

MIL-HDBK-149B

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MILITARY STANDARDIZATION HANDBOOK

RUBBER



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DEPARTMENT OF DEFENSE
Washington, DC 20301

1. This standardization handbook was developed by the Department of Defense in accordance with established procedures.

2. This publication was approved on 5 May 1983 for printing and inclusion in the military standardization handbook series.

3. This handbook will provide instruction and assistance to designers and engineers concerned with the design of rubber components for military material. This handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on rubber and rubber-like materials. It is the intent to review this handbook periodically to ensure its completeness and currency. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions to Army Materials & Mechanics Research Center, ATTN: DRXMR-SMS, Watertown, Massachusetts 02172, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

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Foreword

This handbook is one of a group which cover metallic and nonmetallic materials used in the design and construction of military equipment. The purpose of these handbooks is to provide current technical information and design data of direct usefulness to engineers and designers of military equipment.

The intent of this handbook is to provide, in condensed form, technical information and data of direct usefulness to engineers and designers concerned with rubber. This handbook contains graphical and tabulated presentations of data for a broad range of basic rubber types including performance of some of their characteristic compounds under a wide range of service conditions. Applicable design equations and some typical examples of design calculation are included to aid the designer in achieving rational designs for elastomeric components.

The designer should realize that, more than any other material, rubber is intensely affected by the environment and conditions under which it is employed. The selection of a suitable material must therefore be governed by consideration of the stability of the critical properties within the applicable service environment. This selection should be made only after careful comparative evaluation and matching of rubber capability with service requirements. Since the number of specifically tailored compounds within a given polymer group is practically unlimited, compounding of special rubber types for special applications should be done only by qualified rubber technologists.

The properties and data given in this handbook are not intended to be used for purposes of providing manufacturing or procurement specifications. Such requirements are adequately covered by applicable specifications.

Comments on this handbook are invited. They should be addressed to Director, U.S. Army Materials & Mechanics Research Center, ATTN: DRXMR-SMS, Watertown, Massachusetts 02172.

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1. SCOPE

1.1 Introduction. This handbook provides technical and design information and data concerning rubber and rubber-like materials, useful to designers and engineers for different applications and environments.

1.2 Characteristics of Rubber.

1.2.1 Rubber has several characteristics that make it more suitable than rigid materials for such engineering applications as spring members, resilient mountings, couplings, and seals. Some of these characteristics are:

- (1) Rubber can be highly deformed without breaking.
- (2) Rubber can rapidly and repeatedly recover from deformation.
- (3) Large deformations may be produced at relatively low stress levels.
- (4) A wide range of stress-strain properties can readily be obtained by compounding.
- (5) Stress-strain characteristics are nonlinear, that is, the material becomes stiffer with greater deflections.
- (6) Polymers and copolymers can be vulcanized and exhibit some properties of liquids and some properties of solids, and are, for most practical purposes, noncompressible.

1.3 The Raw Material.

1.3.1 The term "natural rubber" can be used to describe all rubber-like materials that are produced by coagulation of a plant latex. Commercially, the primary natural rubber source has been the Hevea tree, Hevea braziliensis. Hevea grows wild in Central South America, but is more successfully cultivated in other tropical parts of the world, such as Malaysia (including Singapore), Indonesia (including Borneo), Thailand, Sri Lanka (Ceylon), India, Liberia, Nigeria, Philippines, Zaire, Vietnam, and Kampuchea (Cambodia). A rubber tree native to southeast Asia, Ficus elastica, is another source of latex, but it is not the high quality rubber produced by the Hevea tree. Natural rubber, as it appears on the market, contains small amounts of nonrubber substances in addition to the rubber hydrocarbons. These materials, in spite of their low concentration relative to that of rubber hydrocarbons, have a profound effect on the vulcanization of the hydrocarbon and the physical properties of the resulting vulcanizate. See Data Sheet No. 17 in Appendix C for specific properties.

1.3.2 Another source for natural rubber is being developed in the United States and Mexico. The Guayule bush, Parthenium argentatum, a small desert shrub which grows in the arid regions of southwestern United States and northern parts of Mexico, yields a plant sap from which natural rubber may be obtained. Preliminary studies indicate that the molecular structure and properties of Guayule rubber seems to be superior to the Hevea rubber because of a lower level of protein in the Guayule rubber. Studies related to the structure and properties of Guayule rubber are actively being pursued and a "pilot plant" type operation was underway in early 1981. Cultivation and extraction methods are being developed and it is possible that this source of

natural rubber will be available commercially in the future. The references to natural rubber in this Handbook apply to the Hevea type, unless otherwise indicated. See 9.1 and Data Sheet No. 17 for further information.

1.3.3 The term "synthetic rubber" was applied to a group of elastomeric materials developed primarily in the 1940's as a replacement for "natural rubber" that was in limited supply due to world-wide conflicts. Natural rubber is a cis-1,4-polyisoprene that is obtained from a botanical source. Synthetic rubbers (elastomers) are primarily derived from petrochemical hydrocarbons by polymerization. Synthetic (man-made) rubbers account for about 70 percent of the world rubber market.

1.3.4 Rubber and rubber-like materials, natural and synthetic, are basically polymers and copolymers composed of macromolecules. Rubbers can be classified and coded from the chemical composition of the polymer chain; the code letters indicate class designation as shown in ASTM Standard D1419(5):

M - Rubbers having a saturated chain of the polymethylene type.

N - Rubbers having nitrogen in the polymer chain.

O - Rubbers having oxygen in the polymer chain.

R - Rubbers having an unsaturated carbon chain.

Q - Rubbers having silicon in the polymer chain.

T - Rubbers having sulfur in the polymer chain.

U - Rubbers having carbon, oxygen, and nitrogen in the polymer chain.

Z - Rubbers having phosphorous and nitrogen in the polymer chain.

1.3.5 One type of synthetic rubber is based on a chain of alternating silicon and oxygen atoms, rather than the hydrocarbon structure. This polymer type, identified as class "Q", is based on a polysiloxane polymer, with various arrangements and types of organic groups attached to the basic silicon-oxygen chain to achieve different properties. This class of rubbers is called "silicone rubbers."

1.3.6 Raw rubber, produced from the coagulation of latex, has a consistency similar to putty. It is only after vulcanization, that is, the chemical reaction between rubber and sulfur (or other vulcanizing chemical) with heat, that rubber achieves the rubber-like characteristics that make this material suitable for its intended use. After vulcanization, the long-chain rubber molecules are arranged in randomly oriented coils. When the rubber material is stretched, the flexible coil segments are straightened. When the tensile stress is released, the segments return quickly and forcibly to their normally coiled position. An increase in temperature, within moderate limits, enhances the freedom of the segments to seek their initial position, thus increasing the restoring force for a particular elongation. A decrease in temperature will decrease the elongation and restoration upon release. An increase in temperature above a critical value for each polymer will increase the degree in crosslinking and decrease both the elasticity and return to original position. These characteristics will be discussed in more detail in 7.1 and 7.2:

1.4 Rubber Types: Distinctive Characteristics

1.4.1 Functionally, rubber is defined as a natural or man-made material which has been, or can be, vulcanized to exhibit a high reversible

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extensibility. In this handbook, the term describes generally all polymers having this property; such compounds are also known as "elastomers". Table I classifies rubber into elastomer types. The manufacturers and trade names under which they market these materials are noted. Individual rubber fabricators further "compound" these polymers by additions of fillers, extenders, and other additives.

1.4.2 Each elastomer type, therefore, has many variations, each with its own set of physical and chemical properties. These variations differ in the arrangement of the atoms of the polymer-unit molecule, placement of the monomer units in the polymer chain, and their point of attachment to each other.

1.4.3 There are some thermoplastic rubbers which act like vulcanized rubber over a limited temperature range. The advantages of these materials are speed of processing and reuse of scrap, both of which lower costs. Above their useful temperature range and under pressure, parts made from these rubbers become deformed and rendered useless.

1.4.4 The classification of rubber described in Table I is based on ASTM Standard D1418 (5), which established classes of polymer listed in 1.3.4. The ASTM Designation in Table I shows the Class designation in the last element of the symbol. The letter or letters preceding the class designator indicate the monomer(s), diolefins(s), or other groups from which the rubber was prepared, except for natural rubber.

1.4.4.1 The "M" class includes rubbers having a saturated chain of polymethylene type. The following classification is used:

ACM - Copolymers of ethyl or other acrylate and a small amount of monomer which facilitates vulcanization

ANM - Copolymers of ethyl or other acrylate and acrylonitrile

CM - Chloro-polyethylene

CFM - Polychloro-trifluoro-ethylene

CSM - Chloro-sulfonyl-polyethylene

EAM - Copolymers of ethylene and vinyl acetate

EPDM - Terpolymer of ethylene, propylene, and a diene with the residual unsaturated portion of the diene in the side chain

EPM - Copolymers of ethylene and propylene

FFKM - Perfluoro rubbers of the polymethylene type having all substituent groups on the polymer chain either fluoro, perfluoroalkyl, or perfluoroalkoxy groups

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FKM - Fluoro rubber of the polymethylene type having substituent fluoro and perfluoroalkyl or perfluoroalkoxy groups on the polymer chain

IM - Polyisobutene

1.4.4.2 The "O" class includes rubbers having oxygen in the polymer chain. The following classification is used:

CO - Polychloromethyl oxirane (epichlorohydrin polymer)

ECC - Ethylene oxide (oxirane) and chloromethyl oxirane (epichlorohydrin copolymer)

GPO - Polypropylene oxide and allyl glycidyl ether

1.4.4.3 The "R" class includes rubbers prepared from various diolefin(s) and comonomer(s) indicated by the letters preceding the letter R. The following classification is used:

ABR - Acrylate-butadiene rubbers

BIIR - Bromo-isobutene-isoprene rubbers

BR - Butadiene rubbers

CIIR - Chloro-isobutene-isoprene rubbers

CR - Chloroprene rubbers

IIR - Isobutene-isoprene rubbers

IR - Isoprene rubbers, petrochemical

NBR - Nitrile-butadiene rubbers

NCR - Nitrile-chloroprene rubbers

NIR - Nitrile-isoprene rubbers

NR - Isoprene rubber, natural

PBR - Pyridine-butadiene rubbers

PSBR - Pyridine-styrene-butadiene rubbers

SBR - Styrene-butadiene rubbers

SCR - Styrene-chloroprene rubbers

SIR - Styrene-isoprene rubbers

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1.4.4.4 Rubbers of the "R" class having substitute carboxylic acid (COOH) groups on the polymer chain are identified by the prefix "X":

XNBR - Carboxylic-nitrile-butadiene rubbers

XSBR - Carboxylic-styrene-butadiene rubbers.

1.4.4.5 The "Q" class includes polymers based on the silicon-oxygen-silicon chain, rather than the hydrocarbon-base chain of the other rubbers, with the substituent groups on the polymer chain indicated by the letter(s) prior to the silicone ("Q") designation. The M preceding the Q indicates that methyl is one of the substituent groups. The following classification is used:

FVMQ - Silicone rubber having fluorine, vinyl, and methyl substituent groups

PMQ - Silicone rubbers having methyl and phenyl substituent groups

PVMQ - Silicone rubbers having methyl, phenyl, and vinyl substituent groups

MQ - Silicone rubbers having only methyl substituent groups, such as dimethyl polysiloxane

VMQ - Silicone rubbers having methyl and vinyl substituent groups

1.4.4.6 The "U" class includes rubbers having carbon, oxygen, and nitrogen in the polymer chain. The following classification is used:

AFMU - Terpolymer of tetrafluoroethylene, trifluoronitrosomethane, and nitrosoperfluorobutyric acid

AU - Polyester urethane

EU - Polyether urethane

1.4.4.7 The "T" class includes rubbers having carbon, oxygen, and sulfur in the polymer chain. The following classification is used:

OT - A rubber having either a $-\text{CH}_2-\text{CH}_2-\text{O}-\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2-$ group or occasionally an -R- group, where R is an aliphatic hydrocarbon between the polysulfide linkages in the polymer chain

EOT - A rubber having either a $-\text{CH}_2-\text{CH}_2-\text{O}-\text{CH}_2-\text{O}-\text{CH}_2-\text{CH}_2-$ group or $-\text{CH}_2-\text{CH}_2-$ group or occasionally an -R- group, where R is an aliphatic hydrocarbon between the polysulfide linkages in the polymer chain

1.4.4.8 The "Z" class includes rubbers having phosphorus and nitrogen in the polymer chain. The following classification is used:

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FZ - A rubber having a -P=N- chain and having fluoroalkoxy groups attached to the phosphorus atoms in the chain

PZ - A rubber having a -P=N- chain and having aryloxy (phenoxy and substituted phenoxy) groups attached to the phosphorus atoms in the chain

1.4.4.9 When designating latex or latices of any of the above rubbers, the terminology would be, for example, "SBR latex" or "SBR latices."

