AD 749011

NOLTR 72-149

PROBLEMS IN THE ACOUSTIC DETERMINATION OF THE MODULUS OF FIBERS

By
Bruce Hartmann
Jacek Jarzynski*

31 JULY 1972

D D C
SEP 28 1972
B

NOL

NAVAL ORDNANCE LABORATORY, WHITE OAK, SILVER SPRING, MARYLAND

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED

NOLTR 72-149

R

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Naval Ordnance Laboratory
Silver Spring, Maryland 20910

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
Problems in the Acoustic Determination of the Modulus of Fibers

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
Bruce Hartmann and Jacek Jarzynski

6. REPORT DATE 31 July 1972	7a. TOTAL NO. OF PAGES 19	7b. NO. OF REFS 8

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
NOLTR 72-149

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Naval Ordnance Laboratory
Silver Spring, Md. 20910

13. ABSTRACT

Equipment was built to measure the Young's modulus of fibers using ultrasonic pulses. Moduli measured on single straight strands of aluminum and copper wire are in satisfactory agreement with accepted values. However, moduli measured on carbon fiber yarns are as much as 45% lower than the static values. This difference arises because the individual filaments in the yarn are not straight but are twisted into a helix. This conclusion is verified by measurements on multiple stranded copper wire and theoretical calculations.

Details of illustrations in this document may be better studied on microfiche

DD FORM 1 NOV 65 1473 (PAGE 1)
S/N 0101-807-6801

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acoustics						
Fibers						
Young's modulus						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

UNCLASSIFIED
Security Classification

PROBLEMS IN THE ACOUSTIC DETERMINATION OF THE MODULUS OF FIBERS

Prepared by:

Bruce Hartmann
Jacek Jarzynski*

ABSTRACT: Equipment was built to measure the Young's modulus of fibers using ultrasonic pulses. Moduli measured on single straight strands of aluminum and copper wire are in satisfactory agreement with accepted values. However, moduli measured on carbon fiber yarns are as much as 45% lower than the static values. This difference arises because the individual filaments in the yarn are not straight but are twisted into a helix. This conclusion is verified by measurements on multiple stranded copper wire and theoretical calculations.

APPROVED BY: F. Robert Barnet, Chief
Nonmetallic Materials Division
CHEMISTRY RESEARCH DEPARTMENT
NAVAL ORDNANCE LABORATORY
SILVER SPRING, MARYLAND

*Present address: Naval Research Laboratory, Washington, D. C.

NOLTR 72-149 **31 July 1972**

PROBLEMS IN THE ACOUSTIC DETERMINATION OF THE MODULUS OF FIBERS

This program is part of a continuing study on the physics of materials carried out in the Nonmetallic Materials Division of the Naval Ordnance Laboratory. This report describes experimental work done on the speed of sound in fibers and the Young's modulus calculated therefrom.

No special funding was provided for this project; it was carried out as part of the continuing interest of this Division in the properties of carbon fibers. The purpose of this study was to see if an acoustic measurement would be quicker and more accurate than the presently used static method.

The materials discussed in this report were obtained from commercial sources. Their evaluation by the Laboratory in no way implies Navy endorsement of these materials.

ROBERT WILLIAMSON II
Captain, USN
Commander

Daniel J. Love, for

ALBERT LIGHTBODY
By direction

CONTENTS

Page
INTRODUCTION 1
EXPERIMENTAL 2
  Electronics 2
  Acoustic System 2
  Measurement Technique 3
EQUIPMENT CHECKOUT 4
ACOUSTIC MEASUREMENTS ON CARBON FIBERS 4
ACOUSTIC-STATIC MODULUS COMPARISON 5
EXPLANATION OF RESULTS 5
CONCLUSIONS 7
REFERENCES 8

ILLUSTRATIONS

Figure Title
1. Block Diagram of Electronic Setup
2. Photograph of Acoustic Fiber Test Apparatus
3. Sketch of Acoustic Fiber Test Apparatus
4. Fiber Length vs Acoustic Transit Time for an Aluminum Wire
5. Fiber Length vs Acoustic Transit Time for a Single Strand of Copper Wire
6. Fiber Length vs Acoustic Transit Time for Thornel 50
7. Fiber Length vs Acoustic Transit Time for HMG 50
8. Fiber Length vs Acoustic Transit Time for VYB
9. Fiber Length vs Acoustic Transit Time for Impregnated Courtaulds HM
10. Fiber Length vs Acoustic Transit Time for a Multiple Strand Copper Wire

Table Title Page
1. Comparison of Acoustic and Static Young's Moduli 9

INTRODUCTION

One of the most active fields of modern materials research is that of fiber reinforced composites. In particular, carbon fibers have great promise in numerous applications.

One aspect of this research is the measurement of Young's modulus for carbon fibers. The modulus is used not only for design purposes, but also for quality control and inspection. Currently, the method of measurement used at the Naval Ordnance Laboratory is a static test. A number of lengths of yarn are laid side by side and impregnated with an epoxy resin. After curing, the resulting "strand" is tested by applying a tensile load at a slow rate and recording the resultant strain. The major disadvantages of this method are that it is time consuming and that the accuracy of ±5% is often not as good as desired.

Other methods of measuring the Young's modulus of carbon fibers have been suggested. In one method, the speed of sound in the fiber is measured. It is well known[1] that if the wavelength of the sound is much longer than the diameter of the fiber, extensional waves will be propagated and Young's modulus, E, will be given by

$$E = \rho V^2 \tag{1}$$

where ρ is the density of the fiber and V is the speed of sound in the fiber. Commercial equipment is available for these measurements, and the question was raised whether this acoustic method might be better than the static method. To answer this question, the present study was undertaken.

An apparatus for measuring the sound speed of fibers was constructed. The Young's moduli determined with this apparatus for aluminum and copper wires are in good agreement with literature values. For carbon fiber yarns, however, the acoustic moduli are significantly less than the static values. This difference occurs because the individual filaments in the yarn are not straight but are twisted into a helix.

The following sections of this report will describe the experimental equipment used, the results of checking out the equipment, results on several carbon fibers, a comparison with static measurements, an explanation for the difference, and our conclusions and recommendations for this project.

EXPERIMENTAL

Electronics

All of the electronics needed for this project have been described in detail elsewhere.[a] In brief, sinusoidal electrical pulses are generated at a frequency adjustable from 10 kHz to 680 kHz and at a repetition rate of 60 Hz. The length of these pulses is adjustable as is the phase of the beginning of the pulse. The phase is adjusted so that the signal starts at a zero of the sine wave rather than at a maximum or minimum. This eliminates unwanted transients. A block diagram of the electronic setup used is shown in Figure 1.

Acoustic System

Using the above electronics, an acoustic system was designed for use with fibers. In brief, the system consists of a transducer to convert the electrical pulse to a sound wave, a means of getting the sound into the fiber at one end and out of the fiber at the other end, and a second transducer to convert the sound wave back into an electrical signal. By measuring the transit time through a fiber of known length, the sound speed can be found.

