FOREWORD

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ABSTRACT

The objective of this handbook is to provide aerospace weapons system design engineers with useful data on the materials properties of elastomers. The sources of this information are Department of Defense research reports and the technical literature of engineering design and elastomer technology. The elastomeric materials for which data are presented are compounds of high polymers currently available in the U. S. A. The properties considered are original mechanical and physical properties and the changes in these properties that result from aging and exposure to environments of aerospace weapons systems. Elastomer compounding is only briefly treated in this handbook because it is intended for use by structural and mechanical engineers rather than by rubber chemists and technologists. Elastomer part design methods are not reviewed in this handbook because they are the subjects of other Department of Defense reports which this handbook is intended to complement. A selected bibliography of technical literature on elastomers and elastomeric parts is included to aid the handbook user who needs further information on these topics.

PUBLICATION REVIEW

This handbook has been reviewed and is approved.

FOR THE COMMANDER

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TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION

CHAPTER 2 - MECHANICAL AND PHYSICAL PROPERTIES

TABLE OF CONTENTS (Cont'd)

CHAPTER 3 - RESISTANCE PROPERTIES

TABLE OF CONTENTS (Cont'd)

APPENDIXES

LIST OF ILLUSTRATIONS

CHAPTER 2

LIST OF ILLUSTRATIONS (Cont'd)

CHAPTER 2

LIST OF ILLUSTRATIONS (Cont'd)

CHAPTER 2

LIST OF ILLUSTRATIONS (Cont'd)

CHAPTER 2

CHAPTER 3

LIST OF ILLUSTRATIONS (Cont'd)

CHAPTER 3

CHAPTER 4

LIST OF TABLES

CHAPTER 1

CHAPTER 2

CHAPTER 3

LIST OF TABLES (Cont'd)

CHAPTER 4

CHAPTER 1

INTRODUCTION

1.1 PURPOSE AND SCOPE OF REPORT

1.1.1 Purpose

This handbook is a collection of information and data related to behavior of various types of elastomers under a variety of environmental conditions, both natural and induced. It is intended to assist structural and mechanical engineers (rather than rubber chemists and technologists) concerned with the application of elastomeric materials in parts design for air and space weapons systems. An attempt has been made to provide information on which to base decisions as to the selection of an elastomeric material for use as a component.

1.1.2 Scope

The elastomeric materials considered in this handbook include those currently being used in aircraft and missiles. Also, several materials are included which are presently only available in pilot plant quantities.

In addition to the tabulated and graphical data pertaining to the properties of these elastomeric materials, there is also included information on elastomer terminology, testing, and technology. Such information is essential to the structural or mechanical engineer to enable him to properly interpret data, to perform materials evaluation, and to better understand the complexities of elastomeric materials and processes. The primary purpose of this handbook, therefore, is to enable the mechanical and structural engineer to collaborate more effectively with the elastomer technologist in part design. It is felt that such background information is necessary because of the difference in the terminology, testing, and technology of elastomers compared to the engineering materials with which most structural or mechanical engineers are familiar.

Elastomer technology is such a dynamically developing field that the data included herein should not be considered as complete and up-to-date. As more data become available, supplements to sections of this handbook will be issued. The major sources of data presented herein are ASD (formerly WADC and WADD) technical reports, technical literature published within the past ten years, and information provided by the elastomer industry.

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Conclusions, statements, and recommendations made in this handbook are engineering judgments based on information available to the authors, and the review of this information in terms of specific criteria derived from successful air and space weapons systems. The information on which these conclusions, statements, and recommendations are based is presented in its original form in the handbook.

1.1.3 Method of Indexing

The text in this handbook is indexed by numerical prefixes which designate chapter and sequence of subject within the chapter, i.e., 2.2.1 designates that the item is in Chapter 2, is under the second major topic, and is the first subheading under that topic.

The tables and figures are indexed by a number which designates the chapter in which they are listed, and also the numerical sequence in which reference is made to them within that chapter.

The number of the figure or table is followed by a number within parentheses. This number is a cross reference and designates the portion of the handbook where reference is made to the table or figure. For example, Table 2-28 (2.2.2) is the 28th table in Chapter 2, and reference to it can be found in subject heading 2.2.2.

1.2 GENERAL CHARACTERISTICS OF ELASTOMERIC MATERIALS

1.2.1 ASTM Definition of an [Elastomer]*

["An elastomer] is a [rubber-like] material that can be or already is modified to a state exhibiting little plastic flow and quick and nearly complete recovery from an extending force. Such material before modification is called, in most instances, a raw or crude rubber [or a basic high polymer] and by appropriate processes may be converted into a finished product.

"When the basic high polymer is converted (without the addition of plasticizers or other diluents) by appropriate means to an essentially non-plastic state, it must meet the following requirements when tested at room temperature (60-90° F; 15-32° C).

"A. Is capable of being stretched 100%.

"B. After being stretched 100%, held for 5 minutes and then released, it is capable of retracting to within 10% of its original length within 5 minutes after release (ASTM D412-51T)."

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*Brackets indicate change in wording from original quotation.

1.2.2 Characteristic Properties of Elastomers (Refs. 35, 125, 141, 229)

The fundamental mechanical property of elastomers is rubber-like elasticity; that is, elastomers can be subjected to enormous elastic strains without rupture. Many plastic materials can be stretched 100% without rupture, but will not retract to their original length after release. Rubber-like elasticity is exhibited by only a limited number of materials over narrow ranges of temperatures. All such materials known are high polymers, or materials made up of large molecules of high molecular weight. Plastic and fiber materials are also high polymers. High polymers are similar in chemical origin and response, but differ in mechanical properties, processing, and application technology.

Elastomers, when compared with other engineering materials, are characterized by large deformability, low shape rigidity, large energy storage capacity, nonlinear stress-strain curve, high hysteresis, and large variation of stiffness with temperature and rate of loading. The extremely large deformations experienced by elastomers in service, together with their nonlinear response, make the application of engineering analysis to part design very complicated. Elastomers possess volume compressibility of the same order of magnitude as most liquids and about 100 times that of steel.

Certain of the elastomeric materials possess additional useful characteristics such as corrosive chemical resistance and electrical, thermal and permeability properties. Thus, specific elastomeric materials are particularly suited for use in insulating, diaphragm, liner, and coating applications. Rubber-like elasticity, while not required, is usually an asset for such applications because it facilitates ease of installation and increases resistance to fatigue, abrasion and tear.

Elastomer selection must be based on useful service life and for this reason, elastomers are categorized by their original and aged properties. A significant response of elastomers to service environments is change in original properties. The majority of elastomer test results are not physical constants usable in design computations but are comparative measures of material qualities. These properties vary interdependently over large ranges in response to variations in compounding and processing. The role of the elastomer technologist in part design includes analysis of service requirements in terms of standard elastomer property values and the furnishing of a material for the part which will perform satisfactorily in service.

1.2.3 Types of Elastomers

For the convenience of the user of this handbook, Table 1-1 lists the commonly used elastomer materials. Each type of elastomer can be identified by several names. The underlined names in Table 1-1 are those used in this handbook.

1.2.4 Standard Test Methods (Ref. 89)

Table 1-2 lists test result nomenclature related to properties of elastomers according to standard test methods. Only standard test methods in general usage and of direct interest to design engineers are included.

1.3 ELASTOMER TERMINOLOGY (Refs. 44, 45)

The technical language of elastomer technology differs in two important aspects from the usual terminology of structural and mechanical engineering:

(1) Different meanings are assigned to the same words describing physical properties or behavior.

(2) Different words are assigned to the same meanings describing physical properties or behavior.

Elastomer technology also uses words and meanings not commonly employed by other disciplines to express material responses and laboratory test results which are different from those of other materials. For these reasons, a glossary defining terms of specific interest to the designer is included in this report as Appendix I.

1.4 ELASTOMER COMPOUNDING AND PROCESSING

The many types of elastomeric high polymers, the variety of compounding ingredients available to modify their properties, and the different methods of processing and forming available, make it possible to produce custom-made elastomer parts to meet a broad range of requirements.

1.4.1 Elastomer Part Manufacturing Processes (Refs. 92, 120, 121, 144, 161, 209)

As an aid to the designer, Appendix II of this handbook includes descriptions of "Conventional Elastomer Part Manufacturing Processes."

1.4.2 Casting, Potting, Coating, and Room Temperature Vulcanization (R. T. V.) Processes (Refs. 19, 223)

Many of the elastomer applications in air and space weapons systems require fabrication techniques other than the conventional elastomer part manufacturing processes. Examples of these applications are integral fuel tank sealants and coatings, and the potting of electronic components. In the latter application, the material must be installed while it is of liquid or putty like consistency and vulcanized in place on or in the component. The polycondensation product elastomers are especially suited for such application because polymerization and vulcanization reactions can be combined in these materials so that it is never necessary to deal with a plastic high polymer in the processing operation as is the case with the other elastomers. For the other high polymers, it is necessary to use elastomer solutions or dispersions to obtain required consistency.

Certain types of component material or construction do not permit heat induced vulcanization. In these cases, room temperature vulcanization systems must be used. R. T. V. systems for polycondensation product elastomers are extensively reviewed in manufacturers' literature. R. T. V. elastomer specifications and application design depend on storage, handling, and vulcanizing characteristics of these materials as well as their properties after vulcanization. Section 4.5.1 lists some of the current sealant specifications and reviews some of the applications of these materials.

CHAPTER 2

MECHANICAL AND PHYSICAL PROPERTIES

2.1 DISCUSSION OF ELASTOMER PROPERTIES

2.1.1 General (Refs. 27, 37)

The mechanical and physical properties of elastomeric materials are dependent upon the methods employed in compounding and processing them. For this reason, trade names are commonly used by engineers to identify specific elastomeric materials. Therefore, to avoid confusion, trade names, rather than unfamiliar chemical nomenclature, are frequently used in this handbook to describe specific elastomeric materials.

Also, it should be noted that the data presented are obtained by testing specific elastomeric compounds, sometimes identified by trade name, which may be superior, in the particular properties measured, to the general class of elastomers compounded from the same basic high polymer.

A wide range of properties are available to the designer of elastomer parts. This enables the designer to fit his material to the application requirements. The designer must recognize that attainable properties are interdependent so that improvement of a specific property may mean degradation of other properties. This is of considerable importance to the proper evaluation of data and choice of material properties for a particular design. The standard measured properties of elastomers outlined in Table 1-2 are indices of material quality rather than measures of functional response. The quality control properties are related to mechanical properties in unknown fashion, although there does exist quantitative correlation between these two sets of information for particular series of compounds. The designer whose task is prediction of elastomeric part response to loads and environment, should be aware of the following:

(1) The mechanical properties of an elastomer are so dependent on time, temperature, environment, and previous history that the difference between the usual design estimate of these parameters and the actual component service history will generally cause appreciable differences between predicted and actual response.

(2) The applications of elastomers are in the realm of large deformations and nonlinear response where mathematical theory is presently both too limited and complex for practical design use.

(3) The quality control specifications usually permit variation in original mechanical properties of elastomers of the order of ± 15%.

The conventional approach to mathematical analysis of elastomer part response is based on:

(1) The use of an idealized model of the material to reduce test results to numerical values that lend themselves to engineering calculations.

(2) The use of empirically derived relationships between quality control properties and mechanical response.

(3) The use of empirically derived methods of data presentation which facilitate engineering calculations.

2. 2 ANALYSIS OF MECHANICAL BEHAVIOR OF ELASTOMER PARTS

2. 2. 1 Static Response (Refs. 48, 102, 103, 126, 132, 135, 147, 152, 176, 177, 178, 201, 202)

The static problem is based on the response to a single load applied instantaneously, with the function of interest being time dependent deformation. A model commonly used for the static case is presented in Figure 2-1 together with a creep curve for the model which approximates elastomer behavior. The creep curve is based on constancy of materials properties which implies both linear response and no environmentally induced change in the material. These restrictions limit the usefulness of this model to theoretical studies. Figure 2-1 depicts nomenclature and technique for expressing a creep curve in terms of elastic moduli and viscosity by using a mechanical model composed of springs and dashpots. The point T_s corresponds to a static modulus value such as would be obtained by a standard laboratory test.

Another commonly used concept, based on the creep curve type of Figure 2-1 is time dependent modulus. The load-deformation relationship, in the steady state drift region, can be defined by a linear function of time. This time dependent modulus is used in place of the elastic modulus in elastic response equations (see 2. 3. 2. 2).

The most commonly used method of deformation analysis is to consider initial deformation, creep deformation, and set as unrelated phenomena. It is usually impossible to express the characteristic behavior of elastomer parts subjected to complex real service conditions by use of simple models such as that of Figure 2-1.

Figure 2-2 depicts the results obtained by repeated loading and unloading of a natural rubber specimen to constant maximum elongation in a tensile test. It reveals some of the characteristics, including nonlinearity of load-deformation relationship, hysteresis, and continuous change in materials properties during stressing. In this case, the elastomer-reinforcing pigment network is broken down at high elongation so that the elastomer permanently loses the original stiffness which would be measured in a standard tensile test. Change in modulus is also caused by temperature elevation during repeated stressing.

Figure 2-3 depicts equilibrium tensile stress-strain curves for a series of natural rubber compounds identified by Shore A Hardness points. Figure 2-4 shows the small strain portion of these curves, plotted to a larger scale. (The deformations at which these values were measured are small for elastomers, but would be considered large for most engineering materials.) Other convenient methods to use to present such information are as secant moduli values (Figures 2-5 and 2-6), or tangent moduli values (Figures 2-7 and 2-8).

Figure 2-9 depicts equilibrium shear stress-strain curves for the compounds of Figure 2-3. The shape of these curves (Figures 2-3 through 2-9) is characteristic of elastomers. Actual stress-strain response as a function of hardness varies considerably (see Figures 2-29 and 2-30); yet, such curves are commonly used to provide a preliminary estimate of static moduli for design purposes. Figure 2-10, compiled from a number of different sources, depicts variation of static moduli for small strain as a function of hardness. The British have attempted to systematize such correlation by using a hardness scale based on Young's modulus (Figure 2-11). Figure 2-12 is a conversion graph for various commonly used hardness scales. It should be noted that British Standard Industry Hardness Number and British Standard Hardness Degree are different scales.

The preceding curves are useful for predicting initial deformations of tension and shear elements, whose response is little affected by shape (see Ref. 176). They are not satisfactory for compression parts because of the considerable effect of end restraint. Figure 2-13 depicts the deformed shape of bonded sandwich units loaded in compression which determines the compressive stiffness of elastomer parts. Kimmich (Ref. 152) has presented the curves reproduced in Figure 2-14 as suitable for prediction of compressive deformation of parts having parallel loading faces and sides normal to these faces. Direct interpolation between these curves is not recommended; instead, multiply deflection taken from curve of nearest durometer to specimen by the ratio $\frac{\text{elastic modulus for curve durometer}}{\text{elastic modulus for specimen durometer}}$ using moduli values from Figures 2-10 or 2-11. Smith (Ref. 152) has presented the curve reproduced in Figure 2-15 as suitable for prediction of compressive deformation of rectangular slabs. The following examples demonstrate the use of these empirically developed curves in analysis of part performance:

(1) Circular bonded sandwich of Shore A60 elastomer dimensions: 0.84 in. thick × 1.125 in. diameter; 50 lb of shear load; measured deflection 0.28 in. from Figure 2-10, G = 135

$$\text{deflection} = \frac{\text{thickness} \times \text{load}}{\text{shear modulus} \times \text{area}} = \frac{0.84 \text{ in.} \times 50 \text{ lb}}{135 \text{ lb/sq in.} \times 0.995 \text{ sq in.}} = 0.31 \text{ in.}$$

50 lb compressive load; measured deflection 0.06 in.

$$\text{Kimmich's shape factor} = \frac{\pi D^2}{4\pi Dh} = \frac{1.125}{4 \times 0.84} = 0.335$$

from Figure 2-10, $E_{50} = 265$, $E_{60} = 370$

from Figure 2-14, $\Delta h_{0.3}^{50} = 0.095 \times 0.84 = 0.08$

$$\frac{265}{370} = 0.08 = 0.06 \text{ in.}$$

(2) Rectangular rubber slab of Shore A40 elastomer dimensions: 0.75 in. thick × 7.75 in. × 5.75 in.; 2,670 lb compressive load; measured deflection 0.15 in.

$$\text{Kimmich's shape factor} = \frac{44.6}{1.5 \times 13.5} = 2.2;$$

$$\text{loading pressure} = \frac{2,670}{44.6} \text{ psi} = 60.0 \text{ psi}$$

from Figure 2-10, $E_{30} = 140$, $E_{40} = 190$, $E_{55} = 310$

from Figure 2-14, $\Delta h_{2.2}^{30} = 0.27 \times 0.75 = 0.20$

$$\frac{140}{190} \times 0.20 = 0.147 \text{ in.}$$

from Figure 2-15, $\Delta h^{30} = 0.81 \times 0.75 = 0.61$ for unit cube

$$\frac{0.61(0.75 \times 1.35)^{2/3} 310}{(44.6)^{1/2} 190} = 0.15 \text{ in. for slab}$$

Reasonable estimates of static deformations in response to short time loads can be made from a knowledge of moduli or hardness values which are standard measured properties. This is not the case for creep, stress relaxation, or set. The only standard viscoelastic property generally available to the designer is set obtained by a rigidly defined test.

The set value is useful only in order of merit comparison within a series of elastomeric compounds. Creep and stress relaxation data are generally lacking because of (1) the expense of such tests, and (2) the requirement that the conditions of test must closely simulate the conditions of service. The physical process of flow does not offer great difficulties, but the actual response is often dominated by structural and chemical changes in the material. Required information for these responses must usually be developed in the laboratory specifically for the design application, although limiting values can be estimated from the compounder's tabulated values of set.

Compression creep in natural rubber compounds is about 20% less than shear creep, while tension creep is about 30% greater than shear creep. The best room temperature shear creep performance which can be expected is of the order of 20% of elastic deformation in 60 days, and 40% in 3 years under constant load. Creep performance for a particular elastomer is highly dependent, as are all other properties, on compounding and processing of the material. The effects of the in service chemical reactions of elastomers are major reasons that a prohibitive amount of laboratory work would be required to develop complete handbook creep data. A simple change in antioxidant in an SBR compound, for example, may change long term creep magnitude by 200%. Significant chemical reactions which occur are:

(1) Cross link formation during deformation (post cure)

(2) Cross link or molecule rupture during deformation (degradation)

(3) Cross link rupture and formation during deformation

The creep test is used as an index of resistance to aging and deterioration by the elastomer technologist because this response is so sensitive to changes in the material. Percent creep has a special definition in the aging test (ASTM D 1206) which is different from the usual engineering definition. The engineer must be particularly careful to distinguish between the two meanings when using compounder's data.

Figure 2-16 presents a typical creep curve plotted on various coordinate systems for the purpose of showing characteristic form and nomenclature. While these curves resemble those for metals, the internal structure and mechanisms of response are different for elastomeric materials. The mechanisms of elastomeric creep result in curve characteristics which are founded on rate process equations similar in form for viscous flow and chemical reactions. Certain conventional methods of data presentation and problem analysis are used that are based on the characteristics of elastomer creep curves; these methods facilitate elastomer creep calculations. The basic convention is based on the approximation of elastomers to linear viscoelastic behavior; for such a material of specified dimensions, geometry of loading, and temperature, the ratio of creep deformation to initial elastic deformation is a function of time only. This parameter is usually expressed in percent and defined as

$$\%\ \text{Relative Creep} = \frac{(\epsilon_t - \epsilon_1)}{\epsilon_1} \times 100$$

where ϵ_t is total deformation at time t and ϵ_1 is total deformation one minute after loading. As can be seen from the semilog plot of Figure 2-16, primary creep versus log time often approximates linearity very closely. This form is generally used for data presentation. Figure 2-17 is an alignment chart of relative creep data for natural rubber compounds (Figure 2-3), and shows the order of creep magnitude for elastomers.

Primary creep curves for many elastomers deviate considerably from the linearity displayed in Figure 2-16. The timewise deviation from linearity is characteristic of many elastomers for particular environments. Cooper's technique (see Ref. 73 and Figure 2-18) is a method which facilitates analysis of test design and data presentation. The advantage of this method is that the material characteristic curve, $(\epsilon_t - \epsilon_1)/(\epsilon_{10} - \epsilon_1)$, can be obtained by a single simple test and the constant, $(\epsilon_{10} - \epsilon_1)/\epsilon$, obtained for particular geometries and loading configurations in short time tests.

Creep set cannot be calculated and must be measured by prototype testing. The set obtained by standard laboratory tests provides a qualitative order of merit index for both creep set and primary creep, but is not directly correlatable to either parameter. This is because permanent set is a result of a whole set of processes such as gross molecular movement, and physical and chemical changes of the material. Primary creep is a physical process dependent on stress and temperature alone. The log-graph of creep is the best approximation to linearity for the total effect of all these parameters.

Stress relaxation is the time dependent decrease in stress which occurs under continued deformation. Linear viscoelastic creep functions are transformable to stress relaxation functions, if change in material does not occur. Changes in material are usually a dominating factor in determining elastomer response. This procedure is not of practical value to the designer.

The typical stress relaxation curves of Figure 2-19 show the same useful characteristics as the creep curves of Figure 2-16. The ratio S_t/S_o, where S_x = stress at time x, is independent of amount of original deformation. The departure from linearity of the semilog plot can be attributed to structural and chemical changes in the material and is correlatable to set. Standard set values provide an index of stress relaxation properties but cannot be correlated.

Static fatigue life is closely related to permanent set in molecular mechanism, but cannot be correlated with it. Static fatigue life is the time to rupture for a given constant load or deflection. The general characteristics of static fatigue life are:

(1) Rupture often occurs without increase in creep or stress relaxation rate.

(2) Measured values exhibit considerable scatter or deviation from mean.

(3) It is not correlatable with any other materials property.

(4) It is highly dependent on environment and state of stress.

(5) It is of primary interest in the design of parts which are constantly loaded in service (such as mountings that are preloaded in order to increase dynamic fatigue life, see Figure 2-28 and last paragraph of 2.2.2). The static fatigue life curves of Figure 2-20 depict the typical shape of such curves.

A simple device which has been used for measuring stress relaxation is depicted in Figure 2-21. The experimental curves obtained with this apparatus are shown in Figures 2-22, 2-23, and 2-24. Comparison of the shape of these curves with those of Figure 2-19 shows the variation in response resulting from changes in the material. This prevents accurate prediction of long time response from the results of short time tests.

2.2.2 Dynamic Response (Refs. 27, 74, 75, 82, 83, 100, 167, 175, 176)

The dynamic problem is based on the response to a load which varies sinusoidally with time, which is a deformation that (in the steady state) also varies sinusoidally with time. This sinusoidal deformation has the same frequency as the load and is usually out of phase with the load and with an amplitude dependent on both magnitude and frequency of stress. The model of Figure 2-25 also exhibits this type of behavior and, if $S = S_o \cos(\omega t)$ is the load equation, the response equation for the model is:

$$\gamma = S_o \left[\frac{1}{G_1} \cos(\omega t) + \frac{\sin(\omega t - \alpha)}{\sqrt{\omega^2 \eta_2^2 + G_2^2}} + \frac{1}{\omega \eta_3} \sin(\omega t) \right]$$

where

$$\alpha = \tan^{-1} \left(- \frac{1}{\omega \tau} \right)$$

The first term of the response equation is in phase with the applied stress and absorbs no net energy during a cycle; the third term is ninety degrees out of phase with the applied stress and dissipates energy continuously. The middle term is intermediate in phase between the second and third terms and its energy absorption is frequency dependent. This model is suitable and useful as a conceptual aid and as a basis for a mathematical analysis of response of elastomers, although it has the same basic objections as the model of Figure 2-1.

Theoretically, both the creep function and the dynamic function specify the viscoelastic properties of a material if a sufficient number of such models are combined in series or parallel and these functions can be transformed one into the other through the model. The complexity of the mathematics involved presently constrains use of the basic concept and model to the further simplification of use of a single delayed elastic response element. This extremely simplified model is a useful analytical tool, but the degree of approximation of the model response to the behavior of a real material must be kept in mind to avoid errors such as are invited by much of the literature on dynamic behavior of elastomers.

The most common error is to assume that the elastic and viscous moduli, when derived by the application of the simplified model to experimental results, are constants. Elastic and viscous moduli are complicated functions of temperature, frequency (or strain rate), mean stress, stress amplitude, and strain energy. The most obvious result of the variability of these moduli is that the numerical values for moduli obtained by a variety of test procedures are different. It is very seldom that the published values can be used in analysis. Figure 2-25 summarizes the notation commonly used for dynamic moduli of elastomers. Nolle (Ref. 167) lists the effects of frequency and temperature on the moduli of elastomers as follows:

(1) Real part of the modulus always increases or remains constant with increasing frequency.

(2) Imaginary part of the modulus has a maximum with respect to temperature at constant frequency, and vice versa.

(3) Loss factor E_2/E_1 has a maximum with respect to temperature at constant frequency, and vice versa.

(4) Imaginary part of the modulus approaches zero at zero frequency and probably approaches progressively smaller values at high frequencies past the peak.

(5) Imaginary part of the modulus is large where the real part changes rapidly with logarithm of frequency or with temperature.

(6) Real part of the dynamic modulus approaches limiting high value at low temperatures.

(7) Real part of the modulus has limiting values at high and low frequencies.

(8) An increase of frequency is qualitatively equivalent to a decrease of temperature in effect upon the dynamic modulus.

(9) Real part of the modulus decreases with increasing temperature in regions of appreciable dispersion, but increases with increasing temperature at low frequencies.

Most of the standard resilience and hysteresis tests are only semi-quantitative in that the values of dynamic moduli cannot be derived from test results. It is of interest, however, to review the approximate equations which relate these moduli to test results. Figure 2-26 summarizes these relationships which are derived from simple linear theory.

As in the case of time dependent static response, insufficient test data are available to present any comprehensive summary of the viscoelastic properties of elastomers. Figure 2-27 presents curves of values G' and G'' (see Figure 2-25) as measured by Painter (Ref. 175) for neoprene, silicone, and natural rubber elastomeric compounds. Characteristic behavior of these variables is shown in response to variations in test procedure. It is important to remember, especially in the case of reinforced elastomers, that the original mechanical properties of elastomers are altered by applied stress and that specimen conditioning based on predicted stress history is essential to obtaining accurate moduli for particular applications. Also, the design analysis should include the effects of temperature dependence of moduli and the temperature rise caused by elastomer hysteresis and low thermal conductivity of elastomers.

Dynamic creep and dynamic fatigue are also effects of dynamic loading of elastomeric materials that are of interest to the designer. These effects cannot presently be predicted by analysis because of the lack of experimentally obtained data and, therefore, must be measured by prototype testing in part development.

In steady vibration, the dynamic creep curve is similar in shape to the static creep curve. The "transient drift" is considerably greater for dynamic creep than for static creep under equivalent load. The "steady state drift" is somewhat greater for dynamic creep than for static creep. The temperature dependence of dynamic creep is similar to that of static creep.

Dynamic fatigue life of elastomers superficially resembles that of metals but, as in the case of creep, is different in basis. This response has not been studied in sufficient detail to provide data for analysis, thus only descriptive information can be provided. Fatigue life may be defined as: (1) the number of cycles required to alter the part properties so that it is no longer serviceable in its particular application due to decrease in modulus, or (2) failure due to part rupture. Either type of failure is dependent on:

(1) Static load imposed on part

(2) Amplitude and pattern of dynamic loads imposed on part

(3) Environment

(4) Operating temperature

Figure 2-28 depicts the fatigue life behavior of natural rubber components as measured by U. S. Rubber Company tests (Ref. 48). Minimum fatigue life occurs when the component is unstrained during strain cycling. Also, increasing component life by increasing static load is limited by the static fatigue curve. Fatigue failure life by rupture is comprised of time to crack initiation and time for crack growth. Crack initiation is, quite often, attributable to stress concentrations and environmentally induced chemical degradation. The causative agents are not presently subject to analysis, although they radically alter the simplified picture obtained from fatigue tests of simple specimens.

2.3 MEASURED PROPERTIES OF ELASTOMERS

The information contained in this section is provided to aid the engineer in selection of the most suitable materials for use in elastomer parts. Examples of the properties of practical compounds, together with the distinctive properties of particular elastomers, are presented (Refs. 38, 43, 50, 52, 69, 104, 107, 169, 179, 180, 182, 183, 191, 196).

2.3.1 Original Room Temperature Properties

2.3.1.1 Natural Rubber and Substitutes

2.3.1.1.1 Natural Rubber (Ref. 93)

Natural rubber has low compression and permanent set and high resilience, tear and cut growth resistance, abrasion resistance, tensile strength and ultimate elongation. It has poor swelling resistance to oils, fuels and solvents and only fair aging resistance. Its major uses are in tires and vibration isolators.

The following examples of original room temperature properties of practical compounds are only a sampling of sets of available properties. Natural rubber can be compounded to satisfy a wide range of requirements by change of filler, cure system and other processing variables.

	Durometer Hardness (±5 Shore A Degrees)					
	30	40	50	60	70	80
Ultimate Tensile Strength (psi)	2,200	3,500	3,700	4,400	4,100	3,300
Ultimate Elongation (%)	725	680	640	620	490	310
Yerzley Resilience (%)	90	95	90	80	70	60
Crescent Tear (lb/in.)	100	280	370	390	550	490
Compression Set (ASTM B at 158° F)	40	8	10	12	15	26

2.3.1.1.2 Synthetic Polyisoprene

cis-1,4 Polyisoprene is a new elastomer which has the same chemical composition as natural rubber. Elastomer parts using this material are reported to be somewhat inferior in properties, but this could be the result of lack of compounding experience with the newer material.

2. 3. 1. 1. 3 SBR (Ref. 98)

This material is a substitute for natural rubber. It possesses slightly better aging resistance than natural rubber, but is inferior in resilience, tear resistance, strength, compression and permanent set properties.

2. 3. 1. 1. 4 Polybutadiene

The new high cis-1, 4 material is a natural rubber substitute possessing properties slightly inferior to those of natural rubber. Some polybutadienes exhibit better low temperature flexibility than natural rubber. Hydrogenated polybutadiene (Hydropol), being chemically resistant to hydrazine, propyl nitrate, and tricresyl phosphate, is useful for missile applications.

2. 3. 1. 1. 5 Ethylene Propylene Copolymer

This material is currently manufactured in Italy and will soon be available in the United States. Its mechanical properties are somewhat inferior to those of natural rubber but it has superior aging, swelling, and chemical resistance.

2. 3. 1. 2 General Utility Elastomers with Specific Resistance Properties

2. 3. 1. 2. 1 Neoprene (Refs. 186, 214)

Neoprene, when compared to natural rubber, possesses inferior mechanical properties at room temperature and poorer low temperature flexibility. It is ozone and flame resistant, has fair resistance to corrosive chemicals, and moderate swelling resistance to oils, fuels and solvents. Neoprene is used for sealing strips (where sunlight and weathering resistance is essential) and for many applications where it is necessary to obtain good mechanical and moderate resistance properties.

The following examples of original room temperature properties of practical compounds are only a sampling of sets of available properties. It must be remembered that, in addition to the effects of compounding and processing variables, there are 10 variations of the basic high polymer commercially available.

	Durometer Hardness (±5 Shore A Degrees)				
	40	50	60	70	80
Ultimate Tensile Strength (psi)	2, 500	3, 500	2, 800	3, 700	3, 000
Ultimate Elongation (%)	750	620	350	250	250

	Durometer Hardness (±5 Shore A Degrees)				
	40	50	60	70	80
Yerzley Resilience (%)	85	80	70	70	70
Crescent Tear (lb/in.)	100	150	170	160	170
Compression Set (ASTM B at 158°F)	25	15	10	10	5

2.3.1.2.2 NBR (Buna N)

Buna N has high resistance to oils, fuels and aromatic hydrocarbons (intermediate between neoprene and polysulfide). It has inferior mechanical and weather resistance properties when compared to neoprene or natural rubber. Buna N is a standard material for most ordinary hydraulic and hot oil applications. Examples of original room temperature properties of practical compounds are:

	Durometer Hardness (±5 Shore A Degrees)						
	30	40	50	60	70	80	90
Ultimate Tensile Strength (psi)	1, 700	1, 900	2, 100	2, 100	2, 000	2, 100	2, 200
Ultimate Elongation (%)	860	630	750	570	530	120	80
Lupke Resilience (%)*	67	66	64	57	43	56	49
Tear Strength (lb/in.)*	140	230	250	370	370	210	260
Compression Set (ASTM B at 212°F)*	87	85	79	74	71	36	33

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*Note difference in test procedure from natural rubber data.

These examples are only a sampling of available properties because, in addition to the effects of compounding and processing variables, there are more than seven variations of the basic high polymer commercially available. Optimum low temperature flexibility resilience and compression set values are incompatible with optimum oil and solvent resistance and strength properties.

2.3.1.2.3 Butyl (Refs. 41, 47, 68)

Butyl has poor resistance to petroleum oils and fuels. Its outstanding characteristics are low gas permeability, weathering resistance, and resistance to certain specific chemicals. It possesses good heat resistance, electrical insulating properties and low temperature flexibility, having values of these properties intermediate between those of natural rubber and neoprene. Oxidation and ozone resistance is excellent, as is resistance to phosphate ester liquids, vegetable oils, and dilute acids and alkalis.

Butyl's major uses are for shock absorbers and vibration damping members, gas and chemical barrier elements, and static seals for certain specific chemicals. Examples of original room temperature properties of practical ordinary* butyl compounds are:

	Durometer Hardness (±5 Shore A Degrees)				
	40	50	60	70	80
Ultimate Tensile Strength (psi)	1,800	2,200	2,000	2,300	2,100
Ultimate Elongation (%)	800	750	700	600	500
Yerzley Resilience (%)	45	45	40	35	30
Crescent Tear (lb/in.)	150	200	300	500	400
Compression Set (ASTM B at 158° F)	15	20	20	30	30

The mechanical properties of butyl are most dependent on cure system than most elastomers. This fact, together with six grades and three variations of basic high polymer, permits considerable variation in basic properties of the vulcanizate. For the same hardness values of the preceding tabulation, resilience can be increased or decreased by fifty percent; compression set can be decreased by seventy-five percent; and tensile strength can be increased by fifty percent.

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*Ordinary, in this case, refers to cure system. Other cure systems provide butyl elastomers with definite advantages in specific applications; in particular, improved aging, compression set and resilience properties. Other cure systems are resin, sulfur-donor, and low sulfur-high accelerator.

2.3.1.2.4 Chloro Sulfonated Polyethylene (Hypalon) (Refs. 66, 70, 97, 203, 221)

Hypalon exhibits fair mechanical properties and excellent resistance to heat, fatigue, chemicals, ozone and weather. Its major uses are to blend with other elastomers, and for chemical barrier elements and static seals for specific chemicals. Ranges of original room temperature properties of particular compounds are:

Durometer Hardness (±5 Shore A Degrees)	45 - 95
Ultimate Tensile Strength (psi)	500 - 3500
Ultimate Elongation (%)	250 - 450
Yerzley Resilience (%)	45 - 70
Crescent Tear (lb/in.)	100 - 250
Compression Set (ASTM B at 158°F)	20 - 60

2.3.1.3 Special Purpose Elastomers

2.3.1.3.1 Polysulfide (Ref. 128)

Polysulfide possesses outstanding impermeability to liquids and outstanding resistance to swelling by oils, greases and solvents, to attack by oxygen, ozone, and dilute acids and alkalis. It has poor mechanical properties although good resilience can be obtained. Use of polysulfide is restricted to moderate temperature liquid barrier applications where part design can compensate for poor mechanical properties, i.e., sealants, coatings.

Typical practical compound properties are:

	Durometer Hardness (±5 Shore A Degrees)			
	50	60	70	80
Ultimate Tensile Strength (psi)	700	500	1,200	1,200
Ultimate Elongation (%)	450	300	300	400

	Durometer Hardness (±5 Shore A Degrees)			
	50	60	70	80
Compression Set ASTM B at 158°F (%)	100	100	40	100

2.3.1.3.2 Acrylic and Perfluoro Alkyl and Perfluoro Alkoxy Acrylates (Poly FBA)

These materials are used as seal and gasket materials where both minimum and maximum service temperatures are of the order of 50°F higher than for Buna N. Mechanical properties, resistance to aromatics and water resistance are inferior to Buna N properties. Properties of a typical material are:

	Durometer Hardness (±5 Shore A Degrees)
	60
Ultimate Tensile Strength (psi)	1,500
Ultimate Elongation (%)	300
Compression Set (ASTM B at 158°F)	30

2.3.1.3.3 Urethanes (Refs. 32, 84, 85, 138, 139, 165, 192)

This is a group of high polymers which, with the exception of resilience, possesses superior mechanical properties. Their resilience and resistance properties could be classed as good. They are not resistant to acids, alkalis, hot water, or fuels or oils over 250°F. Urethanes are intermediate in low temperature flexibility among elastomers. The stiffness of urethanes at large deformations is greater than for other elastomers of equal hardness which should be taken account of in design. The difference in mechanical properties of urethane elastomers as compared with natural rubber is so pronounced that examples of behavior are presented in Figures 2-29 and 2-30. Typical property values of practical compounds are:

	Durometer Hardness (±5 Shore A Degrees)				
	50	60	70	80	90
Ultimate Tensile Strength (psi)	2,000	3,000	4,000	5,000	6,000
Ultimate Elongation (%)	650	500	450	450	500
Yerzley Resilience (%)	80	75	70	65	60
Graves Tear (lb/in.)	100	150	200	400	500
Compression Set (ASTM B at 158°F)	40	9	12	15	20

These materials have only recently become available in this country and are currently in the application development phase. They offer great potential both for utilization and property improvement.

2.3.1.3.4 Silicones (Refs. 28, 36, 39, 46, 58, 77, 127, 136, 137, 164, 193, 194, 206, 219, 224)

Silicones are high polymers possessing superior resistance to both high and low temperatures. They are indispensable materials for aero-space applications despite their inferior mechanical properties at room or moderate temperatures. Silicone development has been so dynamic that silicones are presently being used in applications which, a few years ago, would have been impossible for elastomers to perform.

LS-53 is a new fluorinated silicone that has excellent resistance to many fuels and oils. Silicones, compared with other elastomers, have remarkable stability of mechanical properties over their temperature range of utilization.

Examples of original room temperature properties of practical silicone compounds are:

Type*	Durometer Hardness, Shore A	Tensile Strength, psi	Elongation, %	Comp. Set 22 hr/300° F, %	Brittle Point, °F	Stiffening Temperature. °F	Tear Strength, lb/in.	Max. Recommended Use Temp., °F
LS-53	55	1000	170	22	- 90	- 80	75	475
General Purpose	50	950	300	24	-100	- 60	80	600
General Purpose	80	800	230	21	-100	- 60	125	600
Nitrile	60	1000	260	60	-120	-100	80	500
Nitrile	80	850	125	35	-120	-100	75	500
Low Comp. Set	55	1000	390	15	-175	-165	80	500
Low Comp. Set	75	600	175	17	-175	-165	75	500
High Tensile	50	1500	550	25	-130	-100	180	500
High Tensile	75	1275	310	25	- 85	- 80	110	500
Low Temperature	50	750	290	60	-175	-165	80	500
Low Temperature	60	700	125	30	-175	-165	75	500
High Temperature	60	800	175	15	- 90	- 60	100	700
High Temperature	60	800	100	50	- 80	- 60	90	700
Conductive (Electrical)	65	840	210	34	- 80	- 60	50	450
Flame Resistant	60	600	200	37	- 80	- 60	50	600

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*Conventionally Processed Vulcanizates

Type*	Durometer Hardness, Shore A	Tensile Strength, psi	Elongation, %	Brittle Point, °F	Tear Strength, lb/in.	Max. Use Temperature, °F	Consistency at Application
LS-53	35**	380	220	-100	--	500	Putty like
LS-53	60	750	160	-100	50	600	Putty like
General Purpose	25**	200	250	-100	--	600	Putty like
General Purpose	60	650	110	-100	50	600	Liquid
General Purpose	50	450	140	-100	25	600	Liquid
General Purpose	30**	275	200	-100	--	600	Liquid

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*Room Temperature Vulcanizates (R. T. V.'s).
**Cured at room temperature and not heat aged.

Temperature limitations of currently available conventionally processed silicones are:

To 300°F	All compounds have indefinite life in either sealed or vented systems.
Above 350°F	In sealed systems, no compound will last more than a few days.
To 400°F	In vented systems, all compounds have indefinite life.
Above 500°F	All compounds in vented systems will hold up for months.
Above 600°F	Special compounds must be formulated, even for vented environment, and dependable service is limited to days.
Above 700°F	These same special stocks have a life expectancy of hours, vented.

Current R. T. V.'s can be used as sealants where pressure differentials are less than 20 psi at 520°F for one hour and 700°F for one-half hour.

2.3.1.3.5 Fluorocarbon Elastomers (Refs. 42, 72, 80, 157, 190, 195, 213, 225)

These materials have outstanding chemical resistance, good mechanical properties that are markedly temperature dependent, good thermal stability, and poor low temperature flexibility. Present applications are limited to seals, liners, and coatings which require chemical resistance not attainable in other materials. An example of typical properties of a practical compound is:

Viton A-HV

Tested at 75°F		Resilience, ASTM - Yerzley	
Modulus at 100%, psi	900	Resilience, %	48
Tensile Strength, psi	3075	Load at 20% Defl., psi	215
Elongation at Break, %	200	Static Modulus, 5% Defl., psi	1060
Hardness, Shore A	70	Effective Dynamic Modulus, psi	1530
Brittle Point, °F	-42		

Viton A-HV (Cont'd)

Tested at 300°F

Tensile Strength, psi	850
Elongation at Break, %	100

Stress-Strain - After 28 Days at 450°F (Oven)

Tensile Strength, % Retained	80
Elongation at Break, % Retained	70
Hardness, Shore A, pts. change	+7

Stress-Strain - After 16 Hours at 600°F (Oven)

Tensile Strength, % Retained	67
Elongation at Break, % Retained	48
Hardness, Shore A, pts. change	+12
Weight Loss, %	7

Compression Set

ASTM - Method B

70 hours at 250°F, %	10
94 hours at 250°F, %	12
118 hours at 250°F, %	11
46 hours at 350°F, %	21
70 hours at 350°F, %	25
94 hours at 350°F, %	36
22 hours at 450°F, %	65
46 hours at 450°F, %	84
70 hours at 450°F, %	87

ASTM - Method A

22 hours at 400°F, %	14

Estimated Maximum Service Life at High Temperatures

Temperature	Time to Brittleness
400°F	2400 hours
450°F	1000 hours
500°F	250 hours
550°F	72 hours
600°F	24 hours

2.3.2 Temperature Effects on Mechanical Properties

Three significant aspects of behavior of elastomers are observed in the measurement of elastomer properties as a function of temperature:

(1) At low temperatures, abrupt changes in slope of curve of measured property versus temperature.

(2) Above this temperature, monotonic and continuous change of property with temperature.

(3) At elevated temperatures, irreversible property changes associated with chemical alteration of the elastomer.

2.3.2.1 Effects of Low Temperature (Refs. 40, 45, 149, 187)

A number of changes can take place in an elastomer as a result of exposure to low temperature. All of these changes are reversible. Returning the composition to room temperature, or slightly elevated temperatures, results in a restoration of its original properties. This is in contrast to the effects of high temperature exposure which permanently change the composition.

Immediate Effects: If the modulus of a specimen is measured at successively lower temperatures, being held at each temperature only long enough for thermal equilibrium to be established, its stiffness will increase as a function of temperature (Figure 2-31). As the temperature is decreased, the specimen becomes progressively stiffer at a gradual rate until a particular temperature is reached. At this point, stiffness increases sharply with a decrease in temperature, so that within a range of about 20°F stiffness may increase a hundredfold or more until another abrupt change in curve shape is attained. Further cooling produces little additional increase in stiffness. The changes which cause the gradual increase in stiffness are known as simple "temperature effects," and the temperatures at which abrupt changes occur in slope of property versus time curves are known as transition points.

At some temperatures, dependent on test technique, the specimen becomes brittle or will shatter on sudden bending or impact. The temperature at which this occurs depends on the rate of application of load. When determined under specific testing conditions, it is known as the "brittle temperature" or, more commonly, the "brittle point." The brittle point bears no definite relationship to the stiffness curve. This is to be expected because of the difference in time scale between stiffness and impact tests.

Time and Temperature Dependent Effects: Long-time exposure produces two other kinds of changes. One such change is known as "crystallization." Crystallization results in stiffening which is only evident after prolonged exposure. It may require hours, days or even weeks, depending upon the exposure temperature and on the particular composition involved. While crystallization results in an increase in stiffness, it does not necessarily result in brittleness. Nor does the fact that crystallization has taken place appear to affect the brittle point of the composition.

Among the common elastomers, natural rubber, butyl rubber and neoprene are crystallizable. Among all of these, the rate of crystallization is increased by placing the vulcanizate under strain. For each elastomer there is a temperature at which crystallization takes place most readily. In fact, at extremely low temperatures (e. g., -50°F) or at elevated temperatures neither neoprene nor natural rubber crystallizes. Since crystallization is a time effect and does not take place at extremely low temperatures, it does not occur if the elastomers are cooled more or less rapidly through the range in which crystallization ordinarily can occur.

The second effect is known as the plasticizer-time effect. Many compounds designed for low temperature service contain substantial quantities of special plasticizers which are used to improve low temperature flexibility and to depress the brittle point of the composition. Under ordinary temperature conditions such plasticizers are highly compatible with elastomers, i. e., they are soluble in the elastomer. Upon prolonged exposure to low temperatures, however, the compatibility of the plasticizer is reduced and a portion of it is thrown out of solution. This portion, of course, is of no value in reducing the brittle point or in promoting flexibility; consequently, plasticizer-time effects may result in two changes in the composition. First, its flexibility at temperatures above the brittle point may be reduced; second, its brittle point may be raised several degrees. Generally speaking, plasticizer-time effects are apparent only after prolonged exposure at extremely low temperatures, such as -40°F, and are noted only when large quantities of certain plasticizers are used.

Actual service low temperature limits are dependent on the application in which an elastomer is used. In seal applications, elastomers are often used at temperatures below stiffening temperatures because elastomeric response is not required by the design, system liquid absorbed by the elastomer acts as a low temperature plasticizer, or system operation keeps elastomeric temperature above nominal environmental temperature. On the other hand, elastomer parts have proven unserviceable or failed at higher temperatures than would be predicted by laboratory data because of stiffening, loss of resilience, or increase in brittle point due to elastomer service history; in particular, plasticizer loss by extraction or "boiling off" at elevated temperature or static exposure at low temperature under strain. Any material for a service application, to operate in environmental temperatures near or below stiffening temperature, should be analyzed in terms of predicted component temperature and strain rate and amplitude histories rather than by mere comparison of recommended service and environmental temperatures derived from laboratory tests.

Typical results of three of the standard laboratory methods used to measure the effects of low temperature on the properties of elastomers are depicted in Figures 2-31, 2-32, and 2-33. Figure 2-31 illustrates the low temperature stiffening of several elastomeric materials as measured by the

Gehman test. The graphs of the degrees "twist versus temperature" of most of the organic elastomer compounds in common use fall in the narrow range between natural rubber and fluorocarbon elastomers.

Figure 2-32 depicts low temperature retraction characteristics of several elastomers; not only are the temperatures at which significant change in retraction behavior occurs considerably different from stiffening temperature, but the order of merit of freeze resistance is different. Results of these tests are highly dependent on differences in both elastomer processing and test technique. In the case of LS-53, for example, the curve presented in Figure 2-32 (Ref. 11) is parallel to, but at about 20°F higher temperature than, test results reported in Reference 95. Figure 2-33 depicts low temperature resilience characteristics of several elastomers. It further demonstrates that minimum service temperature is a function of both the elastomer and the type of response required of the elastomer in service. The change in behavior at low temperatures, measured by the various tests, marks the change in response of the material from that of an elastomer to that of a plastic material and, in this transition region, responses are especially strain rate sensitive. This is the reason, not only for the differences in temperature of marked change in response as measured by the various tests, but also for the variations in recommended minimum service temperatures for different service applications

2.3.2.2 Time and Temperature Dependence of Mechanical Behavior of Elastomers (Refs. 71, 86, 90, 95, 96, 117, 140, 143, 197, 200, 217, 218, 222)

Until recently, the only effects of exposure to elevated temperatures commonly measured were changes in room temperature properties. The high operating temperatures of many aircraft and missile parts require the designer to consider response of elastomers at elevated temperatures as well as the changes in materials caused by such exposure. Recent programs (such as reported in Reference 9) have developed considerable useful design information in this area.

Elastomers exposed to elevated temperatures exhibit two types of response: reversible response, and irreversible response caused by changes in the material. One of the first lessons learned by investigators of these phenomena at elevated temperatures was that it is difficult to separate the two types of response The low thermal conductivity of most elastomers, the high rate of the irreversible changes, and the similarity of the rate equations of the two types of response make separation impractical. Reversible response is referred to as time and temperature dependent behavior, and irreversible response as aging.

Temperature dependent behavior includes time dependent response, i.e., creep resulting from viscous flow. It does not include irreversible processes, i.e., creep resulting from oxidative scission of polymer bonds. Temperature dependent behavior determines elastomer temperature limitations while the aging properties determine elastomer life at temperature limitations.

Very often the compounder can modify each type of response without sacrificing other desirable properties.

The time and temperature dependent behavior of elastomer mechanical properties is analogous to the dependence of liquid viscosity on temperature. The temperature dependence of liquid viscosity can be expressed by equations of the form (Ref. 125)

$$\eta = Ae^{E_{vis}/RT}$$

where

η = viscosity

A = a material constant

E_{vis} = energy of activation of viscous flow

R = a physical constant

T = absolute temperature

This type of relationship is of the same form as the rate equations for simple chemical reactions, such as seem to be involved in elastomer aging. The basic equations are linear, thus graphical analysis and superposition of effects is simplified. As previously mentioned, the complexity of chemical reactions at elevated temperature and the rapidity of some of the reactions render measurement of temperature dependence alone particularly difficult, but the characteristic form of the rate equations involved is of considerable aid in organizing and interpreting actual test results. Figure 2-34A (Mechanical Properties of Teflon) displays how closely the properties of thermally stable Teflon fit a linear relationship.

Figure 2-34B (Mechanical Properties of a Urethane Elastomer) displays the manner in which the properties of a urethane elastomer conform to and deviate from linearity. Teflon may be considered as an unvulcanized and unreinforced polymer below its transition temperature $\cong$ 620° F. The urethane is a cross-linked, reinforced elastomer above its transition temperature $\cong$ -30° F. If the transition temperature range were included in the study it would be evidenced by a discontinuity in the curves but with linear relationship evidenced both above and below it. Inspection of elevated temperature test results (Ref. 140) often shows initial strengthening of the material due to post cure. Also, considerably greater decay of strength properties with temperature increase for the reinforced elastomer than the unreinforced material is often observed.

Urethane was chosen as an example because, except for possibly the room temperature tensile strength value, post cure and reinforcement effects are not significant. However, chemical degradation of urethane at temperatures above 250°F is evident from the results of 8-hour aging at test temperature. At temperatures above 400°F it seems apparent that the reaction rate is so high that significant chemical degradation of urethane has occurred before initial properties can be measured at this temperature.

In Section 2. 2. 1, Static Response, the time dependence of moduli was discussed and it was mentioned that semilog plots of deformation versus time approach linearity when irreversible material changes do not occur and, in Section 2. 2. 2, Dynamic Response, how the behavior of elastomers approximated the Maxwell and Voigt models. Figure 2-35 and 2-36 present actual moduli behavior of three common elastomers as a function of time and temperature. The convenient "coincidence" (Ref. 117) that simple chemical reaction rate equations, temperature dependence of elastomer properties, and time dependence of response all have the same form, provides the engineer with a powerful analytical tool in the superposition principle (or method of reduced variables). The Voigt model, for example, has a basic differential equation

$$\sigma = G\epsilon + \eta\dot{\epsilon}$$

of which the integral is

$$\epsilon = \frac{\sigma}{G}\left(1 - e^{-\frac{t}{\tau}}\right), \quad \epsilon_o = 0 \text{ when } t = 0, \quad \tau G = \eta$$

When dealing with materials whose response functions have linear operators, there is a direct mathematical relationship between the analysis of a body made of these materials and a corresponding elastic body loaded in the same way. The store of results from elastic theory can be used for analysis of components made of these materials. The incompressibility of elastomers further facilitates such computations because Poisson's ratio can be approximated as one-half, and the simplest formulas of elastic theory can be used. Tests of elastomers demonstrate that, within limits, the response of many mechanisms, including some of the chemical degradation ones, are approximately linear so that these effects can be included in the analysis. Instability problems, which involve nonlinear response, cannot be solved by this technique. The simplest method of problem solution using this technique is to use apparent (or time dependent) moduli derived from tests with appropriate time and temperature history in place of the elastic moduli.

The second benefit is that change of temperature can be related to change of the time scale of response to stress (Ref. 197) so that single master moduli curves covering a very wide range of temperature and time (or frequency for the dynamic cases) can be developed from a small number of tests using feasible time duration and temperature values. Also, this provides a quantitative basis and means for correlation of simulated service tests accelerated by elevated temperatures with service behavior. The time-temperature transformation is performed graphically. The following figures and discussion of this technique are taken from Reference 146.

> "Let us suppose that measurements of retarded elastic behavior are made over a range of temperatures up to about room temperature, and over a given range of times, say five seconds to one hour after application of stress. The data will be shown by the heavy lines in [Figure 2-37]. The observations can be reduced to a given temperature, say 25° C, by normalizing the curves so that the equilibrium strain is the same as at the "reduced" temperature; the curves are then shifted along the logarithm of time axis until they overlap. Such a "reduced" curve is shown in [Figure 2-38]. From the amount of lateral shift necessary, the change in time-scale with temperature is found. It appears that, for elastomers, the change in the logarithm of the time-scale varies linearly with the reciprocal of the square of the absolute temperature. It is to be noted that there is no temperature at which the vulcanizate suddenly stiffens. However, the above empirical law implies that the change in time-scale becomes more and more pronounced with decrease in temperature. Hence for experiments carried out with a given time-scale, a marked increase in "stiffness" appears to take place over a limited range of temperature. The "observed" curve corresponding to the highest temperature in [Fig 2-37] is shown to be nearly horizontal. Such a curve is obtained with a natural rubber pure gum vulcanizate at room temperature. With a material such as a butyl rubber vulcanizate, a somewhat higher temperature would be required to obtain the same type of curve over a time range of minutes to hours.
>
> "It would be expected that if a creep test at the highest temperature represented in [Figure 2-37] were carried out for an extended period of time, the true equilibrium strain would be reached. Unfortunately, significant chemical changes take place under these

conditions. Extended creep tests at room temperature and above on materials such as natural rubber gum vulcanizates are more a measure of chemo-rheological phenomena than viscoelastic behavior.