1.4.5 Figure 1 and Tables II and III provide general guides to rubber group capabilities and illustrate those elastomers suitable for a particular use.

TABLE I. SPECIFIC TYPES OF RUBBER^{1/}

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
ACRYLATE-ACRYLONITRILE	ANM	ETHYL ACRYLATE AND ACRYLONITRILE COPOLYMERS (may use other acrylates)	-
ACRYLATE-BUTADIENE	ABR	ETHYL ACRYLATE AND BUTADIENE COPOLYMERS (may use other acrylates)	-
		Cynacril - American Cyanamic Hycar - Goodrich Chemical Paracril - Uniroyal Chemical	
ACRYLONITRILE-BUTADIENE	NBR	Also called NITRILE RUBBER and NITRILE BUTADIENE RUBBER (Formerly designated BUNA-N)	1
		Chemigum - Goodyear Elaprim-S - Montedison USA FR-N - Firestone Hycar NBR - Goodrich Chemical Krynac - Polysar Nysyn - Copolymer Rubber Paracril - Uniroyal Chemical Perbunan-N - Mobay	
ACRYLONITRILE-BUTADIENE- POLYVINYL-CHLORIDE COPOLYMER	-	COPOLYMER OF ACRYLONITRILE- BUTADIENE AND POLYVINYL CHLORIDE Paracril Ozo - Uniroyal Chemical	-

^{1/} Based on the classification in ASTM Standard D1418(5)

^{2/} See Appendix D for manufacturers' complete names

^{3/} See Appendix C for Data Sheets

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
ACRYLONITRILE-ISOPRENE	NIR	ACRYLONITRILE-ISOPRENE COPOLYMER Krynac 833 - Polysar	2
BROMO BUTYL	BIIR	BROMO-ISOBUTYLENE-ISOPRENE Promo Butyl X2 - Polysar	3
BUTADIENE	BR	BUTADIENE COPOLYMERS Ameripol CB - Goodrich Chemical Budene - Goodyear Cisdene - American Synthetic Cis-4 - Phillips Diene - Firestone Duragen - General Tire Synpol E-BR - Texas-US Chemical Taktene - Polysar	4
BUTADIENE-STYRENE	SBR	See STYRENE-BUTADIENE	25
BUTYL	IRR	ISOBUTYLENE-ISOPRENE Bucar - Cities Service Butyl - Exxon Butyl - Polysar	5
CARBOXYLIC-NITRILE- BUTADIENE	XNBR	CARBOXYLIC-ACRYLONITRILE- BUTADIENE COPOLYMERS Krynac 1000, 221 & 211 - Polysar Hycar 1072 - Goodrich Chemical	6
CHLORO BUTYL	CIIR	CHLORO-ISOBUTYLENE-ISOPRENE Chlorobutyl - Exxon	7
CHLORO-ISOBUTYLENE-ISOPRENE	CIIR	See CHLORO BUTYL	7
CHLOROPOLYETHYLENE	CM	CHLORINATED POLYETHYLENE Dow CPE Elastomer - Dow Chemical	8

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
CHLOROPRENE RUBBER	CR	POLYCHLOROPRENE (NEOPRENE is becoming generic) Bayprene - Mobay Butachlor-A - A. Schulman Neoprene - Denka Neoprene - DuPont Neoprene - Petra-Tex	9
CHLOROSULFONATED POLYETHYLENE	CSM	CHLORO-SULFONYL-POLYETHYLENE Hypalon - Dupont	10
DIMETHYL SILICONE	MC	See METHYL SILICONE	24
EPICHLOROHYDRIN COPOLYMER	ECO	ETHYLENE OXIDE & CHLOROMETHYL OXIRANE Herclor-C - Hercules Hydrin-200 - Goodrich Chemical	11
EPICHLOROHYDRIN HOMOPOLYMER		Herclor-H - Hercules Hydrin-100 - Goodrich Chemical	
ETHYLENE OXIDE & CHLOROMETHYL OXIRANE	ECO	See EPICHLOROHYDRIN COPOLYMER	11
ETHYLENE-PROPYLENE	EMP	ETHYLENE-PROPYLENE COPOLYMER Dutral CO - Montedison USA Epcar 306 EPM - Goodrich Chemical Epsyn - Copolymer Rubber Royalene - Uniroyal Chemical Vistalon - Exxon	12
ETHYLENE-PROPYLENE-DIENE MODIFIED	EPDM	 Dutral-TER - Montedison USA Epcar EPDM - Goodrich Chemical Epsyn - Copolymer Rubber Nordel - DuPont Royalene - Uniroyal Chemical Vistalon - Exxon	13
ETHYLENE-VINYL ACETATE	EAM	ETHYLENE-VINYL ACETATE COPOLYMER	

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
FLUOROCARBON		POLYMETHYLENE FLUORO RUBBER WITH FLUORO AND PERFLUORO OR PERFLUORO-ALKOXY GROUPS ON THE POLYMER CHAIN	
	FKM	Fluorel - 3M Viton - DuPont	14
	FFKM	Kalrez - DuPont	15
FLUOROCARBON	CFM	COPOLYMER OF CHLOROTRIFLUORO- ETHYLENE AND VINYLIDENE FLUORIDE	14
		KEL-F Elastomer - 3M KEL-F 3700 - 3M	
FLUROSILICONE	FVMQ	METHYL-VINYL-FLUORINE SILICONE Silastic Fluorosilicone Rubber - Dow Corning	16
ISOBUTYLENE-ISOPRENE	IIR	See BUTYL	5
ISOPRENE RUBBER, NATURAL	NR	See NATURAL RUBBER	17
ISOPRENE RUBBER, PETROCHEMICAL	IR	See POLISOPRENE	17
METHYL SILICONE	MQ	Generally replaced by other silicones	24
METHYL-PHENYL SILICONE	PMQ	See SILICONE RUBBER	24
METHYL-PHENYL-VINYL SILICONE	PVMQ	See SILICONE RUBBER	24
METHYL-VINYL SILICONE	VMQ	See SILICONE RUBBER	24
METHYL-VINYL-FLUORINE SILICONE	FVMQ	See FLUROSILICONE	16
NATURAL RUBBER	NR	ISOPRENE RUBBER, NATURAL, HEVEA	17
	NR	ISOPRENE RUBBER, NATURAL, PARTHENIUM (also called GUAYALE)	17

Many producers of Smoked Crepe
and Technically Specified Rubber

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
NITRILE-CHLOROPRENE	NCR	No longer manufactured	-
NITRILE-ISOPRENE	NIR	See ACRYLONITRILE-ISOPRENE COPOLYMER	2
NITRILE	NBR	See ACRYLONITRILE-BUTADIENE (Although NITRILE is widely used, the preferred terminology is Acrylonitrile-Butadiene.)	1
PERFLUORO ELASTOMER	FFKM	See FLUOROCARBON	15
PHOSPHONITRILIC FLUOROELASTOMER	FZ	PHOSPHONITRILIC FLUOROELASTOMER Polyphosphazene, PNF - Firestone	18
POLYACRYLATE	ACM	ETHYL ACRYLATE (or other acrylates) Cyanacryl - American Cyanamid Elaprim - Montedison USA Reichhold Chemicals Hycar 40xx, 26xx - Goodrich Chemical Vamac - DuPont Vyram - Monsanto	19
POLYCHLOROMETHYL OXIRANE	CO	See EPICHLOROHYDRIN HOMOPOLYMER	11
POLYCHLOROPRENE	CR	See CXHLOROPRENE	9
POLYCHLOROTRIFLUORO- ETHYLENE	CFM	POLYCHLOROTRIFLUOROETHYLENE- VINYLIDENE FLUOROIDE Kel-F Elastomer (KEL-F 3700) - 3M	14
POLYESTER URETHANE	AU	POLYURETHANE ESTER Arcon - Allied Resin Conothane - Conap Cyanaprene - American Cyanamid Multrathane - Mobay Polyglycol Adipates - Inolex Rucoflex - Hooker Solithane - Thiokol Vibrithane - Uniroyal Chemical	20

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
POLYETHER URETHANE	EU	POLYURETHANE ETHER	20
		Adiprene - DuPont	
		Acron - Allied Resin	
		Betathane - Essex Chemical	
		Castall - Polymer West	
		Catapol - Arnco	
		Conothane - Conap	
		Craco-thane - J. M. Cranz	
		Cyanaprene - American Cyanamid	
		Cytor - American Cyanamid	
		Elastothane - Thiokol	
		Esthane - Goodrich Chemical	
		Indpol - E. L. Puskas	
		Fastcast - Arnco	
		Millathane - Tech-Sales	
		Penetrex - Arnco	
		Permatire - Arnco	
		Quickcast - Arnco	
		Reyno-foam - Hoover Universal	
POLYISOBUTENE	IM	POLYISOBUTENE	-
POLYISOPRENE	IR	ISOPRENE RUBBER, PETROCHEMICAL	17
		Ameripol SN - Goodrich Chemical	
		Natsyn - Goodyear	
		TransPip - Polysar	
POLYSULFIDE	EOT	POLYSULFIDE	21
		Thiokol - Thiokol	
POLYURETHANE	AU	See POLYESTER URETHANE	20
	EU	See POLYESTER URETHANE	20
PROPYLENE OXIDE-ALLYL GLYCIDYL ETHER	GPO	POLYPROPYLENE OXIDE-ALLYL GLYCIDYL ETHER COPOLYMER	22
		Parel - Hercules	
PYRIDINE-BUTADIENE	PBR	PYRIDINE-BUTADIENE	23

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TABLE I. (continued)

ELASTOMER TYPE	ASTM DESIGNATION	TRADE NAME AND MANUFACTURER ^{2/}	DATA SHEET NUMBER ^{3/}
SILICONE RUBBER			24
METHYL SILICONE	MQ	Baysilone - Mobay	
METHYL-PHENYL SILICONE	PMQ	Blensil - General Electric	
METHYL-PHENYL-VINYL SILICONE	PVMQ	Electrisil - General Electric	
METHYL-VINYL SILICONE	VMQ	Gensil - General Electric	
		K - Union Carbide	
		Rhodia RS - Rhone-Poulenc	
		RTV-Castall - Polymer West	
		SE - General Electric	
		Silastic - Dow Corning	
		SWS - SWS Silicone	
STYRENE-BUTADIENE	SBR	STYRENE-BUTADIENE COPOLYMER	25
		Ameripol SBR - Goodrich Chemical	
		AMSYN Latexes - American Synthetic	
		ASRC - American Synthetic	
		-- - Arco/Polymers	
		Copo SBR - Copolymer Rubber	
		FR-S - Firestone	
		Gentro - General Tire	
		Gentro-Jet - General Tire	
		Krylene - Polysar	
		Krynox - Polysar	
		Krymix - Polysar	
		Naugatex - Uniroyal Chemical	
		Philprene - Phillips Chemical	
		Plioflex - Goodyear	
		Polysar SS - Polysar	
		Solprene - Phillips Chemical	
		Synpol - Texas-US Chemicals	
STYRENE-CHLOROPRENE	SCR	Not available in USA	-
STYRENE-ISOPRENE	SIR	STYRENE-ISOPRENE-COPOLYMER	26
SULFIDE	EOT	See POLYSULFIDE	21
TETRAFLUOROETHYLENE- TRIFLUORONITROSOMETHANE- NITROSEPERFLUOROBUTYL	AFMU	TERPOLYMER OF TETRAFLUOROETHYLENE, TRIFLUORONITROSOMETHANE, AND NITROSEPERFLUOROBUTYRIC ACID	-

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TABLE II. TENSILE TEAR, AND ABRASION RESISTANCE OF BASIC RUBBER TYPES