Various arrangements were tried, including holding the fiber in both the vertical and horizontal directions, using different amounts of tension, and a variety of attachments. A photograph of the arrangement that was found to give the best results is shown in Figure 2. Front and side views are shown in Figure 3. The incident electrical signal is applied via a coaxial cable to the top connector. From this connector, one lead is soldered directly to the silvered face of the transducer, and the other lead is connected to the aluminum rod via the support ring. The upper transducer is a lead zirconate-lead titanate crystal, 2.5 cm (1.0 in.) in diameter and 1 cm (0.375 in.) thick. It has a resonant frequency of 100 kHz.

The transducer is coupled to the aluminum rod by a thin layer of silicone grease. The purpose of the aluminum rod is to provide a means of attachment for the fiber and to act as a resonator to build up the amplitude of the sound wave. The resonant frequency of the aluminum rod was 100 kHz, and this was the frequency used in the measurements reported here. To prevent the sound from going down the main support rod rather than down the fiber, the aluminum rod is supported only by three pointed screws in the support ring.

The fiber passes through a hole in the bottom of the upper aluminum rod. To reduce the possibility of shearing the fibers, the edges of the hole were carefully rounded. As the aluminum rod oscillates, some of the motion is imparted to the fiber, and the sound travels down the fiber. At the end of the fiber is another aluminum rod. This rod has a small hole in its center into which the end of the fiber is inserted. Then a screw in the rod is tightened to prevent the fiber from slipping out. The fiber end is prepared by coating with a few drops of fast drying cement and then trimming with a scissors. The bottom transducer is only 0.25 cm (0.1 in.) thick in order to reduce the weight on the fiber. This transducer is also a lead zirconate-lead titanate crystal, but because it is thinner than the upper transducer, it has a higher resonant frequency, 750 kHz. It is bonded to the aluminum rod with an epoxy resin. One electrical lead is soldered to the face of the transducer; the other is connected with a small wire to the aluminum rod. Both leads are then soldered to the lower connector. A coaxial cable is connected from this point to an oscilloscope.

Fiber length is measured, on the scale attached to the main support rod, using the pointer. Fiber length is changed by turning the take-up reel, which is covered with adhesive tape. The pointer is then moved, after releasing the locking screw, until it is even with the top of the lower aluminum rod and the locking screw tightened again. Finally, the clamp is used to support the weight of the aluminum rod when measurements are not being made. During a measurement, the clamp is loosened and the rod is allowed to hang freely.

Measurement Technique

A straightforward measurement of the sound speed consists of a measurement of the length of the fiber and the time required for the pulse to travel this length. An estimate of the transit time is found by measuring the time, on the oscilloscope, between the beginning of the incident pulse and the beginning of the received pulse. This measurement is not accurate for two reasons. First, the above measured time includes the time required to go through the two aluminum rods. Second, the received signal is very weak and must be considerably amplified. Due to the resulting noise, it is very difficult to be sure where the beginning of the received pulse is.

To avoid these difficulties, the measurements reported here were all made in the following manner. A particular peak in the received signal is singled out. While watching this peak on the oscilloscope, the take-up reel is turned a few centimeters. Then the pointer is readjusted to be even with the top of the aluminum rod. The difference in fiber length divided by the change in transit time gives the sound speed. Higher accuracy is obtained by repeating this process several times and averaging the results. This is done by plotting fiber length vs transit time and fitting a straight line to the data using the method of least squares. The slope of this line is the desired sound speed. (Since, in this method, only changes in transit time are significant, the zero of transit time can be set arbitrarily and this was done here to make the readings on the oscilloscope more convenient.)

EQUIPMENT CHECKOUT

The accuracy of the experimental equipment and the measurement technique was checked out first using metal wires. Results for an aluminum wire are shown in Figure 4. The measurement yields an extensional sound speed of 5130 m/sec. The literature value depends somewhat on the particular grade of aluminum used, but the nominal value[3] of the extensional sound speed is 5000 m/sec, in good agreement with our measurements.

Results for a single strand of copper wire are shown in Figure 5. In this case, our measured sound speed is 3500 m/sec, while the nominal value[3] of the extensional sound speed in copper is 3750 m/sec. Considering the variations in different grades of copper, this agreement is considered satisfactory.

A final check was made on a carbon fiber. The material was Thornel 50 (a product of Union Carbide Corp.) in the form of a yarn (i.e., many filaments twisted together into a compact bundle). The results are shown in Figure 6. For this material, two peaks in the pulse were followed as the length was changed rather than just one, as usually done. The average sound speed measured for Thornel 50 was 13,000 m/sec. A sample of this same material (not from the same roll) was also sent to a commercial company for evaluation. Their measurement yielded[4] a value of 12,090 m/sec. This agreement is considered good.

On the basis of the above three test runs we concluded that our equipment was working properly, that we could measure extensional sound speeds with an accuracy of ±3%, and that our measurements were as accurate as any of those made on carbon yarn.

ACOUSTIC MEASUREMENTS ON CARBON FIBERS

Measurements were then made on a series of carbon fibers. In Figure 7 are the results for HMG 50 (a product of Hitco Corp.). For this yarn, the sound speed is 9820 m/sec.

Going to a low modulus yarn, results for VYB (a product of Union Carbide Corp.) are shown in Figure 8. Here the sound speed is only 5180 m/sec.

Measurements were also done on Courtaulds HM tow (a product of the Courtaulds Co., Coventry, England, in the form of a thick bundle). Part of the tow was stripped off and twisted into a fiber bundle. Two runs were made, each with two specimen lengths. The average of the two runs was 10,750 m/sec. From the same roll of material used for the above tests, a tensile bar of Courtaulds HM was prepared. This is the form used for the static measurements, and there was a question in our minds what effect the epoxy resin would have on the sound speed measurements. The tensile bar was then tested in the acoustic device by clamping the end to the upper aluminum rod and cutting pieces off to change the length. The results are shown in Figure 9. The sound speed is 10,700 m/sec. Thus the presence of the epoxy made no difference in the measurement. This is because the sound speed in the epoxy is much lower than in the fiber. In our method of detecting the beginning of the sound pulse, only the fastest sound speed matters.

ACOUSTIC-STATIC MODULUS COMPARISON

Using the above measured sound speeds and manufacturers' values for density (of a single filament), the Young's modulus (Equation (1)) of all the materials tested is shown in Table 1. Also given in Table 1 values of Young's modulus determined in static tests. The static values for metals are literature values,[3] the first three carbon fiber values are from the manufacturer's data, and the last value was determined at NOL as an average of five replicates cut from the same tensile bar that was used to obtain the acoustic modulus (Figure 9). (The value obtained at NOL for Courtaulds HM is 4% higher than the manufacturer's value.)

