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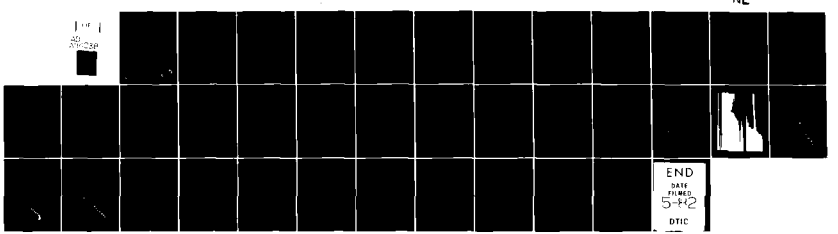

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Technical Report No. 16

THE EFFECT OF STRAIN UPON THE VELOCITY OF SOUND AND THE VELOCITY OF FREE RETRACTION FOR NATURAL RUBBER

by

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May, 1982

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Measurements have been made of the velocity of sound and the velocity of free retraction for stretched strips of vulcanized natural rubber. Both of these velocities are found to increase markedly with increasing strain, in agreement with earlier work. The velocity of sound is shown to be related to the appropriate modulus of elasticity, defined by the slope of the curve relating true stress to tensile strain. Values

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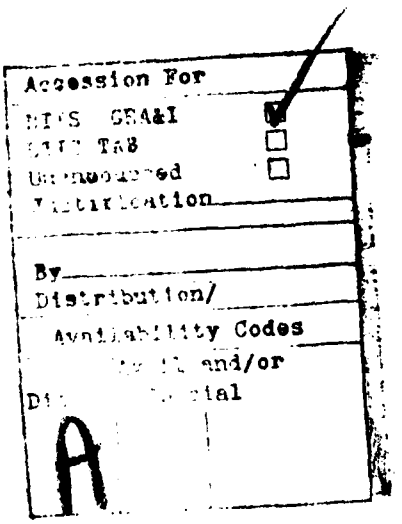
obtained range from about 50 to about 800 m/s. The effects of prior stretching and of stress relaxation on the velocity of sound are shown to arise from corresponding changes in the modulus of elasticity at a given strain. The velocity of free retraction is shown to be directly related to the velocity of sound in the stretched strip, and to the imposed tensile strain, increasing from zero up to about 100 m/s at high strains.



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1. Introduction

When a strip of rubber is stretched to a certain strain and then suddenly released at one end, it undergoes retraction at relatively high speeds. At the instant that the strip is released an unloading pulse begins to move through the strip. Ahead of this pulse the rubber is still in the original state of strain while behind it the rubber has become virtually unstrained and is moving at the retraction velocity, Figure 1. The pulse itself may be thought of as a transition region within which the strain is a complicated function of time and position. It moves through the strip at the velocity of sound.

Not many studies of the process of retraction in a rubber strip can be found in the literature. A very early measurement of the velocity of the unloading pulse was reported by Exner in 1874 (1). He was interested in the effect of temperature on the modulus of natural rubber. As the velocity of the unloading pulse, i.e., the velocity of sound, is dependent on the modulus of the rubber, any change in its value with temperature will reflect a similar change in the modulus. More recently, Mason (2) has analyzed the unloading pulse and derived equations for the velocity of any part of the pulse in terms of the slope of an unloading force-strain curve, the strain itself, and the linear density of the rubber strip.

Experimental measurements of the velocity of retraction have been reported by several researchers in some detail (3-5). Strong effects were found of the strain level, the elastomer used, the filler content and the test temperature. However, no quantitative

comparison was made between the velocity of retraction and the velocity of the corresponding unloading pulse. James and Guth gave a theoretical treatment of retraction, but their solution is limited to small strains (6).

In order to examine the retraction of a rubber strip in greater detail, measurements have now been made of the velocity of sound as a function of strain and of the velocity of retraction from a finite strain, for natural rubber strips, both carbon-black-filled and unfilled. The results are presented below.

2. Experimental details

(i) Materials used

Rubber sheets were prepared using the mix formulations and vulcanization conditions given in the Appendix. Test strips were cut from the sheets about 250 mm long, 10 mm wide, and 0.5 mm thick. Measurements were made of the density of each rubber compound employed. They were found to be 970 kg/m^3 for the unfilled natural rubber vulcanizate A and 1130 kg/m^3 for the carbon-black-filled vulcanizate B.

Measurements were made of the tensile stress-strain relationship for each material, using an Instron test machine operating at a crosshead speed of 20 mm/min corresponding to a strain rate of about $1 \times 10^{-2}\ s^{-1}$. The true stress σ was calculated from the measured force F at any level of tensile strain e:

$$\sigma = F\,(1 + e)/A_0$$

where A_0 is the cross-sectional area of the test strip in the unstrained state. Values of the instantaneous slope of the relation

between true stress $\underline{\sigma}$ and strain $\underline{e}$, denoted here the instantaneous modulus $\underline{E}$,

$$E = \partial\sigma/\partial e ,$$

were determined using several different modes of straining. In the first, the sample was simply taken up to the strain $\underline{e}$ at a constant rate of stretching. In the second, the sample was taken to a strain $\underline{e}$ and then held at this strain for a period of 2 minutes to allow it to relax. After this the sample was loaded further. The slope of the initial portion of the stress-strain curve after loading was resumed was then noted. It was found to be considerably larger than before, Table 1. In the third method, the sample was again loaded to a strain $\underline{e}$. The strain rate was then immediately reversed and the sample taken back to the unstrained state. The slope of the initial portion of an unloading curve was determined in this way.

Three different values for the instantaneous modulus $\underline{E}$ were thus determined at a given strain level $\underline{e}$. Some representative values are given in Table 1.

(ii) Measuring the velocity of sound

Measurements of the velocity of sound in a thin strip of rubber were made using the experimental arrangement shown in Figure 2. The sample was stretched to the desired degree, and clamped to a metal frame. Two phonograph cartridge needles were then placed in contact with the top surface of the sample. The cartridges were held in place by mounts attached to the frame.