Rubber		Tensile	Tear	Abrasion
Acrylonitrile Butadiene	NBR	Good - Fair	Good - Fair	Good - Fair
Acrylonitrile Butadiene-Vinyl Blend		Excellent - Good	Good	Excellent
Bromobutyl	BIIR	Fair	Good	Good
Butyl	IIR	Fair	Good	Good - Fair
Butyl, High Temperature	IIR	Good - Fair	Good	---
Carboxylic-Acrylonitrile-Butadiene	XNBR	Excellent	Good	Excellent
Chlorobutyl	CIIR	Fair	Good	Good
Chloroprene	CR	Excellent	Good	Good
Chlorosulfonated Polyethylene	CSM	Good	Fair	Good
Epichlorohydrin Copolymer	ECO	Fair	Good	Good
Epichlorohydrin Homopolymer	CO	Fair	Good	Good
Ethylene Propylene Copolymer	EPM	Good	Fair	Fair
Ethylene Propylene Diene Modified	EPDM	Good	Good - Fair	Good - Fair
Fluorocarbon	FKM	Good	Good - Fair	Fair
Fluorosilicone	FVMQ	Fair	Poor	Poor
Methyl Vinyl Silicone	VMQ	Fair	Poor	Poor
Methyl Vinyl Silicone, High Strength	VMQ	Good	Fair	Fair
Methyl Vinyl Silicone, High-Temperature	VMQ	Fair	Poor	Fair - Poor
Natural	NR	Excellent - Good	Excellent - Good	Good
Polyacrylate	ACM	Poor	Fair	Fair
Polyurethane, Ester	AU	Excellent - Good	Excellent	Excellent
Polyurethane, Ether	EU	Excellent	Excellent	Excellent
Propylene Oxide	GPO	Fair	Good - Fair	Good - Fair
Styrene Butadiene	SBR	Good	Good - Fair	Good

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TABLE III. RELATIVE OIL, FUEL, AND OZONE RESISTANCE OF RUBBER TYPES (71)

Rubber	Automatic Transmission Fluid, Type A			Automotive Real Axle Types EP Lubes			Synthetic Hydraulic Oils 250°F (120°C)	Aircraft Phosphate Ester Hydraulic Fluid 180°F (80°C)	Automatic Fuel ^b RT	Ozone (No Inhibitors) RT
	200°F (95°C)	300°F (150°C)	350°F (175°C)	200°F (95°C)	250°F (120°C)	350°F (150°C)				
Acrylonitrile Butadiene	A	C	F	C	F	F	C	D	B	D
Acrylonitrile Butadiene, Vinyl Blend	B	F	F	D	F	F	D	-	B	B
Butyl	F	F	F	F	F	F	A	B	F	B-C
Butyl, High Temperature	F	F	F	F	F	F	A	-	F	B
Carboxylic-Acrylonitrile-Butadiene	A	C	F	C	F	F	C	-	B	C-D
Chlorobutyl	F	F	F	F	F	F	A	-	F	A-B
Chloroprene	C	D	F	D	F	F	B	D	C	B
Chlorosulfonated Polyethylene	C	F	F	C	D	F	B	C-D	D	A
Ethylene Propylene	F	F	F	F	F	F	A	A	F	A
Ethylene Propylene Diene Modified	F	F	F	F	F	F	A	A	F	A
Fluorocarbon	A	A	A	A	A	A	F	D	A	A
Fluorosilicone	A	A-B	A-B	A	B	-	F	D	B	A
Methyl Vinyl Silicone	B	B-C	B-C	B	C	F	A-B	B	D	A
Methyl Vinyl Silicone, High-Temperature	B	C	C	B	C	F	A-B	B	D	A
Natural	F	F	F	F	F	F	C	C	F	D
Polyacrylate	A	A	C	A	A	B	D	D	C	A
Polyurethane, Ester	D	F	F	D	F	F	F	D	B	A-B
Polyurethane, Ether	C	D	F	C	D	F	F	D	B	A-B
Styrene Butadiene	F	F	F	F	F	F	B	D	F	D

NOTES: a Skydrol 500
b ASTM Fuel B

LEGEND: A - Excellent
B - Good
A-B, B-C, etc - Intermediate
C - Fair
D - Poor (not recommended)
F - Completely unserviceable

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1.5 Applications

1.5.1 The industrial uses of rubber are too broad to receive detailed coverage in this handbook. Many applications, such as rubber protective coatings, rubber hose, belting, wire insulation, and pneumatic items like tires and inflatable life saving equipment, are highly specialized. Consequently, the data which could be included would be of little use in a design problem. Therefore, the material presented here concerns the applications of rubber in mechanical goods such as shock mounts, spring members, bushings and bearings, seals and gaskets, diaphragms, bellows, grommets, fluid retaining linings, insulation, brake and clutch members, and bumpers. MIL-HDBK-695 provides good insight into all uses of rubber. It gives general guidance to storage life expectancies of all polymers that are a part of military specifications. All military specifications that are about rubber are listed with shelf life review periods provided to guide users. This handbook is a guide and not a requirements document.

1.5.2 For most engineering applications, rubber is most frequently used in shear or in compression. It is seldom used in tension because of its low tear resistance. Under moderate shear loading, rubber displays a nearly linear relationship between stress and strain - much like rigid materials. The stress limits for each linearity vary with rubber hardness (H when hardness is measured by durometer) as can be observed by inspection of Figures 43 and 44. This is not true in tension or compression applications so that Hooke's law, linearity of stress to strain, does not hold true. In compression, the shape and relative position of the stress-strain curve is dependent on a shape factor. This makes design in compression more difficult since it is dependent on specific shape factor curves for each material. Shear loading has an additional advantage over compression loading in that greater deflections can be achieved with any given volume of material.

1.5.3 In resilient mountings, shear loading is the rule, with some precompression to increase stiffness. However, where loads are high and deflections moderate, compression loading is more advantageous.

1.5.4 As an example, in Figure 2, the various methods of loading are shown with respect to a bushing consisting of two steel sleeves with a rubber matrix contained between them, forming a continuous sandwich.

1.6 Engineering Characteristics of Rubber Compared to Other Materials

1.6.1 The physical properties of rubber which determine its engineering characteristics differ fundamentally from those of other commonly used engineering materials. For this reason, customary methods of calculation cannot be applied directly, and must be used in a modified sense. Customary engineering terminology, used to identify and classify material properties, can be applied to rubbers only with caution since they do not have the same meaning or at least not the same significance. The primary reason for this is that, in engineering applications of rubber, much greater deformations are permitted than in more conventional materials. Hence, the stressed-to-unstressed dimensional ratio of a rubber member varies considerably more under stress than that of a steel member for the allowable stress limits for each material. This, in turn, affects the stress-strain relationship.

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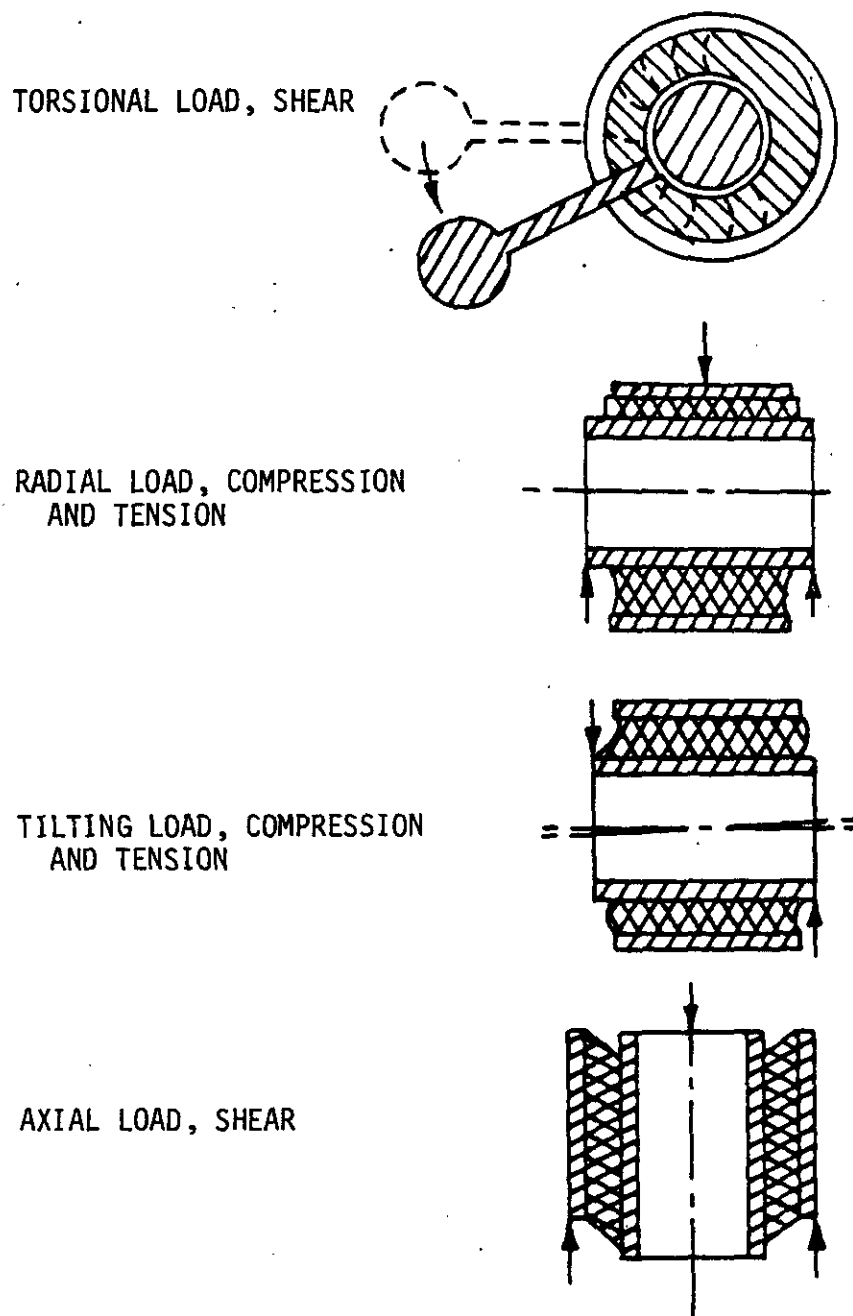


FIGURE 2. RUBBER SANDWICH BUSHING UNDER DIVERSE LOAD APPLICATION (78)

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1.6.2 The stress-strain relationship in rubber, as in other materials, is linear for very small ranges of strain. Unlike other materials, rubber retains its elasticity at relatively large deformations; that is, returns to initial shape when unloaded. However, the stress-strain curve does not remain linear during such extension. Consequently, the modulus of elasticity for rubber is not a constant value but varies with the stress level. Calculations of design data, therefore, depend upon experimental data. The stress-strain relationship is also dependent on the temperature as demonstrated in Figure 3.

1.6.3 The modulus of elasticity of rubber compared to that of other engineering materials is low, indicating that low stress levels produce large strains. On the other hand, its bulk modulus is high, approaching that of a liquid, indicating that rubber vigorously resists changes in volume. As a consequence, any change in one dimension must be accommodated by an equal change in one or more of the other dimensions. Axial tension produces corresponding transverse constriction, and axial compression is accompanied by transverse bulging. This property can be expressed by Poisson's ratio, which is the ratio of the lateral contraction per unit width to the longitudinal extension per unit length when a material is stretched. (See 4.4 for detailed discussion.)

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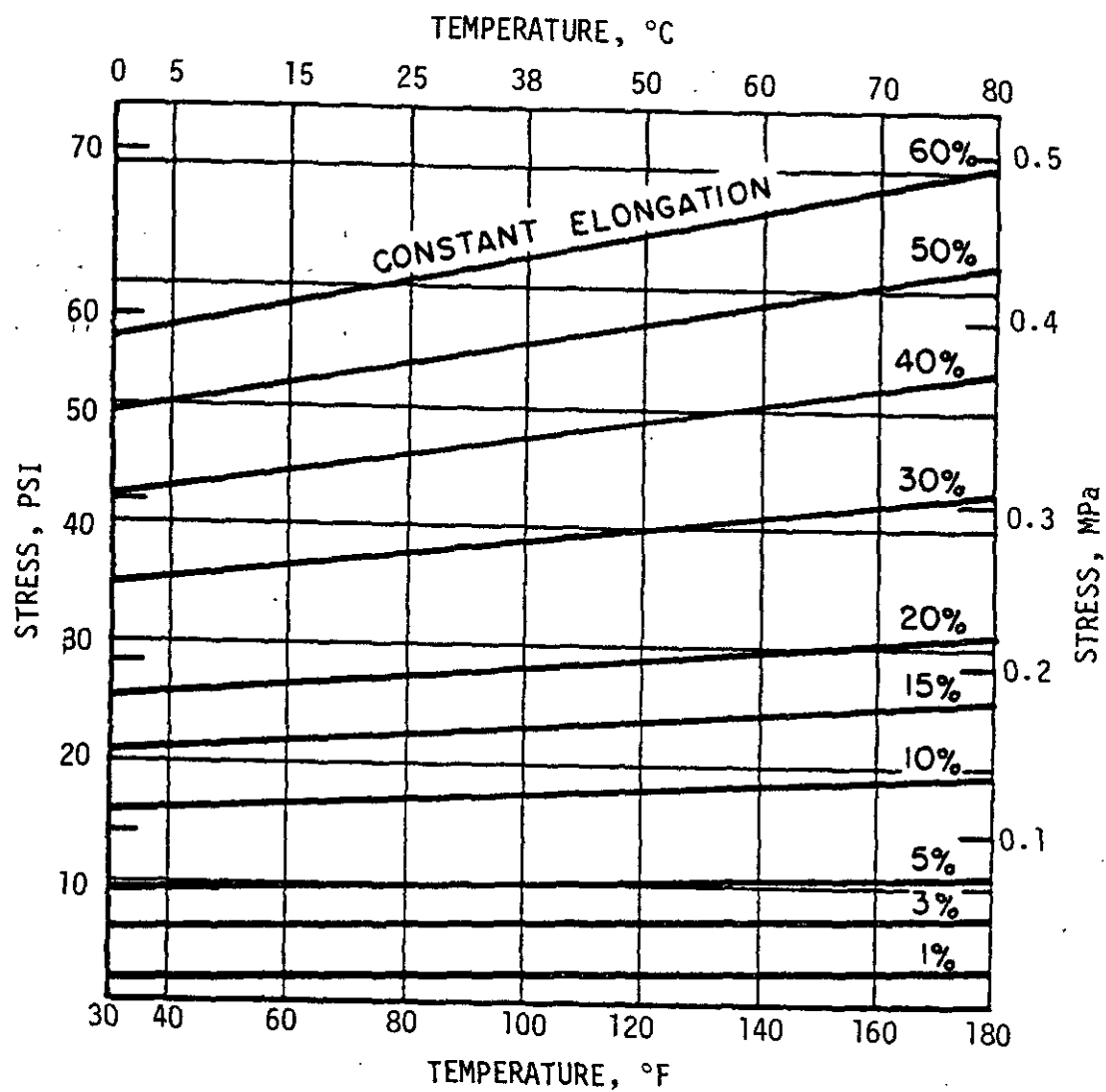