"Another manifestation of the viscoelastic behavior of rubber is found in stress relaxation tests. In such tests a constant deformation, for example, a constant shear strain, is applied suddenly to a specimen of rubber and the decay of stress observed as a function of time. Here again we are interested in tests below room temperature, since tests at elevated temperature measure chemo-rheological behavior. If the behavior is linear, we can represent it by a relaxation modulus. The relaxation modulus G (t) (at a specified temperature) is the shear stress at a time t after the application of a constant unit shear strain at zero time. As before, we can reduce curves of relaxation modulus obtained over a range of temperatures and a limited range of time to a single curve at a "reduced" temperature. Such a reduced relaxation modulus curve is also represented in [Figure 2-38]."

Figure 2-39 furnishes an example of a master curve developed from dynamic tests (Ref. 143).

At first glance it might appear that the departure from linearity of the behavior of these materials at elevated temperature limits the utility of this technique. This is not the case, however, as departure from linearity provides definite evidence of polymer degradation at elevated temperature and is a measure of such degradation. The effects of elevated temperatures on a number of elastomers as measured by the tensile test are depicted in Figures 2-40 through 2-48. The tensile test is very sensitive to changes in material and is simple and inexpensive so that it is generally used by the elastomer technologist to compare aging and heat resistance of elastomers although it does not measure mechanical properties directly.

Figure 2-49 depicts the change of resilience with temperature for several elastomers over a wide range of temperature and Figure 2-50, hardness and compression set of silicones at elevated temperatures. Knowledge of the time and temperature dependence of such properties is more useful to the designer than tensile test results but, unfortunately, such data are not available for most elastomers.

2.4 THERMAL CONDUCTIVITY AND THERMALLY INDUCED DIMENSIONAL CHANGES (Refs. 129, 134)

Elastomer part design must take into account the physical properties of thermal conductivity and thermally induced dimensional changes over narrow ranges of temperatures as compared with requirements of most other engineering materials. The low thermal conductivity of elastomers permits part function in high temperature environments for short periods of time, as in missile applications. On the other hand, component failure often results from thermally induced dimensional changes in elastomer parts rather than their mechanical failure. The thermal conductivity, heat evolved by hysteresis, and dimensional changes of elastomers in service are interrelated factors in service. The dimensional changes of elastomers in service is a particularly serious design problem. These changes derive from the high values of thermal coefficients of expansion relative to those of metals, the Joule effect, and aging effects.

The thermal coefficient of expansion of an elastomer above second order transition temperature approximates that of a normal liquid. Below this temperature the thermal coefficient of expansion is similar to that of a normal crystalline solid. These materials have rubber-like elasticity only when warmer than second order transition temperature; therefore, rubber metal components and assemblies must be designed to accomodate the differences in part geometry or component stresses which develop in response to temperature change. While this response can be used to advantage (as in one shot high temperature seals), it often requires design elaboration to prevent failure. The thermal coefficient of expansion is temperature dependent and a compounding variable. Table 2-1 provides examples of values of linear coefficients of expansion which can be used to estimate severity of expected effects and other thermal properties.

Elastomers exhibit the Joule effect in that: (1) the force in a component maintained at constant deformation approximately varies directly with absolute temperature, and (2) the deformation of a component maintained under constant force approximately varies inversely with absolute temperature. The Joule effect is an entropy effect similar to the compression and release of a gas. This effect causes a stretched O-ring to seize around a rotating shaft as temperature increases, spring deflection to change with temperature, and a rubber band to generate heat when stretched. The Joule effect is superposed on normal thermal expansion when an elastomer part is heated and opposite in direction for a stretched elastomer. The Joule effect applies only to stressed elastomers. Direct dependence of moduli on absolute temperature is generally obscured by other test variables. Change in elastic properties with change in temperature is significant.

The thermal properties of a particular elastomer are readily calculated from the properties of the high polymers and fillers used in compounding. They are also modifiable over a considerable range by selection of compounding ingredients. Part geometry, mold or die design, specification tolerances, and elastomer compounding and processing procedures are interrelated problems.

This is due to the variation in thermal properties of elastomers and the significant dimensional changes that occur over a range of but a few hundred degrees of temperature. Close coordination is required between the elastomer technologist and the engineer in the details of part design.

Component design must also take into account all of the other "in-service" dimensional changes which an elastomeric part might undergo. Consideration should be given to the effects of aging, creep or liquid swelling. These effects are also functions of high polymer, formulation and processing methods. Elastomer technology provides the compounder with a considerable body of empirical data to predict elastomer behavior for most applications.

2.5 ELECTRICAL PROPERTIES (Refs. 13, 119, 133, 151, 155, 168, 227)

The electrical properties of elastomers can be varied by the compounder over such a wide range that elastomers are used both as insulators and as conductors of electricity. Elastomer insulations are available with electrical resistance superior to that of glass and conductive elastomers with electrical conductivity superior to that of aqueous electrolytic solutions.

The desired electrical properties are usually obtained by selection of kind and amount of filler used in the formulation of an elastomer based on a high polymer chosen for resistance to service environment. The electrical properties of primary interest are dielectric strength, insulation resistance, dielectric constant, and power factor. The designer must also consider corona and environmental resistance properties in part design because electrical properties of elastomers are affected by the environment and changes in the material to the same degree as are the mechanical properties.

Dielectric strength is the electrical stress required to puncture a material sample of known thickness measured by a standard test method and expressed in volts per mil thickness.

Insulation resistance is the resistance to flow of current through the insulation of a component or part measured along the path over which the insulation is designed to be effective.

Specific resistance or resistivity is the electrical resistance offered by a material element of unit length and unit cross-sectional area in ohm-cms.

Conductivity is the reciprocal of resistivity expressed in mho-cms.

Dielectric constant, or specific inductive capacity (S.I.C.), is the ratio of the electrical capacity of a condenser having the tested material as a dielectric to the capacity of the same condenser having air as the dielectric.

Power factor is the ratio of energy loss expressed in watts to the volt ampere product of the alternating current flowing in a condenser using the tested material as a dielectric.

Corona resistance is the ability of a tested material to withstand the effects of a flow of electrical energy from a conductor at high potential to the surrounding air which converts oxygen of the air to ozone. Corona discharge occurs at much lower voltage in the rarefied atmosphere of high altitudes so that this is a particularly critical problem in aircraft.

Elastomers are rated in order of merit classifications as electrical insulating materials in Table 2-2. Order of merit is based on some factors not included in the table, such as the degradation product of a silicone insulator being nonconductive silica, flame resistance, etc.

The characteristics of temperature and frequency dependence of electrical properties of elastomers is depicted in Figures 2-51 and 2-52. In addition to the effects of temperature, the electrical properties of elastomers are functions of strain, surface conditions, and chemicals absorbed from the environment.

Electrical properties of practical elastomers, despite a considerable body of theory, cannot be calculated from a knowledge of the ingredients as can thermal properties. For example, compounding natural rubber with large quantities of metallic particles has little effect on its resistivity, while small amounts of certain carbon blacks will change good insulating material into a fair conductor. The interdependence of mechanical, chemical and physical properties of elastomers on type and amount of filler, as well as the differences in the environment and function of electrical and mechanical components, has resulted in the development of a large number of specific elastomers with balanced sets of properties. A diversity of application requirements can be satisfied, varying from electrically conducting tire treads to insulating seals. Considerable information on the properties of these special compounds is available in the technical literature of electrical and electronic engineering.

CHAPTER 3

RESISTANCE PROPERTIES

The information in this chapter is provided to aid the engineer to determine the suitability of elastomers for use in service environments and to estimate the change in resistance properties of particular elastomers which may occur in service.

3.1 ORDINARY AGING (Ref. 55)

The deteriorative agents usually considered in this category are: heat, atmospheric oxygen, atmospheric moisture, light, stress and atmospheric ozone.

3.1.1 Thermal Oxidation (Refs. 122, 199, 210, 230)

The effects of temperature elevation and thermal oxidation are seldom separated in testing or actual practice. Elevated temperature aging tests conducted in vacuum or inert gas environments are used to compare the combined results of heat and oxidation with the result of heat aging alone (see Table 3.1). The rate of oxidation has approximately the same temperature dependence as simple chemical reactions (approximately doubles for each 15° F rise in temperature near room temperature). Reaction rate in some elastomers is influenced by moisture. Light (ultraviolet and the blue end of the spectrum) accelerates oxidative reactions near elastomer surfaces, causing random, shallow surface cracking or crazing (photo-catalytic oxidation). The resistance of an elastomer to thermal oxidation is greatly dependent on the high polymer used in compounding. It is so greatly modifiable by the use of protective agents that even the most susceptible of the high polymers can be compounded into an elastomer with relatively good oxidation resistance.

3.1.2 Ozone Attack (Refs. 87, 99)

Ozone is a highly reactive form of oxygen which is formed in the atmosphere by the action of sunlight on oxygen. It is important because of its effects on natural rubber and SBR, and to a considerably smaller extent on other elastomers.

Atmospheric oxygen produces changes in elastomers by diffusion into the material, followed by oxidation reactions which cause significant changes in the properties of the elastomer. Ozone, on the other hand, reacts only at the surface; this phenomenon has been attributed to the much higher rate of reaction, to the larger size of the molecule (O_3 compared to O_2 for oxygen), or to both. Regardless of the mechanism, ozone affects rubber by causing cracking of stretched rubber, the cracks being perpendicular to the direction of strain. In extreme cases, severe cracking may make rubber items unserviceable; for example, automobile tires have been observed with cracks which penetrated clear through the sidewall so that the fabric was visible beneath.

These effects can occur even at the very low ozone concentrations which are normally found at ground level. Some evidence has been found to indicate somewhat higher values at ground level in Arctic regions due to auroral activity, but for ordinary design purposes, these can be disregarded. For aircraft or other equipment designed to operate or be transported at high altitudes, one must consider the fact that atmospheric ozone concentrations of five to ten parts per million (by volume) are found at altitudes from 60,000 to 90,000 feet, and somewhat lower values may sometimes exist at lower altitudes. Under these conditions, ozone attack may occur much more rapidly than at ground level.

In addition to naturally-occurring ozone as discussed above, ozone may also occur in the atmosphere as a result of the activities of man. In certain urban areas, notably Los Angeles and San Francisco, ozone is produced in quantities larger than those that occur due to natural causes. During periods of moderate to severe conditions, ozone concentrations in the range of 25 to 50 parts per hundred million are measured, and values in excess of 50 parts per hundred million have been reported on rare occasions. In other cities, abnormally high ozone concentrations have been reported very infrequently, although there is growing evidence that the same type of problem sometimes exists on the East Coast of the United States.

From the standpoint of the design engineer, it is sufficient to remember that ozone attack will occur more rapidly in Los Angeles and San Francisco than in other areas, and to design accordingly any items intended for use or storage in those areas. Other urban areas, at the present time, will not be significantly different from rural areas with respect to ozone attack of elastomers. In the future, it seems obvious that the California-type problem will occur with greater frequency in other urban areas, and may need to be considered.

One other special situation needs to be mentioned concerning man-made ozone in the atmosphere. It is well known that ozone is formed in the atmosphere near an electric discharge, and hence for parts to be used in motors or other electrical equipment, some consideration should be given to the possibility of accelerated ozone attack. Due to the instability of ozone, it quickly decomposes in the atmosphere following its formation, and hence serious problems will not normally occur except in the immediate vicinity of electric discharges.

Ozone cracking resistance of an elastomer part is dependent on exposure temperatures, strains, humidities, and ozone concentrations, as well as compounding ingredients and high polymer used. Temperature increase and elongation increase, up to 100%, increase crack number, decrease crack size, and decrease time to first cracking. At low ozone concentrations, product of concentration and time to first crack have been measured as constant at very high concentrations; the time to first cracking is so short it is difficult to measure with any accuracy.* Some compounding ingredients, such as low temperature plasticizers, decrease ozone resistance, while specific inhibitors, called antiozonants, increase resistance. High polymers are classified according to ozone resistance in Table 3-2.

While ozone resistance is primarily a polymer selection and compounding problem, the designer can assist in increasing storage and service life of elastomer parts made of nonresistant elastomers by:

(1) Designing parts to have minimum tensile stresses in storage and service. For example, by designing components so that elastomer parts are not stressed in tension by installation; designing parts using low modulus and high set materials properties; and detailing to eliminate high stress concentrations.

(2) Providing for proper packaging in storage.

(3) Providing for barriers such as flexible coatings in service installation.

(4) Reducing part operating temperature.

(5) Avoiding location of electrical components which generate ozone near elastomer parts which must be made of nonresistant material.

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*Private communication from A. E. Juve to C. E. Jaynes.

3.2 LIQUID COMPATIBILITY

3.2.1 General (Refs. 2, 18, 63, 64, 65, 166, 228)

Two relationships are of primary importance in the interaction of chemical compounds: solution and reaction. Many liquids are good solvents for particular elastomers, but do not react with the material; these liquids when in contact with parts, cause reversible swelling and property changes. Other liquids are not solvents but are highly reactive; these liquids deteriorate elastomers by surface attack. Intermediate between these two extremes are liquids which vary in solubility and reactivity and cause both swelling and irreversible changes in the properties of the bulk of the material at rates dependent on their solubility in and reactivity with the elastomer. Both solubility and reactivity derive from chemical constitution of liquid and elastomer so that serviceability of particular elastomers for service in contact with specific liquids is predictable qualitatively, if not quantitatively.

3.2.2 Compatibility with Conventional Petroleum Based Oils, Fuels, Lubricants, Hydraulic Liquids, and High Performance Substitutes (Refs. 67, 154, 162, 172, 184)

Organic liquids are often classified according to molecular structure and chemical composition in categories selected as indicative of elastomer swelling behavior. (The similarity in swelling behavior of elastomers immersed in similar liquids is so pronounced that swelling behavior of a liquid can be estimated by knowledge of the behavior of a similar liquid.) Commonly used classifications are:

> Aliphatic Hydrocarbons. Straight chain hydrocarbons and their derivatives such as hexane, heptane, and isooctane.
>
> Aromatic Hydrocarbons. Benzene and its derivatives such as toluene and xylene are examples of aromatic hydrocarbons. Usually aromatic hydrocarbons cause greater swelling effects than the straight chain hydrocarbons so that, for hydrocarbon mixtures such as petroleum fuels, it is useful to have a measure of aromaticity (as illustrated by Figures 3-1, 3-2, and 3-3). The aniline point (lowest temperature at which the hydrocarbon is miscible with an equal volume of aniline) or mixed aniline point (lowest temperature at which the hydrocarbon mixed with an equal volume of normal heptane will dissolve an equal volume of aniline) is used for this purpose. Decrease in aniline point corresponds to increase in percent aromatics and swelling. This is not always true for aircraft fuels and oils.

Halogenated Hydrocarbons. Hydrocarbon derivatives such as methylene chloride, carbon tetrachloride, ethylene dichloride, which have halogens substituted for hydrogen atoms or added at double or triple bond sites. Halogenated derivatives usually have greater solvency power than the parent hydrocarbon.

Hydrocarbon. An organic compound containing only carbon and hydrogen.

Nitrogen Compounds. Any organic compound containing nitrogen. Examples are aniline and nitrobenzene.

Oxygenated Compounds. Any compound which contains oxygen. Organic compounds containing oxygen may be divided into classes such as alcohol, ketones, esters, and ethers.

The standard test for liquid resistance is sample immersion at a temperature selected from a standard list to approximate service temperature. Table 3-3 lists standard oils, fuels, aromatics, temperatures, and immersion periods used in immersion tests. The ASTM immersion test standard states, "owing to the wide variations often present in service conditions, no direct correlation between these accelerated tests and service performance may be given or implied." Table 3-4 lists volume change in response to liquid immersion of selected elastomers in a variety of organic liquids.

A rule of thumb sometimes used to evaluate such data is: Volume change less than 16%, elastomer-liquid probably compatible; volume change less than 40%, elastomer-liquid may be compatible; volume change greater than 40% , elastomer-liquid incompatible. As indicated by the quotation from ASTM standards, such data are suitable only for preliminary elastomer screening purposes, and the results of more comprehensive tests, as well as the exercise of engineering judgment, are required before a specific elastomer can be selected as a suitable material for a particular service application. Among the many reasons why such tabulated data is not sufficient for elastomer choice are:

(1) It refers to a specific elastomer which most probably was compounded for optimum resistance to the liquid in which it was tested without regard for other elastomer properties.

(2) The volume change measured does not take into account the effects of the many other service variables such as part restraint, stress,and actual amount of exposure of a part to the liquid.

(3) In addition to volume change caused by immersion, the designer needs to know the values of other elastomer properties while a part is swollen by the liquid and after loss of the liquid.

The standard tests also provide information on changes in compounder's properties in response to liquid immersion (see Table 3-5). This table also shows the lack of correlation between volume swell and property changes. The tensile test results are very sensitive to change in materials properties but, as they are not correlatable to physical properties, are only a merit index. The military specifications provide serviceability index tests and criteria which should be used whenever they are applicable (see Tables 3-6, 3-7, and 3-8). There are hundreds of liquid and elastomer standards and specifications and many liquids and elastomers in use for which there exist no applicable specifications. The examples chosen for these tables of liquids, elastomers, and their compatibility were selected from ASD sources on serviceable seals as representative of present good practice. The military specifications themselves should be referred to for information on properties required for particular service applications, their measurement, and typical acceptable property values.

3.2.3 Compatibility with Rocket and Space Power Source Liquids, Fuels, and Oxidizers (Refs. 12, 156, 163)

This class of liquids includes materials which are both highly reactive and have high solvent power. Environmental temperatures of parts exposed to these liquids may range from near absolute zero to over 2000°F. Required service requirements of parts may include near instantaneous response after long periods of inactivity. These parts may also be exposed to other environmental agents of deterioration such as nuclear and ultraviolet radiation, high ozone concentrations, mechanical erosion, and high vacuum. These environments are so severe that, for some chemicals, suitable engineering materials have not yet been found to enable use of the chemicals in aero-space weapons systems. The inherent advantages of elastomers as materials for fabrication of such important parts as gaskets, seals, diaphragms, expulsion bladders, tank and accumulator liners and coatings, hose, and electrical insulation are so significant that they should be considered for use in these applications despite the apparent incompatibility of familiar elastomeric materials with such severe environments. Considerable research effort is currently devoted to development of more resistant elastomers, component and part design details which will extend the range of usefulness of available elastomers, and inorganic material combinations which have elastomeric properties (see Refs. 8, 12, 22).

In this area of interest (in which much of the available information is proprietary or classified and cannot be included in this report),the designer is faced with the following problems:

(1) The lack of design precedent in the form of examples of successful service use of elastomer parts in similar applications.

(2) The lack of test procedures as well as of test data which correlates elastomer properties to serviceability for specific applications.

(3) The lack of specifications and standards for liquids, elastomers, and part details required.

(4) The considerable difference that often is required in design criteria and acceptable quality control tolerances of elastomer parts for aero-space weapons systems as contrasted with ordinary elastomer utilization.

For all these reasons, the information provided in this section of the report is not as complete and accurate an index of elastomer serviceability as information provided in preceding sections.

In actual practice, properly compounded and designed elastomer parts have been found to be far more serviceable in extreme environments than would be predicted by application of the usual evaluation methods used in part design. An important characteristic of elastomers is that materials which have superior specific resistance properties are often inferior in some of the physical properties to commonly used elastomers. Physical properties are not always considered in ordinary design practice because the usual elastomers have adequate property values for serviceability. In those cases where elastomers with inferior physical properties must be used, part and component design details may need to be modified from usual standards to compensate for this deficiency. For example, compared with Buna N seal compounds, the Kel-F elastomers have a high strain relaxation rate; LS-53 has poor tear and abrasion resistance; and Viton A has a high brittle temperature. Nevertheless, these fluoroelastomers with superior chemical resistance properties are being used successfully in parts for which usual design standards require low strain relaxation rate, high tear and abrasion resistance, and low brittle temperature.

Table 3-9 lists some of the chemicals of interest as space weapons systems energy sources. These chemicals must be contained and transferred in typical rocket motors, vernier engines, and power sources. In addition to these chemicals, lubricant, coolant, and hydraulic liquids, serviceable in extreme environments, must also be controlled. Several of the chemicals used as energy sources and working liquids are listed in Tables 3-6 and 3-8. A particularly severe problem in power source devices is that different chemicals must often be separated by seals, and, although materials are available which have satisfactory resistance to each of the chemicals, no one of the materials may be resistant to both of them. Also, many aero-space weapons systems must be designed to permit change in energy source and working liquids as well as for operation in diverse environments without extensive modification and part replacement. Another characteristic of elastomer-reactive chemical interaction is that seemingly minor amounts of compounding ingredients, processing contaminants, or surface contaminants acquired by an elastomeric part in handling may initiate or catalyze reactions which would not otherwise occur.

The following brief paper by Jordan (Ref. 131) is reprinted in its entirety because it illustrates so many of the typical problems encountered in evaluating elastomers for use in contact with highly reactive liquids. In connection with this article, it should be noted that successful LOX seals in current use are made from elastomers such as Buna N, as well as Teflon, aluminum, and stainless steel.

> "Although liquid oxygen impact tests are used as criteria for measuring the utility of materials to be used in systems containing liquid oxygen, from experiments conducted it appears that liquid oxygen impact resistance has no connection with the chemical or physical properties of most elastomers. These experiments also reveal several other points that should be of interest to engineers responsible for design of sealed devices.
>
> "The standard test measures the ability of the material to withstand an impact load in the presence of liquid oxygen. It has been determined, however, that even an oily fingerprint can cause a detonation in this test. Elastomeric O-rings are used in certain types of fittings in liquid oxygen systems. The engineering staffs of firms designing such systems often request that the O-rings be impact resistant. Furthermore, they feel that it is desirable to use packings having good impact resistance in the associated equipment of a weapon system, to minimize the possibility of creating a hazardous condition by accidentally interchanging O-rings.
>
> "Experimental work recently conducted at Parker Seal Company indicated that the following conclusions were justified. (1) The

performance of the several elastomer types tested varied sufficiently to indicate that utility cannot be predicted on the basis of elastomer type; that it is necessary to conduct impact tests on each compound to determine its suitability. (2) Compounds V271-7 (a compound of the fluorocarbon type) and 1011-10 (a nitrile) have the best impact resistance of all the materials evaluated.

TEST DATA AND PROCEDURE

"The test results shown in Table I (3-10 of this report) are listed in decreasing order of utility in liquid oxygen systems, based upon resistance to detonation.

"The test samples were 2-214 O-rings cured in accordance with our standard process specifications. These O-rings have a nominal cross section of 0.013 inch and an O. D. of 1.3 inches. The O-rings were cut into 3/4-inch lengths in order to obtain a specimen size which would easily fit into aluminum foil cups holding the liquid oxygen. The test specimens were then cleaned for liquid oxygen service, i. e., washed in detergent and rinsed in trichloroethylene.

"Impact test machine consisted of a 40-lb. weight, dropped along guide rods onto the sample. The initial height of the weight could be adjusted so that various impact loads could be applied, i. e., a drop of one foot resulted in an impact of 40 ft. lbs., a drop of one and a quarter feet applied 50 ft. lbs., and a drop of one and a half feet applied 60 ft. lbs. The weight was held by an electromagnet which could be de-energized remotely, thereby reducing the hazard to laboratory personnel.

"The elastomer specimens were placed in aluminum foil containers approximately 3/4-inch in diameter by 1/2-inch deep. The foil container was then immersed in liquid oxygen (contained in quart glass thermos). When the liquid oxygen stopped boiling, the foil container was removed, placed on an anvil under the impact head, and the electromagnet de-energized.

"During any handling of containers or samples, liquid oxygen cleaning techniques were used. A blank container containing no elastomer, just liquid oxygen, was run before each series of tests. No detonations were obtained on the blanks.

"Since resistance to impact detonation at 60 ft. lbs. has been generally spoken of as a desirable parameter for materials in this service, initial tests were conducted at this level. In the first ten tests none of the O-ring materials would consistently meet this requirement. Consequently, testing at this level was discontinued, and our sights were set on 50 ft. lbs. and 40 ft. lbs. with a sample lot size of ten at each level. This explains why all the materials were not tested at 60 ft. lbs., and why the sample lot size at this test level is less than ten.

RESULTS

"Liquid oxygen impact resistance appears to have no correlation with the chemical or physical properties of the elastomeric materials tested. It has been argued that detonation is simply very rapid burning and therefore, fireproof materials should display greater resistance to detonation than materials which readily burn. Yet a flame retardant chloroprene had greater impact sensitivity than a highly plasticized nitrile. Also, all the fluorocarbon compounds, the fluorinated silicone compounds, and the two chloroprenes are more fire retardant than any of the nitriles.

"It might be argued that there should be correlation between impact resistance and excess curing agent (excessive in respect to the stoichiometric quantity). Yet again, a nitrile which is noted for a calculated excess of curing agent performed better than fluorinated silicone, which has a very small portion of curing agent, and various fluorocarbons which are cured at 400°F for 24 hours. (Certainly the elastomer here should have taken up most of the curing agent.)

"The third agrument which has been advanced is that highly flexible materials would be less impact sensitive, due to their ability to absorb energy at the test temperature (-297°F). Yet, again, a fluorocarbon material is our best performer, whereas all the nitriles, the chloroprenes, and the fluorinated silicone compounds had lower brittle points.

VARIED PERFORMANCE

"One other point that should be stressed is the lack of a definite pattern in impact sensitivity, i. e., the performance of the fluorosilicones varied in almost the same way at each impact level. Consequently, it is rather difficult to extrapolate this type of data. This variation also requires that at least ten separate tests be performed before final acceptance. It is conceivable that due to the statistical probabilities (using small samples), a transposition may occur by which an inferior material would be selected over a material having greater impact resistance.

"Summing up, material selection based upon impact resistance can be intelligently accomplished only by using a statistically acceptable quantity of tests for each individual compound under consideration.

"The application of 60 ft. lbs., which is the same as dropping one pound 60 ft., is a rigorous condition. Consequently, we believe this requirement is too high for known elastomeric compounds. It should be remembered, too, that the unit loading is based upon the area of the specimen. Consequently, it is always necessary to indicate the size of the O-ring when specifying impact resistance."

Table 3-11 presents selected data on the compatibility of a number of liquids of Table 3-9 with resistant elastomers (or plastics). The elastomers of this table were developed specifically for resistance to the particular chemicals they were tested with and should not be considered as typical of the set of elastomers referred to by the high polymer name used. Fluorine is an example of a chemical for which a resistant elastomer has not been developed.

3.3. GAS PERMEABILITY (Refs. 9, 51, 78, 106, 220)

Permeability is related to solubility but, because solubility of gases in elastomers is not usually measured except in high vacuum studies, gas permeability is usually considered independently of gas solubility. The equation used to define permeability constant is

$$\frac{dQ}{dt} = \frac{AP(p_2 - p_1)}{d}$$

where

Q is the quantity of gas that goes through a membrane when the pressure is higher on one side than on the other, and steady state flow rate is achieved

t is the time

A is the area of the membrane

d is the thickness of the membrane

P is the permeability of the membrane material

$(p_2 - p_1)$ is the pressure differential across the membrane

Permeability can be expressed as the product of two factors, solubility and diffusion constant which are sometimes reported. Most permeability data are reported in cgs units:

Q in cubic centimeters reduced to 0°C, standard atmosphere (N. T. P.)

t in seconds

A in square centimeters

d in centimeters

p_1, p_2 in atmospheres

P is in $cc/cm^2/cm/sec/atm$ or $\frac{cm^2}{sec\ atm}$

Permeability increases sharply with temperature and is very dependent on gas and type of elastomer as can be seen by reference to Figure 3-4 and Table 3-12. Table 3-12 presents permeability data collected from a number of sources, primarily References 9 and 220.

3.4 RADIATION EFFECTS (Refs. 1, 30, 53, 61, 76, 101, 114, 115, 116, 198, 232)

Elastomers are particularly sensitive to radiation damage because of both their chemical composition and the dependence of their behavior on molecular structure. Radiation damage effects are similar and complementary to aging effects and the mechanisms of damage are closely related to those of aging. As in the case of aging, it is easy to describe the effects but difficult to measure them quantitatively. A considerable amount of empirical work has been performed on radiation damage to elastomers in terms of the response of compounder's property values to radiation, but it has not yet organized into usable engineering design information, particularly for the case of the effect of combined environments.

The forms of radiation of interest are:

(1) Charged particles such as alpha particles (helium atom nuclei) and beta particles (high-speed electrons) released during atomic fission.

Charged particles do not penetrate deeply into solid materials and are readily removed by shielding. They are produced in some irradiated materials by neutron absorption.

(2) Neutrons are highly penetrating particles:

(a) Fast uncharged nuclear particles not in thermal equilibrium with their environment and possessing fairly high kinetic energy that can lose this energy only by direct collision with atoms.

(b) Thermal or slow neutrons moving at velocities equal to molecular kinetic motion which have little direct effect except to induce radioactivity in a material.

(c) Epithermal neutrons having intermediate kinetic energy values.

(3) Gamma photons or electromagnetic radiation, similar in nature to X-rays but more energetic and penetrating, which interact with electrons of irradiated materials.

Ionization, excitation, and free radical production are the significant mechanisms of radiation energy absorption. These processes break molecular bonds and cause molecular rearrangement by chemical reaction between the resulting fragments. It has been fairly well demonstrated that damage is dependent only on dosage, or amount of radiation energy absorbed, irrespective of the form of radiation within a factor of two.

Dosage units are:

Ergs/gram (dosed carbon) used as standard by ASD.

Roentgen, reserved for X-ray or gamma radiation measurement in air, is that quantity of radiation which will produce 1 esu of ions in 1 cc of air at 0°C and 760 mm, or will cause the absorption of 83.8 ergs of energy by 1 gram of air.

Rep (roentgen equivalent physical) is that quantity of ionizing radiation of any type which will cause the absorption of 83.8 ergs of energy in one gram of animal tissue.

Rad is that quantity of ionizing radiation which will cause the absorption of 100 ergs of energy in one gram of the material being irradiated.

A rule of thumb is 1 rad ≅ 1.2 roentgens ≅ 1.1 rep ≅ 100 ergs/gram (dosed carbon). Rad values are a function of the material being irradiated as well as radiation field, so that this approximation is not strictly valid.

Dosage rate is an important factor in elastomers only where significant degradation from other agents is occurring simultaneously and where other reactants, such as oxygen, are available to the system. Surprisingly enough, the least heat resistant of the elastomers displays the most radiation resistance. Polyurethane, which should be the most thermally unstable of the elastomers because reaction equilibria favor dissociation at high temperatures, displays superior radiation stability. Table 3-13 compares the thermal aging and radiation stability of specific elastomeric compounds (different compounds for the different measurements); in this case, thermal aging includes the effects of atmospheric environment.

A set of data presented as simply as in Table 3-13 is not adequate design information because it does not display the variation in radiation resistance with compounding, processing, and environment, nor is it in terms of engineering property values. Tables 3-14 through 3-20 are included to present the diversity of effects which occur in elastomers exposed to nuclear radiation and recommended radiation dosage limitations for elastomers. The information from which Table 3-14 is taken is summarized in Figure 3-5.

Property retention values are not in themselves design criteria. There are many other factors involved in component design such as original property values and the relationship between measured properties and application requirements. Also, as in the case of other resistance properties, maximum radiation resistance cannot be expected to be obtained in an elastomer not specifically tailored for such resistance. Compounders have learned many ways of improving radiation resistance of ordinary elastomers, such as proper choice of filler, plasticizer, cure system and the use of antirads. More dramatic improvements are made by modification of the basic high polymer. Figure 3-6 presents the results of Dow Corning's development of a silicone elastomer specifically for radiation resistance. The methyl and phenyl elastomers of these curves are the materials for which data are presented in the tables. These graphs display the dramatic improvement achievable in radiation resistance in specially designed elastomers as compared with the standard materials.

3.5 HIGH VACUUM EFFECTS

A deteriorating factor of space environment not previously considered is high vacuum. An elastomer exposed to high vacuum quickly loses the fluids absorbed from its previous environment as well as volatile compounding ingredients. These compounding ingredients may include low temperature plasticizer, antioxidant, antiozonant, antirad, and ultraviolet absorbers designed to protect the material from photochemical degradation. Since space environments include exposure to low temperature, unfiltered solar radiation, and other forms of high energy radiation, the loss of protective ingredients can result in higher rate of elastomer deterioration than would occur at higher pressures in the same environment. Lower molecular weight high polymer constituents could also be lost by the materials. On the other hand, removal of deteriorating chemicals, such as oxygen,from the elastomer and its environment may reduce deterioration rate or change mode of deterioration. Studies of these effects are currently in progress.

The following quotations are from Reference 173.

"Several conclusions may be made on the basis of the data (presented in the paper):

"1. Exposure to high vacuum does not affect the stress-strain properties of the vulcanizates to a significant degree unless accompanied by elevated temperatures.

"2. Air oven aging is generally more severe at any given temperature than is high vacuum exposure, indicating that the presence of oxygen represents a more severe condition than the extreme vacuum.

"3. The low temperature flexibility of elastomers containing plasticizers is adversely affected by exposure to a high vacuum at both room temperature and elevated temperatures.

"4. Large weight losses were noted only in the case of those compounds containing high levels of plasticizers. There is little evidence to indicate any severe loss of the elastomer itself. Only the ingredients having the highest vapor pressures appear to be significantly affected in this regard. This is borne out also by an infrared analysis made on condensate resulting from these exposures. This analysis reveals the presence of the two plasticizers, i. e., dioctyl sebacate and trioctyl phosphate, as well as the dioctyl p-phenylene-diamine (DOP 88) antiozonant, all of which have relatively high vapor pressures.

"5. Where the ozone resistance of the vulcanizate is contributed by an antiozonant, this resistance is lost after exposure to high vacuum at either room or elevated temperature."

Also see Reference 23 and Reports of Contract No. AF 33(616)-7310 which is currently in progress.

3.6 MICROBIOLOGICAL ATTACK (Ref. 148)

Elastomers are inherently resistant to microbiological attack compared with other organic compoundings, with the exception of the susceptibility of natural rubber polysulfides and some plasticizers to fungal attack. The deteriorative effects usually observed are changes in materials properties due to plasticizer loss, minor surface etching, delamination (where adhesive or bonding agent is consumed), and electrical short circuits caused by conductive, moist elements of fungi on part surfaces. In some environments, such as are encountered in tropical climates and in petroleum fuel tanks containing some water where fungi have been found to proliferate, fungal attack has been found to be more severe. In these cases, a susceptible elastomer may be consumed to a degree where the part becomes unserviceable. Specifications for elastomers to be used in moist environments should include tests of fungi resistance if fungal attack may decrease part serviceability.

CHAPTER 4

ELASTOMER PARTS

The purpose of this chapter is to familiarize the design engineer with the uses of elastomer parts in aero-space weapons systems.

4.1 GENERAL (Refs. 105, 108, 109, 112, 150, 153, 174, 188, 207, 226)

Elastomers are useful materials of construction for aero-space weapons system vehicle parts such as:

(1) Airframe

  a. Pressurization system sealing parts

  b. Structural system vibration damping elements

  c. Control system power source, actuator, servo, and vibration damping parts

  d. Chemical, thermal, and abrasion resistant coatings and parts

  e. Electrical system parts

  f. Heating and cooling system parts

(2) Instrument, Weapon, Indicator, and Guidance Systems

  a. Power source and transmission parts

  b. Electrical insulation

  c. Shock absorption and vibration damping parts

  d. Chemical, thermal, and abrasion resistant coatings and parts

(3) Landing Gear System

  a. Tires

- b. Shock absorption and vibration damping parts
- c. Braking device parts
- d. Retraction mechanism parts

(4) Propulsion System

- a. Fuel containment and transfer element parts
- b. Actuator and servo parts
- c. Shock absorption and vibration damping parts
- d. Electrical insulation
- e. Solid propellant ingredients

Many of the elastomer parts referred to are specialized items such as tires, fuel cells, flexible hose, radome rain erosion coatings, and elastomeric solid propellants with which a designer is concerned only to the extent of selecting suitable available parts or establishing performance requirements for development by others of suitable parts. Many of the other applications of elastomers, for those uses where off-the-shelf parts cannot be used, require a designer to participate in part design and development.

Part design in elastomers differs from design in other materials in that, because materials properties of elastomers are capable of variation within wide limits, relevant data on mechanical response of the specific elastomeric compound most suitable for part fabrication are not always available to the designer. Also optimum part design details and tolerances are dependent on compounding and processing variables as well as part service requirements. As a result, elastomer part development is necessarily a cooperative effort of design engineer and elastomer technologist. An example of a design procedure flow chart depicting a typical sequence of design steps leading to development of a serviceable elastomer part is presented on the following page.

The critical initial step of the preliminary design phase is the designers' consideration of elastomer parts for use in a component. Elastomer parts can seldom be substituted directly for parts made of other materials (and vice versa), and component characteristics usually depend on whether or not elastomer parts are used. The decision to reject or to use elastomer parts in component design may result in impairment of potential weapons system performance or necessary later component redesign, particularly if satisfactory elastomer parts cannot be developed for the application. A number of examples of recent design problems, with alternate solutions that were considered, illustrates the differences in resulting component characteristics involved:

(1) Sonic Fatigue Damage Prevention

   a. Elastomer coating of skin

   b. Crack arrestor banding

(2) Liquid Transfer from Reservoir at Any Flight Attitude

   a. Elastomeric expulsion bladder in spherical reservoir

   b. Piston in cylindrical reservoir

   c. Coil from reservoir with interface

(3) Equipment Vibration Control in Extreme Environment

   a. Elastomer springs

   b. Metal springs and friction elements with plastic snubbers

(4) Integral Fuel Tank Fluid Tightness

   a. Elastomeric sealants and seals with riveted construction

   b. Full seam welding

   c. Structural adhesive seam assembly with riveted construction

(5) Prevention of Chemical Attack on Missile Fuel Tank Walls

   a. Elastomer fill and drain coating

   b. Plastic tank liner

(6) Landing Gear to be Located in Area Whose Surface is Heated to Excessive Temperatures for Off-the-Shelf Pneumatic Tires

   a. Develop a heat resistant elastomer tire

b. Air condition wheel wells

c. Use "wire brush" tires or skids

(7) Shock Absorber in Extreme Environment

a. Elastomer pad

b. Hydraulic recoil cylinder

c. Metal spring and friction element with plastic snubbers

In each of these cases, the preferred solution was the first one listed, but the feasibility of this solution depended on the environmental resistance of available elastomers with suitable physical properties for the application. And, in all of these cases, prototype part development studies were required to evaluate feasibility because of lack of experience with suitable elastomers in the particular applications and environments involved. Success was achieved in excess of fifty percent of these cases with resulting improvement of weapons system characteristics.

The second important step in the design procedure is part design and performance testing. These tests must bear a close relationship to service conditions. They must measure part response required for serviceability, and test results should be carefully reviewed in order to provide correct information for part redesign in case of unsatisfactory performance of prototype.

Examples of performance tests and their results to illustrate these recommendations are:

(1) A part made of material compatible with hydrogen peroxide ignited in service as a result of reaction initiated by mold release agent on production parts. This effect had not been evaluated in the carefully cleaned prototype parts that had successfully passed performance tests.

(2) Short term tests were used to measure low temperature flexibility of collapsible fuel cell material for arctic service. This resulted in acceptance of a material that had unsatisfactory flexibility after long term storage at low temperatures.

(3) Burst test of a filament wound plastic pressure bottle designed for minimum weight resulted in premature rupture. The

elastomer liner material that was used crystallized under compression, resulting in reduction of ultimate elongation below that required. A change to a noncrystallizing elastomer produced a successful design.

The first two cases, above, demonstrate inadequate problem analysis, while the third is an example of excellent scientific analysis of a test failure that resulted in development of a superior part instead of rejection of the proposed design.

After a prototype part has proven successful in service, the final steps in design are: (1) to analyze and measure the materials properties and part characteristics of the prototype which are necessary for serviceability, (2) choose or design acceptance tests which measure these properties and characteristics, and (3) incorporate these tests into procurement specifications. The military specifications are excellent guides to choice of required materials properties, part characteristics, and methods of test.

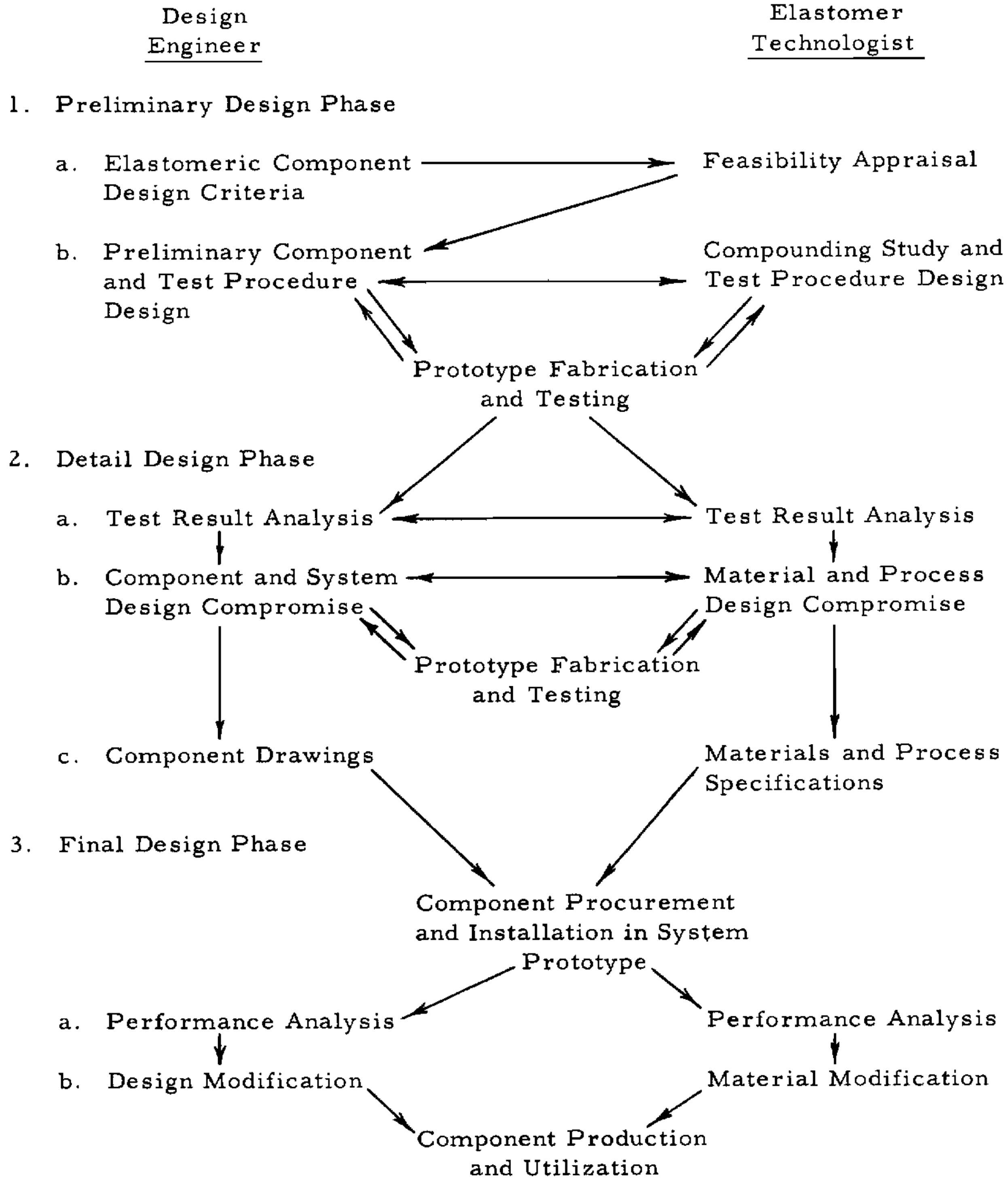
The main difference between elastomer material specifications and specifications with which the engineer is usually more familiar, is that elastomer specifications are based on required performance and not on definition of a particular elastomeric compound processed by a specified method. Wherever possible, required performance capability should be measured by standard laboratory tests, and test properties should be limited to those required by the application. Often, nonstandard part performance tests, such as cycling tests in a prescribed environment for hydraulic system parts, must be included along with the standard laboratory tests to assure part serviceability. MIL-P-25732A is an excellent example of an elastomer part specification which includes realistic performance tests, and MIL-R-25988 of an elastomeric material specification. References 19 and 25 describe a part development study and a compounding study of the types on which such specifications are usually based.

4.2 VIBRATION AND SHOCK ISOLATION AND DISSIPATION (Refs. 5, 15, 17, 74, 81, 111, 112, 113, 118, 123, 158, 170, 178, 185, 204, 205, 215, 231)

4.2.1 Vibration Analysis

Elastomer parts are usually considered as simple springs whose constants are estimated by procedures outlined in the references or measured if prototypes are available.

Flow Chart for a Vibration Isolator Design



4.2.2 Elastomer Springs (Refs. 79, 142)

The three major advantages of elastomer springs are that they can be designed: (1) as a single, simple unit to serve both as a vibration isolator and shock absorber, (2) to have desired flexibility in any direction of loading, and (3) to provide almost any desired shape of load-deflection curve. The major limitations of elastomer springs are their change of properties in service and environmental sensitivity. Table 4-1 lists comparative characteristics of different kinds of springs used as shock absorbers. Table 4-2 compares steel and elastomer springs as vibration isolators.

In aero-space weapons systems, an important use of elastomers for vibration and shock isolation is as potting compounds and pads used in electrical and electronic component assemblies. These materials also serve as sealants and seals, thermal and electrical insulators, as well as shock and vibration isolators.

The complexity of requirements of aero-space weapons systems does not usually permit the use of simple elastomer springs of the type used in vehicles or factory machinery and which can be analyzed by the methods of the references. Reference 20 provides a good example of design procedure used to develop a satisfactory part even though the unit concerned is based on a steel spring.

4.3 SEALS FOR MECHANICAL COMPONENTS (Refs. 8, 10, 16, 21, 22, 24, 25, 26, 33, 34, 56, 57, 62, 88, 94, 145, 171, 181, 189)

4.3.1 Elastomeric Static Seal or Gasket-Type Seal Capability (Ref. 160)

The elastomer seals, where environmental conditions permit their use, usually provide simpler, lighter, and smaller joint assemblies than are attainable with compression seals using other materials. Currently available materials permit the use of elastomer seals (neglecting liquid compatibility factors, see Chapter 3) as follows:

(1) Standard Military Specification O-Ring and Gasket Materials and Design Details

  a. Pressures less than 4,000 psi and greater than ordinary vacuum

  b. Temperatures less than +400°F and greater than -100°F

(2) Special Elastomeric Compounds and Design Details up to

  a. Pressures of 15,000 psi

  b. Temperatures of + 600°F

These limits are for continued serviceability and, for many limited time applications, elastomers can be used at higher temperatures and pressures as in the chamber-nozzle seals for solid propellant rockets where the nominal seal environmental temperature is in thousands of degrees for times measured in seconds. Reference 134 demonstrates how the thermal insulating properties of elastomers permit such utilization. Figures 4-1, 4-2, 4-3, and 4-4 are taken from this reference. Figure 4-5 (from Ref. 104) depicts present elastomer temperature resistance capabilities in terms of time in service as well as projection of future needs and capabilities in this regard.

4.3.2 Elastomeric Dynamic Seal or Packing Capability (Refs. 7, 124, 216)

The environmental limitations, other than liquid compatibility, on elastomers used as dynamic seals are:

(1) Standard Military Specification O-Ring and Similar Elastomer Packings

  a. Pressures less than 1500 psi and greater than ordinary vacuum

  b. Temperatures less than +275°F and greater than -65°F

(2) Special Elastomeric Compounds and Design Details up to

  a. Pressures of 4,000 psi

  b. Temperatures of +400°F

Applicable specifications for ordinary applications include:

(1) Installation and Groove Design

MIL-P-5514

(2) Hydraulic System O-Ring and Similar Seals

MIL-P-5516	-65°F to 160°F seal material
MIL-P-25732	-65°F to 275°F seal material
MIL-G-5510	compression-type seal material

(2) Fuel System O-Ring and Similar Seals

MIL-P-5315	-65°F to 160°F

Additional recommended references are a paper in Reference 11 by F. R. Straus, "Evaluation and Testing of Hydraulic O-Rings," which is a discussion of MIL-P-25732 in terms of the requirements of that specification and their basis which presents correlation between quality control properties of elastomer parts and their serviceability in the subject application; and Reference 145. The exacting requirements of dynamic seals in aerospace weapons system components are so different from those of ordinary vehicle and equipment components that the design recommendations provided in commercial manuals and handbooks should not be accepted without critical evaluation.

4.4 AIRFRAME SEALS (Refs. 19, 54, 130, 212)

4.4.1 General

The requirements of high performance aircraft, rockets and missiles, and space vehicles for access aperture, viewing port, aerodynamic and aerobalance, and intercompartment sealing have resulted in the development of two highly specialized types of elastomer parts which will be reviewed in this and the following section of the handbook by discussing such parts in terms of specific applications of these two types of parts. The airframe seal is considered typical of those seals used for closures such as are required by doors, canopies, inspection plates, firewalls, and movable controls and control surfaces. The integral fuel tank sealant (see Section 4.5) is considered typical of those elastomer parts which adhere to and, more or less, permanently seal fabrication seams, gaps, and joints.

4.4.2 Present Airframe Seal Capabilities

Composite seals are in current use on aircraft that are fluid resistant, operable at skin temperature ranges from -65°F to 400°F, and have low leakage rates. Liquid cooled inflatable seals serviceable for skin temperatures of 700°F have been developed for missile applications. These parts are usually fabric or wire reinforced and, since they must seal against pressure differentials of the order of only 15 psi, are based on hollow or foam filled units to increase conformability over that provided by a solid elastomer. The references cited in 4.4.1 provide excellent examples of current design practice.

4.5 ELASTOMERIC INTEGRAL FUEL TANK SEALANTS (Refs. 6, 14, 208, 209, 212)

4.5.1 General

The usage of sealants is not limited to integral fuel tank construction, nor are sealants used in all integral fuel tanks, but this application has been chosen as a typical use of sealants.

4.5.2 Present Fuel Tank Seal Capability

Filleting system, using a fillet of sealing compound along all seams and around fasteners:

(1) Temperatures of -65°F to 250°F with aircraft and jet fuels.

(2) Temperatures up to 500°F for pressure cabin sealant when exposure is limited to air.

Faying surface system, using a sealing material placed between metal surfaces:

(1) Temperatures of -65°F to 275°F with aircraft and jet fuels.

(2) Temperatures of -100°F to 550°F for pressure cabin sealant when exposure is limited to air.

Channel or groove sealant system, using a sealing compound injected into channel or groove:

(1) Capabilities of faying surface system.

(2) Required closer tolerance workmanship and heavier construction.

(3) Permits repair by groove reinjection.

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Memorandum No. 8, " The Effect of Nuclear Radiation on Seals, Gaskets, and Sealants."

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APPENDIX I

GLOSSARY

APPENDIX I - GLOSSARY

(See also A. S. T. M. Special Technical Publication No. 184, "Glosssary of Terms Relating to Rubber and Rubber-Like Materials.")

abrasion - the wearing away of a surface in service by mechanical action such as rubbing, scraping, or erosion.

accelerated test - (1) a test procedure in which conditions are intensified to reduce the time required to obtain a result. (2) any set of test conditions designed to reproduce in a short time the deteriorating effect obtained under normal service conditions.

accelerator - a substance which hastens the vulcanization of an elastomer causing it to take place in a shorter time or at a lower temperature.

aging - the changing of the material with time in response to its constitution and environment.

antioxidant - an organic substance which inhibits or retards oxidation.

antiozonant - a substance that retards or prevents the appearance of cracks from the action of ozone when the elastomer is exposed under tension, either statically or dynamically, to air containing ozone.

average room conditions - 40% relative humidity at a temperature of 77°F.

bench marks - the lines on tensile specimens marking gage length (q. v.).

brittle point - the highest temperature at which an elastomer fractures in a prescribed impact test procedure. See freeze resistance and transition points.

calender - a multiroll device used to form elastomer sheet to close tolerances, or to build up an elastomer ply on a sheet of other material.

coefficient of elasticity - the reciprocal of Young's modulus in a tension test.

cold flow - a synonym for set or strain relaxation.

cold resistance - a synonym for freeze resistance.

compounder's modulus - a stiffness measurement extensively used by rubber technologists and is expressed as "modulus at 300%" or "300% modulus" (any other percent elongation may be indicated, but 300% is commonly used). By this is meant the tensile stress at the indicated elongation (see modulus).

compression modulus - the ratio of the compressive stress to the resulting compressive strain (the latter expressed as a fraction of the original height or thickness in the direction of the force). Compression modulus may be either static or dynamic.

compression set - the deformation which remains in rubber after it has been subjected to and released from a specific compressive stress or strain for a definite period of time at a prescribed temperature. Compression set measurements are for the purpose of evaluating creep and stress relaxation properties of rubber.

concavity factor - rubber has no elastic limit, and the entire stress-strain curve is concave toward the stress axis or away from the strain axis. The relative amount that rubber varies from the Hooke's law ideal curve is known as "concavity factor" determined as the ratio between the energy of the extension curve to the straight line curve to the same point. It may be expressed as:

$$\frac{\text{proof resilience}}{1/2 \ \text{tensile product}}$$

conditioning - subjecting a material to a prescribed environmental and/or stress history prior to testing.

creep - the increase in deformation after initial deformation under sustained constant load.

crystallization - a change in physical properties resulting from crystalline orientation of molecular segments caused by temperature and stress.

cure - a synonym for vulcanization.

damping - the decay with time of the amplitude of free vibrations of a specimen (see hysteresis).

deformation - any change of form or shape in a body; (in this report) the linear change of dimension of a body in a given direction produced by the action of external forces.

diluent - an inert powdered substance added to an elastomer to increase its volume.

drift - a synonym for set; also change in durometer reading with time.

dynamic fatigue - part failure under cyclic loading analogous to fatigue in metals testing.

dynamic modulus - the ratio of stress to strain under vibratory conditions. It is calculated from data obtained from either free or forced vibration tests, in shear, compression, or elongation. It is usually expressed in psi for unit strain.

dynamic resilience - the percentage of the vibrational energy which persists in the second of two successive free vibrations.

elongation - the deformation of the gage length in a tensile test, expressed as a percentage of the original gage length.

extruder - a screw fed die which produces a continuous strip which can be of intricate cross section.

filler - a material added in substantial volume to alter end item properties.

flexing - the repeated distortion of a material by bending, extending or compressing forces or combinations of them.

flex resistance - the fatigue life of a material tested in a flexing machine according to a prescribed procedure.

freeze resistance - the resistance to the effect of low temperatures of a specimen subjected to flexure, torsion or impact according to prescribed test procedures. Freezing is a time dependent phenomenon in that prolonged exposure to low temperatures results in increase in freezing point and brittle point as well as increased stiffness. See transition points.

freezing point - the temperature at which a specimen exhibits a sudden increase in stiffness as it is slowly cooled. See freeze resistance and transition points.

gage length - (in this report) length over which deformation is measured.

growth - the increase in dimension of an article resulting from a continued tensile stress being applied to the material during service.

hardness - the resistance to surface indentation usually measured by the depth of penetration (or arbitrary units related to depth of penetration) of a blunt point under a given load using a particular instrument according to a prescribed procedure.

heat build up - the temperature rise in a part resulting from dissipation of applied strain energy as heat. See hysteresis.

heat resistance - the property or ability of elastomers to resist the deteriorating effects of elevated temperatures.

hot tensile - tensile strength at 212°F.

hysteresis - the percent energy loss per cycle of deformation or the ratio of the energy absorbed to the total energy input.

immediate set - the deformation found by measurement immediately after the removal of the load causing the deformation.

inert filler or pigment - a material added in substantial volume to alter end item properties.

