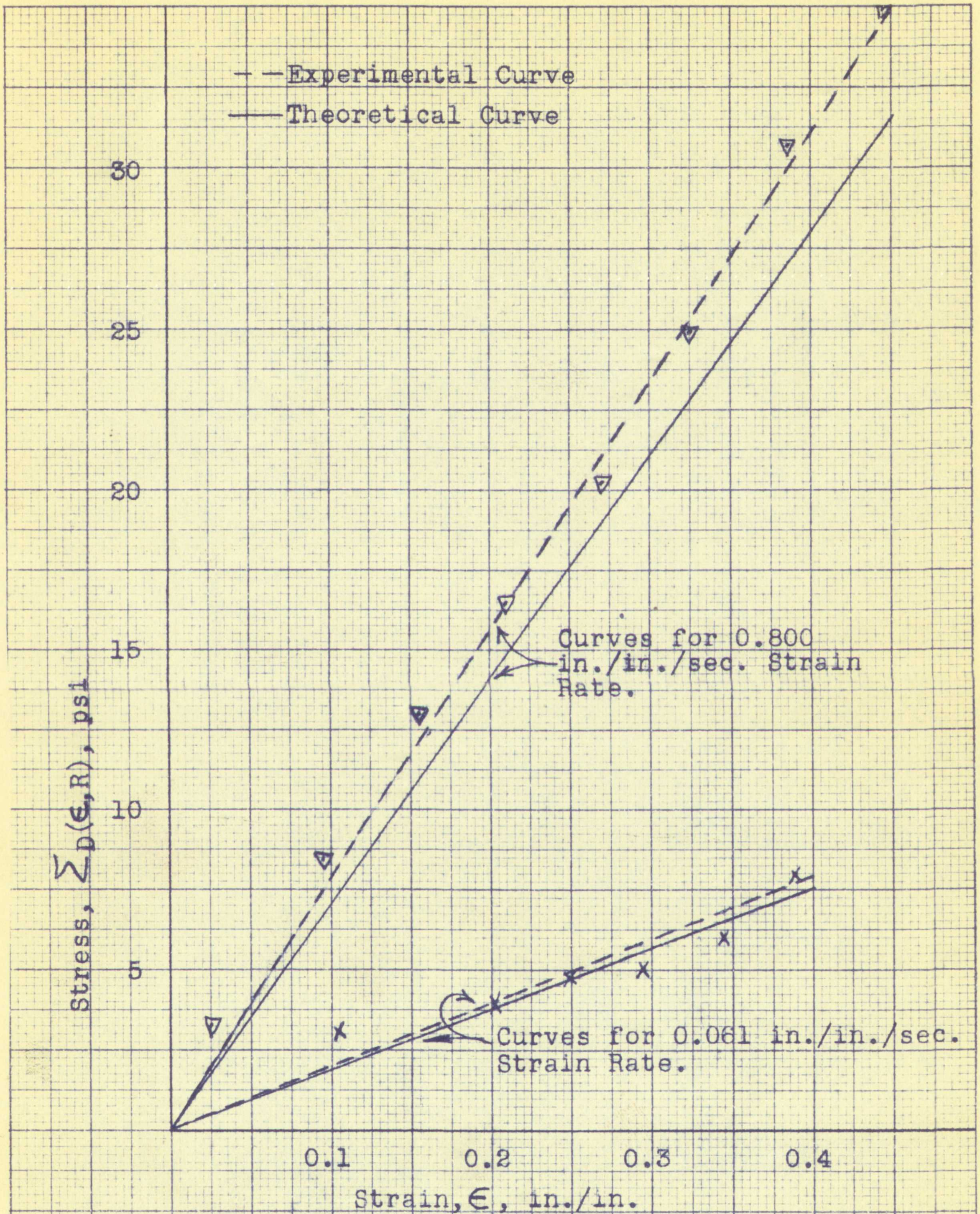


Figure 25. Experimental and Theoretical Stress-Strain Curves for Specimen #2 at 0.800 and 0.061 in/in./sec. Strain Rates.