The agreement between acoustic and static modulus for the aluminum and copper wires is seen to be satisfactory while for the carbon fibers the acoustic values are all lower than the static values. In particular, the most controlled tests were run on Courtaulds HM and in this case the acoustic value is 45% lower than the static value.

EXPLANATION OF RESULTS

The reason for the difference between the acoustic and static moduli is that the individual carbon filaments are twisted and do not lie straight along the fiber direction. Starting with a suggestion[8] to this effect, some measurements were done with multiple stranded copper wire to verify this interpretation. Results for sound speed measurements on the multiple (seven) strand wire are shown in Figure 10. The average sound speed for two separate runs was 3330 m/sec. After making these measurements, the wire was unwound and a single strand was tested. These results were already given in Figure 5. The sound speed measured on the single strand was 3500 m/sec. Thus the multiple strand speed is 4.9% lower than it should be. The overall length of the stranded wire was 55.85 cm. When unwound, a single strand had a length of 59.40 cm. This represents a 6.4% change in length. Thus, to within the accuracy of our measurements, sound speed measurements on a twisted wire are low just because of the twist. The sound wave follows the path of an individual strand rather than straight along the wire. Thus the distance traveled by the sound wave is longer than that measured in our test, and this leads to a lower calculated sound speed.

Some work has already been done on acoustic propagation in helical shapes. Wittrick[6] has given a detailed analysis of elastic wave propagation in helical springs which indicates that a helical structure is highly dispersive and there is coupling between shear, extensional and rotational modes. It is not clear whether this theory can be applied directly to twisted fibers. Work very similar to ours was reported by Zorowski and Murayama.[7] They measured sound speed in a variety of fibers: nylon, polyester, acetate, and viscose. These fibers were twisted known amounts. They then found that the measured dynamic modulus decreased to as little as 30% of the untwisted value when the fibers were twisted. In our case, the problem is more difficult because the exact amount of twist is not known and also because the filaments are not always continuous. However, some calculations were done using the simplifying assumptions that the sound propagates in a pure extensional mode along each fiber and that each fiber is continuous. While some broken filaments are present, there are sufficient continuous filaments to give a measurable signal so the broken ones can be ignored.

Assume the individual filaments are twisted into a circular helix whose axis is the z axis. In parametric form, the equation of the helix is[8]

$$x = a \cos \omega t, \quad y = a \sin \omega t, \quad z = bt \qquad (2)$$

where a, b, ω are positive constants. The path length along the helix is given by

$$s = \sqrt{a^2 \omega^2 + b^2} \int dt \qquad (3)$$

where appropriate limits of integration are to be supplied. When $t = 0$, $x = a$, and $z = 0$. When $t = 2\pi/\omega$, x is again equal to a, and $z = 2\pi b/\omega$. Thus one complete turn of the helix occurs between $t = 0$ and $t = 2\pi/\omega$. Also the repeat distance, that is the distance along the z axis for one complete turn of the helix, is just $r = 2\pi b/\omega$. Then

$$s = \sqrt{a^2 \omega^2 + b^2} \int_0^{2\pi/\omega} dt = 2\pi/\omega \sqrt{a^2 \omega^2 + b^2}$$

$$= \sqrt{4\pi^2 a^2 + 4\pi^2 b^2/\omega^2} = \sqrt{(2\pi a)^2 + r^2} \qquad (4)$$

Note that the radius of the helix is a. If $a = 0$, the helix degenerates into a straight line and $s = r$, as it should. If $r = 0$, the helix degenerates into a circle and $s = 2\pi a$, as it should.

To apply the above to our case, s represents the filament length and r represents the bundle length. The percent difference in length is then

$$\frac{s - r}{s} = \frac{\sqrt{(2\pi a)^2 + r^2} - r}{\sqrt{(2\pi a)^2 + r^2}} = \frac{\sqrt{(2\pi a/r) + 1} - 1}{\sqrt{(2\pi a/r) + 1}} \qquad (5)$$

For the metal wire, the repeat distance is about 5.1 mm (0.2 in.) while the radius of the helix is about 0.32 mm (0.0125 in.). From Equation (5), we would then expect a difference of 7.0%, close to the observed value of 6.4%.

For the carbon fibers, a repeat distance of about 2.5 mm (0.1 in.) is typical while the radius is again about 0.32 mm (0.0125 in.). From Equation (5), we would then expect a difference of 21% in the sound speed. By Equation (1), this would correspond to a 38% difference in Young's modulus, close to the observed value of 45% for Courtaulds HM. (Note that we had twisted this material to make the measurements easier.) Changing the repeat distance slightly from the above value, one can calculate even higher differences.

CONCLUSIONS

Based on the measurements done with metal wires and carbon fibers, we have reached the following conclusions:

(1) The extensional sound speed in single metal wires can be measured to an accuracy of about ±3%.

(2) To a first approximation, an extensional wave propagated in a multiple element bundle follows the individual elements rather than the bundle.

(3) An acoustic measurement of the Young's modulus of carbon fibers in the form of a bundle of filaments is too low by an amount proportional to the amount of twist.

(4) If the amount of twist in a carbon fiber yarn is known, a correction can probably be made to the acoustic determination of Young's modulus that would give results equal to the static value.

REFERENCES

1. Lord Rayleigh, Theory of Sound, Vol. 1, Dover, 1945.
2. B. Hartmann and J. Jarzynski, NOLTR 69-83, June 1969.
3. W. P. Mason, Physical Acoustics and the Properties of Solids, Van Nostrand, Princeton, 1958.
4. H. M. Morgan Co., letter dated August 27, 1968.
5. J. V. Larsen, private communication.
6. W. H. Wittrick, Int. J. Mech. Sci. 8, 25 (1966).
7. C. F. Zorowski and T. Murayama in Dynamics of Structural Solids, G. Herrmann, Ed., American Society of Mechanical Engineers, New York, 1968. p 47-61.
8. G. B. Thomas, Jr., Calculus and Analytic Geometry, Addison-Wesley, Cambridge, 1953. p 468.