FIGURE 3. STRESS INCREASE IN RUBBER WITH INCREASING TEMPERATURE (2)

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1.6.4 The energy-storing characteristics of rubber exceed those of steel by far. Furthermore, because of its molecular structure, rubber offers high hysteresis, and therefore may have good damping characteristics. The fact that rubber can readily translate a two-dimensional force into a three-dimensional change makes it unique. The fact that volume changes due to pressure can be neglected unless the pressure is very high also makes it interesting as an engineering material. However, the most commonly overlooked characteristic of rubber is its thermal volume change rate. Mechanical designers tend to think in terms of room temperature dimensions and fail to appreciate the shape and force changes that exist at the service temperature extremes.

1.6.5 The mechanical properties of natural rubber vulcanizates and other materials are compared in Table IV.

1.7 Standards on Rubber

1.7.1 A number of standardization documents have been developed to define material properties and methods of evaluating them. These are generally referred to as "procurement specifications" (or "material specifications"), which define the properties of a particular material (should be only those properties required to ensure reproducibility of material), and "test method standards," which define the procedures used to determine individual properties. An engineer usually designates the rubber material to be used to make a part, and calls out on his drawing the material specification that lists the material property requirements and the individual test methods to be used to determine compliance with the specification.

1.7.1.1 Standardization of a test method means that many of its users have agreed on all of its procedural requirements and that these requirements have been developed by a standardization group. Furthermore, the method probably will have been evaluated in an interlaboratory program so that its repeatability within a laboratory and reproducibility between laboratories are known. The test scope, significance, interfaces, and applicable definitions, as well as specific specimen size and details of procedure, will have been documented to minimize understanding.

1.7.2 In the United States there have developed several series of standardization documents.

1.7.2.1 Military and Federal specifications, standards, and test method standards. These documents have been developed primarily for use by Government agencies in procurement and test. Currently, however, there is an increasing usage of industry developed documentation by Government agencies. See Appendix B for a listing of typical Government specifications and standards.

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TABLE IV. COMPARATIVE MECHANICAL PROPERTIES OF RUBBER AND OTHER MATERIALS

Material	Tensile Strength psi (MPa)	Ultimate Elongation %	Modulus of Elasticity for Small Deformations psi (MPa)	Modulus of Rigidity for Small Deformations psi (MPa)	Poisson's Ratio Per Unit Length	Bulk Modulus psi (MPa)
Rubber, Vulcanized, Soft, 30 Durometer A Hardness	3,000 (20.68)	800	150 (1.03)	50 (0.34)	0.50	400,000 (2,760)
Rubber, Vulcanized, Firm, 70 Durometer A Hardness	4,000 (27.58)	450	500 (3.45)	160 (1.10)	0.50	600,000 (4,135)
Rubber, Hard, Ebonite	10,000 (68.95)	6	150,000 (1,035)	---	0.20	750,000 (5,170)
Cellulose Acetate	10,000 (68.95)	---	300,000 (2,068)	---	---	---
Copper, Annealed	35,000 (241.3)	35	16,000,000 (110,300)	6,000,000 (41,370)	0.35	18,000,000 (124,105)
Iron, Cast Gray	50,000 (344.7)	---	15,000,000 (103,420)	5,000,000 (34,475)	---	10,000,000 (68,950)
Aluminum Alloy, Wrought, Heat Treated	68,000 (468.8)	20	10,300,000 (71,000)	3,800,000 (26,200)	0.33	10,000,000 (68,950)

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1.7.2.2 Industry Specifications, Standards, and Test Procedures. While many individual companies develop their own series of documents, the industry-wide documents have been developed primarily by the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers, Inc. (SAE). In the land vehicle area, the ASTM D-series and the SAE J-series of documents are widely used for rubber. In aerospace applications the SAE Aerospace Material Specifications (AMS) are widely used. The AMS specifications rely heavily on ASTM test methods. The Federal test method series are being replaced by ASTM procedures. Specific documents are listed in Appendix B.

1.7.3 Generally most countries have a national body with overall review responsibility for such standardization. In the U.S.A., this is the American National Standards Institute (ANSI), which coordinates the output of various nonmilitary groups that actually write the standards. The ASTM, Committee D-11, has the principal responsibility for standards in rubber; these are published in Section 9 of the Annual Book of ASTM Standards, and include test methods, specifications, classifications, definitions, and practices. Reference to an ASTM method often includes the date of its latest revision. Generally, all industry documents are kept up to date by review every five years.

1.7.4 International standards on rubber are written mostly by Technical Committee 45 of the International Organization for Standardization (ISO/TC 45). These are usually consistent with ASTM standards.

1.7.5 ASTM standards of particular interest to engineers include those listed below. Other individual ASTM standards will be referenced in later discussion of rubber properties; see also Appendix B for a more complete listing.

ASTM D1349 "Rubber - Standard Temperatures and Atmospheres for Testing and Conditioning." This standard provides guidelines for temperature selection for all tests on rubber and thereby aids in comparing properties of different rubbers.

ASTM D1418 "Rubber and Rubber Latices - Nomenclature." This recommended practice establishes a system of general classification for the basic rubbers in both dry and latex forms determined from the chemical composition of the polymer chain.

ASTM D1566 "Standard Definition of Terms Relating to Rubber." This standard is a compilation of definitions of technical terms used in the rubber industry. It has been kept consistent with the corresponding International Standard ISO 1382.

ASTM D2000 (Same as SAE J200) "Standard Classification System for Rubber Products in Automotive Applications." This classification system tabulates the properties of vulcanized elastomeric materials (natural, reclaimed, and man-made rubber, alone or in combination) that are intended for, but not limited to, use in rubber products for automotive application. It is based on the premise that the properties of all rubber products can be arranged into characteristic material designations. These designations are determined by types, based on resistance to heat aging, and classes, based on resistance to swelling in oil. Basic levels are thus established that, together with values describing additional requirements, permit complete description of the quality

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of all elastomeric materials. The purpose of the classification system is to provide guidance to the engineer in selection of practical, commercially available elastomeric materials, and further to provide a method for specifying these materials by use of a simple "line call-out" designation. See Appendix B for a more detailed discussion of ASTM Standard D2000 (Table XLVIII in Appendix B).

ASTM D3162 through D3192 These methods specify standard materials, describe equipment, and prescribe processing methods for evaluating compounding materials in various types of polymers, carbon blacks in natural rubber, and for evaluating polybutadiene and butadiene copolymers.

2. REFERENCED DOCUMENTS

2.1 See Appendix A, ACKNOWLEDGMENTS, for documents cited in this handbook. Figure, table, and text references are coded by parenthetical code numbers "(1)".

2.2 See Appendix B, SPECIFICATIONS AND STANDARDS, for listing of documents applicable to rubber. Typical current documents are listed in addition to text referenced specifications and standards.

3. DEFINITIONS

3.1 Many terms and concepts, mechanical properties, and equations for derivation and determination of concepts are defined at the point of discussion in the text.

3.2 General terms used in rubber production are contained in "Standard Definitions of Terms Relating to Rubber," ASTM Standard D1566, published by the American Society for Testing and Materials, in Section 9 of the Annual Book of ASTM Standards. Additional definitions may be found in the individual documents cited in this handbook, as well as individual specifications and standards listed in Appendix B.

4. ENGINEERING PROPERTIES OF RUBBER AND THEIR SIGNIFICANCE TO DESIGN

4.1 Modulus of Elasticity.

4.1.1 The important engineering property, modulus of elasticity, is the quotient of the stress to corresponding strain in compression, shear, or tension. Unique values are obtained over the useful stress and temperature ranges of rigid materials, but not of rubber. The modulus of elasticity remains truly constant only for small deflections and over a narrow temperature range; measurements made in compression or shear are valid up to only about 15 percent deflection.

4.1.1.1 Over a small stress range, the following equation applies:

$$E = \frac{S}{d}$$

Eq. 1

Where

E = modulus of elasticity, psi or Pa

S = stress, psi or Pa

d = strain, in./in. or mm/mm

4.1.1.2 For larger deflections, the modulus of elasticity is determined by either of two methods. In the first method, the slope of a stress-strain curve is measured at a point on the curve. This results in a tangent modulus value which is representative only of the region in which it is measured, since the tangent does not necessarily intersect the origin. The second method, resulting in a secant modulus value, measures the slope of a line connecting any point on the stress-strain curve with the origin. The secant modulus defines the stress-strain relationship only for the one point at which it is obtained. Neither method is wholly suitable, and both methods result in some approximation. The tangent modulus yields more accurate results at low stress levels where the tangent intersects the axis near the origin. The tangent modulus is also applicable to dynamic tests of relatively low stress range, as may be the case where a preload is applied in the equilibrium position and the deflection from that position is small. Unless otherwise stated, the "modulus" of a rubber is the tangent modulus at near zero elongation.

4.1.2 Typical curves for the tangent modulus for rubber in tension, compression, and shear are presented in Figure 4. Note in Table IV that the modulus of elasticity values are much smaller than those of rigid materials.

4.1.3 Compounds with high stress values at low percentages of elongation are referred to as "high modulus" materials, while those that do not reach high stress values until after a high percentage of elongation are called "low modulus" materials.

4.1.4 A low stress method for determining Young's Modulus is the subject of ASTM Standard D797.

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4.2 Percent Modulus.

4.2.1 Rubber techonologists have used the term "percent modulus", for example, 100 percent modulus of 1000 psi (6.9 MPa), to describe the stress attained in extension of a given amount. These modulus values do not refer to any kind of elastic modulus in the conventional engineering sense, but rather to the stress level at which a given strain is observed.

4.2.2 A 300 percent modulus is the tensile stress, based on the initial cross section, required to produce a 300 percent elongation in a tensile specimen. A more appropriate and less confusing term is stress at 300 percent elongation.