A metal rod pendulum was attached to the sample near one end, as shown in Figure 2. By tapping the pendulum on the side opposite that of the cartridges a small unloading stress pulse could be made to travel along the sample towards the cartridges. Alternatively, by tapping on the other side, a small loading stress pulse could be made to travel along the sample.

The output of the phonograph cartridges was monitored with a storage oscilloscope. From the difference in time for the loading or unloading pulse to reach the two pickups, placed at a known distance apart, the velocity of sound in the rubber was measured.

The oscilloscope trace was triggered by taking advantage of the fact that the velocity of a stress pulse in metal is much higher than in rubber. When the pendulum was tapped, a signal traveled through the frame in addition to the one transmitted through the sample and reached the phonographic cartridges long before the signal passing through the rubber. This initial pulse was used to trigger the oscilloscope trace.

(iii) Measuring the velocity of retraction

Measurements of the velocity of retraction were made using the experimental arrangement shown in Figure 3. The stretched sample was placed so that its lower end obstructed the optical path of a ½ milliwatt laser light source, aimed at an optical trigger. When the rubber strip was released and the light beam reached the optical trigger, it caused three photographic flash tubes to fire in rapid succession, and also triggered an oscilloscope trace. The oscilloscope was used to indicate the intensity

of light in the room and thus the instant at which each flash was fired. In this way the elapsed time between flashes was measured. The apparatus was set up in a dark room with a 35mm camera focused on the sample. The shutter of the camera was kept in the open position.

The bottom end of the sample was held by a small lightweight clamp attached to the frame with a piece of string or wire. The sample was released by cutting the string or wire with scissors. As the sample retracted,it allowed the laser beam to illuminate the optical trigger, and thus started the oscilloscope trace and fired the three flashes, giving a triple exposure. By measuring the distances moved by the retracting end between the three exposures and by determining the corresponding time intervals between flashes, the mean velocity $\underline{v_r}$ of retraction of the strip was determined.

It was found that the flash duration of the flashtubes (Spiralite Sr., Spiratone Inc.) was too long, about 1 ms, to give good enough resolution of the moving strip on the photographic film to allow the velocity of retraction to be determined accurately. The duration of a photographic flash depends upon the discharge rate of a storage capacitor within the unit. These were found to be electrolytic paper-wound capacitors with a rather high inductance and voltage-decay time. They were therefore replaced with oil-filled foil-wound capacitors, having virtually no inductance compared to the electrolytic type. A lower capacitance was selected also, which further reduced the duration of

the flash to about 100 μs. The rise time to maximum intensity was reduced to less than 10 μs in this way, and satisfactory triple exposures were obtained. A representative photograph is shown in Figure 4.

In order to determine the effect of the mass of the lower clamp upon the velocity of retraction, measurements were made using two different clamps, one weighing only about 0.2 g and the other about 2 g. No measurable effect was found on the observed velocity of retraction in the range 10 - 40 m/s, Figure 5. It is concluded that the use of lightweight clamps does not affect the velocity of retraction significantly. It should be noted, however, that measurements were made only after the strip end had retracted about 100 mm in order to avoid the initial acceleration of the clamp.

3. Results and discussion

(i) Velocity of sound

Experimental results for the velocity v_s of sound are plotted in Figure 6 against the imposed strain. For unfilled natural rubber the results were not affected significantly by prestretching the strip to a larger extension before carrying out measurements at a given extension. For the carbon-black-filled material B, however, there was a pronounced reduction in v_s at all strains less than the previously-imposed value. As the imposed strain approached the prior strain, the velocity of sound increased sharply towards the initial value. This effect of prestretching is similar to the characteristic stress-softening shown by filled rubber. It reflects the reduction in instantaneous modulus, as described later.

For both filled and unfilled materials there is clearly a pronounced effect of the imposed strain. The velocity of sound increases from about 60 m/s at zero strain up to about 600-800 m/s at high strains for the unfilled material A, and for the filled material B it reaches 800 m/s at relatively modest strains, starting from about 160 m/s at zero strain. These results undoubtedly reflect the increase in instantaneous modulus (strain-hardening) as the rubber is subjected to increasing strains. The quantitative relationship between the velocity of a stress pulse and the instantaneous modulus of elasticity is explored in the following section of the paper.

(ii) Relation between the velocity of sound and the instantaneous modulus of elasticity

The velocity of sound is clearly related to the elastic modulus

of the rubber but the form of the relationship is not an obvious one for stretched strips. A brief derivation is given here. Consider an element of the strip, of length dx and cross-sectional area A in the strained state. The mass of the element is given by $\rho A\, dx$ where ρ is the density of the rubber, assumed to be independent of strain in view of the virtual incompressibility of rubber (7). The motion of the element is governed by the relation

$$\partial F/\partial x = \rho A \left(\partial^2 u/\partial t^2\right) \qquad (2)$$

where $\partial F/\partial x$ denotes the rate of change of tension F along the strip, i.e., in the x direction, and u denotes the additional small displacement in the x direction caused by the stress pulse.

An effective modulus of elasticity E' may be defined as

$$E' = (1/A)\left(\partial F/\partial e'\right) \qquad (3)$$

where e' is the incremental strain $\partial u/\partial x$ referred to the strained state. The term $\partial F/\partial x$ in equation 2 is then given by

$$\partial F/\partial x = AE'\left(\partial^2 u/\partial x^2\right)$$

and the velocity v_s of sound is obtained from equation 2 as

$$v_s = (E'/\rho)^{\frac{1}{2}}. \qquad (4)$$

It is now necessary to relate the effective modulus E', defined by equation 3, to the instantaneous modulus E. From the definition of E, equation 1,

$$\begin{aligned} E &= \partial\,(F/A)/\partial e \\ &= (1/A)\left(\partial F/\partial e\right) + \sigma/(1+e) \end{aligned} \qquad (5)$$

In the definition of E', equation 3, the incremental strain e' is referred to the strained state. Using the unstrained state as the reference state instead,

$$E' = (1/A)(1+e)\left(\partial F/\partial e\right).$$

Hence, from equation 5,

$$E^1 = (1 + e)\, E - \sigma,$$

and from equation 4,

$$v_s = [(1 + e)\, E - \sigma]^{\frac{1}{2}} / \rho^{\frac{1}{2}}. \qquad (6)$$

This relation is equivalent to that derived by Mason (2) for the velocity of an unloading pulse in a stretched strip. In the small-strain limit it reduces to that obtained by James and Guth (6),

$$v_s = (E/\rho)^{\frac{1}{2}}.$$

(iii) Comparison between theory and experiment for v_s

Values of the velocity of sound were calculated from equation 6 using values of the instantaneous modulus E determined in various ways. When E was obtained from the slope of experimental relations between true stress and strain during continuous loading, the resulting values, represented by broken curves in Figure 6, did not show good agreement with experimental data for v_s. The calculated values were far too low at high strain levels. When E was obtained from the slope of unloading relations between true stress and strain, the results were considerably higher and agreed reasonably well with the measured values of v_s. These results are represented by full curves in Figure 6.