Joule effect - the heating of an elastomer when it is elongated adiabatically and the contracting of elongated elastomers when heated.

memory - the after-effect response of a material to an event which, superimposed on the response to a later event, alters the behavior of the material from that which would result from response to the later event alone.

modulus - (1) a coefficient of numerical measure of a property, (2) for elastomers, modulus usually refers to one of several measurements of stiffness or resistance to deformation. The use of the word without modifying terms may be confusing, and such use should not be encouraged. Modulus of elastomers may be either static or dynamic; static moduli are subdivided into tangent, chord, and compounder's. Compounder's modulus is always in tension, but all the others may be in shear, compression, or tension. Other terms used in connection with modulus are stiffness; rigidity; Young's; tangent; elongation.

modulus (cont'd) - (3) all elastic moduli in rubber (except compounder's) are ratios of stress to the strain produced by that stress; the strain is expressed fractionally; the units of the modulus are the same as those for the stress, usually psi.

modulus at 300% (or other % elongation) - the tensile stress at the indicated elongation. (Also see compounder's modulus.)

mold - a form or matrix used to shape elastomers while in a fluid or plastic condition.

oil resistance - the ability to withstand contact with an oil without deterioration of physical properties, or geometric change to a degree, which would impair part performance.

permanent set - (1) permanent set is the deformation remaining after a specimen has been stressed in tension a prescribed amount for a definite period and released for a definite period. (2) for creep tests, permanent set is the residual unrecoverable deformation after the load causing the creep has been removed for a substantial and definite period of time.

plasticizer - a substance added to an elastomer to decrease stiffness or improve low temperature properties, thus improving processing properties and altering end item properties.

proof resilience - the tensile energy capacity of work required to stretch an elastomer from zero elongation to the breaking point expressed in foot-pounds per cubic inch of original dimension.

reinforcing pigment or agent - a finely divided filler substance which, when properly dispersed in an elastomer, stiffens or produces improved physical properties in the vulcanized product (also see Section 1. 4. 2).

relaxation - decrease in stress under sustained constant strain or creep and rupture under constant load.

relaxation time - the time required for a stress under a sustained constant strain to diminish to (1/e) of its initial value.

resilience - the ratio of energy returned on recovery from deformation to the work input required to produce the deformation usually expressed as a percentage.

rigidity - a synonym for stiffness.

room temperature vulcanization (R.T.V.) - vulcanization by chemical reaction at room temperature.

set - irrecoverable deformation or creep usually measured by a prescribed test procedure and expressed as a percentage of original dimension.

set at break - elongation measured ten minutes after rupture on reassembled tension specimen.

shape factor - the distortional behavior of an elastomeric component depends upon exterior constraints and for elastomers in compression this is accounted for by using an empirical function called shape factor.

shear modulus - the ratio of the shear stress to the resulting shear strain (the latter expressed as a fraction of the original thickness of the rubber measured at right angles to the force). Shear modulus may be either static or dynamic.

shelf-aging - the change in materials properties which occurs in storage.

spring constant - the number of pounds required to compress a specimen one inch in a prescribed test procedure.

standard laboratory atmosphere - whenever the materials to be tested are known to be sensitive to variations in temperature or moisture, or both, the tests shall be conducted in a room or chamber of controlled humidity and temperature. Unless otherwise specified, the tests shall be made in the standard laboratory atmosphere having a relative humidity of 50 ± 2% at a temperature of 23 ± 1°C (73 4 ± 1.8°F).

average room conditions - 40% relative humidity at a temperature of 77°F.
dry room conditions - 15% relative humidity at a temperature of 85°F.
moist room conditions - 75% relative humidity at a temperature of 77°F.

static fatigue - part failure under a continued static load, analogous to creep-rupture failure in metals testing, but often the result of aging accelerated by stress.

static modulus - the ratio of stress to strain under static conditions. It it calculated from static stress-strain tests, in shear, compression, or tension. It is expressed in psi unit strain.

stiffness - the relationship of load and deformation. A term often used when the relationship of stress to strain doesnot conform to the definition of Young's modulus. See stress-strain.

strain - a synonym for elongation. In this report, the term is used as a synonym for deformation or to mean a deformation divided by gage length.

strain relaxation - a synonym for creep.

stress - a synonym for tensile stress. In this report, the term is used to mean internal force per unit of area which resists a change in size or shape of the body.

stress decay - a synonym for stress relaxation.

stress relaxation - the decrease in stress under sustained constant strain.

stress-strain - a synonym for stiffness usually expressed in pounds per square inch or kilograms per square centimeter at a given strain.

subpermanent set - strain retained at the end of a finite interval following release of stress.

T-10, T-50 - the temperatures at which a specimen which has been elongated, frozen, unloaded, and slowly heated recovers, respectively, one-tenth and one-half of initial elongation.

tangent modulus - the slope of the line at any point on a static stress-strain curve expressed in psi per unit strain represents the tangent modulus at that point in shear, extension, or compression as the case may be.

tear resistance - the force required to tear completely across a notched specimen tested according to prescribed procedures expressed in pounds per inch of specimen thickness.

tensile product - the product of tensile strength and elongation at break, usually divided by 10,000, or the product of tensile strength and gage length plus deformation at break. The latter definition is an approximation (assuming no volumetric change) to actual rupture stress.

tensile strength - nominal stress at rupture (based on original cross-section area).

tensile stress - a synonym for modulus.

tensile pull - failure load in a tension test usually restricted to part testing where the term tensile strength is not applicable.

tension modulus - the ratio of the tension stress to the resulting tension strain (the latter expressed as a fraction of the original length). Tension modulus may be either static or dynamic.

transition points - the elastomeric behavior of certain high polymers is considered to be the phenomenological manifestation of thermal micro-Brownian movements consisting of vibrations and rotations executed by molecular segments. These movements decrease with temperature so that a curve of, for example, stiffness vs temperature for rubber exhibits two transition points (or abrupt changes in slope). The transition point of highest temperature is called first order transition or freezing point and is the temperature below which the elastomer is hard and stiff but not necessarily brittle. The lowest temperature point is called the glass or second order transition point and is the temperature below which the material is glass-like in behavior. The gradual disappearance of the rubber-like state and changes in other physical properties of this class of materials, as measured during cooling, is a function of a great many variables in the composition and service history of these complex materials as well as of test procedure. Thus, the actual published values of transition temperature for the various elastomers furnish only a first approximation to the low temperature limit of useful properties for elastomers, and the actual service conditions must be considered in determining the effect of low environment temperature on component performance.

ultimate elongation - the elongation at rupture.

vulcanization - the process of creating a useful elastomeric material from basic compounding ingredients by heating the mixture with sulfur, or by other chemical reactions, which result in changes in materials properties.

APPENDIX II

CONVENTIONAL ELASTOMER PART MANUFACTURING PROCESSES

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The basic process of elastomer technology is the conversion of a plastic high polymer (raw gum) into an elastomer by vulcanization. It is necessary to include in the processing operations the mixing of the compounding materials required to provide desired end item properties and the forming of the material to proper shape and dimensions.

Compounding materials may be classified as:

Raw Elastomer

Vulcanizing Agent - a material which produces vulcanization of the elastomer.

Vulcanizing Accelerator - a substance which hastens the vulcanization of an elastomer, causing it to take place in a shorter time or at a lower temperature. Most accelerators enhance physical properties and many improve age resistance.

Accelerator Control - a material which activates the accelerator, retards vulcanization during processing without decreasing activity under vulcanizing conditions, or otherwise modifies accelerator action.

Protective Ingredients - materials which improve specific resistance properties of the elastomer. Examples of these materials are:

Antioxidant - an organic substance which inhibits or retards oxidation.

Antiozonant - a substance that retards or prevents the appearance of cracks from the action of ozone when the elastomer is exposed under tension, either statically or dynamically, to air containing ozone.

Antirad - a material which inhibits radiation damage.

Fillers - materials added in substantial volume to alter end item properties. Examples of these materials are:

Reinforcing Pigment or Agent - a finely divided substance which, when properly dispersed in an elastomer, stiffens or produces improved physical properties in the vulcanized product.

Diluent - an inert powdered substance added to an elastomer to increase its volume.

Plasticizer - a substance added to an elastomer to decrease stiffness or improve low-temperature properties, thus improving processing properties and altering end item properties.

Special Purpose Ingredients such as colorants and blowing agents to make foam.

The mixing of compounding materials may be accomplished on open-roll mills or internal mixers. The open-roll mill uses rolls turning at different speeds and the internal mixers are blade-type (Banbury) or screw-type (Gordon plasticator). An essential part of the mixing process is the working of the raw elastomer into a soft, plastic state by mechanical breakdown, plasticization, and heat so that the other compounding materials can be properly blended into it without premature vulcanization occurring while the compound is in process. This requirement sometimes limits the compounding materials which can be used and end item properties which can be attained. Variations in mixing equipment and technique often cause variations in end item properties and an important part of the compounder's task is to develop a time, temperature and order-of-addition schedule for the mixing process. The product of the mixing operation may be slabs as cut off of open-roll mill, continuous strip from a mixer fed mill, pellets or continuous strip from an extruder. This stock is cooled and stored or continued in process

Forming of the elastomer is usually accomplished with special equipment including.

Calender - a multiroll device used to form elastomer sheet to close tolerances or to build up an elastomer ply on a sheet of other material.

Extruder - a screw fed die which produces continuous strip which can be of intricate cross section.

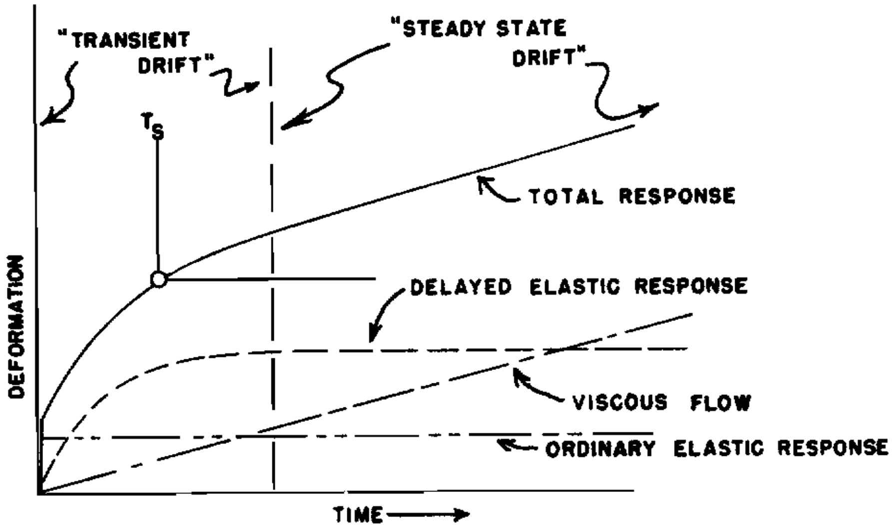
Mold - a form or matrix used to shape elastomers while in a liquid or plastic condition.

Complex parts may be built up by the assembly of individual pieces of raw elastomeric material formed by the aforementioned types of equipment when the elastomer possesses adequate building tack (the characteristic of coalescing of surfaces when stuck together).

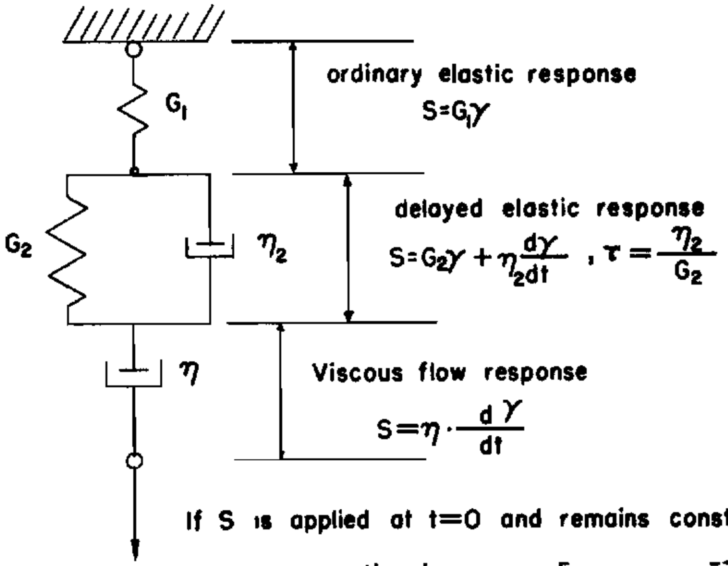
Vulcanization of the elastomer is usually induced and accelerated by heat although it is also accomplished at room temperature and by high energy radiation. Vulcanization is performed after calendering or extrusion and simultaneously with molding.

Post vulcanization operations may include die cutting, lathe cutting, machining, or other finishing operations such as trimming or cold tumbling to remove mold flash.

ILLUSTRATIONS



Simplest Mechanical Model for Creep Curve



If S is applied at $t=0$ and remains constant, the response equation is $\gamma = S\left[\frac{1}{G_1}+\frac{1}{G_2}\left(1-\epsilon^{-\frac{t}{\tau}}\right)+\frac{1}{\eta_3}t\right]$

FIGURE 2-1 (2.2.1). TYPICAL CREEP CURVE - INSTANTANEOUS LOADING AT TIME = 0 (SwRI AND REFS. 27, 125, 147)

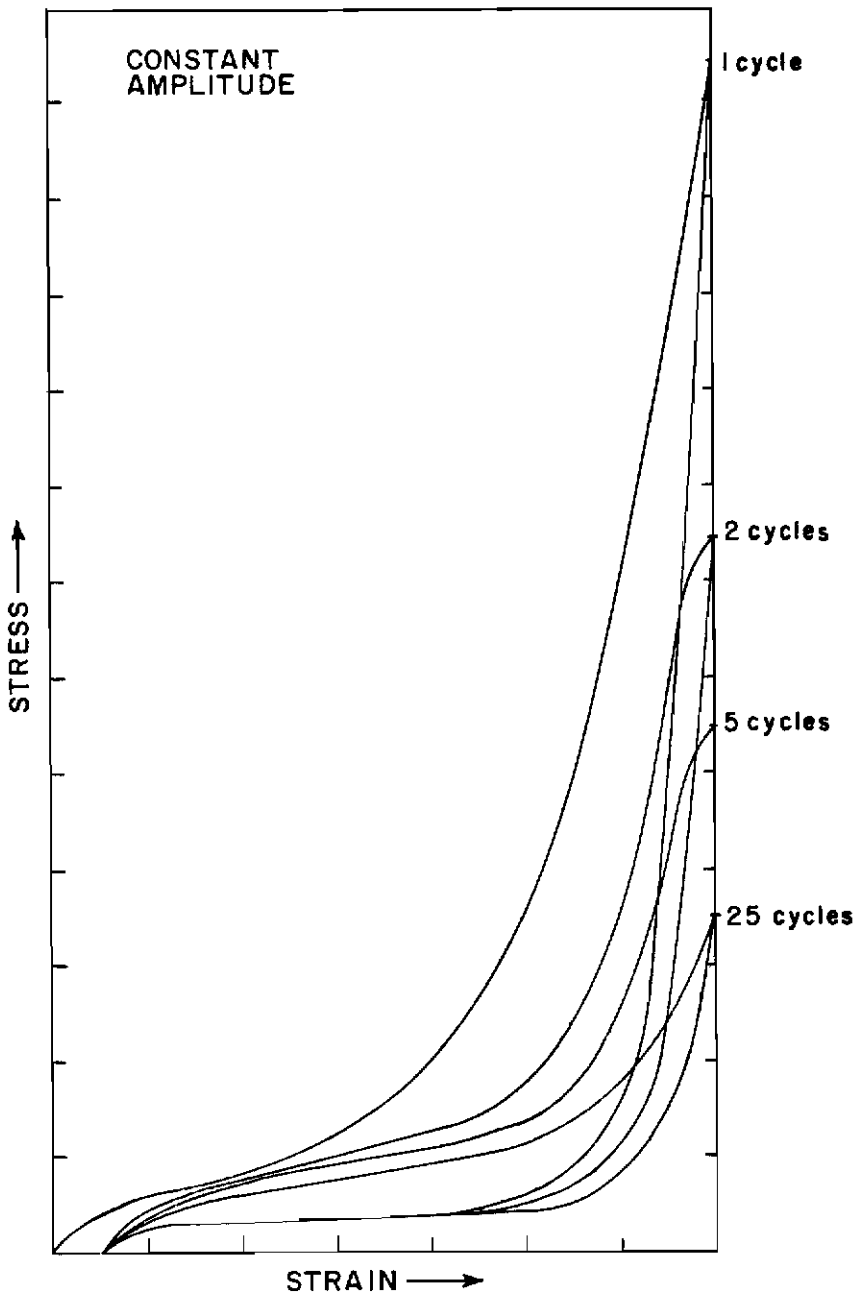


FIGURE 2-2 (2.2.1). REPEATED STRESS-STRAIN CURVES FOR A NATURAL RUBBER (SwRI)

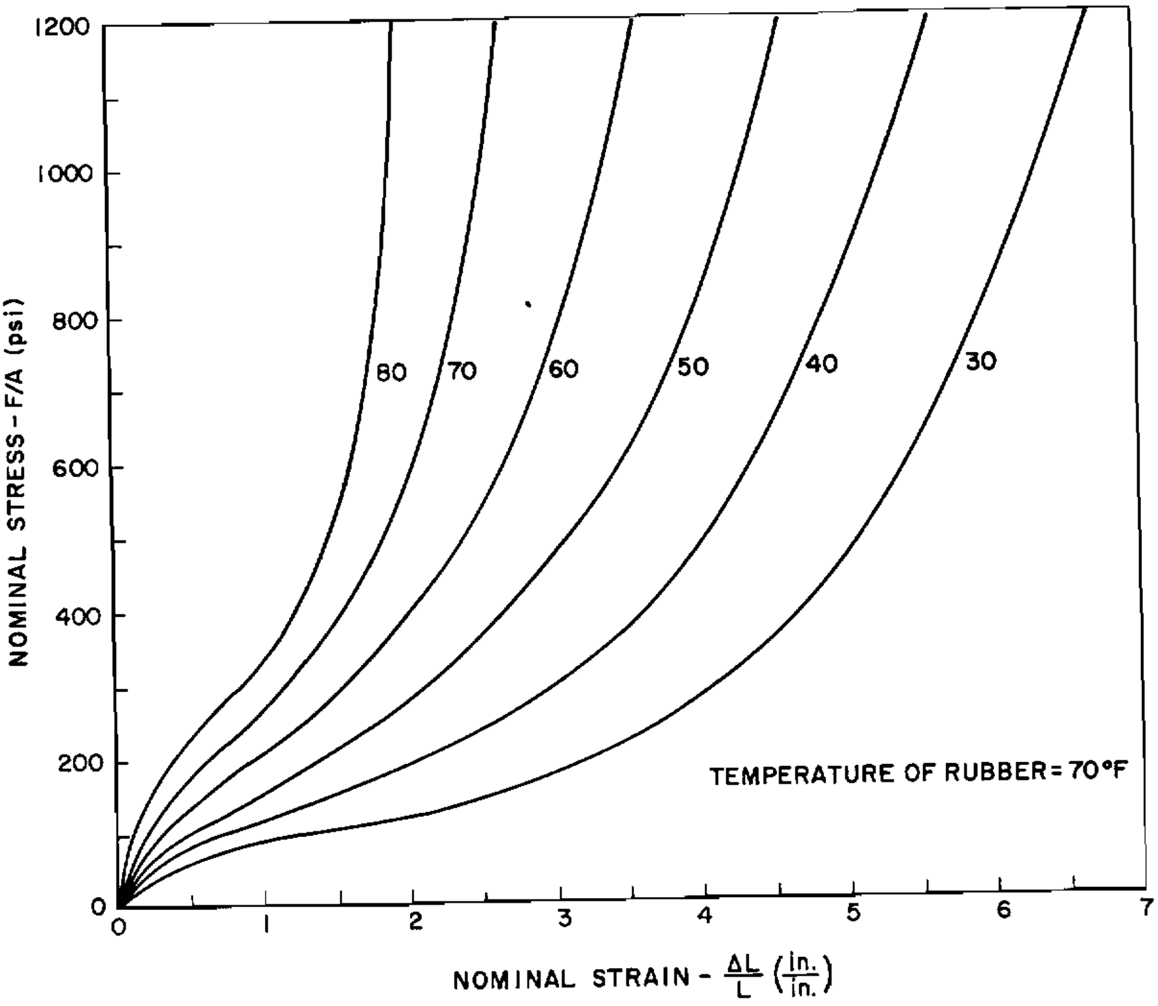


FIGURE 2-3 (2.2.1). EQUILIBRIUM TENSILE STRESS-STRAIN CURVES FOR A DUROMETER SERIES OF NATURAL RUBBER (REF. 48)

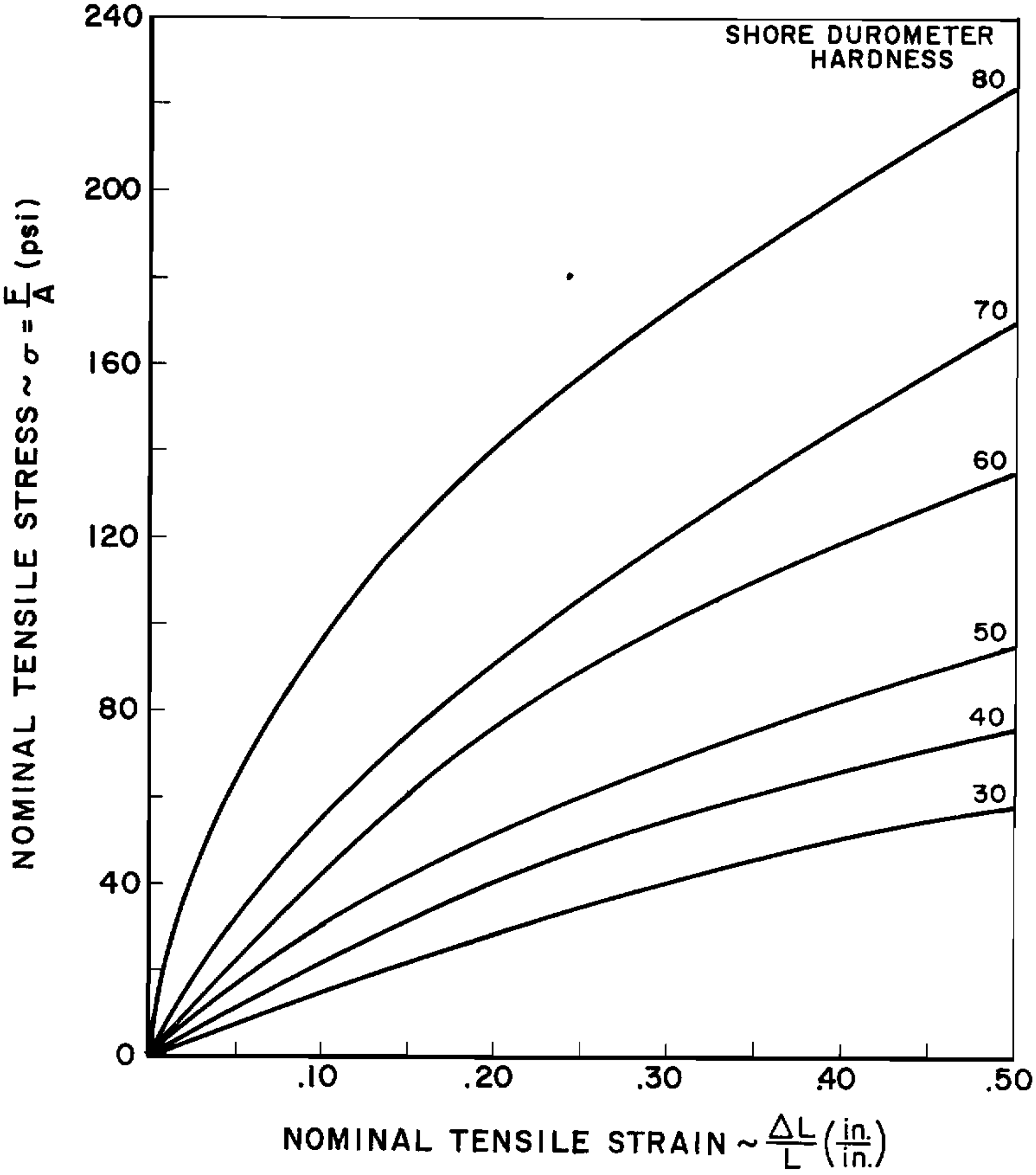


FIGURE 2-4 (2.2.1). SMALL STRAIN PORTION OF FIGURE 2-3 (REF. 48)

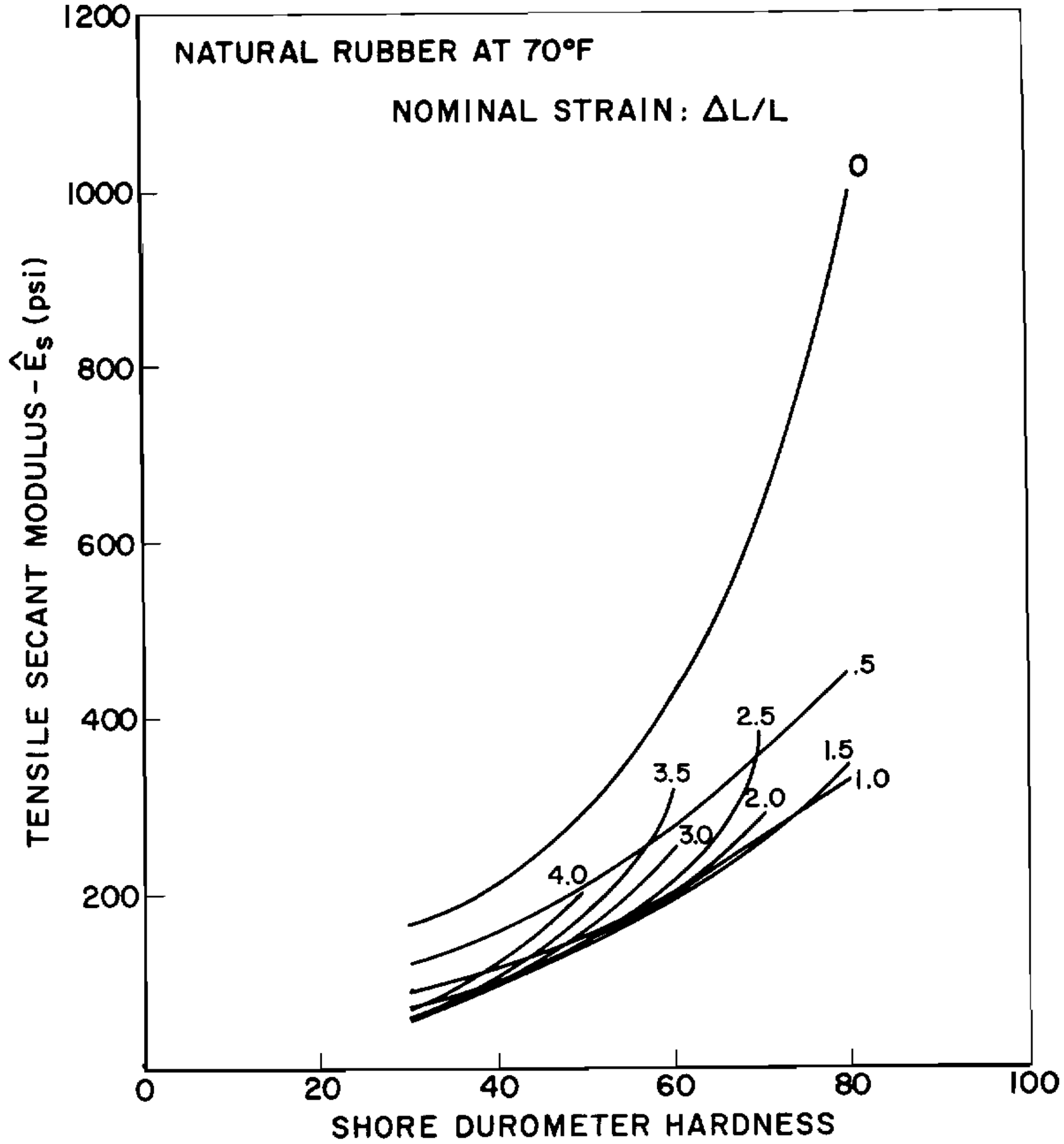


FIGURE 2-5 (2.2.1). SECANT MODULI VALUES DERIVED FROM FIGURE 2-3 (SwRI)

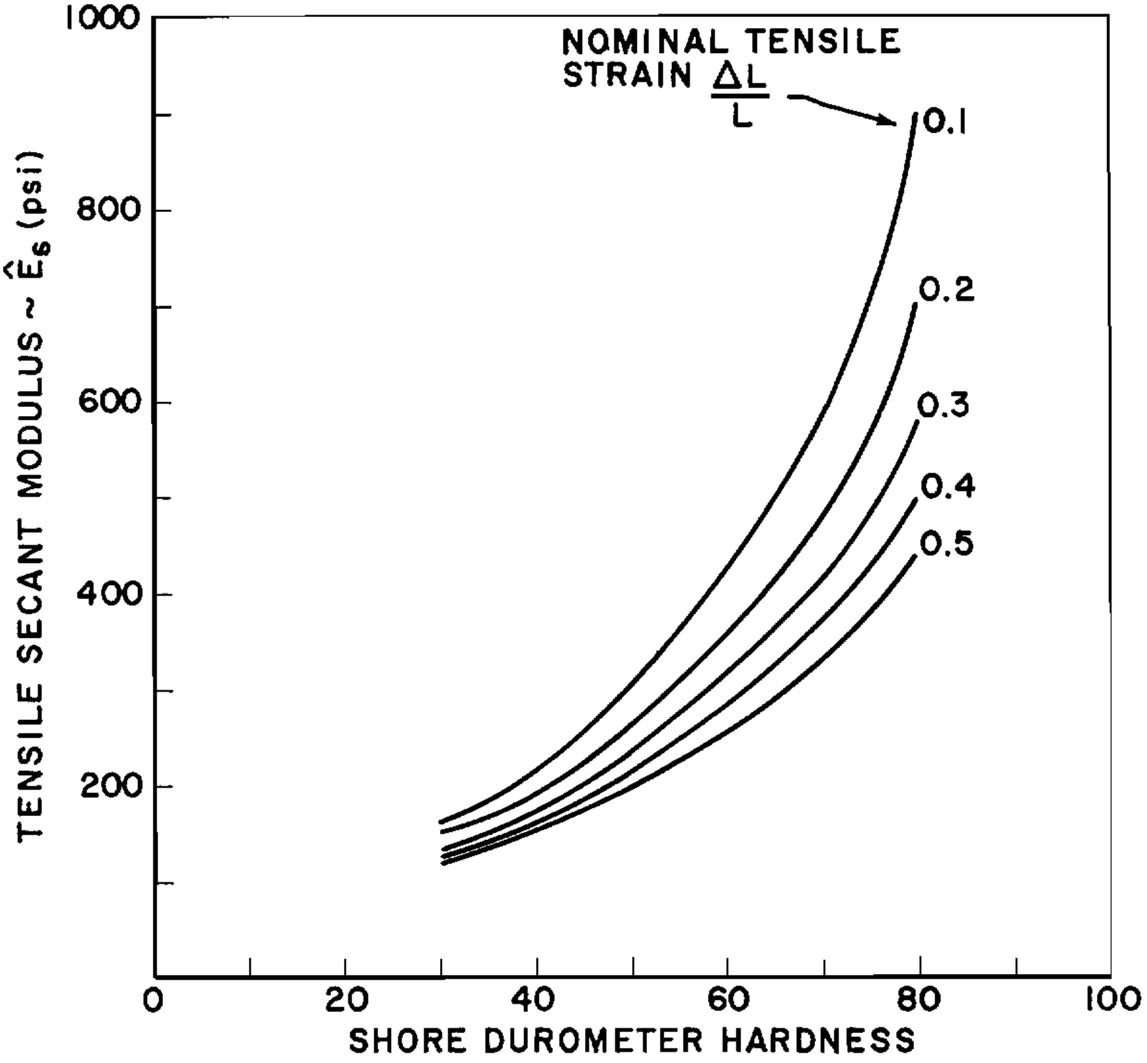


FIGURE 2-6 (2.2.1). SECANT MODULI VALUES DERIVED FROM FIGURE 2-4 (SwRI)

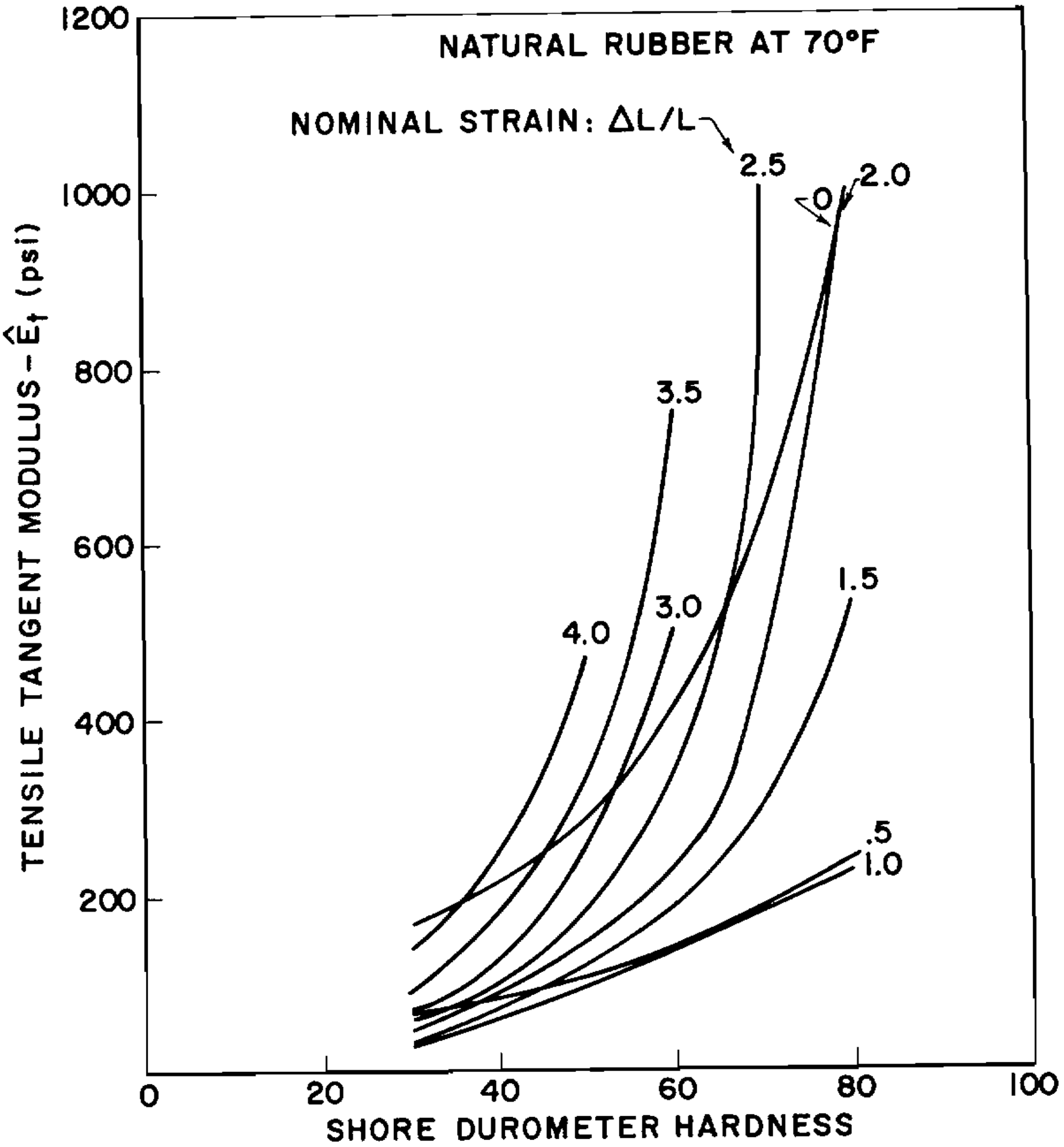


FIGURE 2-7 (2.2.1). TANGENT MODULI VALUES DERIVED FROM FIGURE 2-3 (SwRI)

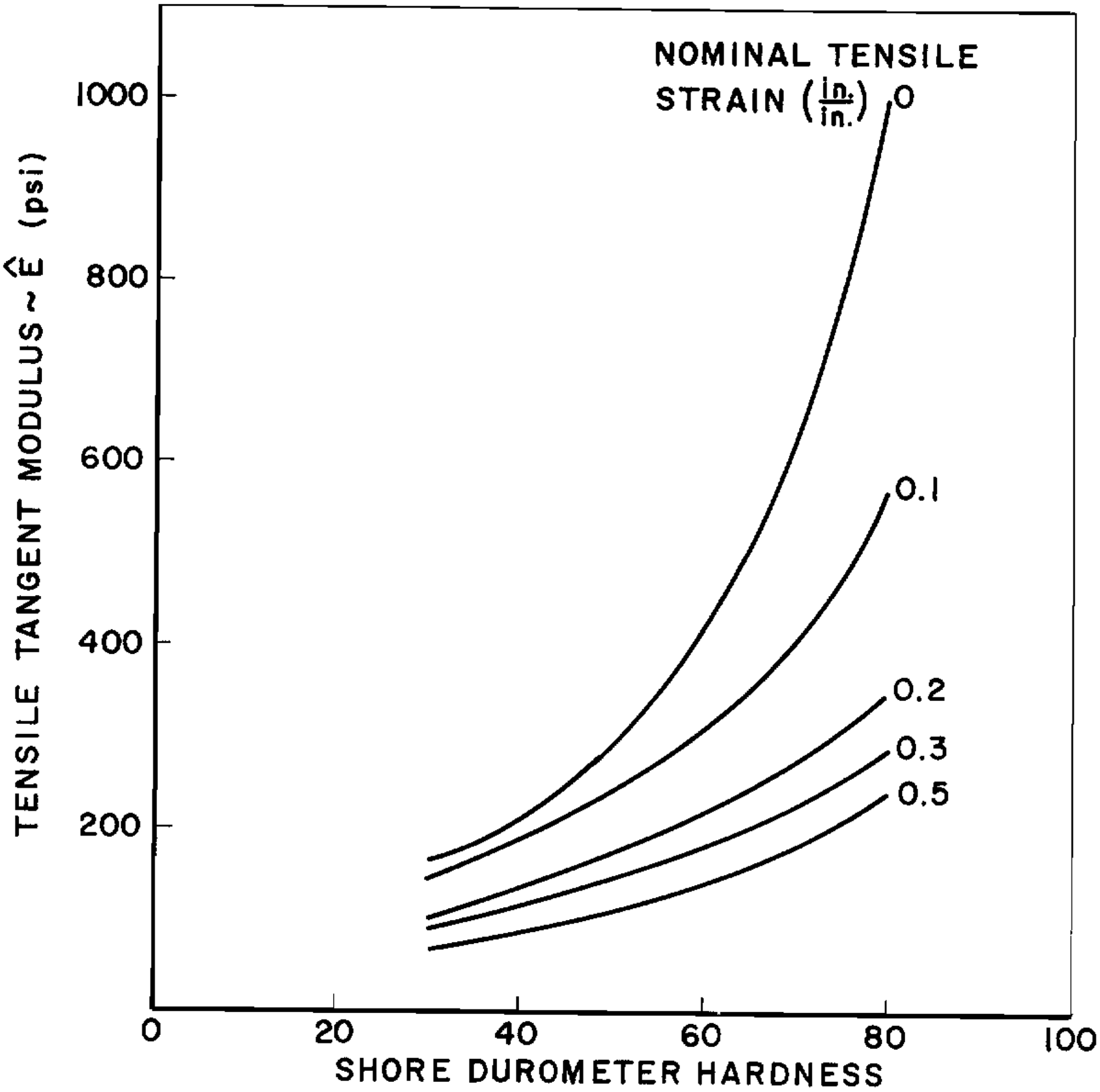


FIGURE 2-8 (2.2.1). TANGENT MODULI VALUES DERIVED FROM FIGURE 2-4 (SwRI)

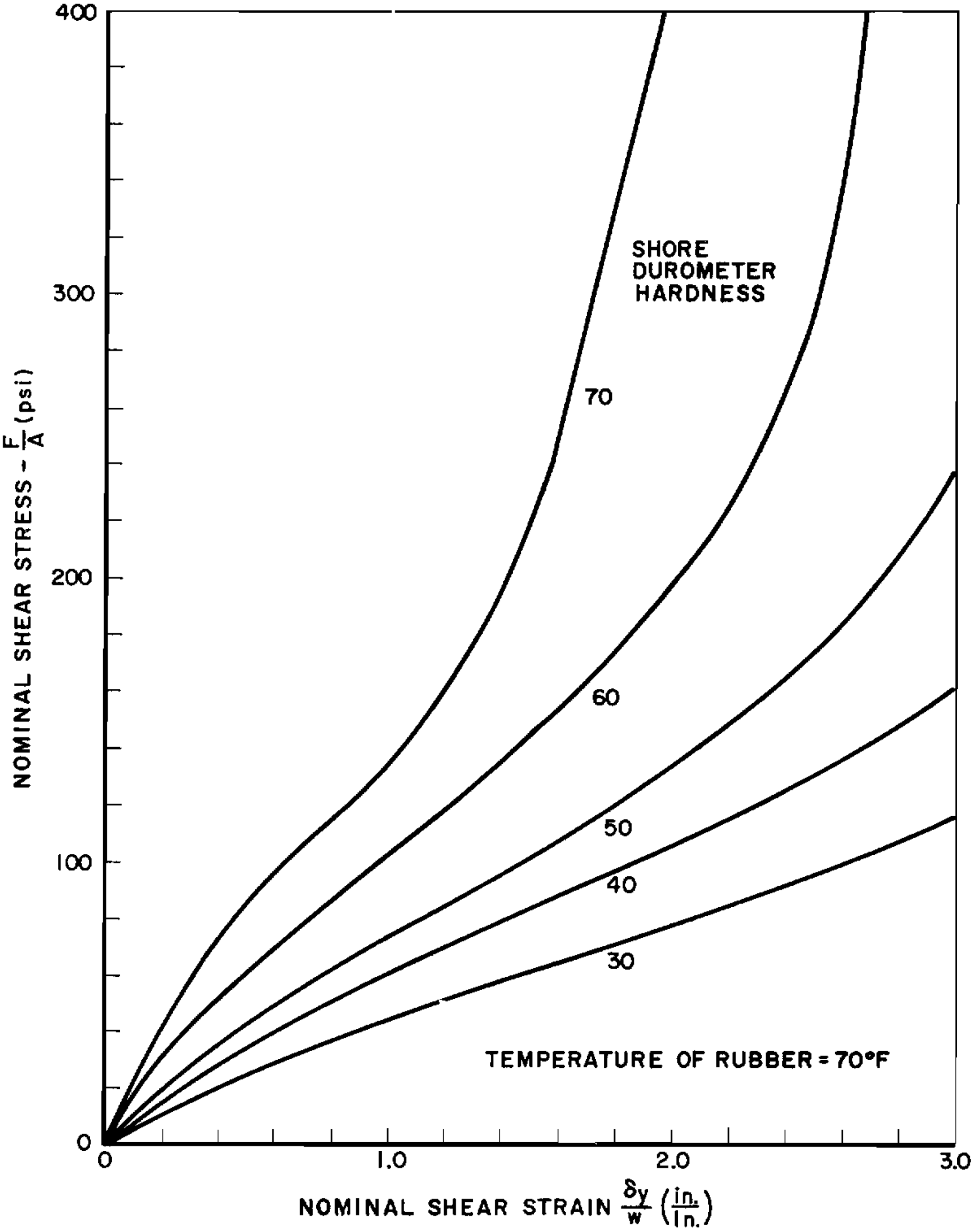


FIGURE 2-9 (2.2.1). EQUILIBRIUM SHEAR STRESS-STRAIN CURVES FOR THE COMPOUNDS OF FIGURE 2-3 (REF. 48)

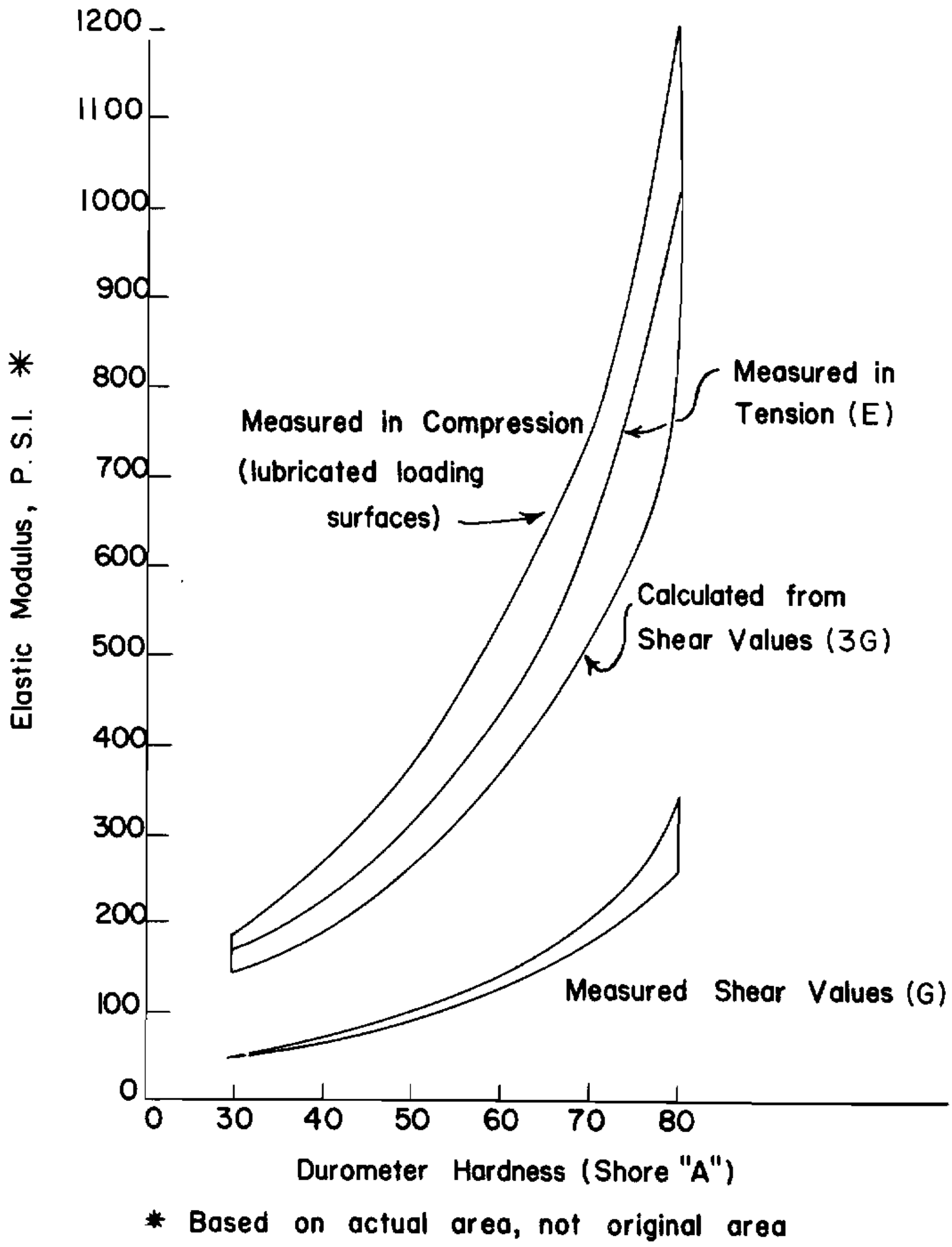


FIGURE 2-10 (2.2.1). SCATTERBANDS OF VALUES OF ELASTIC MODULI VERSUS DUROMETER (SwRI)

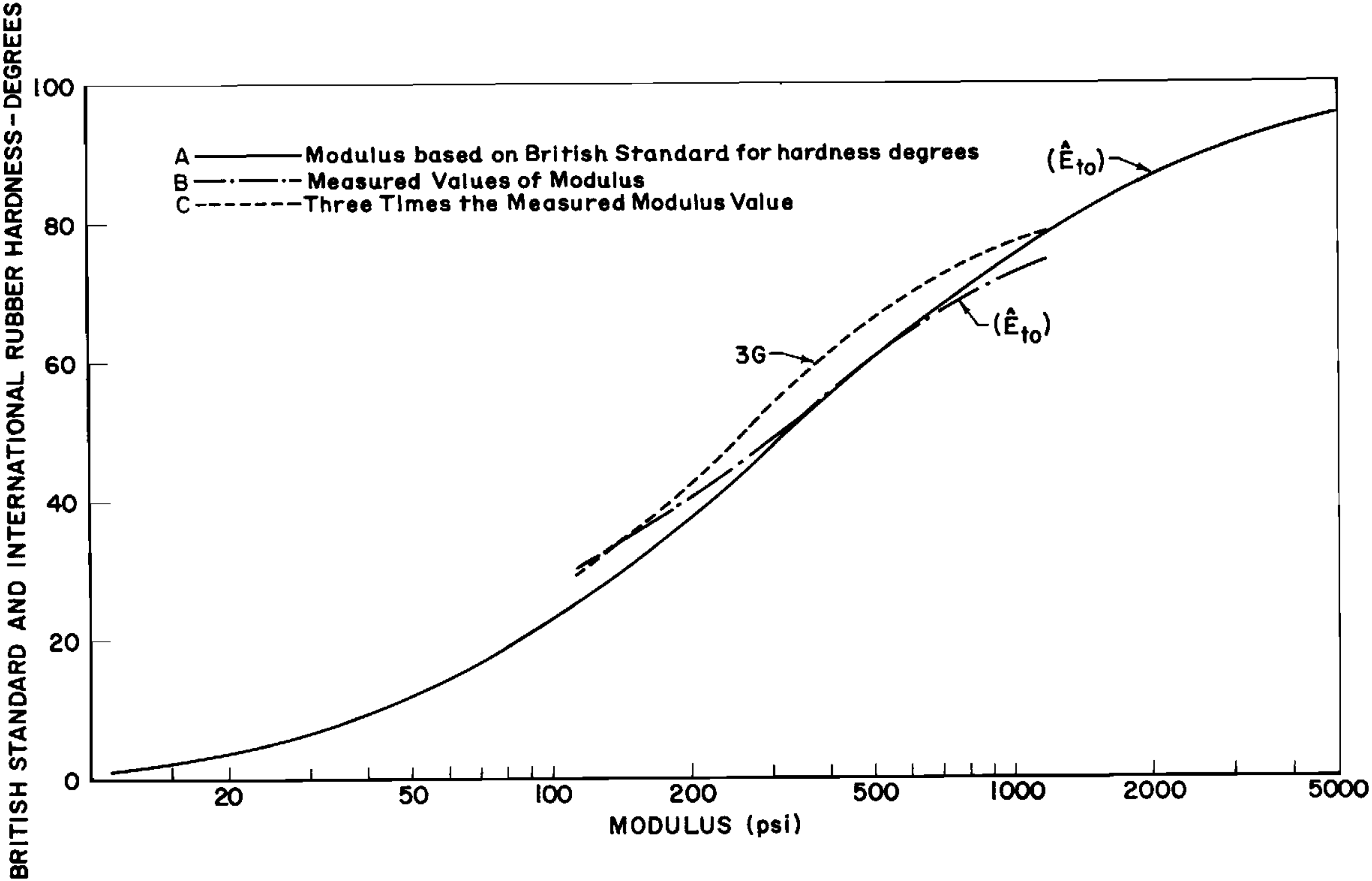
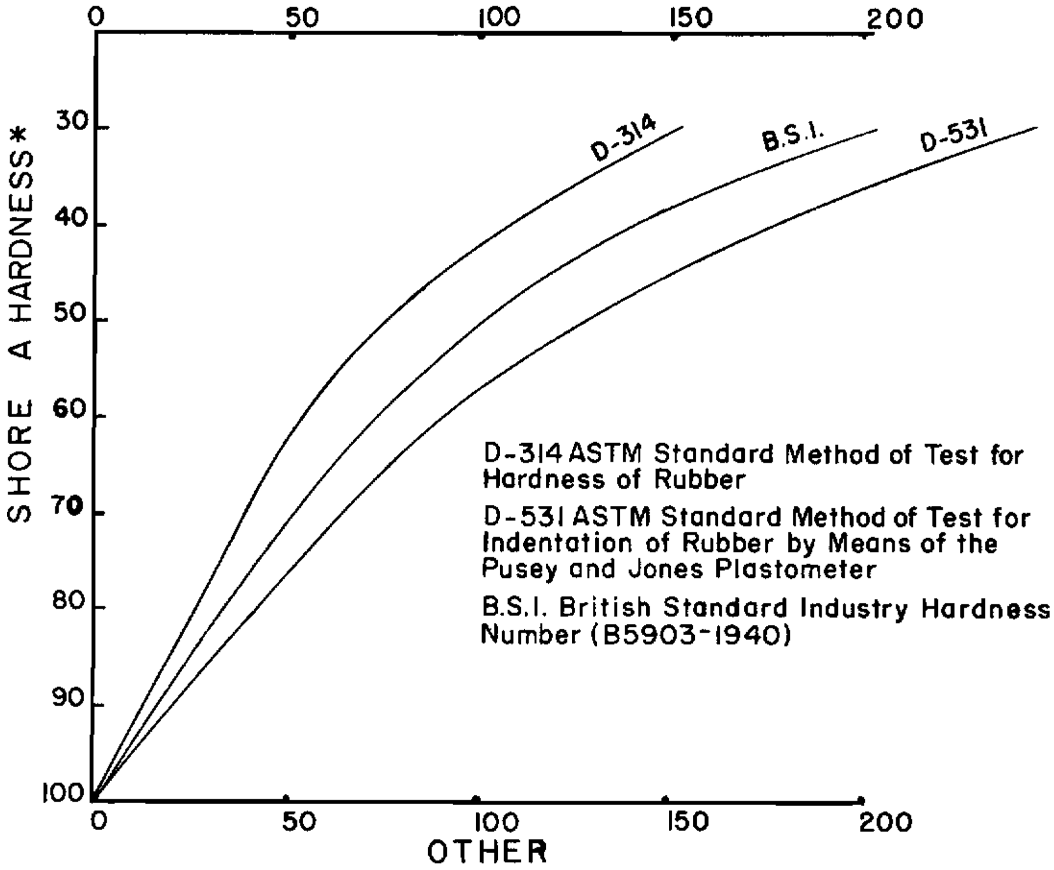


