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U.S. Naval Ordnance Lab., White Oak, Md.

Acoustical Properties of Rubber as a Function of Chemical Composition

Cramer, W.S.; Silver, I. Feb'51 53pp tables, graphs

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Materials - Acoustic properties Physics (62)
Rubber - Chemical properties Radiation (5)
Elastomers

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ACOUSTICAL PROPERTIES OF RUBBER AS A FUNCTION OF CHEMICAL COMPOSITION

Prepared by:

W. S. Cramer and I. Silver

ABSTRACT: Measurements have been made of the complex bulk modulus of 49 separate rubber formulations at 1500 cps and 30°C. and of the complex Young's modulus for the same samples over the frequency range 1-5 kc at 30°C. The bulk modulus was measured by a resonant water column method, and the Young's modulus was obtained by measuring the velocity and attenuation of progressive sound waves in thin rubber rods. Both results are given in the form of a complex modulus $E(1 + i\eta)$ where E, the real part, is primarily a measure of stiffness, and η, the loss factor, measures the proportion of the total available energy lost per cycle.

The samples tested were made from eight common types of rubber in which variations in the type and content of filler and/or plasticizer were carried out. Results on these samples showed that the real part of the Young's modulus, for these frequencies, ranged from 2×10^7 to 2×10^9 dynes/cm^2 with an associated loss factor of from 0.1 to 1.4. The real part of the bulk modulus ranged from 2.1×10^{10} to 3.3×10^{10} dynes/cm^2 with a bulk loss factor of from 0 to 0.110. In the range studied the real part of the Young's modulus and the associated loss factor both increased with frequency.

The analysis of the data in terms of the chemical composition led to the following main conclusions:

a. The real part of the Young's modulus increased monotonically with filler content. The small particle-size carbon black reinforcing type of filler produced substantially more change for a given weight than larger particle-size blacks and non-reinforcing type fillers such as titanium dioxide. It was also found that a given filler did not have the same proportionate effect on the Young's modulus for different rubbers.

b. The real part of the bulk modulus showed a similar but smaller effect with filler content. For example, the addition of 50 parts by weight (to 100 parts of pure rubber) of a carbon black filler increased the Young's modulus by approximately 500% while the bulk modulus increased by about 15% for the same material. Also, it was found that for some non-reinforcing fillers a point was reached after which increased loading gave a decreasing modulus.

c. The addition of a plasticizer to the material resulted in a substantial decrease in the real parts of both moduli for one type of plasticizer while other types produced no change or a slight increase.

d. The bulk velocity changed very little with loading or rubber type. The values ranged between 1.4×10^3 m/sec and 1.6×10^3 m/sec for all samples. For the same samples the strip velocity varied between 44 m/sec and 410 m/sec.

e. The characteristic acoustic impedance (ρc) of the butyl, natural, and GR-S rubbers could be made to match that of water with small amounts of loading. The other types of rubber had substantially higher values than that of water.

f. The loss factor η for the Young's modulus was highest for Hycar PA and butyl with values over 1.0 while natural rubber and GR-S had the lowest with values of the order of 0.3 or less.

g. The loss factor for the Young's modulus increased slightly with loading for small amounts of filler (about 10 parts) and then decreased strongly with loading for larger amounts of filler. There is some evidence that the loss may start to increase again with still higher loadings possibly due to frictional losses between the filler particles.

h. The loss factor for the bulk modulus was less than 0.020 for most samples and quantitative conclusions on the effects of filler and plasticizer concentrations are in general not warranted. The loss factor for unloaded butyl was 0.110 which is considerably higher than that of any other rubber tested. Loading the butyl decreased this loss factor.

U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NAVORD Report 1778 February 1951

This report presents data obtained under a research program entitled "The Acoustic Properties of Plastic Materials". The NOL task number of this project is FR-5-51. This report has been preceded by NAVORD Report 1534 describing a set of apparatus used in obtaining the data and will be followed by other reports on various phases of this work. Much of the data contained herein is not available in published form elsewhere and is presented here in detail for the information and possible use of workers in this field. This report is presented jointly by the Physics Research Department and the Engineering Department since personnel from both departments collaborated in obtaining the data. The division of responsibilities is explained in the introduction of the report.

W. G. SCHINDLER
Rear Admiral, USN
Commander

Leslie W. Ball

LESLIE W. BALL
Chief, Physics Research Department
By direction

S W Booth

S. W. BOOTH
Chief, Engineering Department
By direction

CONTENTS

ILLUSTRATIONS

ACOUSTICAL PROPERTIES OF RUBBER AS A FUNCTION OF CHEMICAL COMPOSITION

INTRODUCTION

1. This report presents some preliminary results of a study of the dynamic properties of elastomeric[1] materials by acoustic methods. This project is made possible by a collaboration between the Physics Research Department (Acoustics Research Division) and the Engineering Department (Chemistry Division, Plastics Subdivision). The Acoustics Research Division is responsible for the design and development of the acoustical apparatus, the taking of data, and the validity of the results. The Chemistry Division is responsible for planning and carrying out a program to provide representative rubber specimens with regard to type, choice of compounding ingredients, molding procedures, and molecular weights. Both divisions will attempt to correlate the acoustical behavior with the chemical structure of the rubber.

2. In addition to the authors, substantial contributions to this work were made by the following: C. S. Sandler, now at the Bureau of Ordnance, who designed and developed the equipment used in obtaining the bulk measurements; M. E. Ebel, now at Iowa State College, who obtained a large part of the bulk data presented; and A. Fisher, Plastics Subdivision, NOL, who prepared most of the samples used.

3. This study emphasizes the variations in acoustical behavior of these elastomers with changes in chemical composition. The acoustical properties are also affected very substantially by such things as frequency, temperature, static pressure or tension, etc. It is planned that future studies will consider the effects of these other variables more completely.

4. An experimental study of the acoustic properties of rubber is of interest for several reasons:

a. The propagation behavior of acoustic waves in a medium is related to the basic molecular structure. Consequently, acoustic data on chemically known compounds are of great aid in formulating and testing theoretical hypotheses explaining these relationships.

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[1] The words "elastomeric" and "elastomer" refer to plastics which have rubberlike characteristics.

b. Rubber has many practical applications in acoustics. Since it is a good acoustical match with water, it is used extensively as a protective coating for hydrophones and other underwater acoustic devices. It is the main material used to prevent the transmission of structure-borne sounds; it is also very often used to absorb airborne sounds, and it it almost the only means of absorbing liquid-borne sounds effectively. These important applications make it desirable to have detailed acoustic data on many varieties of rubber. With this information the acoustic behavior of a material of known composition can be predicted under almost any conditions, and new materials with given characteristics can be specified.

5. The next section of this report will define some of the acoustical terms used and attempt to give some concept of their physical significance. This will be followed by a description of the apparatus and a brief discussion of acoustic measurements on plastics by other workers in this field. The acoustical data are then presented and followed by an analysis of the data from both an acoustical and a chemical standpoint. The discussion of the acoustical terminology, the description of the apparatus, and the presentation of the data were prepared for the Acoustics Research Division by W. S. Cramer. The analysis of the data from a chemical viewpoint and Tables I and II showing chemical details of the samples were prepared for the Chemistry Division by I. Silver.

ACOUSTICAL TERMS

6. It is generally desirable to present the acoustic data in the form of a complex dynamic modulus $\bar{E} = E(1 + i\delta)$. One reason for doing this is that the modulus is largely characteristic of the material itself, and has a minimum of dependence on the dimensions of the sample and characteristics of the surrounding media. Also, it lends itself easily to calculations on any kind of acoustical problem involving this material. Alternatively, the propagation characteristics are often presented in the form of the velocity and attenuation per unit length for a plane, progressive wave in the medium. Some basic definitions and physical concepts involving the modulus will be reviewed in the next paragraph. For a more complete discussion on this subject it is suggested that reference (a) (particularly Chapter III) and reference (b) be consulted.

7. The elastic modulus E is defined as the ratio of stress to strain when a material is subjected to a force. If these quantities are static and the elastic limit is not exceeded the modulus is a real number. The velocity of sound in a medium having a modulus E and neligible attenuation is $\sqrt{E/\rho}$ where ρ is the density. If the stress is not constant but is a simple harmonic force of the form $\sigma = \sigma_0 e^{i\omega t}$ there results a strain of the form $\epsilon = \epsilon_0 e^{i(\omega t - \delta)}$ where δ is the phase angle between the stress and the strain. The ratio σ/ϵ is known as the dynamic modulus. We then have

$$\bar{E} = \sigma/\epsilon = \sigma_0/\epsilon_0 \, e^{i\delta}$$

or

$$\bar{E} = \sigma_0/\epsilon_0 (\cos\delta + i \sin\delta)$$

or

$$\bar{E} = E(1 + i\eta) \qquad (1)$$

where $E = \sigma_0/\epsilon_0 \cos\delta$ and $\eta = \tan\delta$.

8. In order to give a clearer picture of the acoustical significance of the quantity η, equation (1) will be considered further. In Figure 1 we have a typical problem encountered in underwater acoustics. A thin layer of material of thickness d and modulus $\bar{E}$ is cemented firmly to a rigid backing. A plane sound wave with a wavelength very much larger than the thickness impinges from the right.

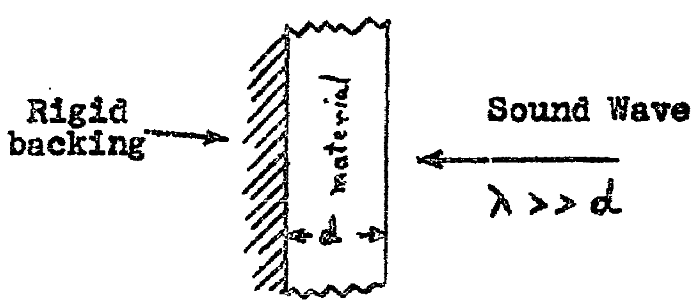

Figure 1.

Sound wave incident on a thin absorbent coating.

The sound wave subjects the material to a periodic force producing a periodic strain. Since the wavelength is much larger than the thickness all parts of the material deform in phase with each other. If the stress σ is graphed as the ordinate and the strain ϵ as the abscissa, and we carry the motion through one complete cycle, we have a curve similar to that of Figure 2. For a phase angle δ of zero, the figure becomes a straight line with the slope equal to the dynamic

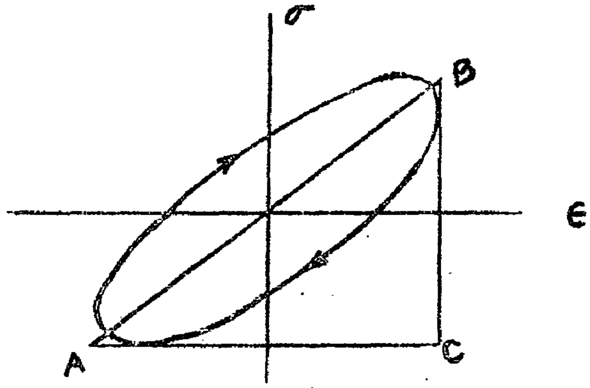

Figure 2.

Stress - Strain Diagram for one cycle.

modulus. The area of the ellipse (which is equal to $\pi\sigma_0\epsilon_0 \sin\delta$) is proportional to the energy lost per cycle in the form of heat. The total energy applied during a cycle is approximately proportional to the area of the triangle ABC ($2\sigma_0\epsilon_0$). The ratio of the area of the ellipse to the area of the triangle is the fraction of the total available energy which is dissipated per cycle. This ratio is approximately equal to $\pi/2(\sin\delta)$. Since for small angles $\sin\delta \approx \tan\delta$, this should explain why the quantity η (or $\tan\delta$) is called the loss factor and is frequently used as a figure of merit for the absorptive properties of a material. It is shown in references (a) and (b) that for plane, progressive waves the factor η is also almost directly proportional to the attenuation in decibels per wavelength.

9. The previous discussion mentioned only the elastic modulus E. It is customary in elastic theory to distinguish three basic types of moduli. These are the Young's modulus, the bulk modulus, and the shear or rigidity modulus. From an acoustical standpoint the differences are as follows:

(a) Young's modulus (Y). This is the modulus of interest for a longitudinal sound wave when the wavelength is much larger than the effective lateral dimensions of the medium. The velocity for a wave of this type, assuming negligible attenuation, is

$$C_Y = \sqrt{Y/\rho}. \qquad (2)$$

This is the velocity of sound in a thin rod or strip in air. (That is, the sides are not constrained but are free to expand and contract). The same condition is approached in some measure with a solid of large lateral dimensions when the material contains a large number of air-filled holes, providing some measure of pressure release.

(b) Shear modulus ( ). This is the effective modulus for a wave whose particle displacement is perpendicular to the direction of propagation[2]. The velocity of a shear wave with negligible attenuation is

$$c_\mu = \sqrt{\mu/\rho}. \quad (3)$$

(c) The bulk modulus (E_b). This is the modulus concerned when a material undergoes a compressional stress resulting in a change of volume rather than a change of shape. In acoustical work this modulus is important when plane wave propagation takes place in a medium where the lateral dimensions are much larger than a wavelength. In this case the effective modulus, known as the <u>bulk wave modulus</u>, is a combination of basic moduli of the form ($E_b + 4/3\mu$). So, the velocity of a wave under this condition is

$$c_b = \sqrt{\frac{E_b + 4/3\mu}{\rho}}. \quad (4)$$

The three basic moduli usually differ considerably in magnitude. All are needed to completely describe the acoustic behavior of a material. Since each modulus consists of a real and an imaginary part, this means that six numbers are needed. Then, of course, these six quantities will vary more or less independently with frequency, temperature, etc. In elementary elastic theory, which assumes no losses, simple equations are given relating the various moduli. As to how far these relationships hold with the complex moduli and especially how the respective loss factors are related is not completely clear at present. In considering any propagation problem one must decide which modulus or moduli are significant. This is frequently rather difficult when the structure is not simple and many borderline cases occur.

APPARATUS

10. Apparatus were developed to measure the bulk modulus and the Young's modulus. Some exploratory work was carried out on the measurement of the shear modulus but these data are not complete and will not be included in this report. The description

2. This definition is true only for a plane wave. For discussion of the general case consult a theoretical book such as Page's "Introduction to Theoretical Physics".

of the apparatus used follows:

(a) The bulk modulus (E_b) was measured by a resonant tube method originally used for this purpose by Meyer and Tamm in 1942 (reference c). The present apparatus was developed by Sandler and described rather completely by him in reference (d) and in abstract form in reference (e). The following quotation, taken from reference (e), is given here for convenience. "The apparatus consists of a water-filled steel tube one meter long, with 3/8 inch wall thickness. Standing waves are set up in the water column by means of a magnetically driven diaphragm mounted at the bottom of the tube. The sample to be measured is inserted at a pressure antinode and by considering the water column as a resonant transmission line, the bulk modulus and its loss factor are deduced from the change in Q and shift of resonant frequency when the sample is inserted. The operating frequency is (approximately) 1500 cps and a beat frequency technique is used for measuring the small changes in frequency involved." Temperature is controlled by surrounding the tube with a water jacket which was thermostatically controlled at 30°C. for these tests. These measurements must be done quite carefully as the presence of small air bubbles on the surface of the material would seriously affect the results. It was found that an experienced operator could repeat measurements so that the average deviation from the mean for successive readings is less than ±1% for E and ±0.002 for [illegible]. (This estimate is based on results from 47 measurements on 16 different materials).

(b) The apparatus used at NOL for measuring the Young's modulus has only been described in an abstract (reference f). It is essentially the same apparatus developed by Nolle and described by him in reference (b). It will be discussed briefly with the aid of Figure 3. The measurements were made on thin, rubber rods 1/8 inch in diameter and about 10 inches long. The sample is suspended horizontally and acoustically driven at one end with a record cutter head suitably coupled to the rod. The other end of the rod is supported with a leaf spring arrangement which was set to apply a constant tension of about 2 x 10^6 dynes/cm^2 to the rod. The amplitude of the sound wave is measured with a crystal phonograph unit with the needle bearing lightly on the underside of the rubber rod. The pickup arm is mounted on a motor driven carriage and the output signal from the pickup, suitably amplified and filtered, is fed to a Speedomax sound level recorder. The same motor drives the Speedomax and the pickup carriage. This arrangement enables the operator to make an automatic, continuous record of the logarithm of the amplitude versus the distance along the rod. The wavelength is obtained by beating the signal from the pickup with the direct signal from the driving oscillator and observing the Lissajou pattern on the screen of the

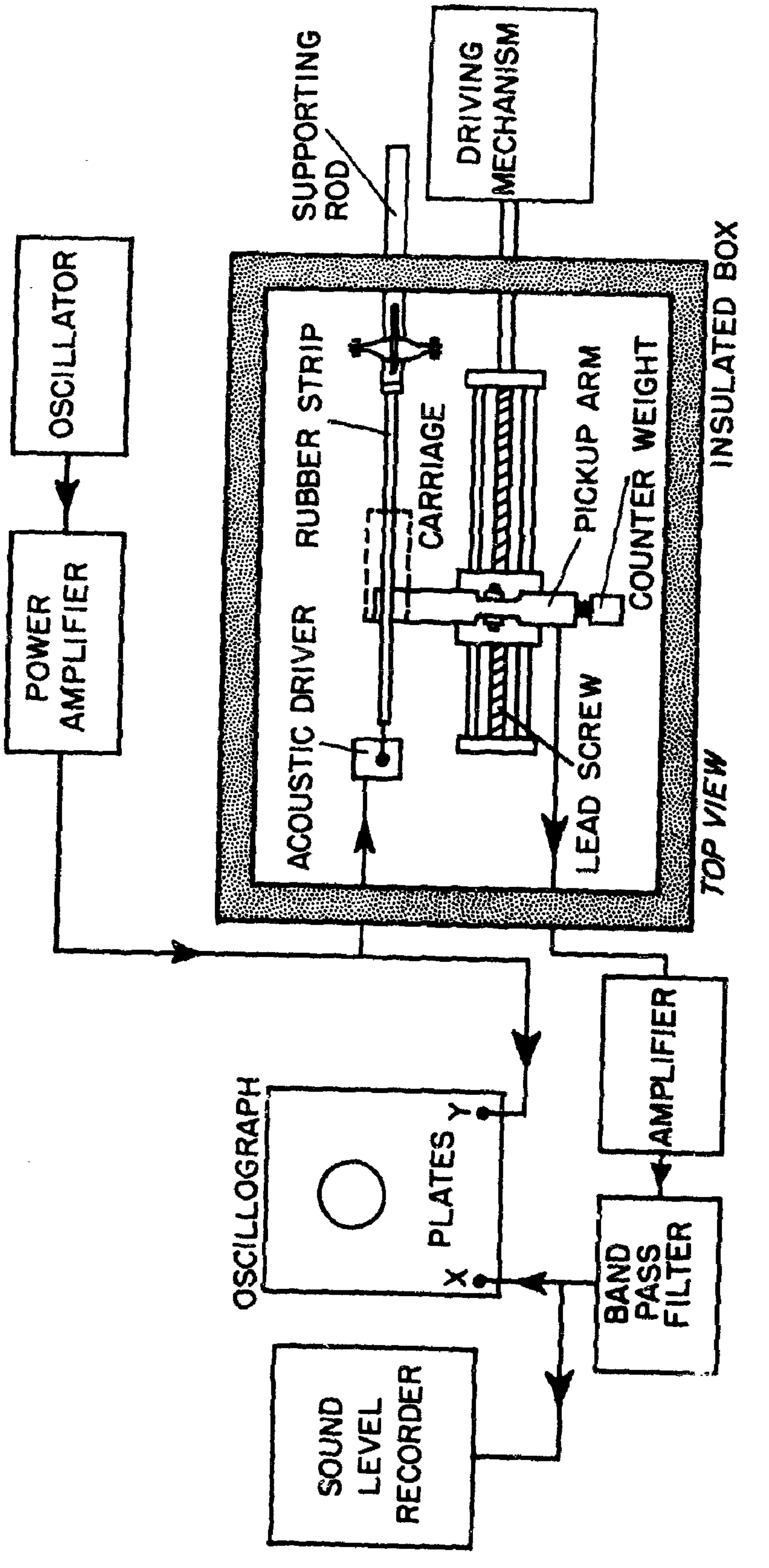

FIG.3 APPARATUS FOR DETERMINING THE YOUNG'S MODULUS AND ASSOCIATED LOSS FACTOR FOR VISCO-ELASTIC MATERIALS

oscilloscope. The points of 0° and 180° relative phase difference can be recognized and the separation of these points, viz., the half wavelength, can be measured. The velocity can then be calculated using the known frequency. The lower frequency limit of operation of this apparatus is set by the condition that the attenuation in decibels per centimeter, which increases with frequency, must be sufficiently large so that negligible reflection is received from the end opposite the source. In other words, we must have an effectively infinite line. The lower limit for must rubbers at 30°C. is in the vicinity of 1 kc. The upper frequency limit occurs when the wavelength is no longer substantially larger than the diameter of the rod, or the upper frequency limitation of the apparatus is reached. This limit usually occurred between 5 and 13 kc for a temperature of 30°C. In this investigation the range studied was limited to from 1 to 5 kc. The whole unit was mounted in a heat-insulated box and thermostatically-controlled air at 30°C. was circulated through the box. This temperature can be maintained to within perhaps ±0.2°C. Measurements showed that a very satisfactory straight line, as predicted by theory, could be obtained when the plot of the logarithm of the amplitude versus the distance was made. The results of the attenuation and velocity measurements in general are repeatable to within perhaps 5% and the accuracy is increased by obtaining readings at a number of frequencies and connecting the points with a smooth curve. The velocity and attenuation figures can then be used to calculate the real and imaginary parts of the Young's modulus.