Now the velocities v_s of a stress pulse were determined for both an incremental loading pulse and for an incremental unloading pulse. They were found to be indistinguishable. However, in all cases the sample had been held stretched for several minutes before the measurement was made. It was found that values of E determined for material B on beginning to stretch further a specimen that had been rested in this way were relatively large, similar to those obtained on unloading and considerably higher than those obtained during steady

extension, Table 1. The corresponding relation for v_s is represented by the chain curve in Figure 6.

(iv) Velocity of retraction

Experimental measurements of the velocity v_r of retraction are plotted in Figure 7 against the imposed strain e. The filled circles denote results obtained for the carbon-black-filled material B, stretched for the first time to the extension e and then released. The crosses denote results obtained when the strip had been stretched previously to $e = 2.5$. The open circles represent the results for the unfilled natural rubber compound A, for which no significant effect of prestretching was found.

It is seen that the retraction velocity increases with the level of imposed strain in all cases. It is considerably higher for the filled material B than for the unfilled material A but after a large prestretch the softened material B retracts with about the same velocity as A, for strains up to the level of prior straining.

(v) Relation between the velocity of retraction and the velocity of sound

The retracting strip can be divided into three parts. Ahead of the unloading pulse, a part of the strip, of unstretched length L_1 has not yet undergone any retraction and is therefore still stationary, at the strain e. The unloading pulse itself occupies a transition region, of unstrained length L_2, with material at one end still stretched to a strain e and material at the other end already relaxed to zero strain. The ends of the unloading pulse are also moving at different velocities, in general, one end with the velocity v_s of sound at a strain level e and the other end with the velocity of sound, denoted v_0, in an

unstretched strip. The average strain in the unloading pulse is denoted by $\bar{e}$ and its unstretched length by L_2. As a result of the generally higher velocity v_s of the leading end, the pulse will generally increase in length as it travels along the strip. The already-relaxed part of the strip is assigned a length L_3. Thus, the overall stretched length L of the strip is given by

$$L = (1 + e) L_1 + (1 + \bar{e}) L_2 + L_3$$

and the velocity v_r of retraction of the free end by

$$v_r = - dL/dt$$

$$= v_s e/(1 + e) - (v_s - v_o)\bar{e}/(1 + \bar{e}) \qquad (7)$$

An attempt was made to calculate values of the velocity - weighted mean strains $\bar{e}$ from the experimentally-determined relations between the velocity of sound and strain, Figure 6. The values obtained were $0.73e$ for the unfilled material A and $0.85e$ for the filled material B, in place of the expected value of $0.5e$ for a linear dependence of velocity upon strain.

(vi) Comparison between theory and experiment for v_r

Using the above values for $\bar{e}$, the retraction velocities for both materials were calculated by means of equation 7, using the experimentally-determined relations for the velocity of sound. The results are represented by the full curves of Figures 8 and 9 and are seen to describe the experimentally-measured retraction velocities with reasonable success. For the filled material B, the velocities of sound in a prestretched strip were employed in equation 7, because the material undergoing retraction has, of course, been previously stretched.

It may be concluded that equation 7 accounts satisfactorily for the observed velocities of retraction of stretched rubber strips in terms of the velocities of stress pulses. Those velocities, in turn, can be calculated from the elastic properties of the material by means of equation 6.

4. Conclusions

Velocity of sound

1. The velocity of sound has been found to depend strongly upon the level of imposed strain in both unfilled and filled natural rubber. In unfilled NR it increased with increasing strain from an initial value of about 55 m/s at zero strain. In carbon-black-filled NR the velocity of sound initially decreased somewhat up to about 30% strain after which it increased markedly. The initial value in this case was about 160 m/s. Depending upon the particular value of strain, the velocity of sound was 3 - 10 timeshigher in the filled rubber than in the unfilled rubber.

2. The velocity of sound is expected to be a function of the modulus of the material and accordingly should be affected by stress-softening. Measurements on filled NR showed that this was, indeed, the case. Prior stretching of the sample to a higher strain led to a substantial decrease in the velocity of sound.

3. Simple theoretical considerations lead to a relation for the velocity of sound in stretched rubber, given in equation 6 in terms of the instantaneous slope $\underline{E}$ of the relation between true stress and strain. This relation was found to give good agreement with measured values as long as care was taken to determine the modulus $\underline{E}$ in an appropriate way. In particular, stress relaxation must be taken into account. However, it was not found necessary to take into account the different rates of extension in stress pulses compared to those employed for determining $\underline{E}$. Apparently viscoelastic effects are not important in natural rubber over this range of rates.

Velocity of retraction

1. The velocity of retraction was found to increase more or less linearly with increasing strain for stretched strips of both filled and unfilled NR. It was found to be about twice as large for filled NR as for unfilled NR, on release from the same strain.

2. Stress softening was found to have a pronounced effect on the velocity of retraction for filled NR. After a large prestrain, the velocity was reduced to a value similar to that for unfilled NR.

3. The velocity of sound and the velocity of retraction have been shown to be related by equation 7, using a mean strain $\bar{e}$ for the unloading pulse that lies between the imposed strain e and zero. From the relations between the velocity of sound and strain, maximum values of $\bar{e}$ were deduced of about $0.85e$ for filled NR and $0.73e$ for unfilled NR. These values gave good agreement with the measured retraction velocities over a wide range of strains although the results are not especially sensitive to the exact values chosen for $\bar{e}$.