TABLE 1

COMPARISON OF ACOUSTIC AND STATIC YOUNG'S MODULI

Material	Density (g/cm^3)	V (ext) (m/sec)	Y (acoustic) (10^6 psi)	Y (static) (10^6 psi)
Aluminum	2.70	5130	10	10
Copper	8.96	3500	16	18
Thornel 50	1.63	13,000	40	50
HMG 50	1.80	9820	25	50
VYB	1.32	5180	5.1	6
Courtaulds HM	1.94	10,700	32	58

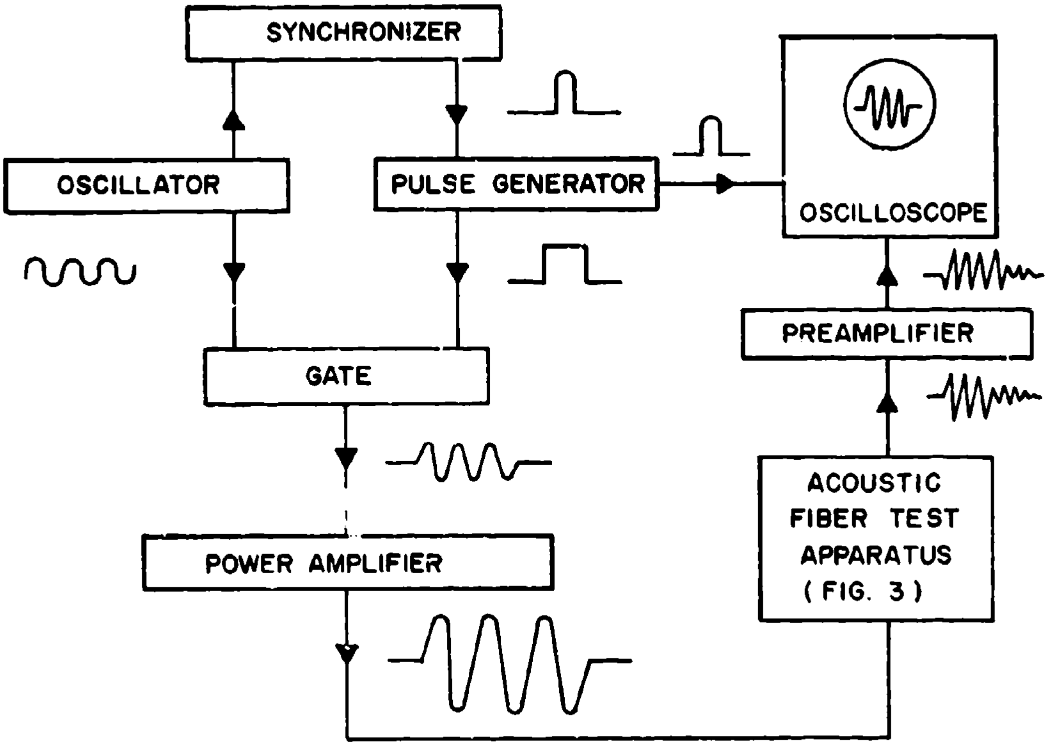

FIG. 1 BLOCK DIAGRAM OF ELECTRONIC SETUP

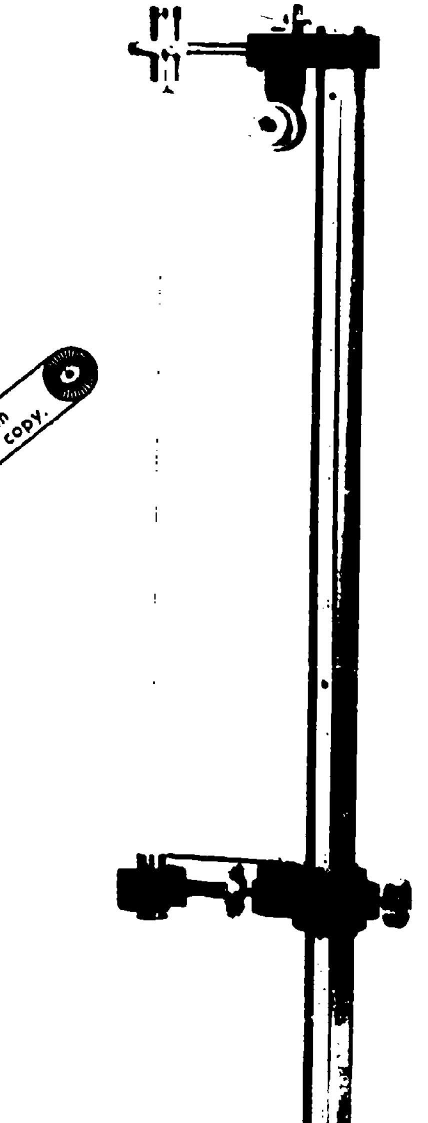