(c) Although no extensive data were collected on the shear modulus, some exploratory work showed that the real part of the shear modulus is approximately 1/3 that of the Young's modulus and the respective loss factors are approximately equal. This is in line with conclusions reached by other workers in this field. The technique of measurement used was to study the propagation of torsional waves (instead of longitudinal waves) in the thin rubber rods with the Young's modulus apparatus. The values of the resulting velocity and attenuation can be used to calculate the complex shear modulus.

SURVEY OF MEASUREMENT TECHNIQUES

11. It might be well to pause at this point to discuss briefly some other experimental studies on the acoustic properties of rubber. The literature on this subject is fairly extensive and no attempt will be made to be exhaustive. Emphasis will be placed on experiments covering frequencies in the upper audible and lower ultrasonic regions. The discussion will be divided according to the type of modulus most directly concerned.

(a) Bulk modulus. There have been comparatively few measurements of this quantity. The resonant tube method of Meyer and Tamm (reference c) has been used in the vicinity of 1 to 2 kc. The quantity measured here is the complex bulk modulus associated with an all-sided compression of the material (E_b). As explained in section 9(c) this is not the modulus associated with actual bulk wave propagation ($E_b + 4/3\mu$). However, it is an important part of it, and by itself it is of considerable theoretical interest. There have been quite a few measurements on the velocity and attenuation associated with bulk wave propagation. The frequency range studied has been from 40 kc to 30 mc. The technique generally used has been to immerse a comparatively thin disk in water and compare its acoustic properties with that of the displaced water. This has been done by Mason (reference g) and others using the method of acoustic interferometry, while Nolle and Mowry (reference h) and others used pulse techniques. Considerable data have been submitted by these authors.

(b) Young's modulus. This quantity has been measured satisfactorily over a frequency range from a fraction of a cycle per second to 30 kc and above. A survey of many of the techniques used in measuring this quantity is given in an article by Nolle (reference i) and in Chapter III of Meyer's book (reference a). Most of the studies above 500 cps have used the progressive wave technique described in section 10(b) of this report. It is a convenient reliable method that lends itself easily to routine collection of data. Above 30 kc it becomes rather difficult to measure the Young's modulus as the experimental conditions are hard to obtain (viz., the lateral dimensions must be small compared with a wavelength). An interesting study by Nolle of the behavior of the real and imaginary parts of Young's modulus as a function of frequency and temperature (a perspective three-dimensional drawing is used) over a considerable range of both quantities is available (reference j).

(c) Shear modulus. The measurement of the dynamic shear modulus has received less attention than that of the Young's modulus. At the very low frequencies (a few cycles per second), a torsional pendulum method of measurement can be used. At higher frequencies up to several kilocycles per second a resonance method is frequently used in which the rubber in shear acts as the stiffness element in a vibrating system driven at resonance. The usual procedure is to sandwich the material between two rigid plates, keep one fixed and drive the other parallel to its face. The resonant frequency is detected by tuning the system for maximum amplitude. This frequency along with the physical dimensions of the system and the width of the resonance curve gives enough information to obtain the dynamic shear modulus. This method can only be used as long as the thickness of the material is considerably less than the wavelength of a shear wave in the rubber. For a more complete description of this type of apparatus and technique, the work of Dillon, Prettyman, and Hall is suggested (reference k). Measurements have also been carried out in the megacycle region using a pulse technique in which a sample is inserted in a solid acoustic transmission line (liquids will not in general support shear waves) and its velocity and attenuation measured. The upper audible and lower ultrasonic regions offer more difficulty for shear studies and have received less attention.

ACOUSTIC DATA

12. Acoustic data are presented in Figures 4 to 15 and Table III on 49 separate rubber formulations, consisting of variations of eight different basic rubbers. The legend on each figure will indicate which basic rubbers are included in the figure and each curve will have a code number for the particular formulation used. Reference should then be made to Tables I and II for the chemical details. As a convenience to the reader a table of the variable loadings will be included on each graph whenever possible. This table gives the amounts and types of filler and plasticizers used in each formulation. The abbreviations used are explained in Table I and the number of parts (abbreviated p.) is with reference to 100 parts by weight of the basic rubber. Each formulation contains, in addition to the filler and plasticizer, certain compounding ingredients which are necessary for vulcanization. These materials, given in Table II, are kept constant for the variations of a given basic rubber but vary for the different basic rubbers because of chemical considerations.

13. Figures 4 to 8 inclusive show the strip velocity (c) (that is, the velocity associated with the Young's modulus) as a function of frequency from 1 kc to 5 kc at 30°C. for all samples. The experimental points are included for reference. The attenuation in decibels per centimeter (α) was measured for the same samples at the same frequencies. These attenuation data are not presented completely but the curves for three formulations each of neoprene (GNA) and GR-S rubber are presented, with experimental points, in Figure 9 as an example. In Figure 10 the attenuations at 5 kc for all samples are summarized in graphical form. This form of presentation was used to give a clearer picture of relative values. In Figure 11 several examples are submitted of

the real part of the Young's modulus[3] plotted against the frequency. The values of the modulus at 1.5 kc are summarized for all samples in Figure 12. This frequency was used for the summary since the bulk data were taken at the same frequency. Similarly in Figure 13 typical curves are presented of the loss factor[4] η for samples of butyl and natural rubber. The butyl has one of the highest loss factors of the homogeneous rubbers and natural rubber has one of the lowest. The graphical summary of all samples was made at 5 kc, since the accuracy here is higher than at the low frequencies, and is presented in Figure 14.

14. The bulk data were taken at only one frequency (1530 cps). The real part of the bulk modulus, which is obtained directly from the resonant frequencies and curve widths, is presented for all samples in graphical form in Figure 15. No bulk data are included on the Thiokol type rubber due to surface irregularities on the available samples which brought the validity of the results into question. The loss factors associated with the bulk modulus are very small (less than 0.10) for the most part and closely grouped together in magnitude so it was doubted if the graphical presentation of the data used heretofore would serve a useful purpose. These data are presented in Table III.

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[3] The expression relating the real part of the modulus to the experimentally determined values of c and α follows:

$$E = \frac{\rho c^2 (1 - r^2)}{(1 + r^2)^2}$$

where ρ is the density and $r = \alpha\lambda/54.6$

[4] The loss factor η is related to the experimental values as follows:

$$\eta = \frac{2r}{1 - r^2}$$

15. From an acoustic standpoint several comments on the data might be made:

(a) The real part of the bulk modulus is quite high, being of the order of that of water. The real part of the Young's modulus, on the other hand, is about two orders of magnitude smaller. This means that rubber is very incompressible in bulk but can be deformed quite easily. The latter effect is a matter of daily observation but the former is less apparent without special tests.

(b) The fact that the bulk modulus is very substantially larger than the Young's modulus (and the shear modulus) for rubbers makes it the most effective modulus when studying acoustic propagation through sheets of homogeneous rubber. Recall that the bulk wave modulus, which is the effective modulus unless the material is structured, is of the form E (bulk wave modulus) = $E_b + 4/3\mu$ where E_b is the bulk modulus and μ is the shear modulus (see section 9 c).

(c) The increase in strip velocity (and the real part of the Young's modulus) with frequency is noted as is also the fact that different basic rubbers and different formulations have different rates of dispersion. The work of Nolle (reference j) showed that the modulus will continue to increase with frequency until some limiting value is approached at very high frequencies.

(d) The loss factor associated with the Young's modulus is usually about one order of magnitude higher than that associated with the bulk modulus. The latter, indeed, is so small in most cases that in former years it was assumed to be zero. Since η is almost proportional to the loss in decibels per wavelength (see footnote[4]), the twofold effect of a larger η and a smaller wavelength make the attenuation in decibels per centimeter associated with the Young's modulus substantially higher than that for the bulk effect.

(e) The loss factor associated with the Young's modulus increased with frequency. The work of Nolle (reference j) showed that the loss factor tended to peak somewhat above the present frequency range of measurements and then decreased to a constant value. The position and magnitude of the peak depends on the rubber type.

(f) The present experiments give no information on the variations of E and η with frequency for the bulk modulus. However, the work of others, principally Meyer and his associates, indicate that the real part of the modulus changes comparatively little while the loss factor may increase by a factor of three or a little more in the frequency range 1 kc to 1 mc.

(g) It is interesting to note that two different rubber rods with the same attenuation per unit length (α) may have widely different attenuations per wavelength because of the difference in velocity. A material such as natural crepe rubber has a comparatively high value of α under our conditions of measurement but has one of the lowest loss factors of all the materials tested. (The loss factor (η) is a function of the attenuation per wavelength as explained in footnote 4). In choosing a material for an application requiring a high loss the relative importance of α and η depend on the particular application in mind and other properties of the material, and no simple generalizations can be made.

Table I

Chemicals Used in the Investigation

Symbol	Common Name	Descriptive Detail
Elastomers		
HC-15	Hycar OR-15	Butadiene-acrylonitrile rubber (55:45)
HC-25	Hycar OR-25	Butadiene-acrylonitrile rubber (67:33)
FA	Thiokol FA	Polysulfide rubber
PA	Hycar PA	Polyacrylic rubber
GR-S	GR-S-50	Butadience-styrene rubber (71:29)
NR	Natural Rubber	Natural Crepe Rubber
GNA	Neoprene	Chloroisoprene
GR-I	Butyl	GR-I-15; isobutylene-isoprene
Fillers		
F.T.	Fine Thermal Black	P-33; 150-200 microns
H.M.F.	High Modulus Furnace Black	Continex H.M.F.: 50 to 60 microns
E.P.C.	Easy Processing Channel Black	Cont. AA; 30 to 33 microns
SIL	Silene E.F.	Calcium Silicate - extra fine
TiO_2	Titanium Dioxide	duPont's R-300
CEL	Celite 505	Diatomaceous earth
ASB	Asbestos	Powdered
Plasticizers		
D.B.P.	Dibutyl phthalate	
CUM	Cumar P-25	Para-courmarone-indene resin and coal tar comp. M.P. 25°C.
PIC	Picco 25	Para-coumarone-indene resin; M.P. 25°C.

Table II

FORMULATIONS OF SPECIMENS USED IN THESE TESTS

	Sample Number (HC-15-)													
Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hycar OR-15(HC-15)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Zinc Oxide	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Stearic Acid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Altax	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sulfur	2	2	2	2	2	2	2	2	2	2	2	2	2	2
(D.B.P.) Dibutyl Phthalate		12.5		30	75	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
H.M.F. (Carbon black)		30	30	30	30	90	50							
F. T. (Carbon black)								10	30	50				
Silene E.F.(SIL)											10	30	50	
Titanium Dioxide(TiO_2)														10
Celite 505 (CEL)														
E.P.C.(carbon black)														
Asbestos (ASB)														
Cumar P-25 (CUM)														
Picco 25 (PIC)														
Hardness-shore A	60	69	78	60	42	92	78	55	65	70	57	66	79	52

The curing cycle was 30 minutes at 310°F. for all samples on this page.

The number of parts is with respect to weight.

Table II
(continued)

FORMULATIONS OF SPECIMENS USED IN THESE TESTS

Sample Number (HC-15-)

Material	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Hycar OR-15(HC-15)	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Zinc Oxide	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Stearic Acid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Sulfur	2	2	2	2	2	2	2	2	2	2	2	2	2	2
(D.B.P.) Dibutyl Phthalate	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5			12.5	12.5	12.5
H.M.F.(carbon black)														
F. T. (carbon black)														
Silene E.F.(SIL)														
(TiO_2) Titanium Dioxide	30	50												
Celite 505(CEL)			10	30	50									
E.P.C.(carbon black)						10	30	50				30		
Asbestos (ASB)												20	10	30
Cumar P-25 (CUM)										12.5				
Picco 25 (PIC)											12.5			
Hardness-shore A	54	60	62	75	85	62	75	85	52	55	57	75	58	62

The curing cycle was 30 minutes at 310°F. for all samples on this page.

The number of parts is with respect to weight.

Table II
(continued)

FORMULATIONS OF SPECIMENS USED IN THESE TESTS

	HC-25-			FA-			PA-			GR-S-		
Material	1	2	3	1	2	3	1	2	3	1	2	3
Hycar OR-25(HC-25)	100	100	100									
Thiokol FA (FA)				100	100	100						
Hycar PA (PA)							100	100	100			
GR-S-50 (GR-S)										100	100	100
Zinc Oxide	5	5	5	10	10	10				5	5	5
Stearic Acid	1.5	1.5	1.5	0.5	0.5	0.5				2	2	2
Altax	1.5	1.5	1.5	0.3	0.3	0.3				1.5	1.5	1.5
D.P.G.				0.1	0.1	0.1						
Butyl Zimate										0.1	0.1	0.1
Sulfur	2	2	2							2	2	2
Wool Grease							5	5	5			
Hydrated Lime							5	5	5			
$NaSiO_3.5H_2O$							10	10	10			
Agerite Stalite										1	1	1
(D.B.P.) Dibutyl Phthalate		12.5	12.5									
F.T. (carbon black)					30	50						
E.P.C. (carbon black)		30	50					30	50	10	30	50
Hardness-Shore A	47	58	72	42	58	65	45	58	65	34	55	68
Curing Cycle Time	30 min.			30 min.			45 min.			45'	30'	30'
Curing Cycle Temperature	310°F.			300°F.			310°F.			280° F.	290° F.	290° F.

Table XI
(continued)

FORMULATIONS OF SPECIMENS USED IN THESE TESTS

Material	NR-			GNA-			GR-I-		
	1	2	3	1	2	3	1	2	3
Natural Crepe (NR)	100	100	100						
Neoprene (GNA)				100	100	100			
Butyl (GR-I)							100	100	100
Zinc Oxide	5	5	5	5	5	5	5	5	5
Stearic Acid	1	1	1	0.5	0.5	0.5	1	1	1
Altax	1	1	1						
Butyl Zimate							0.5	0.5	0.5
Tuex							1.5	1.5	1.5
MgO				4	4	4			
Sulfur	3	3	3				2	2	2
Agerite Alba	0.5	0.5	0.5						
Agerite Stalite				2	2	2			
E.P.C. (carbon black)		30	50		30	50		30	50
Hardness-Shore A	26	43	54	45	65	78	32	47	57
Curing Cycle Time	30 min.			30 min.			30 min.		
Curing Cycle Temperature	290°F.			290°F.			300°F.		

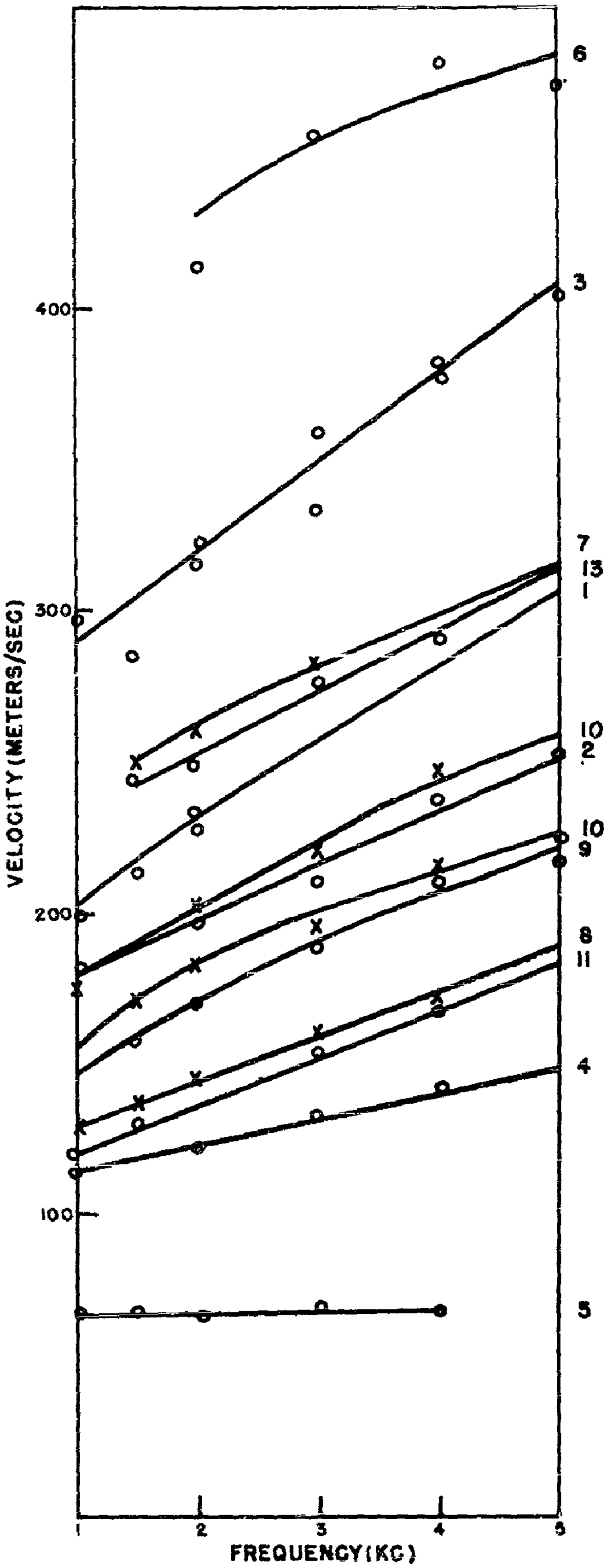


FIG. 4

STRIP VELOCITY vs FREQUENCY FOR SEVERAL FORMULATIONS OF HYCAR OR-15; T=30°C

Variable Loading*

#6 90 p HMF; 12.5 p DBP

#3 30 p HMF

#7 50 p HMF; 12.5 p DBP

#13 50 p SIL; 12.5 p DBP

#1 no loading

#10 50 p FT; 12.5 p DBP

#2 30 p HMF; 12.5 p DBP

#12 30 p SIL; 12.5 p DBP

#9 30 p FT; 12.5 p DBP

#8 10 p FT; 12.5 p DBP

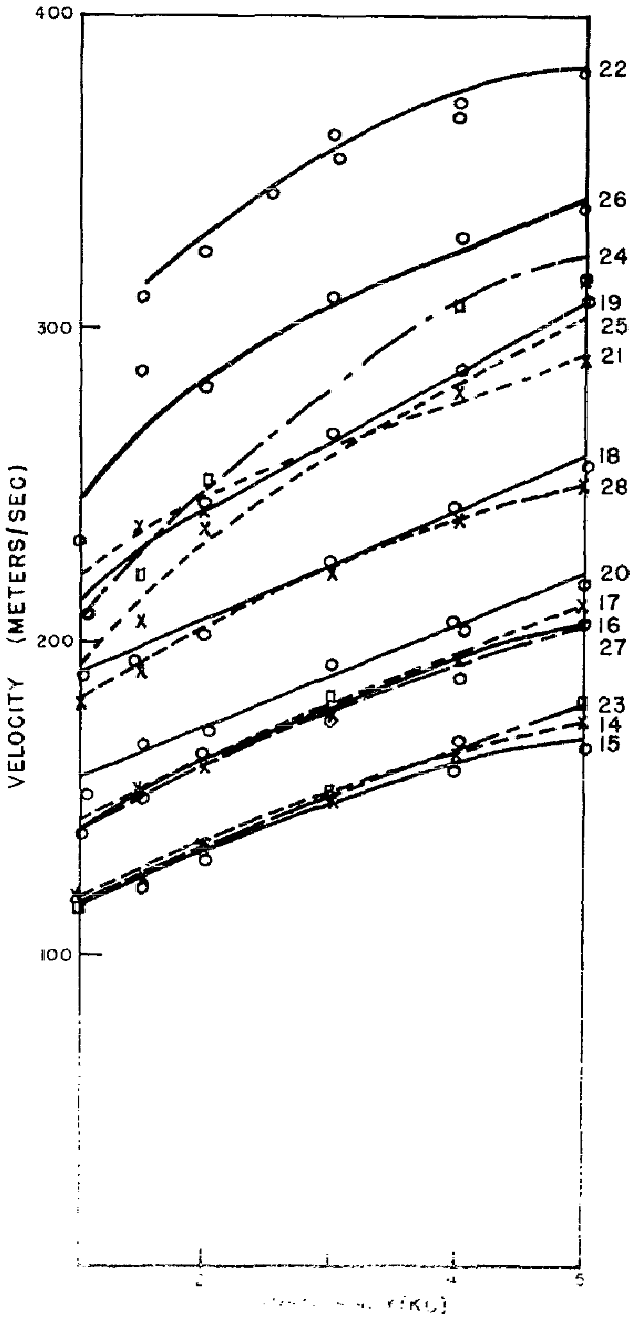
#11 10 p SIL; 12.5 p DBP

#4 30 p HMF; 30 p DBP

#5 30 p HMF; 75 p DBP

* Abbreviations explained in Table I.