Acknowledgements

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Appendix

The mix formulations are given below in parts by weight.

Unfilled natural rubber (A):

Natural rubber (SMR-5L), 100; zinc oxide, 5; stearic acid, 2; phenyl-2-naphthylamine, 1; N-cyclohexyl-2-benzothiazyl sulfenamide, 0.6; sulfur, 2.5.

Carbon-black-filled natural rubber (B):

As for A, with the addition of N330 carbon black (Vulcan 3, Cabot Corporation), 50.

The compounds were vulcanized in the form of thin sheets by heating them in a press for 24 min at 150°C.

TABLE 1: Values of instantaneous modulus $\underline{E}$ (MPa) determined in various ways for an unfilled (A) and a carbon-black-filled (B) vulcanizate of natural rubber.

Strain level $\underline{e}$	From loading curve	From unloading curve	Loading after resting	Unloading after pre-straining to e = 2.5
		Material A		
0	1.45 ± 0.3	-	-	-
1	1.55 ± 0.25	1.35 ± 0.35	0.8 ± 0.25	-
2	2.40 ± 0.3	2.4 ± 0.35	1.95 ± 0.35	-
3	4.2 ± 0.4	5.2 ± 0.25	6.5 ± 0.4	-
4	8.25 ± 1.4	29.5 ± 2.2	21.7 ± 2.0	-
5	-	125 ± 16	-	-
		Material B		
0	5.9 ± 1.2	-	-	-
0.5	6.4 ± 1.8	31 ± 3	14.0 ± 0.2	0.90 ± 0.1
1	11.0 ± 1.2	73 ± 8	35.3 ± 0.5	0.75 ± 0.1
1.5	21.5 ± 2	118 ± 12	89 ± 1	2.1 ± 0.2
2	29 ± 4.5	308 ± 23	132 ± 5	42 ± 2

Figure Captions

Figure 1. Sketch of retracting strip. Velocities are denoted as follows: v_s, velocity of sound at strain level e; v_0, velocity of sound at zero strain; v_r, velocity of retraction.

Figure 2. Method of measuring the velocity of sound v_s in a stretched rubber strip.

Figure 3. Method of measuring the velocity of retraction v_r.

Figure 4. Triple-exposure photograph of a retracting strip of material A retracting from a strain $e = 4.1$.

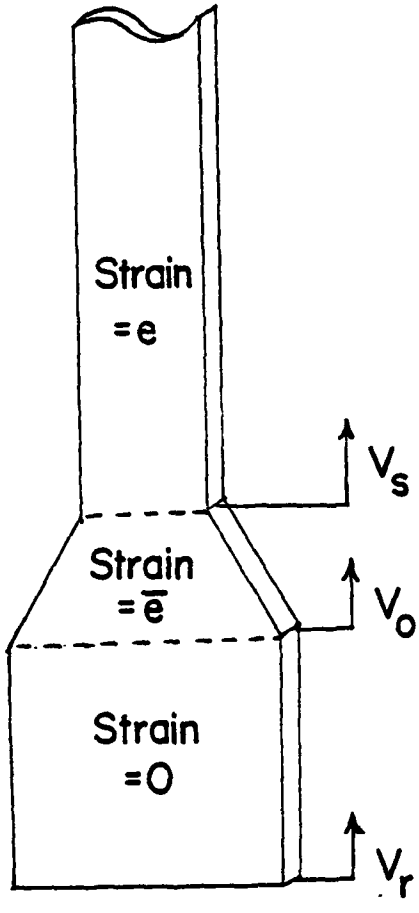
Figure 5. Observed retraction velocities for material A using clamp masses of 0.2 g (●) and 2 g (○).

Figure 6. Velocities v_s of sound in materials A (○) and B (●) and in material B after pre-stretching to $e = 2.14$ (+). Full curves: calculated from equation 6 using values of E from unloading stress-strain relations. Broken curves: calculated using loading stress-strain relations. Chain curve: calculated using loading-after-resting stress-strain relations.

Figure 7. Velocities v_r of retraction for materials A (○), B (●), and B after a strain of $e = 2.5$ had been imposed (+).

Figure 8. Measured velocities v_r of retraction for material A, denoted by open circles, compared with the predictions of equation 7.

Figure 9. Measured velocities v_r of retraction for material B, denoted by open circles, compared with the predictions of equation 7.



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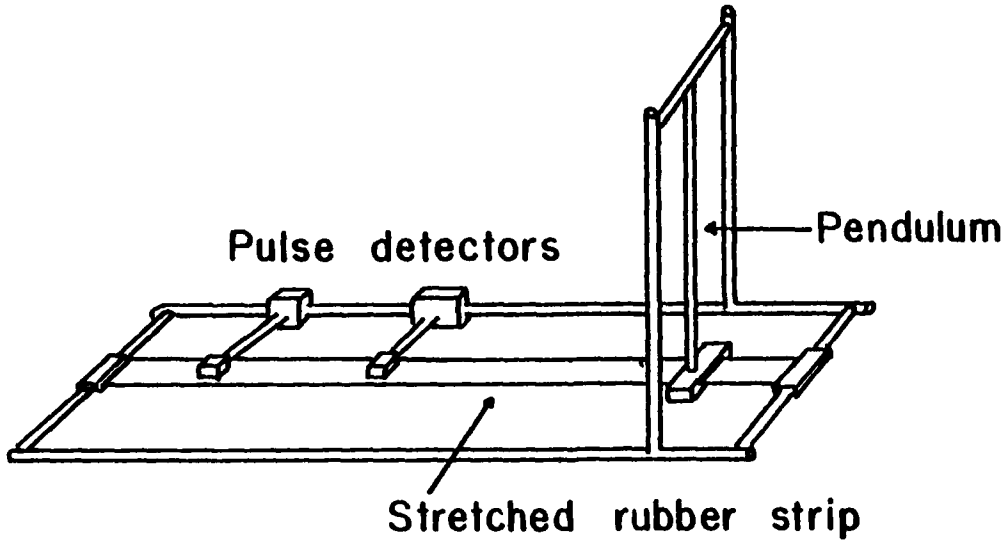