FIGURE 2-11 (2.2.1). CORRELATION CURVE BETWEEN YOUNG'S MODULUS AND BRITISH STANDARD DEGREES (≅ SHORE A POINTS) (SwRI)



*Shore A Hardness ≅ British Standard Degrees >30 Degrees International Rubber Hardness Degrees

FIGURE 2-12 (2.2.1). CONVERSION GRAPH FOR HARDNESS READINGS (SwRI)

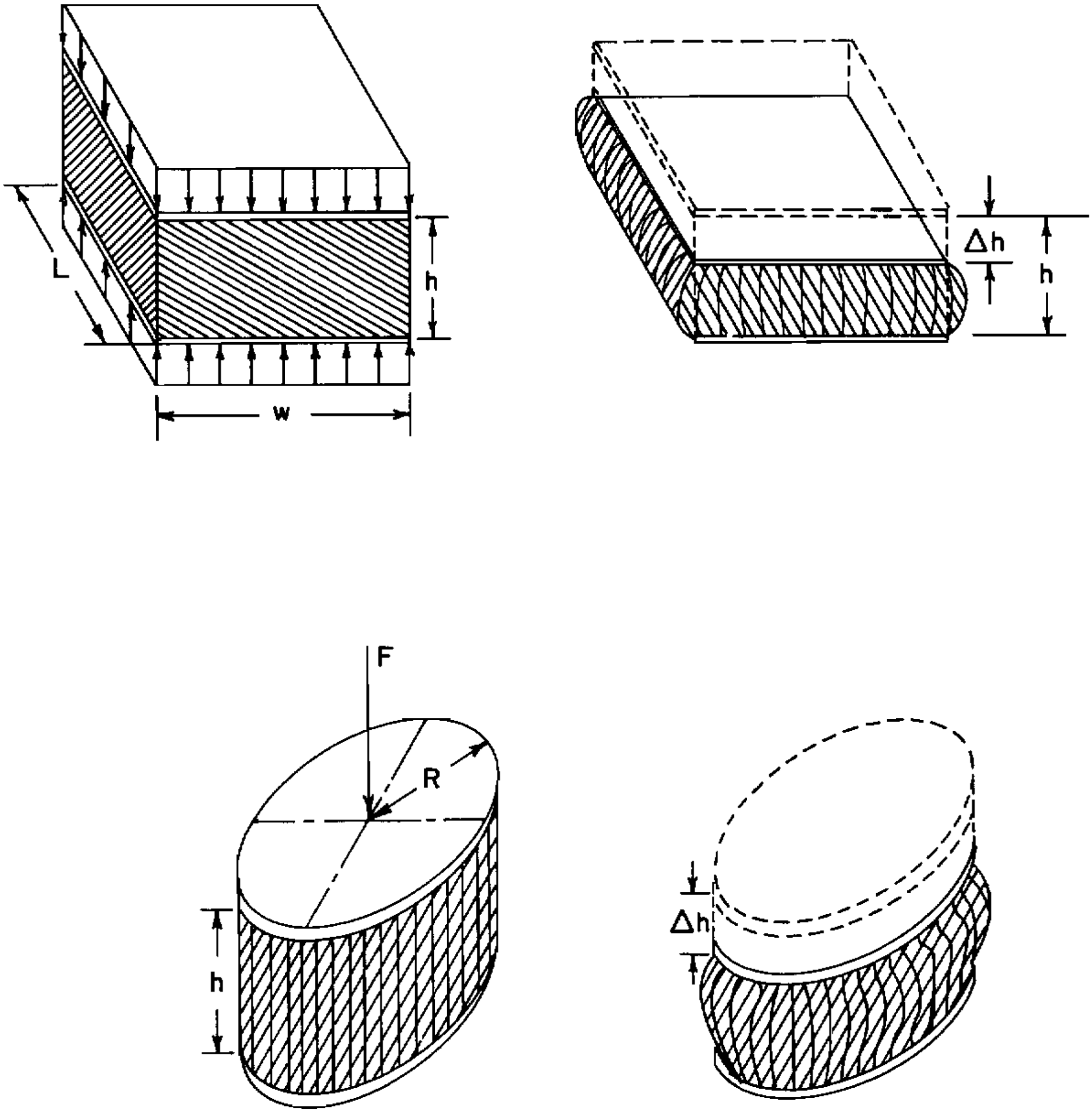
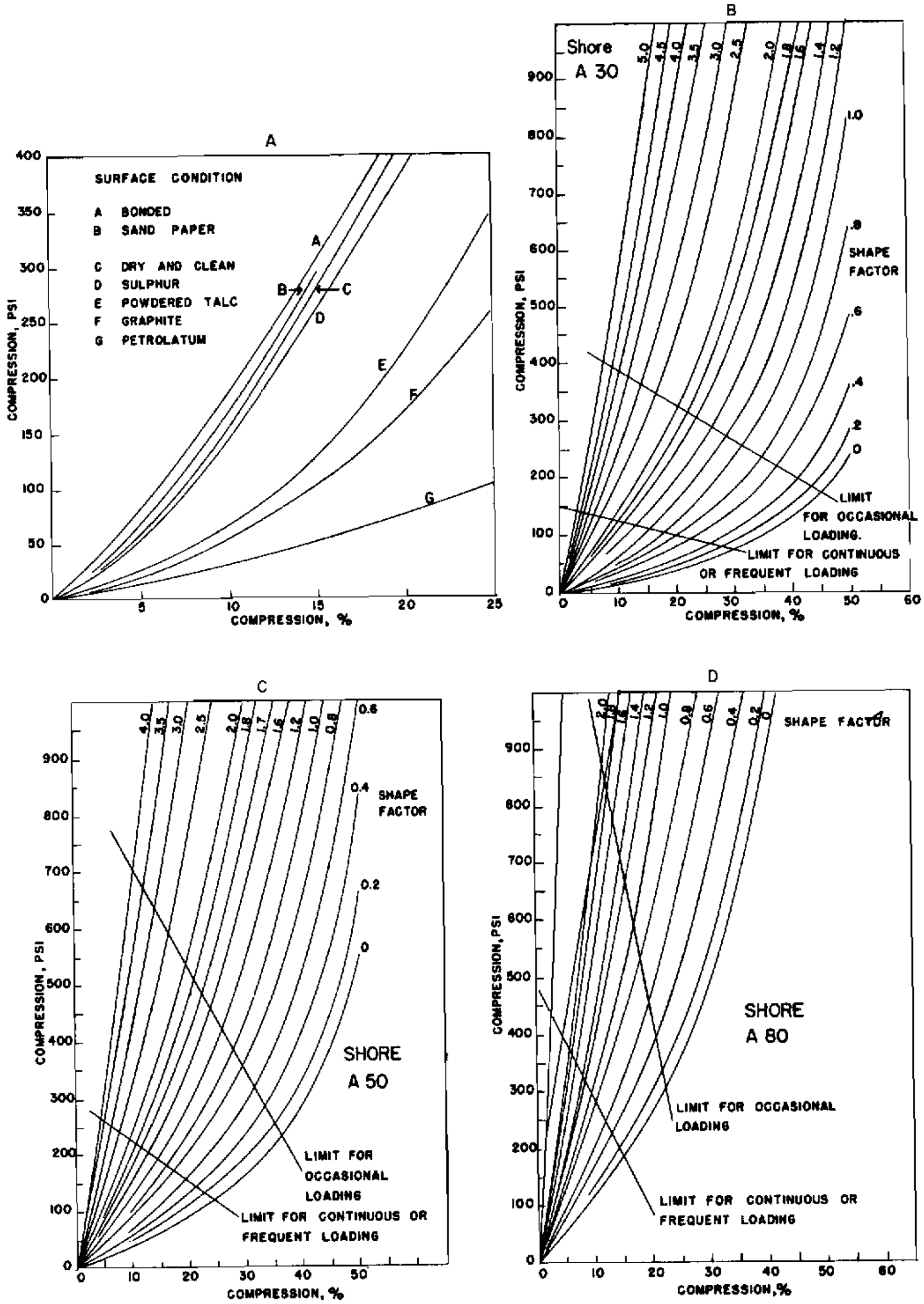


FIGURE 2-13 (2.2.1). BONDED SANDWICH UNITS LOADED IN COMPRESSION (SwRI)



NOTE: SHAPE FACTOR $= \frac{\text{area of one loaded face}}{\text{area of free surface}}$

i.e. $S = \frac{ab}{2t(a+b)}$

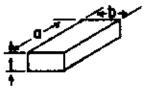
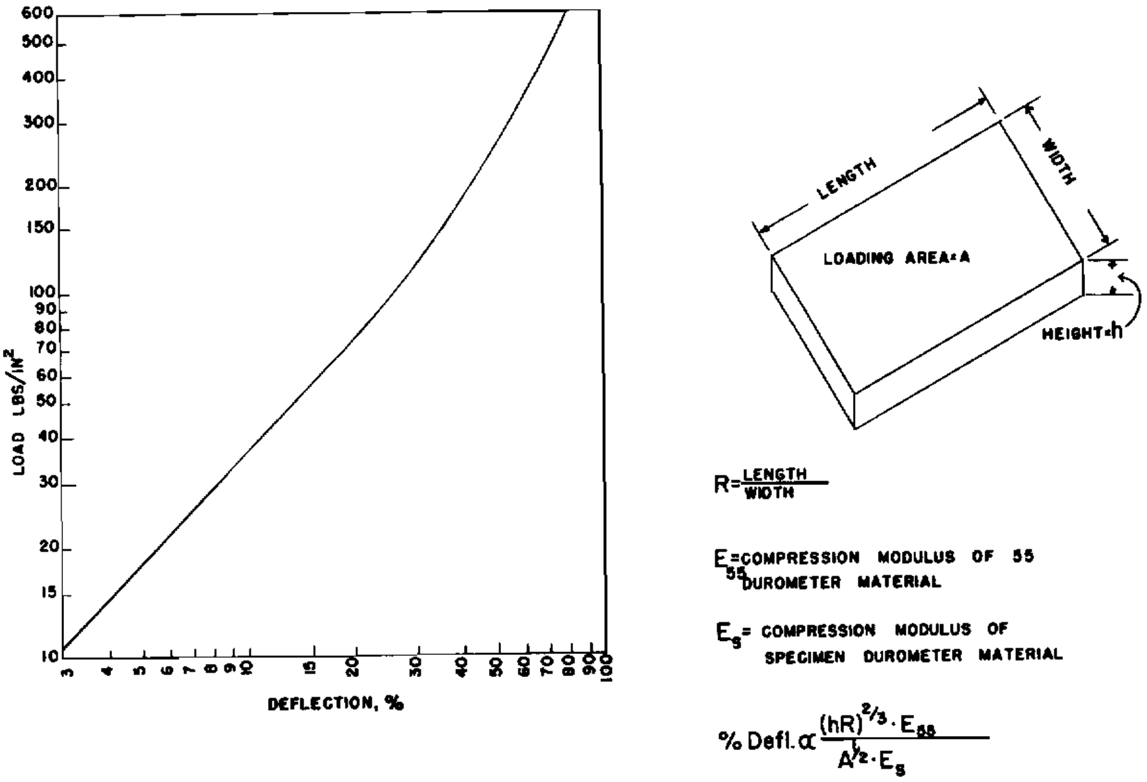


FIGURE 2-14 (2.2.1). EFFECT OF SURFACE CONDITIONS ON THE DEFLECTION OF RUBBER IN COMPRESSION AND COMPRESSION STRESS-STRAIN CURVES FOR 30, 50 AND 80 DUROMETER SPECIMENS (REF. 152)



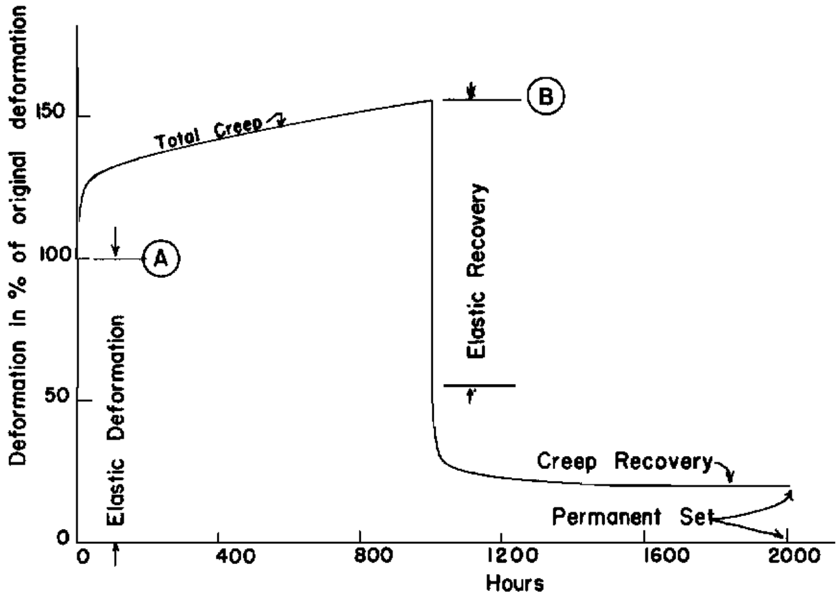
$R = \frac{\text{LENGTH}}{\text{WIDTH}}$

E_{55} = COMPRESSION MODULUS OF 55 DUROMETER MATERIAL

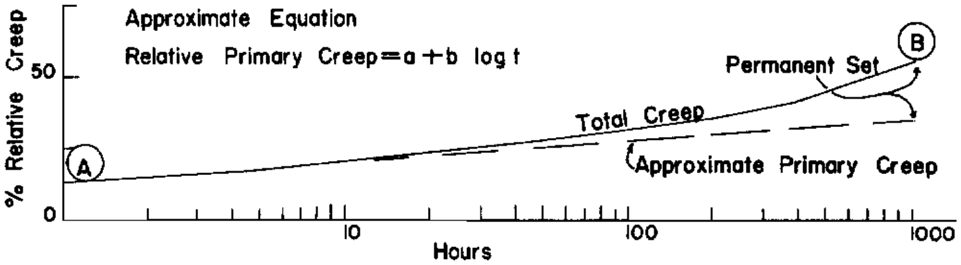
E_s = COMPRESSION MODULUS OF SPECIMEN DUROMETER MATERIAL

$$\%\ \text{Defl.} \propto \frac{(hR)^{2/3} \cdot E_{55}}{A^{1/2} \cdot E_s}$$

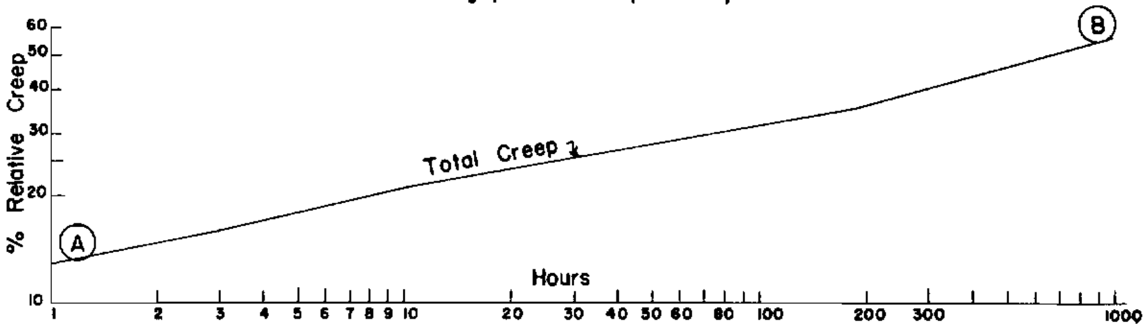
FIGURE 2-15 (2.2.1). COMPRESSION LOAD DEFORMATION CURVE FOR CALCULATING SPRING DEFLECTION (REF. 152)



Typical creep recovery curve in ordinary coordinates

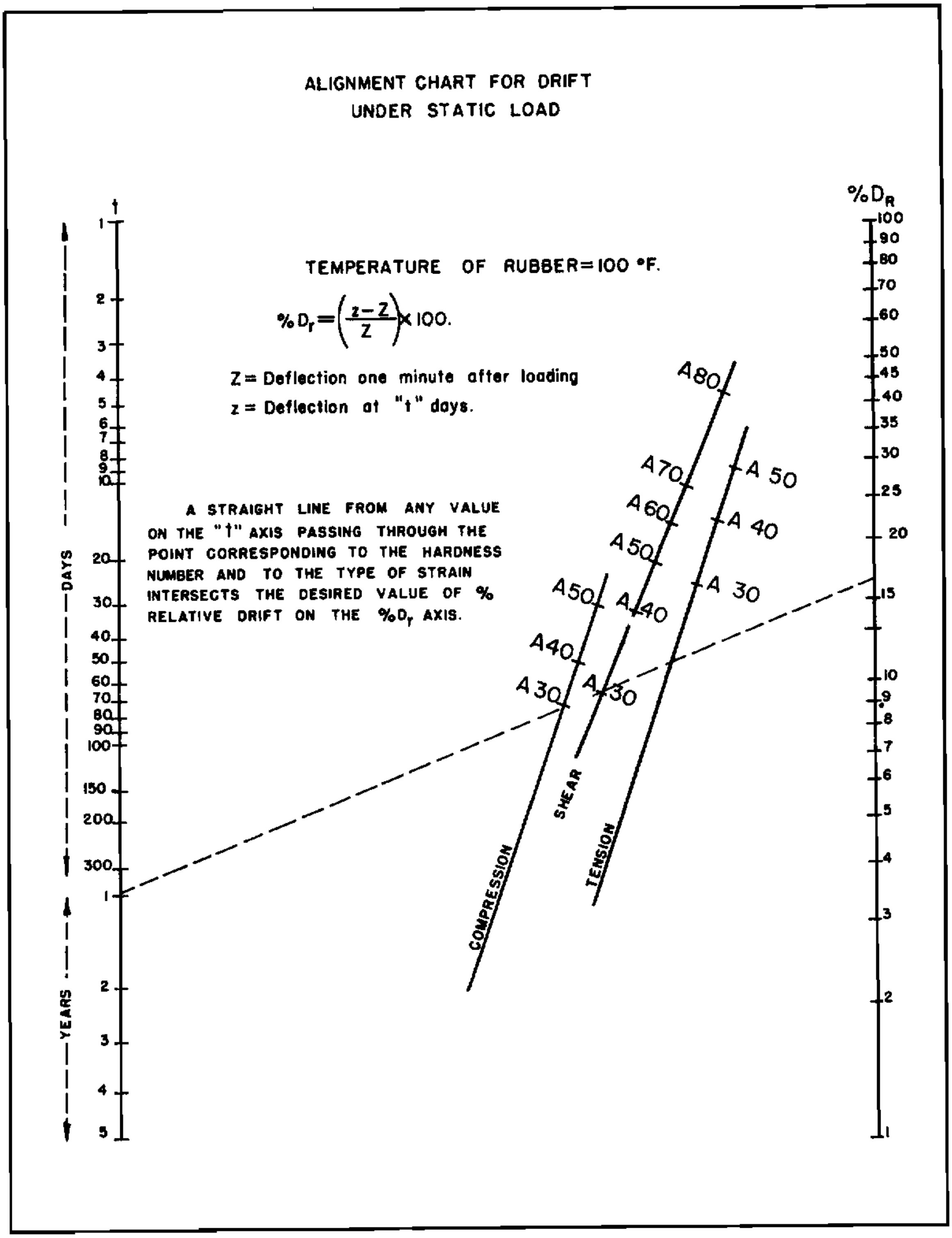


Semi-log plot of Creep Curve, Portion A-B



Log-Log Plot of Creep Curve, Portion A-B

FIGURE 2-16 (2.2.1). TYPICAL CREEP CURVE PLOTTED ON VARIOUS COORDINATE SYSTEMS (SwRI)



ALIGNMENT CHART FOR DRIFT UNDER STATIC LOAD

TEMPERATURE OF RUBBER = 100 °F.

$$\%D_r = \left(\frac{z - Z}{Z}\right) \times 100.$$

Z = Deflection one minute after loading

z = Deflection at "t" days.

A STRAIGHT LINE FROM ANY VALUE ON THE "t" AXIS PASSING THROUGH THE POINT CORRESPONDING TO THE HARDNESS NUMBER AND TO THE TYPE OF STRAIN INTERSECTS THE DESIRED VALUE OF % RELATIVE DRIFT ON THE $\%D_r$ AXIS.

FIGURE 2-17 (2.2.1). RELATIVE CREEP OF NATURAL RUBBER COMPOUNDS OF FIGURE 2-3 (REF. 48)

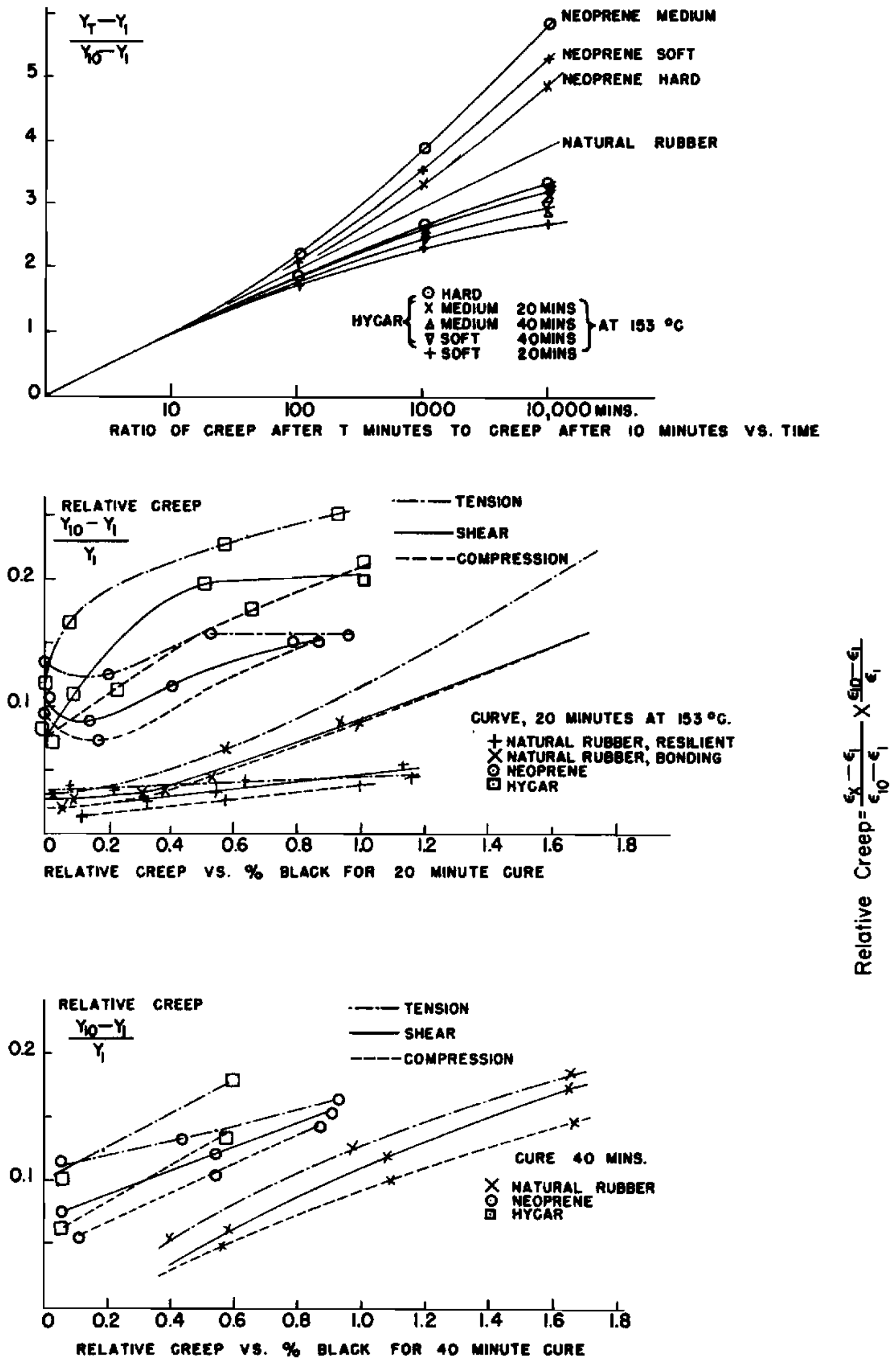


FIGURE 2-18 (2.2.1). RELATIVE CREEP OF ELASTOMERS (REF. 73)

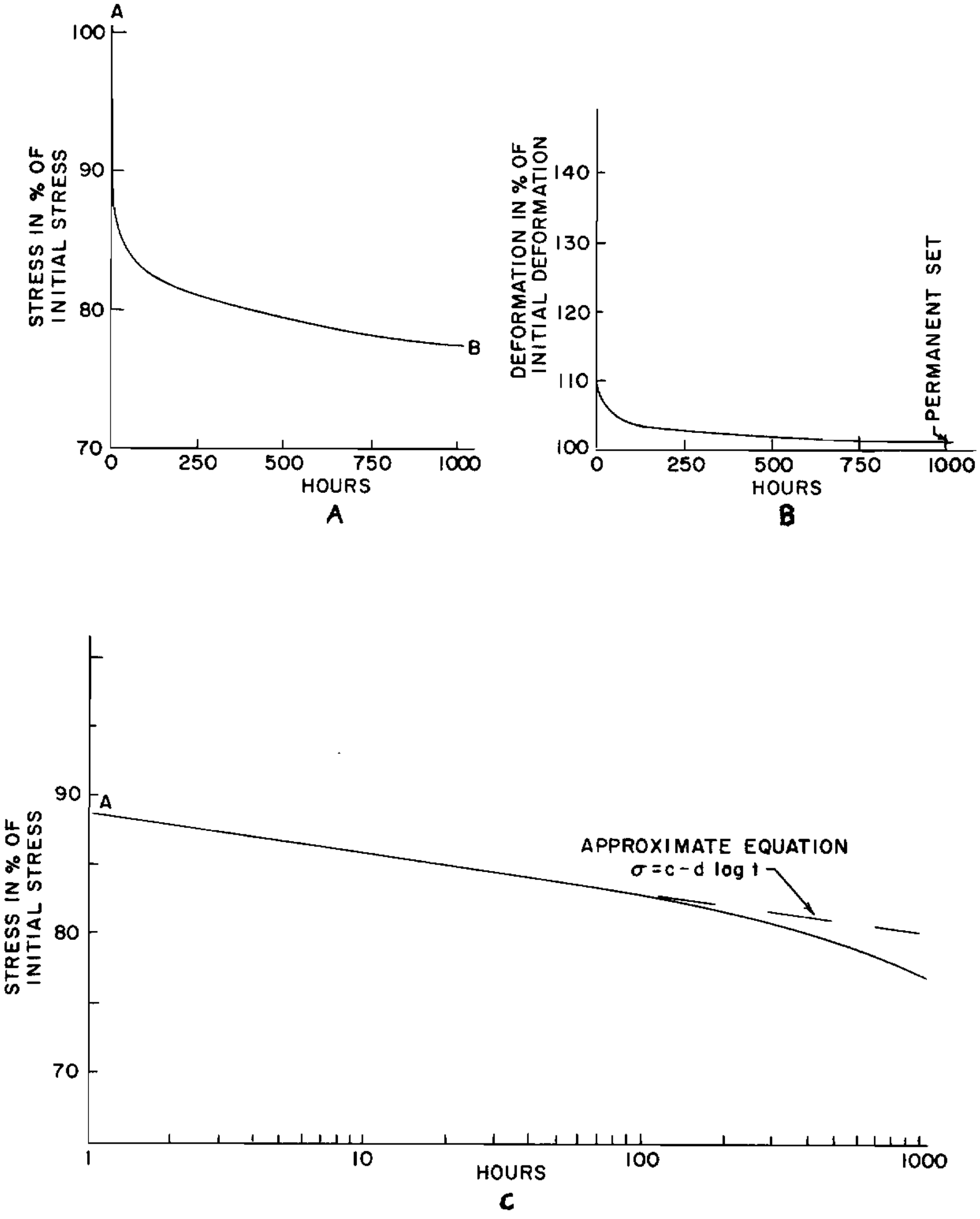


FIGURE 2-19 (2.2.1). TYPICAL STRESS RELAXATION AND RECOVERY CURVES (SwRI)

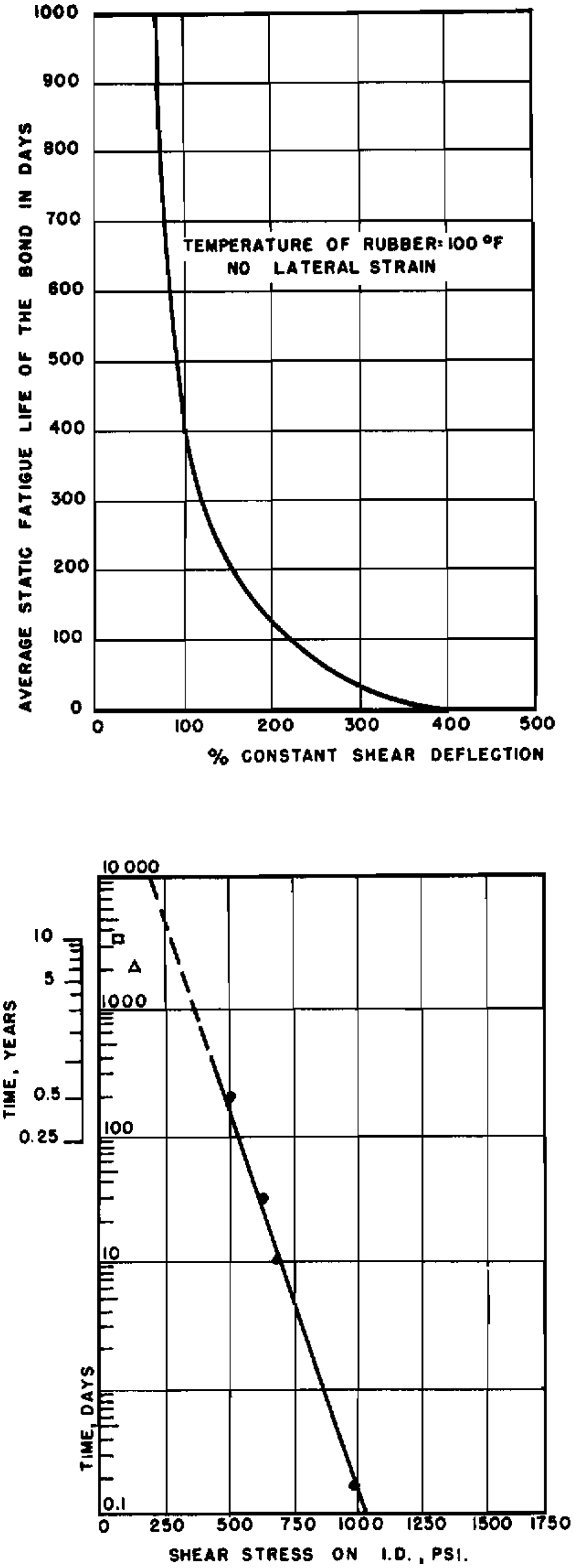


FIGURE 2-20 (2.2.1). TYPICAL STATIC FATIGUE LIFE CURVES (REFS. 48, 152)

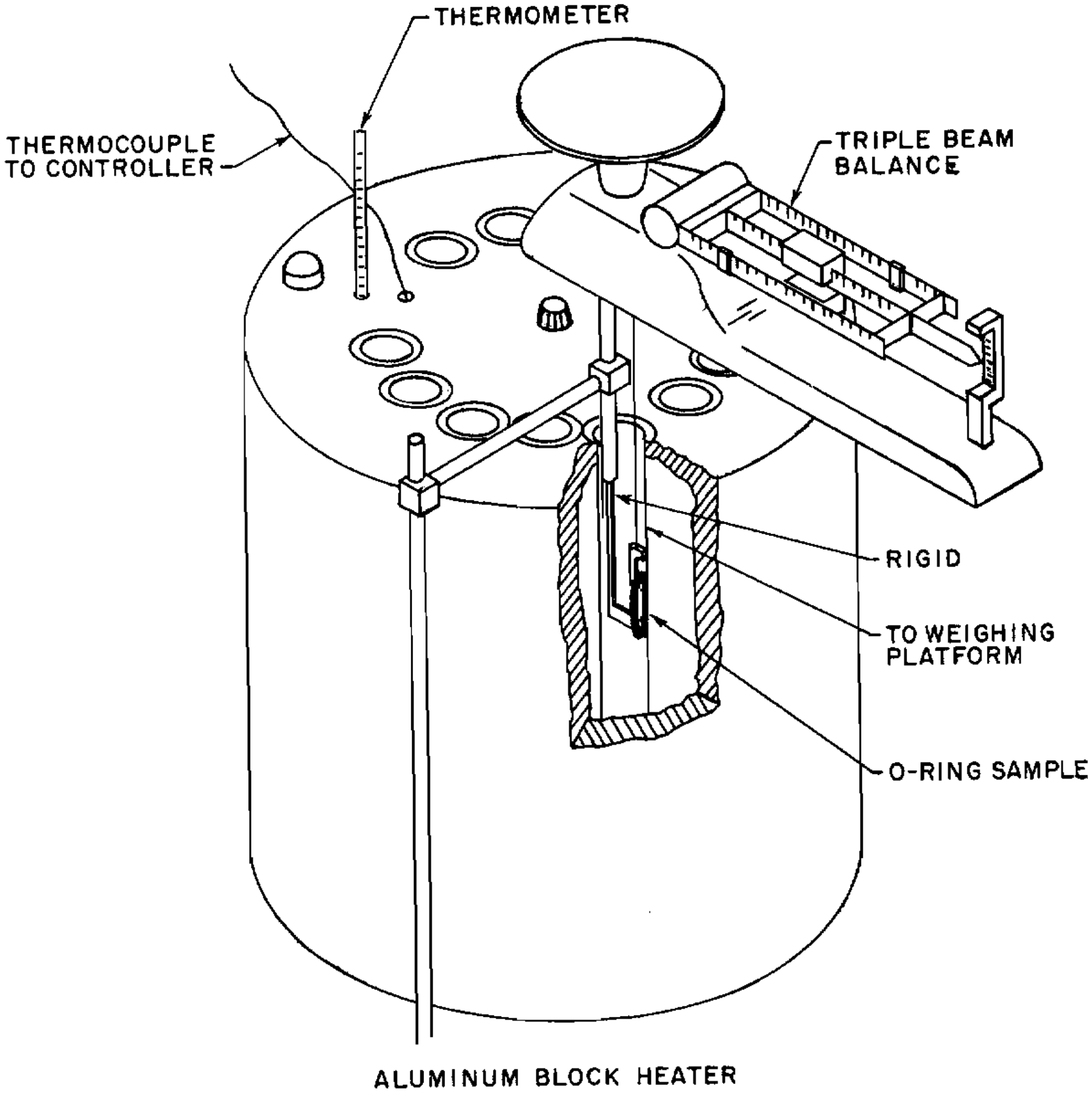


FIGURE 2-21 (2.2.1). HIGH TEMPERATURE TENSILE STRESS RELAXATION MEASUREMENT APPARATUS (REF. 8)

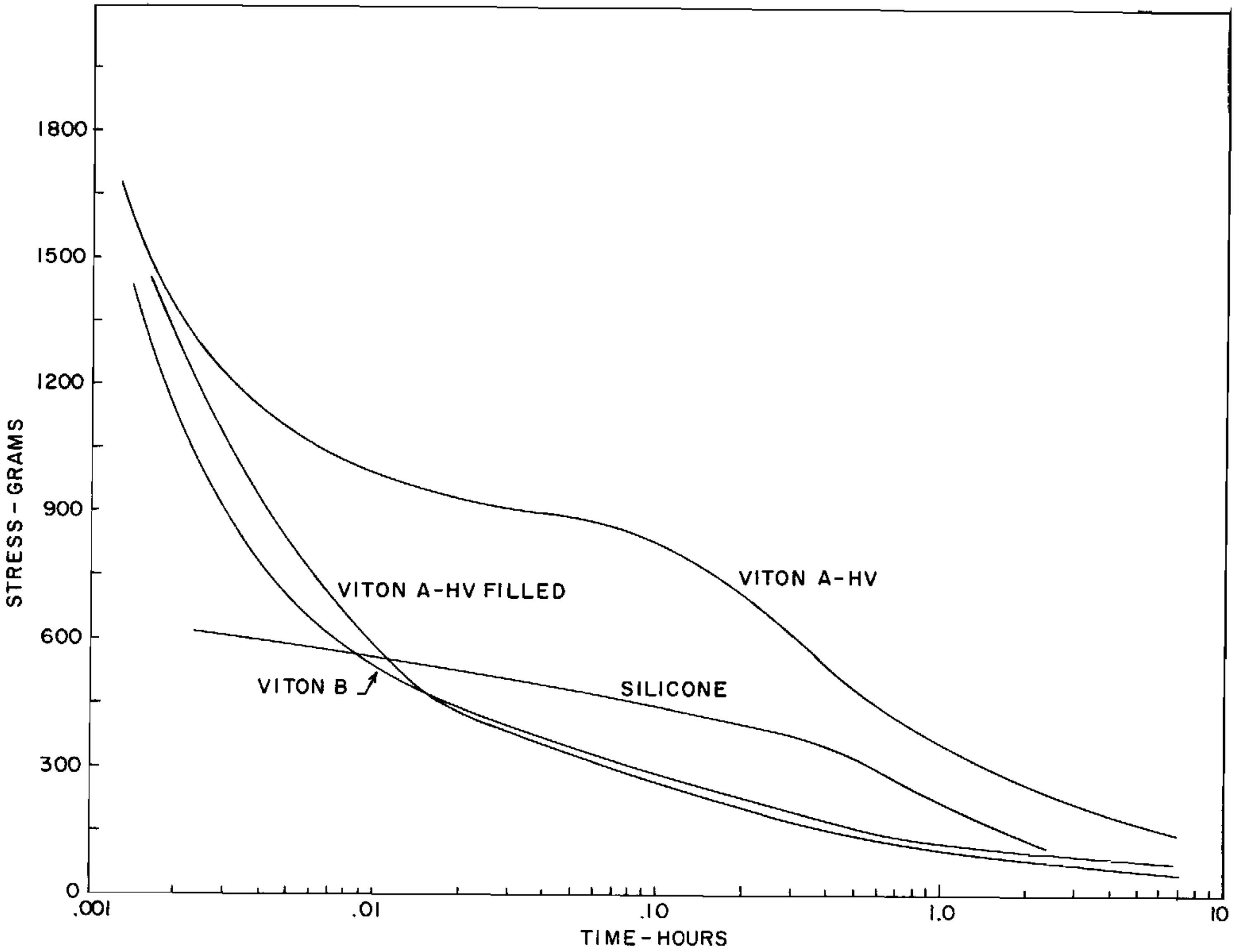


FIGURE 2-22 (2.2.1). TENSILE STRESS RELAXATION OF VITON AND SILICONE O-RINGS AT 600°F AND 20% ELONGATION (REF. 8)

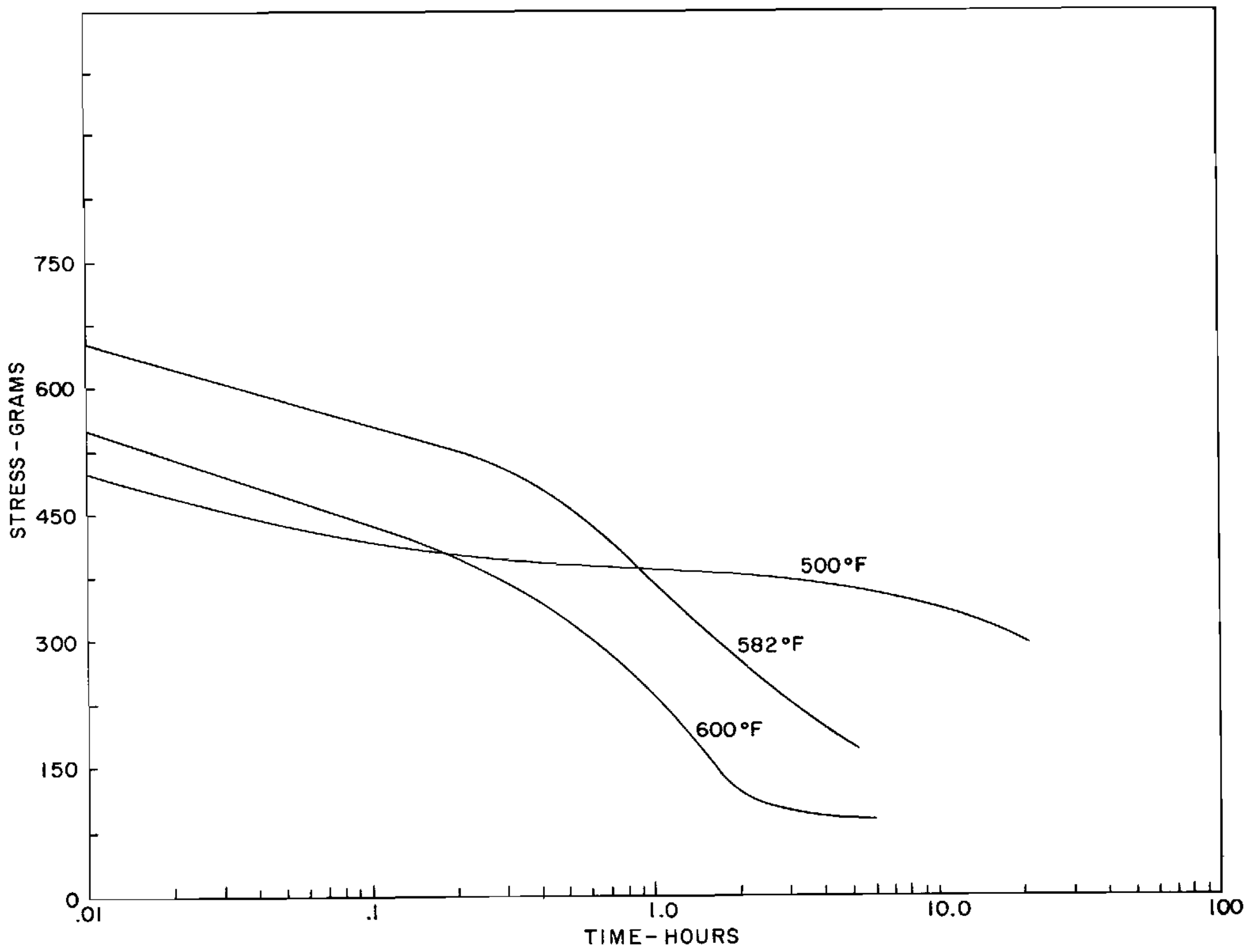


FIGURE 2-23 (2.2.1). TENSILE STRESS RELAXATION OF A SILICONE ELASTOMER O-RING AT VARIOUS TEMPERATURES AND 20% ELONGATION (REF. 8)

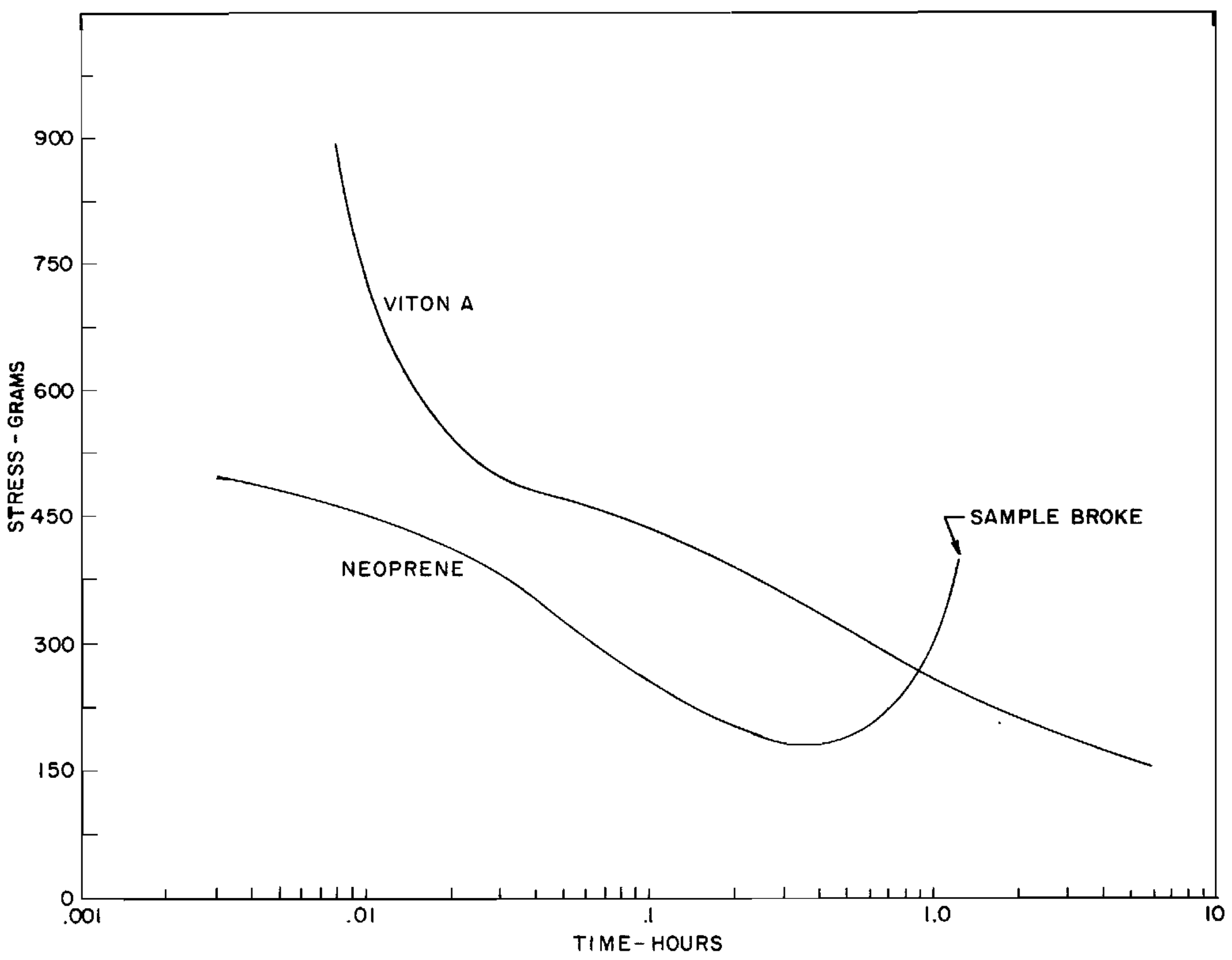
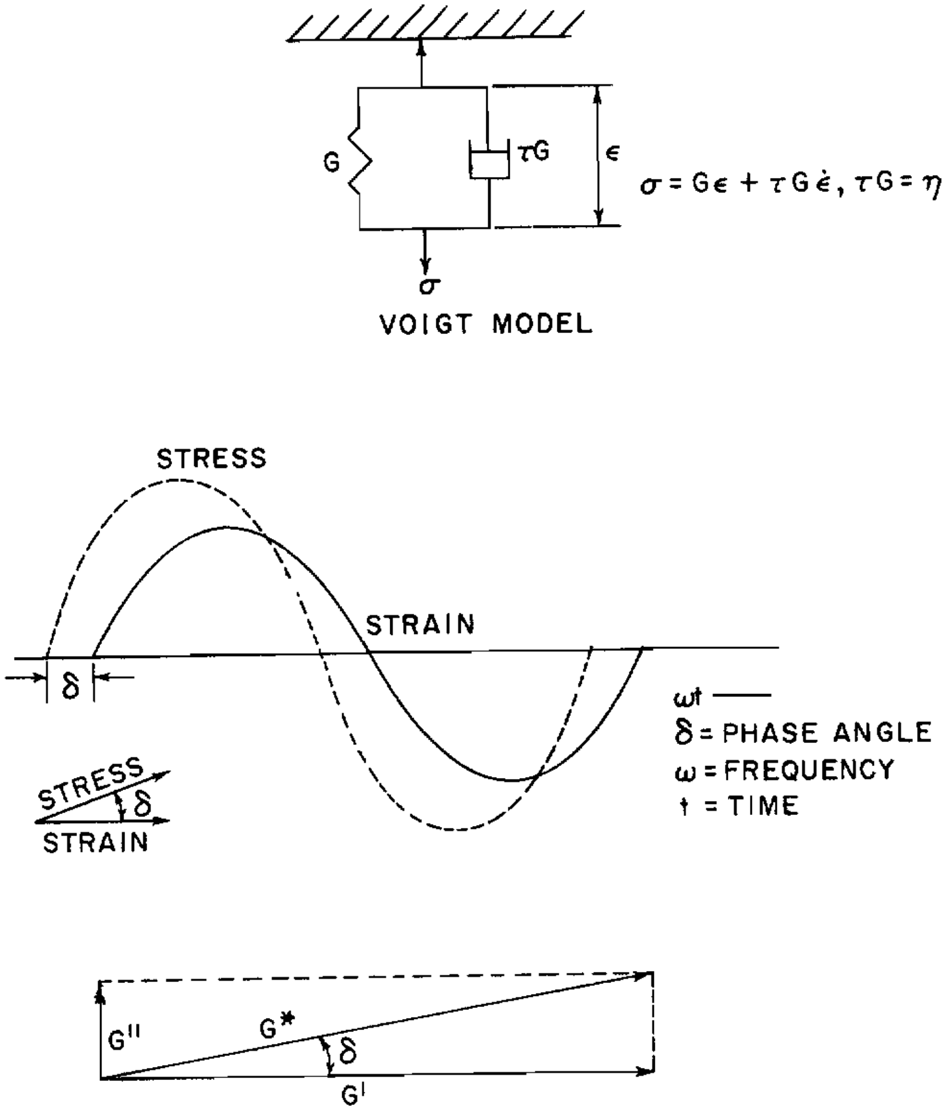


FIGURE 2-24 (2.2.1). TENSILE STRESS RELAXATION OF VITON AND NEOPRENE AT 600°F AND 20% ELONGATION (REF. 8)



$$G' = \frac{\text{COMPONENT OF STRESS IN PHASE WITH STRAIN}}{\text{STRAIN}}$$

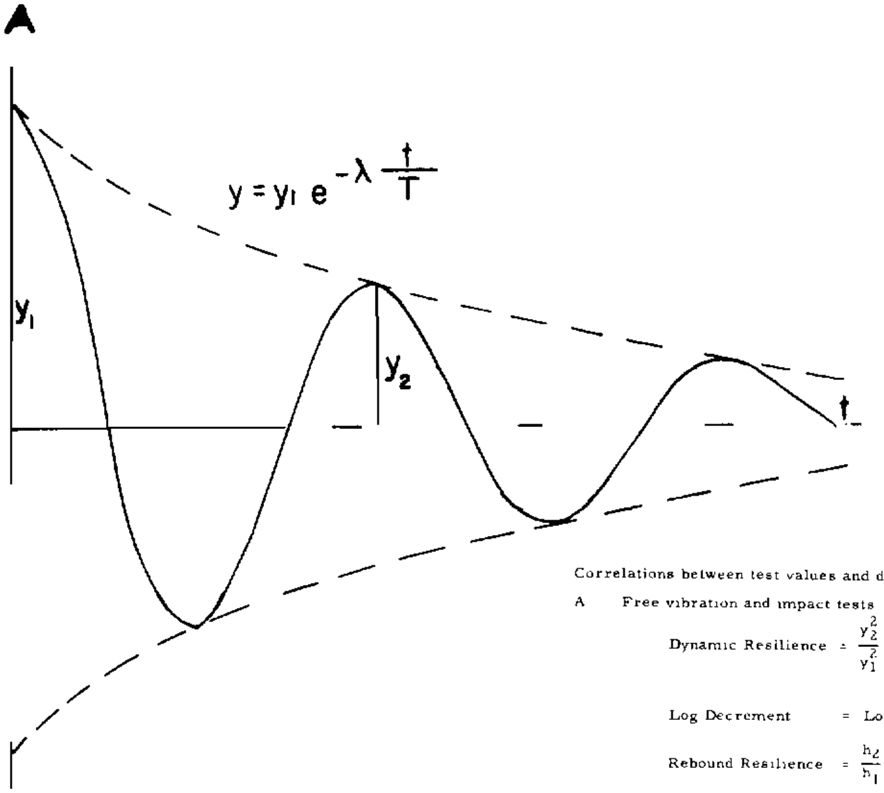
$$G'' = \frac{\text{COMPONENT OF STRESS 90° OUT OF PHASE WITH STRAIN}}{\text{STRAIN}}$$

$$G^* = G' + i\,G''$$

$$\tan\delta = \frac{G''}{G'} \qquad G'' = \eta\omega = \tau G\omega$$

(G IS CONVENTIONALLY USED FOR SHEAR MODULUS $\cong \frac{E}{3}$)

FIGURE 2-25 (2.2.2). MECHANICAL MODEL FOR DYNAMIC RESPONSE OF ELASTOMERS (SwRI AND REFS. 25, 125, 147)



Correlations between test values and dynamic moduli.

A Free vibration and impact tests

Dynamic Resilience $= \frac{y_2^2}{y_1^2} \cong \exp(-2\pi \tan\delta)$

Log Decrement $= \mathrm{Log}_e \frac{y_1}{y_2} = \frac{G''}{G'}$

Rebound Resilience $= \frac{h_2}{h_1} \cong \exp(-\pi \tan\delta)$ where h_2 = rebound heigh
h_1 = drop height

B Nonresonant forced vibrations.

$\frac{G'}{q} = \frac{\sigma_a}{\epsilon_a}$ · $\delta = \tan^{-1} \frac{\sigma_{\epsilon m}}{\sigma_a}$ · $\sigma = \sigma_m + \sigma_a \cos \omega t$ · ϵ_m · $\epsilon_a \cos(\omega t - \delta)$

where q shape factor

Dynamic Stiffness, $D = A_1/A_2$

where A_1 - Area within hysteresis loop
A_2 = Area bounded by maximum deformation abcissa, minimum load ordinate, and upper boundary of hysteresis loop

$\mathrm{Tan}\ \delta = \frac{2}{\pi} \frac{A_1}{A_2}$

Dynamic Resilience $\cong \exp(-4D)$

Energy dissipated per cycle. $H = \pi G'' \epsilon_{max}^2$

for constant vibration amplitude, X:

$H_x \cong (100 - R)\, G'\, X^2$

for constant maximum stress amplitude, F.