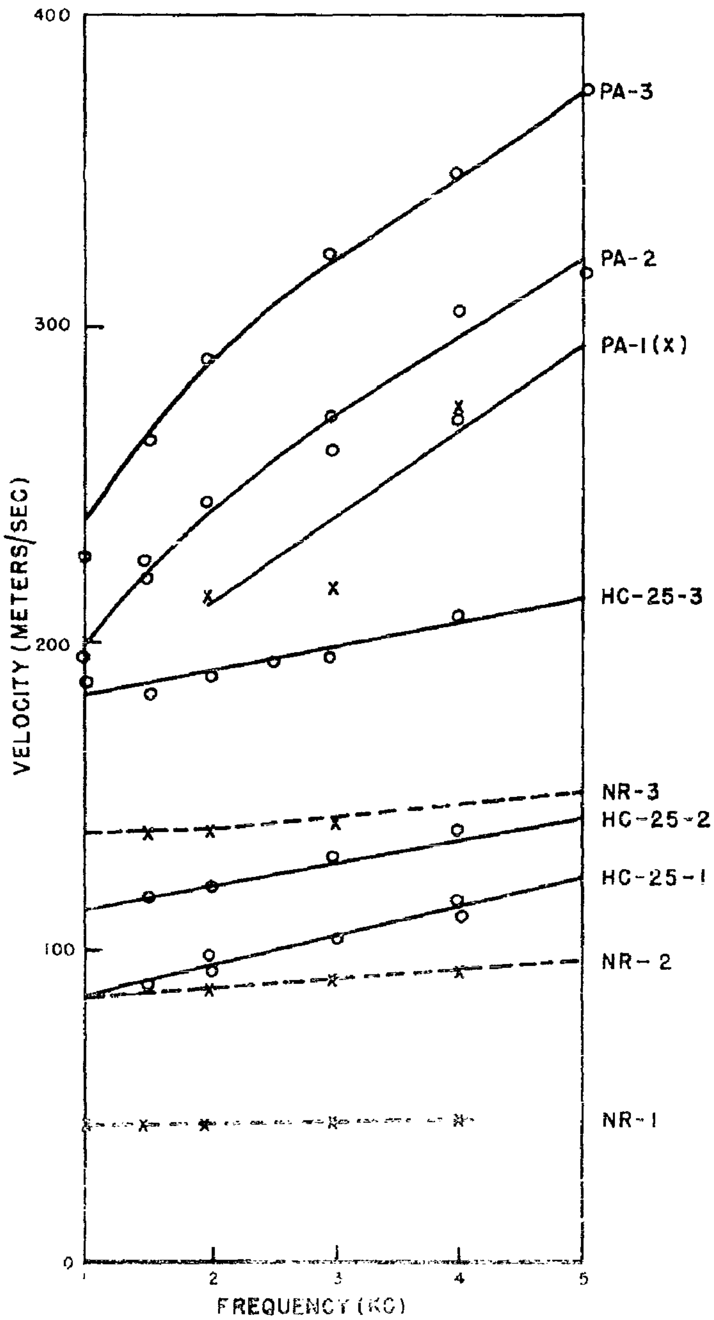
FIG. 5
STRIP VELOCITY VS FREQUENCY FOR
SEVERAL FORMULATIONS OF HYCAR OR-15; T = 30° C



Variable Loading

#22	50	p EPC; 12.5 p DBP
#26	30	p EPC; 20 p ASB; 12.5 p DBP
#24	12.5	p CUM
#19	50	p CEL; 12.5 p DBP
#25	12.5	p HIC
#21	30	p EPC; 12.5 p DBP
#18	30	p CEL; 12.5 p DBP
#28	30	p ASB; 12.5 p DBP
#20	10	p EPC; 12.5 p DBP
#16	50	p TiO_2; 12.5 p DBP
#27	10	p ASB; 12.5 p DBP
#23	12.5	p DBP
#14	10	p TiO_2; 12.5 p DBP
#15	30	p TiO_2; 12.5 p DBP
#17	10	p CEL; 12.5 p DBP

FIG.6
STRIP VELOCITY VS FREQUENCY FOR SEVERAL FORMULATIONS EACH OF HYCAR PA, HYCAR OR-25 (HC-25), AND NATURAL CREPE RUBBER (NR); T= 30° C



Variable Loading

PA-3	50 p EPC
PA-2	30 p EPC
PA-1	no loading
HC-25-3	50 p EPC; 12.5 p DBP
NR-3	50 p EPC
HC-25-2	30 p EPC; 12.5 p DBP
HC-25-1	no loading
NR-2	30 p EPC
NR-1	no loading

FIG. 7
STRIP VELOCITY vs FREQUENCY FOR
SEVERAL FORMULATIONS EACH OF
NEOPRENE (GNA) AND THIOKOL FA
T=30°C

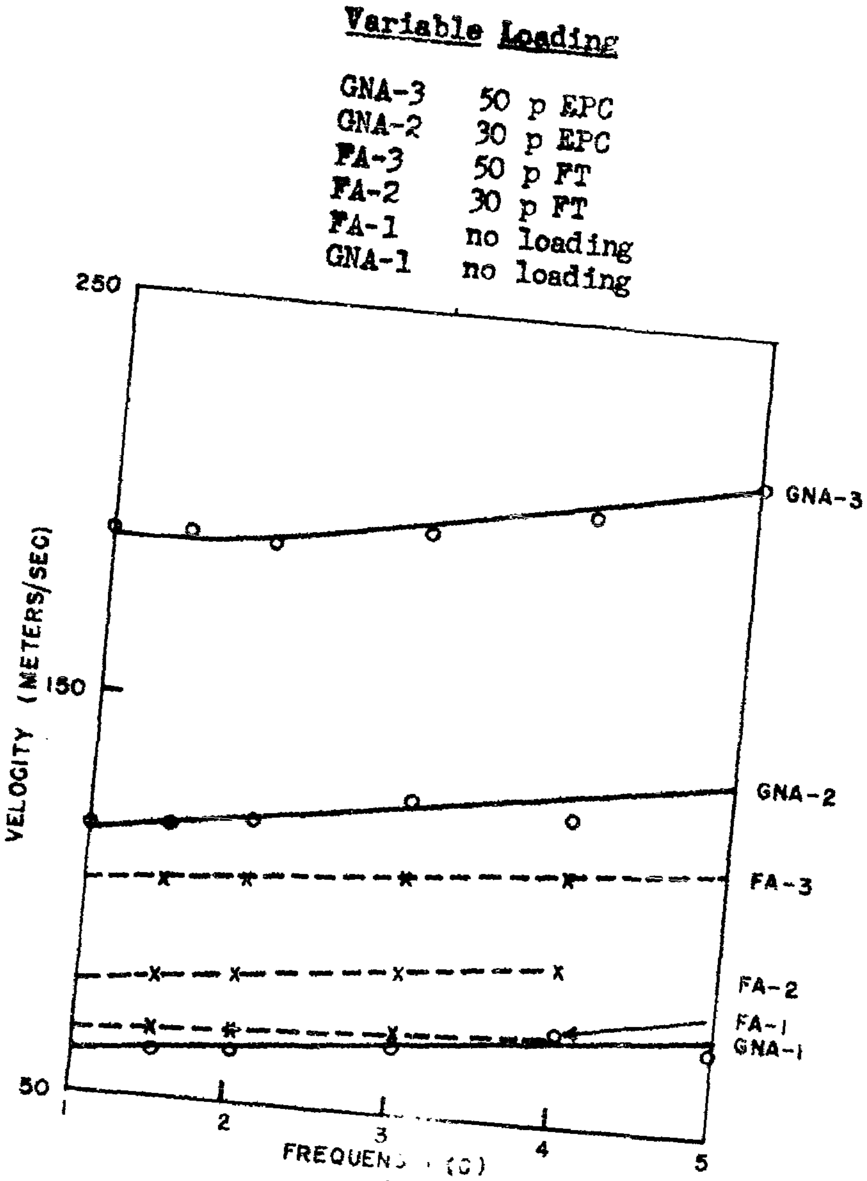
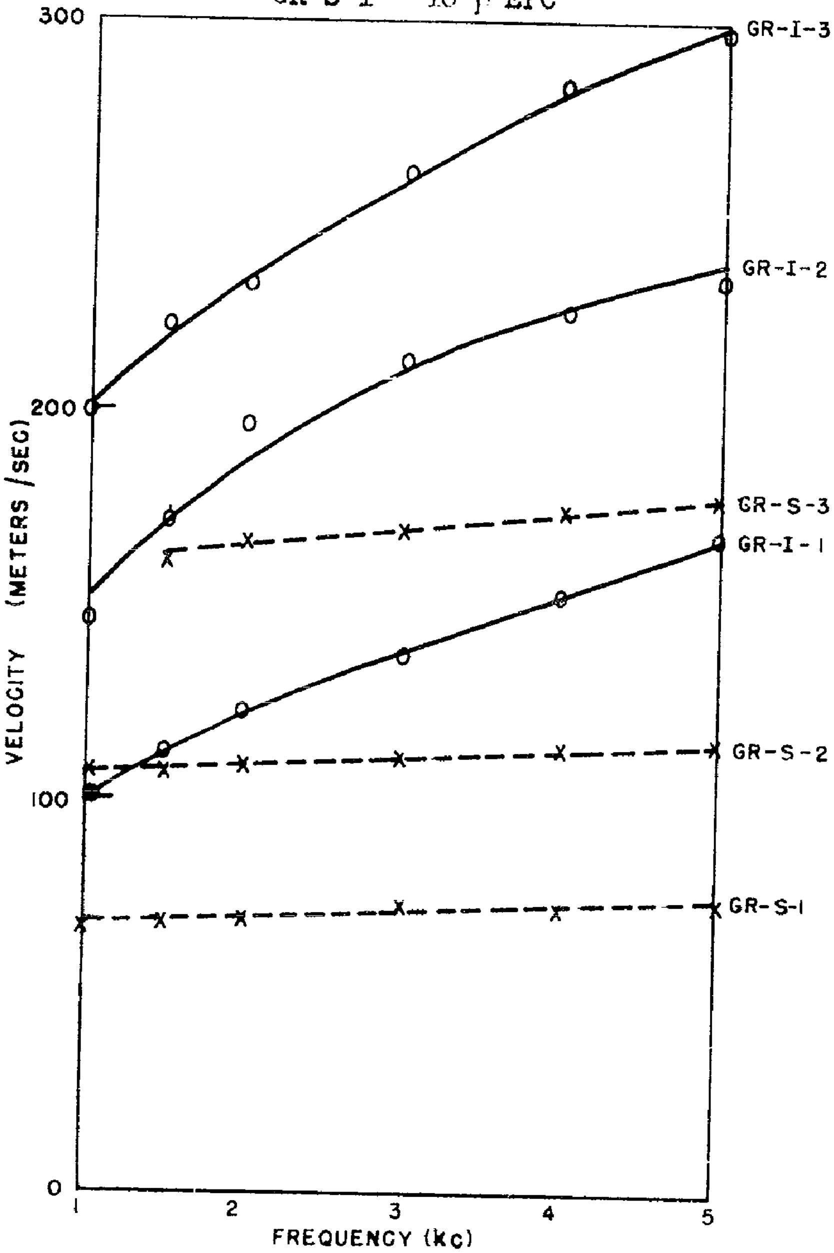


FIG. 8
STRIP VELOCITY vs FREQUENCY
FOR SEVERAL FORMULATIONS EACH
OF BUTYL (GR-I) AND GR-S-50
T = 30°C

Variable	Loading
GR-I-3	50 p EPC
GR-I-2	30 p EPC
GR-S-3	50 p EPC
GR-I-1	No loading
GR-S-2	30 p EPC
GR-S-1	10 p EPC



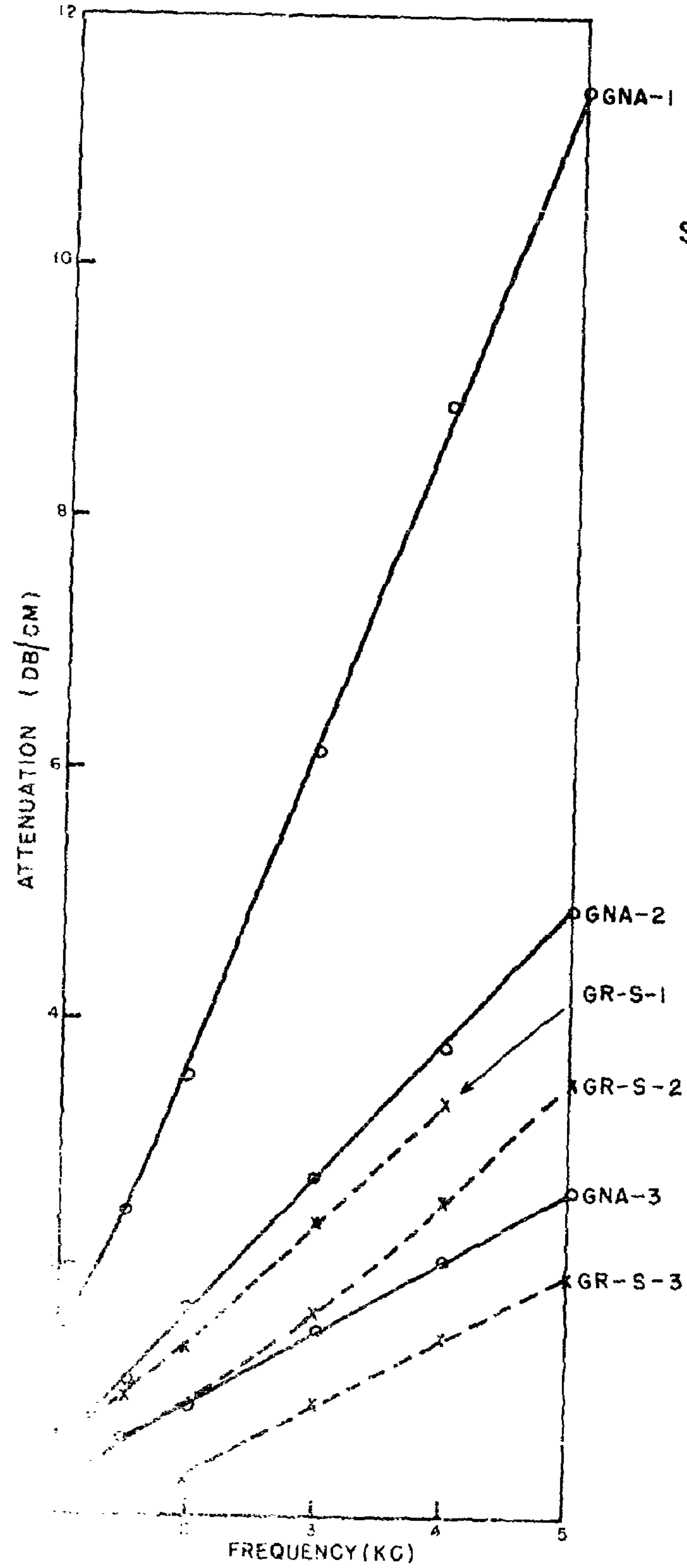


FIG. 9
ATTENUATION vs FREQUENCY FOR SEVERAL FORMULATIONS EACH OF NEOPRENE (GNA) AND GR-S-50 (GR-S) RUBBER; T = 30°C

Variable Loading

GNA-1	no loading
GNA-2	30 p EPC
GR-S-1	10 p EPC
GR-S-2	30 p EPC
GNA-3	50 p EPC
GR-S-3	50 p EPC