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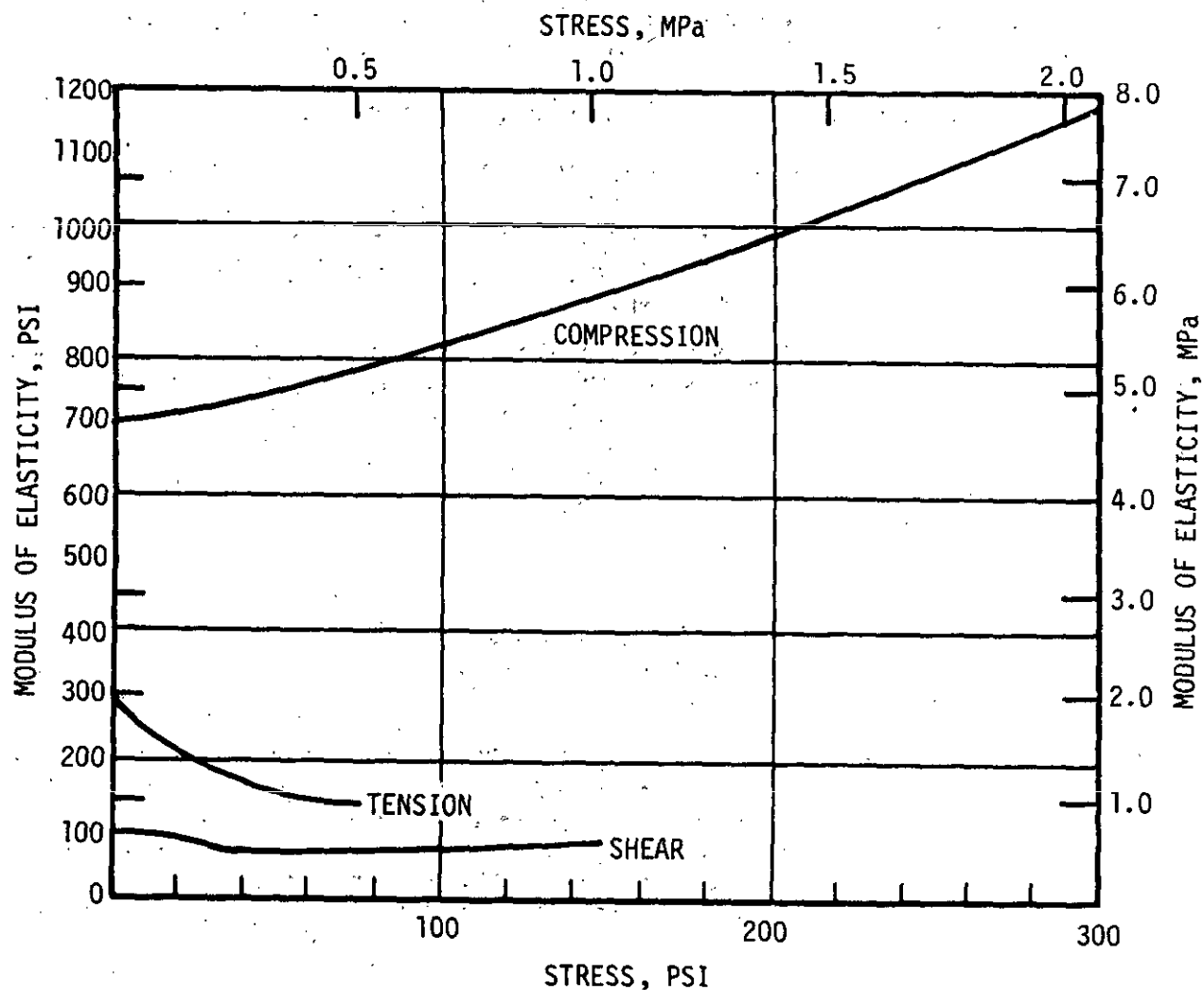


FIGURE 4. COMPARISON OF MODULUS OF ELASTICITY IN SHEAR, TENSION AND COMPRESSION, NATURAL RUBBER WITH HARDNESS OF 50 DUROMETER A

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4.2.3 Since most technical load carrying applications of elastomers are in compression or shear and since in these applications the strains are usually limited to small values, the significance of the 300 percent modulus is quite limited. It is not useful as a material property in engineering calculations, but is a convenient index for use in determining the effect of compounding changes on physical properties.

4.2.4 Rubbers are sometimes characterized by their modulus at 100 percent elongation. Since rubber is rarely used at elongations over 25 percent, the 100 percent modulus is a useful criterion only to predict usability in a specific application. Some material specifications include 100 percent modulus to control flexibility and "liveliness" of a rubber compound.

4.3 Modulus of Elasticity in Shear (Modulus of Rigidity).

4.3.1 In conventional elastic theory describing small deformation, the shear modulus, G , is taken as equal to S_s / θ , where S_s is the shear stress and θ is the shear strain in radians. For rubber, where deformations are large and the tangent of the shear angle is not approximately equal to the shear angle itself, G equals $S_s / \tan \theta$.

4.3.2 The relationship between the modulus of elasticity in tension and the modulus of elasticity in shear, which for rigid engineering materials can be taken as that shown in Eq. 2, is applicable only to small deformations.

$$G = \frac{E}{2(1 + \nu)}$$

Eq. 2

Where

G = modulus of elasticity in shear
 E = modulus of elasticity in tension
 ν = Poisson's ratio (See 4.4)

4.3.3 If ν is taken as 0.5, E equals $3G$. This can be checked by comparing values of Figure 4; for example, a material with hardness of 50 Durometer A, E for zero stress is found to be 300 psi (2 MPa), whereas G for zero stress is approximately 100 psi (0.7 MPa). At greater deformations, this proportion is no longer constant because of the influence of strain on Poisson's ratio (see 4.4). In most low strain technical designs, however, the relation $E = 3G$ can be assumed.

4.4 Poisson's ratio.

4.4.1 Poisson's ratio, the quotient of the lateral deformation divided by the longitudinal deformation of a specimen under tension or compression, is approximately 0.5 for rubber at low deformation. Addition of coarse fillers reduces the Poisson's ratio; its value may be less than, but never greater than, 0.5. Poisson's ratio approaches zero for foam rubber.

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4.4.2 Knowing Poisson's ratio, the change in the lateral dimensions of a component which accompanies the deformation in the direction of applied stress can be calculated. The final lateral dimension will be

$$b_f = (1 + \nu d)b_o \quad \text{Eq. 3}$$

Where

ν = Poisson's ratio
 b_o = the original transverse dimension
 b_f = the final lateral dimension
 d = the deformation in the direction of stress divided by the original dimension

4.4.3 The changes in longitudinal and transverse dimensions are always in opposite sense. When d is positive, the sign preceding d must be negative and vice-versa.

4.5 Bulk Modulus and Volume Compressibility.

4.5.1 The bulk modulus of elasticity expresses the resistance to volume change in a material from a change in pressure. The bulk modulus of rubber is large, approaching that of liquids; rubber is often referred to as a "noncompressible" material. The volume of a rubber subject to tension, compression, or shear remains constant, for all practical purposes; an enforced deformation in one direction must be compensated by a corresponding deformation in another direction. Bulk modulus, K , is determined by:

$$K = \frac{(P_2 - P_1)}{\frac{\Delta V}{V_o}} \quad \text{Eq. 4}$$

Where

P_1 = initial pressure
 P_2 = final pressure
 ΔV = change in volume
 V_o = initial volume

4.5.2 The volume compressibility, which is the reciprocal of the bulk modulus, is approximately 5×10^{-5} per atmosphere for vulcanized natural (NR) and SBR rubber. Other polymer rubbers and harder compounds of any of the rubbers tend to have somewhat lower compressibility or higher bulk modulus. This modulus also increases with increase of pressure. Available data has been arranged in chart form in Figure 5 to indicate the range of compressibility to be expected. Note that extreme pressures are required to produce minute changes of volume. Water has compressibility approximately equal to the maximum curve in Figure 5. The compressibility shown in Figure 5 results from force acting hydrostatically, not in one direction as dealt with in 4.13, Set. or 5.6, Compression in Design.

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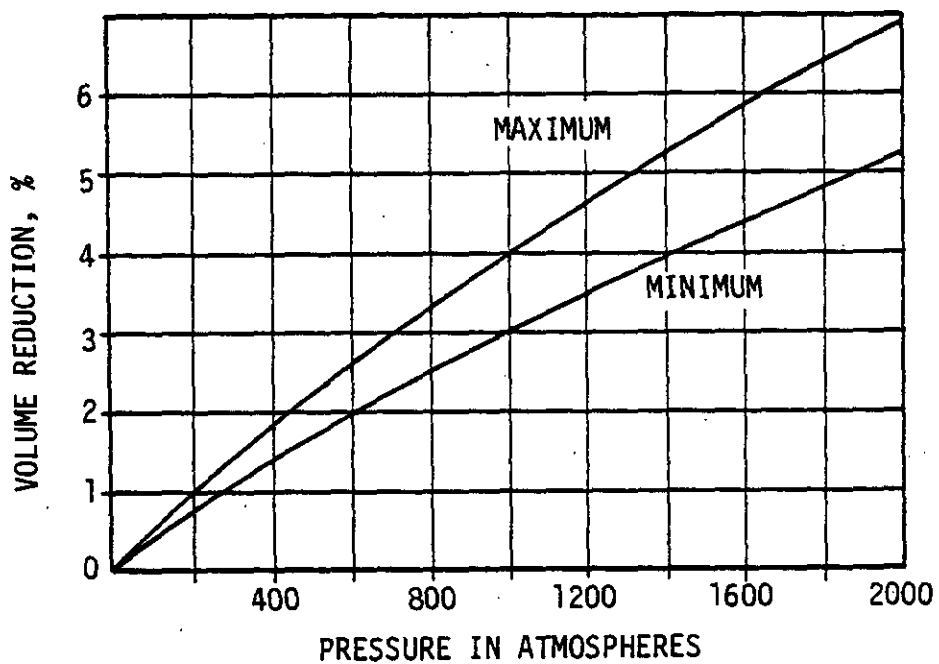


FIGURE 5. VOLUME COMPRESSIBILITY OF RUBBER COMPOUNDS AT ROOM TEMPERATURE

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4.6 Dynamic Modulus.

4.6.1 The nearly ideal elastic behavior of rubber under static loading cannot be assumed to hold under dynamic loading. Its force-deformation behavior is very time-dependent, that is, it is viscoelastic. The relative contribution of the viscous and elastic components depends on time, temperature, stress, and strain rate as well as on material properties of the rubber itself. Any change in material or in operating condition that delays the response of a molecular segment to a forcing function increases the apparent dynamic modulus. The result is that maximum stress amplitudes and maximum strain amplitudes do not occur at the same instant.

4.6.2 In Figure 6 the rubber is being subjected to sinusoidal cycles of constant strain amplitude. The resultant nearly sinusoidal stress cycle, with amplitude S^* , is out of phase with the strain. It can be resolved, however, into two stress cycles, that with amplitude S' representing the purely elastic contribution being in phase with the strain, and that with amplitude S'' representing the viscous contribution being 90 degrees out of phase with the strain. The phase angle between S^* and S' is the loss angle, usually represented by the loss tangent, given by $\tan \delta = S''/S'$. From the figure it is obvious that:

$$S^* = \sqrt{(S')^2 + (S'')^2} \quad \text{Eq. 5}$$

4.6.2.1 The same relationship applies to shear moduli G ; that is, the absolute value of the complex shear modulus, G^* , is given by:

$$|G^*| = \sqrt{(G')^2 + (G'')^2} \quad \text{Eq. 6}$$

Where

G' = the elastic or storage modulus

G'' = the loss modulus.

4.6.2.2 Likewise, the complex Young's modulus, E , obtained in tension or compression, is given by:

$$|E^*| = \sqrt{(E')^2 + (E'')^2} \quad \text{Eq. 7}$$

4.6.2.3 It can be seen that:

$$\tan \delta = G''/G' = E''/E' \quad \text{Eq. 8}$$

4.6.2.4 The word "complex modulus" is used because the resultant modulus, say G^* , can be represented by a complex number that is the sum of the real modulus, G' , and the imaginary modulus, iG'' , that is:

$$G^* = G' + iG'' \quad \text{Eq. 9}$$

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4.6.3 The viscoelastic behavior of rubber is not linear; stress is not proportional to strain, particularly at high strains. The nonlinearity is more pronounced in tension or compression than in shear, as shown in Figures 7 and 8, where static and dynamic moduli are plotted as functions of static strain. Both figures show the dynamic modulus to be higher than the static, but the difference between the two is less for the natural rubber than for the silicone. The dynamic tests were made at 24 hertz.

4.6.4 The dynamic modulus of rubber tends to decrease with increase in amplitude of vibration, as shown in Figure 9 for an SBR tire tread compound.

4.6.5 Further discussion of dynamic modulus is given in 4.23 where it is considered in the broader context of dynamic properties in general.