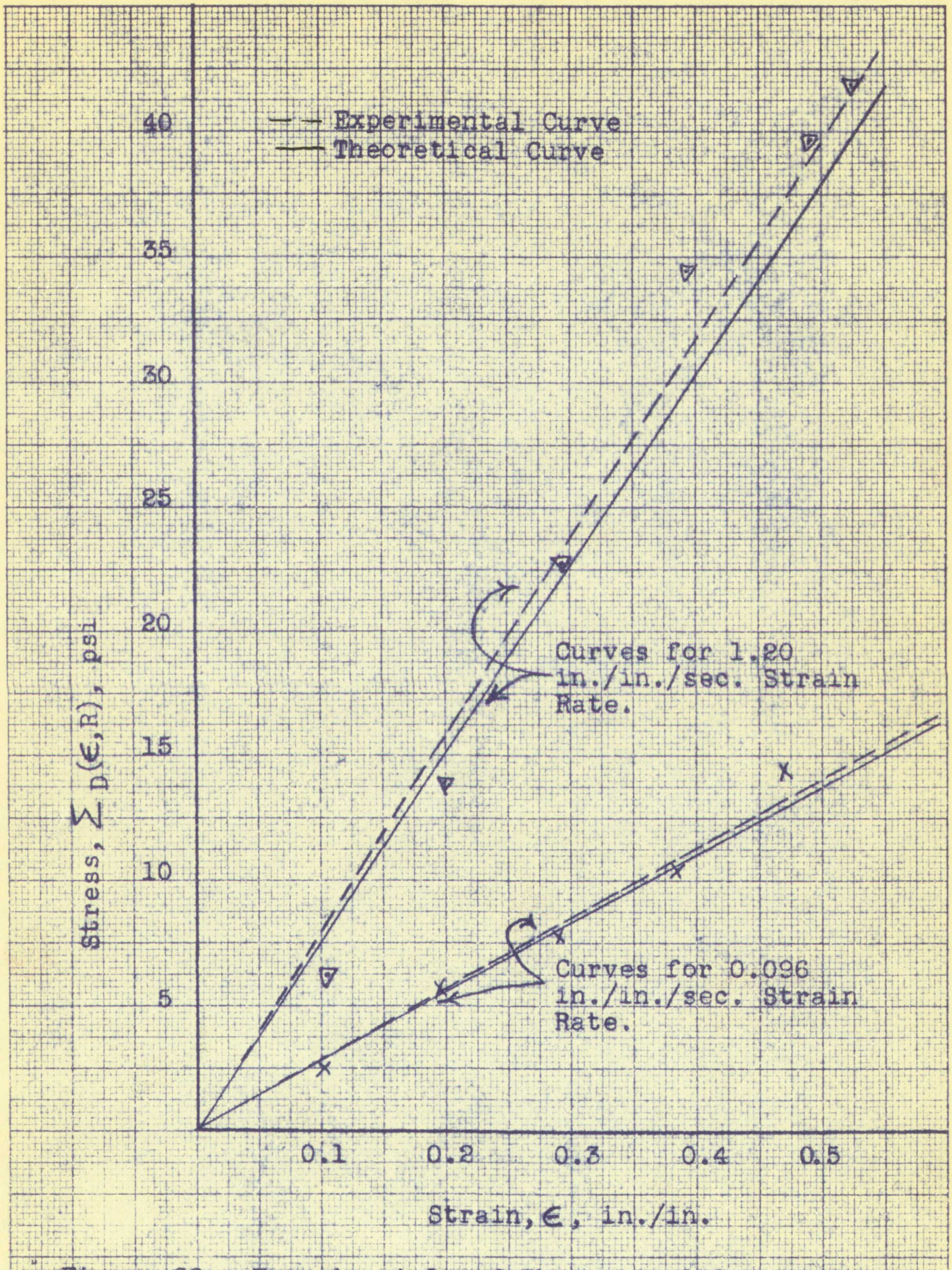
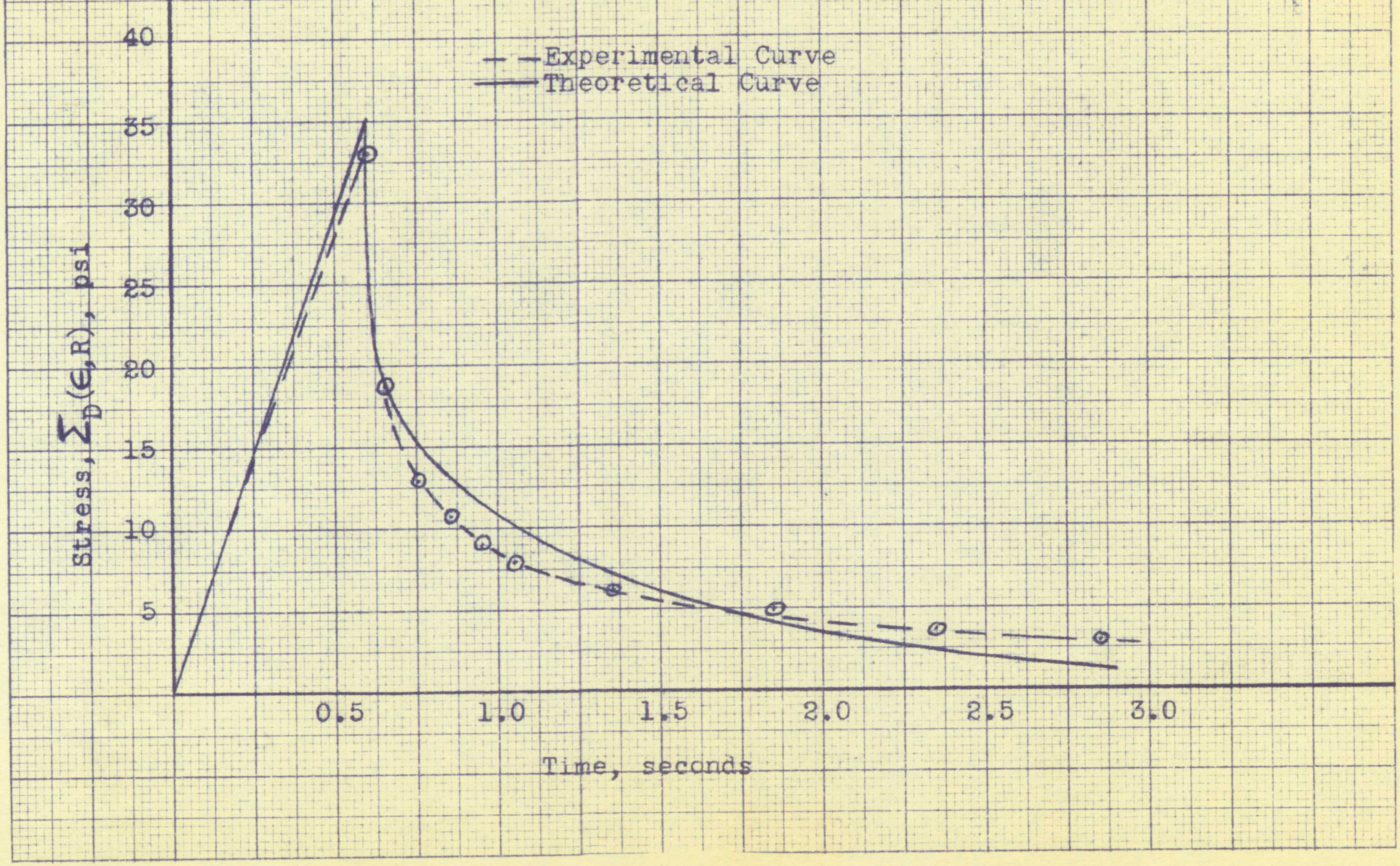


Figure 26. Experimental and Theoretical Stress-Strain Curves for Specimen #3 at 1.20 and 0.096 in./in./sec. Strain Rate.

Figure 27. Stress vs. Time Curve for Specimen #2 Strained 0.50 in/in. at a Rate of 0.91 in./in./sec. and Then Held Constant.



VIII. CONCLUSIONS

From the preliminary tests it was concluded that the stress-strain curve of both the rigid and recoverable foam plastics was sensitive to rate of strain. The rigid type foam plastics were definitely sensitive to strain rate although they were not nearly as sensitive as the recoverable type foam plastics. Figures 10 and 11 which are stress-strain curves of the two types of rigid foam plastics tested show a definite increase in the modulus with an increase in rate.