FIG. 10

COMPARISON OF ATTENUATIONS
FOR ALL SAMPLES AT 5 KC AND 30°C

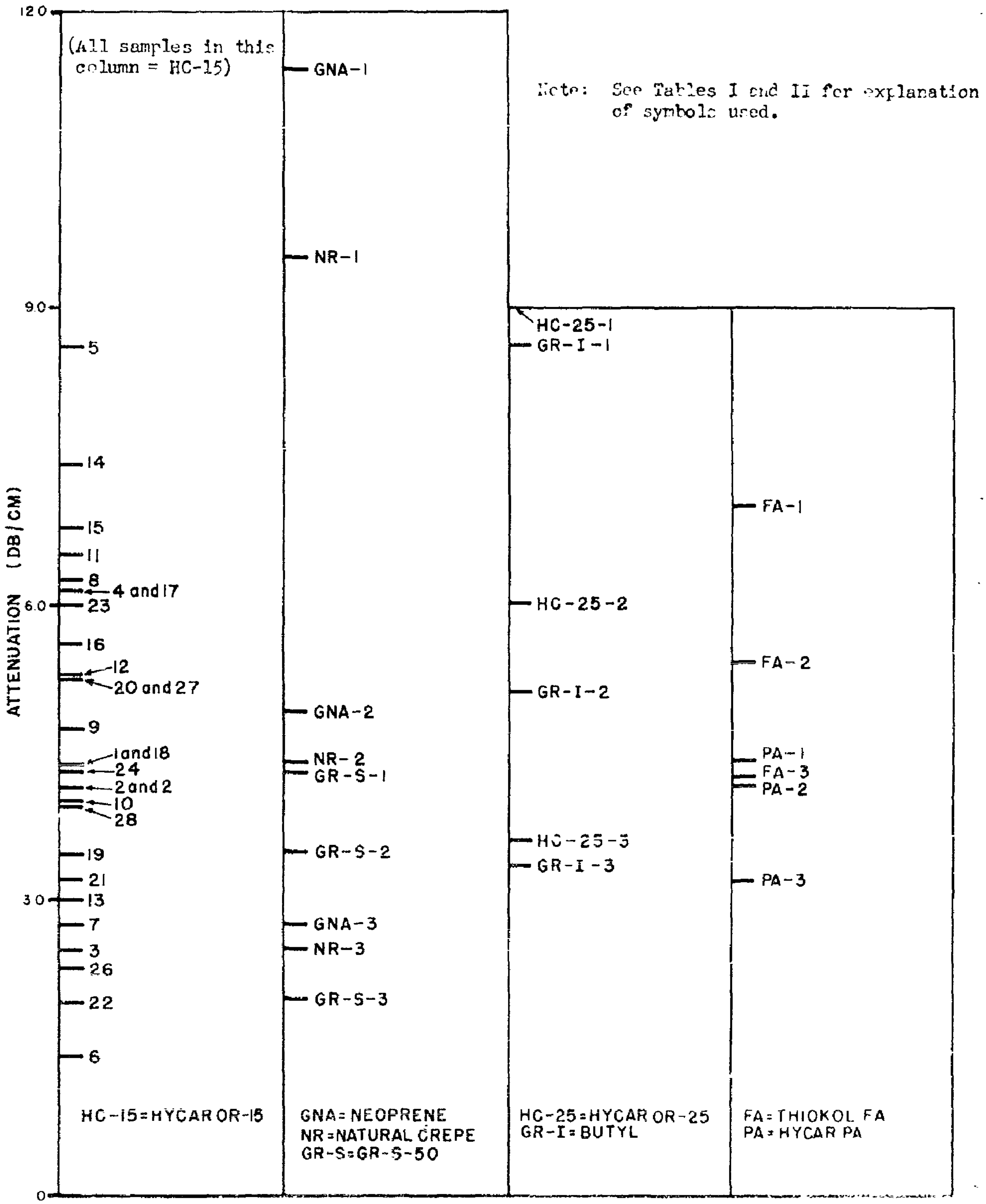


FIG. 11
THE REAL PART OF THE YOUNG'S MODULUS VS FREQUENCY FOR SEVERAL FORMULATIONS EACH OF BUTYL (GR-I) GR-S-50 (GR-S), AND NEOPRENE (GNA)
T = 30°C

<u>Variable</u>	<u>Loading</u>
GR-I-3	50 p EPC
GNA-3	50 p EPC
GR-S-3	50 p EPC
GR-I-2	30 p EPC
GNA-2	30 p EPC
GR-S-2	30 p EPC
GR-I-1	no loading
GR-S-1	10 p EPC
GNA-1	no loading

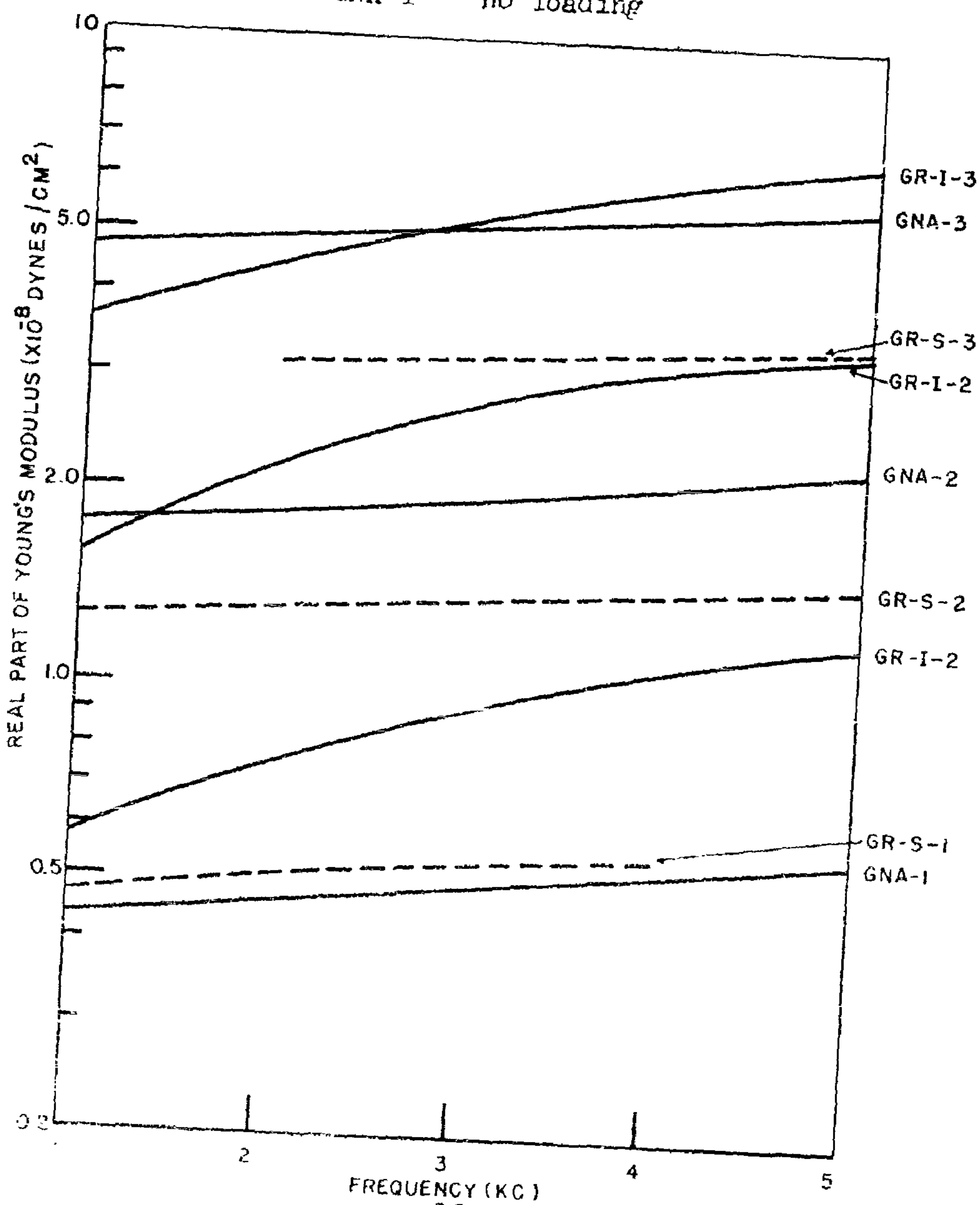


FIG. 12
COMPARISON OF THE REAL PARTS OF YOUNG'S MODULUS
FOR ALL SAMPLES AT 1.5KC AND T=30°C

Note: See tables I and II for complete explanation of symbols used.

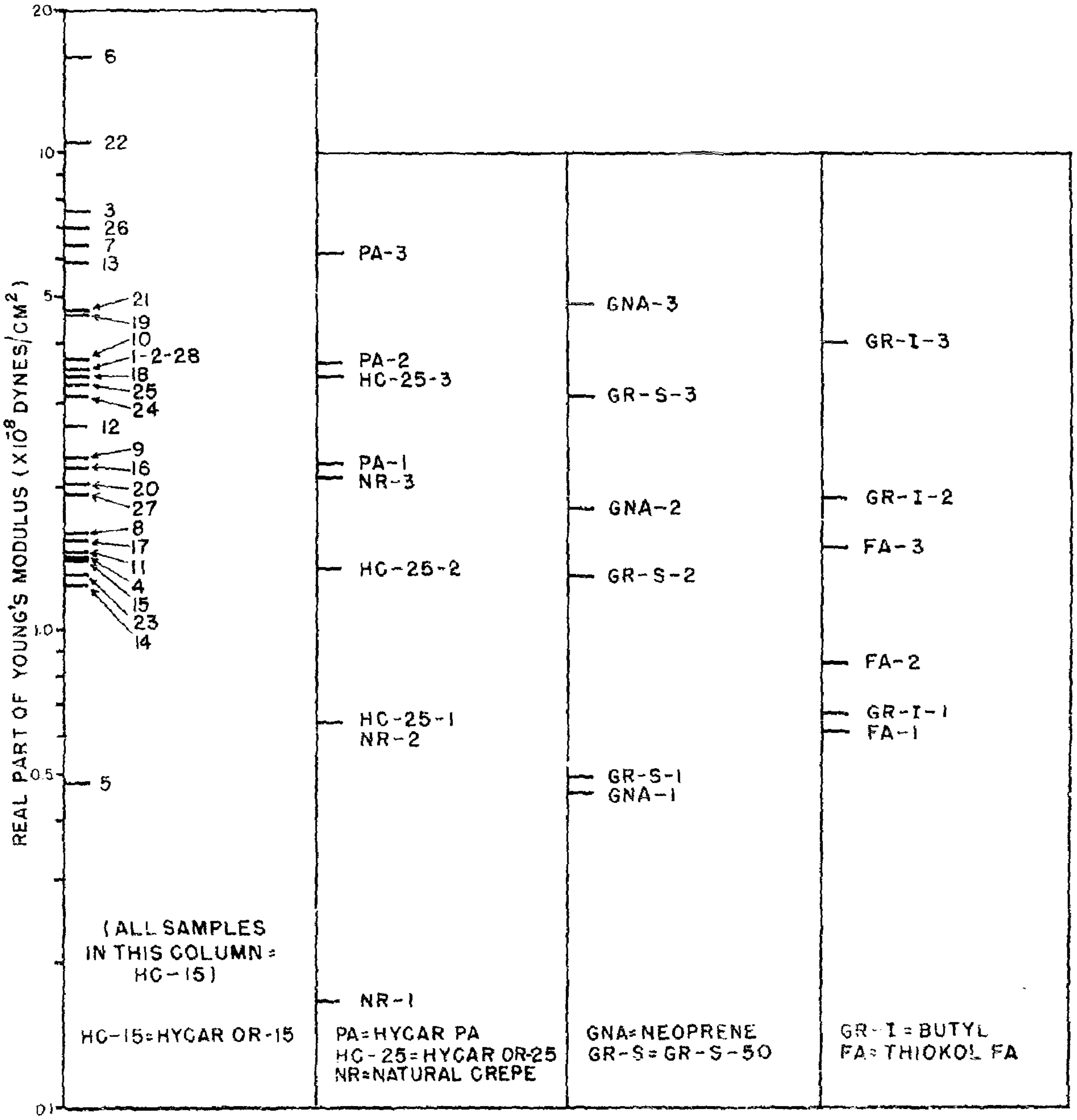


FIG.13

LOSS FACTOR FOR YOUNG'S MODULUS VS FREQUENCY FOR SEVERAL FORMULATIONS EACH OF BUTYL (GR-I) AND NATURAL CREPE RUBBER (NR)

T=30°C

<u>Variable Loading</u>

GR-I-1	no loading
GR-I-2	30 p. EPC
GR-I-3	50 p. EPC
NR-1	no loading
NR-2	30 p. EPC
NR-3	50 p. EPC