FIG. 2 PHOTOGRAPH OF ACOUSTIC FIBER TEST APPARATUS

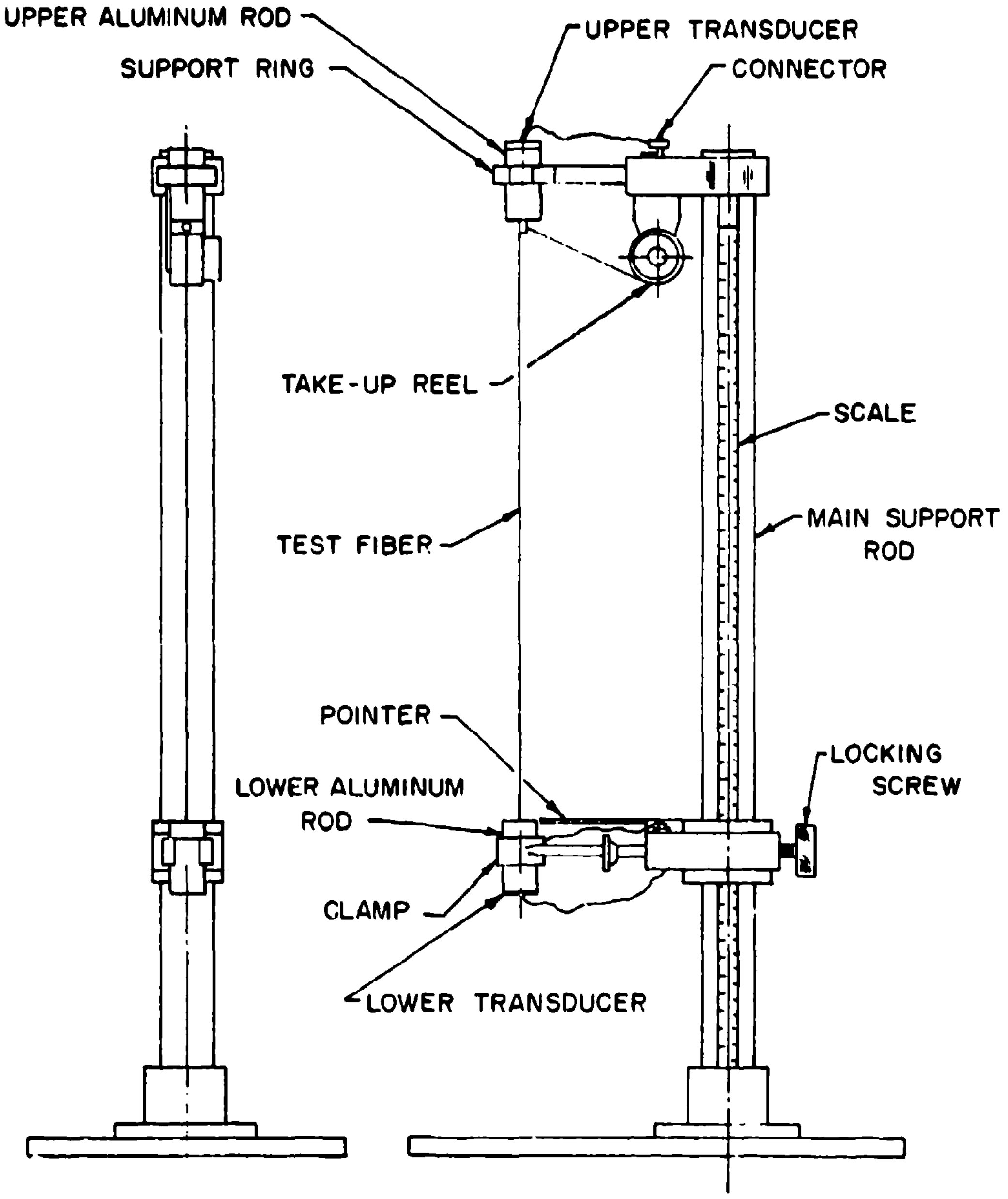

FIG 3 SKETCH OF ACOUSTIC FIBER TEST APPARATUS

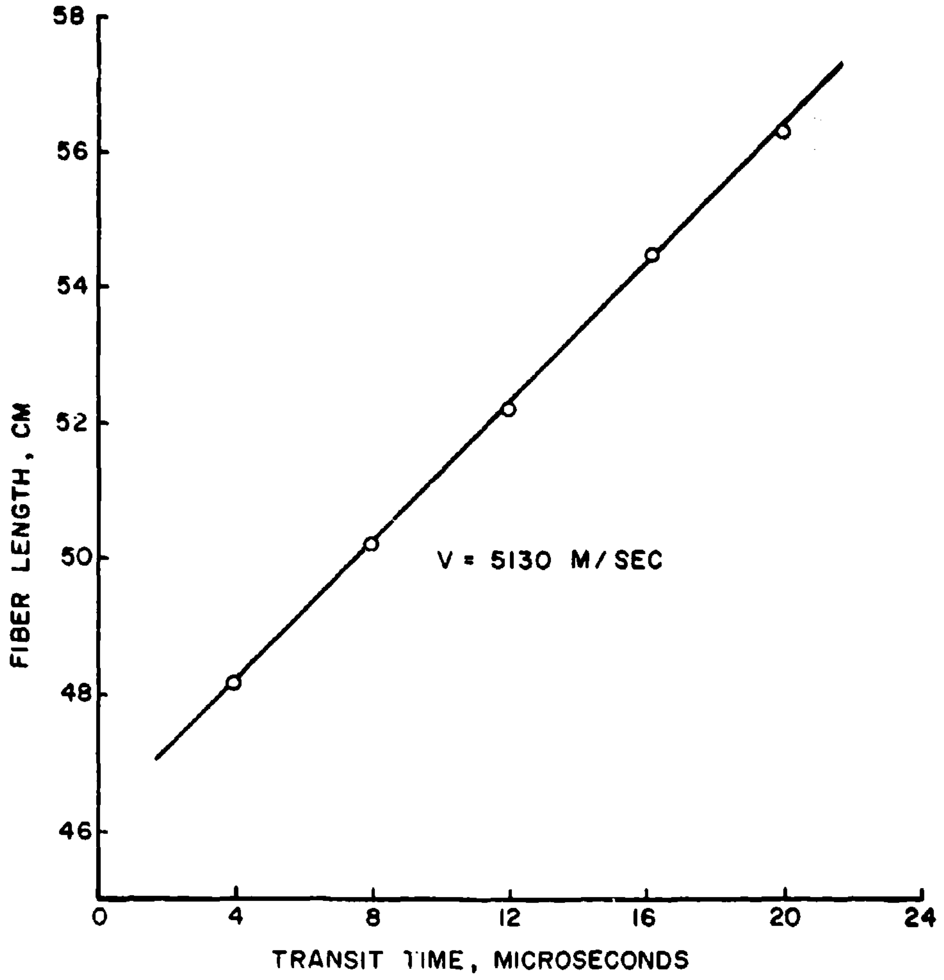

FIG. 4 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR AN ALUMINUM WIRE

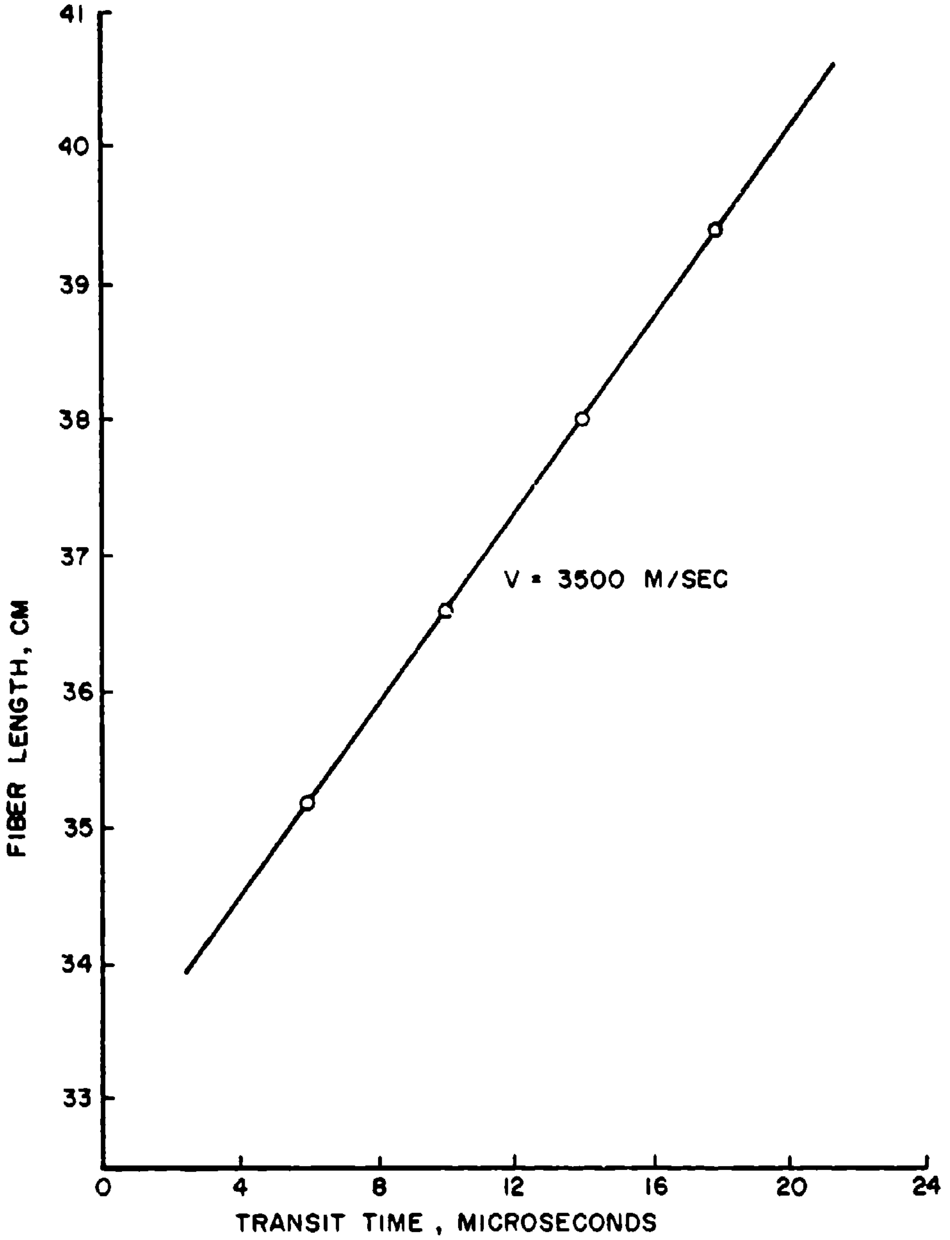

FIG. 5 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR A SINGLE STRAND OF COPPER WIRE