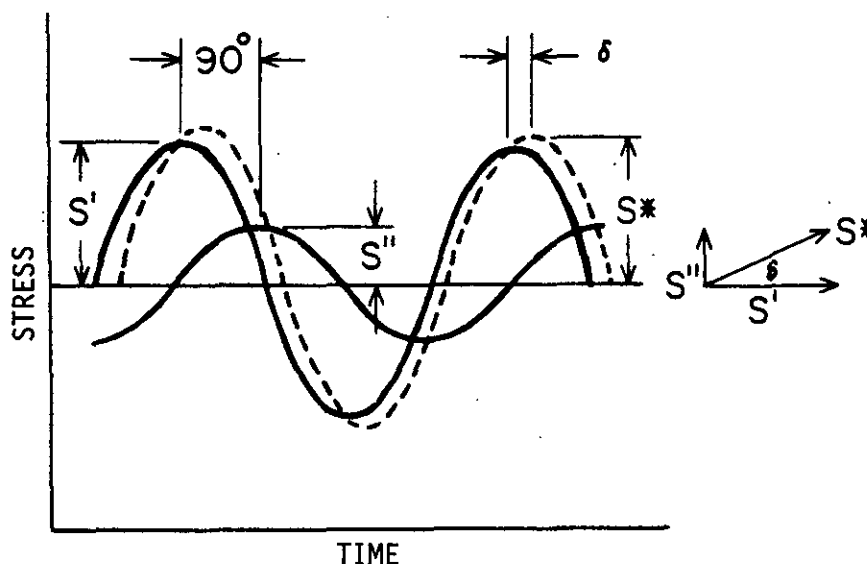


FIGURE 6. PHASE RELATIONSHIP OF ELASTIC, VISCIOUS, AND RESULTANT STRESS (7)

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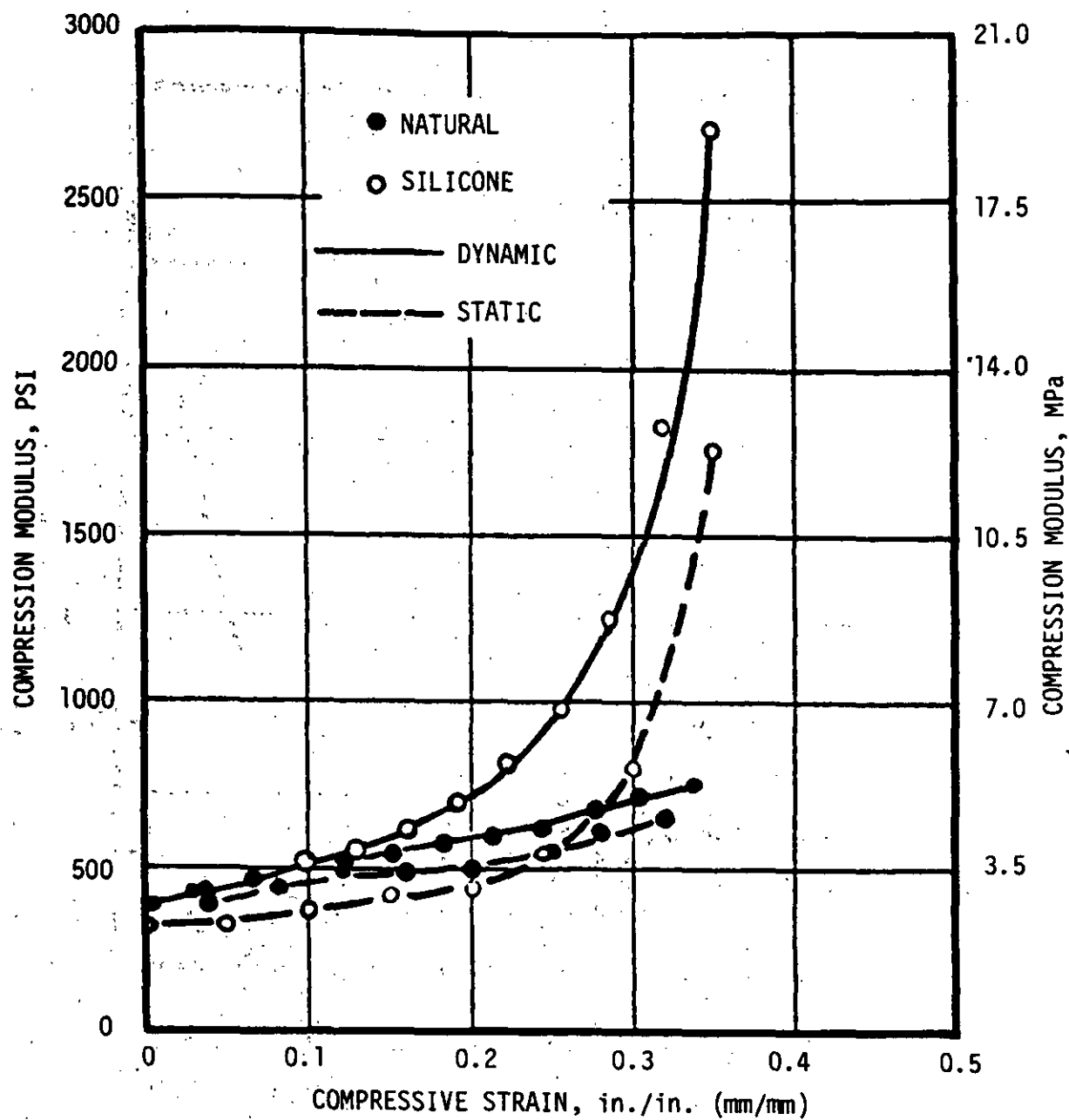


FIGURE 7. VARIATIONS OF DYNAMIC AND STATIC COMPRESSION MODULUS WITH COMPRESSIVE STRAIN (58)

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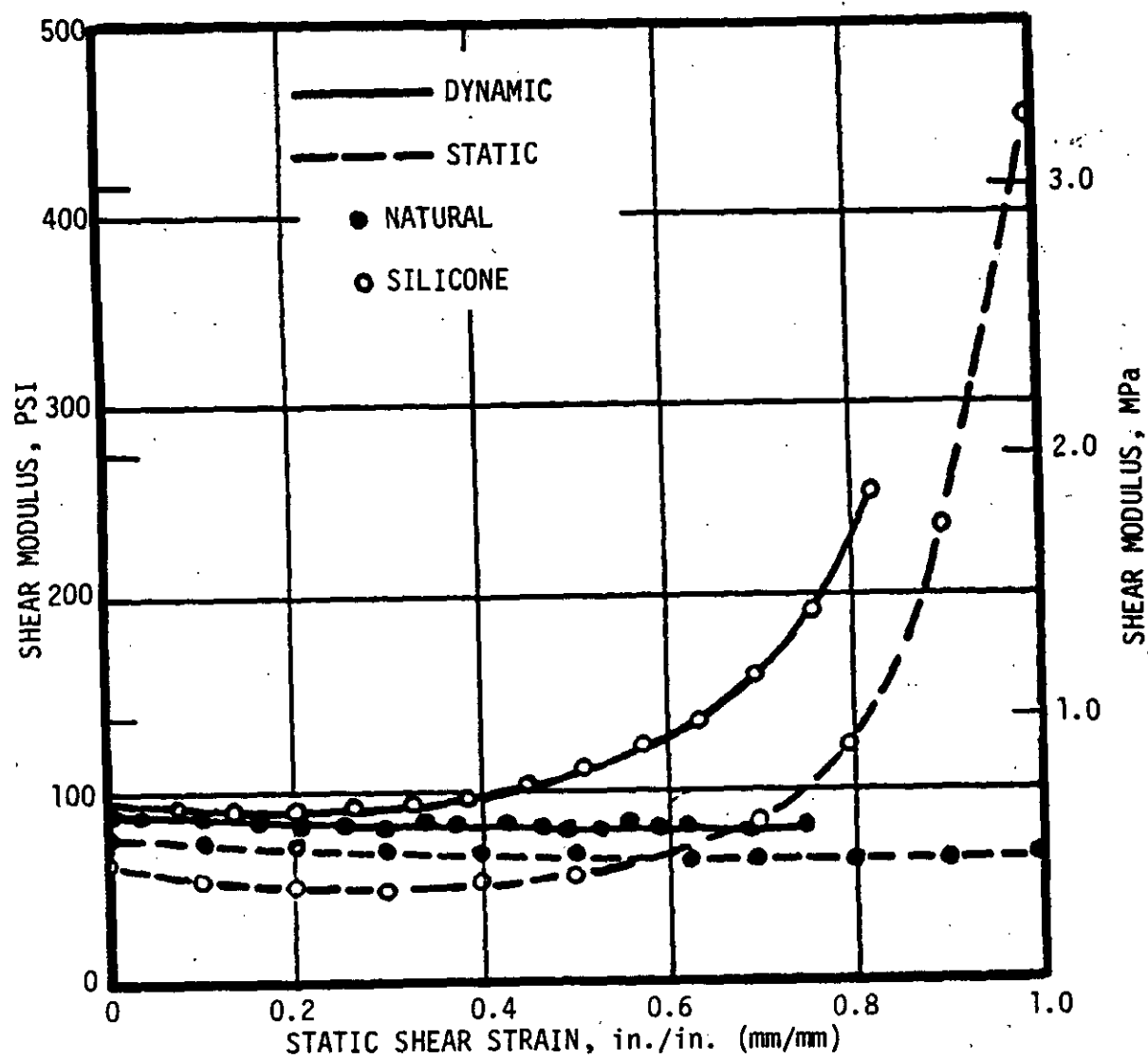


FIGURE 8. VARIATION OF DYNAMIC AND STATIC SHEAR MODULUS WITH STATIC SHEAR STRAIN (58)

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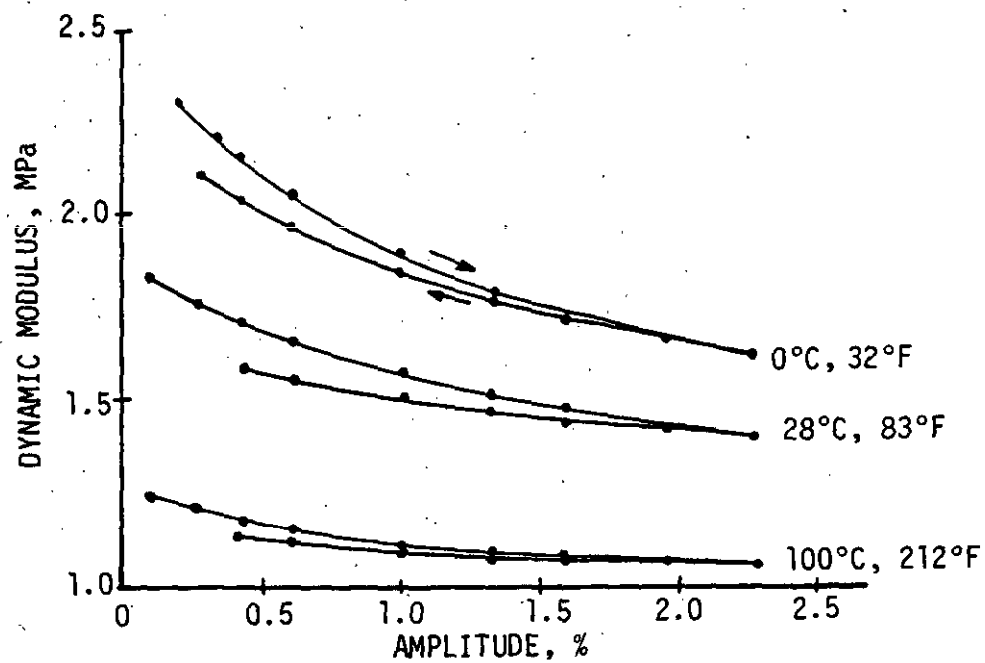


FIGURE 9. EFFECT OF AMPLITUDE ON THE DYNAMIC MODULUS OF AN SBR TIRE TREAD COMPOUND (35)

4.7 Hardness.

4.7.1 The hardness of rubber is a measure of its resistance to indentation involving deformations in tension, shear, and compression. Since the moduli controlling these deformations are closely related, hardness can be regarded as a simple way to roughly evaluate modulus.

4.7.2 Many instruments are used to measure hardness, and their results do not agree well with each other numerically, although they generally can be related. Therefore, when quoting or specifying hardness, the instrument and its condition of use must also be given. A "50 H" rubber may be understood by some persons as meaning a 15-second reading at room temperature on a hand-held spring-loaded instrument calibrated as Durometer A, but other persons, especially outside the U.S.A., may not understand. (Note: "Shore A", through common usage, is accepted to mean ASTM Standard D2240, Type A, as determined with a Type A durometer.)

4.7.3 The internationally accepted standard dead-load method for measuring hardness is the IRHD (International Rubber Hardness Degree) described in ISO Standard 48 for use with rubbers of 30 to 85 IRHD, in ISO Standard 1400 for use with rubbers of 85 to 100 IRHD, and in ISO Standard 1818 for use with rubbers of 10 to 35 IRHD. The IRHD scale is closely related to the rubber modulus and to the Type A Durometer scale described in ASTM Standard D2240, and as shown in Figure 10, taken from ASTM Standard D1415.

4.7.4 In ASTM Standard D2240, the term "durometer" is used for the small pocket-type of hardness measurers, which use spring loading. The Durometer A series is to be used for hardnesses up to 90 on its scale. For harder rubbers, the Durometer D series should be used. See Figure 11 for a relative comparison of the Durometer scales.