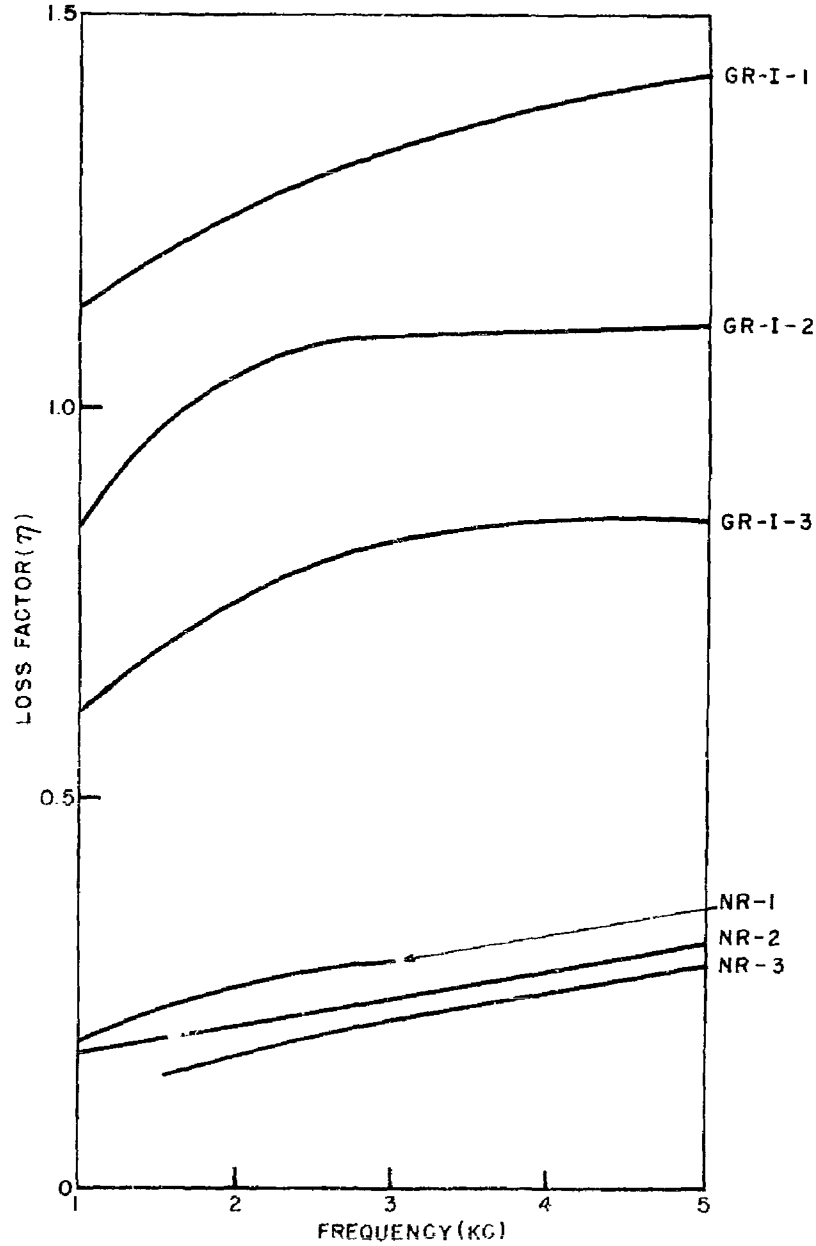


FIG. 14
COMPARISON OF THE LOSS FACTORS ASSOCIATED WITH THE YOUNG'S MODULUS FOR ALL SAMPLES
AT 5 KC AND T=30°C

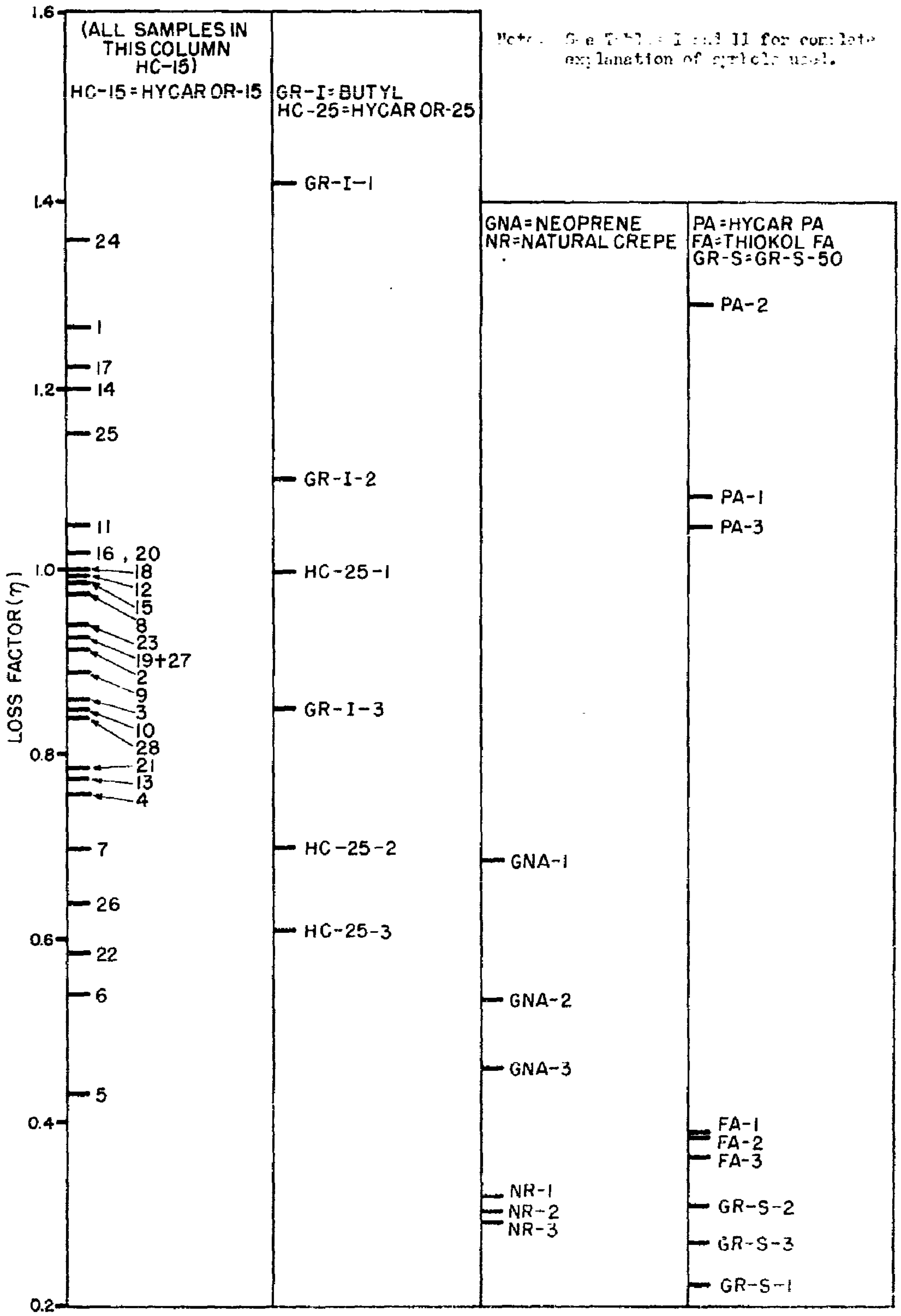


FIG. 15
COMPARISON OF THE REAL PARTS
OF THE BULK MODULUS FOR ALL SAMPLES
AT 1.5 KC AND T=30°C

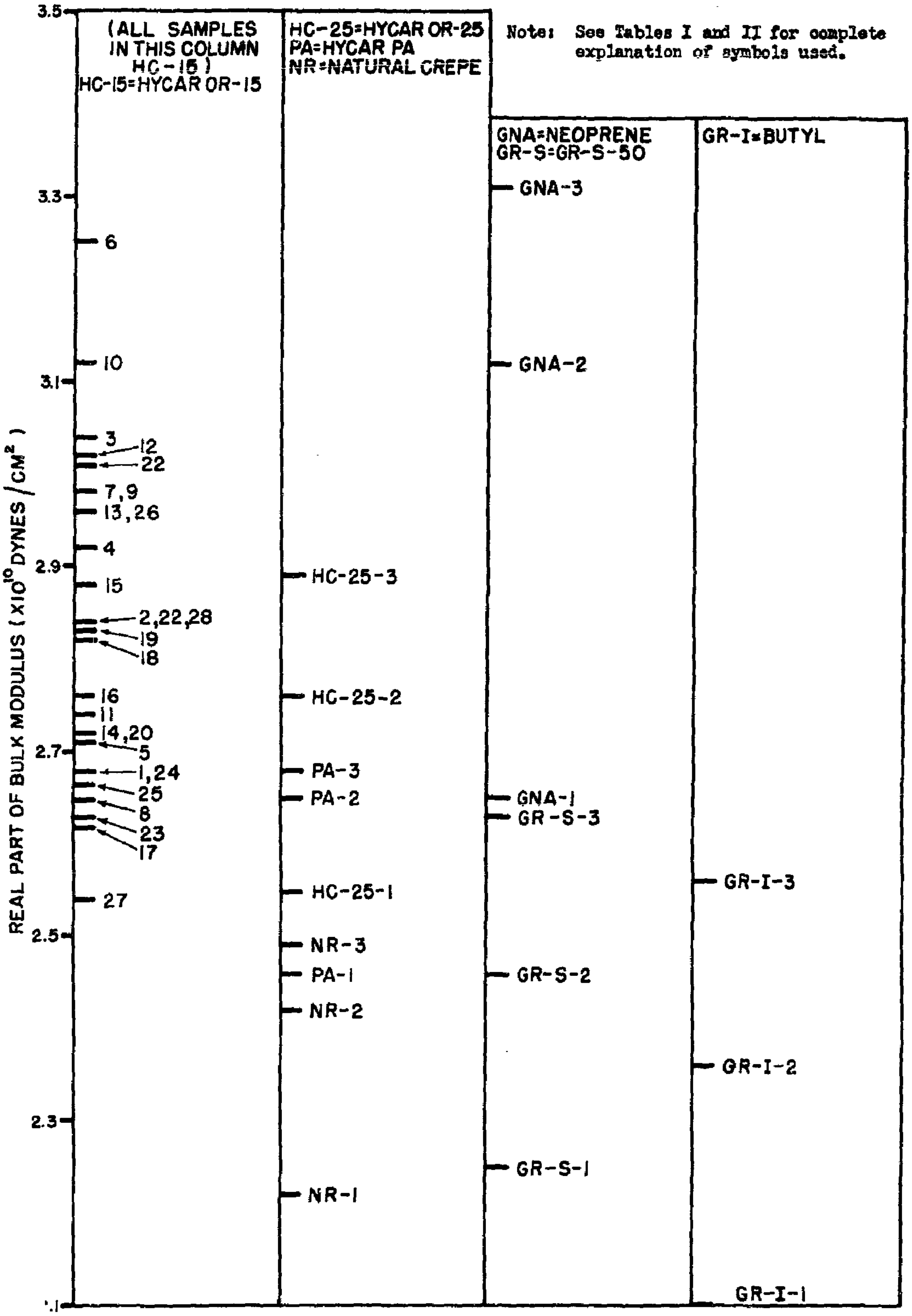


Table III

Loss Factors for the Bulk Modulus

Symbol	Name of Elastomer	Variable Loading	Loss factor (average)
HC-15-1	Hycar OR-15	no loading	0.011
HC-15-2	"	30 p. H.M.F.; 12.5 p. D.B.P.	0.012
HC-15-3	"	30 p. H.M.F.	0.005
HC-15-4	"	30 p. H.M.F.; 30 p. D.B.P.	0.005
HC-15-5	"	30 p. H.M.F.; 75 p. D.B.P.	0.009
HC-15-6	"	90 p. H.M.F.; 12.5 p. D.B.P.	0.000
HC-15-7	"	50 p. H.M.F.; 12.5 p. D.B.P.	0.010
HC-15-8	"	10 p. F.T.; 12.5 p. D.B.P.	0.006
HC-15-9	"	30 p. F.T.; 12.5 p. D.B.P.	0.004
HC-15-10	"	50 p. F.T.; 12.5 p. D.B.P.	0.012
HC-15-11	"	10 p. SIL.; 12.5 p. D.B.P.	0.006
HC-15-12	"	30 p. SIL.; 12.5 p. D.B.P.	0.014
HC-15-13	"	50 p. SIL.; 12.5 p. D.B.P.	0.010
HC-15-14	"	10 p. TiO_2; 12.5 p. D.B.P.	0.009
HC-15-15	"	30 p. TiO_2; 12.5 p. D.B.P.	0.005
HC-15-16	"	50 p. TiO_2; 12.5 p. D.B.P.	0.019
HC-15-17	"	10 p. CEL.; 12.5 p. D.B.P.	0.042 *
HC-15-18	"	30 p. CEL.; 12.5 p. D.B.P.	0.010
HC-15-19	"	50 p. CEL.; 12.5 p. D.B.P.	0.015
HC-15-20	"	10 p. E.P.C.; 12.5 p. D.B.P.	0.019
HC-15-21	"	30 p. E.P.C.; 12.5 p. D.B.P.	0.014
HC-15-22	"	50 p. E.P.C.; 12.5 p. D.B.P.	0.013
HC-15-23	"	12.5 p. D.B.P.	0.011
HC-15-24	"	12.5 p. GUM.	0.015
HC-15-25	"	12.5 p. PIC.	0.010
HC-15-26	"	30 p. E.P.C.; 20 p. ASB.; 12.5 p. D.B.P.	0.006
HC-15-27	"	10 p. ASB.; 12.5 p. D.B.P.	0.045 *
HC-15-28	"	30 p. ASB.; 12.5 p. D.B.P.	0.009
HC-25-1	Hycar OR-25	12.5 p. D.B.P.	0.006
HC-25-2	"	30 p. E.P.C.; 12.5 p. D.B.P.	0.011
HC-25-3	"	50 p. E.P.C.; 12.5 p. D.B.P.	0.024 *
GR-I-1	Butyl	no loading	0.112 *
GR-I-2	"	30 p. E.P.C.	0.049 *
GR-I-3	"	50 p. E.P.C.	0.019
NR-1	Natural	no loading	0.003
NR-2	"	30 p. E.P.C.	0.011
NR-3	"	50 p. E.P.C.	0.010
GR-S-1	GR-S-50	10 p. E.P.C.	0.006
GR-S-2	"	30 p. E.P.C.	0.012
GR-S-3	"	50 p. E.P.C.	0.044 *
GNA-1	Neoprene	no loading	0.013
GNA-2	"	30 p. E.P.C.	0.013
GNA-3	"	50 p. E.P.C.	0.013
PA-1	Hycar PA	no loading	0.017
PA-2	"	30 p. E.P.C.	0.018
PA-3	"	50 p. E.P.C.	0.019

* Values > 0.020

RELATIONSHIPS BETWEEN ACOUSTIC PROPERTIES AND CHEMICAL COMPOSITION

16. This section of the report is concerned with the analysis of the acoustic data in terms of the specific effects of the compounding ingredients. Heretofore most information or data derived from pertinent literature on the subject were based on the acoustical analysis of a relatively few types of rubber formulations. Very little attention has been given to a study of basic rubber types with regard to the effect of compounding ingredients on the acoustical properties of the final material. Since large variations in the mechanical properties of a particular rubber can be obtained through compounding it is reasonable to expect similar important changes in acoustic properties.

17. This program was planned to cover large modifications in formulation of the basic rubber types listed in Table I. These rubbers are representative of those types presently in commercial use with the exception of the silicones. The latter rubber was not included pending further study of the acoustic effect of the characteristic small air voids in the material. In order to facilitate the investigation and perhaps eliminate what may be considered possible duplication, Hycar OR-15, a butadiene acrylonitrile rubber, was compounded with several plasticizers and a wide range of types and amounts of black and non-black fillers in the hope that effects obtained would be applicable to the other rubbers under study. The remainder of the rubbers, with the exception of the Thiokol, were compounded only with varying amounts of a carbon black (E.P.C.)

18. The acoustical data reported in Figures 4 to 15 and in Table III are analyzed from the viewpoint of the effect of the basic type of rubber and compounding variables on the following properties of acoustical interest:

- (a) Real parts of the Young's and bulk moduli
- (b) Velocity - strip and bulk
- (c) Density
- (d) Characteristic acoustic impedance
- (e) Attenuation - strip
- (f) Loss factor - Young's modulus and bulk modulus.

19. Real parts of the Young's and bulk moduli (E). The incorporation of black and non-black fillers in Hycar OR-15 results in an increase in the real part of the Young's modulus as shown in Figure 16. Of the carbon black, the highest modulus occurs with the use of the black with the smallest particle size. Continental AA, an easy processing channel black (E.P.C.) having a particle size of 30 to 33 microns and having good reinforcing properties, gives the greatest increase, while P-33, a fine thermal black (F.T.) having a particle size of 150 to 200 microns gives the smallest increase. Continex H.M.F., a high modulus furnace black of 50-60 microns diameter has an intermediate value. The use of the E.P.C. filler in rubbers other than Hycar OR-15 results in an increase in the Young's modulus as shown in Figure 17.

20. Correspondingly, the increase in the real part of the bulk modulus is similar to that of the Young's modulus in that within certain limits of filler concentration the general trend is toward a higher modulus as seen in Figure 18. However, certain important differences do occur particularly with the non-black fillers such as Celite 505, Silene E.F., and TiO_2 in that a maximum bulk modulus occurs with approximately 30 parts of filler concentration. This concentration may possibly represent the point of maximum reinforcement by these fillers. The value of E continues to increase, however, with filler concentration for carbon blacks even up to 90 parts in the case of the H.M.F. black. The behavior of the bulk modulus of several different basic rubbers when loaded with various concentrations of the E.P.C. filler is shown in Figure 19. The moduli for water is added to this figure for comparison. It can be observed that the relationships are approximately linear with some evidence, in the case of certain materials, of a saturation condition being approached at the highest concentrations. It is also interesting to observe that the acoustical reinforcing properties of E.P.C. are not the same for every rubber. For example, the neoprene and Hycar OR-15 have approximately the same modulus value for no filler but diverge by about 10% with 50 parts of E.P.C. filler.

21. Within the time expended on this investigation, only a limited number of plasticizers could be studied for their effect on the modulus and the other acoustical properties of rubber. As with the fillers, these plasticizers were used with Hycar OR-15. The three plasticizers, dibutyl phthalate, Picco 25, and Cumar P-25, all result in a decrease in the real part of the Young's modulus for equal concentrations (12.5 parts). In bulk modulus, for equal concentrations, Picco 25 resulted in an increase, whereas the other two plasticizers caused slight decreases. The data for the Young's modulus and the bulk modulus of Hycan OR-15 as a function of type and amount of plasticizer are given in Figure 20. Even with the limited work carried out, it is important to note that the choice of filler and plasticizer and the concentration of each will exert considerable influence in varying the modulus from that of the basic rubber type.

22. It is customary in rubber technology to specify the hardness of a rubber by the durometer reading, a static measurement of the hardness of rubber using arbitrary units and a standard procedure. These values on the Shore A scale have been given in Table II for all samples. In figures 21 and 22 these durometer readings are compared with the logarithm of the real part of the Young's modulus and the real part of the bulk modulus, respectively. The experimental points are marked and a single line connects all points of a given basic rubber. As might be expected there is a positive but not too strong a correlation between the durometer reading and these other quantities.

23. Velocity (c) The effect of the fillers on the velocity as measured in the Young's modulus test apparatus parallels very closely the effect on the real part of the Young's modulus itself. This is to be expected as the two properties are related mathematically by the expression

$$E = \rho c^2 (1 - r^2)/(1 + r^2)^2$$

as already explained in footnote 3. The c^2 term is the predominant factor since r rarely exceeds 0.6. Referring to Figure 23, the E.P.C. black (with the smallest particle size) has the largest dispersion and TiO_2, the smallest, approximating the relationship for fillers established for the Young's modulus. The results of adding E.P.C. filler to the different basic rubbers is shown in Figure 24. Note that the Thiokol FA was loaded with F.T. black instead of E.P.C. It would be expected that this substitution would tend to reduce the dispersion in the Thiokol. These same data are then plotted in Figure 25 as a percentage change in velocity as a function of loading, and a considerable difference among the basic rubbers noted. The effect of plasticizers on the velocity appears to be a function of the type and amount used so that wide variations in velocity are obtained (Figure 26). For example, dibutyl phthalate reduces the velocity whereas Cumar P-25 results in an increase. Equal concentrations (12.5 parts) of plasticizers in Hycar OR-15 result in velocities of approximately 180, 300, and 320 meters per second for dibutyl phthalate, Picco 25, and Cumar P-25, respectively. The effect of fillers on velocities obtained from the bulk measurements (see Figure 27) differs considerably from strip data in that increasing the amount of E.P.C. black produces relatively little change in velocity in most of these rubbers. This can be contrasted with the bulk modulus itself where increasing filler concentrations usually result in a higher modulus. In Hycar OR-15 the non-black fillers such as TiO_2, Celite 505, and Silene E.F. cause a decrease in velocity with increased loading as seen in Figure 27. Also shown is the comparatively slight influence of the amount and type of plasticizer on the bulk velocity. Larger concentrations of plasticizer, however, may result in substantial changes in velocity.

24. Density (ρ) Since the density of a material is a quantity of acoustical importance, its variation with different types and amounts of filler and plasticizer is considered in Figure 28. It is interesting to observe that for a given rubber, the resulting density for different types of filler differ substantially for the same loading by weight. Similarly, the same filler with different rubbers gives different results.

25. Characteristic acoustic impedance (ρc) The characteristic acoustical impedance of rubber is an important acoustical property particularly in underwater applications where it may be desirable to match the impedance of water. Since the degree of matching is determined largely by the quantity ρc, those factors affecting the density and velocity in bulk become important in this connection. According to Figure 29, the ρc values for GR-S-50, natural crepe rubber, and butyl are relatively low so that the impedance could be adjusted to match that of water by adding the proper amount of filler. This variation is probably due mainly to the increase in density rather than an increase in velocity since it was shown in Figure 27 that increasing the amount of carbon black (E.P.C.) will not alter the velocities in these rubbers very much. On the other hand, Hycar OR-15, Hycar Pa, and Neoprene have characteristic acoustic impedance values considerably higher than that of water. To enable these rubbers to match the impedance of water, it can be seen that incorporation of extremely large amounts of low density plasticizer to reduce the velocity would be necessary. In actual compounding, it is usually desirable to employ a reinforcing filler so that the addition of a plasticizer would have to counteract the effect of increased velocity and density resulting from the filler. The relative effects of the different types of filler and plasticizer on the characteristic acoustic impedance of Hycar OR-15 is shown in Figure 30.

26. Attenuation (α). As explained previously the attenuation sometimes refers to the attenuation in decibels per centimeter (which we call α) and sometimes to the loss factor η, which is approximately proportional to the attenuation in decibels per wavelength (see footnote 3). The relative importance of each in predicting sound absorption is to some extent a function of the particular acoustical application. This paragraph is concerned with the attenuation per unit length (α). With Hycar OR-15 the attenuation decreases with the addition of black and non-black fillers as seen in Figure 31, the greatest decrease being obtained with the E.P.C. black. It should be recalled that this filler has the smallest particle size of the carbon blacks and it was the one which had the greatest effect on the velocity. The use of the non-black fillers results in a tendency towards an increase in attenuation for about 10 parts loading but a decrease at higher loadings, the smallest decrease being effected by TiO_2. In Figure 32 the change in attenuation with loading of E.P.C. filler for the different basic

rubbers is plotted. Then in Figure 33 these same data are plotted in percentages giving some idea of the relative influence on the different rubbers. These curves should be compared with those in Figure 25 showing percentage changes of velocity with loading. Plasticizers vary in their effect on the attenuation of the rubber. For example, the addition of dibutyl phthalate to Hycar OR-15 results in a substantial increase in attenuation whereas Cumar P-25 and Picco 25 cause slight decreases (see Figure 34).

27. Loss Factor. On the basis of results shown in Figure 14 and in Table III for the loss factors in both the Young's modulus and the bulk modulus tests, it is evident that wide variations in loss factors can be obtained. The specific effect of a plasticizer and filler on the loss as with the other acoustical properties studied is a function of the type and amount of compounding ingredients and the basic nature of the rubber employed. In regard to loss factors determined in the Young's modulus test, the highest results over a range of 1 to 5 kc are found in the gum vulcanizates of butyl, Hycar OR-15 and Hycar PA, respectively. The lowest loss factors are found in natural rubber and GR-S-50. It is interesting to note that neoprene which has one of the highest attenuations per centimeter is among those with the lowest loss factors. The change in the loss factor as a function of E.P.C. loading is shown in Figure 35. The addition of 50 parts of loading results in a decrease of the loss factor for all rubbers tested, the greatest decrease usually occurring in those rubbers having the highest initial loss factor (butyl and Hycar OR-15). One can interpret these results in terms of the data of Figures 25 and 32. In these figures the percentage increase in velocity with loading for various rubbers and the percentage decrease in attenuation with loading are plotted. Then since η is a function of the product $\alpha\lambda$ only, it is merely a question of the relative influence of the loading on the velocity and attenuation. The addition of different fillers to Hycar OR-15 causes a varied effect on the loss factor for the Young's modulus depending again on the type and amount (see Figure 36). At 10 parts most of the fillers increase the loss factor somewhat, the greatest increase occurring with TiO_2 and Celite 505. At 50 parts the reinforcing fillers, such as E.P.C., H.M.F., and Silene E.F., result in decreases in loss, the largest decrease occurring with E.P.C., the most reinforcing of the fillers. TiO_2, Celite 505, and F.T. black appear to cause a leveling off and even a slight increase at 50 parts filler concentration. On the basis of the data obtained with Hycar OR-15, it is quite probable that at loadings greater than 50 parts, non-reinforcing blacks or non-blacks may result in higher loss factors possibly due to frictional losses between the filler particles.

28. As with the other acoustical properties studied, the use of a plasticizer can result in wide differences in the loss factor

for the Young's modulus (see Figure 14). Dibutyl phthalate in Hycar OR-15 results in a large decrease in loss in contrast to the results for attenuation per centimeter where an increase was obtained for the same plasticizer. Picco 25 also results in a decreased loss factor but Cumar P-25 increases it slightly. Referring to Figure 26 and 34 we observe that the Picco 25 effects the velocity (and therefore the wavelength) very little and causes a slight decrease in the attenuation. The results is a decrease in attenuation per wavelength (and a lower loss factor). The Cumar on the other hand causes a noticeable increase in velocity but very little change in attenuation. The result in this case leads to a large attenuation per wavelength.

29. In connection with the discussion of the loss factor it might be of interest to consider the term "resilience" which is frequently mentioned in rubber work. According to Shaw (reference 1) the "resilience is the ratio of energy given up on recovering from deformation to the energy required to produce the deformation". As pointed out in Section 8 and in Figure 2 the energy which is not returned but dissipated in the form of heat is proportional to the loss factor. The resilience and loss factor then are complementary terms; that is, a material with a high resilience has a low loss factor and vice versa. A discussion of resilience tests and a complete bibliography are given in reference (1). The resilience can be derived for sinusoidal deformations at small amplitude from acoustic data, but most of the results quoted in the literature are obtained from impact tests and it is well to keep this in mind when comparing data. Referring to the work of Shaw (reference 1) we find that the elastomers with the highest inherent resilience are neoprene, natural rubber, and GR-S which according to our data are among those with the lowest loss factor. On the other hand elastomers with the lowest resilience such as butyl and Hycar OR-15 have the highest loss factors. In regard to plasticizers, the addition of dibutyl phthalate to Hycar OR-15 results in an increase in resilience and a decrease in loss factor whereas Cumar P-25 results in a decrease in resilience and an increase in the loss factor. The addition of fillers is reported to result in a decrease in resilience (which would mean an increase in the loss factor). In general this has not been true in our tests. However, the relationship between the impact resilience and the acoustic loss factor is not too clear and requires further study.

30. Loss factors obtained in the bulk modulus tests, although of a lower magnitude than those obtained in the Young's modulus test, are similar in certain respects. Vulcanized gum butyl has the highest loss and GR-S-50 and natural rubber are among the lowest. E.P.C. black causes a sharp decrease in the loss factor in both the butyl and Hycar OR-15 elastomers although several of the rubbers do show an increase in loss on the addition of E.P.C.