It was concluded from the preliminary investigation that the greater sensitivity of the recoverable type foam plastic would give results that would be easier to interpret and utilize. The type of recoverable foam plastic tested was extremely sensitive to rate of strain. An increase in the rate of strain from 0.0022 %/millisec. to 3.65 %/millisec. increased the modulus by a factor of approximately 20.

The test equipment that was designed and constructed proved to be entirely suitable for the rates of strain that it was designed to produce. It produces compression at speeds from 0.0087 in./sec. to approximately 15 in./sec. The minimum force that it could measure is about one pound and the maximum force is approximately 250 pounds. The range could be extended by changing transducers.

The prediction equation described the stress as a function of strain, strain rate, and time accurately over the range of variables. This can be seen by Figures 24, 25 and 26.

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It was concluded from the preliminary investigation that the greater sensitivity of the recoverable type foam plastic would give more data that would be easier to interpret and utilize. The type of recoverable foam plastic tested was extremely sensitive to rate of strain. An increase in the rate of strain from 0.002 in./in./sec. to 200 in./in./sec. increased the modulus by a factor of approximately 20.

The test equipment that was designed and constructed proved to be entirely suitable for the rates of strain that it was designed to produce. It produces compression at speeds from 0.0007 in./sec. to approximately 15 in./sec. The minimum force that it would measure is about one pound and the maximum force is approximately 250 pounds. The range could be extended by changing transducers.

The prediction equation described stress as a function of strain, strain rate, and time accurately over the range of variables. This can be seen by Figures 24, 25 and 26.

IX. RECOMMENDATIONS

As already noted, the tests described in this report were made on a limited number of types of foam plastics. Investigation is needed over a wider range of foam plastic types. The rigid plastics tested showed a definite sensitivity to rate of strain. The different types of rigid foam plastic should be tested over their entire range of densities and cures.

Only one type of recoverable foam plastic was tested. The material did have three different cures; however, no attempt was made to control the quality of the specimens. The various types of recoverable foam plastics with their different densities and cures should also be tested.

Dynamic tests should be run on all types of foam plastics over their entire range of strain. Compressing until all of the voids in the material close will cause changes in the stress-strain curve. The changes at different strain rates should be of interest.

Much work needs to be done on the standardization of specimen size of both the rigid and recoverable type foam plastics. The specimen size of material with large voids or a light density may be more critical than the more dense materials. The specimen size will affect the amount the specimen bows out on the side. This will affect the mechanical properties of the specimen. The end restraint, or the expansion at the ends perpendicular to the axis of compression of the specimen, will also affect the properties of the specimen.

The specimens used for these tests were much more dense around the

edges than at the center. An investigation should be made to find what size molds should be used and what part of the volume of the mold will produce satisfactory representative specimens. The variation in the mechanical properties between specimens and the dependence of the properties on specimen size could then be studied.

The effect of temperature on the mechanical properties of the foam plastics would be an interesting problem and a fundamental one. The variation of temperature during the tests run in this investigation was about $\pm 6^{\circ}$ from the mean of 75° F. Any difference in the mechanical properties caused by this small variation in temperature was not noticed.

Information gained from an extensive study of the stress-relaxation of the various types of foam plastics would be valuable. It is felt that a more extensive investigation will show the stress relaxation factor to be a function of strain, strain rate, and time although the relaxation curve for this material was closely approximated by making it a function only of time.

Further investigation of wave propagation and the effect of strain at still higher rates should be conducted. The rates of strain should be increased until there is a definite effect of wave propagation to find the relationship between high rates of strain and strain wave propagation. This should lead to the definition of the true dynamic properties of these materials.

Another field that deserves further investigation is the effect of different types of vibration or standing waves on the different materials. Since, when subjected to forced vibration the material is subjected to a certain rate and duration of strain, it should be feasible to predict the

effect of vibration by use of rate of strain and stress relaxation equations.

In the investigation described in this report, the materials were strained at only constant rates. It should be possible to predict the results at non-linear rates of strain and by the use of proper cams on the testing machine, check the prediction equation.

Another interesting problem would be to compress the specimens at different rates to different strains, hold the strain constant for different periods of time, then release the specimen and check its rate of return to its original shape. Other variations of this experiment would be to compress the specimen at different rates and check its rate of strain when subject to constant stresses for different periods of time (i.e., creep tests).

An investigation of the effect of density upon the dynamic stress-strain curve might reveal a method of predicting the stress-strain curve for a general type of material without running tests on each different type of material.

A recommended improvement on the equipment is the use of a magnetic brake to hold the compression rod so that the maximum strain on the specimen may be held constant. Also, the flywheel, clutch, and cam should be better balanced to reduce the vibration of the machine and the effect of vibration on the results. Higher rates of compression can be produced by designing new cams. If rates of strain in the range where strain wave propagation has an effect are desired, a new machine should be designed. It would be desirable to isolate as many parts as possible to reduce the effect of all vibration that will be introduced.

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8. LITERATURE CITED

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XI. ACKNOWLEDGMENTS

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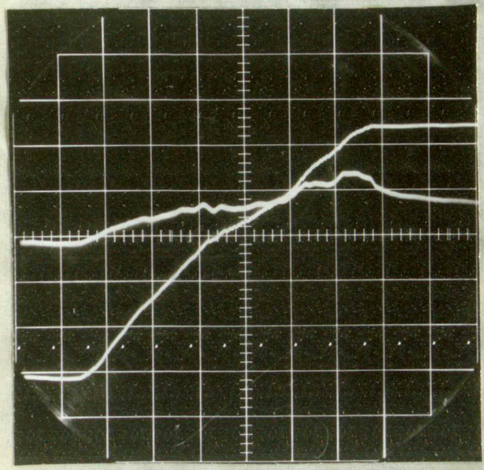
XII. APPENDIX

Records and Data from Evaluation and Calibration Tests

The following data was taken from the Hewlett-Packard Oscillograph, Model 130A, with a 35mm DuMont Oscillograph Camera, Type 296. Two traces appear in each picture. One trace is stress-time and the other trace is strain-time. The stress-strain and stress-time tables which appear later in the appendix were derived from these curves. The calibration graphs for these curves are shown on pages 64 and 65.