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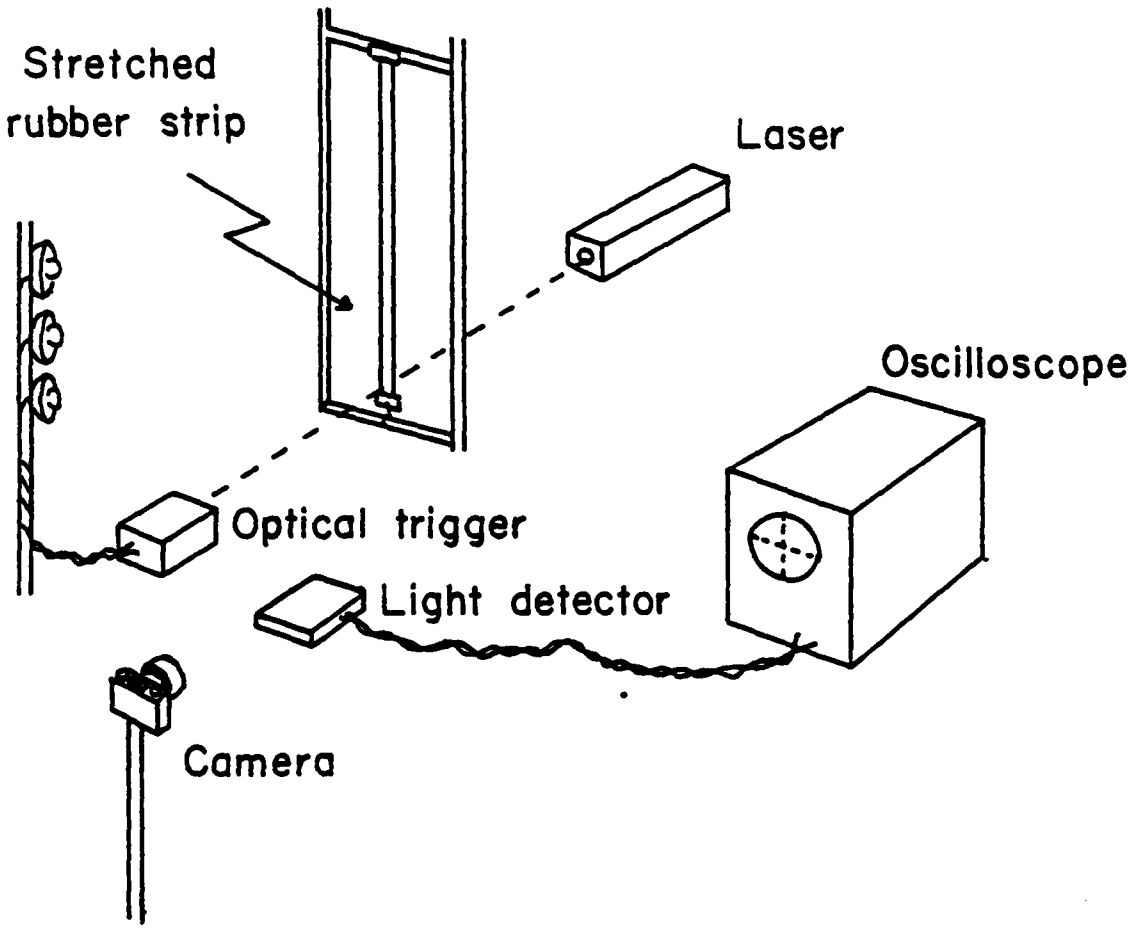
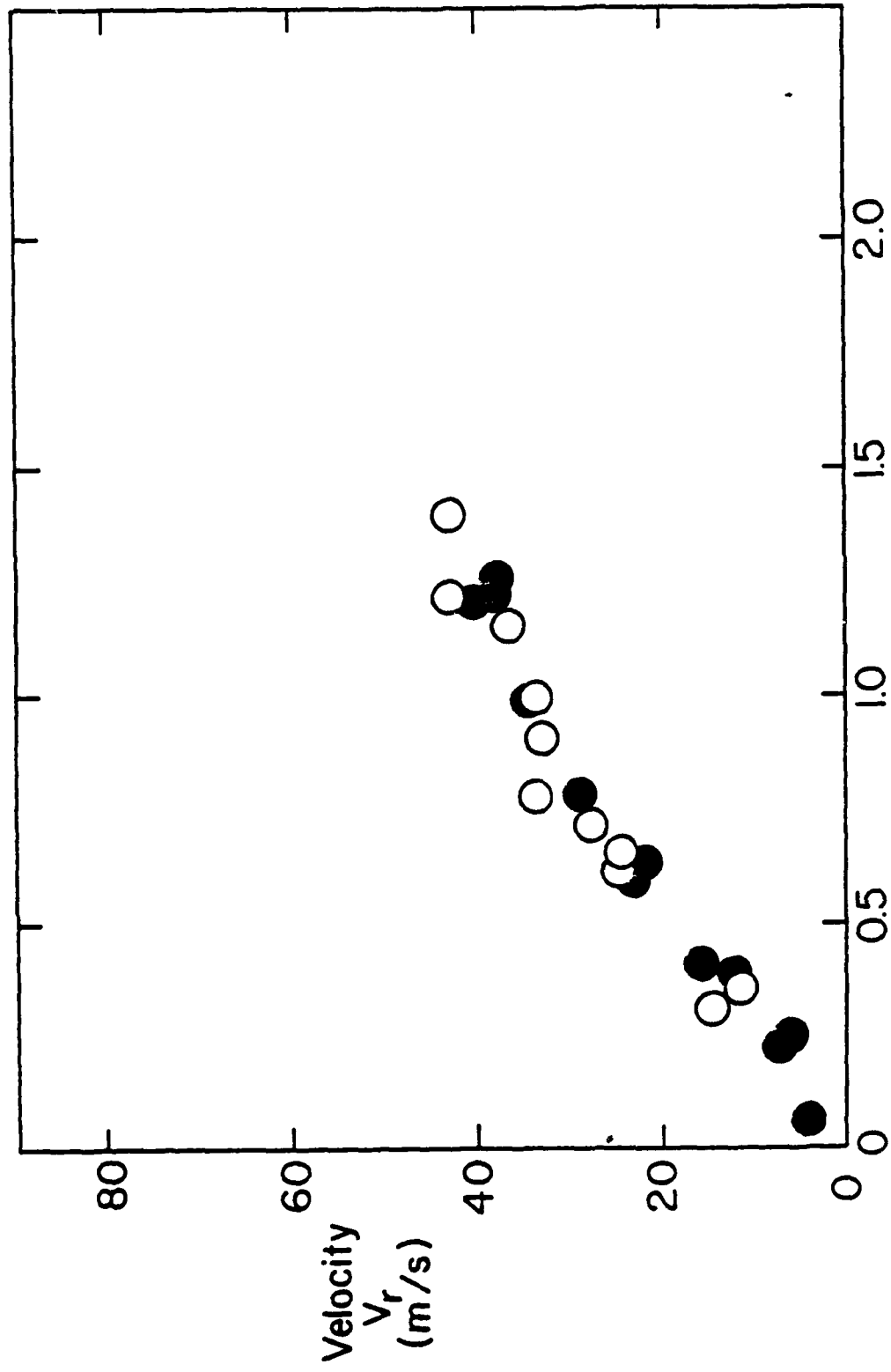