At concentrations of 50 parts several of the fillers including TiO_2, Celite 505, and F. T. black tend to cause an increase in loss. This is similar to the effect observed in the loss factors in the Young's modulus measurements. Plasticizers vary in their effect and as in the Young's modulus test, the addition of Cumar P-25 increases the loss. Due to basic inaccuracies in measuring the very small loss factors too much significance should not be given to small differences. The fact that the unloaded butyl gives a loss factor substantially above any other material tested is perhaps the most significant result of the measurements of this factor.

CONCLUSIONS

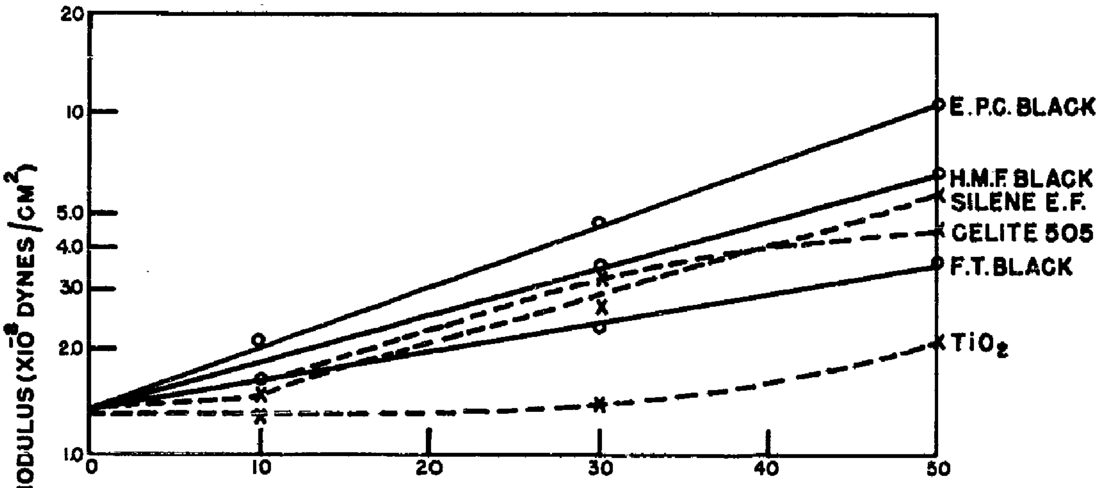
31. On the basis of the work covered in this investigation, it is apparent that within certain limitations wide variations in acoustical properties of rubber elastomers can be obtained by the use of varying amounts and types of compounding ingredients. The limitations on the degree of variation depend to a considerable extent on the basic acoustical properties of the elastomer which are a function of its particular molecular structure and upon the physical properties desired for a specific application. Thus in matching the impedance of water, it is evident from the data presented that several rubbers (GR-S, NR, and GR-I) can be matched very easily by the addition of carbon black fillers. On the other hand elastomers such as neoprene and Hycar OR-15 have such high initial velocities that high loadings of low density plasticizer would be required with a considerable reduction in physical properties.

32. Further work in the study of the effect of compounding ingredients on loss factors and other pertinent acoustical properties is indicated. Although the work in this investigation has been limited to a relatively small number of fillers and plasticizers, definite trends appeared to be developing and should be pursued further. For example, several of the non-reinforcing fillers at higher concentrations give some evidence of increasing the loss factor. The use of selected plasticizers may also be a factor in obtaining higher losses. Of the elastomers studied, butyl in the vulcanized gum state has the highest loss factor although the incorporation of a carbon black (E.P.C.) results in sharp decreases. Nevertheless, further study with this rubber should be carried out with particular emphasis on variations in unsaturation content, in fillers and plasticizers, and milling and molding procedures.

FIG. 16

REAL PART OF YOUNG'S MODULUS OF HYCAR vs NUMBER OF PARTS FILLER FOR VARIOUS FILLER TYPES. FREQUENCY=1.5KC

T=30°C



REAL PART OF YOUNG'S MODULUS vs NUMBER OF PARTS E.P.C. FILLER FOR VARIOUS BASIC RUBBERS. FREQUENCY=1.5KC

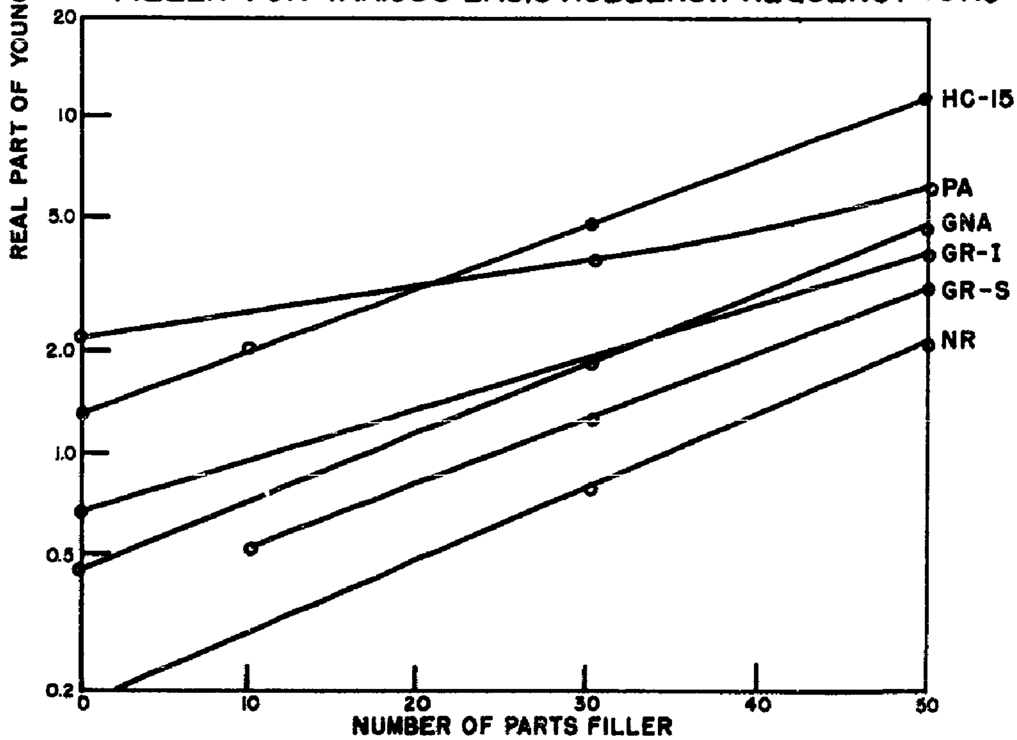
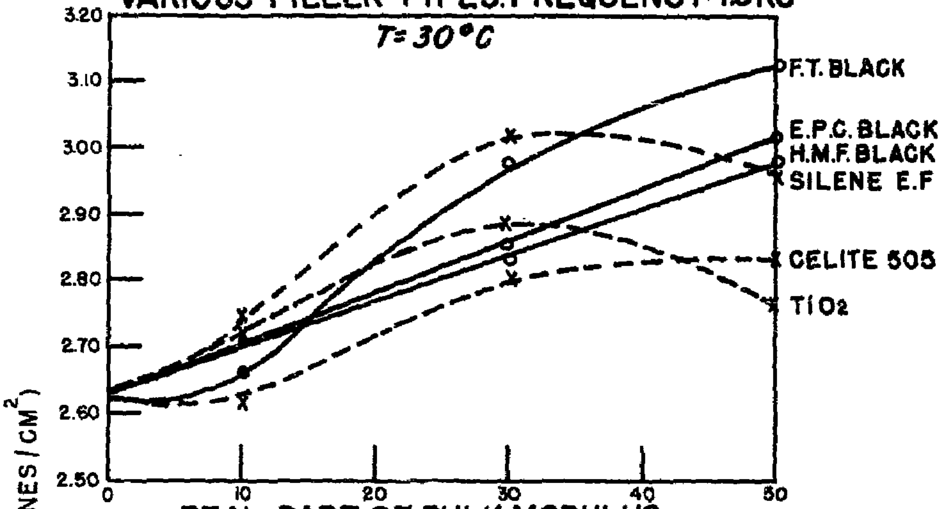


FIG. 17

FIG. 18

REAL PART OF BULK MODULUS OF HYCAR OR-15 vs NUMBER OF PARTS FILLER FOR VARIOUS FILLER TYPES. FREQUENCY=1.5KC



REAL PART OF BULK MODULUS vs NUMBER PARTS E.P.C. FILLER FOR VARIOUS BASIC RUBBERS FRQUENCY=1.5 KC

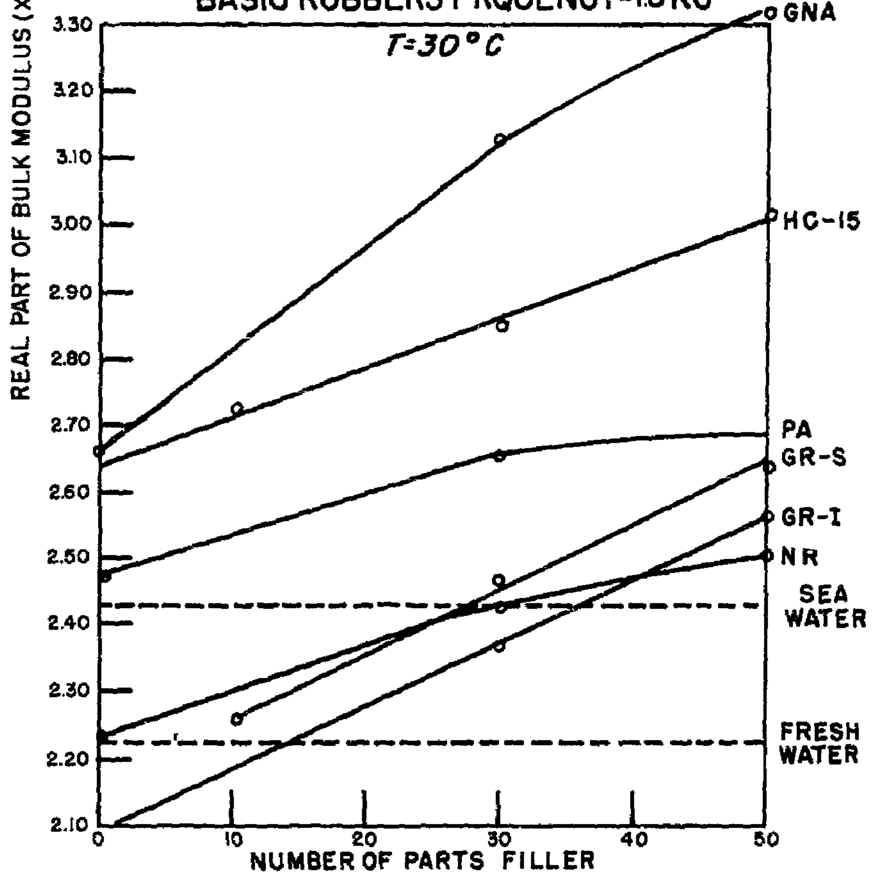
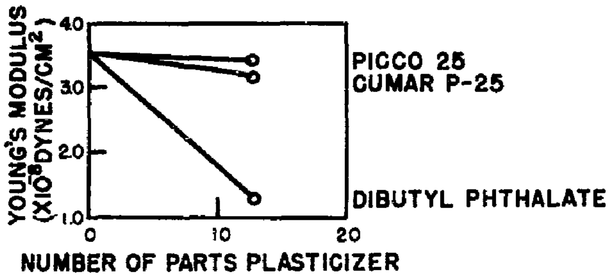


FIG. 19

FIG. 20
REAL PARTS OF THE YOUNG'S MODULUS AND THE BULK MODULUS OF HYCAR OR-15 vs NUMBER OF PARTS PLASTICIZER. FREQUENCY=1.5KC
T=30°C



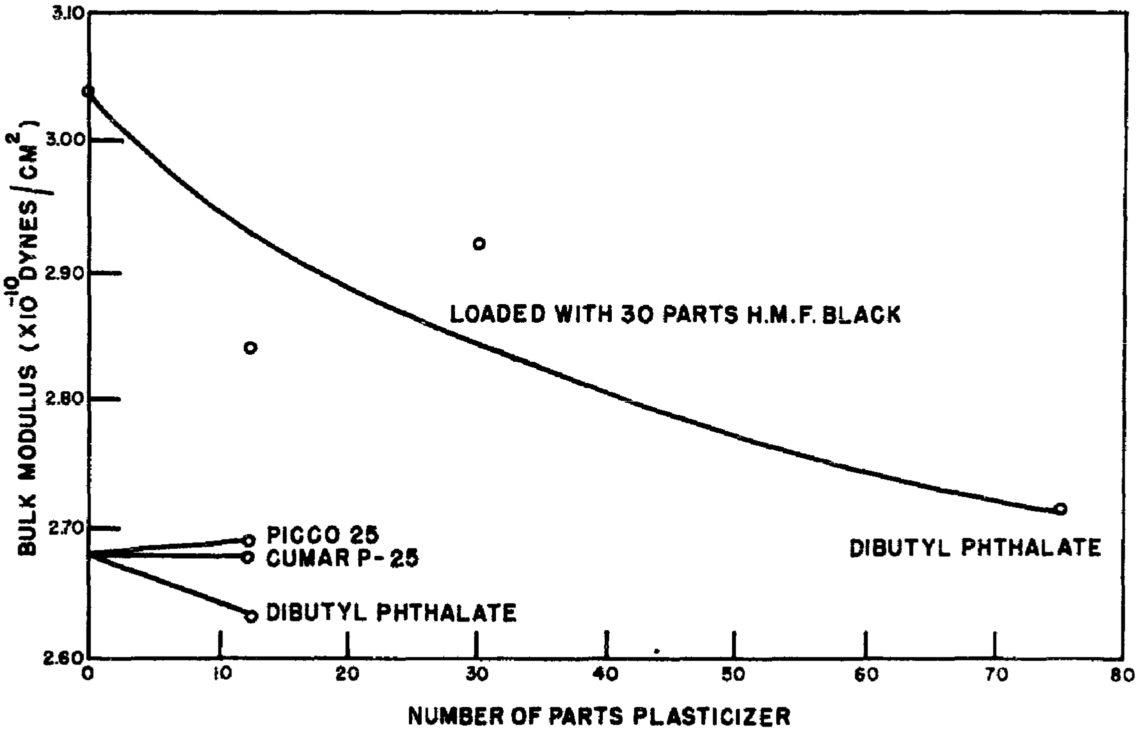


FIG.21

COMPARISON OF THE REAL PART OF THE YOUNG'S MODULUS WITH DUROMETER READING FREQUENCY=1.5 KC

T=30°C

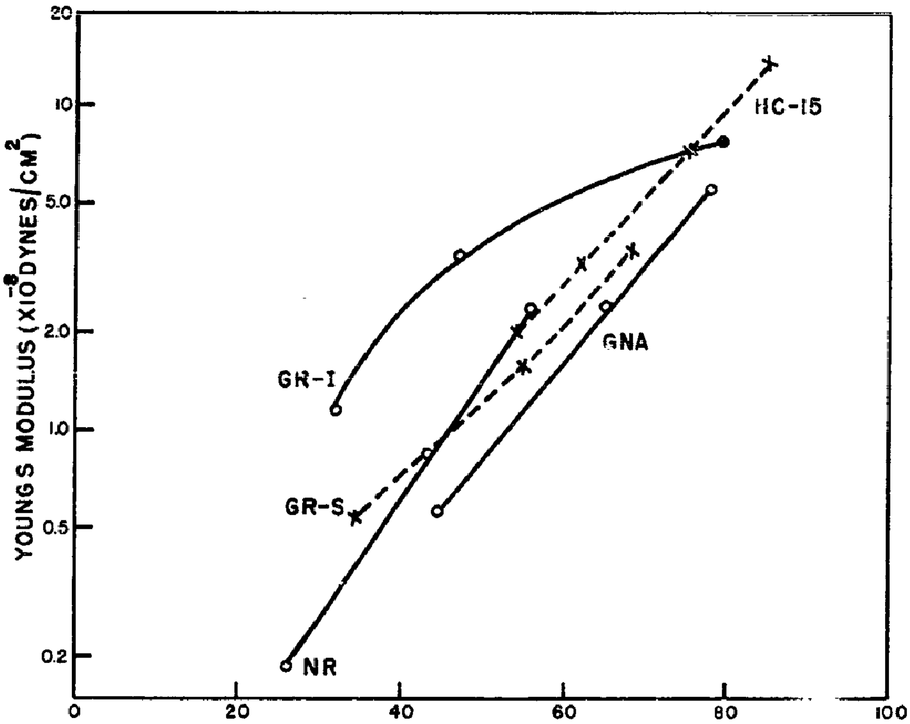


FIG.22

COMPARISON OF THE REAL PART OF THE BULK MODULUS WITH DUROMETER READING. FREQUENCY=1.5KC

T=30°C

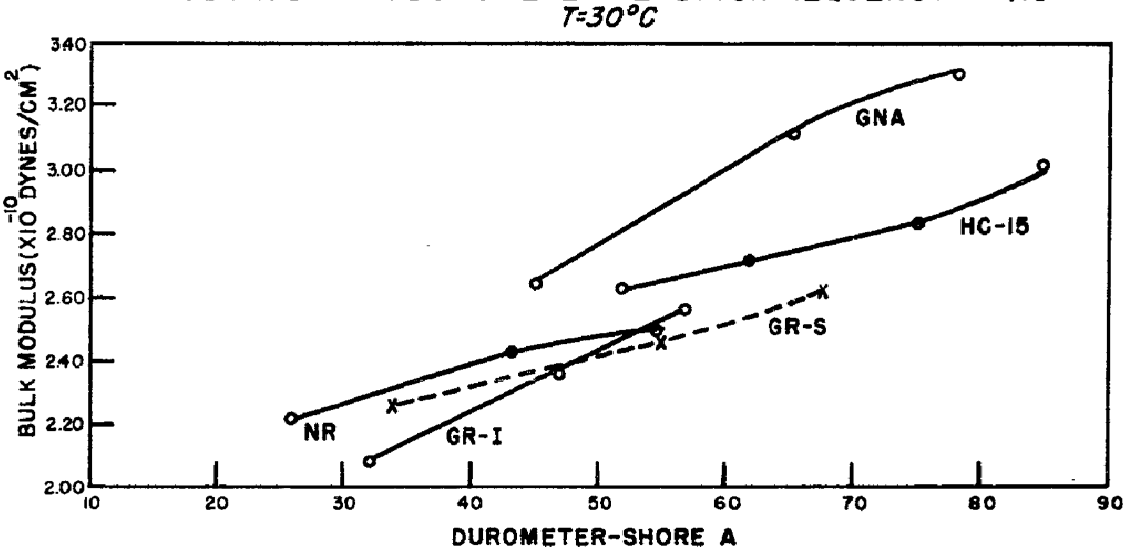


FIG. 23
STRIP VELOCITY IN HYCAR OR-15
vs NUMBER OF PARTS FILLER
FOR VARIOUS FILLER TYPES
FREQUENCY = 5 KC
$T = 30°C$

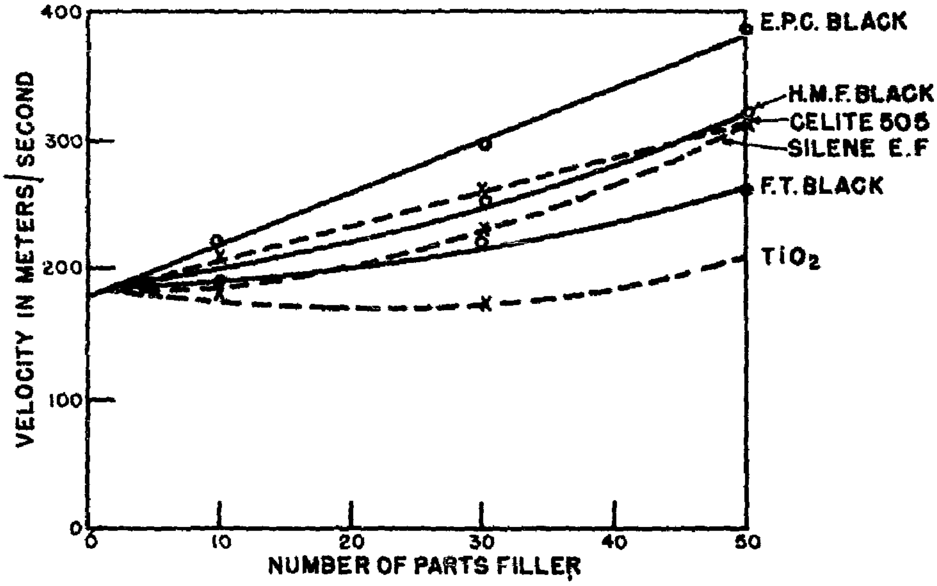


FIG. 24
STRIP VELOCITY vs NUMBER OF PARTS E.P.C.
FILLER FOR FOR VARIOUS BASIC RUBBERS.
FREQUENCY = 5 KC
$T = 30°C$

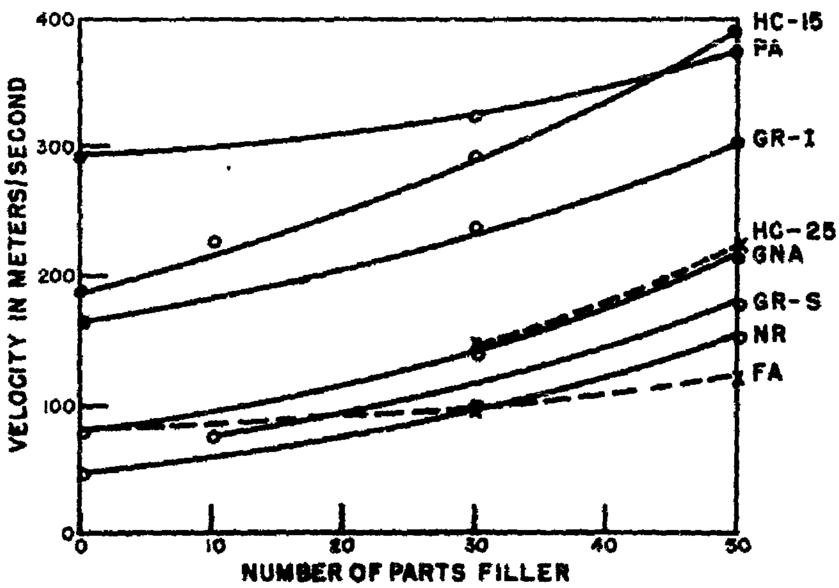


FIG. 25
PERCENTAGE INCREASE IN STRIP VELOCITY FOR VARIOUS BASIC RUBBERS vs NUMBER OF PARTS E.P.C. FILLER FREQUENCY=5KC
T=30°C