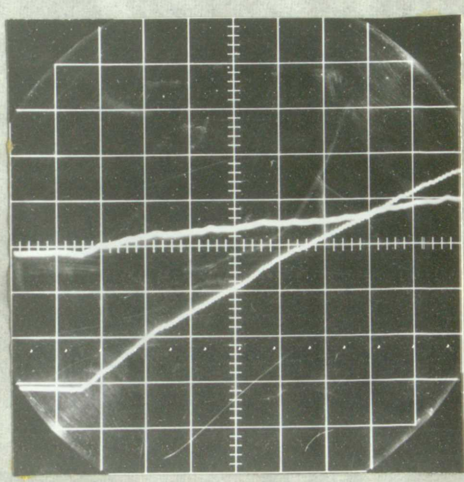
Run Number 635

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 2 sec./cm



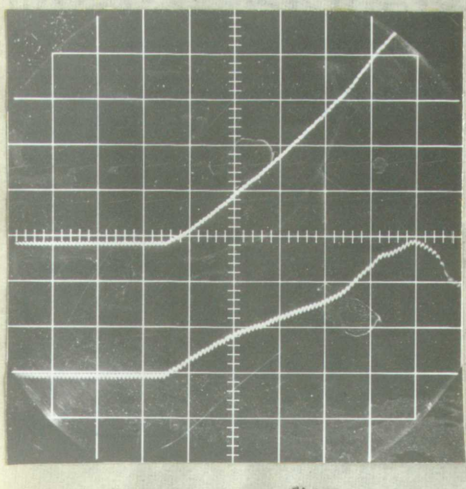
Run Number 637

Specimen #2

Top Trace - Stress vs. Time

Bottom Trace - Strain vs. Time

Sweep Speed - 2 sec./cm



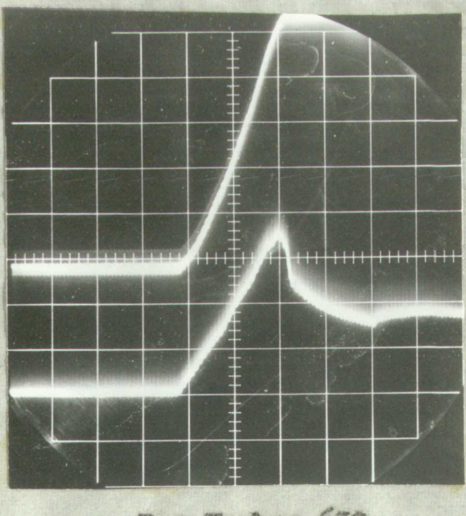
Run Number 647

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.2 sec./cm



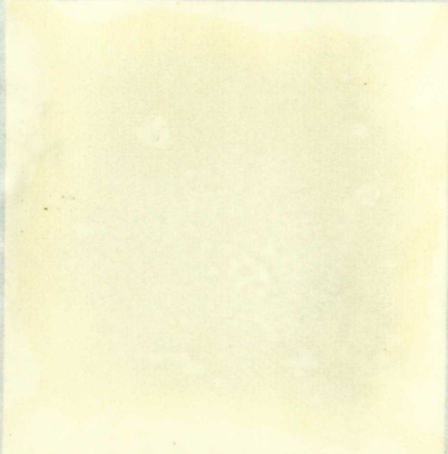
Run Number 650

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.2 sec./cm



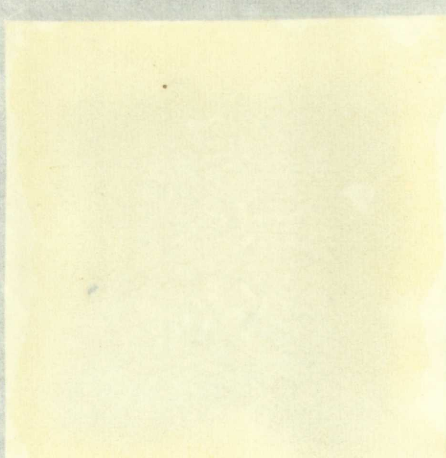
Run Number 635

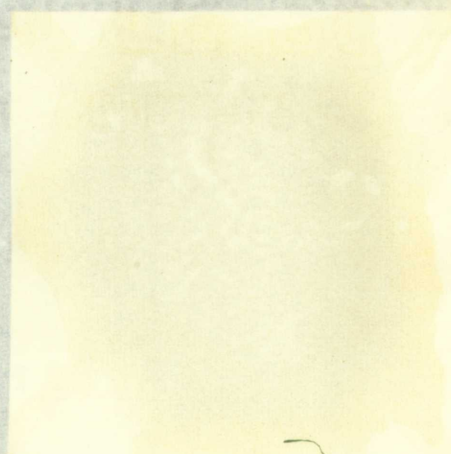
Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 2 sec./cm