Stretched
rubber strip
Laser
Oscilloscope
Optical trigger
Light detector
Camera

Figure 3

Figure 4



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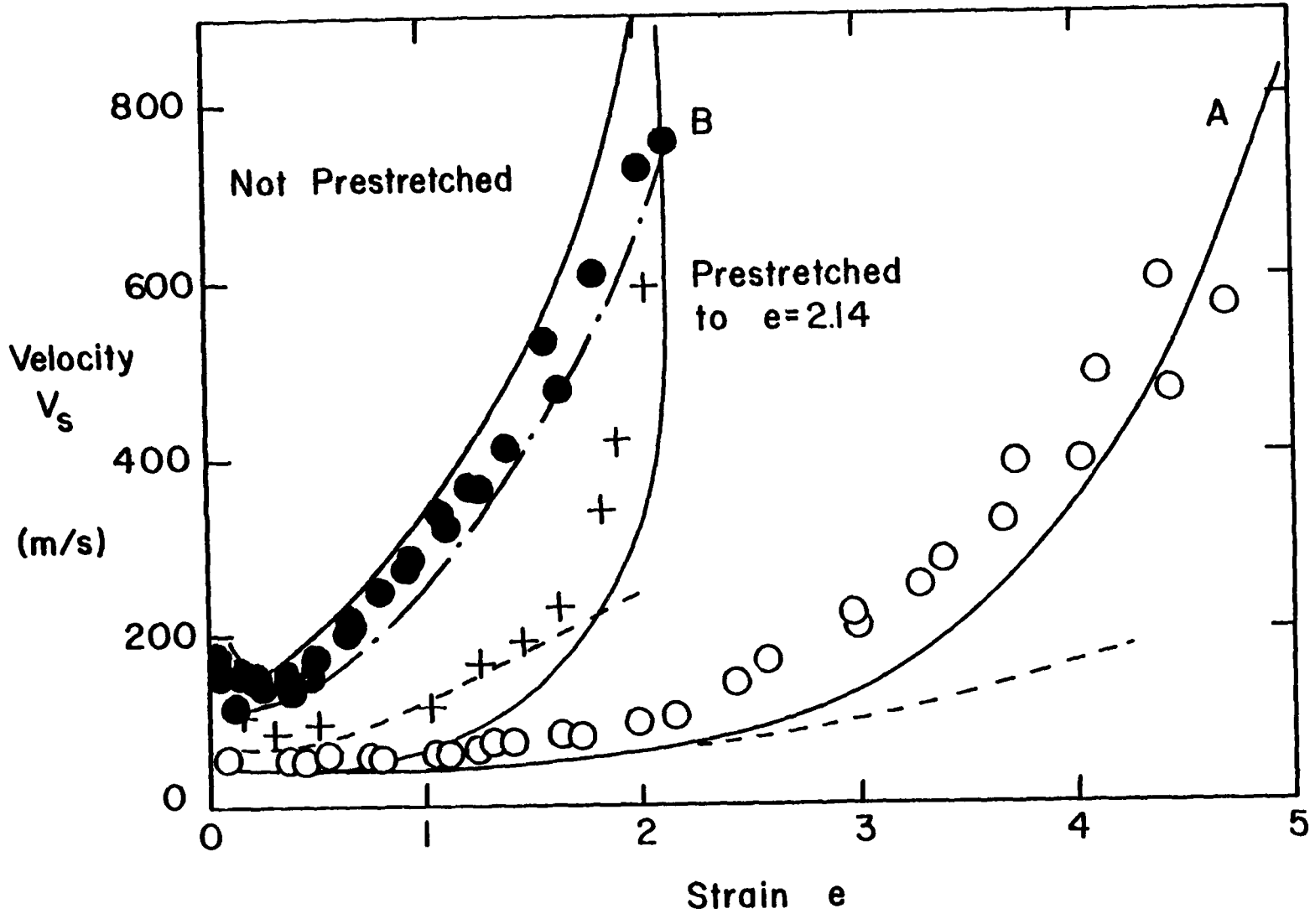
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Figure 6