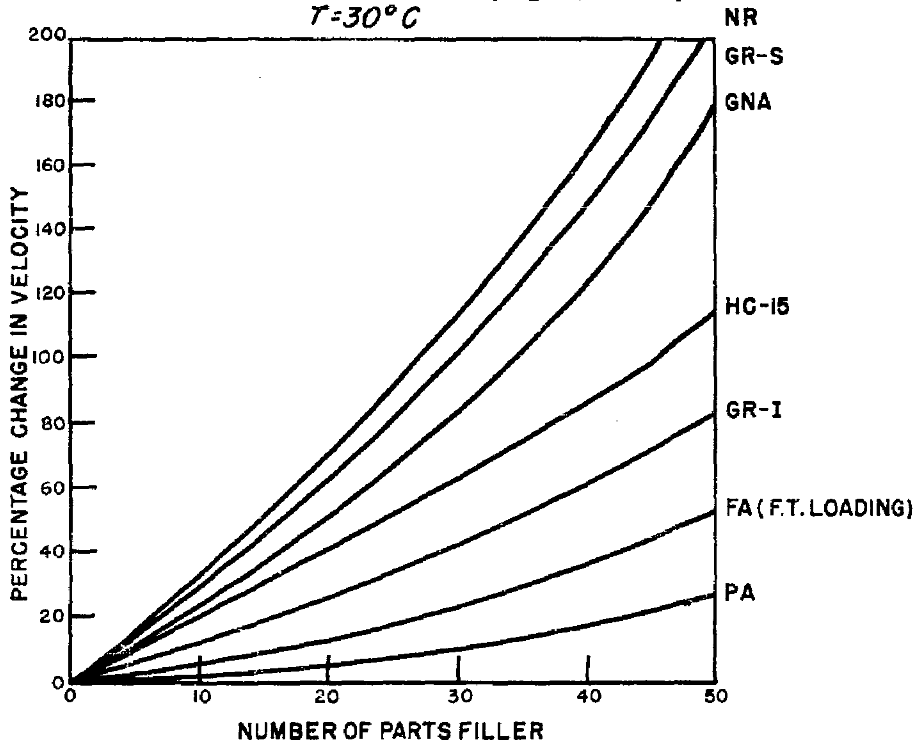
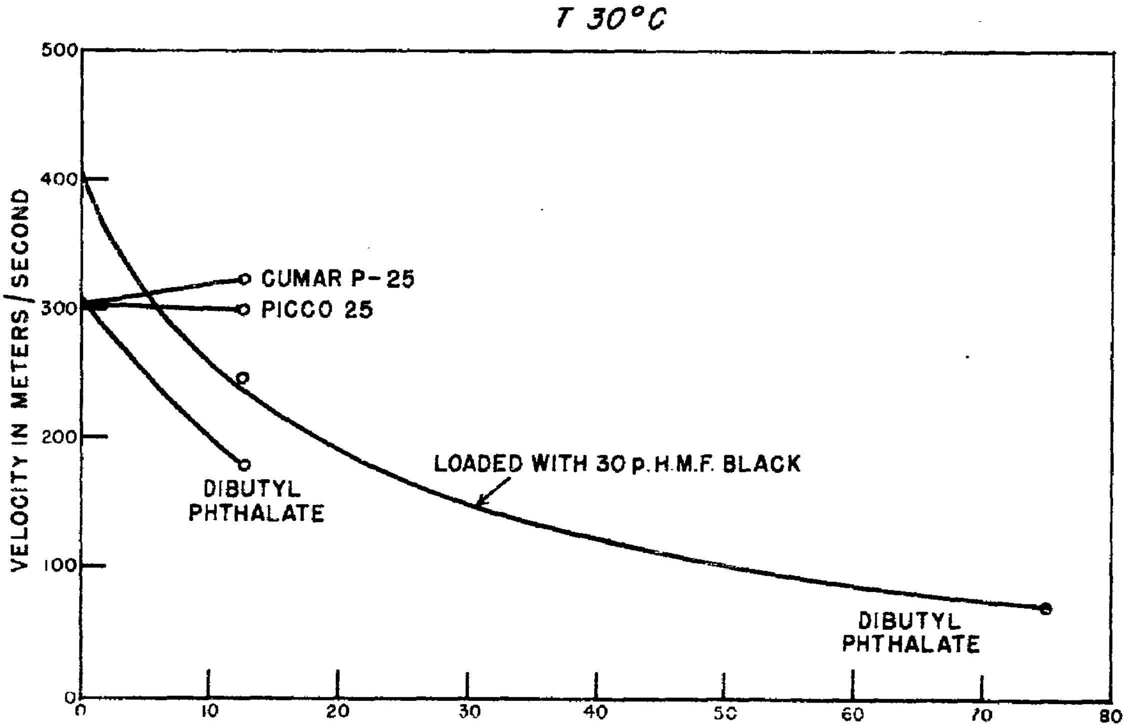


FIG.26
STRIP VELOCITY IN HYCAR OR-15 vs NUMBER OF PARTS PLASTICIZER FOR VARIOUS TYPES OF PLASTICIZER. NO LOADING UNLESS INDICATED. FREQUENCY=5KC
T 30°C



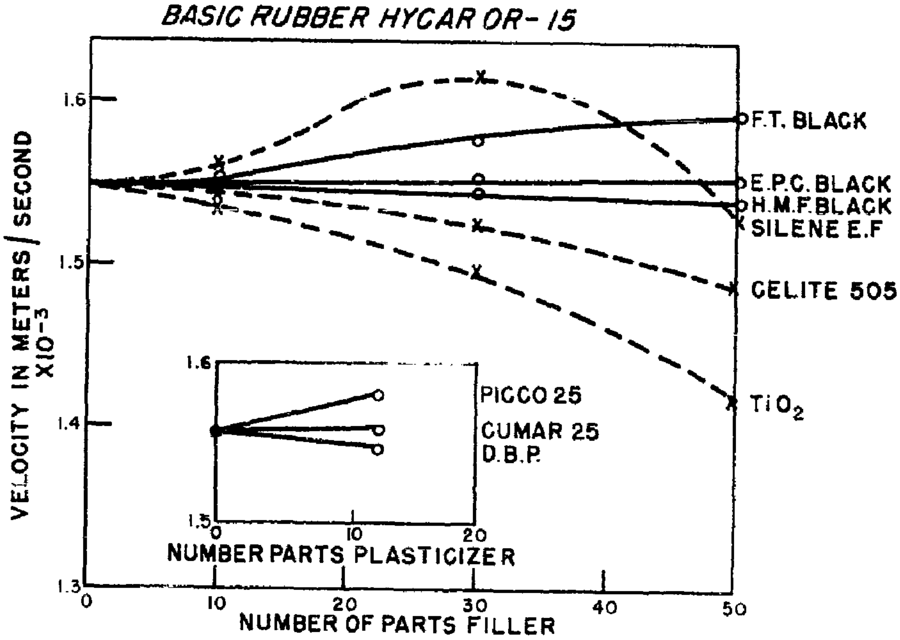


FIG.27
BULK VELOCITY IN VARIOUS BASIC RUBBERS
AS A FUNCTION OF TYPE AND AMOUNT OF FILLER AND
PLASTICIZER CONTENT. FREQUENCY = 1.5 KC
$T = 30°C$

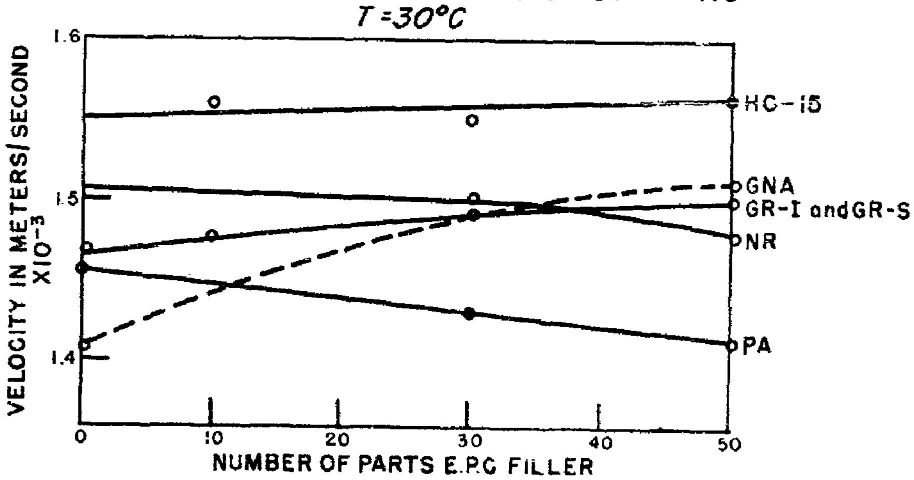
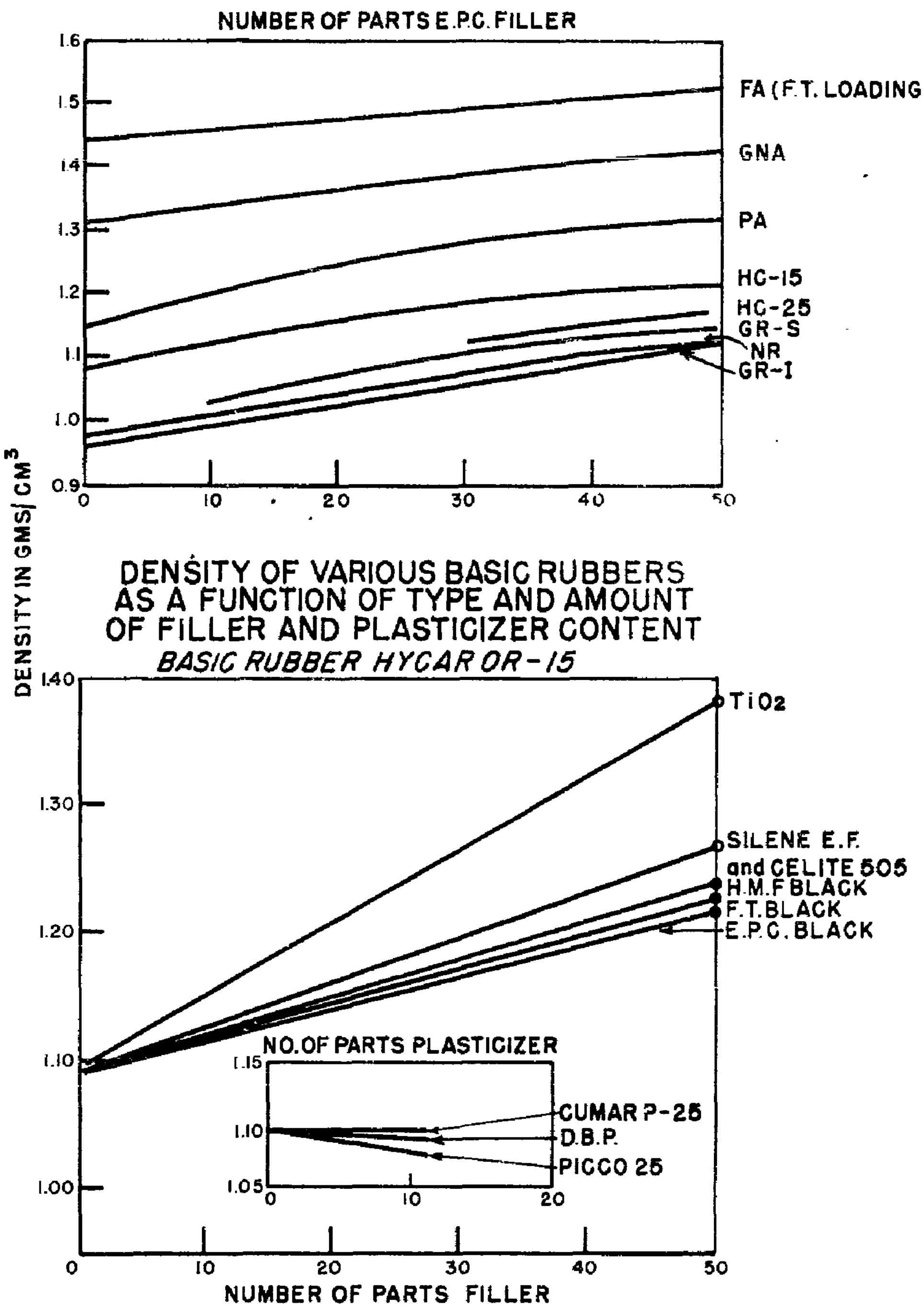


FIG.28



DENSITY OF VARIOUS BASIC RUBBERS AS A FUNCTION OF TYPE AND AMOUNT OF FILLER AND PLASTICIZER CONTENT

FIG.29
CHARCTERISTIC ACOUSTIC IMPEDANCE (ρC) vs NUMBER OF PARTS E.P.C FILLER FAR VARIOUS BASIC RUBBERS. FREQUENCY=1.5KC
T=30°C

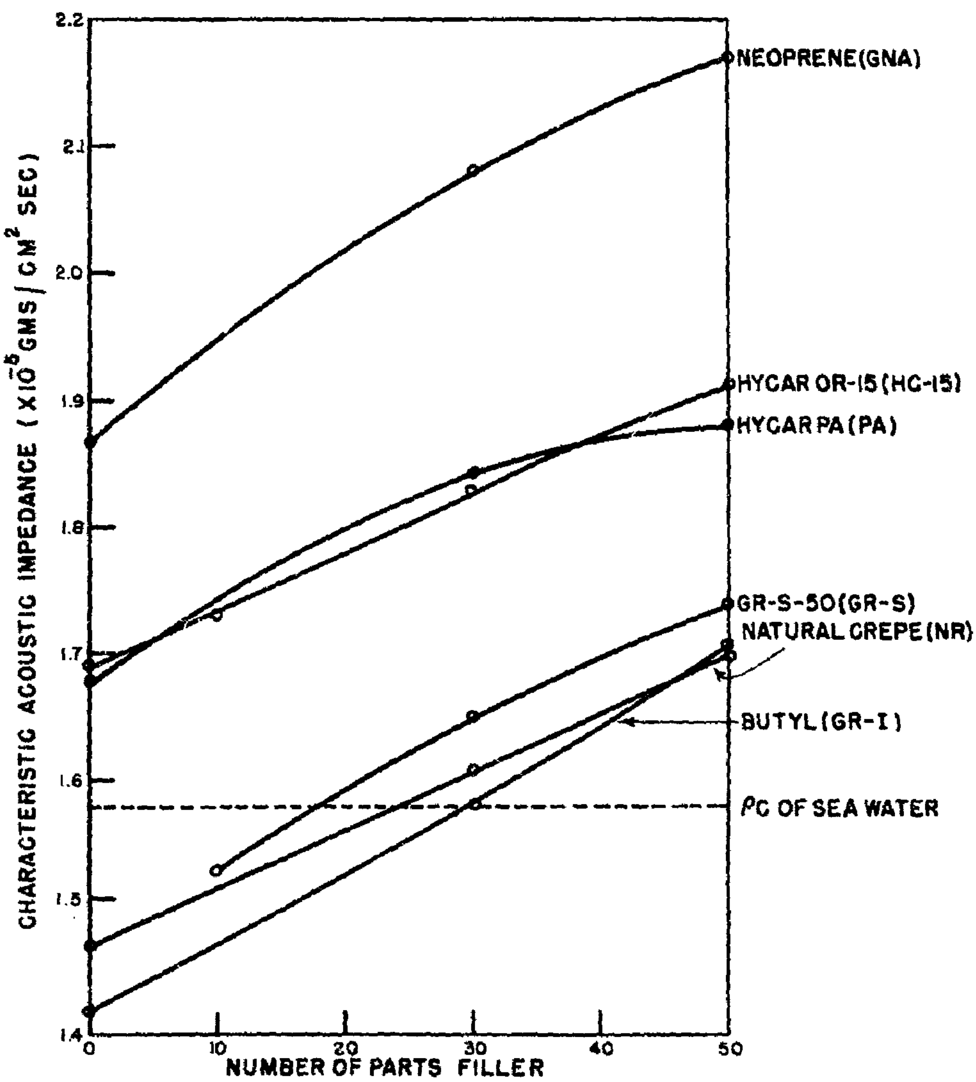


FIG. 30
COMPARISON OF CHARACTERISTIC ACOUSTIC IMPEDANCE (ρC) OF HYCAR OR-15 FOR VARIOUS TYPES AND AMOUNTS OF FILLER AND PLASTICIZER. FREQUENCY = 5KC
$T = 30°C$