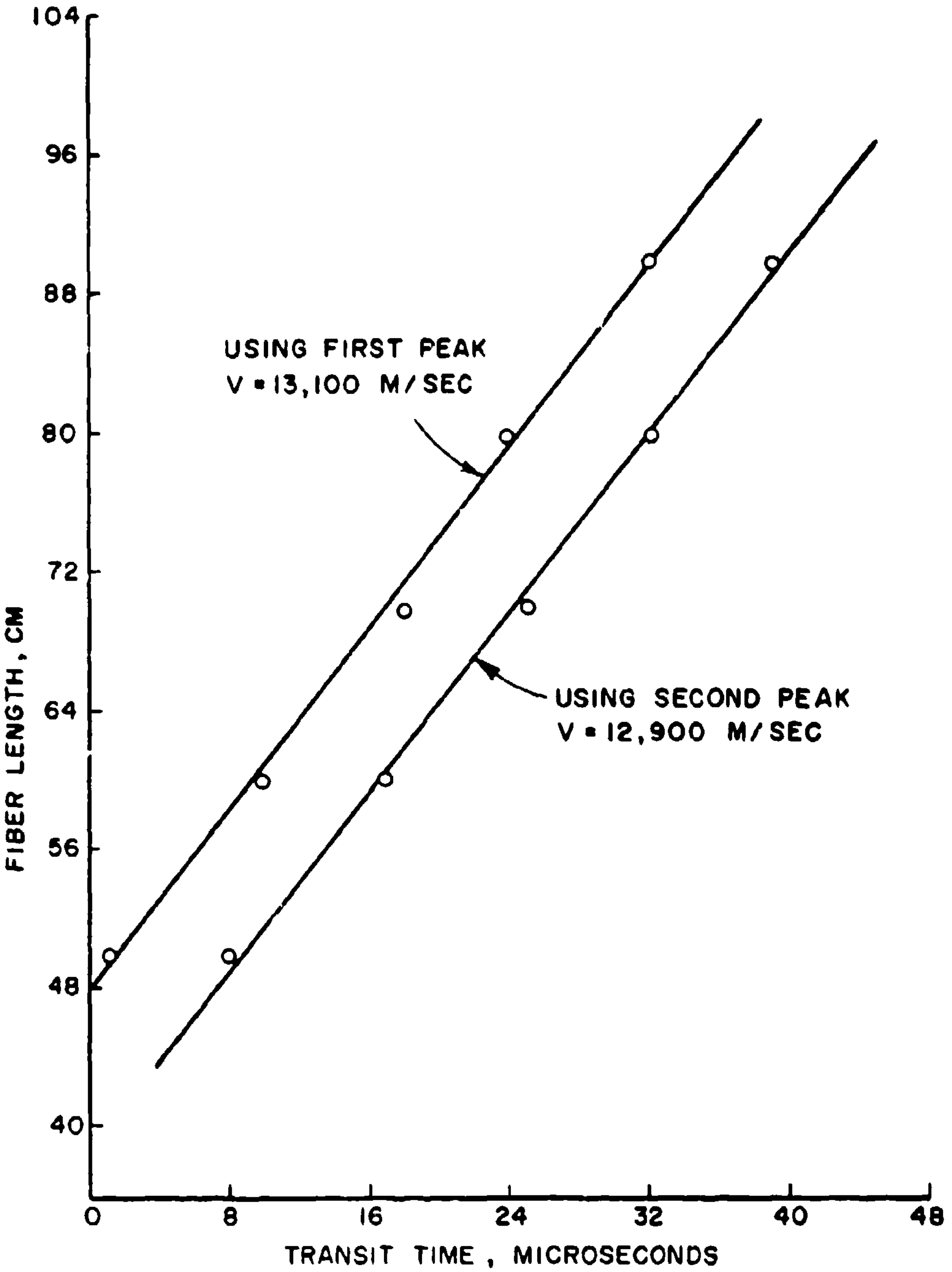

FIG. 6 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR THORNEL 50

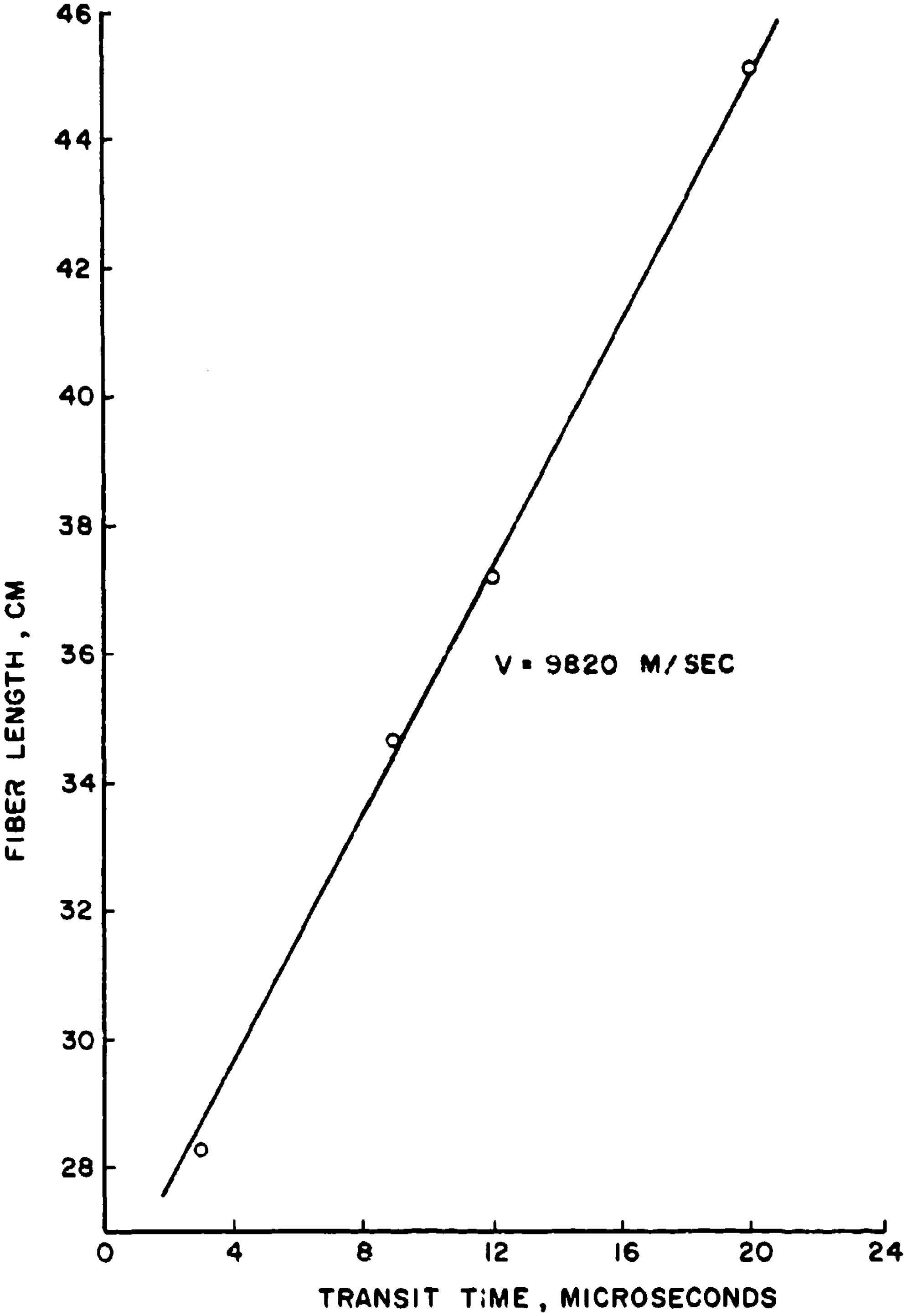

FIG. 7 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR HMG 50

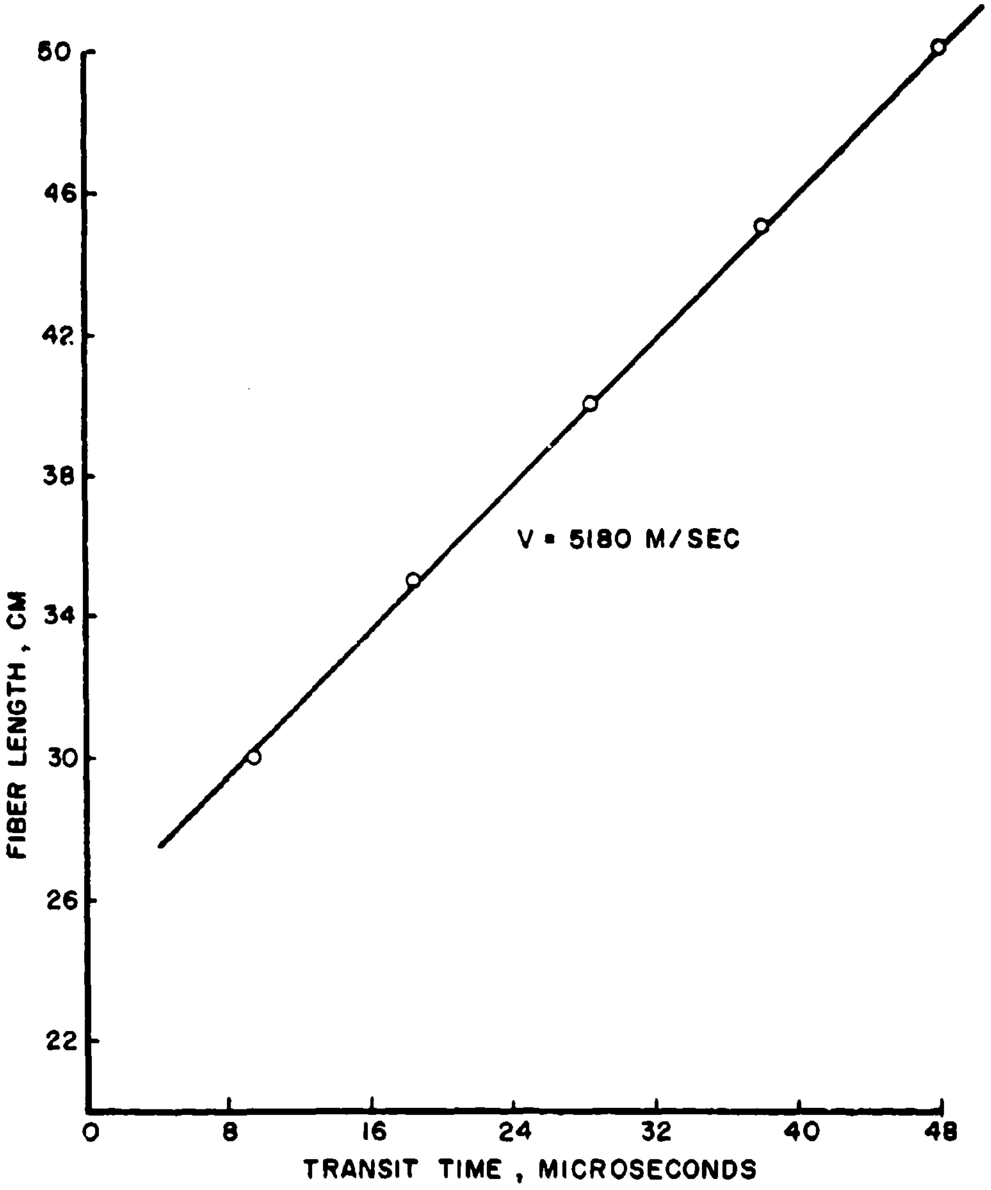

FIG. 8 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR VYB

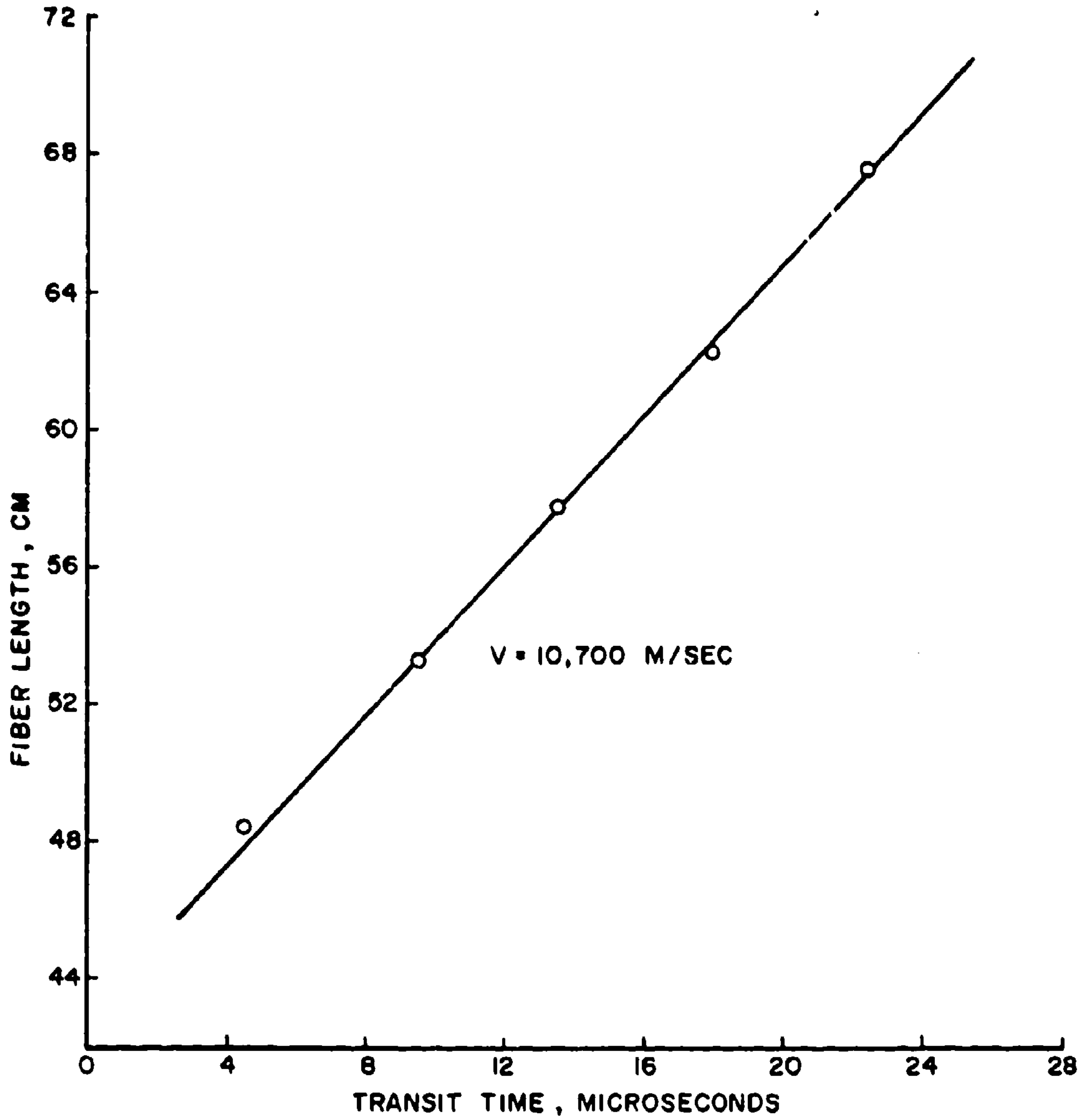