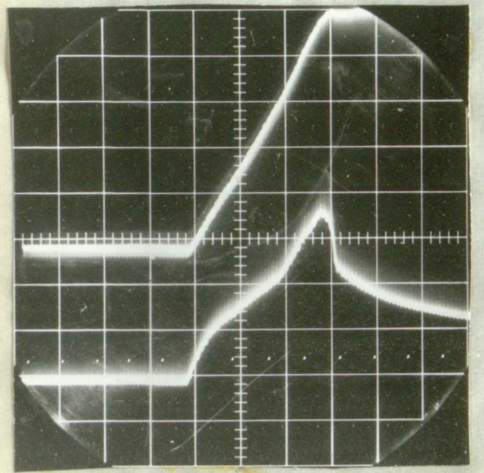
Run Number 647

Specimen #4

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.2 sec./cm



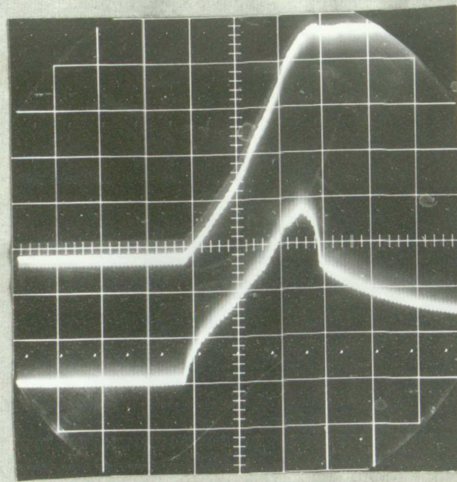
Run Number 651

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.2 sec./cm



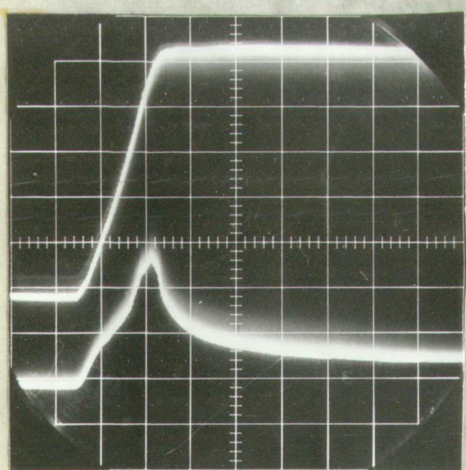
Run Number 652

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.2 sec./cm



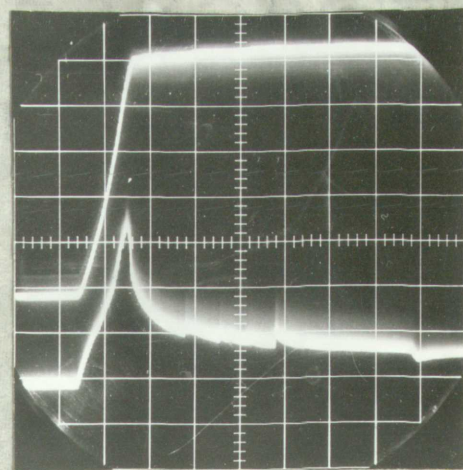
Run Number 666

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



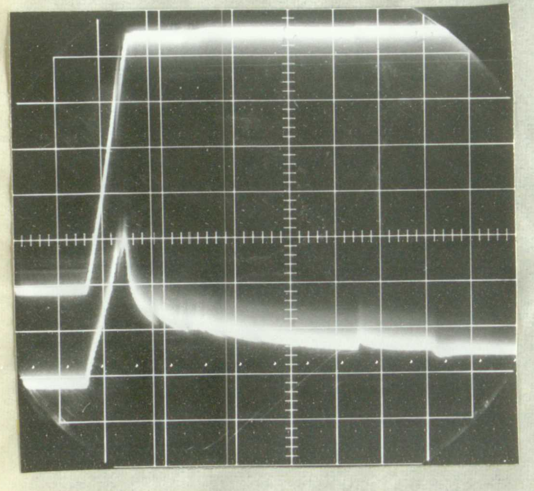
Run Number 667

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



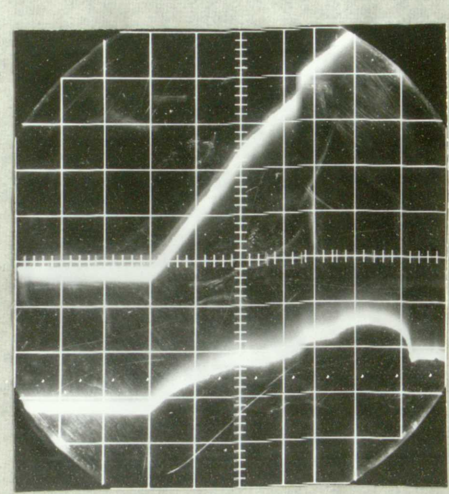
Run Number 668

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



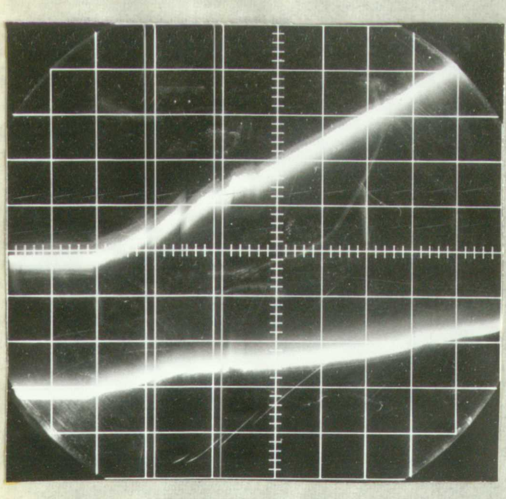
Run Number 672

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



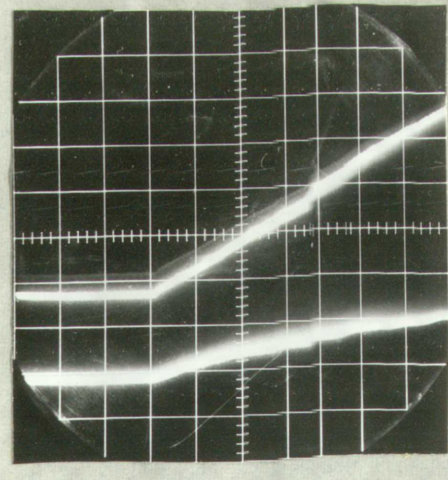
Run Number 673

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



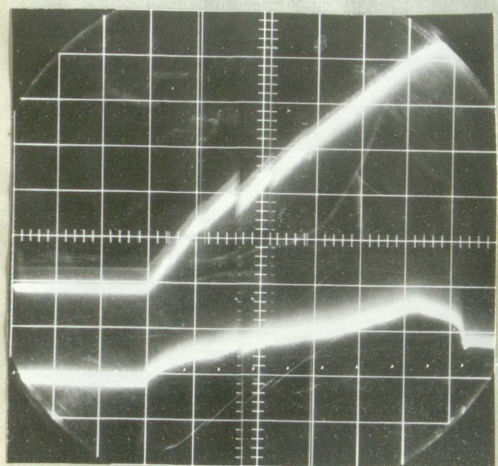
Run Number 676

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



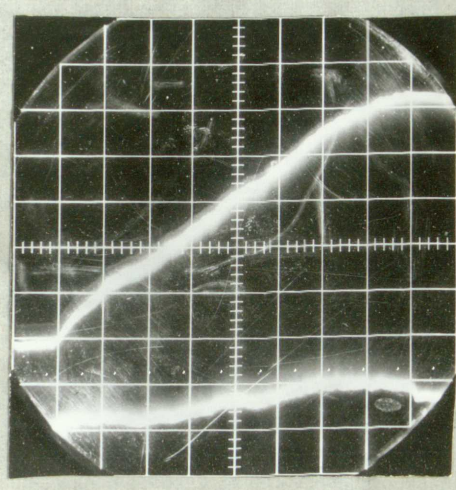
Run Number 678