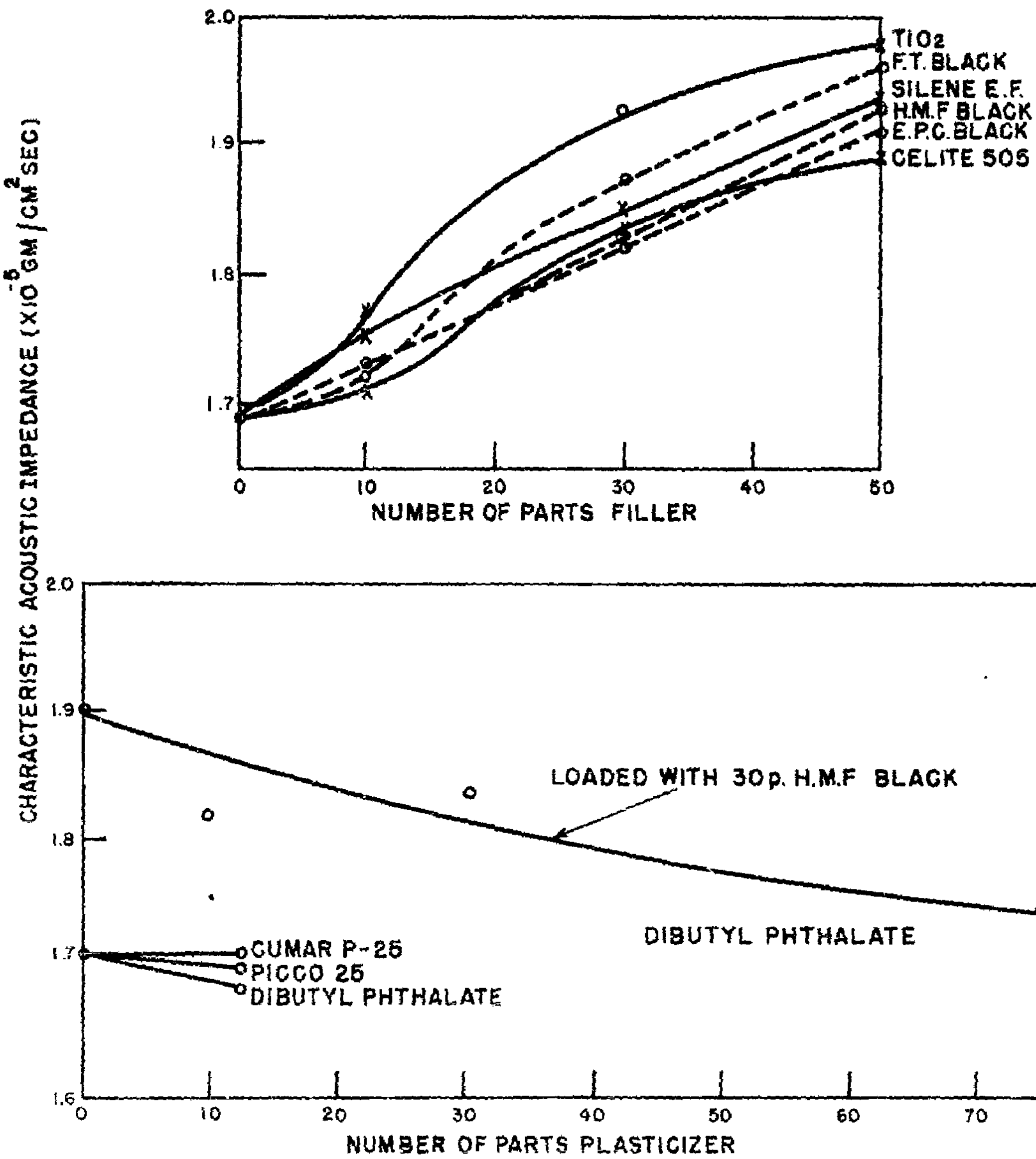


FIG. 31
STRIP ATTENUATION IN HYCAR OR-15
vs NUMBER OF PARTS FILLER FOR
VARIOUS FILLER TYPES. FREQUENCY=5KC
T=30°C

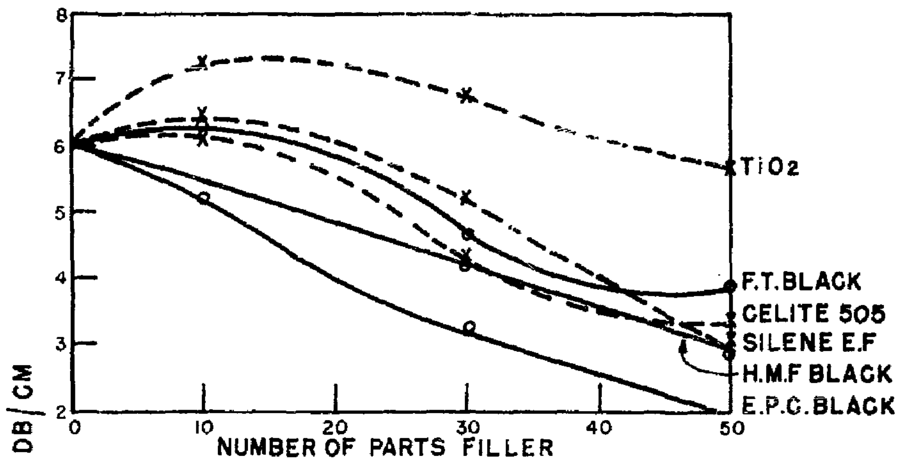
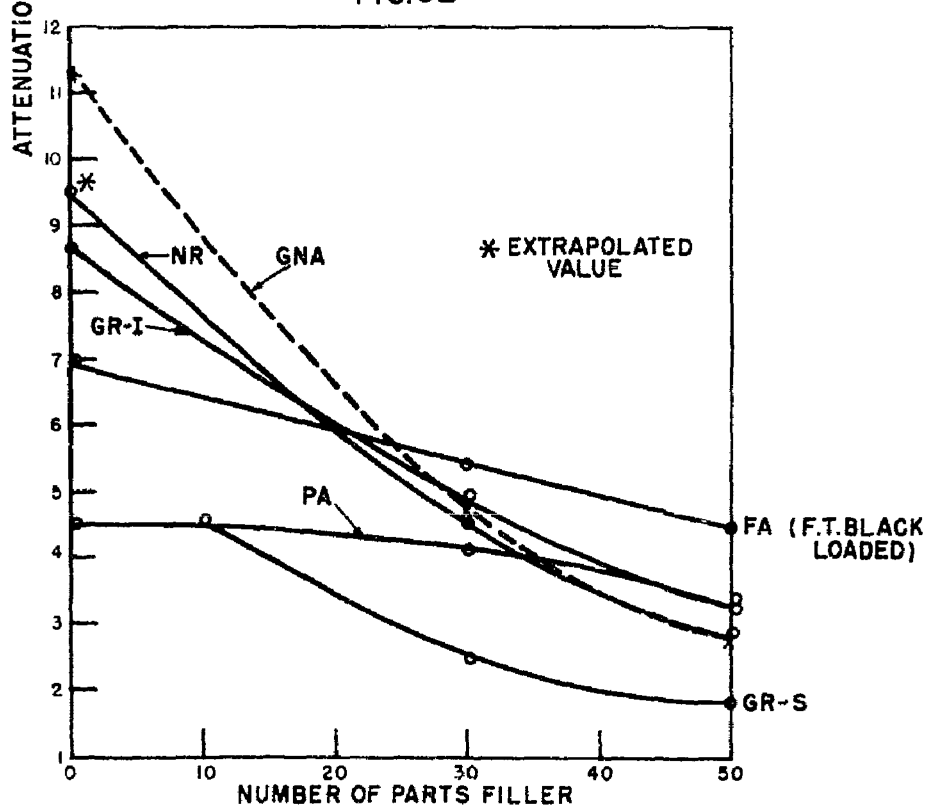


FIG. 32



STRIP ATTENUATION vs NUMBER OF
PARTS E.P.C. FILLER FOR VARIOUS
BASIC RUBBERS. FREQUENCY=5KC

FIG.33
RATIO OF STRIP ATTENUATION IN LOADED TO THAT IN UNLOADED BASIC RUBBER vs NUMBER OF PARTS E.P.C FILLER. FREQUENCY=5KC
$T=30°C$

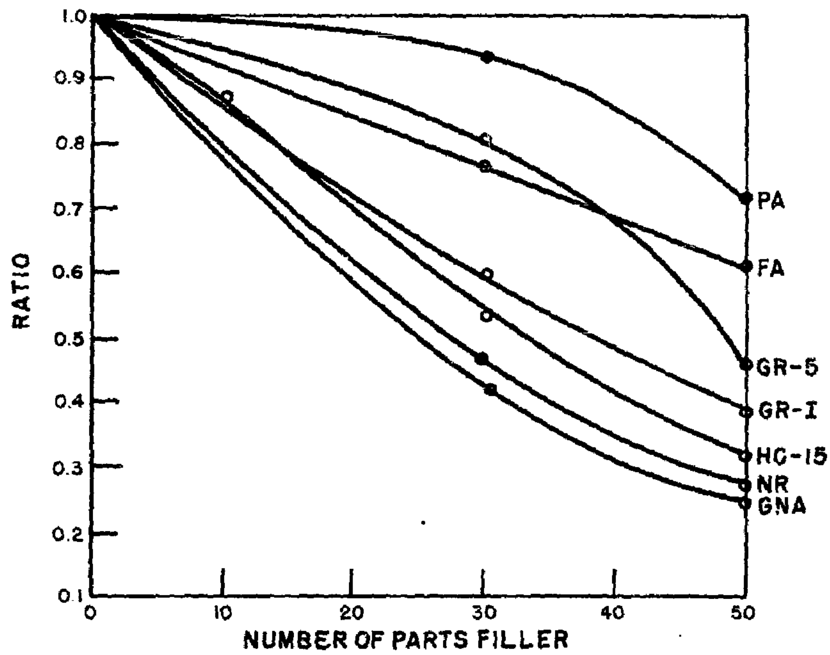
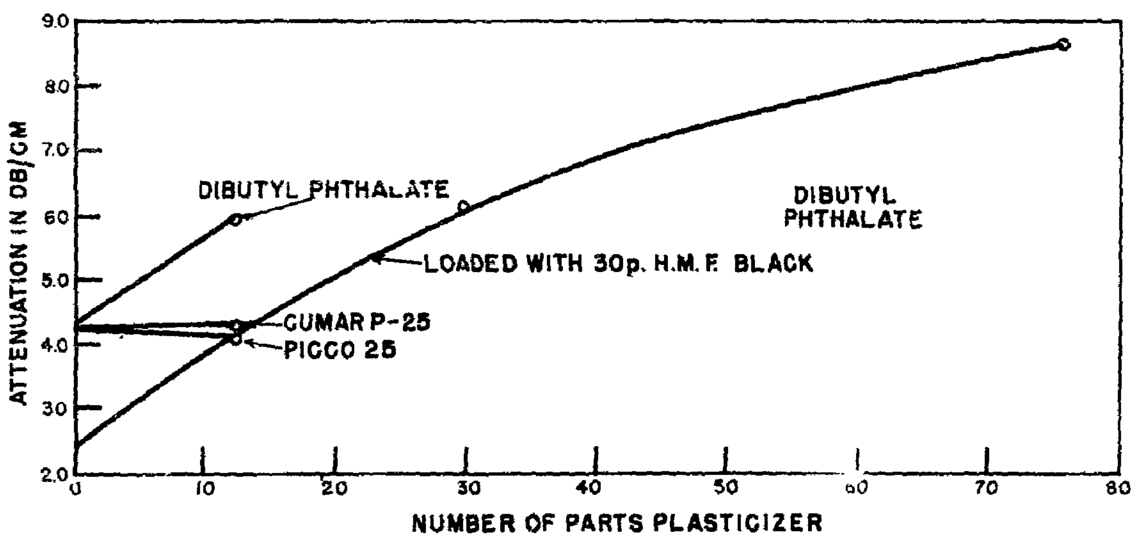


FIG.34
STRIP ATTENUATION IN HYCAR OR-15 vs NUMBER OF PARTS PLASTICIZER FOR VARIOUS PLASTICIZER TYPES



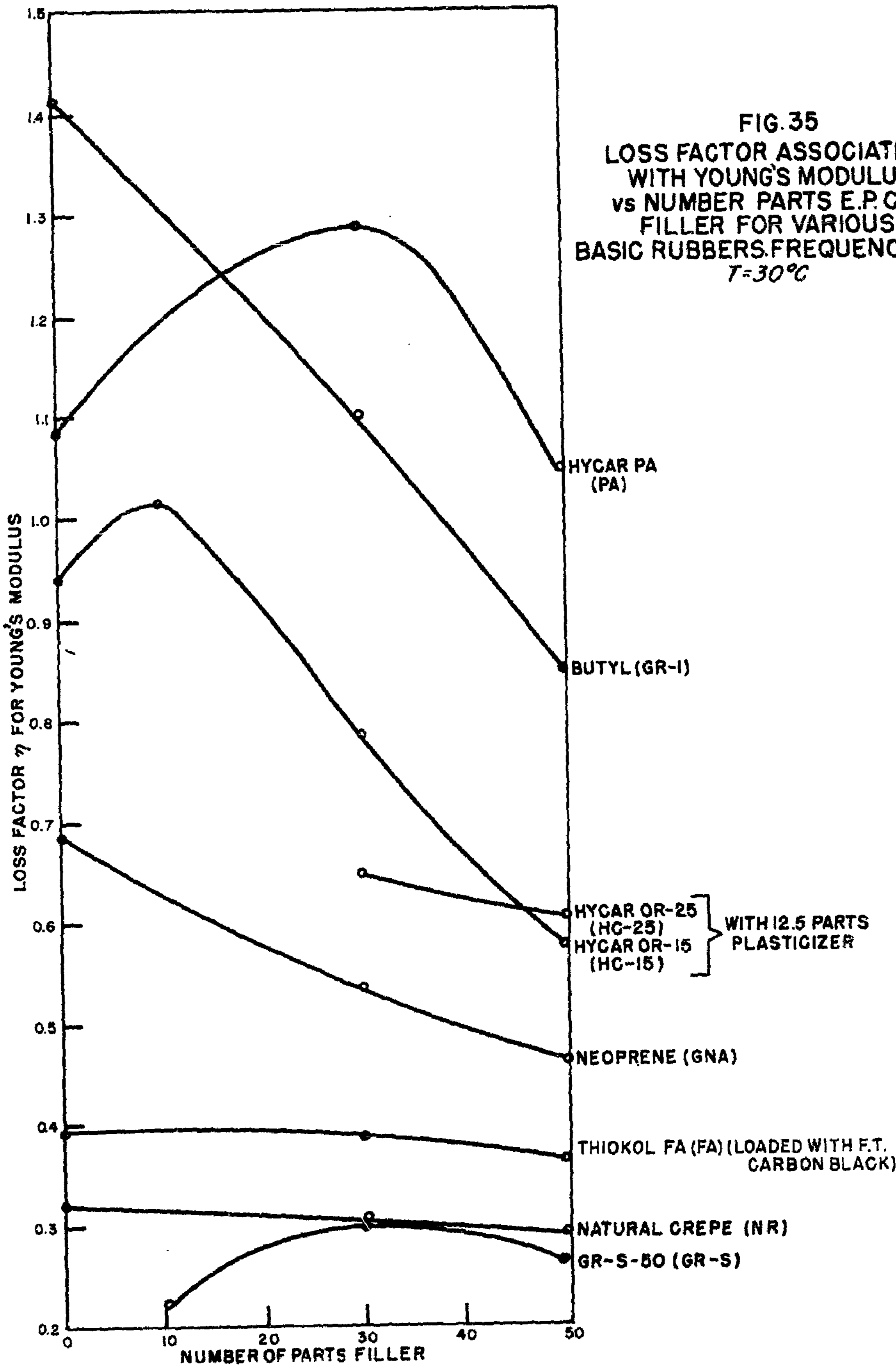
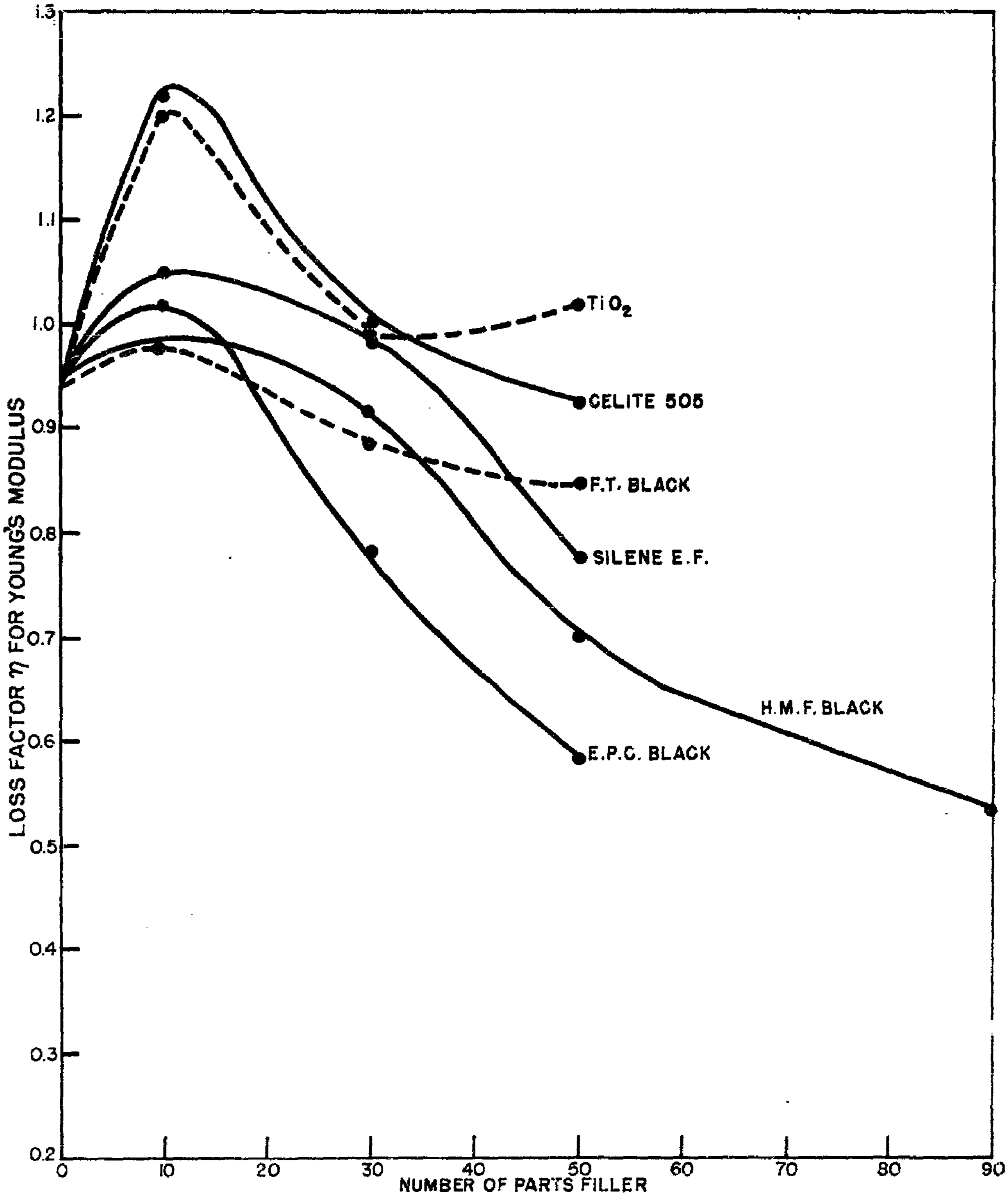


FIG. 35
LOSS FACTOR ASSOCIATED WITH YOUNG'S MODULUS vs NUMBER PARTS E.P.C. FILLER FOR VARIOUS BASIC RUBBERS. FREQUENCY = 5 KC
$T = 30°C$

FIG. 36

LOSS FACTOR ASSOCIATED WITH
WITH YOUNG'S MODULUS FOR HYCAR OR-15 vs
NUMBER OF PARTS FILLER FOR
VARIOUS FILLER TYPES. FREQUENCY=5KC
$T=30°C$



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