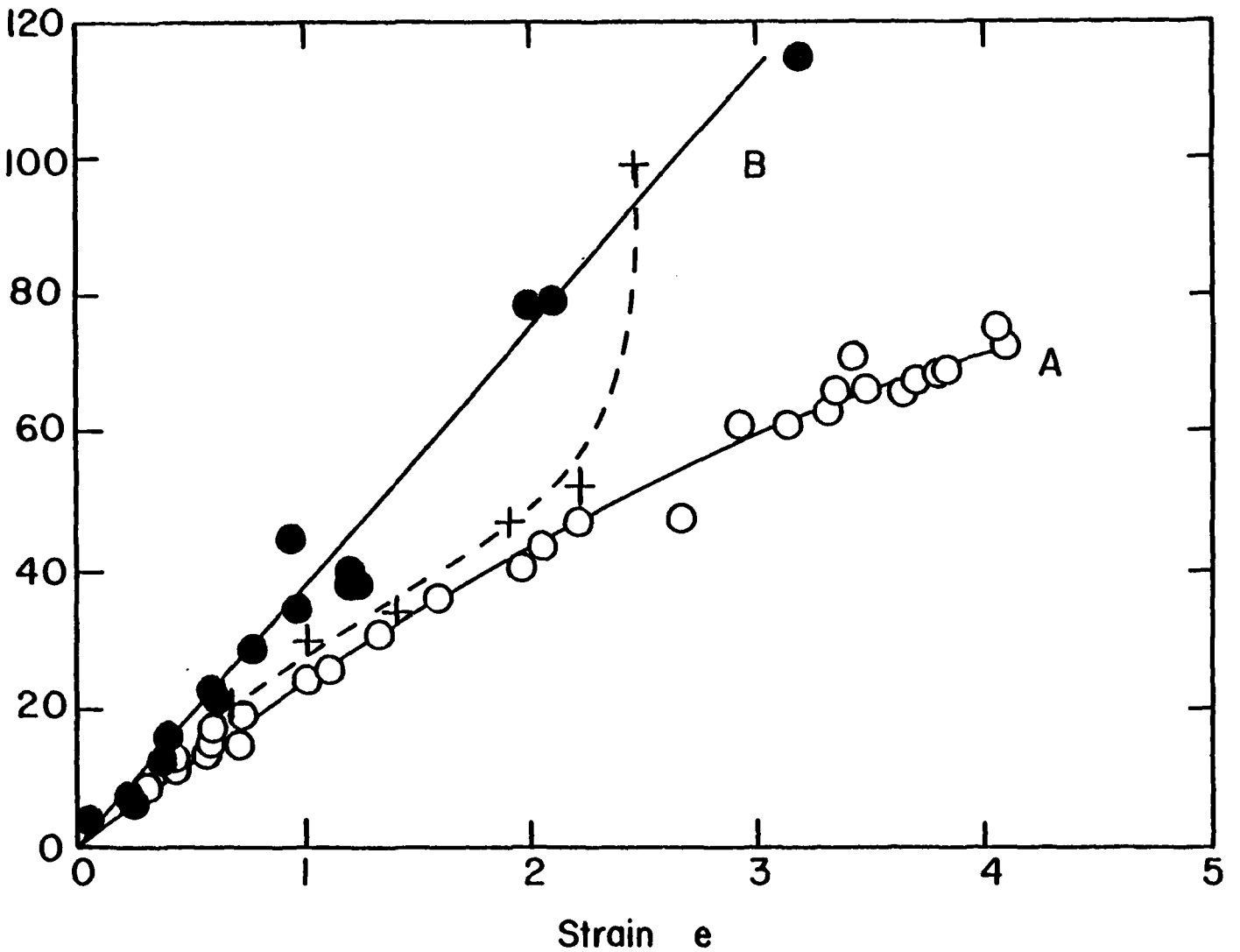

Figure 7

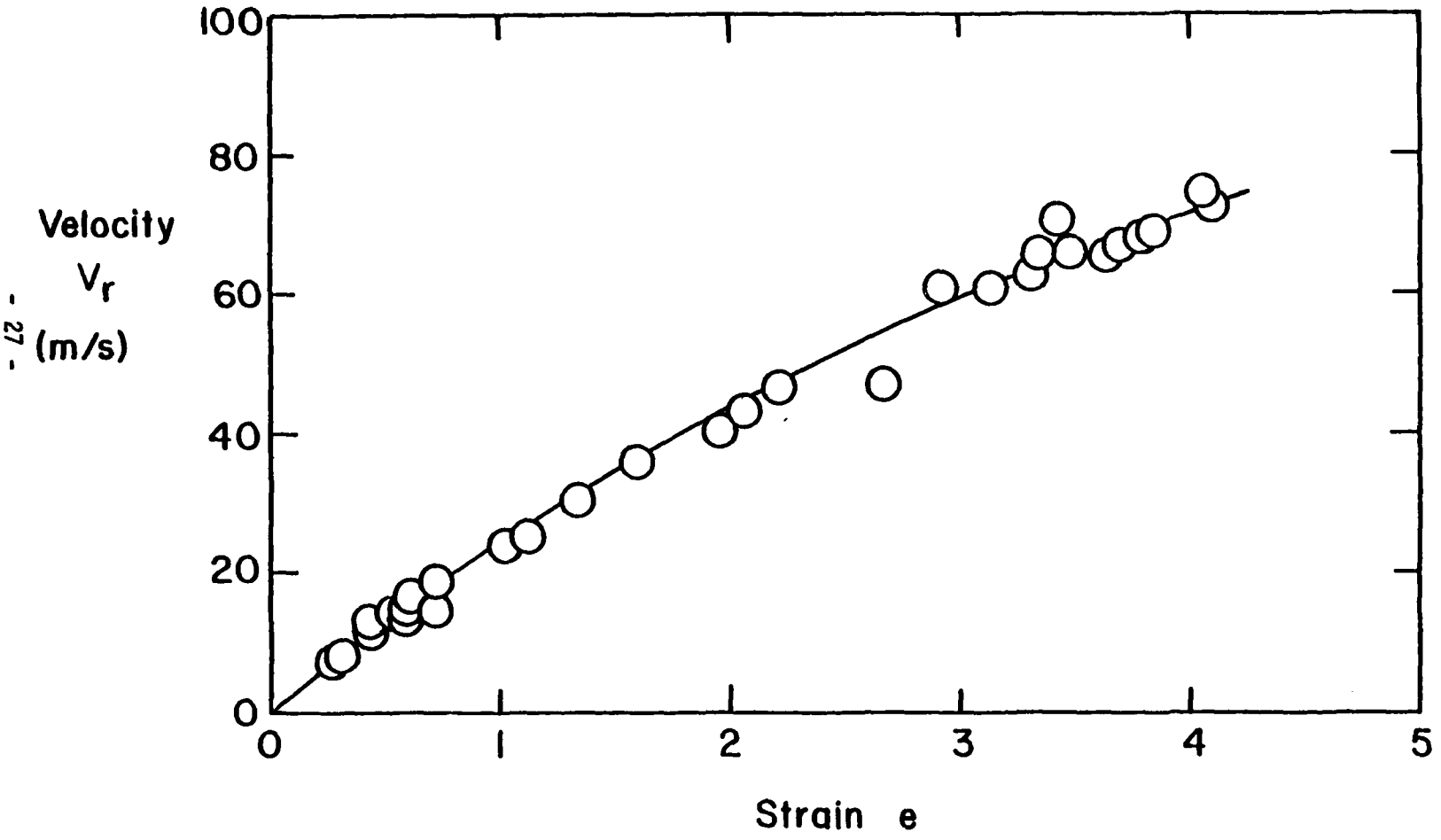

Figure 8

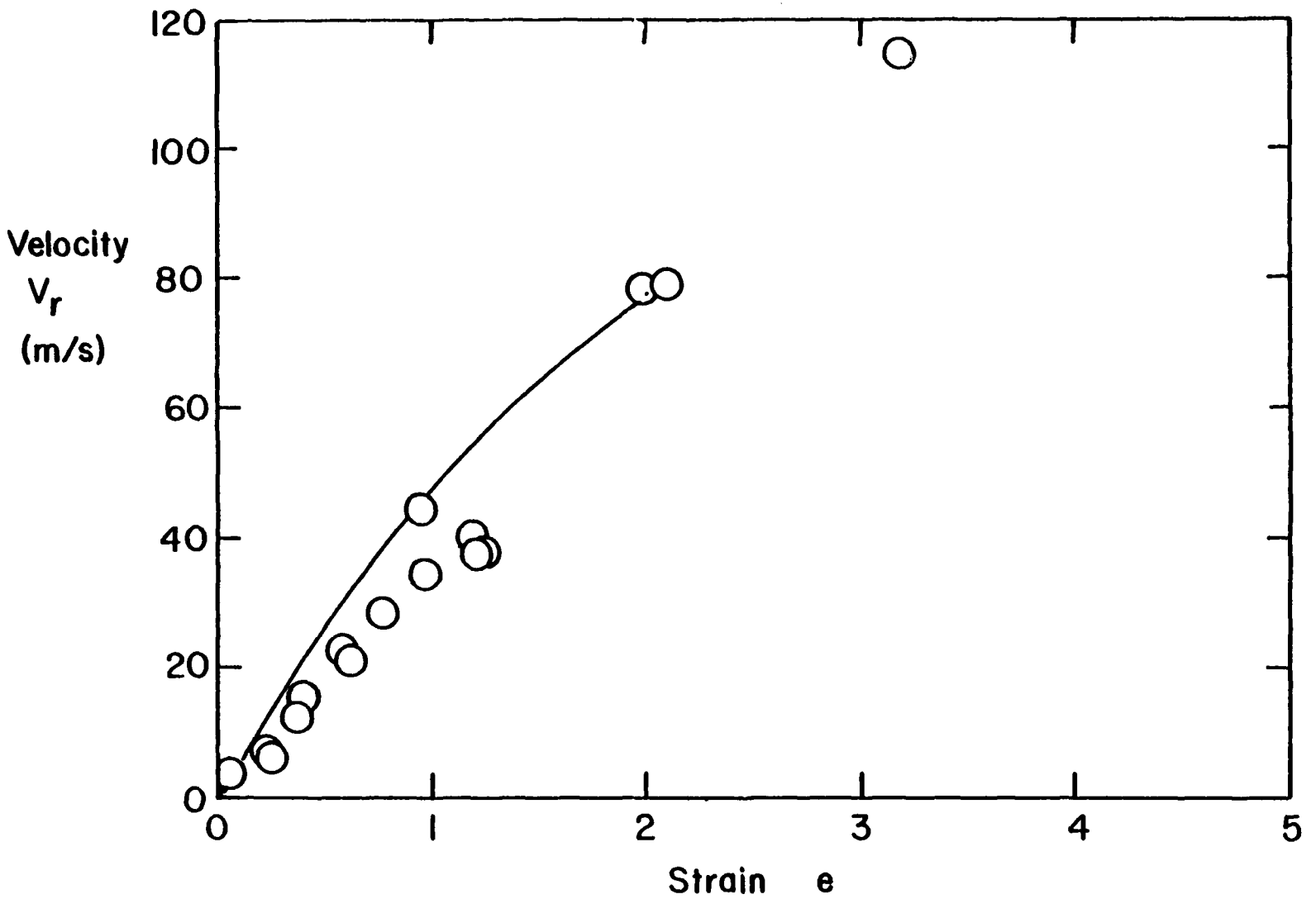

Figure 9

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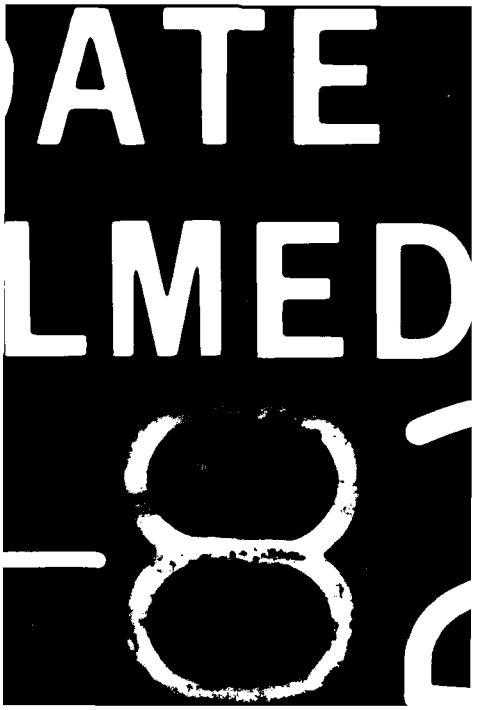
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