4.7.5 The time after loading before the hardness reading is taken must be specified since the indenter continues to creep into the rubber. Sometimes an "instantaneous" reading is specified, but 15 seconds is more common, and most bench models are designed to be read after a definite period such as 30 seconds. Reproducibility of durometer results by different operators is poor; variations of 10 to 12 points are not rare, but 5 points is considered normal. However, an experienced operator can obtain repeatable hardness readings to about plus or minus one point. (Note: U.S. Department of Commerce, National Bureau of Standards, "Interlaboratory Programs for Rubber Analysis No. 36, April-June 1978" (44) shows, for two kinds of material, repeatability of 1.03 and 0.98; reproducibility among 30 laboratories was 4.38 and 4.63.)

4.7.6 The fact that this test method requires the use of a thick, flat button specimen has caused problems when trying to apply the test for measuring hardness on parts of other shapes and sizes, especially smaller sizes. Another commercially available tester, a micro hardness tester, has been used to measure thin sections preferably mounted as cut sections; and an instrument for specifically measuring O-ring hardness by a squeeze force method has been introduced. All of these instruments correlate their dial readings to the IRHD standard. The usually specified tolerance of ± 5 points becomes even more important when correlating button readings between different instruments.

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4.7.7 Rubber can be compounded to give a wide range of hardness. For most applications Durometer A values of 30 to 90 are used. Table V lists the Durometer A values of several representative rubber products.

4.7.8 Most nonreinforced rubber vulcanizates exhibit hardness of about 40 to 50 Durometer A without the use of plasticizers. To obtain softer vulcanizates a compounder usually adds plasticizers or extender oils. Such additives are often volatile to some degree, or are leached by fluids during immersion in service. For this reason, use of soft compounds, usually less than 40 Durometer A, should be carefully evaluated. Some 30 Durometer A compounds will gradually harden in service to higher than 40 or 50 Durometer A points; service performance based on the low hardness would therefore be lost.

4.7.9 The hardness of SBR compounds continues to increase with increased cure time. That of natural rubber compounds increases to a maximum, then decreases because of reversion. Hardness is easy to measure but rarely relates directly to practical uses. A direct measure of modulus might be better for procurement specifications, since it can be made more precisely; however, hardness is generally used because it is so easy to determine.

4.7.10 Hardness values are related to resilience and elongation at break. As hardness increases, resilience and elongation at break generally decrease.

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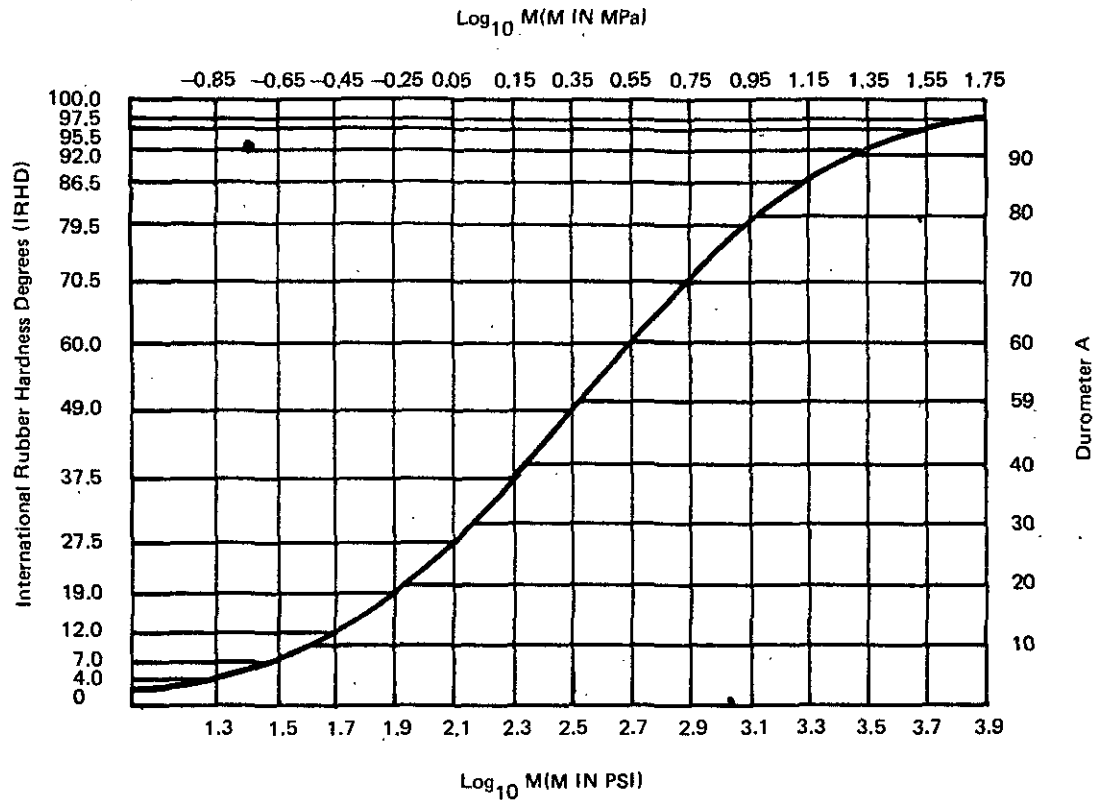


FIGURE 10. PROBIT CURVE TO RELATE $\log_{10} M$ AND THE HARDNESS IN INTERNATIONAL RUBBER HARDNESS DEGREES AND DUROMETER A (4)

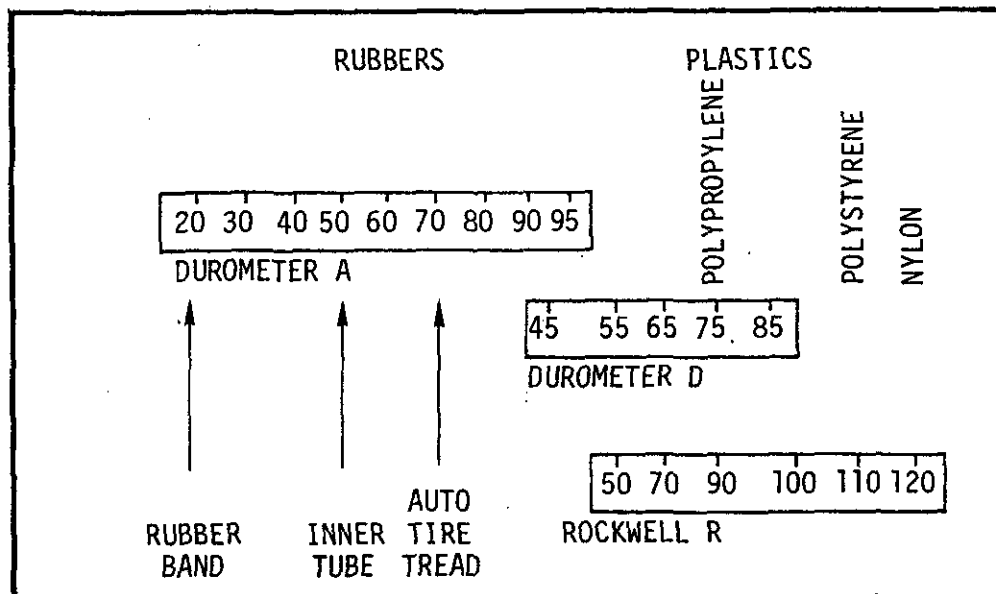


FIGURE 11. HARDNESS SCALES: DUROMETER A, DUROMETER D, AND ROCKWELL R (31)

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TABLE V. HARDNESS OF REPRESENTATIVE RUBBER PRODUCTS

HARDNESS DUROMETER A	RUBBER PRODUCT	HARDNESS DUROMETER A	RUBBER PRODUCT
40 \pm 5	Ammunition Box Gasket	70 \pm 5	Obturator Pads
	Artillery Muzzle Plug		O-rings for Dynamic Seals
	Electrical Cable Jacket		V-belts
	Sandblast Hose		Gaskets
	Rubber Band		Shoe Heels
50 \pm 5	Bellows	80 \pm 5	O-rings for Dynamic and Static Seals
	Tire Inner Tubes		Shoe Soles
	Tire Sidewalls		
60 \pm 5	Brake Cups	90 \pm 5	Obturator Rings
	Conveyor Belts		O-rings for Static Seals and Packings
	Recoil Mechanism Packings		
	Steam Hose		
	Tire Treads		

4.8 Hysteresis.

4.8.1 Hysteresis in rubber, as in ferromagnetism, is the lagging of an effect behind its cause. In rubber, hysteresis is the lagging of strain behind the stress during a deformation. The effect that is commonly called hysteresis is actually the hysteresis loss, that is, the loss of mechanical energy due to hysteresis. The loss is the difference between the amount of energy required to deform a unit and that recovered during return to the original position (unloading). Figure 12 is a typical stress-strain curve. Since the area between the loading curve and the strain axis represents, in this case, the work of deformation and the area between the unloading curve and the strain axis represents the work returned, the area between the two curves is the hysteresis loss. The loss is often expressed as energy per unit volume per cycle when the deformation is homogenous. The ratio of loop area to the area under the loading curve is the specific damping capacity.

4.8.2 The hysteresis loop is elliptical for a unit in which the deformation is proportional to the force and the force does not return to zero during the cycle. This situation is closely attainable in rubbers only at small deformations and is promoted by centering the loop around the origin of coordinates. Shear deformations yield better ellipses than do those in tension or compression because the stress-strain curve is more nearly linear. Assuming the existence of an ellipse provides a desirable advantage in many calculations.

4.8.3 A rubber must be subjected to several cycles of full deformation before its hysteresis is measured. Otherwise the measured loss will include stress-softening contributions such as breaking of secondary bonds or rubber-filler attachments.

4.8.4 Hysteresis of natural rubber shows a well-defined minimum at a cure time that agrees closely with optimum cure as judged by modulus tests. In SBR, the minimum, if it exists at all, is at a cure time which by other criteria is considered to be a long overcure.

4.8.5 Hysteretic damping may be either an advantage or a disadvantage. It may be used to reduce vibration amplitudes in structures that undergo near-resonance oscillations in service. It serves as a shock absorbing mechanism and may result in less noise than that produced by highly elastic materials. Since the mechanical energy is converted into heat energy, the rubber part may suffer heat damage. In the case of tires and other uses, moreover, the energy lost is wasteful.

4.8.6 Although hysteresis loops have been used to illustrate mechanical losses in rubber, they are seldom used for test purposes. Better methods will be described in 4.23 on Dynamic Properties.

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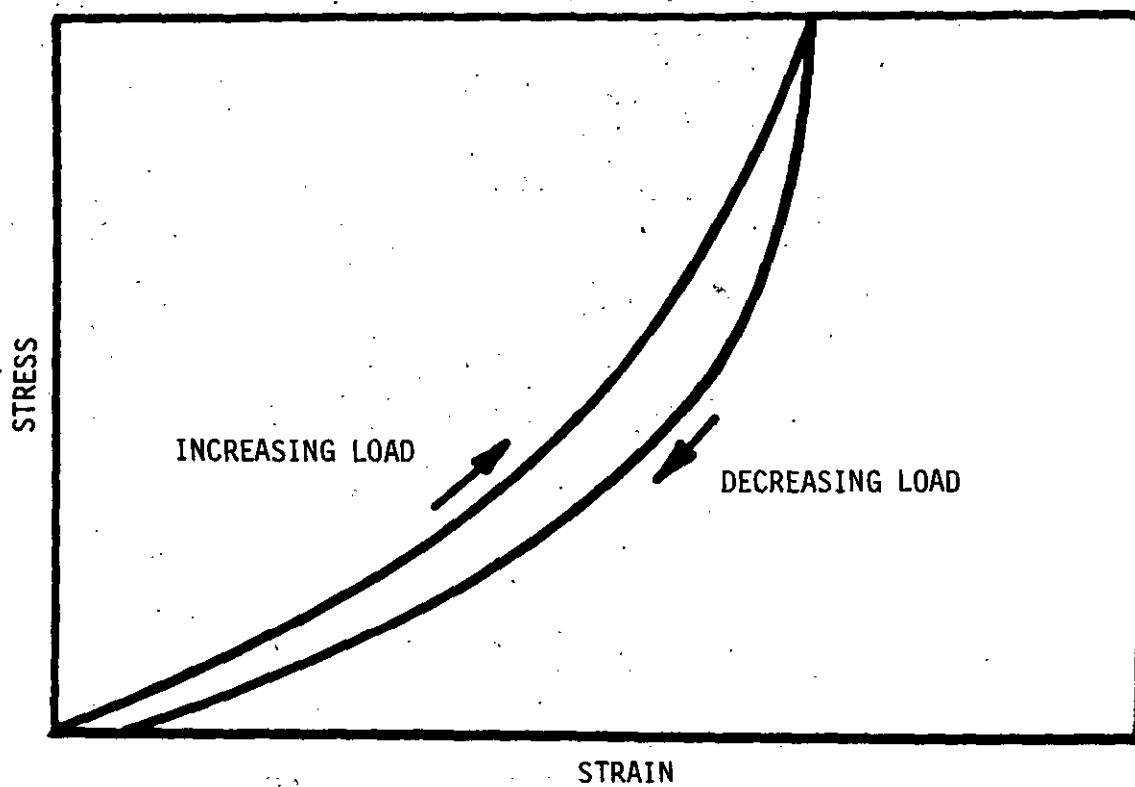


FIGURE 12. TYPICAL LOADING AND UNLOADING CURVES,
RUBBER IN COMPRESSION (58)

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4.9 Resilience.