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 0.5 sec./cm



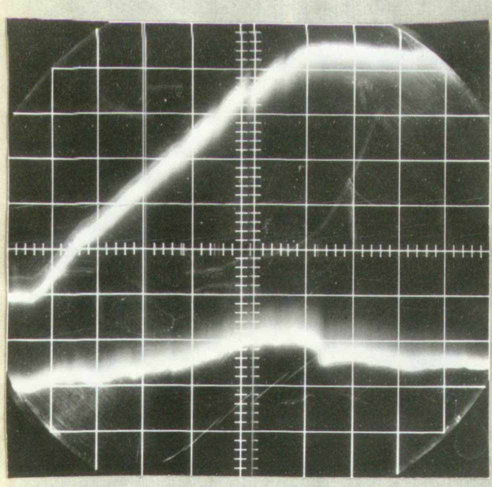
Run Number 679

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 5 sec./cm



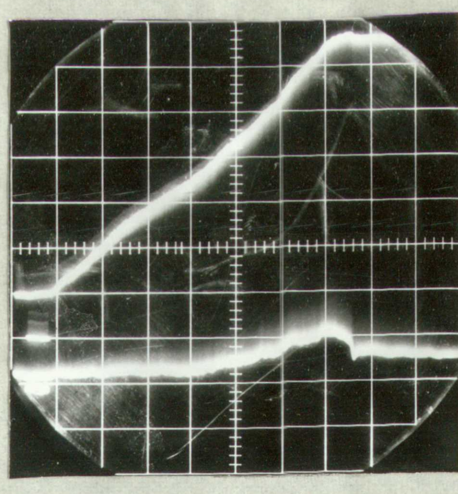
Run Number 680

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 5 sec./cm



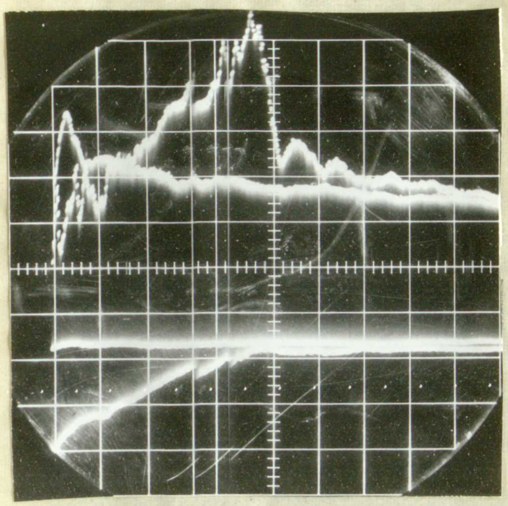
Run Number 681

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 5 sec./cm



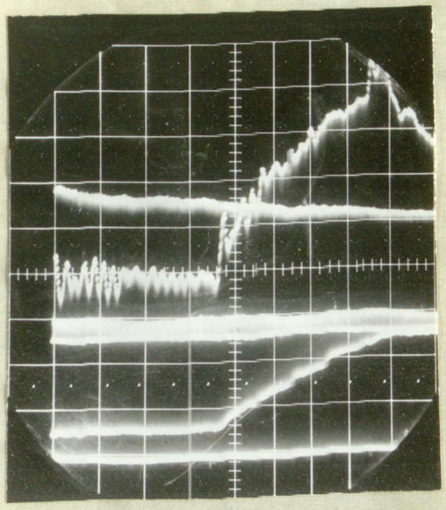
Run Number 690

Specimen #11

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 5 millisec./cm
(2 sweeps of trace)



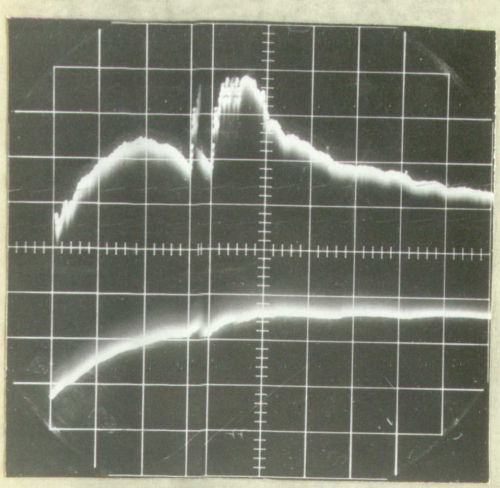
Run Number 691

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 5 millisec./cm
(3 sweeps of trace)



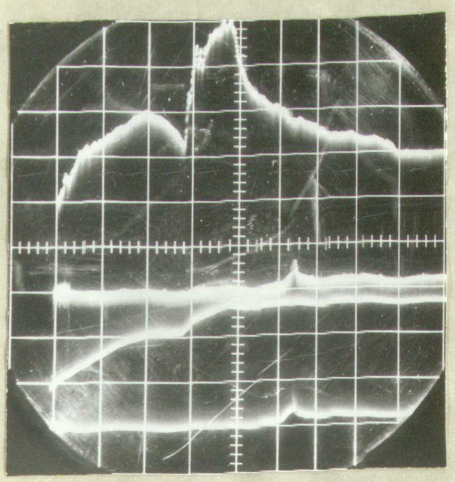
Run Number 693

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 10 millisec./cm



Run Number 694

Specimen #2

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 10 millisec./cm

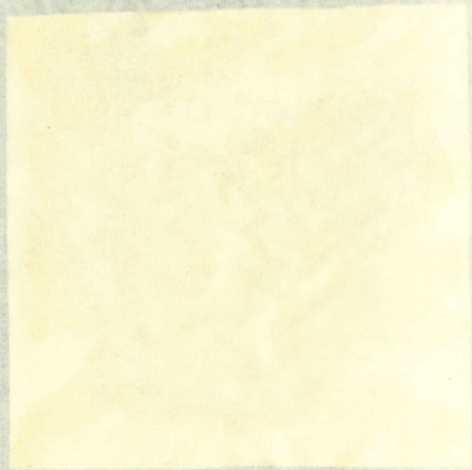
Run Number 590

Specimen #1

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - [illegible] millisec./cm
(2 sweeps of trace)