$H_f \cong \frac{(100 - R)\, F^2}{G'}$

where R = dynamic resilience
H = heat buildup

(See Figure 2-25 for other symbols)

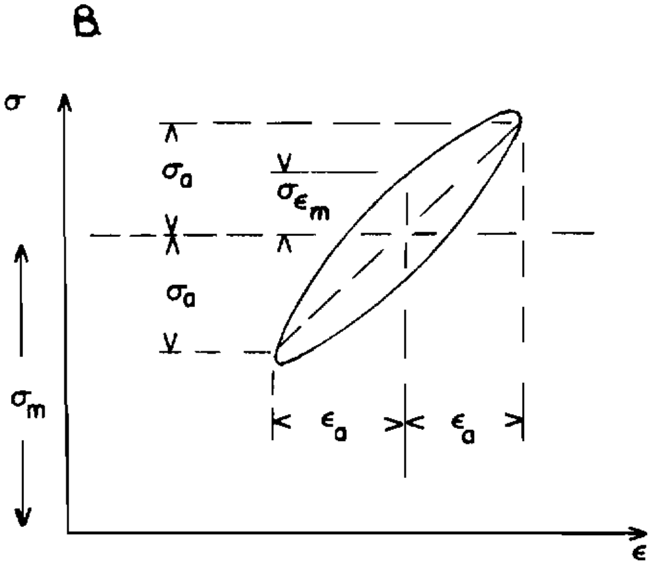
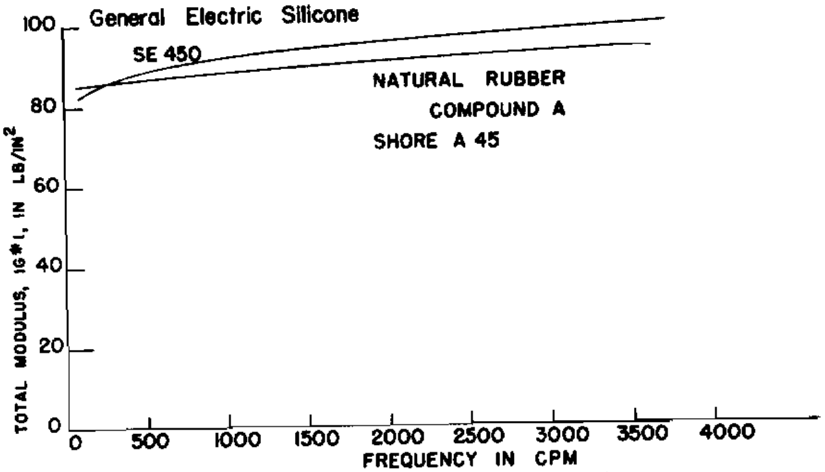
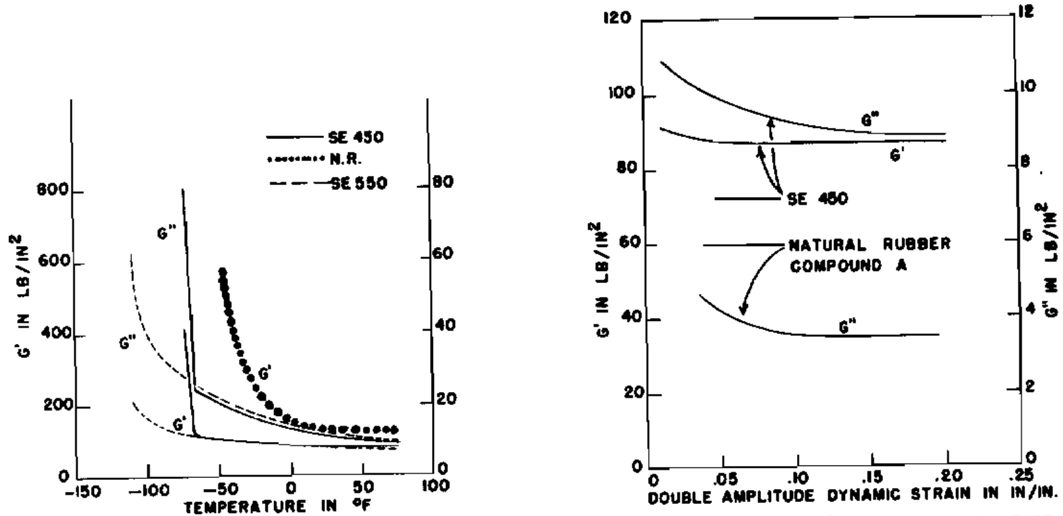


FIGURE 2-26 (2.2.2). CORRELATIONS BETWEEN TEST VALUES AND DYNAMIC MODULI (SwRI AND REFS. 100, 178)

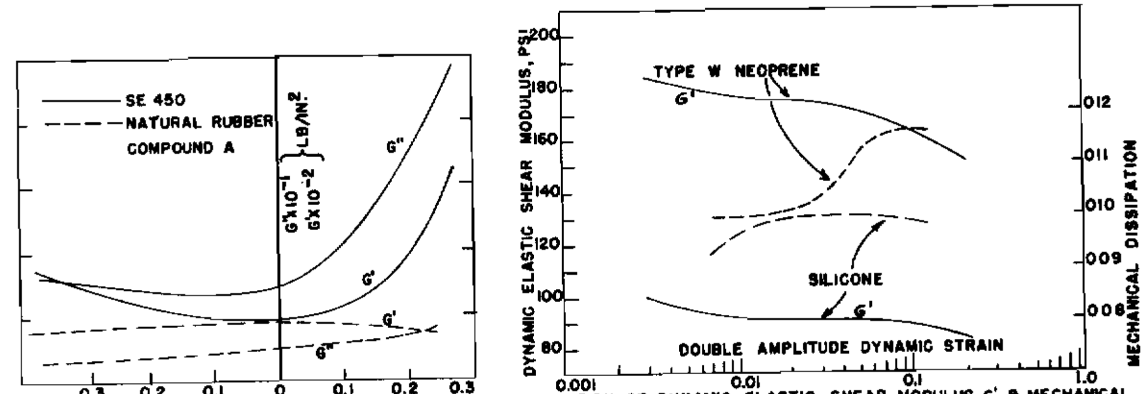


VARIATION OF TOTAL MODULUS |G*| WITH FREQUENCY



VARIATION OF G' & G" WITH TEMPERATURE AT 24 CPS

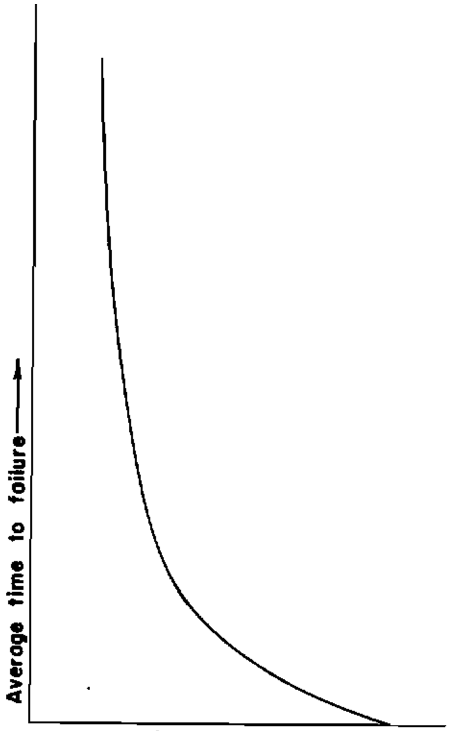
VARIATION OF G' & G" WITH DOUBLE AMPLITUDE OF DYNAMIC STRAIN AT 24 CPS.



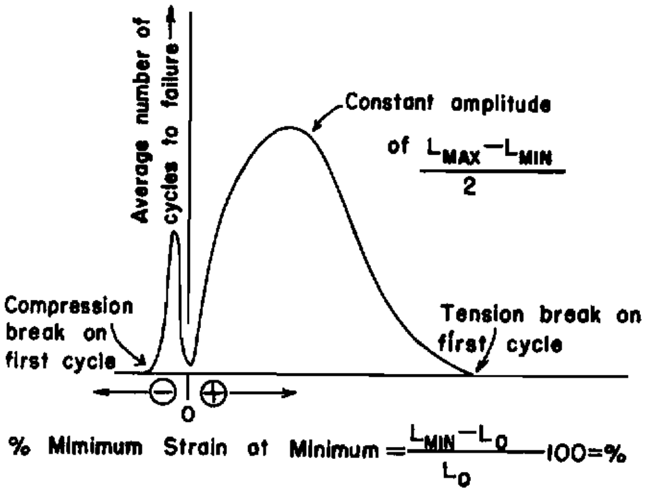
EFFECT OF STATIC COMPRESSION & TENSION PRESTRAIN APPLIED PERPENDICULAR TO DIRECTION OF DYNAMIC SHEAR STRAIN AT 24 CPS.

VARIATION OF DYNAMIC ELASTIC SHEAR MODULUS, G', & MECHANICAL DISSIPATION FACTOR, G"/G', WITH DYNAMIC STRAIN AT 25 CPS, 75 °F MECHANICAL DISSIPATION FACTOR CAN BE USED IN CALCULATING RESILIENCE.

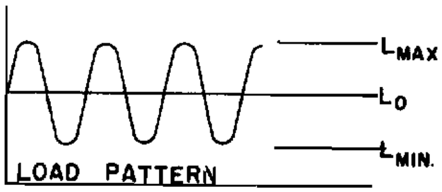
FIGURE 2-27 (2.2.2). G' AND G" VALUES (REF. 175)

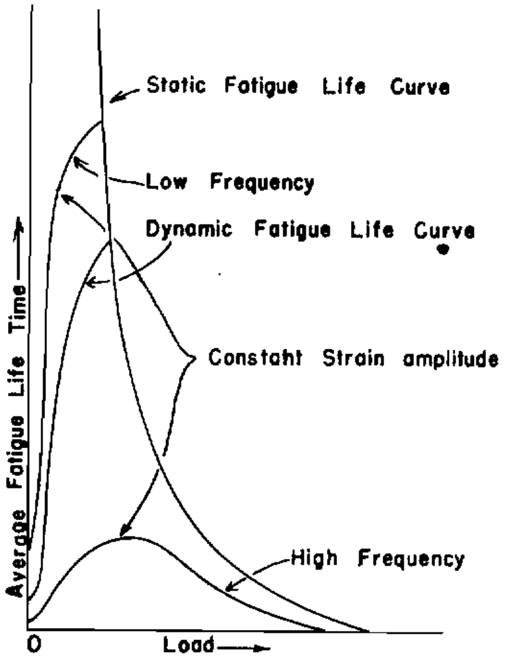


Typical Static Fatigue Life Curves at Constant Temperature

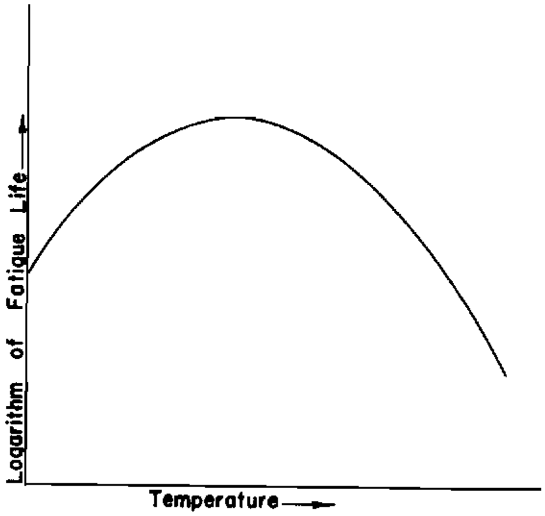


Typical Dynamic Fatigue Life Curve at Constant Temperature



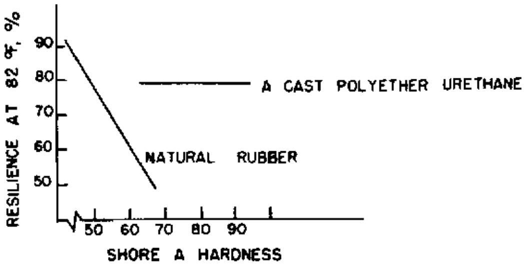


Superposition of Static Fatigue Life Curve



Variation of Fatigue Life with Temperature

FIGURE 2-28 (2.2.2). CHARACTERISTIC FATIGUE LIFE CURVES FOR ELASTOMERS (REF. 48)



RESILIENCE CHANGE WITH HARDNESS

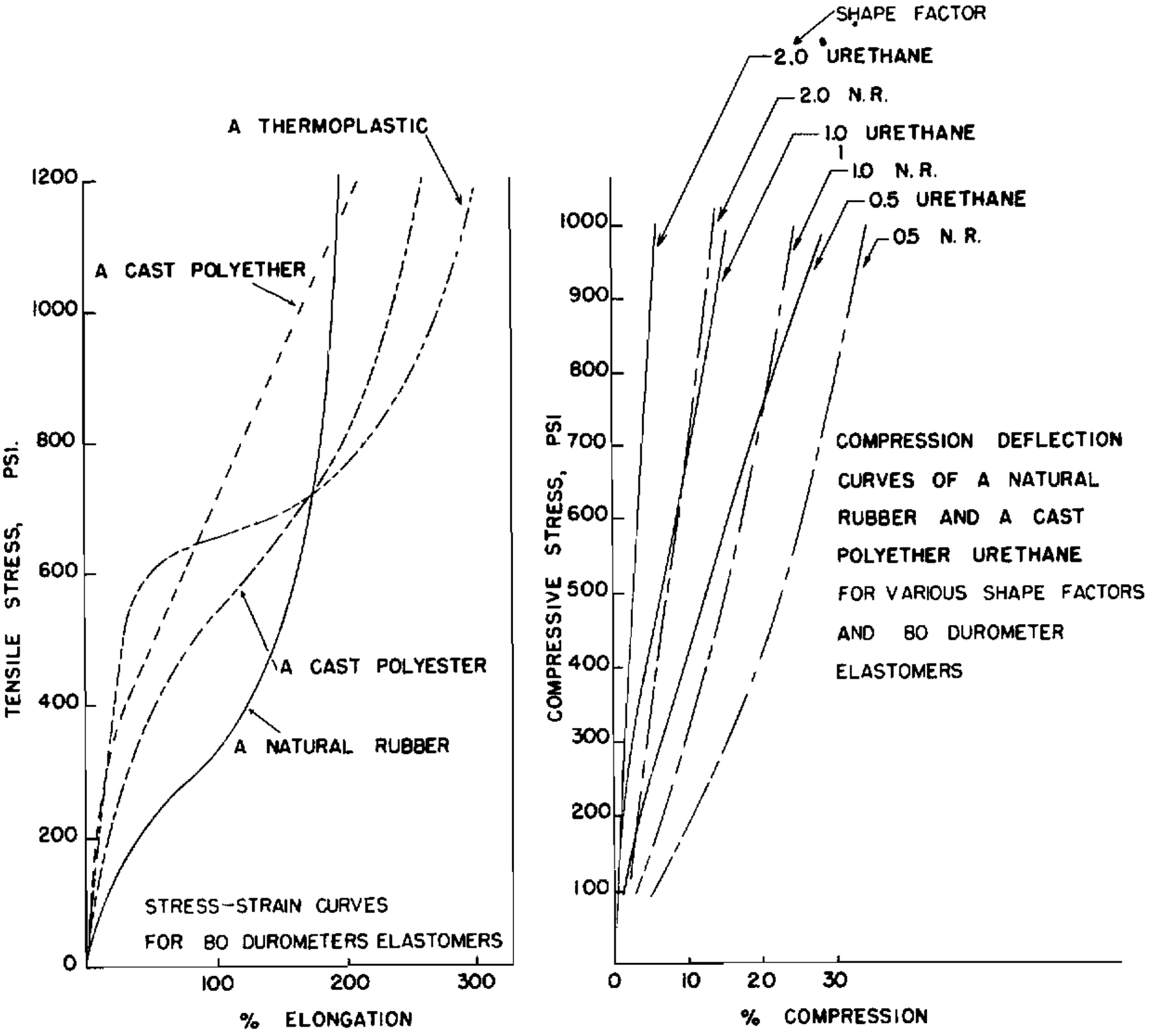
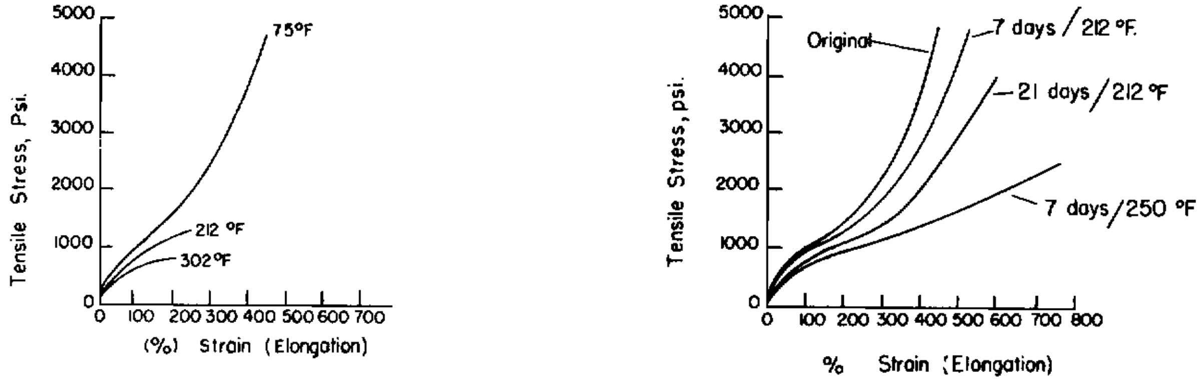
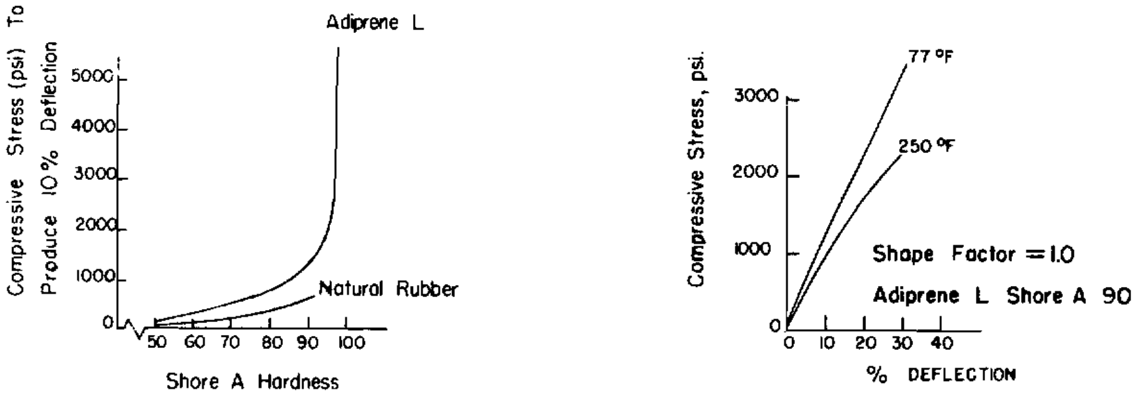


FIGURE 2-29 (2.3.1.3.3). COMPARISON OF MECHANICAL PROPERTIES OF URETHANES WITH NATURAL RUBBER (SwRI)



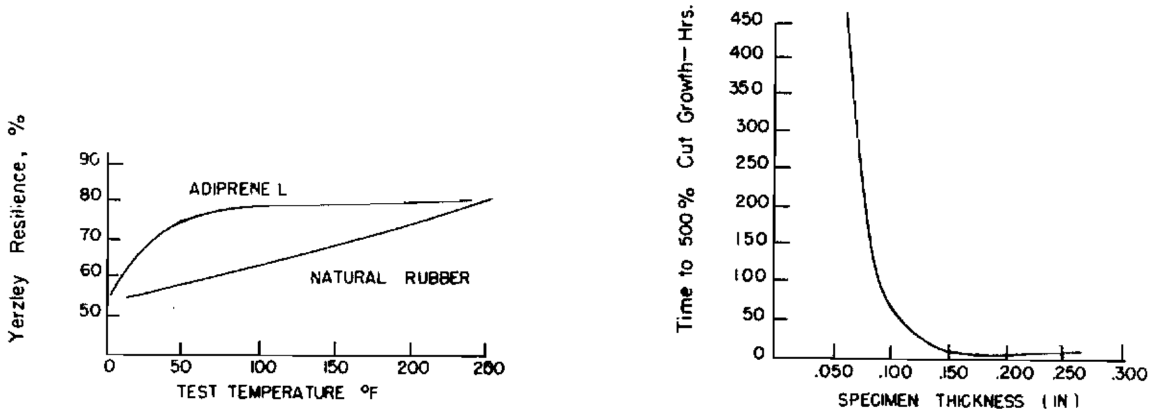
Elevated Temperature Stress-Strain Curves for Shore A 90

R. T. Stress Strain Curves for Shore A 90 Adiprene L after Heat Aging.



R T. Deflection–Hardness Curves

Compression—Deflection Curves



Resilience Temperature Curve for Shore A 60 Materials.

Flexing Resilience of Shore A 90

FIGURE 2-30 (2.3.1.3.3). MECHANICAL PROPERTIES OF A CAST POLYETHER URETHANE (REF. 84)

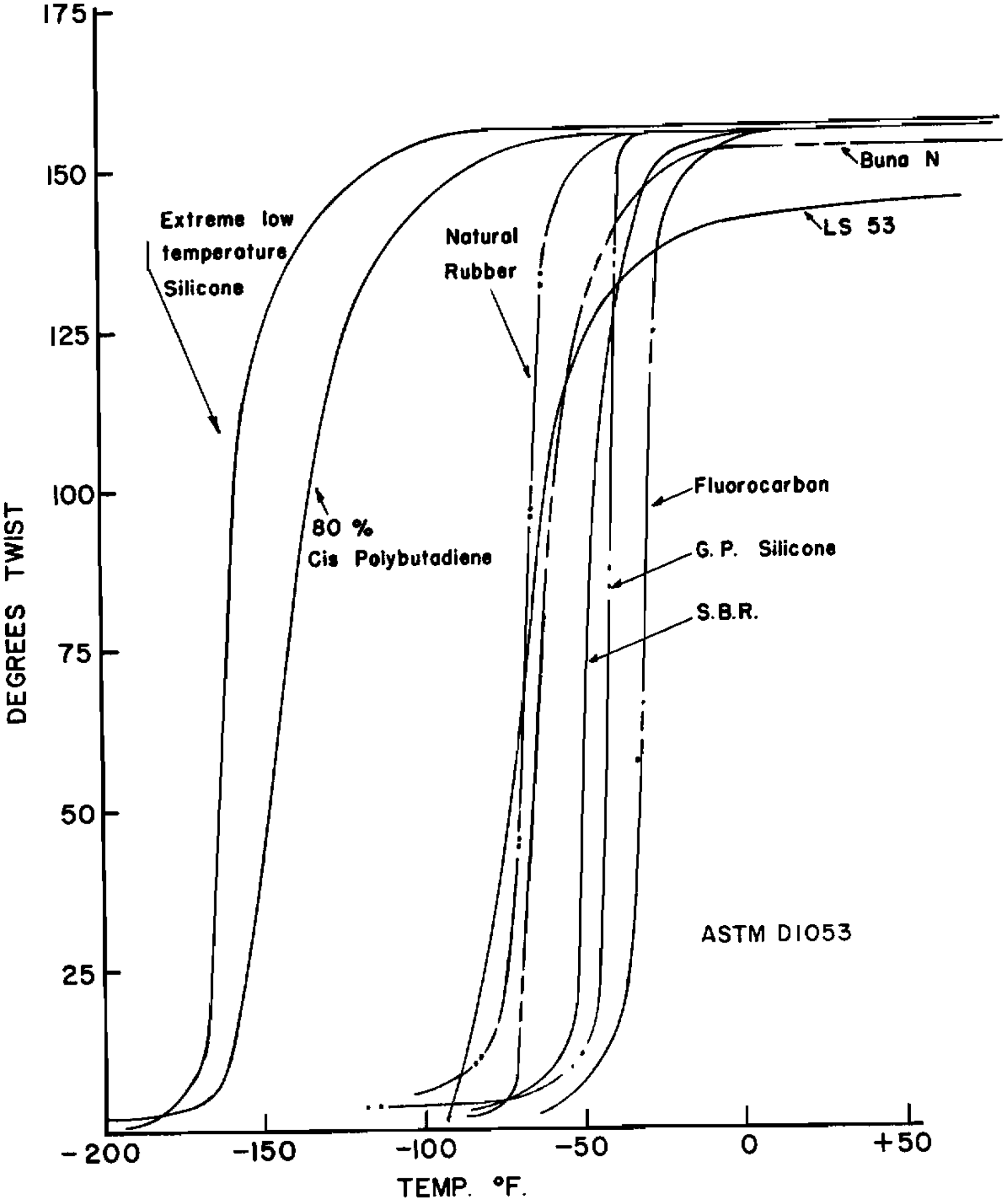


FIGURE 2-31 (2.3.2.1). STIFFENING OF ELASTOMERS AT LOW TEMPERATURES (SwRI)

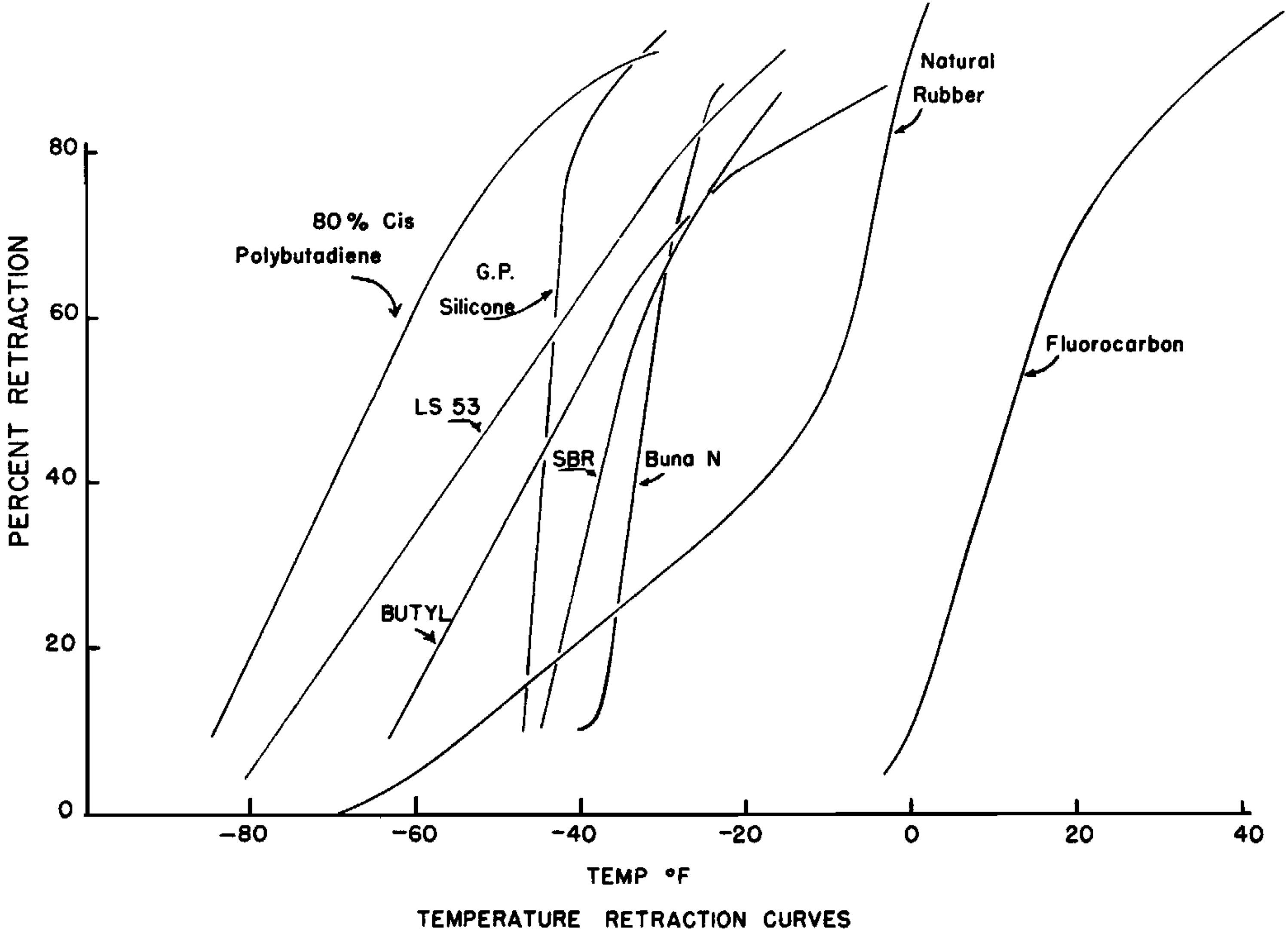


FIGURE 2-32 (2.3.2.1). STIFFENING OF ELASTOMERS AT LOW TEMPERATURES (SwRI AND REF. 11)

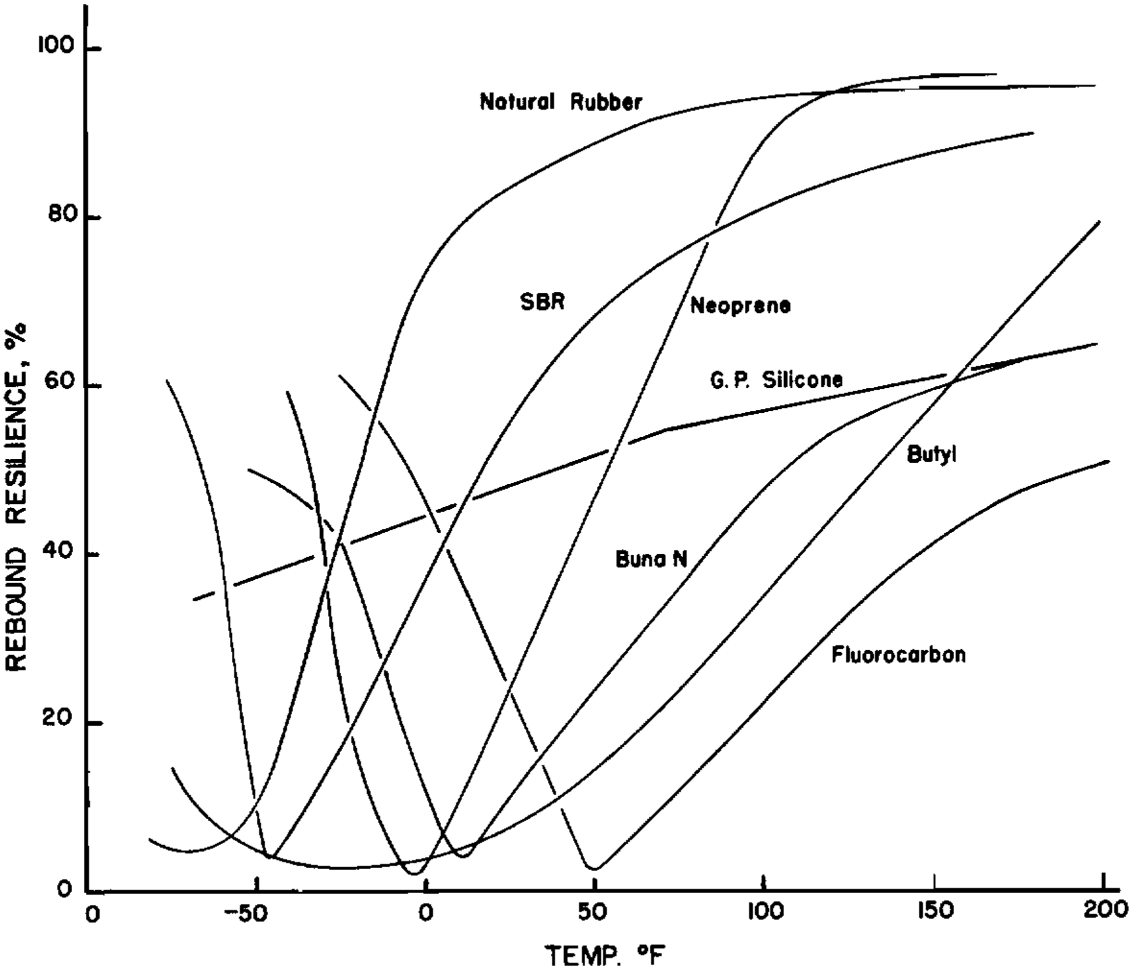
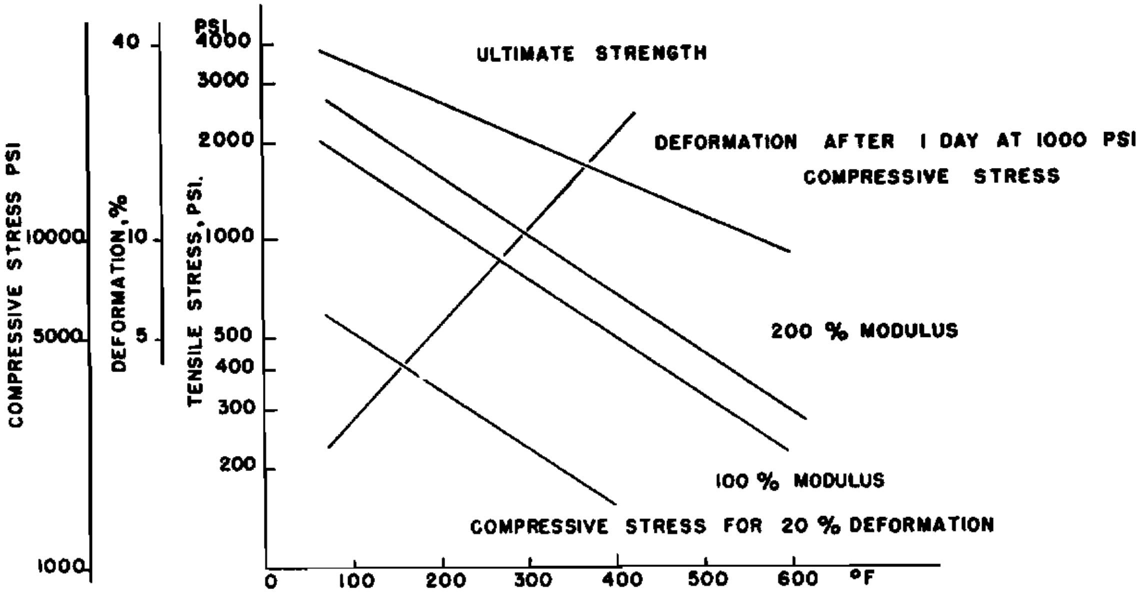
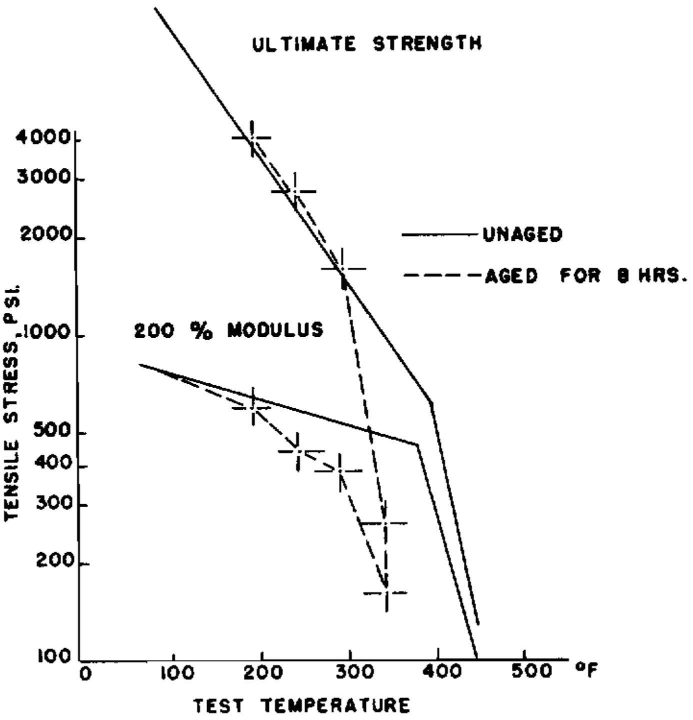


FIGURE 2-33 (2.3.2.1). STIFFENING OF ELASTOMERS AT LOW TEMPERATURES (RESILIENCE) (SwRI)



A Mechanical Properties of Teflon



B Mechanical Properties of Urethane

FIGURE 2-34 (2.3.2.2). EXAMPLES OF THE EFFECTS OF EXPOSURE TO ELEVATED TEMPERATURE OF A PLASTIC AND AN ELASTOMER (SwRI)

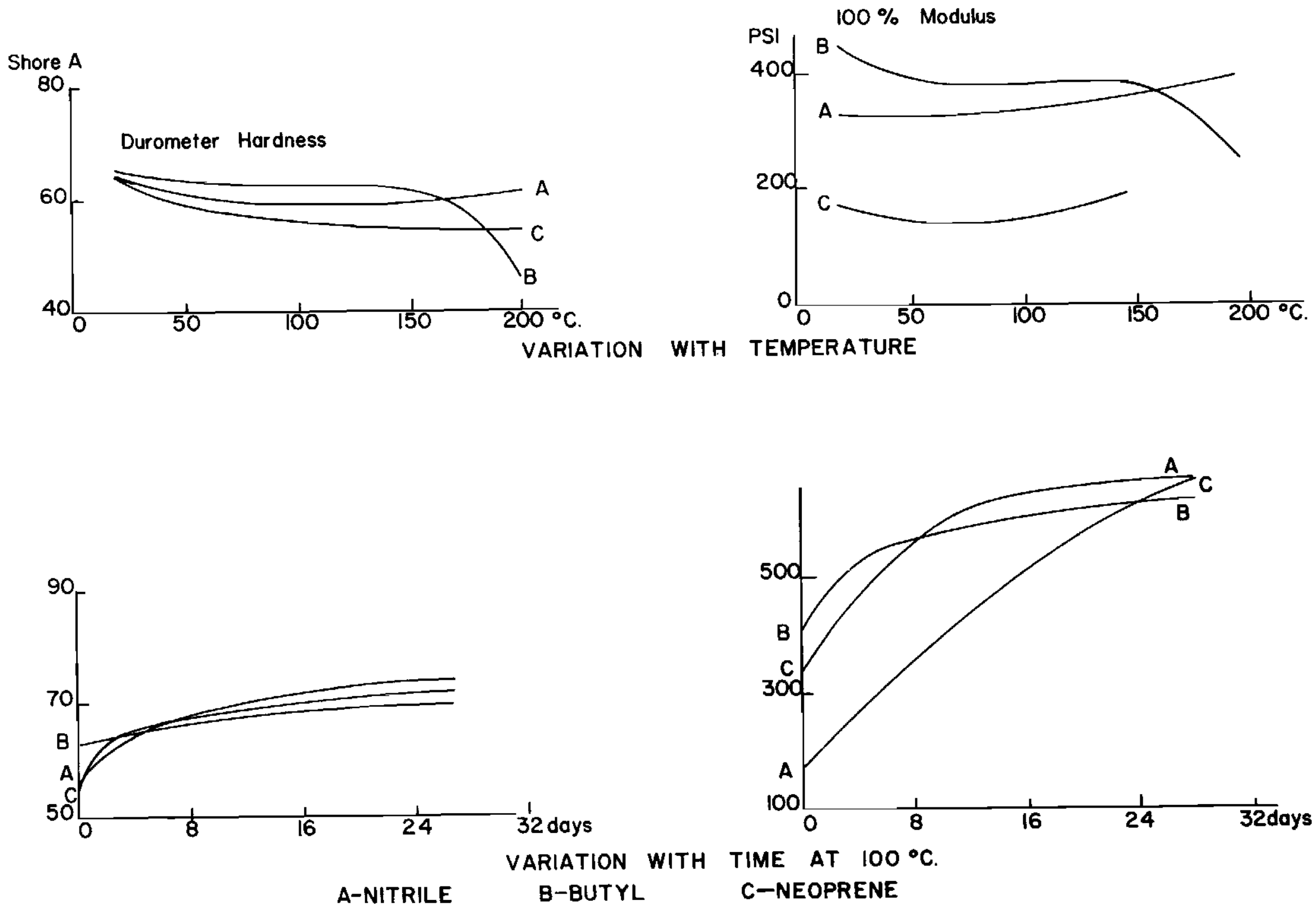


FIGURE 2-35 (2.3.2.2). MODULI BEHAVIOR OF THREE ELASTOMERS AS A FUNCTION OF TIME AND TEMPERATURE (REF. 233)

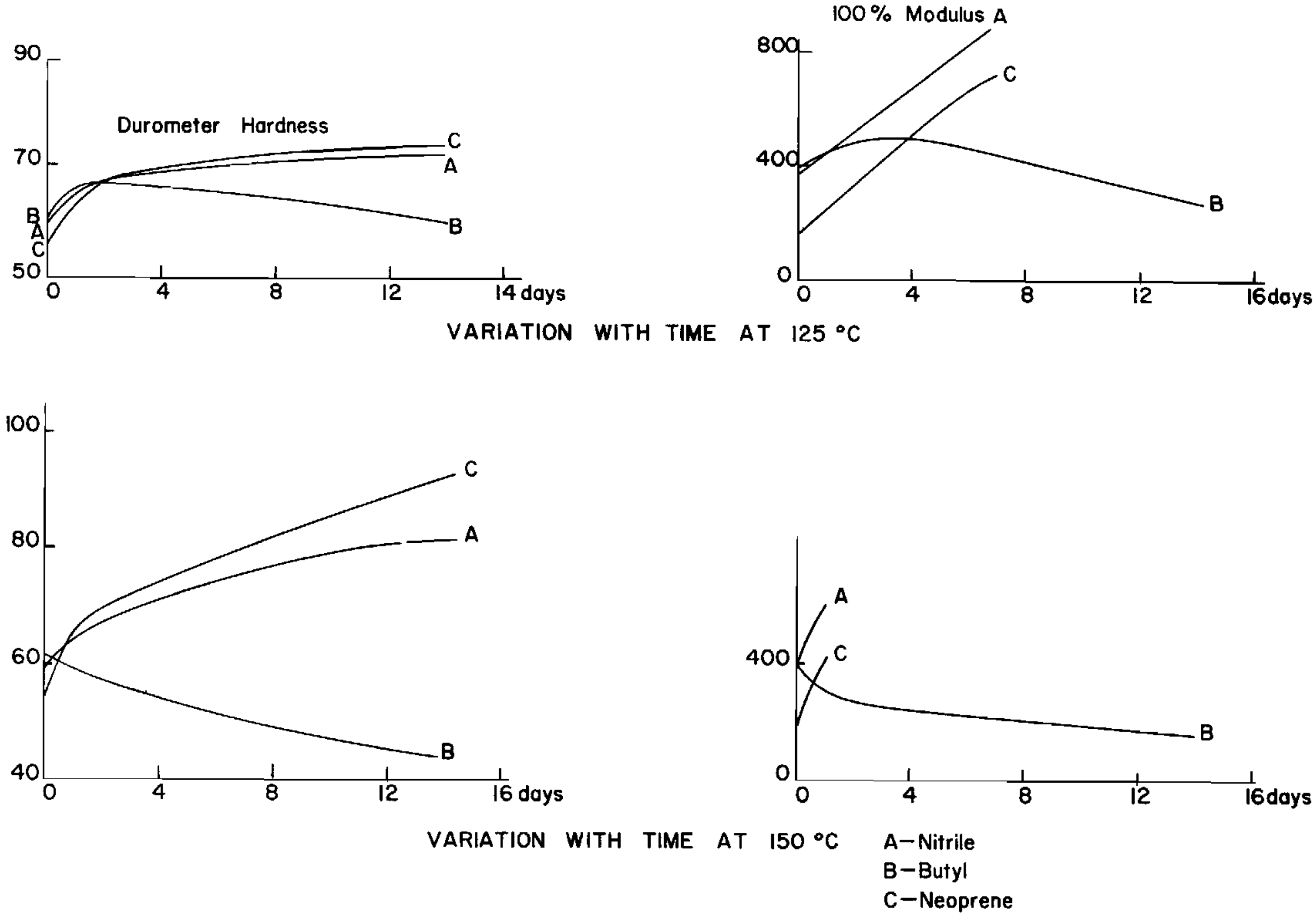


FIGURE 2-36 (2.3.2.2). MODULI BEHAVIOR OF THREE ELASTOMERS AS A FUNCTION OF TIME AND TEMPERATURE (REF. 233)

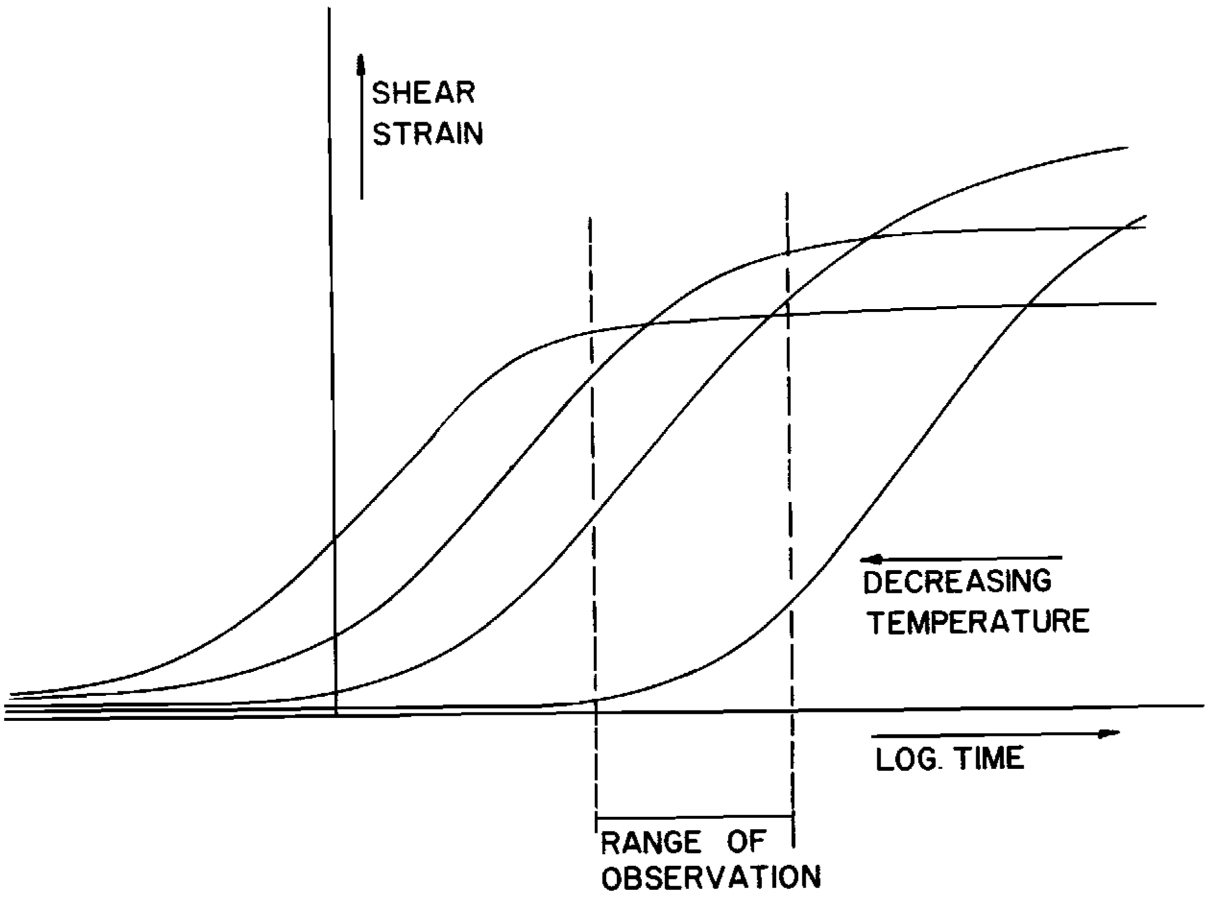


FIGURE 2-37 (2.3.2.2). TYPICAL TEST RESULTS OF CREEP RESPONSE OVER A RANGE OF TEMPERATURES (REF. 146)

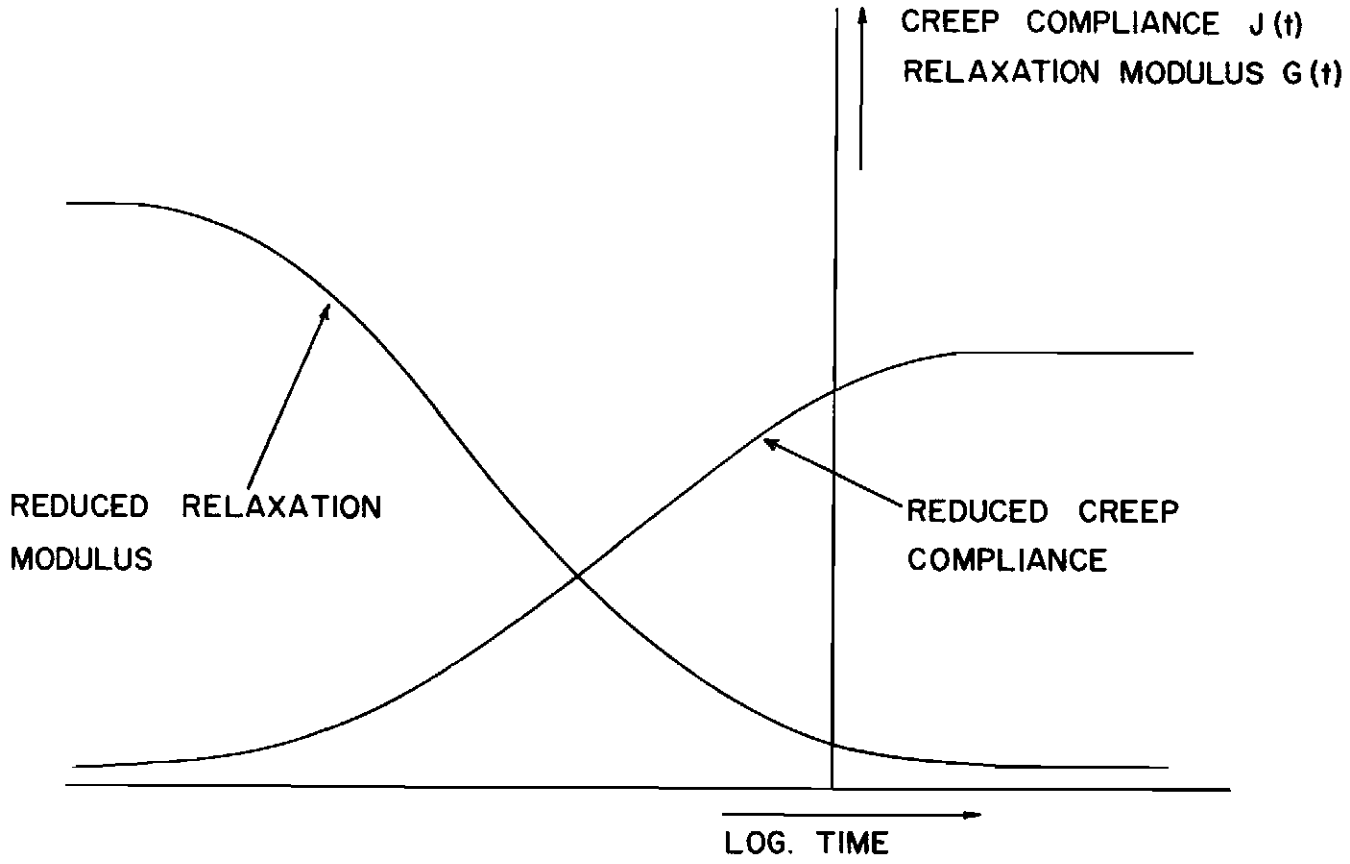
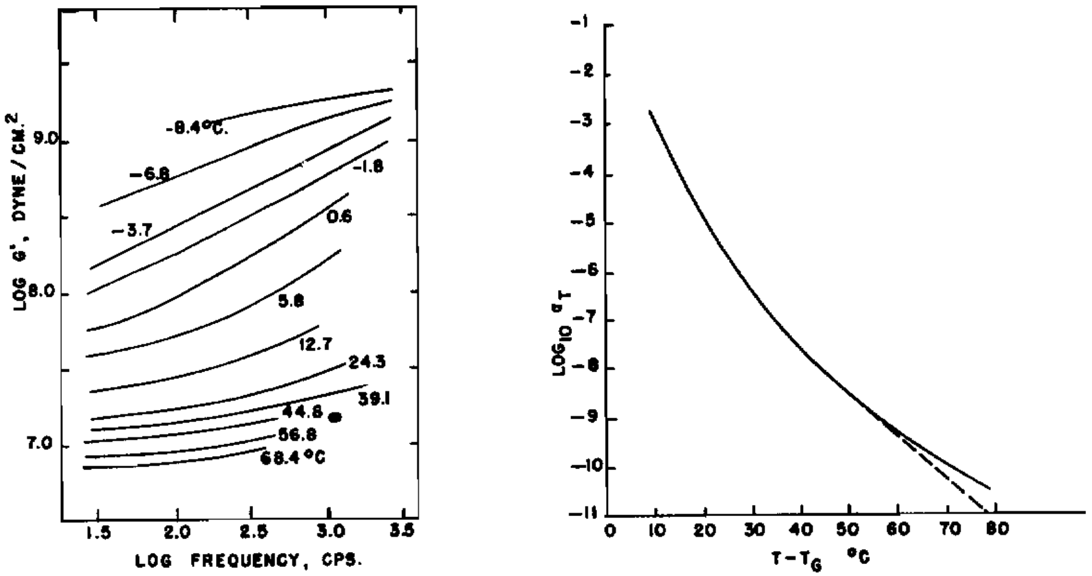
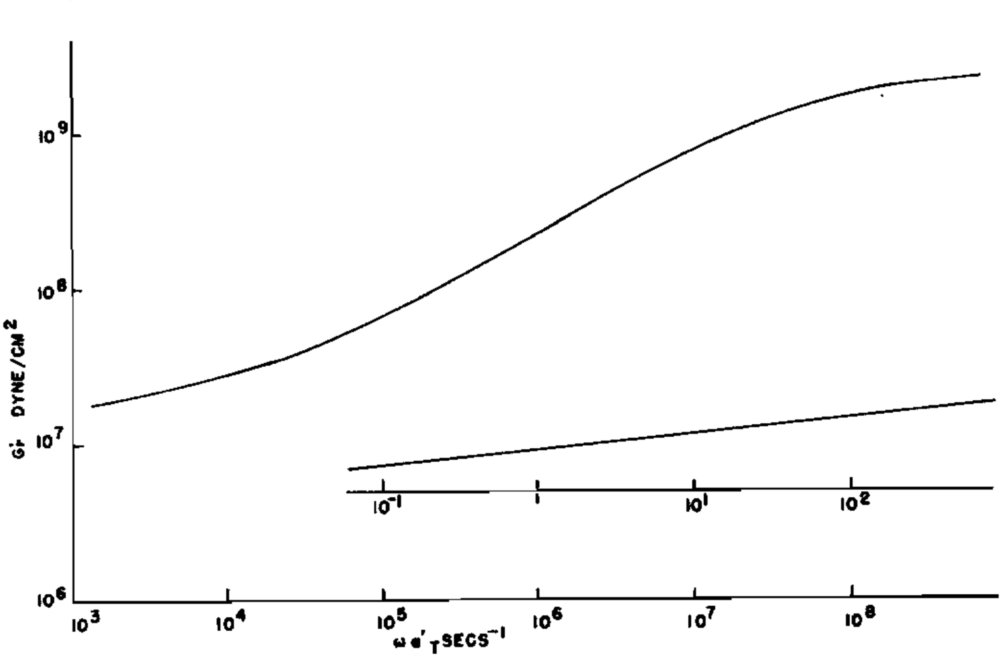