FIG. 9 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR IMPREGNATED COURTAULDS HM

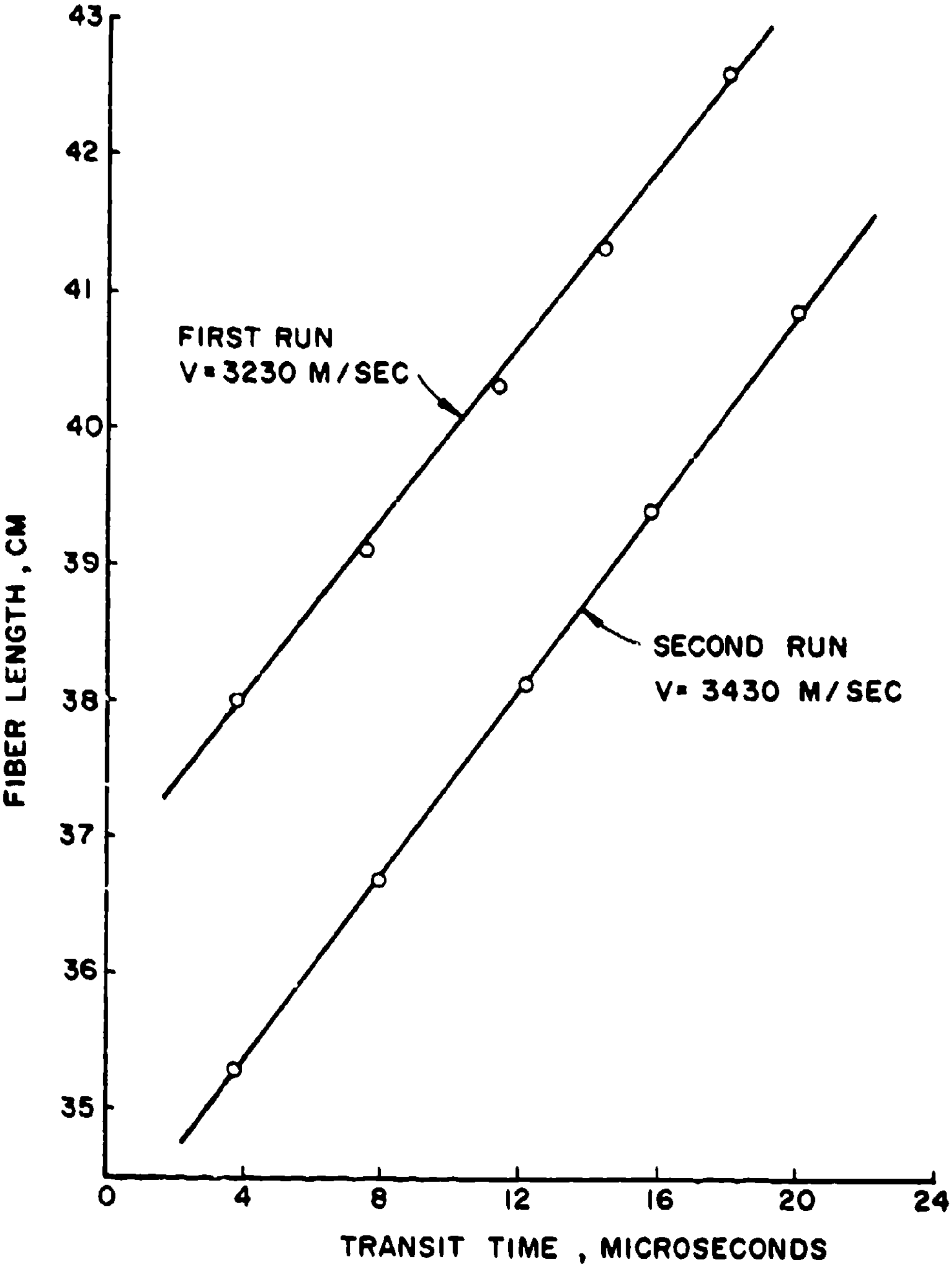

FIG. 10 FIBER LENGTH VS ACOUSTIC TRANSIT TIME FOR A MULTIPLE STRAND COPPER WIRE