Run Number 593

Specimen #3

Top Trace - Strain vs. Time

Bottom Trace - Stress vs. Time

Sweep Speed - 1.0 millisec./cm

Note:

1. Vertical sensitivity of oscilloscope- 0.05 volts/cm. Hewlett-Packard, Model 130A.

2. Attenuation of DuMont Electronic Switch, Model 330— 100

3. Gain of G.E. Oscilloscope, Type ST-2B, used as a pre-amplifier- maximum

4. Bridge current for the strain gage bridge- 5 milliamp.

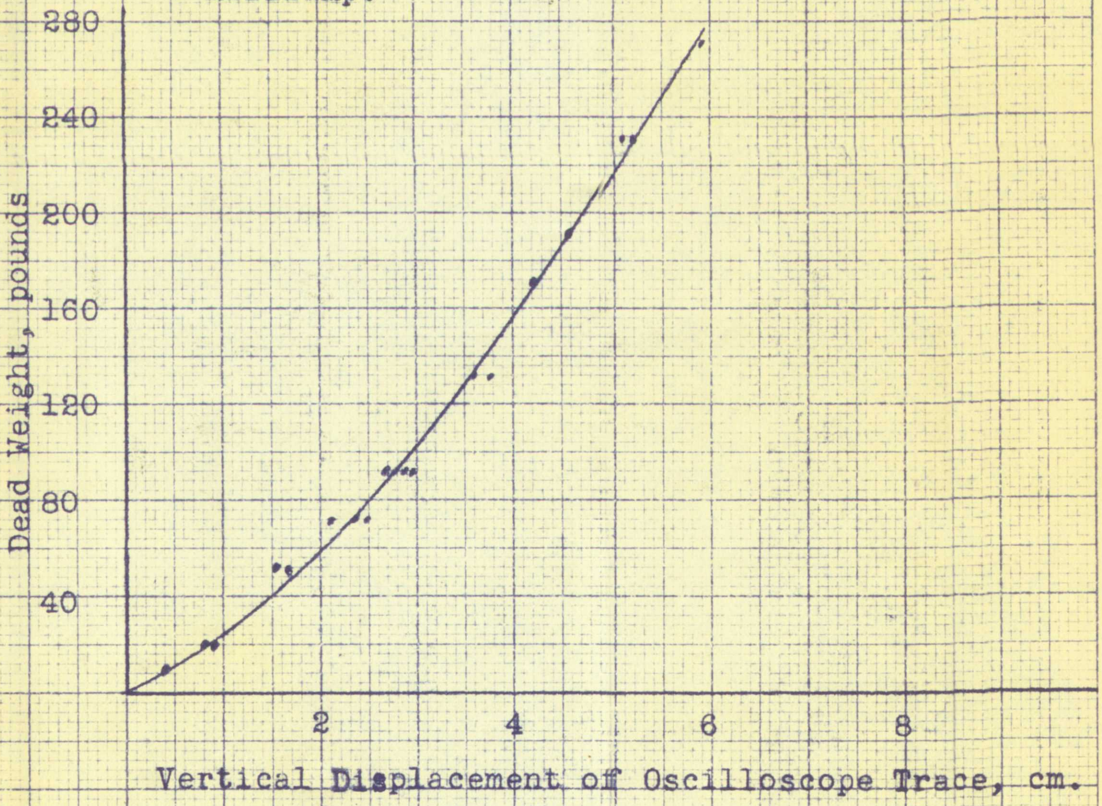


Figure 28. Stress Calibration Curve.