FIGURE 2-38 (2.3.2.2). EXAMPLE OF A MASTER CREEP CURVE DEVELOPED FROM TEST RESULTS OVER A RANGE OF TEMPERATURES (REF. 146)



TEST RESULTS

TEMPERATURE REDUCTION FACTORS FOR HYPALON-20 REDUCED TO -24.5 °C



REAL COMPONENT G', OF THE REDUCED COMPLEX SHEAR MODULUS (25°C) FOR HYPALON-20

FIGURE 2-39 (2.3.2.2). EXAMPLE OF USE OF TIME TEMPERATURE SUPERPOSITION PRINCIPLE (REF. 143)

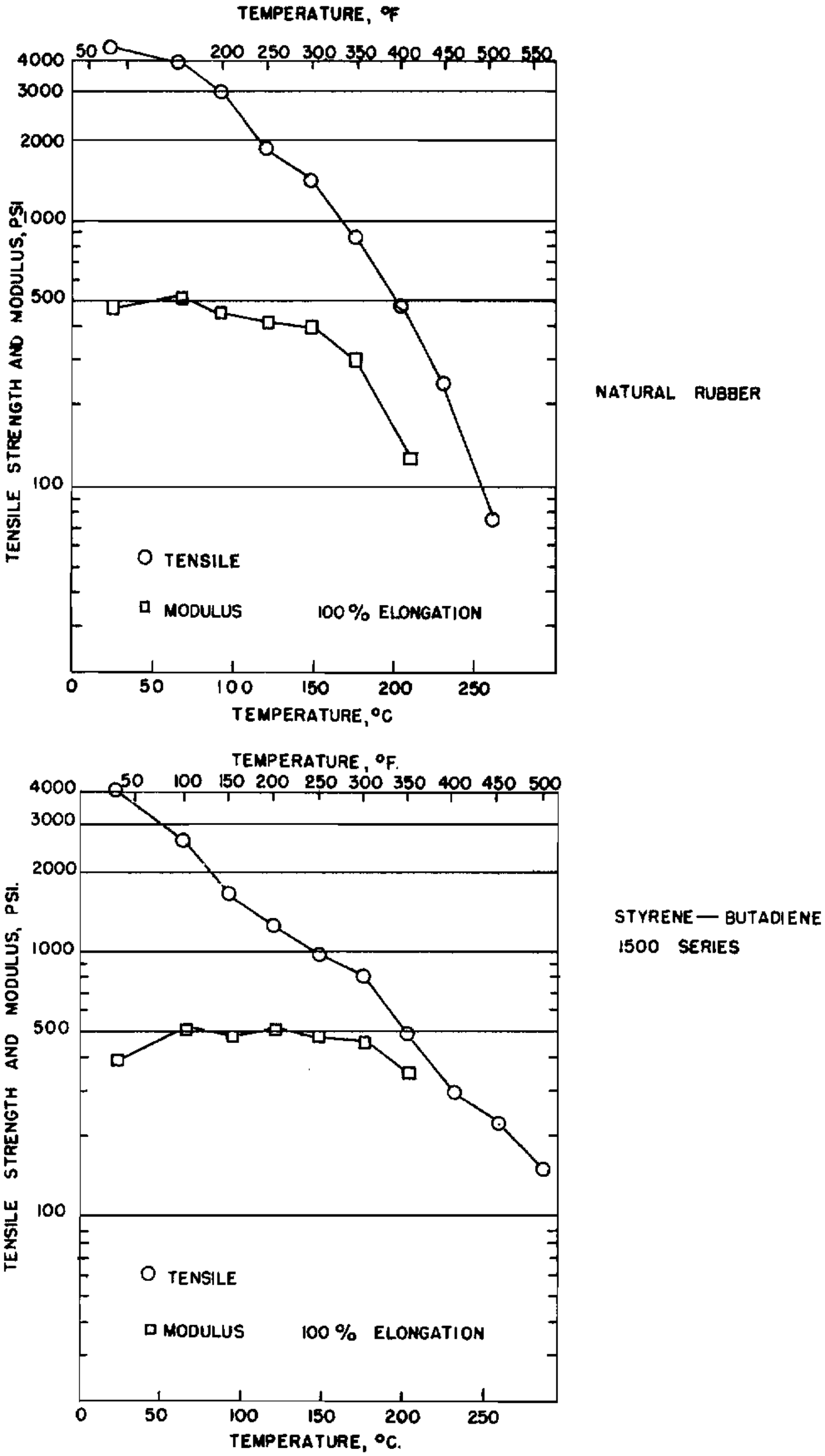


FIGURE 2-40 (2.3.2.2). THE PROPERTIES OF NATURAL RUBBER AND SBR COMPOUNDS AS A FUNCTION OF TEMPERATURE (REF. 9)

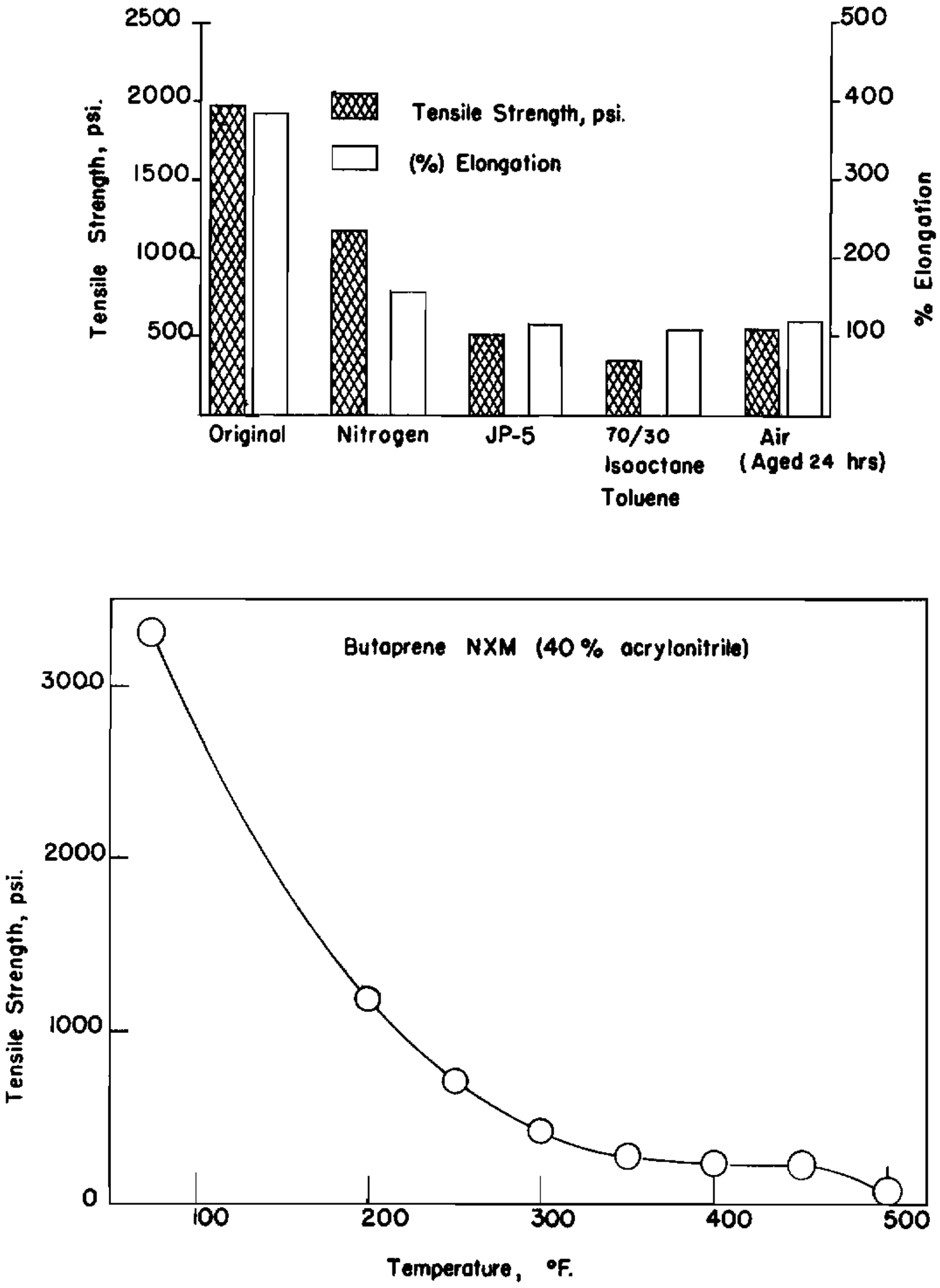


FIGURE 2-41 (2.3.2.2). PROPERTIES OF A BUNA N AT 325°F AFTER AGING FOR 72 HOURS AT TEMPERATURE IN VARIOUS MEDIA (REF. 9)

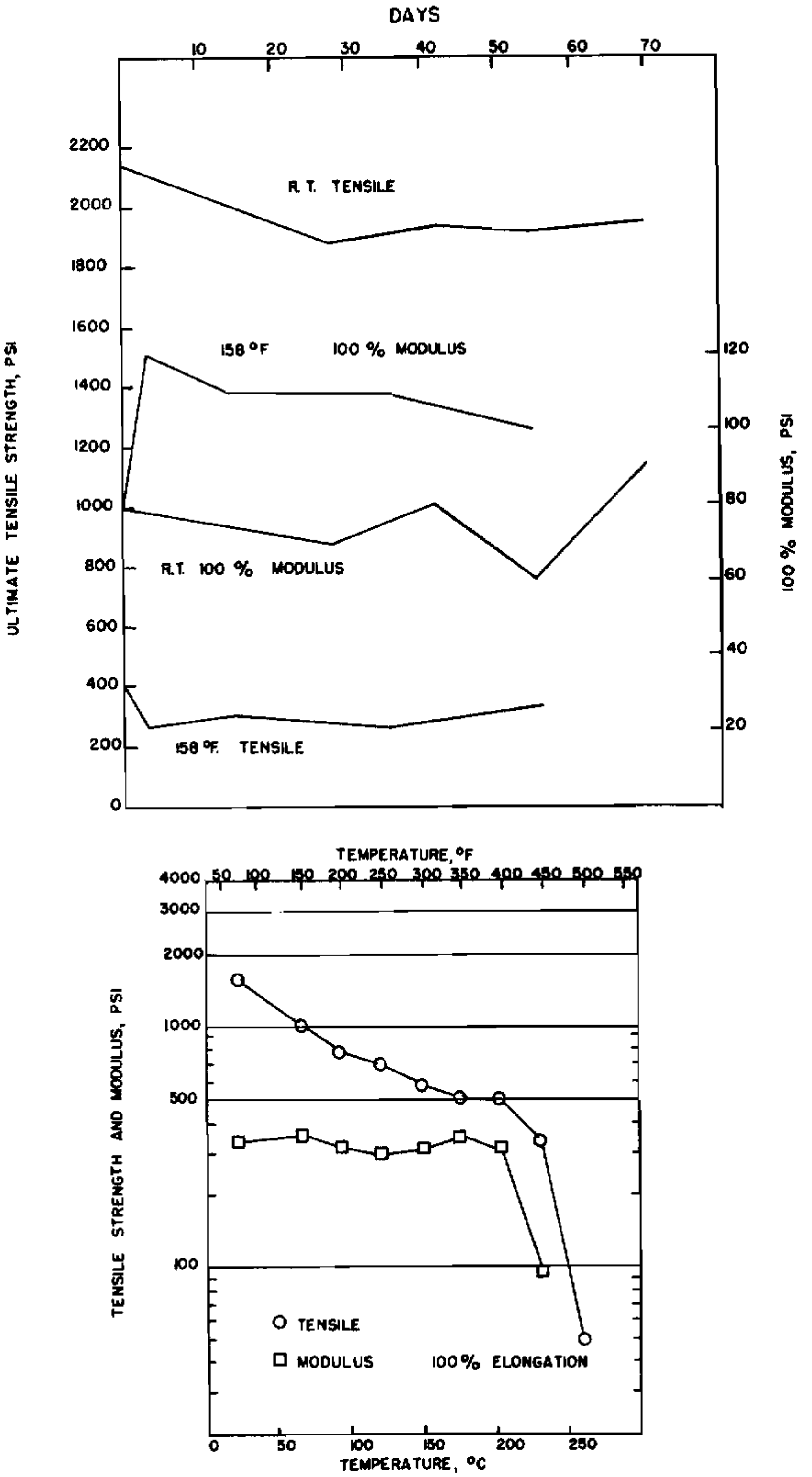


FIGURE 2-42 (2.3.2.2). THE EFFECT OF LONG TIME EXPOSURE AT 158°F ON PROPERTIES AND THE EFFECT OF SHORT TIME EXPOSURE TO VARIOUS TEMPERATURES ON PROPERTIES OF NEOPRENE (REF. 9)

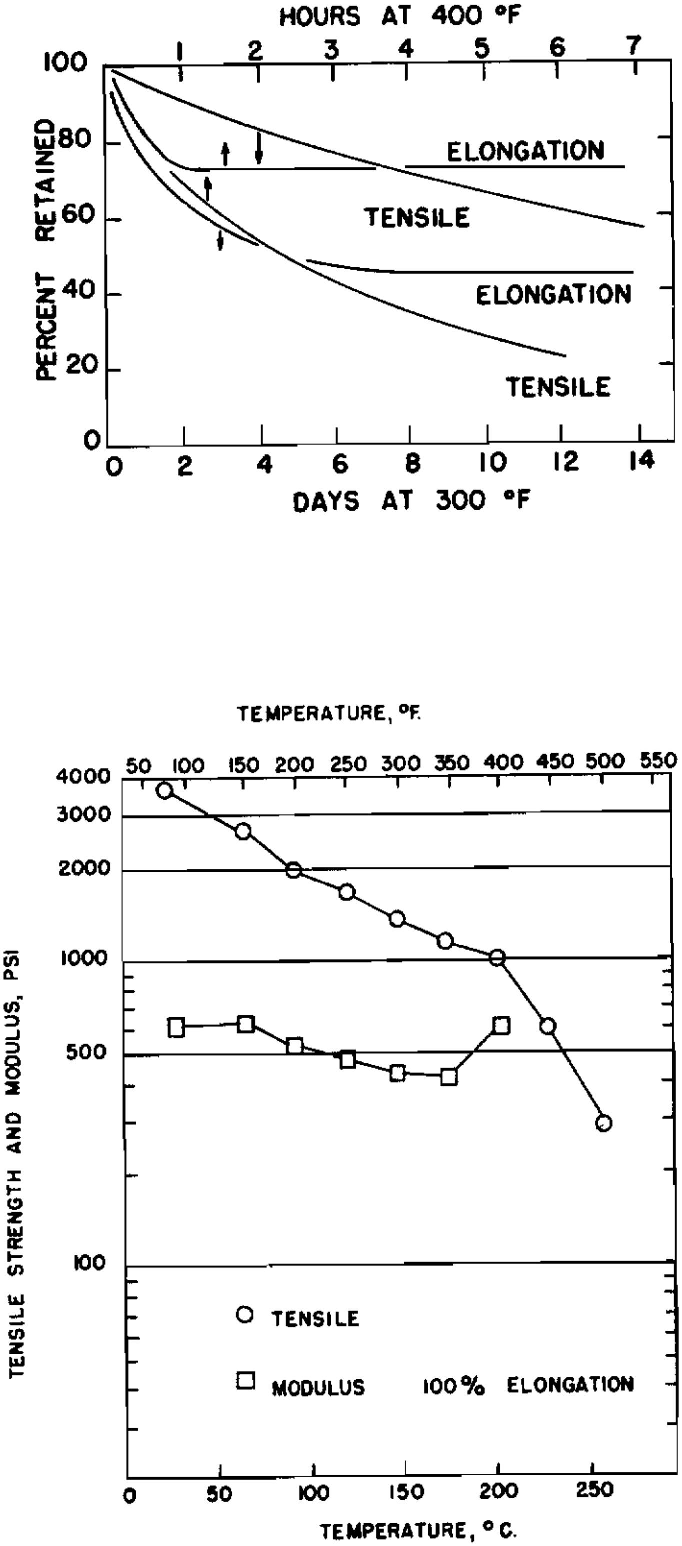


FIGURE 2-43 (2.3.2.2). THE EFFECTS OF ELEVATED TEMPERATURES ON ORDINARY BUTYL ELASTOMERS (REFS. 9, 47)

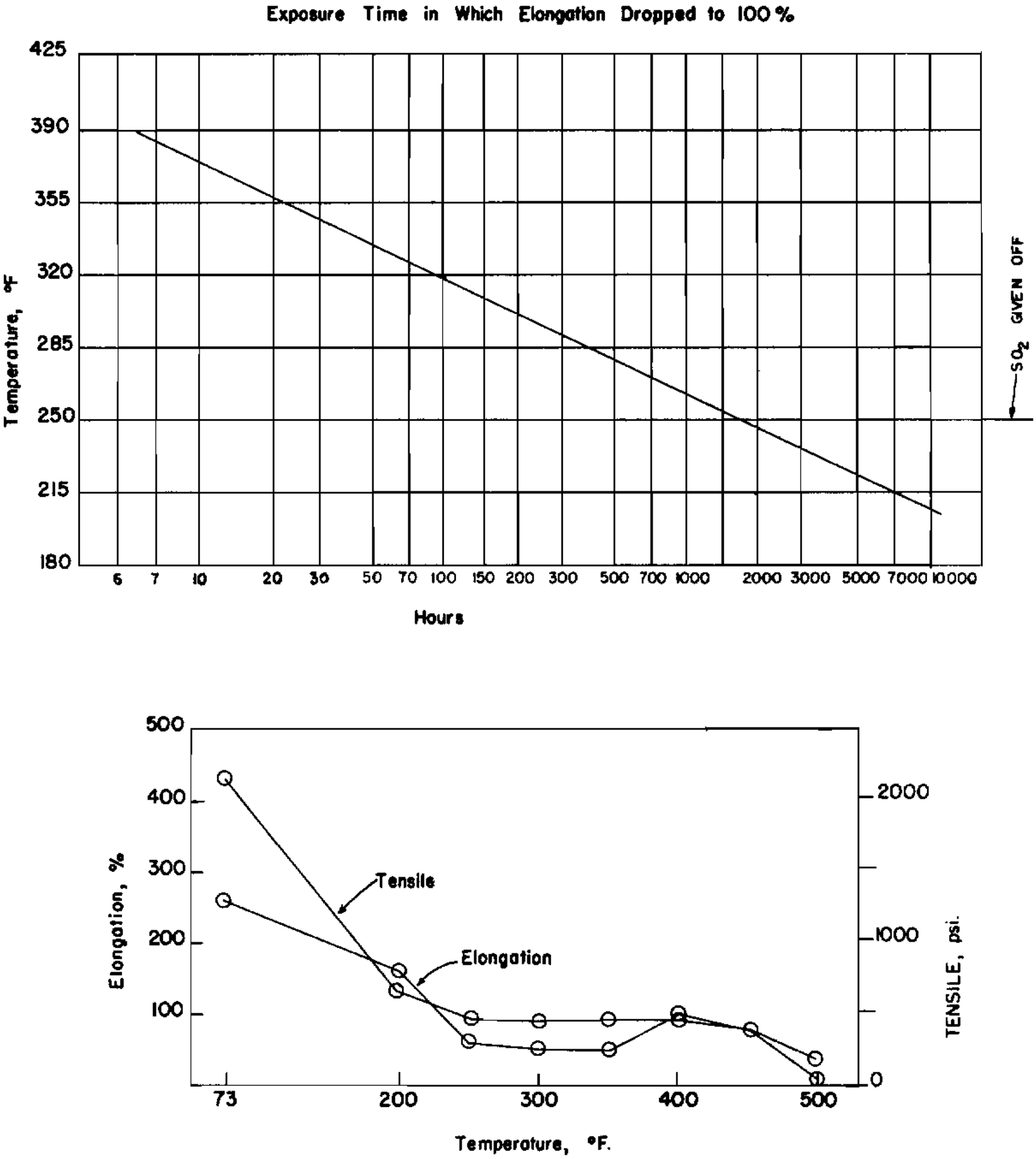


FIGURE 2-44 (2.3.2.2). THE EFFECTS OF ELEVATED TEMPERATURES ON HYPALON (REF. 9 AND MFRS. LITERATURE)

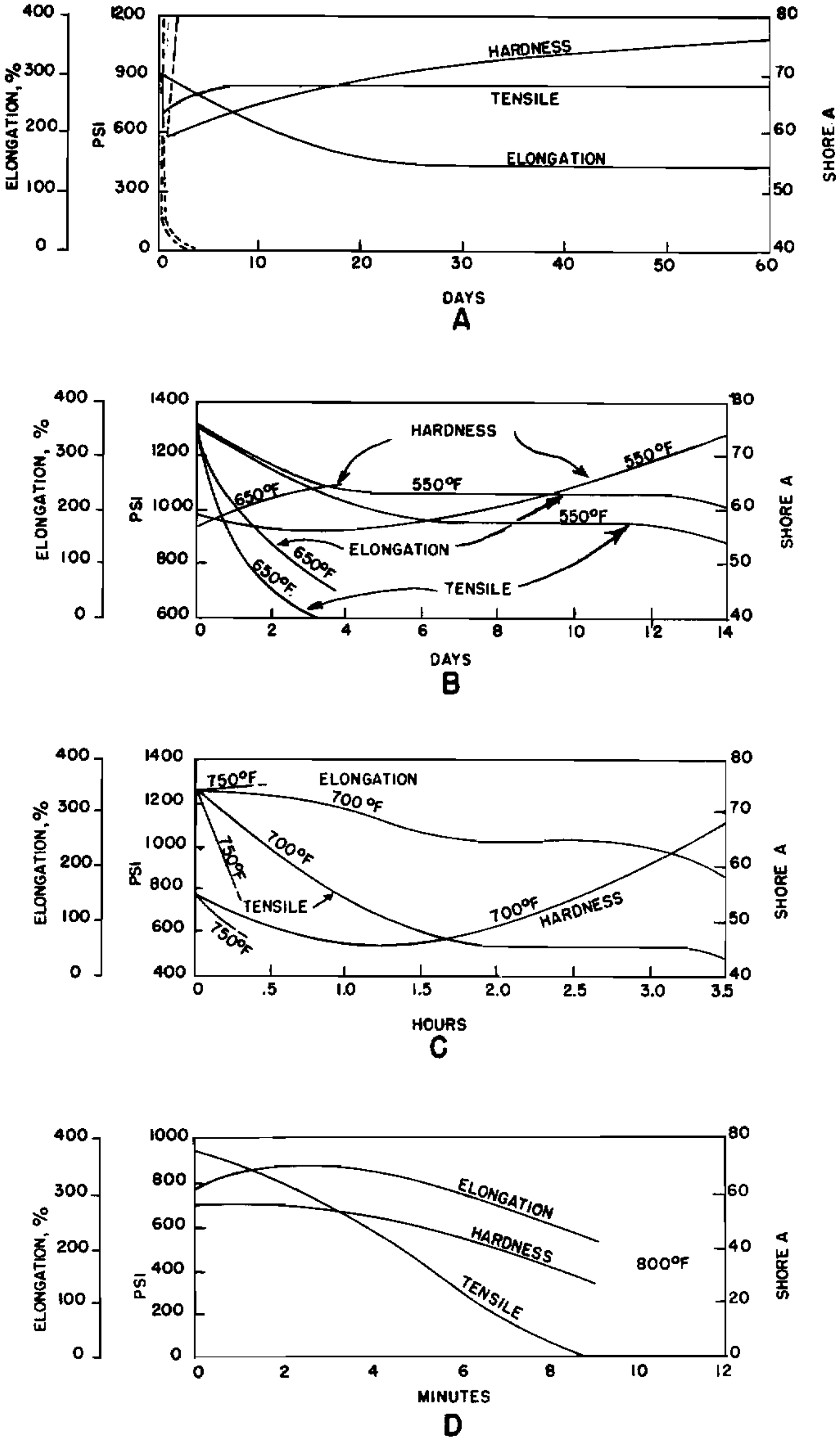


FIGURE 2-45 (2.3.2.2). TEMPERATURE EFFECTS ON SILICONES (REF. 46)

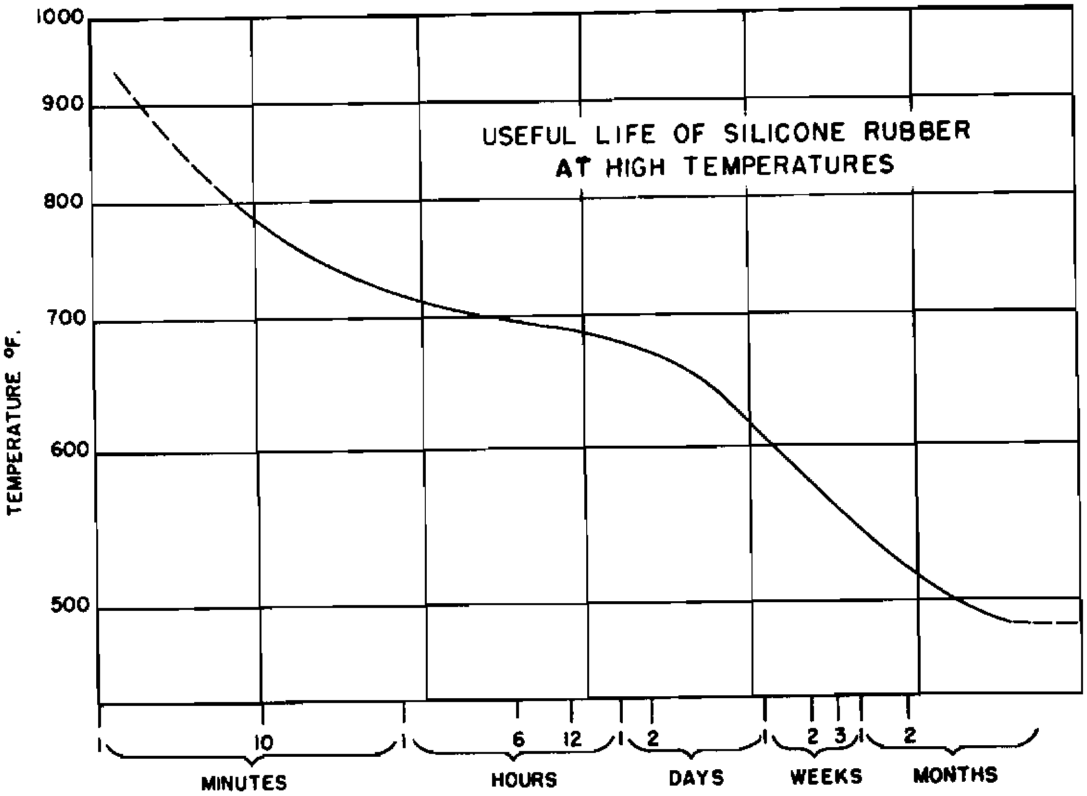


FIGURE 2-46 (2. 3. 2. 2). SILICONE LIFE AT TEMPERATURE CURVE OF BEST HIGH TEMPERATURE COMPOUNDS DEVELOPED FROM DATA OF FIGURE 2-45 (REF. 46)

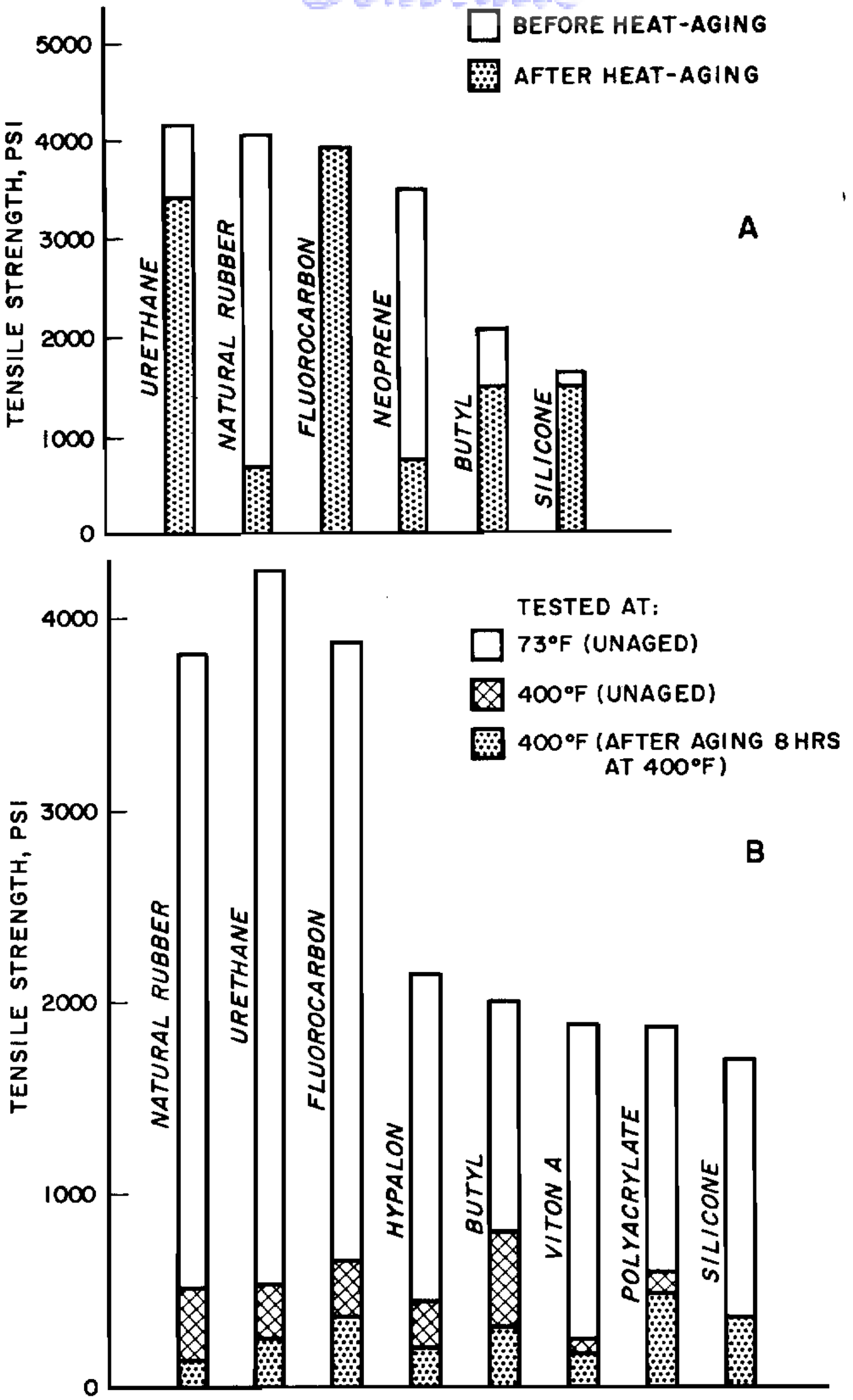


FIGURE 2-47 (2.3.2.2)

A. ROOM TEMPERATURE TENSILE STRENGTH OF ELASTOMERS BEFORE AND AFTER AGING AT 350°F FOR 8 HOURS (REF. 9)

B. TENSILE STRENGTH AT ROOM TEMPERATURE AND 400°F BEFORE AND AFTER AGING AT 400°F FOR 8 HOURS (REF. 9)

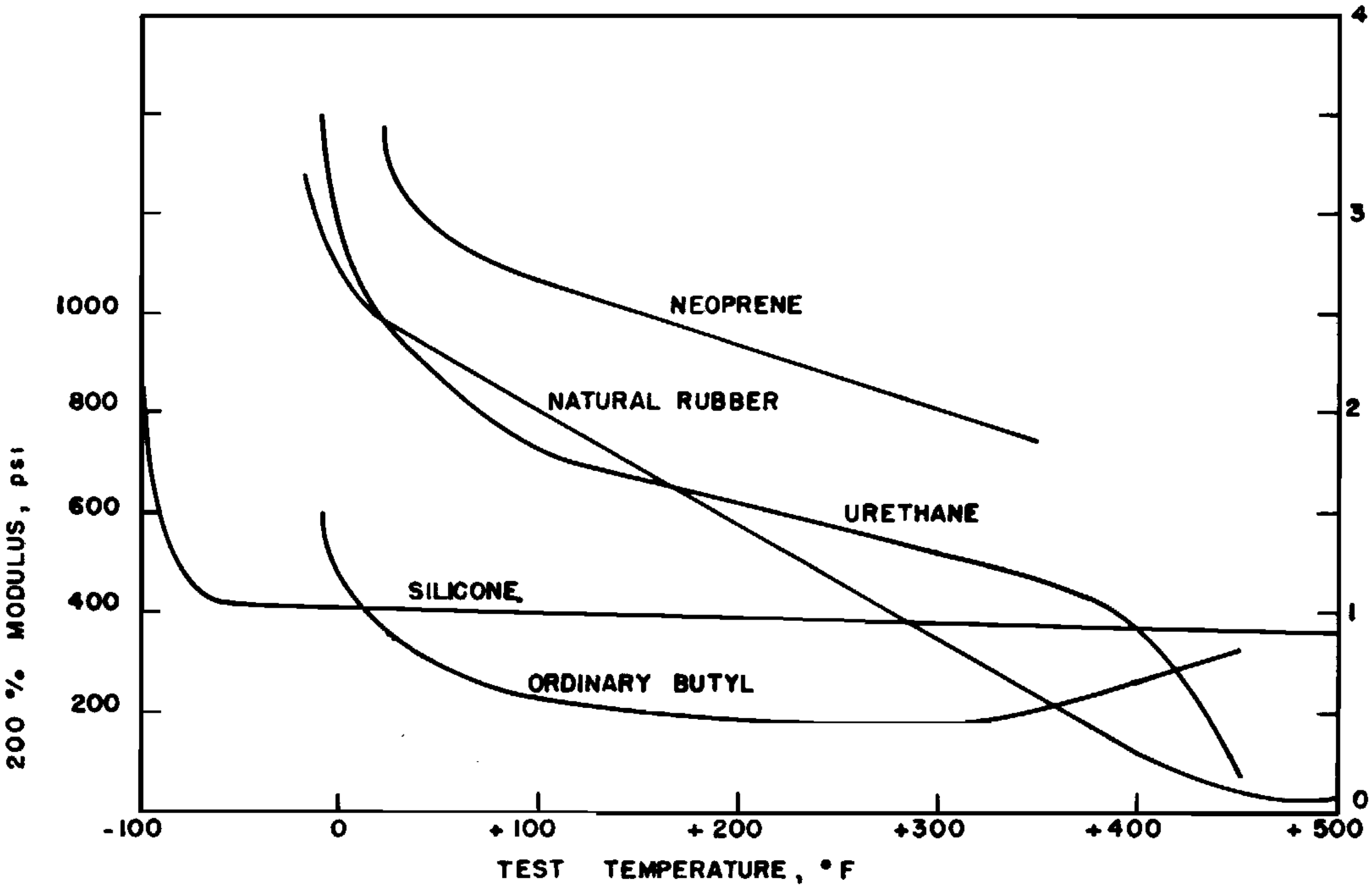


FIGURE 2-48 (2.3.2.2). STIFFNESS OF VARIOUS ELASTOMERS OVER A BROAD TEMPERATURE RANGE (REF. 9)

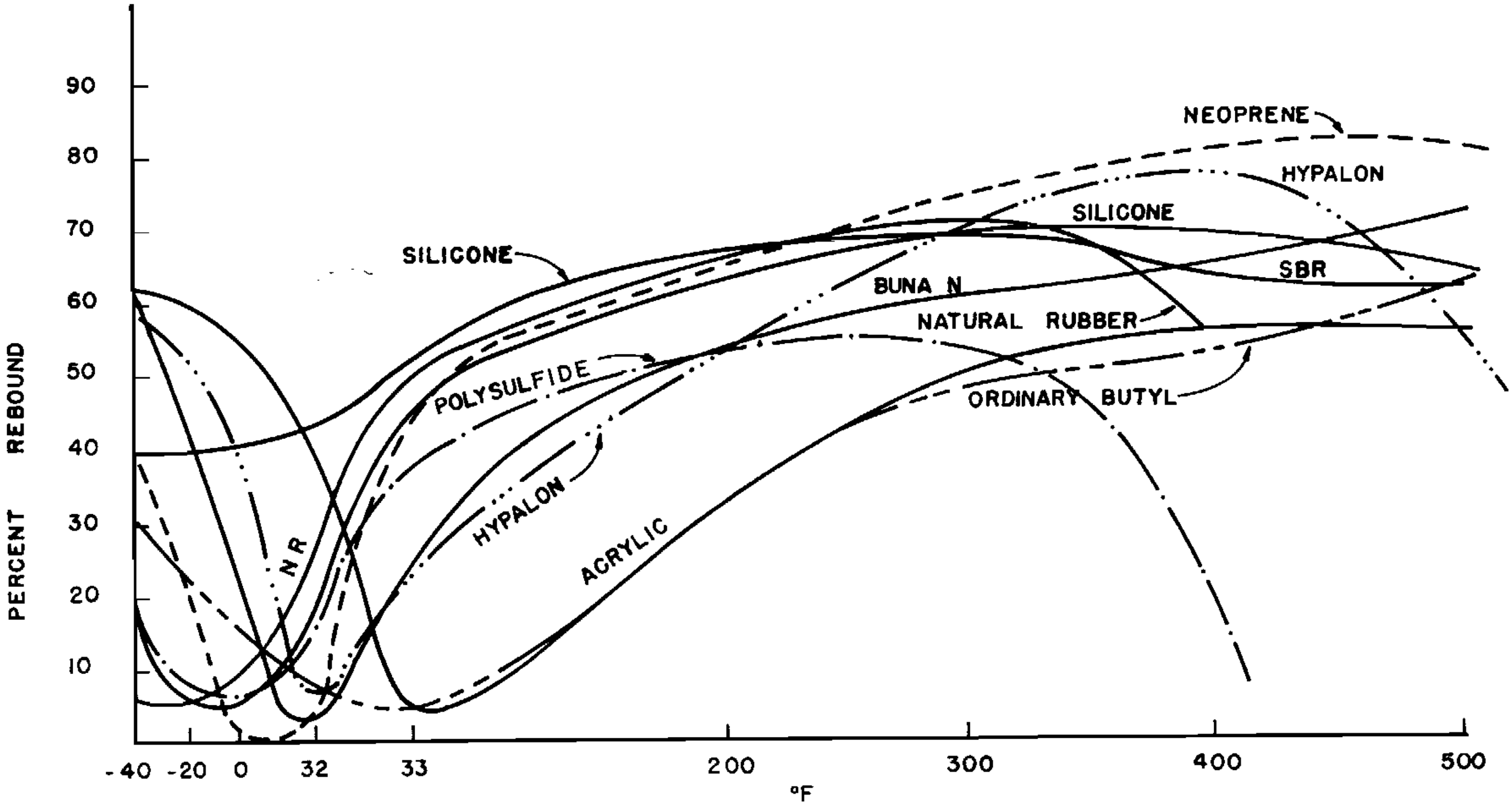


FIGURE 2-49 (2.3.2.2). STEEL BALL REBOUND RESILIENCE OF SEVERAL ELASTOMERS OVER A BROAD TEMPERATURE RANGE (REF. 9)

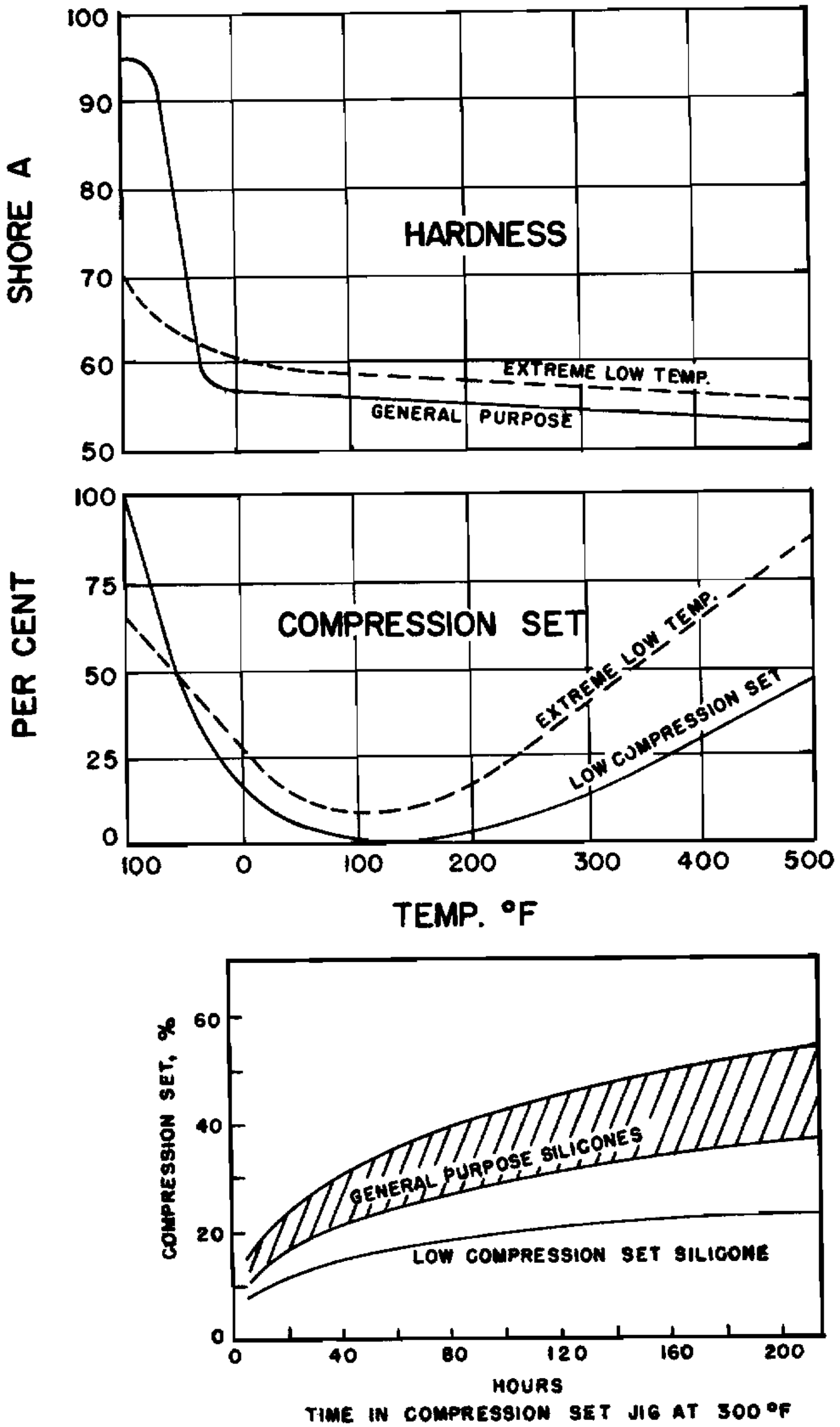


FIGURE 2-50 (2.3.2.2). COMPRESSION SET AND HARDNESS OF SILICONES AS A FUNCTION OF TEMPERATURE AND COMPRESSION SET AS A FUNCTION OF TIME (REF. 46)

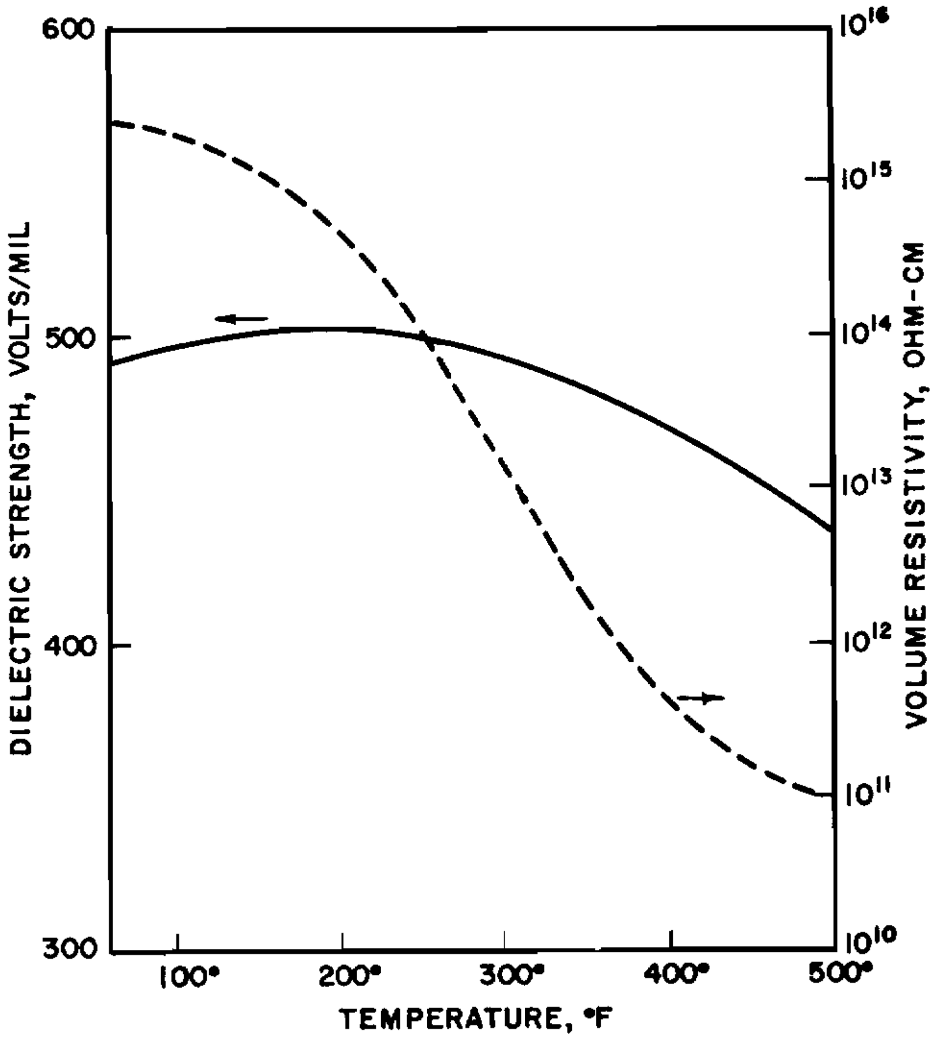


FIGURE 2-51 (2.5). TEMPERATURE DEPENDENCE OF DIELECTRIC PROPERTIES OF A SILICONE (REF. 46)

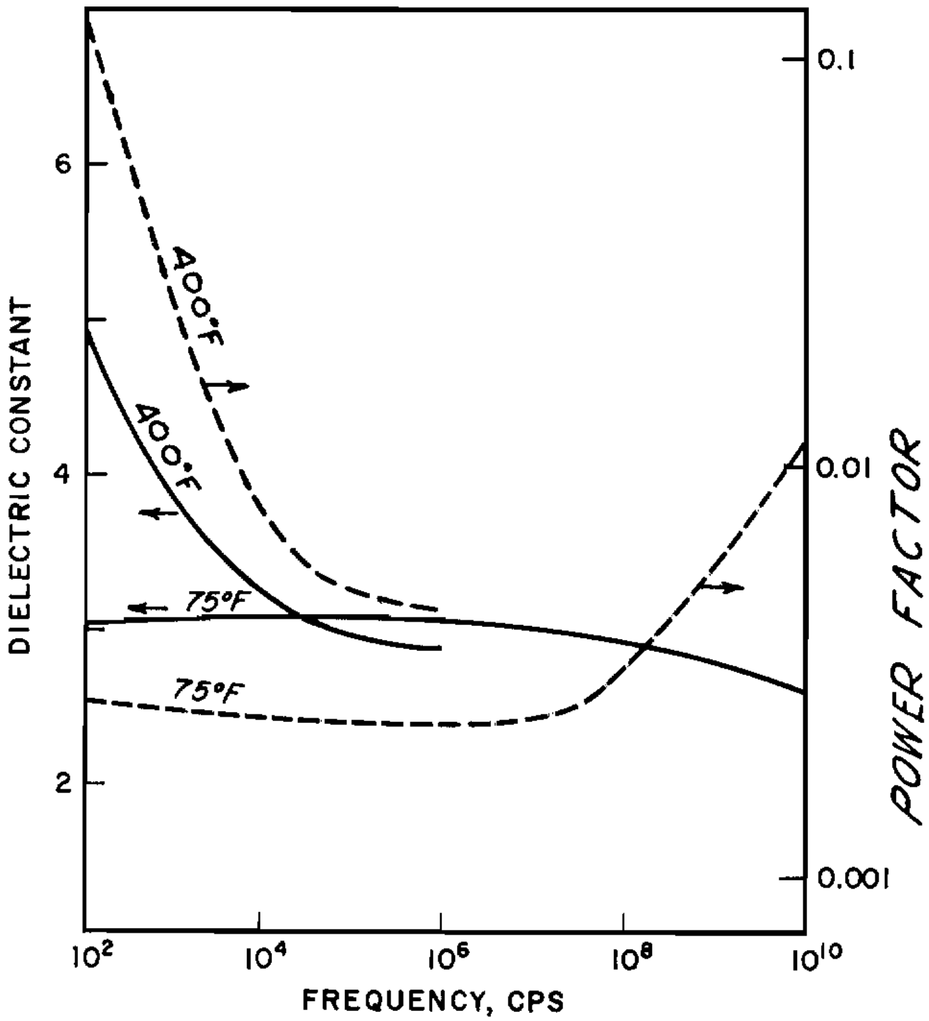


FIGURE 2-52 (2.5). FREQUENCY AND TEMPERATURE DEPENDENCE OF DIELECTRIC PROPERTIES OF A SILICONE (REF. 46)

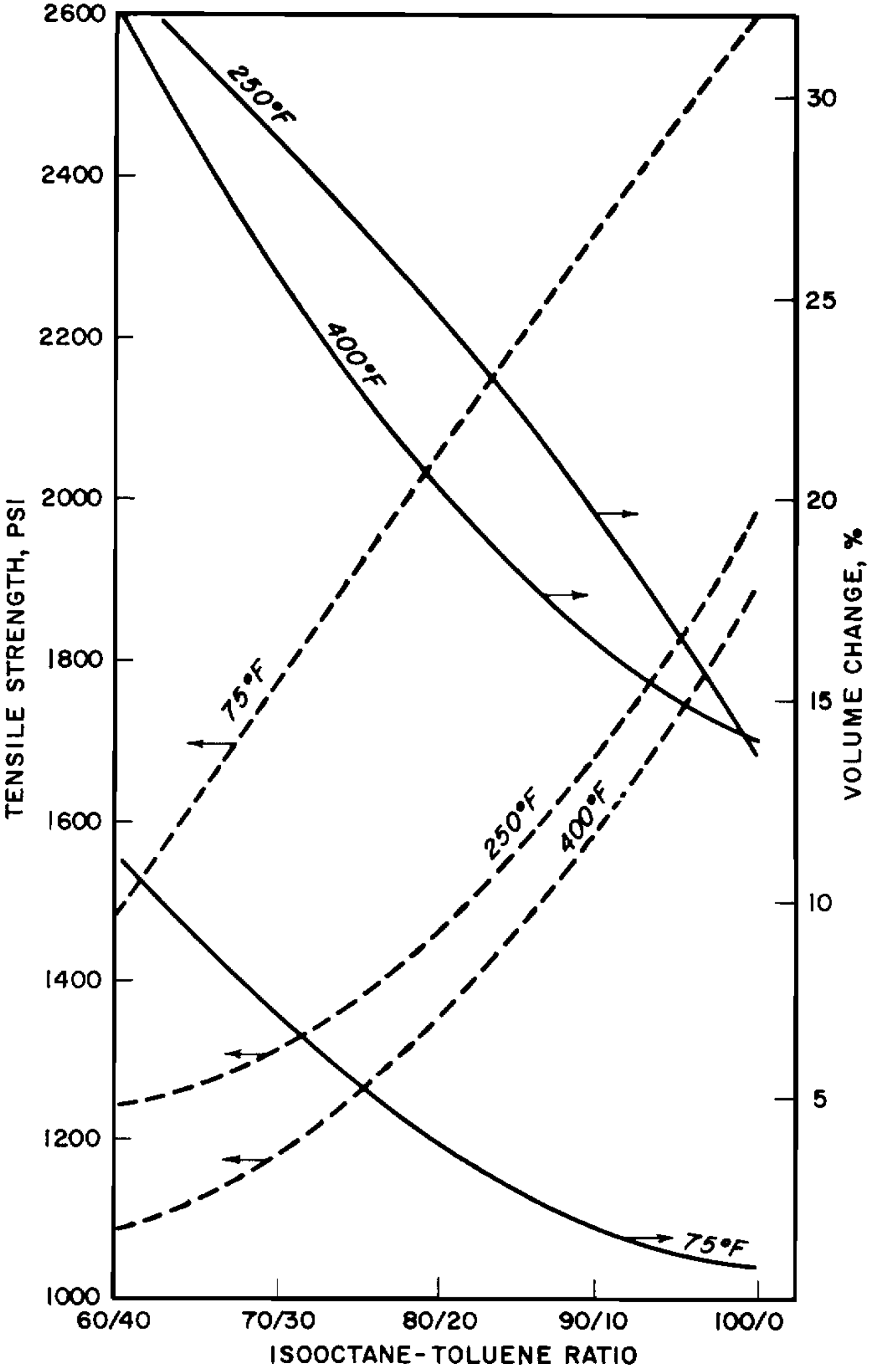


FIGURE 3-1 (3.2.2). EFFECT OF FUEL AROMATICITY ON KEL-F 3700 ELASTOMER AT 75°F, 250°F, AND 400°F (REF. 11)

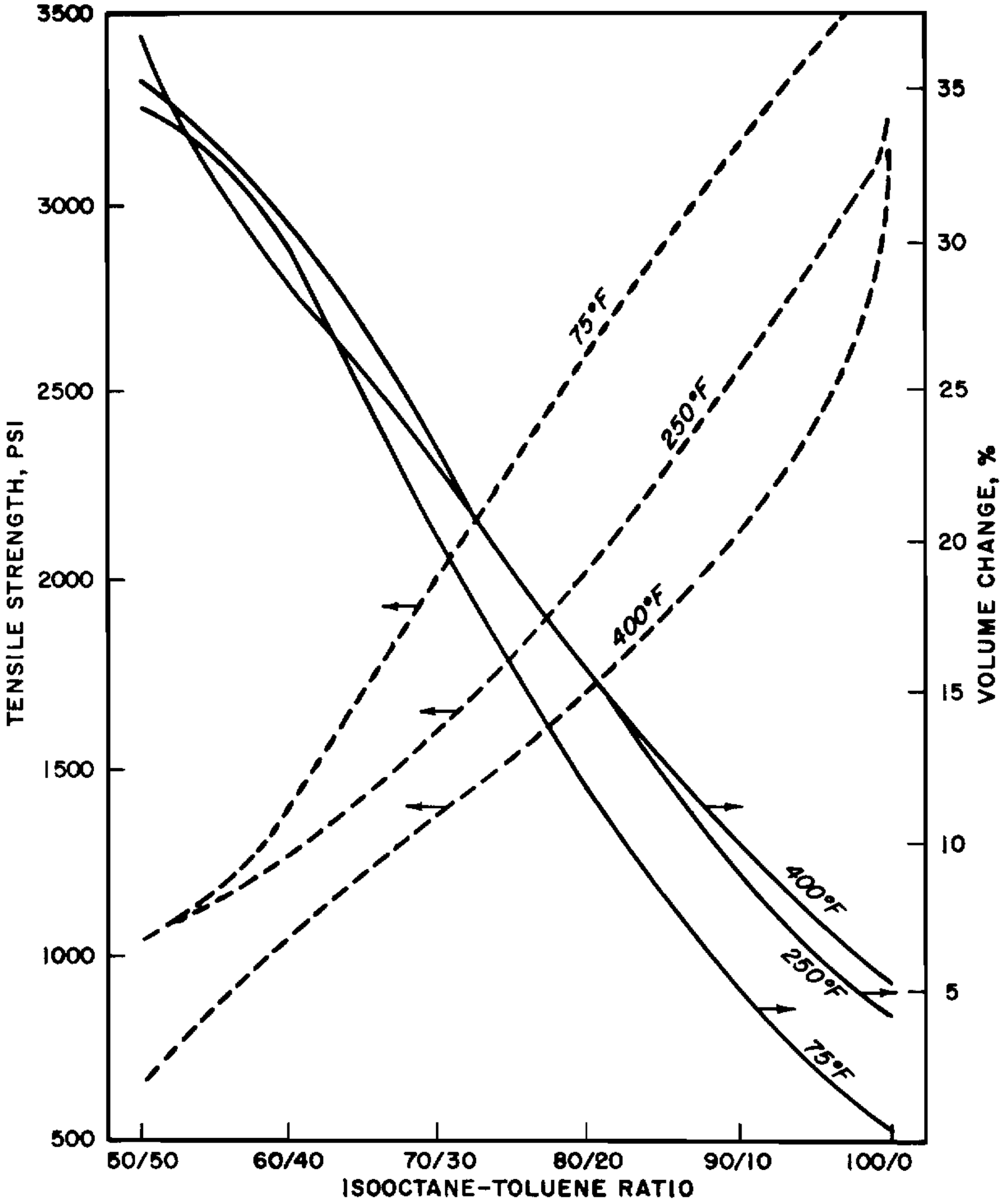


FIGURE 3-2 (3.2.2). EFFECT OF FUEL AROMATICITY ON BUNA N AT 75°F, 250°F, AND 400°F (REF. 11)

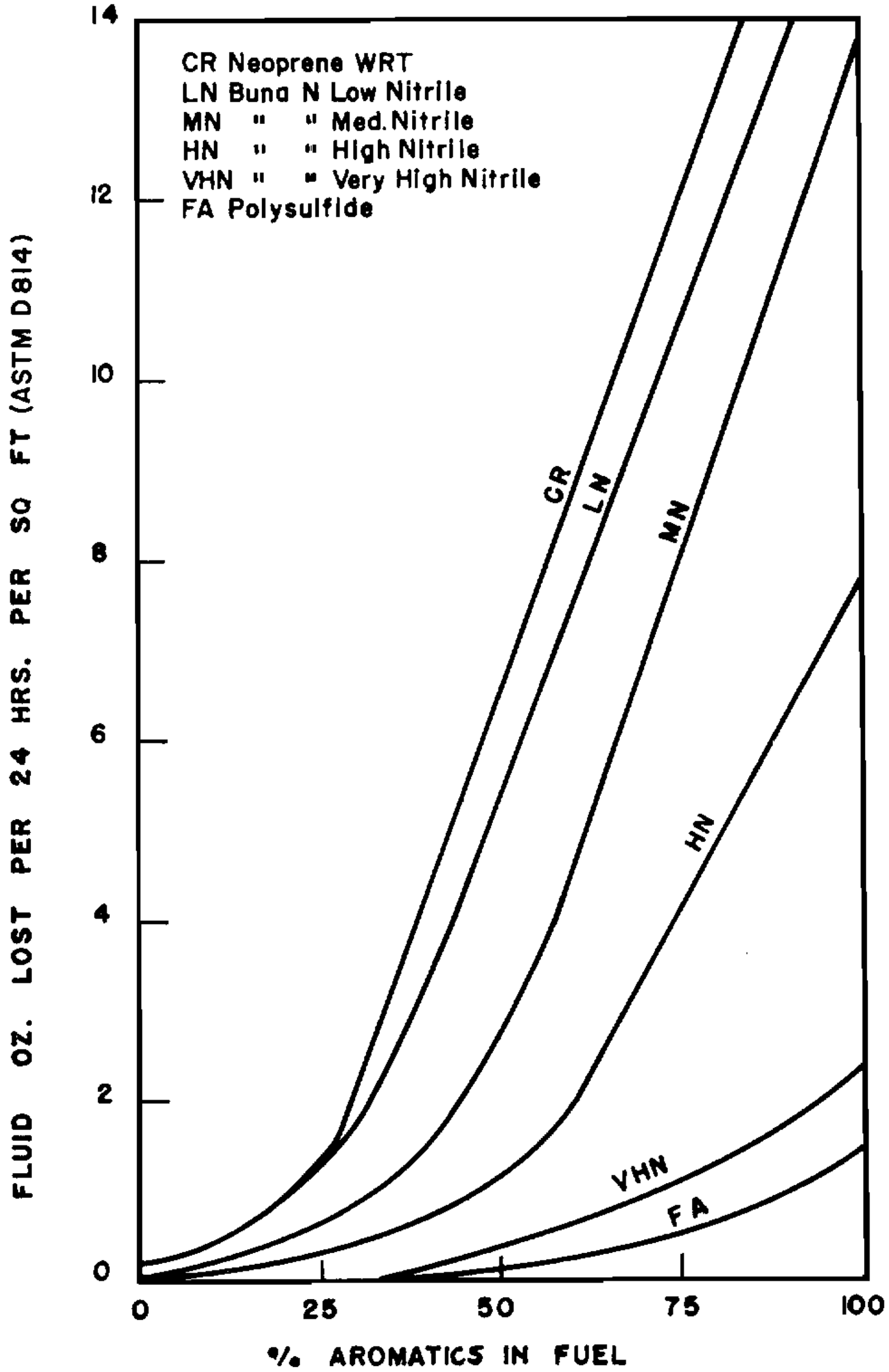


FIGURE 3-3 (3.2.2). CHANGE IN RATE OF PERMEABILITY WITH INCREASING AROMATIC CONTENT IN FUELS (MFRS. LITERATURE)

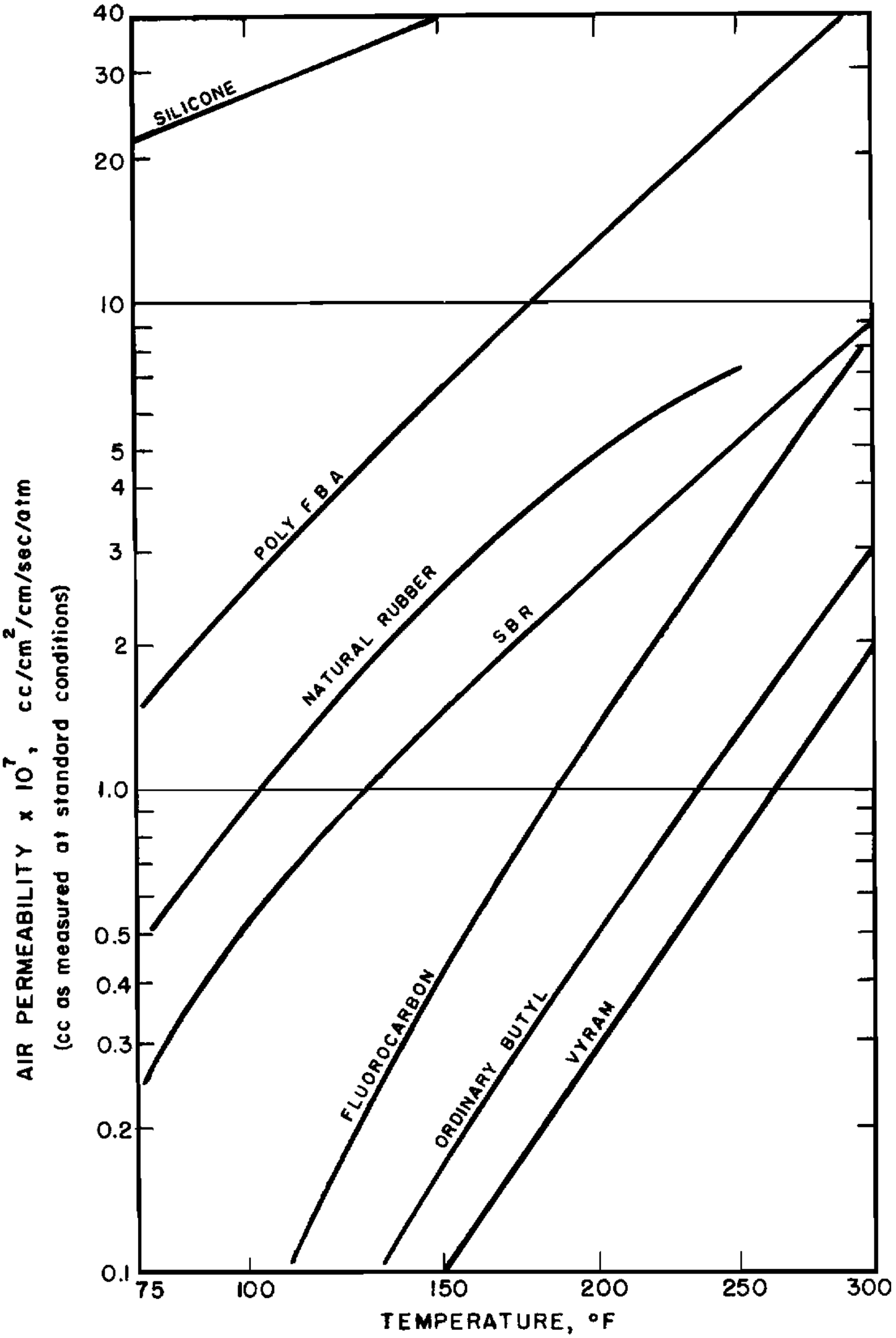


FIGURE 3-4 (3.3). AIR PERMEABILITY OF ELASTOMERS AS A FUNCTION OF TEMPERATURE (REF. 9)

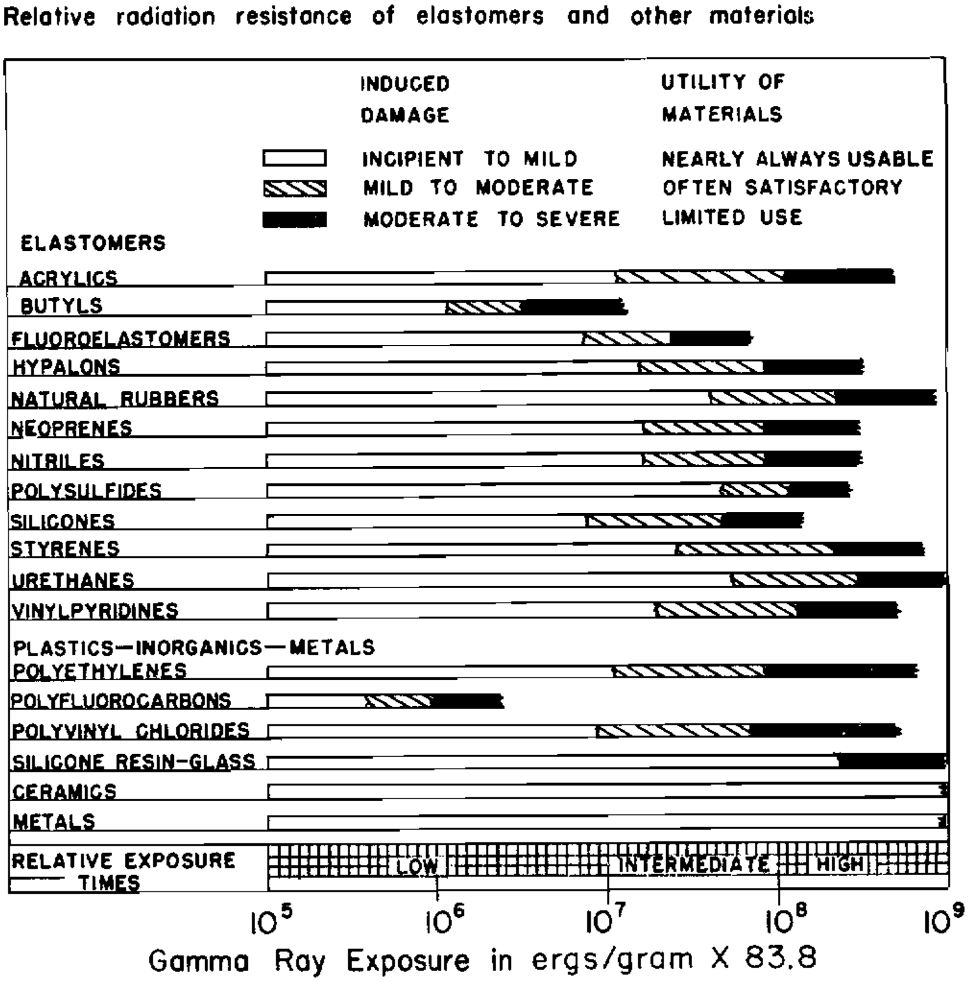


FIGURE 3-5 (3.4). GRAPH OF RELATIVE RADIATION RESISTANCE OF ELASTOMERS AND OTHER MATERIALS (REF. 232)

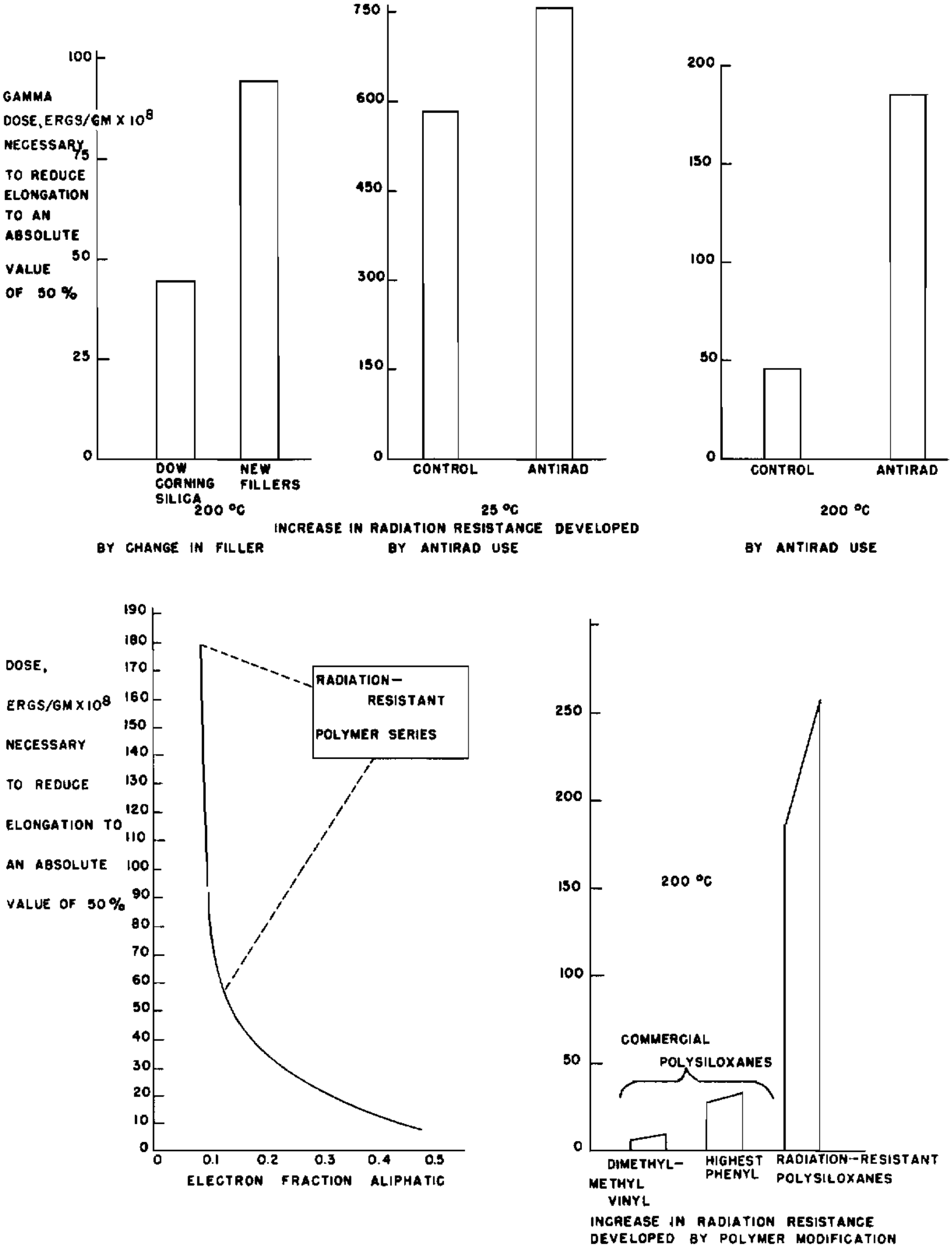


FIGURE 3-6 (3.4). VARIATION OF RADIATION RESISTANCE OF SILICONES (SHOWING THE EFFECTS OF COMPOUNDING VARIABLES AND HIGH POLYMER MODIFICATION) (REF. 91)

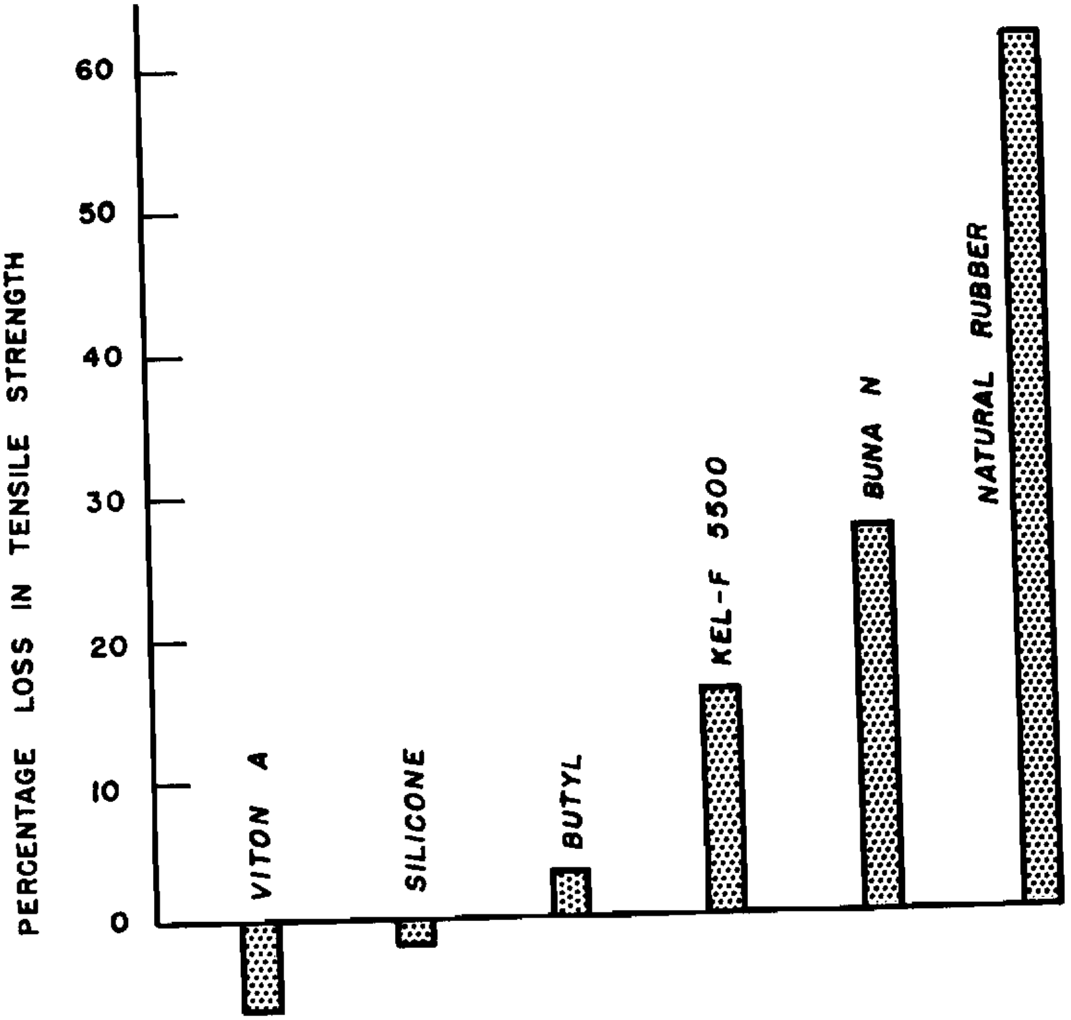


FIGURE 4-1 (4.3.1). PERCENTAGE LOSS OF TENSILE STRENGTH OF SECOND 0.075-IN. SLAB IN RUBBER PAD CONTACTED WITH 800°F METAL SURFACE FOR 3 MINUTES (REF. 134)

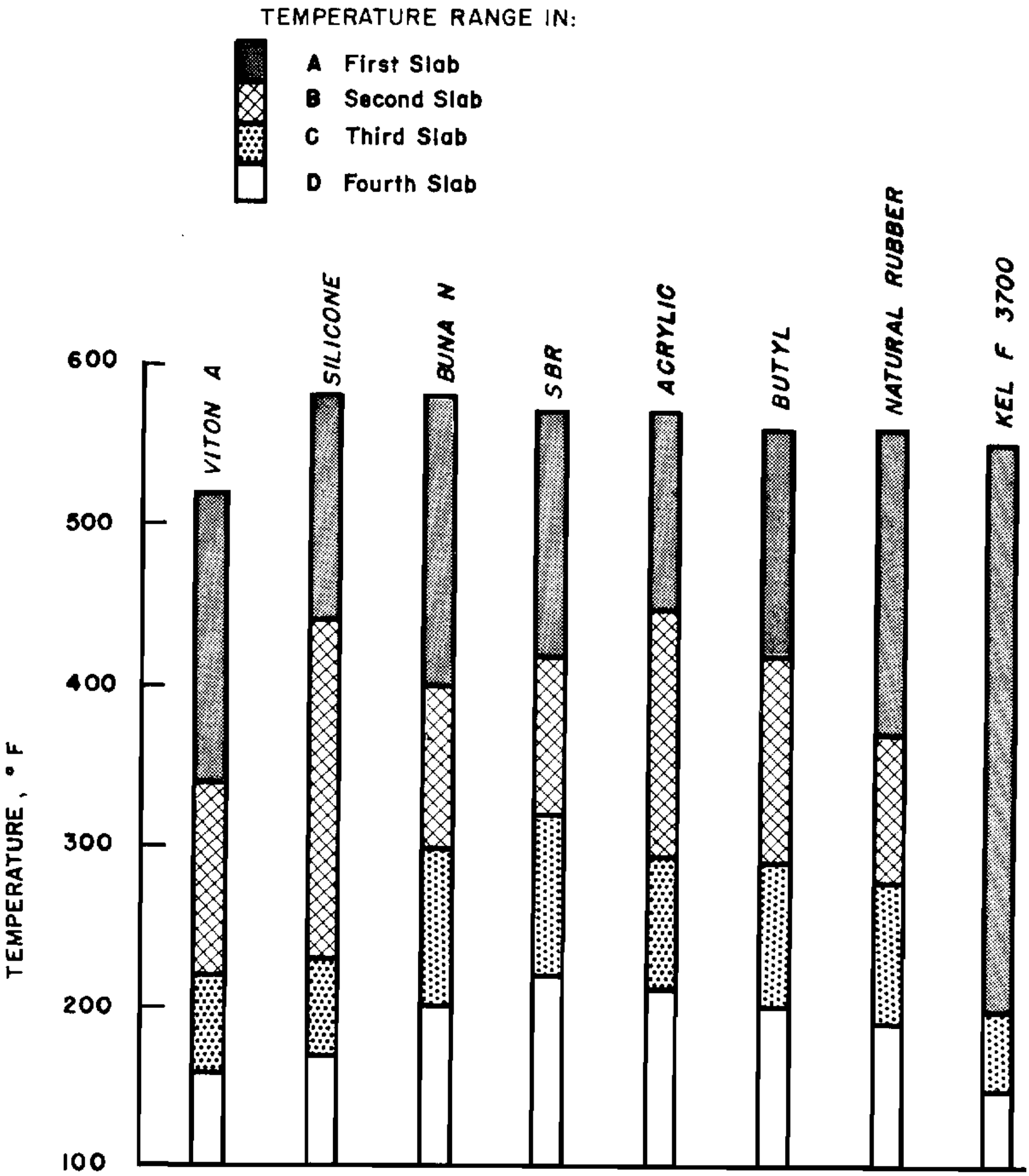


FIGURE 4-2 (4.3.1). TEMPERATURE DISTRIBUTION IN PAD OF 0.075-IN. RUBBER SLABS AFTER 3-MINUTE CONTACT WITH 800°F METAL SURFACE (REF. 134)

√

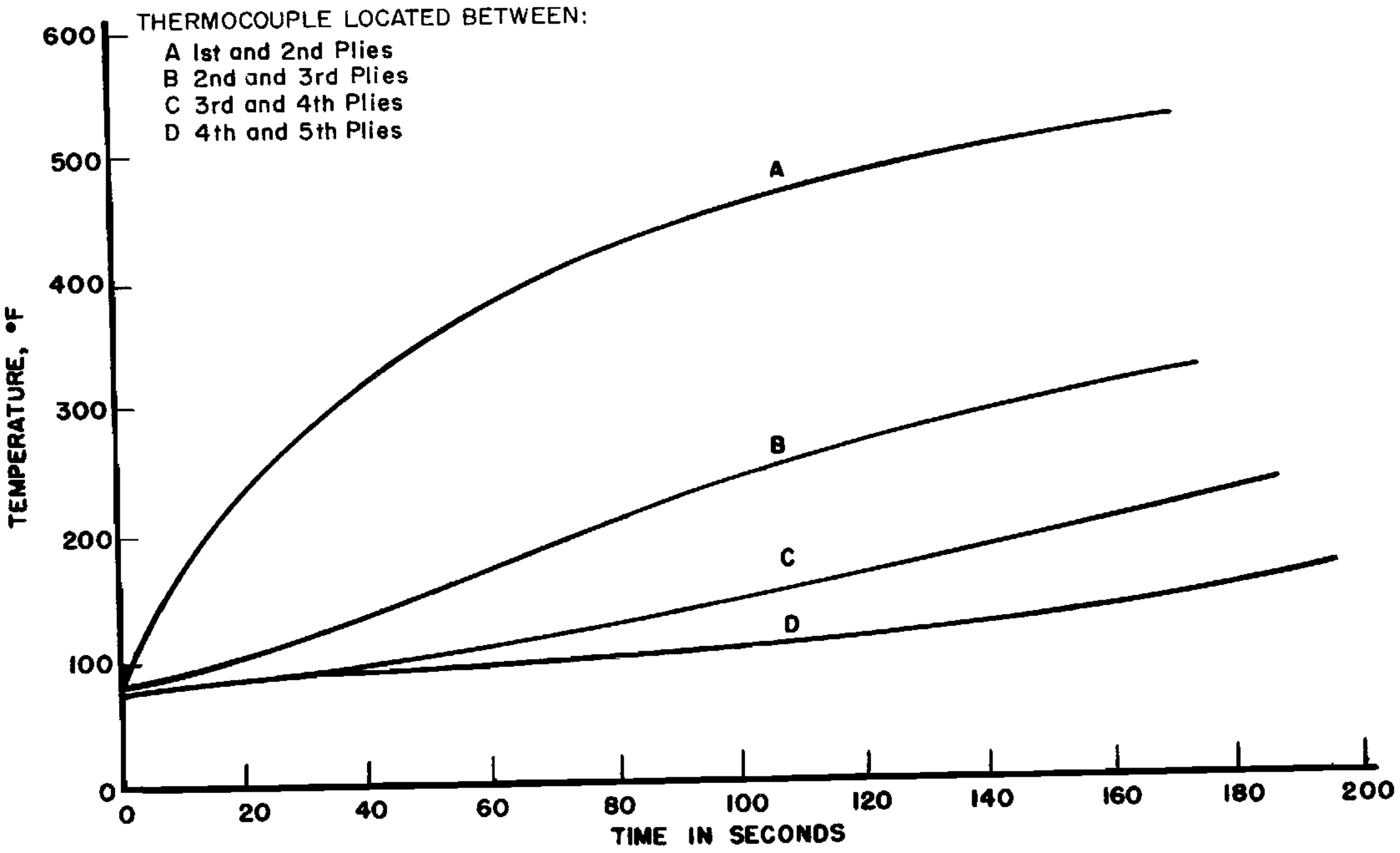


FIGURE 4-3 (4.3.1). TEMPERATURE VERSUS TIME OF VITON A IN CONTACT WITH METAL HOT PLATE AT 800°F (0.075-IN. SLABS) (REF. 134)

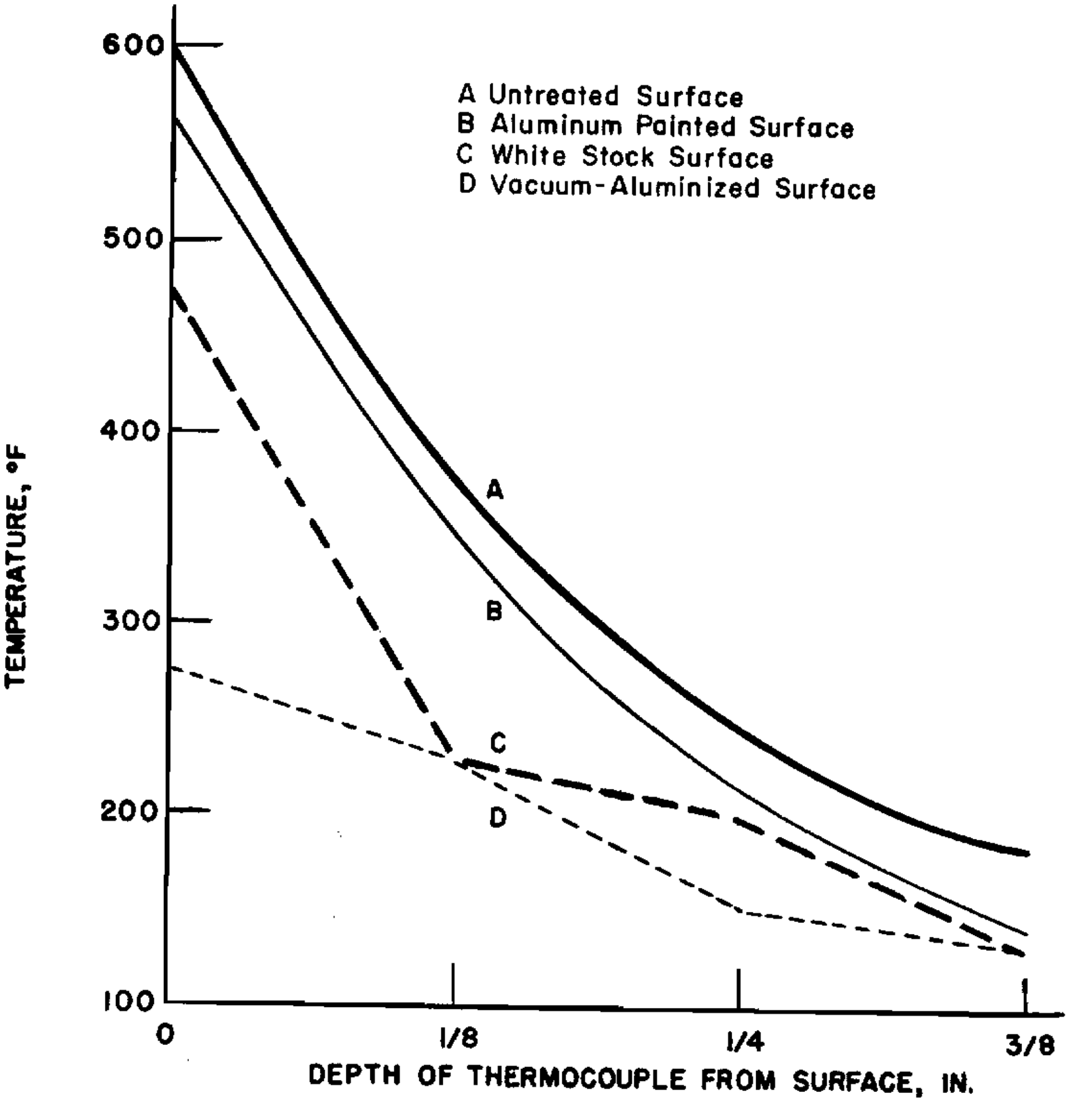


FIGURE 4-4 (4.3.1). TEMPERATURES IN 6 IN. × 6 IN. × 0.5 IN. BUTYL RUBBER SLAB AFTER 3-MINUTE EXPOSURE 0.25 IN. FROM A 1000°F METAL SURFACE (REF. 134)

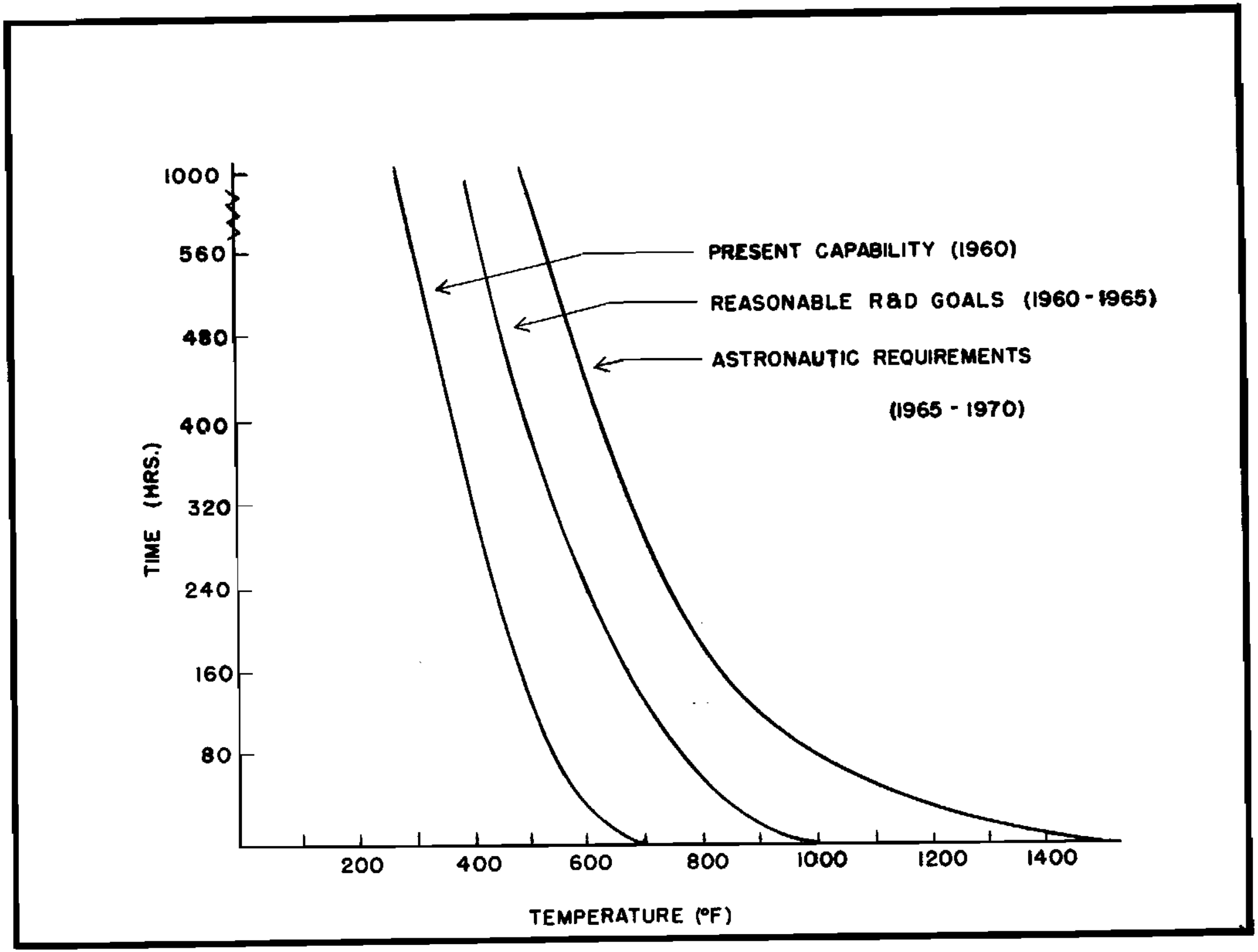


FIGURE 4-5 (4.3.1). TIME-TEMPERATURE USEFULNESS OF ELASTOMERS (REF. 104)

TABLES

TABLE 1-1 (1, 2, 3). ELASTOMER CLASSIFICATION*

Chemical Name	Common & Trade Names	Monomer or Polymer Names
Chemically Converted Plastic		
Halogen substituted thermoplastic	Hypalon	Chloro sulfonated polyethylene
Homopolymer		
Natural Rubber	NR, Crude Rubber, Hevea, Smoked Sheet, Crepe	Isoprene
Synthetic Polyisoprene	IR, Coral Rubber, Ameripol SN, Natsyn	
Polybutadiene	BR, Butadiene, Diene, Buna 85, Philprene-cis-4, cis-1	Butadiene
Polychlorobutadiene	CR, Chloroprene, Neoprene, GR-M, Perbunan C	2-chloro-1, 3-butadiene
Polyacrylate	Vyram	2-cyano ethoxy ethyl acrylate
Fluoroacrylate	Poly FBA, 3M1F4, 3M2F4	Perfluoro alkyl and perfluoro alkoxy acrylates
Copolymer		
Styrene-Butadiene	SBR, Buna S, GR-S, Styrene, Ameripol, ASRC, Baytown, Carbomix, Copo, FR-S Gentro, Naugapol, Philprene, Plioflex, Polysar (Kryflex, Krylene, Krynol & S), Shell, Synpol	Styrene & butadiene
Isobutylene Isoprene	IIR, Butyl, GR-(I)	Isobutylene & isoprene
Bromobutyl	Hycar 2202	Brominated IIR
Chlorobutyl	Enjay MD-551	Chlorinated IIR
Nitrile Butadiene	NBR, Nitrile, Buna N, Perbunan, Butaprene Chemigum, Herecol,	Acrylonitrile & Butadiene

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*Each type of elastomer can be identified by several names. This table groups the more commonly used names according to chemical classification. The underlined names designate those used in this handbook.

TABLE 1-1 (1. 2. 3). ELASTOMER CLASSIFICATION* (Cont'd)

Chemical Name	Common & Trade Names	Monomer or Polymer Names
Nitrile Butadiene (Cont'd)		
	Hycar, Paracril, Polysar Krynac	
Carboxylic	Hycar 1072	Carboxylated NBR
Ethylene-Propylene Copolymer	Montecatini (Italy) C23	Ethylene and Propylene
Polyacrylic	Hycar 4021, Hycar PA, Lactoprene EV,	Ethyl acrylate & chloroethyl vinyl ether
	Acrylon BA, Lactoprene BN,	Butyl acrylate & acrylonitrile
	Acrylon EA, Acrylic	Ethyl acrylate & acrylonitrile
Butadiene MVP	Philprene VP, Vinyl Pyridine (also terpolymer with acrylonitrile)	Butadiene & 2-methyl-5 vinylpyridine
Fluorocarbon	Kellogg 214, Viton, Fluorel	Vinylidene fluoride & hexafluoro propylene
	Kel-F Elastomer	Vinylidene fluoride & chloro-trifluoro ethylene
Polycondensation Product		
Polysulfide	Thiokol	Sodium polysulfides & aliphatic dihalogens
Polysiloxanes	Silicone (G. E. & Union Carbide), Dow Corning Silastic	Dimethyl, methyl phenyl, methyl vinyl, and methyl phenyl vinyl polysiloxanes
Fluorinated	LS-53	Methyl trifluoro propyl polysiloxane
Cyano Substituted	Nitrile Silicone	Cyano Ethyl or cyano methyl substituted dimethylsiloxane
Diisocyanate	Urethane, Adiprene, Chemigum SL, Daykollan,	Diisocyanates & polyesters or polyethers

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*Each type of elastomer can be identified by several names. This table groups the more commonly used names according to chemical classification. The underlined names designate those used in this handbook.

TABLE 1-1(1, 2, 3). ELASTOMER CLASSIFICATION* (Cont'd)

Chemical Name	Common & Trade Names	Monomer or Polymer Names
Diisocyanate (Cont'd)		
	Elastocast, Estane, Flexithane, Genthane, Multrathane, Neothane, Rigithane, Solithane, Vibrothane, Vulkollan	
Fluorinated Polyester	Polyester	Adipyl chloride and hexafluoro pentanediol

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Each type of elastomer can be identified by several names. This table groups the more commonly used names according to chemical classification. The underlined names designate those used in this handbook.

TABLE 1-2.(1.2.4). STANDARD TEST METHOD OUTLINE

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
I. Test Methods Related to Mechanical Properties of Elastomers		
A. Durometer Hardness	D676	FTM3021 FTM5511
B. Tension Properties		
1. Tensile Stress or Modulus	D412	FTM4131
2. Tensile Strength	D412	FTM4111
	D1414	
3. Ultimate Elongation	D412	FTM4121
	D1414	
4. Set at Various Elongations	D412	FTM4411
5. Set at Break	D412	---
C. Tear Strength		
1. Crescent and Angle Tear Resistance	D624	FTM4211
2. Strip Tear Resistance	---	FTM4221
D. Static Compression Properties		
1. Deflection as a Function of Load	D575	---
	D945	---
2. Load at Specified Deflection	D575	---
	D945	---
3. Tangent Modulus	D945	---
4. Compression Set	D395	FTM3311
	D945	FTM3311
5. Compression Stress Relaxation	D1390	---
6. "Compression"	---	FTM3321
7. "Recovery"	---	FTM3321
		FTM3331
8. Compressibility	---	FTM3331
9. Creep	D945	---

TABLE 1-2. (1. 2. 4). STANDARD TEST METHOD OUTLINE (Cont'd)

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
E. Static Shear Properties		
1. Static		
a. Load-Deformation	D945	---
b. Static Modulus	D945	---
c. Modulus of Rigidity	D1043 D1053	FTM5611
d. Set	D945	---
e. Creep	D945	---
F. Abrasion Resistance	D394	FTM1411
G. Dynamic Properties		
1. Response		
a. Effective Dynamic Modulus	D945	FTM3411
b. Frequency	D945	FTM3411
c. Spring Constant	D945	FTM3411
d. Yerzley Resilience	D945	FTM3411
e. Set	D623 D945	FTM3411
f. Heat Buildup	D623	---
2. Flexing		
a. Cycles to Failure	D430 D623	---
b. Severity of Cracking	D430	---
c. Cracking Rate	D430	---
d. Permanent Set	D623	---
e. Crack Growth	D813 D1052	---
f. Heat Buildup	D623	---
g. Equilibrium Temperature	D623	---

TABLE 1-2. (1.2.4). STANDARD TEST METHOD OUTLINE (Cont'd)

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
3. Impact		
a. Resilience	D1054	---
b. Penetration	D1054	---
H. Low Temperature Properties		
1. Brittleness	D736 D746	FTM5311 FTM5321
2. Brittle Temperature	D736 D746	---
3. Young's Modulus	D796	---
4. Relative Modulus	D796 D1043 D1053	---
5. Modulus of Elasticity	D796 D1043 D1053	---
6. Modulus of Rigidity	D1043 D1053	---
7. Relative Modulus Temperature	D1043 D1053	---
8. Retraction Temperature	D1329	---
9. Beam Stiffness	---	FTM5211
10. Durometer Hardness	---	FTM5511
II. Test Methods Related to Physical Properties of Elastomers		
A. General Physical Tests		
1. Specific Gravity	D297	FTM14011 FTM14021
2. Permeability		
a. Liquids	D814	---
b. Gases (Hose Air Leakage Test Only)	---	FTM10111

TABLE 1-2. (1.2.4). STANDARD TEST METHOD OUTLINE (Cont'd)

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
B. Thermal		
1. Coefficient of Expansion	---	---
2. Conductivity	---	---
3. Specific Heat	---	---
C. Electrical		
1. Insulation Resistance	D257	---
2. Volume Resistivity	D257 D991	FTM9111
3. Surface Resistivity	D257	---
4. Dielectric Constant	D150	---
5. Dielectric Strength	D149	---
6. Power Factor	D150	---
7. Power Angle	D150	---
8. Loss Angle	D150	---
9. Breakdown Voltage	D149	---
III. Test Methods Related to Specific Applications of Elastomers		
1. Adhesion to Metal	D429	FTM8031
2. Adhesive Strength		
a. Metal to Metal	D1002	---
b. Rubber to Metal	D429	ETM8031
c. Rubber to Rubber	---	FTM4311
d. Strength of Splice	---	FTM4311
3. Sealant Properties		
a. Initial Sealing Pressure	D1081	FTM3211
b. Aged Sealing Pressure	D1081	FTM3211

TABLE 1-2. (1.2.4). STANDARD TEST METHOD OUTLINE (Cont'd)

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
4. Hose Tests		
a. Bursting Strength		
(1) Straight Specimen	---	FTM10011
(2) Curved Specimen	---	FTM10021
b. Air Leakage	---	FTM10111
IV. Test Methods Related to Resistance in Change of Properties of Elastomers		
A. Effect of High Temperatures	D454 D572 D573 D865 D1206 D1672	FTM7111 FTM7211 FTM7221 FTM7231 FTM7241
B. Effect of Ozone	D518 D750 D1149 D1171	FTM7311 --- --- ---
C. Effect of Sunlight and Ultraviolet Radiation	D518 D750 D1171	FTM7311 --- ---
D. Effect of Oxygen	D454 D518 D572 D573 D750 D865 D1206 D1672	FTM7111 FTM7211 FTM7221 FTM7231 FTM7241 FTM7311 --- ---

TABLE 1-2.(1.2.4) STANDARD TEST METHOD OUTLINE (Cont'd)

Test Result Nomenclature	ASTM Test Method (Ref. 29)	Federal Test Method (Ref. 89)
E. Effect of Stress	D518	---
	D1149	---
	D1171	---
	D1206	---
	D1672	---
F. Effect of Temperature Changes	D518	FTM7311
	D750	---
	D1171	---
G. Effect of Moisture and Moisture Changes	D518	FTM7311
	D750	FTM7411
	D1171	FTM7421
	---	FTM7431
H. Effect of High Energy Radiation	D1672	---
I. Effect of Immersion		
1. Hydrocarbons	D471	FTM6111
	D1460	FTM6121
	---	FTM6211
	---	FTM6231
	---	FTM6241
	---	FTM6251
2. Water	---	FTM6611
	---	FTM6631
3. Phenol	---	FTM6711

TABLE 2-1 (2.4). THERMAL COEFFICIENTS OF TYPICAL ELASTOMERS COMPARED WITH OTHER ENGINEERING MATERIALS

Material	Coefficient of Linear Expansion, 0.00000 in./in./°F	Specific Heat, BTU/lb/°F	Thermal Conductivity BTU/hr/sq ft/°F/ft
Aluminum*	12.7	0.22	90
Magnesium*	14.3	0.25	60
Plexiglas*	90	0.35	0.15
Mild Steel*	6.5	0.12	27
302 Stainless*	9.8	0.12	9.4
Titanium*	4.0	0.14	4.3
Natural Rubber**	80	0.4	0.08
SBR**	100	0.4	0.14
Buna N**	70	0.4	0.14
Neoprene**	70	0.4	0.11
Butyl**	90	0.4	0.05
Silicone**	150	---	0.12
Fluorocarbon**	80	---	---
Urethane	100	---	---

---

*These values are provided for order of magnitude comparison with elastomer values for the range 70°F to 100°F.

**Values presented are "typical" values recommended for preliminary design use only. Actual values are dependent on temperature range and compounding materials. Conditions of restraint must not be forgotten in predicting behavior; a bonded rubber sandwich, for example, will expand almost three times the linear rate in the unrestrained dimension when heated.

Source: SwRI. Also References 38 and 129.

TABLE 2-2 (2.5). SUMMARY OF ELECTRICAL INSULATING QUALITIES OF SELECTED ELASTOMERS

	Examples of Insulation Values		
	Volume Resistivity, ohms-cm	Power Factor, %	Dielectric Strength, v/mil
Excellent			
Silicone	10^{14}	1	600
Fluorocarbon	10^{13}	4	500
Good			
Butyl	10^{16}	2	600
Natural Rubber	10^{16}	5	500
Hypalon	10^{14}	3	600
SBR	10^{13}	7	500
Fair			
Urethane	10^{12}	4	500
Polysulfide	10^{12}	30	250
Neoprene	10^{10}	20	350
Acrylic	10^{9}	20	350
Poor			
Buna N Insulating	10^{9}	30	350
(Buna N Conductive)	10^{2}	---	---

Source: SwRI. Also References 38, 48, 125, 223, 229.

TABLE 3-1 (3. 1. 1). TENSILE PROPERTIES OF VULCANIZATES BEFORE AND AFTER HEAT AGING IN AIR AND IN NITROGEN

Elastomer Type	Tensile Strength, psi			Elongation, %			200% Modulus, psi		
	A	B	C	A	B	C	A	B	C
Natural Rubber	4125	1125	1775	480	230	230	1400	950	1475
SBR	3725	3100	3000	520	270	250	1000	2100	2225
Butyl (ordinary)	2125	2150	2150	510	450	470	1400	975	975
Hypalon	1225	1650	1500	390	370	350	600	900	950
Neoprene	1325	1525	1450	420	420	410	375	575	600
Buna N	1200	1250	1300	940	780	730	250	325	475
Urethane	5500	5425	5525	430	430	430	1600	1400	1550

A. Original room temperature properties.
B. Room temperature properties after 8 hours at 250° F in air.
C. Room temperature properties after 8 hours at 250° F in nitrogen.

Temperature at which These Elastomers Lose 25% of Room Temperature Tensile Strength when Exposed for Eight Hours at Test Temperature

Natural Rubber	215° F
SBR	275° F
Butyl (ordinary)	325° F
Hypalon	345° F
Neoprene	310° F
Buna N	215° F
Urethane	350° F

Source: Reference 9.

TABLE 3-2 (3.1.2). Z. T. OSSEFORT'S CLASSIFICATION OF ELASTOMERS ACCORDING TO OZONE RESISTANCE

Inherently Ozone-Resistant Elastomers*

- Acrylons
- Hypalon
- Vyram
- Hycar 4021
- LS-53
- Kel-F Elastomer
- Poly FBA
- Silicone
- Viton A

Ozone Resistant (without antiozonant) If Properly Compounded

- Brominated Butyl
- Butyl
- Neoprene
- Urethane (Genthane S)

Ozone Resistant If Properly Compounded with Antiozonant

- Buna N
- Carboxylic Buna N
- SBR
- Vinyl Pyridine
- Natural Rubber
- Synthetic cis 1-4 Polyisoprene
- cis 1-4 Polybutadiene
- Conventional Polybutadiene
- Mercaptan modified adducts of Polybutadiene
- Polysulfide
- Urethane (Adiprene B, C)

---

*Many of these designations are trade names referring to specific elastomers, see Table 1-1 for classification of these materials.

TABLE 3-2 (3.1.2). Z. T. OSSEFORT'S CLASSIFICATION OF ELASTOMERS ACCORDING TO OZONE RESISTANCE (Cont'd)

Time to First Crack of Some of the Elastomers Whose Ozone Resistance is Dependent on Compounding

Elastomer Type*	Ozone Concentration 25 ± 5 pphm	50 ± 5 pphm	Outdoors	Remarks
Carboxylic	1 day	6 hours	13 weeks	No antiozonant
Carboxylic	3 days	1 day	11 months	With antiozonant
Carboxylic	>1 year	>1 year	>1 year	With another antiozonant
Urethane # 1	8 days	7 days	2 weeks	No antiozonant
Urethane # 2	4 days	---	2 weeks	No antiozonant
Urethane #3	>30 days	>30 days	>1 month	No antiozonant
Polysulfide #1	1 day	6 hours	---	No antiozonant
Polysulfide #2	1 day	6 hours	---	No antiozonant
cis 1-4 Polyisoprene	2 hours	2 hours	4 days	No antiozonant
cis 1-4 Polyisoprene	4 hours	4 hours	>1 month	With antiozonant
cis Polybutadiene	2 hours	2 hours	6 days	No antiozonant
cis Polybutadiene	4 hours	2 hours	>1 month	With antiozonant

---

*Many of these designations are trade names referring to specific elastomers. See Table 1-1 for classification of these materials.

Source: Reference 31.

TABLE 3-3 (3.2.2). LIQUID IMMERSION TEST STANDARDS

ASTM and FTM Oils Used in D 471 and Federal Methods 6111, 6121, 6211, 6231 and 6251

	Oils ASTM No. 1 FTM Med. 1	Oils ASTM No. 2 FTM Med. 2	Oils ASTM No. 3 FTM Med. 3	
	Low Swelling	Medium Swelling	High Swelling	ASTM Methods*
Aniline Point	123.9 ± 1°C (255 ± 1.8 °F)	93 ± 3° C (199.4 ± 5.4° F)	69.5 ± 1°C (157.1 ± 1.8°F)	D 611
Saybolt Universal Viscosity, sec	98 ± 5**	100 ± 5**	155 ± 5***	D 88
Flash Point	470° F min	475 ± 10° F	330 ± 5° F	D 92

---

*These designations refer to the following methods of the American Society for Testing Materials:

D 88 - Test for Saybolt Viscosity (Ref. 29).
D 92 - Test for Flash and Fire Points by Cleveland Open Cup (Ref. 29).
D 611 - Test for Aniline Point and Mixed Point of Petroleum Products and Hydrocarbon Solvents (Ref. 29).

**Measured at 210 °F.

***Measured at 100 °F.

TABLE 3-3 (3.2.2). LIQUID IMMERSION TEST STANDARDS (Cont'd)

ASTM Reference Fuels Used in D 471*

Reference Fuel A FTM Medium 4	Isooctane**
FTM Medium 5	Isooctane, 60 volumes Benzene, 5 volumes Toluene, 20 volumes Xylene, 15 volumes
Reference Fuel B FTM Medium 6	Isooctane**, 70 volumes Toluene***, 30 volumes
Reference Fuel C	Isooctane**, 50 volumes Toluene***, 50 volumes

Recommended Immersion Periods for Federal Immersion Tests

22 ± 1/4 hours
46 ± 1/4 hours
70 ± 1/4 hours
166 ± 1/4 hours
30 days

---

*See MIL-S-3136. These ASTM Reference Fuels have been selected to provide the maximum and minimum swelling effects which will be produced by commercial gasolines. Reference Fuel A has a mild action on elastomeric vulcanizates and produces results of the same order as low-swelling gasolines of the highly paraffinic, straight-run type. Reference Fuel B has a more severe swelling action on elastomeric vulcanizates and exceeds the swelling action of commercial gasolines. Reference Fuel C has a swelling action on elastomeric vulcanizates which is more severe and which is typical of that experienced with highly aromatic premium grades of automotive gasolines.