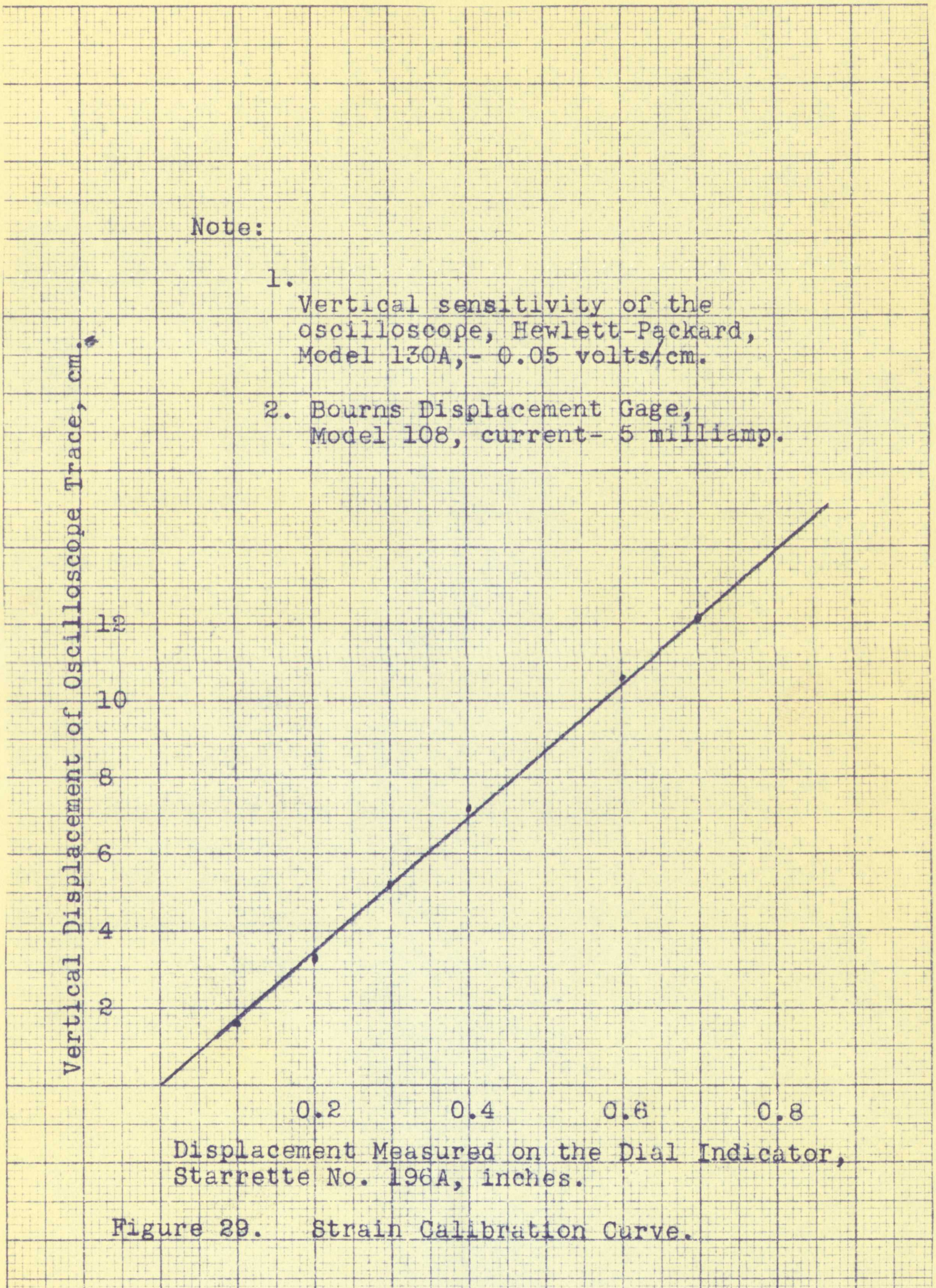


Figure 29. Strain Calibration Curve.

TABLES

Stress-Strain

Specimen #1

Run Number 647

Strain Rate - 0.446 $\frac{in./in.}{sec.}$

Strain, in./in.	Stress, psi
0.019	1.0
0.115	7.0
0.211	8.5
0.307	12.5
0.365	16.5
0.403	20.75
0.450	22.0

Run Number 672

Strain Rate - 0.226 $\frac{in./in.}{sec.}$

Strain, in./in.	Stress, psi
0.111	4.0
0.206	5.75
0.302	6.25
0.374	9.0
0.398	9.5
0.485	12.75

Run Number 679

Strain Rate - 0.0136 $\frac{in./in.}{sec.}$

Strain, in./in.	Stress, psi
0.096	0.4
0.288	2.25
0.384	3.0
0.480	5.0

Run Number 61

Strain Rate - 0.83 $\frac{i./in.}{sec}$

Strain, in./in.	Stres, psi
0.110	8.0
0.168	11.4
0.283	17.5
0.425	38.4
0.492	35.75

Run Number 66

Strain Rate - 0.12 $\frac{i./n.}{ec}$

Strain, in./in.	Stres, psi
0.024	0.6
0.120	2.6
0.260	4.1
0.312	6.1
0.384	9.0

Run Number 69

Strain Rate - 22.60 $\frac{i./in.}{ec}$

Strain, in./in.	Stres, psi
0.048	5.75
0.096	17.25
0.192	20.25
0.288	33.75
0.384	35.5

TABLES

Stress-Strain

Specimen #2

Run Number 637

Strain Rate - 0.0256 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.010	0.25
0.029	0.75
0.105	1.25
0.202	2.0
0.307	3.6
0.403	5.75
0.460	6.5

Run Number 652

Strain Rate - 0.800 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.021	3.3
0.098	8.5
0.155	13.0
0.213	16.5
0.271	20.25
0.328	25.0
0.386	30.75
0.443	35.0

Run Number 673

Strain Rate - 0.061 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.105	3.0
0.202	4.0
0.250	4.75
0.298	5.0
0.346	6.0
0.394	8.0

Run Number 680

Strain Rate - 0.0144 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.096	1.0
0.192	1.25
0.288	2.75
0.384	4.25
0.480	6.25
0.500	7.0

Run Number 694

Strain Rate - 10.85 $\frac{in./in.}{sec.}$	
Stress, in./in.	Stress, psi
0.029	8.5
0.048	14.5
0.067	16.5
0.105	18.5
0.144	22.0
0.221	27.0

TABLES

Stress-Strain

Specimen #3

Run Number 635

Strain Rate - 0.0435 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.105	2.62
0.202	3.77
0.293	5.88
0.394	7.85
0.490	13.1

Run Number 650

Strain Rate - 1.20 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.105	6.3
0.202	14.0
0.291	22.9
0.394	34.6
0.513	41.8

Run Number 678

Strain Rate - 0.096 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.101	3.77
0.197	5.8
0.293	7.97
0.388	10.5
0.485	14.9

Run Number 681

Strain Rate - 0.0171 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.072	0.32
0.168	0.785
0.265	1.7
0.360	2.94
0.455	5.23
0.505	6.53

Run Number 691

Strain Rate - 15.4 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.019	6.54
0.038	7.84
0.077	14.0
0.115	25.5
0.153	26.5

Run Number 693

Strain Rate - 9.36 $\frac{in./in.}{sec.}$	
Strain, in./in.	Stress, psi
0.034	4.9
0.073	11.2
0.150	18.3
0.188	23.2

TABLES

Stress-Time

Specimen #1

Run Number 666

Time, seconds	Stress, psi
0.00	24.25
0.05	17.25
0.10	16.75
0.20	14.0
0.40	7.5
0.60	6.1
0.90	5.0
1.40	4.75
2.40	3.1

Specimen #2

Run Number 667

Time, seconds	Stress, psi
0.00	33.0
0.01	29.0
0.05	18.75
0.15	13.1
0.25	10.75
0.35	9.0
0.45	8.0
0.55	7.25
0.75	6.25
1.25	5.0
1.75	3.75
2.25	3.2
3.25	2.75

Specimen #3

Run Number 668

Time, seconds	Stress, psi
0.00	36.2
0.05	23.5
0.075	20.6
0.100	19.3
0.150	16.0
0.200	14.4
0.300	13.7
0.800	8.5
1.30	6.82
1.80	6.2