**Isooctane conforming to Section 214 of the 1956 ASTM Manual for Rating Motor Fuels by Motor and Research Methods.

***Toluene conforming to the Standard Specifications for Industrial Grade Toluene (ASTM Designation: D 842).

TABLE 3-3 (3.2.2). LIQUID IMMERSION TEST STANDARDS (Cont'd)

Federal Test Aromatic Mediums Used in Federal Test Methods 6111, 6121, 6211, 6231 and 6251

Medium 7	Benzene - conforming to Federal Specification VV-B-231, Grade 1
Medium 8	Toluene - conforming to Federal Specification TT-T-548
Medium 9	Xylene - conforming to Federal Specification TT-X-916
Medium 10	Distilled Water

Recommended Temperatures for Aging of Specimens for D 471 and Federal Immersion Tests

Degrees Fahrenheit	Degrees Centigrade
73.4 (± 2 ASTM ± 3.61 FTM)	23 (±1.1 ASTM ± 2 FTM)
158 (± 1.8 ASTM ± 3.6 FTM)	70 (± 1 ASTM ± 2 FTM)
212 (± 1.8 ASTM ± 3.6 FTM)	100 (± 1 ASTM ± 2 FTM)
257 (± 1.8 ASTM ± 3.6 FTM)	125 (± 1 ASTM ± 2 FTM)
302 (± 1.8 ASTM ± 3.6 FTM)	150 (± 1 ASTM ± 2 FTM)
347 (± 1.8 ASTM ± 3.6 FTM)	175 (± 1 ASTM ± 2 FTM)
392 (± 1.8 ASTM ± 3.6 FTM)	200 (± 1 ASTM ± 2 FTM)
482 (± 1.8 ASTM ± 3.6 FTM)	250 (± 1 ASTM ± 2 FTM)

Recommended Immersion Periods for Aging of Specimens for D 471

22 ± 1/4 hours
70 ± 1/4 hours
166 ± 1/4 hours
28 days

TABLE 3-4 (3.2.2). EXAMPLES OF RESISTANCE OF SPECIFIC ELASTOMERS TO COMMON SOLVENTS EVALUATED BY VOLUME CHANGE OF ELASTOMER IMMERSED IN THE LIQUID

	Immersion			Non-Oil Resistant			Oil Resistant(4)					Heat Resistant				
										Polysulfide						
Liquid	Solvent Classification	Time	Temperature	Natural Rubber	SBR	Ordinary Butyl	Neoprene	Buna N	Urethane	FA	ST	Hypalon	Poly-acrylate	Silicone	LS-53	Viton A
Acetone	Oxygenated, Ketone	70 hrs	R. T.	+3(1)	+18	+2	+31	S	S	17	37	18(1)	S	+18	S	S
Aniline	Amine	70 hrs	R. T.	+10(2)	+24	+1	+51	S		S	S	25(1)	S	+2	-4	+1
ASTM Oil #1	See Table 3-3	70 hrs	212°F	S	+44	S	+8	-2	-3	-2(5)		N. D.	+2	+7	N. C.	N. C.
ASTM Oil #3	See Table 3-3	70 hrs	212°F	S	S	S	+68	+15	+10	+5(5)		N. D.	+16	+23	+3	+1
Benzene	Aromatic, Polarizable	70 hrs	R. T.	S	S	+92	S	S	S	96	S	N. D.	S	+70	+23	+10
Carbon Disulfide	Sulfur derivative	70 hrs	R. T.	S	S	S	S	+56	15	+51(5)		N. D.	+51	+48	+20	+1
Carbon Tetra-chloride	Halogenated, Non-Polar	70 hrs	R. T.	S	S	S	S	+81	+40	36	46	S(1)	S	S	+12	+1
Castor Oil	Vegetable oil	70 hrs	212°F	+1	+4	N. C.	+10	+6	+1	-3(5)		N. D.	+11	+2	N. C.	N. C.
Chloroform	Halogenated	70 hrs	R. T.	S	S	S	S	S	N. D.	S(5)		N. D.	S	+99	+36	+9
Dioxane	Oxygenated	70 hrs	R. T.	S	S	+10	S	S	N. D.	S(5)		N. D.	S	+23	+32	S
Ethyl Alcohol	Oxygenated, Hydroxy	7 days	R. T.	+1	+3	N. C.	6	+18(7)	+30	2	2	0(1)	S	N. C.	+8	+68
Ethyl Ether	Aliphatic ether	70 hrs	R. T.	S	+82	+51	+64	+44	+5	+12(5)		N. D.	+99	S	+60	+97
Ethylene Glycol	Oxygenated, Hydroxy	70 hrs	212°F	N. D.	+4	-1	+7	+3	N. D.	2	0	-1(1)	+37	+3	+1	+1
Glycerol	Oxygenated, Hydroxy	70 hrs	212°F	N. C.	+1	N. C.	+4	+1	N. D.	1	1	N. D.	+16	+1	N. C.	N. C.
Nitrobenzene	Nitro, aromatic	70 hrs	R. T.	S(1)	+66	+2	S	S	S	S(5)		S(2)	S	+3	+68	+22
Tributyl Phosphate	Aliphatic ester	70 hrs	212°F	38(3)	+72	+18	S	S	N. D.	+78(5)		10(3)	S	+36	D	S
Turpentine	Hydrocarbon	70 hrs	R. T.	S	S	S	+60	9	N. D.	3	4	N D	+22	+98	+13	+1
Water	Polar, Inorganic	70 hrs	212°F	N. D	+10	+1	+7	+11	+5(6)	+45(5)		2(1)	+23	+3	N. C.	N. C.

Explanatory Notes:

Numerical values are % volume change

R. T. - room temperature
S - over 100% volume change
D - deteriorated excessively
H - hardened excessively
N. C. - no change
N. D. - no data
(1) - 7 days immersion
(2) - 3 days immersion
(3) - 1 day immersion
(4) - 30 days immersion at room temperature
(5) - type unknown, immersion according to left hand columns
(6) - at room temperature
(7) - Methyl alcohol; 70 hours at 158°F

TABLE 3-5. (3.2.2) IMMERSION TEST DATA ON COMPOUNDER'S PROPERTY VALUES OF BUNA N, LS-53, VITON A, AND KEL-F ELASTOMER EXPOSED TO FTM MEDIUM 6 (ASTM REFERENCE FUEL B, 70/30 ISO-OCTANE-TOLUENE)

	Immersion		Original Properties			After Immersion Properties			
Elastomer	Time	Temp., °F	T	E	H	T	E	H	V. C.
Buna N	70 hr	75	3,800	520	70	2,020	480	58	+20.7
(see Figure 3-2)	70 hr	250	3,800	520	70	1,890	340	62	-19.1
(see Figure 3-2)	70 hr	400	3,800	520	70	1,455	160	67	+21.2
Kel-F 3700	70 hr	75	2,860	300	71	1,840	240	63	+ 7.0
(see Figure 3-1)	70 hr	250	2,860	300	71	1,230	220	58	+29.7
(see Figure 3-1)	70 hr	400	2,860	300	71	1,165	180	63	+21.9
LS-53	70 hr	325	1,150	180	63	800	185	60	+20
LS-53	70 hr	325	1,150	180	63	460	130	45	+22.6
LS-53	70 hr	400	1,150	180	63	240	160	35	+20.6
Viton A-HV	70 hr	75	3,075	200	70	2,890	200	71	2.5
Viton A	72 hr	250	2,100	320	73	1,280	190	66	+18.2
Viton A	70 hr	400	2,400	200	67	1,010	160	50	+29.0
Viton A	70 hr	400	1,850	230	60	710	160	50	+31.3
Poly FBA	72 hr	250	940	280	83	250	80	43	+33.1
Poly FBA	70 hr	325	915	100	81	260	80	57	+45.4

T - Tensile strength, psi
E - Ultimate elongation, %
H - Hardness, Shore A Durometer
V. C. - Volume change, %

Source: Reference 4.

TABLE 3-6 (3. 2. 2). REFERENCE LIST OF COMMON MILITARY LIQUID SPECIFICATION NUMBERS

Fuels

MIL-G-3056	Automotive Combat Gasoline
MIL-G-5572	Aviation Gasoline
MIL-F-5624	JP3, JP4, JP5
MIL-F-25524	Aircraft Turbine and Jet Engine, Thermally Stable
MIL-F-25558	RJ-1 (ramjet)
MIL-F-25576	RP-1 (rocket propellant)
MIL-F-25604	Unsymmetrical Dimethyl Hydrazine
MIL-F-25656	JP-6

Petroleum Lubricating Oils

MIL-L-2104	Internal Combustion Engine, Heavy Duty
MIL-L-2105	Gear
MIL-O-6081	Jet Engine
MIL-O-6082	Aircraft, Reciprocating Engine
MIL-L-6086	Gear
MIL-L-7870	General Purpose, Low Temperature
MIL-L-8383	Internal Combustion Engine
MIL-L-9000	Diesel
MIL-L-10295	Internal Combustion Engine, Sub-Zero
MIL-L-10324	Gear, Sub-Zero
MIL-L-15016	General Purpose
MIL-L-17672	Hydraulic and Light Turbine, Noncorrosive
MIL-L-21260	General Purpose

Greases

MIL-G-3278	Aircraft and Instrument, Low and High Temperature
MIL-L-3545	High Temperature Lubricating
MIL-G-7711	Aircraft, General Purpose
MIL-G-15793	Instrument

TABLE 3-6 (3.2.2). REFERENCE LIST OF COMMON MILITARY LIQUID SPECIFICATION NUMBERS (Cont'd)

Petroleum Hydraulic Oils

MIL-H-5606	Aircraft and Ordnance
MIL-H-6083	Preservative
MIL-O-7083	Aircraft, Nonflammable (water-glycol base)
MIL-H-15017	Lubricating Oil
MIL-F-25598	Missile

Synthetic Lubricants

MIL-O-6085	Oil, Instrument, Aircraft, Low Volatility
MIL-O-6387	(Diester)
MIL-L-7499	Extreme Pressure, Low Volatility
MIL-L-7808	Aircraft Turbine Engine (diester)
MIL-C-8188	Aircraft Gas Turbine, (Corrosion Preventive)
MIL-L-9236	Aircraft Turbine Engine, High Temperature
MIL-L-14107	Aircraft Weapons (silicone)
MIL-L-25336	Aircraft Turbine Engine, High Film Strength
MIL-L-25968	Aircraft Gas Turbine, Medium Temperature

Synthetic Base Hydraulic Fluids

MLO-8200	Silicate Ester
MIL-H-8446	Aircraft
MLO-8515	Diester

Phosphate Ester Hydraulic Fluids

MIL-F-7100	
MIL-H-19457	

Miscellaneous

MIL-S-3136	Standard Test Fluids; Hydrocarbon and Isooctane
MIL-E-5559	Ethylene Glycol, Inhibited
MIL-F-5566	Isopropyl Alcohol, Anti Icing Fluid
MIL-A-6091	Ethyl Alcohol, Special Denatured
MIL-F-7024	Calibrating Fluids for Fuel System Components
MIL-F-7197	Reference Fuel, High Swell
MIL-H-7644	Castor Oil Base Hydraulic Fluid
MIL-F-17111	Power Transmission Fluid

TABLE 3-6 (3.2.2). REFERENCE LIST OF COMMON MILITARY LIQUID SPECIFICATION NUMBERS (Cont'd)

Other Fluid Designations Commonly Encountered

Aroclor 1248 and 1254	Chlorinated Hydrocarbon
Cellulube 220	Phosphate ester, Hydraulic Fluid
DC 200	Silicone Fluid Lubricants and Hydraulic Fluids
DC F-4029	Liquid Spring Silicone Fluid
Dowtherm A	Diphenyl
Houghtosafe 1120	Phosphate ester, Hydraulic Fluid
Lindol	Tricresyl Phosphate
OS-45	Silicate Ester Hydraulic Fluid
Pydraul F-9	Phosphate Ester Hydraulic Fluid
Skydrol 7000	Phosphate Ester Hydraulic Fluid
Skydrol 500	Phosphate Ester Hydraulic Fluid

TABLE 3-7 (3.2.2). REFERENCE LIST OF COMMON ELASTOMER SPECIFICATIONS

Specification	Types	Class	Suitable or Required High Polymer	Remarks
MIL-R-1149A	I & II	1	Neoprene	Rubber Sheets, Strips, and Gaskets; Solid, Synthetic, Medium and Medium Hard
		2	SBR	
		3	Butyl	
		5	Buna N	
MIL-P-5315A			Buna N	Packing, "O" Ring, Hydrocarbon, Fuel Resistant
MIL-G-5510A			Buna N	Gasket; Straight Thread Tube Fitting, Boss
MIL-P-5516B			Buna N	Packings & Gaskets, Preformed, Petroleum Hydraulic Fluid Resistant
MIL-R-5847C		I	Silicone	Extreme Low Temperature Resistant
		II	Silicone	High Temperature Resistant
MIL-R-6855		I	Buna N	Fuel Resistant
		II	Neoprene	Oil Resistant
		III	SBR	Non-Oil Resistant
		IV	Buna N	Oil Resistant (For Contact with Acrylic Plastics)
		V	SBR	Non-Oil Resistant (For Contact with Acrylic Plastics)
MIL-R-7362B		Comp A, Low Temp	Buna N	Synthetic Oil Resistant
		Comp B High Temp	Buna N	Synthetic Oil Resistant
MIL-P-25732			Buna N	Packing, Preformed, Petroleum Hydraulic Fluid Resistant, 275°F
MIL-R-25897			Viton	Rubber, High Temperature Fluid-Resistant
MIL-R-25988			LS-53	Rubber, Silicone, Oil and Fuel Resistant

TABLE 3-8. (3.2.2). LIQUID MEDIA GUIDE FOR ELASTOMER SELECTION BY MILITARY SPECIFICATIONS

Fluid	Elastomer	Temperature Limits
MIL-L-2104	MIL-P-5516B	-65°F to +160°F
	MIL-P-25732	-65°F to +275°F
MIL-G-3278	MIL-R-1149A Type II, Class 5	-40°F to +250°F
MIL-L-3545	MIL-P-5516B	-65°F to +160°F
	MIL-P-25732	-65°F to +275°F
MIL-E-5559	MIL-P-5516B	-65°F to +160°F
MIL-F-5566	MIL-R-6855 Class III	-65°F to +160°F
	Buna N	-65°F to +212°F
MIL-F-5572	MIL-P-5315A	-40°F to +180°F
MIL-H-5606	MIL-G-5510A	-65°F to +160°F
	MIL-P-5516B	-65°F to +160°F
	MIL-P-25732	-65°F to +275°F
MIL-F-5624	MIL-P-5315A	-65°F to +160°F
MIL-O-6081	MIL-P-5516B	-65°F to +160°F
	MIL-R-25897	-30°F to +400°F
MIL-L-6082	MIL-G-5510A	-65°F to +160°F
	MIL-P-5516B	-65°F to +160°F
	MIL-P-25732	-65°F to +275°F
MIL-L-6085	MIL-R-7362B-Comp. A	-65°F to +275°F
	MIL-R-25897	-30°F to +400°F
MIL-L-6086	MIL-R-6855 Class I	-65°F to +200°F
MIL-A-6091	MIL-R-6855 Class III	-65°F to +160°F
	MIL-R-1149A Type II, Class 5	-40°F to +212°F
MIL-O-6387	Neoprene (Static Seal Only)	-65°F to +325°F
MIL-F-7024	MIL-R-6855 Class I	-65°F to +160°F
	MIL-R-1149A Type II, Class 5	-40°F to +212°F
MIL-O-7083	MIL-R-25897	-30°F to +400°F
MIL-F-7100	Butyl	-65°F to +212°F
MIL-G-7711	MIL-P-5516B	-65°F to +160°F
	MIL-P-25732	-65°F to +275°F

TABLE 3-8. (3.2.2). LIQUID MEDIA GUIDE FOR ELASTOMER SELECTION BY MILITARY SPECIFICATIONS (Cont'd)

Fluid	Elastomer	Temperature Limits
MIL-L-7808	MIL-R-7362B, Comp. A	-65° F to +275° F
	MIL-R-25897	-40° F to +450° F
MIL-L-7870	MIL-P-5516B	-65° F to +160° F
	MIL-P-25732	-65° F to +275° F
MIL-C-8188	MIL-R-7362B, Comp. A	-65° F to +275° F
MLO-8200	MIL-P-5516B	-65° F to +160° F
MIL-H-8446	Neoprene	-65° F to +350° F
	MIL-R-25897	-40° F to +450° F
MLO-8515	MIL-R-25897	-30° F to +400° F
MIL-L-10295	MIL-P-5516B	-65° F to +160° F
	MIL-P-25732	-65° F to +275° F
MIL-L-17672	MIL-P-25732	-65° F to +275° F
MIL-H-19457	Butyl	-65° F to +212° F
MIL-L-25336	MIL-R-7362, Comp. A	-65° F to +275° F
MIL-F-25558	MIL-R-25897	-30° F to +400° F
MIL-F-25604	Butyl	----- -- -----
MIL-F-25656	MIL-R-25988	-65° F to +350° F
	MIL-R-25897	-30° F to +400° F

TABLE 3-9. (3.2.3). A REFERENCE LIST OF SPACE WEAPONS SYSTEM ENERGY SOURCE CHEMICALS OF CURRENT INTEREST

Oxidizers

Bromine Pentafluoride
Chlorine Trifluoride (CTF)
Fluorine
Hydrogen Peroxide MIL-H-16005
Nitric Acid [WFNA, RFNA, & (IRFNA) MIL-N-7254B, Type III]
Nitric Oxide
Nitrogen Tetroxide (NTO)
Nitrous Oxide
Oxygen (LOX)
Ozone
Tetranitromethane

Monopropellants

Diethylene Glycol Dinitrate
Ethylene Oxide
Ethyl Nitrate
Hydrogen Peroxide
Nitroglycerin
Nitromethane
N-propyl Nitrate (MIL-N-8722)

Fuel

Anhydrous Ammonia
Aniline
Beryllium
Boron
Carbon
Decaborane
Diborane
Diisopropenyl Acetylene (DIPA)
Ethyl Alcohol
Ethylene Diamine
Furfuryl Alcohol
Gasoline
Hydrazine

TABLE 3-9. (3.2.2). A REFERENCE LIST OF SPACE WEAPONS SYSTEM ENERGY SOURCE CHEMICALS OF CURRENT INTEREST (Cont'd)

Fuel (Cont'd)

Hydrogen
JP, RJ & RP Hydrocarbon Fuels (MIL-F-5624, -25558, -25576, -25656)
Kerosene
Lithium
Lithium Hydride
Methyl Alcohol
Monoethyl Aniline
Pentaborane
Unsymmetrical Dimethyl Hydrazine (UDMH; MIL-F-25604)

Other Fluids

Liquified Inert Gases (Nitrogen, Helium)
Hot Gases from Solid Propellant Combustion

TABLE 3-10 (3.2.3). RESULTS OF LOX IMPACT TESTS (REF. 131)

Elastomer Type	Liquid Oxygen Impact Test		
	40 ft lb	50 ft lb	60 ft lb
Viton	10 pass 0 fail	9 pass 1 fail	No Test
Buna N	10 pass 0 fail	6 pass 4 fail	No Test
Buna N	9 pass 1 fail	2 pass 8 fail	2 fail
Buna N	8 pass 2 fail	4 pass 6 fail	No Test
Kel-F Elastomer	7 pass 3 fail	5 pass 5 fail	2 pass 2 fail
Kel-F Elastomer	7 pass 3 fail	4 pass 6 fail	1 pass 2 fail
LS-53	6 pass 4 fail	7 pass 3 fail	4 pass 2 fail
Viton	6 pass 4 fail	3 pass 7 fail	2 fail
Viton	6 pass 4 fail	3 pass 7 fail	2 fail
Viton	5 pass 5 fail	3 pass 7 fail	2 fail
Neoprene	6 pass 4 fail	1 pass 9 fail	2 fail
Buna N	6 pass 4 fail	0 pass 10 fail	2 fail
Neoprene	6 pass 4 fail	0 pass 10 fail	2 fail
Buna N	4 pass 6 fail	1 pass 9 fail	1 pass 2 fail
Spec. Comp. Neoprene (Fire Retard. Plast.)	4 pass 2 fail	No Test	2 fail

TABLE 3-11 (3.2.3) ELASTOMER-LIQUID COMPATIBILITY

Liquid	High Polymer	Immersion		Hardness, Shore A	Ultimate Tensile Strength, psi	Ultimate Elongation, %	Volume Swell, %
		Time	Temperature				
JP-X (UDMH/ JP-4, 40/60 mixture)	Buna N (High acrylonitrile)	Original		73	3500	200	
		21 days	R. T.	60	1600	140	21
		42 days	R. T.	70	2900	250	9
		14 days	R. T.	55	1000	150	50
		21 days	R. T.	65	840	140	53
		60 min	350° F	65	1640	150	47
		60 min	400° F	68	2880	225	7
IRFNA	Kel-F 5500	Original		89	3460	310	
		14 days	R. T.	65	1500	275	10
		21 days	R. T.	60	840	300	13
Hydrazine	SBR	Original		80	2500	200	
		21 days	R. T.	75	2440	125	9
		42 days	R. T.	84	3020	150	10
		3 mos	R. T.	78	2200	110	14
		6 mos	R. T.	80	2360	125	10
		14 days	160° F	75	2400	125	12
		21 days	160° F	82	2200	150	12
		3 mos	160° F	80	1840	125	8
		60 min	400° F	60	1520	140	10
	Polybutadiene (cis 4)	Original		67	2000	300	
		7 days	R. T.	64	2160	300	2
		21 days	R. T.	65	1850	325	4
		42 days	R. T.	80	2360	350	3
		3 mos	R. T.	75	2300	225	3
		5 mos	R. T.	70	1800	250	5
		3 mos	160° F	80	2800	225	1

R. T. room temperature

TABLE 3-11 (3.2.3). ELASTOMER-LIQUID COMPATIBILITY (Cont'd)

Liquid	High Polymer	Immersion		Hardness, Shore A	Ultimate Tensile Strength, psi	Ultimate Elongation, %	Volume Swell, %
		Time	Temperature				
UDMH	Butyl	Original		80	1800	400	
	(Resin cured)	14 days	R. T.	72	1680	350	13
		21 days	R. T.	72	1710	350	18
		7 days	160° F	65	1550	400	17
		14 days	160° F	61	1560	330	16
	Polybutadiene	Original		67	2000	300	
	(cis 4)	7 days	R. T.	65	2000	300	9
		3 mos	R. T.	65	2000	260	4
		6 mos	R. T.	65	1860	300	-5
		7 days	160° F	60	2100	260	16
		60 mins	400° F	65	1760	275	12
Liquid	LS-53	Original		71	1320	225	
NTO	(Elastomer)	1 day	R. T.	55	840	150	40
Liquid	Teflon	Original		98	1500	200	
NTO	(Plastic)	7 days	R. T.	98	2300	200	2
		16 days	R. T.	98	1800	200	3
		21 days	R. T.	97	1300	200	7
N-Propyl	Hydropol	Original		97	3260	230	
Nitrate	(hydro-	6 mos	R. T.	95	3300	250	5
	genated	3 mos	160° F	79	2800	125	13
	polybutadiene)	6 mos	160° F	97	1700	100	4
90% H_2O_2	Viton A-HV	Original		87	2850	375	
(3.2% active oxygen loss)		7 days	R. T.	85	2000	600	0
	Silicone	Original		60	840	275	
(2.5% active oxygen loss)		7 days	R. T.	60	600	225	9

TABLE 3.11 (3.2.3). ELASTOMER-LIQUID COMPATIBILITY (Cont'd)

Liquid	High Polymer	Immersion Time	Immersion Temperature	Hardness, Shore A	Ultimate Tensile Strength, psi	Ultimate Elongation, %	Volume Swell, %
DIPA	Urethane*	Original		100	4740	550	
		72 hr	R. T.	86	2100	625	19
		7 days	R. T.	95	3760	600	4
		7 days	160°F	95	3280	680	2.9
	Viton A*	Original		70	2260	625	
		72 hr	R. T.	74	1700	400	21
		7 days	R. T.	74	2180	575	4
		8 days	160°F	68	1150	200	70
	LS-53*	Original		60	970	190	
		7 days	R. T.	62	910	180	11
		7 days	160°F	59	800	160	12.2
Ethylene Oxide	Butyl	Original		80	1380	650	
		7 days	160°F	50	640	450	20.2
Anhydrous Ammonia	Hypalon	Original		74	2740	200	
		7 days	R. T.	75	2460	250	1.5
		7 days	160°F	79	1600	200	-1
Anhydrous Ammonia	Butyl	Original		52	2240	600	
		7 days	R. T.	45	2280	625	-1
		7 days	160°F	52	950	550	-1

All of these materials affected propellant stability excessively

TABLE 3-11 (3.2.3). ELASTOMER-LIQUID COMPATIBILITY (Cont'd)

Liquid	High Polymer	Immersion Time	Immersion Temperature	Hardness, Shore A	Ultimate Tensile Strength, psi	Ultimate Elongation, %	Volume Swell, %
	Buna N	Original		77	3200	375	
		7 days	R. T.	75	3360	300	-1.9
		7 days	160° F	78	1740	225	-1.4
	Neoprene	Original		70	1820	775	
		7 days	R. T.	66	1580	500	-3
		7 days	160° F	69	775	400	-3

Other Properties of Some of the Liquid Resistant Elastomers

High Polymer	Comp. Set, * %, 70 hr/250° F	TR 10, ** ° F	TR 30, ** ° F	TR 50, ** ° F	Liquid	Permeability, *** Wt. Loss
Buna N	22	---	---	---	JP-X	7.0
Buna N	---	+1	+6	+10	---	---
Butyl	31	-49	-36	-26	UDMH	0.73
Polybutadiene	37	-56	-37	-31	---	---
Polybutadiene	---	---	---	---	UDMH	1.07
Polybutadiene	---	---	---	---	Hydrazine	0.28
SBR	55	-46	-40	-34	---	---
SBR	---	---	---	---	Hydrazine	10.6
SBR	---	---	---	---	Hydrazine	0.15
Hydropol	37	-8	+20	+34	---	---
Hydropol	---	---	---	---	N-Propyl Nitrate	1.16

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*FTM 3311, Reference 89.

**ASTM D-1329, Reference 29.

***ASTM D-814, Reference 29. Ten-mil sheet specimens, fl oz/day - sq ft.

Source: Reference 12.

TABLE 3-11 (3 2 3). ELASTOMER-LIQUID COMPATIBILITY (Cont'd)

Other Properties of Some of the Liquid Resistant Elastomers (Cont'd)

High Polymer	Comp. Set, * %, 70 hr/250°F	TR 10, ** °F	TR 30, ** °F	TR 50, ** °F	Liquid	Permeability, *** Wt. Loss
	%, 70 hr/300°F					
LS-53	31	-89	-76	-69	---	---
Silicone	12	-47	-46	-44	---	---
	%, 70 hr/250°F					
Kel-F	50	+30	+33	+36	---	---
Viton A	10	-7	-2	+10	---	---
Poly FBA	15	+5	+15	+20	---	---

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*FTM 3311, Reference 89.
**ASTM D-1329, Reference 29.
***ASTM D-814, Reference 29. Ten-mil sheet specimens, fl oz/day - sq ft.

Source: Reference 12.

TABLE 3-12 (3.3). GAS PERMEABILITY CONSTANTS $\times 10^7 \frac{cm^2}{sec\ atm}$ AT ROOM TEMPERATURE*

High Polymer	N_2	O_2	Air	H_2	CO_2	He	CH_4
Natural Rubber	2	2	1	3	3	3	2
SBR	0.5	1	0.7	3	9	2	2
Butyl	0.08	0.05	0.1	0.4	0.2	0.9	---
Hypalon	---	---	0.7	---	---	---	---
Neoprene	0.1	0.3	0.1	1	2	0.6	0.2
Buna N**	0.02	0.07	0.1	0.2	0.4	0.1	0.04
Thiokol FA	---	0.02	---	0.3	---	---	---
Silicone	70	---	10-70	---	200	100	---
Poly FBA	---	---	2	---	---	---	---
Urethane	0.04	0.1	0.05	---	---	---	---
Vyram	---	---	0.007	---	---	---	---
Polyethylene	0.09	0.3	---	0.8	---	0.6	---
Teflon	0.02	0.8	---	2	---	60	---

Water Vapor Permeability Constants $\times 10^8$ measured in gm/hr/cm^2/cm thickness/vapor pressure mm Hg.

Natural Rubber	7
SBR	10
Neoprene	3
Polysulfide	0.2

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*Values are given only to one significant figure because of variation in permeability caused by compounding variables.

**This is a specific elastomer compounded for impermeability. Most Buna N's have permeability constants comparable to those given for Neoprene.

Source: SwRI. Also Reference 9.

TABLE 3-13 (3.4). COMPARISON OF THERMAL AND RADIATION STABILITY OF ELASTOMERS

Elastomer	Temperature (Ref. 9) at which 25% of original tensile is lost in 8 hr of heat aging	Dosage at which 25% change in original properties occurs (for specific compounds)	Heat Aging Order	Radiation Damage Order
Silicone				
aliphatic sidegroup		4.2×10^8 ergs/gm (Ref. 49)	1	7
aromatic sidegroup	480°F	12.0×10^8 ergs/gm	1	4
Viton	450°F	4×10^8 ergs/gm	2	8
Acrylic	425°F	3.3×10^8 ergs/gm	3	9
Urethane	350°F	4.2×10^9 ergs/gm	4	1
Hypalon	350°F	4.2×10^8 ergs/gm	4	7
Buna N	340°F	7×10^8 ergs/gm	5	5
Butyl	335°F	4×10^8 ergs/gm	6	8
Neoprene	325°F	5.5×10^8 ergs/gm	7	6
Polysulfide	285°F	1.5×10^8 ergs/gm	8	10
SBR	275°F	1.5×10^9 ergs/gm	9	3
Natural Rubber	210°F	2.5×10^9 ergs/gm	10	2

Note: Radiation resistance is highly dependent on compounding and environmental variables so that these figures are useful only for comparison of materials.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS

Elastomer	Dose, ergs/gm $\times 10^8$	Initial Properties and Percent Change			Remarks**
		Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, psi; Δ%	
LS-53	0	59	220	1405	Red
	5	3.4	-18.7	-34.9	
	10	3.4	-36.1	-51.8	
	50	15.3	-72.2	-82.3	
	100	23.7	-90.9	-84.5	a
Silicone	0	68	255	735	White
	3	-4.4	-13.0	15.5	
	6	1.5	-26.9	17.0	
	30	10.3	-54.5	36.3	h
	60	20.6	-78.3	5.9	i
	90	25.0	-82.2	-10.1	a, c
Silicone	0	80	205	690	White
	3	2.4	-12.6	13.9	
	6	1.8	-40.1	9.1	
	30	4.8	-56.3	24.2	
	60	9.5	-78.2	47.6	g
	90	11.9	-80.5	62.1	a, g
Methyl Phenyl Vinyl Silicone	0	60	590	1590	Grey
	5	6.7	-24.1	-7.1	
	10	16.7	-36.4	-8.6	r
	50	35.0	-86.4	-41.3	r
	100	45.0	-91.5	-51.6	a, r

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky, c = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream, h = slightly grey, i = light blue-grey, k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3. 4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, psi; Δ%	Remarks**
Methyl Phenyl Silicone	0	63	210	660	Light tan
	3	0.0	-4.3	7.6	
	6	3.2	-13.9	0.8	
	30	7.9	-44.9	-6.1	
	60	19.0	-66.5	-13.3	k
	90	30.2	-79.0	-6.8	a, l
Methyl Vinyl Silicone	0	80	170	300	Red
	3	-16.3	-3.8	-5.3	
	6	-15.0	-16.7	0.0	
	30	-10.0	-49.4	30.2	
	60	-1.3	-73.2	33.2	a
	90	6.3	-75.0	100.0	a
Poly FBA	0	71	150	1200	Black
	5	5.6	6.7	9.7	
	10	15.5	-33.3	2.1	
	59	23.9	-76.7	-44.9	
	100	28.2	-86.7	-33.8	a
Kel-F Elastomer	0	75	640	1100	White
	3	-12.0	4.4	13.6	b
	6	-6.7	-10.4	27.4	d
	60	-10.8	-14.8	-36.4	e

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; c = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change			Remarks**
		Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, psi; Δ%	
Viton A	0	55	350	2070	Black
	50	49.1	-84.4	-23.4	a
	100	60.0	-84.3	-24.3	a
Viton A	0	80	130	2125	Brown
	5	13.8	-28.5	-2.2	
	50	22.5	-80.8	-5.5	a
	100	25.0	-84.6	49.2	a
Urethane	0	62	530	4300	Black
	5	-1.5	-10.4	-	
	10	-2.9	-13.2	-	
	50	-1.5	-40.6	-30.4	
	100	-12.9	-57.6	-53.3	
	300	-1.5	-74.5	-75.7	
	500	17.3	-83.4	-80.1	
	1000	15.9	-87.7	-80.4	
Urethane	0	77	700	6500	Tan
	5	1.3	2.6	-	
	10	-1.3	5.0	-	
	50	0.0	-44.3	-52.5	t
	100	5.2	-68.1	-76.4	
	300	9.1	-95.0	-86.7	
	500	10.4	-96.4	-90.3	
	1000	20.8	-95.7	-89.9	

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; c = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change Hardness, Shore A; Δ%*	 Elongation, %; Δ%	 Tensile, psi; Δ%	Remarks**
Acrylon BA-12	0	79	225	1590	Black
	5	1.3	-21.5	9.9	
	10	1.3	-32.7	-8.2	
	50	7.8	-66.4	-15.8	
	100	12.5	-77.6	-7.6	
	150	15.6	-86.5	-3.1	
	300	19.0	-86.5	2.6	a
	500	21.5	-86.5	44.9	a
	1000	26.6	-98.2	20.1	a
Acrylon EA-5	0	70	545	1580	Black
	5	0.0	-9.9	8.0	
	10	0.0	-32.0	5.1	
	50	8.6	-68.9	4.4	
	100	14.3	-85.3	-10.2	
	150	20.0	-87.2	-7.6	
	300	28.6	-87.2	16.1	a
	500	34.3	-90.8	38.6	a
	1000	40.0	-97.7	32.1	a
Vyram	0	68	275	970	Black
	5	8.8	-23.4	28.2	
	10	10.2	-28.8	28.9	

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; c = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm $\times 10^8$	Initial Properties and Percent Change			Remarks**
		Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, psi; Δ%	
Vyram (Cont'd)	50	27.9	-87.2	-3.0	a
	100	38.2	-87.2	7.1	a
	150	38.7	-92.7	15.6	a
Acrylic	0	64	390	1785	Black
	3	-3.1	-12.4	-13.6	
	6	-3.1	-25.3	-15.8	
	30	3.1	-66.5	-61.8	
	60	9.4	-75.5	-64.0	
	90	12.4	-80.7	-54.8	
	300	31.8	-89.6	-18.0	a
Hypalon	0	76	265	1160	Black
	3	-3.9	1.9	38.4	
	6	-6.6	-5.7	20.3	
	30	-2.6	-35.9	32.5	
	60	9.2	-52.8	20.3	
	90	11.8	-60.4	20.3	
Neoprene	0	56	730	2195	Brown
	5	10.7	-16.7	-2.5	
	10	12.5	-43.6	-59.4	
	50	25.0	-82.2	-80.6	
	100	48.2	-96.9	-81.9	a
	150	69.6	-96.9	-25.6	a

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; c = grey; d = tackiness increased; e = flow marks on surface: g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3. 4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, pse; Δ%	Remarks**
Neoprene	0	64	635	2120	Black
	5	1.6	-4.1	-1.1	
	10	4.7	-15.9	-9.6	
	50	14.1	-60.7	-51.2	
	100	28.1	-80.3	-55.1	
	150	40.6	-89.8	-32.2	
	300	66.7	-92.2	39.8	a
Buna N	0	68	565	3210	Black
	5	5.9	-5.7	2.2	
	10	5.9	-8.7	4.1	
	50	11.8	-45.0	-4.2	f
	100	19.1	-68.1	-1.4	
	150	25.0	-73.4	-1.7	
	300	36.8	-87.9	7.9	
	500	47.1	-98.2	-	a
Carboxylic Buna N	0	81	380	3630	Black
	5	7.4	-15.8	7.5	
	10	11.1	-31.6	13.4	
	50	17.3	-67.1	23.6	
	100	23.5	-89.5	29.2	
	300	23.5	-100.0		a

---

*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; e = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change Hardness, Shore A; Δ%*	Elongation, %; Δ%	Tensile, psi; Δ%	Remarks**
SBR	0	69	435	2155	Black
	5	5.8	-16.7	3.2	
	10	10.1	-17.4	11.5	
	50	18.8	-73.6	13.3	f
	100	29.0	-81.7	13.3	
	300	43.5	-93.1	16.3	a
	500	44.9	-100.0	31.3	a
SBR	0	66	720	2905	Black
	5	1.5	-5.6	0.9	
	10	3.0	-6.9	-2.1	
	50	9.1	-38.9	-33.9	
	100	21.2	-72.2	-31.6	f
	300	33.3	-91.3	-40.5	
	500	42.4	97.9	-61.5	a
Butyl	0	71	440	1490	Black
	1	0.0	-1.9	-5.5	
	5	0.0	-5.5	-6.9	
	10	0.0	-12.4	-27.9	
	30	-29.6	-17.1	-87.5	b
	50	-38.4	15.2	-96.6	c
	60	-40.9	2.3	-100.0	d

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*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; e = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change			Remarks**
		Hardness, Shore A; Δ%	Elongation, %; Δ%	Tensile, psi; Δ%	
Brominated Butyl	0	73	345	2130	Black
	3	-2.7	3.2	-9.2	
	6	-5.5	-8.4	-31.9	e
	30	-19.2	-12.8	-79.3	b
	60	-20.5	-27.3	-87.8	c
	90	-38.4	-12.8	-100.0	d
Natural Rubber	0	54	200	395	Brown
	5	3.7	-22.5	-17.0	f
	22	11.3	-42.5	-28.8	
	55	20.3	-55.0	-26.6	
	100	24.1	-67.5	-23.3	
	300	51.9	-92.5	-22.8	
	500	61.0	-95.0	-17.7	a
	1000	94.0	-100.00	171.6	a
Thiokol	0	71	220	1065	Black
	5	1.4	-8.0	2.3	
	30	2.8	-27.3	-4.2	
	55	2.8	-40.0	-12.2	
	100	-1.4	-50.4	-28.5	
	300	0.0	-71.7	-50.6	a
	500	-	-100.0	-100.0	a, j

---

*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; e = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

TABLE 3-14 (3.4). EFFECTS OF GAMMA RADIATION ON PHYSICAL PROPERTIES OF ELASTOMERS (Cont'd)

Elastomer	Dose, ergs/gm × 10^8	Initial Properties and Percent Change			Remarks**
		Hardness, Shore A; Δ%	Elongation, %; Δ%	Tensile, psi; Δ%	
Kel-F 5500	0	62	550	1810	Grey
	1	0.0	9.1	44.2	
	5	0.0	-8.2	19.6	
	22	3.2	-41.8	-28.8	e
	55	16.1	-73.6	-24.9	y
	100	25.8	-80.0	-13.9	e

---

*Δ% is percent change of original properties.

**a = broke when bent 180°; b = slightly tacky; e = grey; d = tackiness increased; e = flow marks on surface; g = slightly yellow-cream; h = slightly grey; i = light blue-grey; k = slightly yellow; l = dark amber; t = dark brown.

Source: References 114, 115, 116

TABLE 3-15 (3.4). THE EFFECT OF RADIATION ON COMPRESSION SET

Elastomer	Compression Sets (%) After Indicated Treatment: Control Air Exposed RT*	Control Air Exposed O**	Control Water Exposed RT	Control Water Exposed O	Compression Sets (%) After Indicated Treatment***: Exposed to 10^9 ergs/gm RT	Exposed to 10^9 ergs/gm O	Exposed to 10^{10} ergs/gm RT	Exposed to 10^{10} ergs/gm O	Exposed to 10^{11} ergs/gm RT	Exposed to 10^{11} ergs/gm O	(Inverse Hardness) Mast Indentation Value**** After Indicated Treatment: Control Water Exposed	Exposed to 10^9 ergs/gm	Exposed to 10^{10} ergs/gm	Exposed to 10^{11} ergs/gm
Natural Rubber	7	3	6	2	30	20	84	80	99	99	72	65	39	11
Natural Rubber	6	2	6	2	27	18	79	73	98	97	80	79	50	20
SBR	3	1	3	1	26	21	78	75	100	99	84	76	43	2
SBR	3	1	3	1	15	12	64	60	98	97	89	87	60	12
SBR	3	0	3	1	13	10	63	59	99	98	77	74	48	2
SBR	5	0	6	0	38	32	84	81	99	98	91	80	40	2
SBR	5	1	4	1	26	22	77	73	98	96	93	86	52	6
Buna N	8	2	7	2	47	40	92	90	100	100	86	69	25	2
Buna N	8	2	7	1	39	32	87	85	100	100	95	85	42	2
Buna N	5	1	5	1	29	24	84	81	100	99	81	71	32	1
Buna N	4	0	4	1	24	17	76	72	100	98	86	82	50	2
Buna N	5	1	6	1	21	15	74	69	99	98	86	81	51	2
Buna N	5	0	5	1	21	15	76	71	99	98	82	81	51	1
Buna N	5	0	5	0	25	18	79	75	100	99	93	87	51	1
Buna N	5	1	5	1	26	20	81	77	100	98	86	80	42	1
Buna N	7	1	7	1	28	19	80	76	99	98	90	86	47	2
Buna N	5	1	6	1	29	23	81	78	99	99	87	81	43	2
Buna N	5	1	6	1	26	20	80	76	100	98	91	85	46	2
Buna N	11	2	10	2	58	51	92	91	100	100	108	82	31	2
Vinyl Pyridine	16	0	16	0	28	13	90	77	99	98	74	64	12	2
Neoprene	5	2	5	2	36	30	88	84	99	97	69	57	21	1
Acrylic	4	0	3	1	45	41	90	90	99	99	111	96	48	28
Urethane	6	3	4	3	17	14	59	58	101	102	66	65	54	29
Urethane	2	1	3	2	18	15	82	81	101	101	77	82	103	62
Viton A-HV	38	1	46	0	83	71	100	100	104	102	67	60	23	2
Silicone	36	26	30	27	93	92	98	98	103	102	207	60	22	5
Silicone	44	34	45	38	89	88	97	97	101	101	204	80	30	9
LS-53	7	4	7	5	68	65	104	103	107	108	146	133	49	15

The vulcanizates were exposed to gamma radiation in the form of compressed cylindrical specimens. The specimens, originally 0.75 inch in diameter and 0.50 inch thick, were held compressed during exposure to a thickness of 0.35 inch (30% compression).

*Compression set after recovery period of 24 hours at room temperature (73.5°F).

**Compression set after additional recovery period of four hours in oven at 212°F.

***Percent compression set $= \frac{T_o - T_r}{T_o - T_c} \times 100$

where

T_o = specimen thickness before compression,
T_c = specimen thickness when compressed, and
T_r = specimen thickness after recovery.

****Mast indentation values are similar to ASTM D 531-56 values.

Source: Reference 159.

TABLE 3-16 (3.4). RADIATION EFFECTS ON VIBRATION CHARACTERISTICS OF ELASTOMERS

Elastomer	Exposure, 10^{11} ergs/gm	Dynamic Young's Modulus E_1, 10^8 dynes/sq cm	Modulus Ratio, E_2/E_1
GROUP I			
Natural Rubber Compound A	0	2.3	0.7
	0.19	2.8	0.05
	1.4	9.2	0.15
SBR Compound A	0	1.8	0.07
	0.19	2.6	0.07
	1.4	270	0.07
GROUP II			
Natural Rubber Compound B	0	0.33	0.16
	0.19	0.7	0.06
	0.43	0.9	0.06
	1.0	2.0	0.10
	0	0.25	0.12
	0.19	0.5	0.06
	0.43	0.8	0.04
	1.0	1.8	0.06
	0	0.30	0.12
	0.19	0.4	0.04
	0.43	0.8	0.04
	1.0	2.3	0.06
	0	0.47	0.16
	0.19	0.8	0.06
	0.43	1.3	0.08
	1.0	3.8	0.10
Polybutadiene	0	0.9	0.15
	0.19	1.6	0.06
	0.43	2.3	0.1
	1.0	10	0.2
Buna N	0	1.2	0.5
	0.19	2.1	1
	0.43	80	1
	1.0	350	0.1

TABLE 3-16 (3.4). RADIATION EFFECTS ON VIBRATION CHARACTERISTICS OF ELASTOMERS (Cont'd)

Elastomer	Exposure, 10^{11} ergs/gm	Dynamic Young's Modulus E_1, 10^8 dynes/sq cm	Modulus Ratio, E_2/E_1
GROUP II (Cont'd)			
SBR Compound B	0	1.2	0.3
	0.19	5.6	0.06
	0.43	20	0.09
	1.0	270	0.1
Neoprene	0	1.2	0.08
	0.5	4.0	0.2
	1.1	50	0.3
	2.5	250	0.03
Polysulfide	0	4.0	0.20
	0.10	4.0	0.20
	0.20	4.0	0.20
	0.50	6.3	0.20
Silicone	0	0.3	0.3
	0.19	1.1	0.02
	0.43	3.5	0.02
	1.0	11	0.03
Natural Rubber Compound C	0	0.6	0.09
	0.19	1.4	0.04
	0.43	3.1	0.06
	1.0	8.6	0.5
Acrylic	0	0.7	0.4
	0.19	1.4	1
	0.43	3.3	1
	1.0	13	1
Hypalon	0	3	0.3
	0.5	5	0.4
	1.1	30	0.4
	2.5	200	0.1

Source: Reference 60.

TABLE 3-17 (3.4). RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED IN SEALS AND GASKETS AT TEMPERATURES BELOW 300° F.

Material	Use	Temperature Range, °F	Fuel and Oil Stability	Radiation Stability Maximum dosage, ergs/gm in air
ELASTOMERS				
Natural rubber	O-Rings			5×10^{10}
SBR				1.5×10^{9}
Buna N	O-Rings Seals Gaskets Sealant	-40 to 280	Oil resistant	1×10^{10}
Neoprene	O-Rings Seals Gaskets	-40 to 250	Oil resistant	1×10^{9}
Butyl				4×10^{8}
Urethane				1×10^{11}
PLASTICS				
Polystyrene				1×10^{11}
Polyvinyl chloride				1×10^{10}
Polyethylene	Gaskets			1×10^{11}
Epoxy				9.5×10^{10}
Polyurethane				1×10^{11}

TABLE 3-17 (3.4). RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED IN SEALS AND GASKETS AT TEMPERATURES BELOW 300° F. (Cont'd)

Radiation Stability of Elastomers and Plastics Used as Sealants

Elastomer	Temperature Range, °F	Radiation Stability Maximum dosage, ergs/gm
Viton A	to 450	1×10^9 (in air)
RTV Silicone	to 450	1×10^9 (in air)
Polysulfide	to 140	3.5×10^9 (in JP-4 fuel)
Buna N	to 280	1×10^{10} (in air at room temp.)
Neoprene	to 250	1×10^9 (in air at room temp.)

Source: Reference 232.

TABLE 3-18 (3 4). RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED FOR SEALS AND GASKETS FOR OPERATION ABOVE 300°F

Material	Use	Temperature Range, °F	Fuel and Oil Resistance	Radiation Stability in Listed Environment Maximum Dosage, ergs/gm	Remarks
Elastomers					
Viton A	O-Rings Seals	-65 to 600°F	Diester oils	1×10^{10} in diester oil at 400°F. 6×10^{9} in air at room temperature	Tensile strength decreases by 75% when exposed to 5×10^{8} ergs/gm at 400°F in argon gas
Fluorel	O-Rings Seals	-65 to 600°F	Diester oils Silicate ester fluids	1×10^{10} in diester oil at 400°F	
Poly FBA	Seals Gaskets	0 to 450°F	Diester oils	6×10^{9} in diester oil at 400°F. 1×10^{10} in air at 65°F	
Kel-F	O-Rings Seals	to 400°F	Silicate ester fluids	$<6 \times 10^{8}$ in air at room temperature	Becomes soft and tacky
Silicone	O-Rings Seals	-70 to 450°F		1.34×10^{9} in air at room temperature as samples	Broke when handled at 8.3×10^{9} ergs/gm
Silicone	O-Rings Seals			8.3×10^{9} in air at room temperature as samples	
Silicone	O-Rings Seals			2×10^{11} as vacuum seal at room temperature	Did not hold at 61×10^{12} ergs/gm

TABLE 3-18 (3.4). RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED FOR SEALS AND GASKETS FOR OPERATION ABOVE 300°F (Cont'd)

Material	Use	Temperature Range, °F	Fuel and Oil Resistance	Radiation Stability in Listed Environment Maximum Dosage, ergs/gm	Remarks
Plastics					
Teflon	O-Rings Seals Gaskets	to 500°F	Jet turbine oil	8.7×10^8 in air at room temperature	Crumbled at 8.3×10^8 ergs/gm. Felted Teflon holds seal better than solid Teflon
Kel-F				2×10^9 in air at room temperature	Very brittle at 2.4×10^{10}

Source: Reference 232.

TABLE 3-18 (3.4). RADIATION STABILITY OF ELASTOMERS AND PLASTICS USED FOR SEALS AND GASKETS FOR OPERATION ABOVE 300°F (Cont'd)

Material	Use	Temperature Range, °F	Fuel and Oil Resistance	Radiation Stability in Listed Environment Maximum Dosage, ergs/gm	Remarks
Elastomers (Cont'd)					
Silicone	O-Rings Seals			2×10^{11} as vacuum seal at room temperature	Did not hold at 3.7×10^{11} ergs/gm
Silicone	Gaskets	to 450°F		1×10^{9} as gasket in contact with oil at 450°F	
Acrylic	O-Rings Seals			2×10^{11} as vacuum seal at room temperature	Did not hold at 2×10^{12}
Buna N	O-Rings Seals			1.9×10^{11} as vacuum seal at room temperature	Did not hold at 1.4×10^{12}
LS-53		-80 to 400°F	Gasoline, jet engine fuels, hydraulic fluids, engine oils*	$<5 \times 10^{8}$ in air at room temperature	Resistance to oils decreases as temperature increases

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*See Tables 3-6, 3-7, and 3-8.

TABLE 3-19 (3 4). RADIATION STABILITY OF FLUOROPOLYMERS

Polymer	Radiation Tolerance, ergs/gm	Environment	Temperature, °F
Teflon	3.4×10^6 (25% damage)	Air	Room Temperature
	4.3×10^9*	Oil	Room Temperature
	$<4.4 \times 10^7$	Air	400
	10^8	MIL-L-7808 oil	400
Kel-F	1.8×10^9 (25% damage)	Air	Room Temperature
Kel-F Elastomer	4.5×10^8	Air	Room Temperature
	8.7×10^{10}**	Air	250
Viton A	$>2.0 \times 10^9$	Oronite 800 fluid	Room Temperature
	8.4×10^9***	Diester oil	400
	6×10^9	Air	Room Temperature
Poly FBA	8.4×10^9	Air	65
	4.2×10^9	Diester oil	400
LS-53	$<5 \times 10^8$	Air	Room Temperature

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*Teflon backup rings were tested for a total of 500 hours

**Material tested as a coating

***Duration of test was 260 hours

Source: Reference 232.

TABLE 3-20 (3. 4). THE EFFECTS OF ENVIRONMENT ON RADIATION RESISTANCE OF VITON AND TEFLON

			Physical Properties		
Material*	Environment	Dosage, ergs/gm	Tensile, psi	Elongation, percent	Hardness, Shore A
Viton A	Air	Original	1044	192	66.2
Viton A	Air	8.7×10^7	----Disintegrated----		
Viton A	Argon	2.0×10^8	2145	172	72
Viton A	Argon	5.0×10^8	742	63	76
Viton A	MIL-L-7808 Oil	8.7×10^7	1112	208	64.8
Viton A	MIL-L-7808 Oil	4.4×10^8	1028	211	64.4
Viton A	MIL-L-7808 Oil	1.7×10^9	961	117	64.8
Teflon	Air	Original	2435	234	97.5
Teflon	Air	4.4×10^7	1342	0	97.6
Teflon	Air	4.4×10^8	616	0	97.8
Teflon	MIL-L-7808 Oil	8.7×10^6	1471	33	97.2
Teflon	MIL-L-7808 Oil	8.7×10^7	1534	4.6	97.8
Teflon	MIL-L-7808 Oil	8.7×10^8	834	0	98.8

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*Samples were tensile dumbbells.

Source: Reference 232.

TABLE 4-1 (4, 2, 2). ORDER OF MERIT RATINGS OF VARIOUS SPRING TYPES AS SHOCK ABSORBERS

Characteristic	Elastomer Spring	Metal Spring	Damped Metal Spring	Air Spring	Hydraulic Spring	Liquid Spring
Efficiency, %	~60	~50	~70	~40	~80	~75
Construction	1	1	2	3	3	3
Reliability	1	1	2	4	2	3
Weight	4	5	6	3	1	2
Recoil Damping	2	4	3	4	1	1
Environmental Resistance	3	1	1	3	2	2
Resilience (lb in. /lb)	15, 000	1, 000	800	12, 500	10, 000	8, 500

Efficiency, % = $\dfrac{\text{area under load deflection curve}}{\text{maximum load} \times \text{maximum deflection}} \times 100$

Construction = 1. Simplest
3. Most complicated

Reliability = 1. Can be designed fail safe
4. May fail suddenly without prior indication detectable by preventive maintenance inspection

Weight = 1. Lightest
6. Heaviest for equal capacity

Recoil Damping = 1. Highest energy absorbing capacity
4. Least energy absorbing capacity

Environmental Resistance = 1. Inherently resistant
2. Most sensitive to environment

Resilience = Maximum load × deflection/spring weight (for a particular design in each case)

Source SwRI

TABLE 4-2 (4. 2. 2). COMPARISON OF STEEL AND ELASTOMER SPRINGS AS VIBRATION ISOLATORS

Characteristic	Elastomer Spring	Steel Spring
Damping Capability	Inherent	Requires auxiliary device
Size	Small for high energy storage capacity; bulky if large deflections required.	Large for high energy storage capacity; small for large deflections.
Environmental Resistance	Limited	Superior
Construction	Simple	Complex
Sound Insulation	Inherent	Requires auxiliary material
Stability of Properties		
Frequency	Dependent	Independent
Temperature	Dependent	Independent
Loading History	Dependent	Independent
Snubbing	No dead stop	Requires auxiliary device
Load-Deflection Curve	Highly variable	Limited
Lateral Stability	Inherent	May require auxiliary device
Minimum Natural Frequency	Limited	Unlimited
Response to Dead-Weight Load	Creep, static fatigue	No effect
Design Analysis	Empirical basis	Mathematical basis

Source: SwRI