4.9.1 Resilience, sometimes called "snap" by rubber technologists, is the ratio of mechanical energy output to mechanical energy input in a rapid (or free) full recovery of a deformed article. Resilience can be related to hysteresis, which was defined as energy input minus energy output. Therefore, hysteresis = energy input times (1 minus resilience). Resilience is usually determined by measuring "rebound" of either a pendulum or a free-falling object, such as a plunger (ASTM Standard D2632) or a steel ball.

$$\text{Resilience, percent} = \frac{\text{Rebound height}}{\text{Drop height}} \times 100 \quad \text{Eq. 10}$$

4.9.2 Different rebound instruments do not necessarily give equal values, so if resilience is specified, the method for its measurement must also be given. ISO Method DIS4662 specifies pendulum parameters with appropriate tolerances to control essentials such as striking energy and velocity. It states that the "apparent strain energy", related to impact strain, should be held constant to obtain equivalent results. Another requirement for reproducible results is that the specimen be "broken-in" by several preliminary bounces before a reading is taken. This "stress-softening" affect is automatically handled in a true dynamic test, but a rebound is only a half cycle deformation.

4.9.3 High resilience is obviously desirable in such objects as golf balls. "Super balls" of high-cis butadiene polymers are outstanding examples of high resilience. More generally, any mechanical energy input that is returned as mechanical energy is not lost as heat. Dynamic uses of rubber are usually cyclical, and dynamic properties measured in cyclic tests are more often used for evaluating energy losses than are individual impact tests. Such tests are discussed in 4.23 on Dynamic Properties. Resilience also enters into the energy absorption discussed in 5.12.

4.9.4 As the ambient temperature is lowered below room temperature, resilience of rubber decreases until a minimum is reached at some 15 to 20°C above the glass transition temperature, T_g (see 7.2.3). As the temperature is lowered beyond this point, the resilience increases but it is now rigid or plastic, rather than rubbery in nature. As the ambient temperature is raised above room temperature, rubbery resilience increases. The effects of high and low temperatures on resilience are functions of both the polymer and the compounding. An example of the effect of polymer is shown in Figure 13. Rebound is increased by increasing the state of cure or by using larger particle size carbon black. It is decreased by increasing the amount of carbon black. Figure 14 shows that temperature has a different effect on the resilience of an unfilled natural rubber compound than on one containing carbon black.

4.9.5 Typical rebound values at different temperatures for vulcanizates of various polymers are shown in Table VI.

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TABLE VI. TYPICAL REBOUND OF VULCANIZATES OF VARIOUS POLYMERS AT DIFFERENT TEMPERATURES (18)

Temp °C	Percent Rebound						
	NR	SBR	NBR	CR	IIR	T	VMQ
-20	12	13	13	8	15	-	-
20	45	37	33	35	9	47	43
100	71	47	63	67	50	-	-

4.9.6 Rebound resilience of natural rubber and chloroprene compounds typically increase with increase in time of cure. That of SBR decreases and that of butyl is unaffected.

4.9.7 Resilience of rubber is also affected by conditions, such as magnitude and duration of load, frequency of load application, and method of loading. Compression-loaded parts, for example, show higher resilience if bonded to a metal base than if the connection between the rubber and metal surfaces is frictional.

4.9.8 Measurements of resilience by analysis of a damped free oscillation trace of samples deformed in either compression or shear can be made in accordance with ASTM Standard D945. These values should not be compared directly with those determined by rebound methods.

4.10 Effect of Resilience on Transmissibility of Shock and Vibration

4.10.1 The term transmissibility may be applied to either the force or displacement amplitude of a vibration. A common convention is to express the isolation of a body from a vibrating support as the ratio of the transmitted displacement amplitude to the forcing displacement amplitude. Isolation of a support from a vibrating body, however, would be in terms of force amplitude ratios. In either case the relationship of output to input disturbance may be alternatively expressed as decibels rather than as direct ratios.

4.10.2 The effect of resilience on vibration isolation or absorption must be considered in relation to the imposed frequency, as exemplified in Figure 15. When the imposed frequency equals the natural frequency (f_n), the system resonates and the amplitude is restricted only by the damping. At frequencies near this point, therefore, low resilience promotes low transmissibility. For highly resilient compounds, the force transmitted through a mounting at resonant frequency may reach seven times that expected from calculations based on low frequency data. When the imposed frequency exceeds 2 times the natural frequency, isolation is favored by high resilience.

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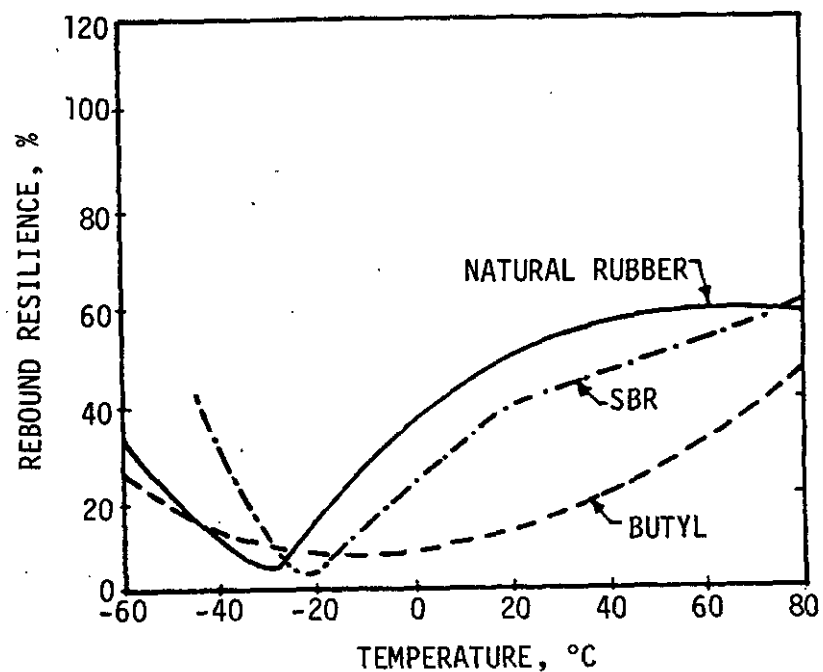


FIGURE 13. EFFECT OF TEMPERATURE ON REBOUND OF VARIOUS RUBBERS (14)

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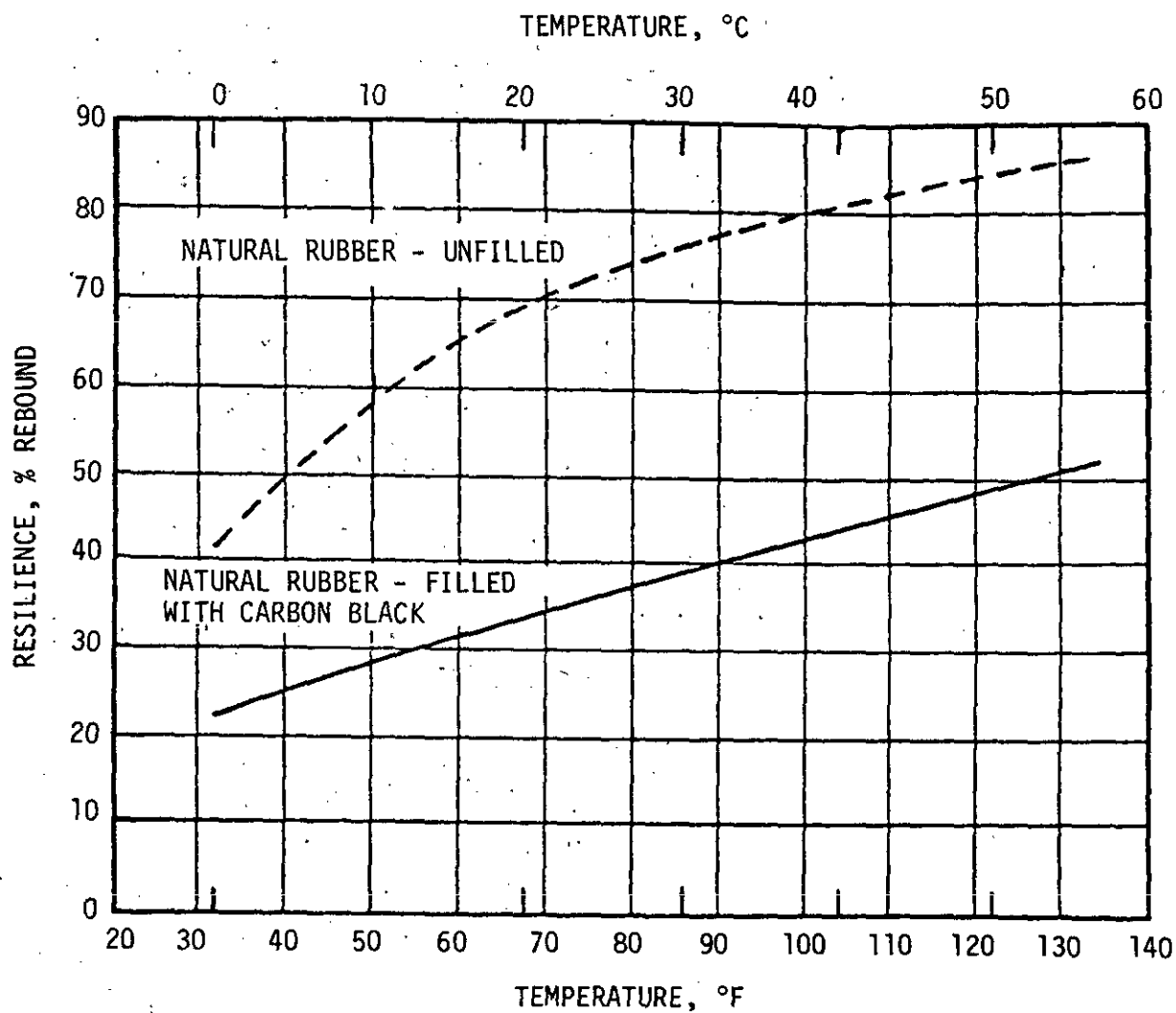


FIGURE 14. EFFECT OF ADDITIVES ON RESILIENCE, NATURAL RUBBER (3)

4.10.3 A shock absorber needs high energy absorption and low resilience, which is contrary to the requirements for isolation of continuous vibration. A rubber-metal component may function at times in either capacity, or even as both simultaneously. In such cases a compromise must be made that favors the most important function.

4.10.4 Figure 15 shows typical transmissibilities of vulcanizates of several polymers, related to the natural frequencies of each. As discussed in 6.4, the natural frequency is affected by the stiffness of the unit and by the applied force. Figure 16 shows that an increase in carbon black content of a rubber will increase the natural frequency. The transmission peak is also lowered since the damping is higher. The choice of polymer and of its compounding offer complementary routes to the desired resilience properties of a given unit for vibration control.

4.11 Creep and Recovery.

4.11.1 Creep, sometimes called strain relaxation or drift, is the time-dependent increase in deformation of a rubber without any increase in the applied force. Its value can be expressed as the actual dimensional changes of an article, or as the change relative to the initial deformation or to the initial dimension. A common form is:

$$\text{Relative Creep, percent} = \frac{\text{Total Deformation} - \text{Initial Deformation}}{\text{Initial Deformation}} \times 100 \quad \text{Eq. 11}$$

4.11.2 A difficulty with this index is that the initial deformation has no unique value. Some creep will have occurred before any "initial" measurement made after an article or specimen has been loaded, regardless of how soon that measurement is made; creep occurs even during the load application.

4.11.3 Creep is often defined as the nonelastic portion of strain, but this is impractical to measure or to apply to engineering formulas. Elastic portions of strains in rubbers or plastics cannot be separated in practice from nonelastic portions. Therefore, in test methods such as ASTM Standards D2990 and D1780, creep in extension or compression is obtained by dividing the total deformation by the initial gage length, then multiplying by 100 to get the percentage creep.

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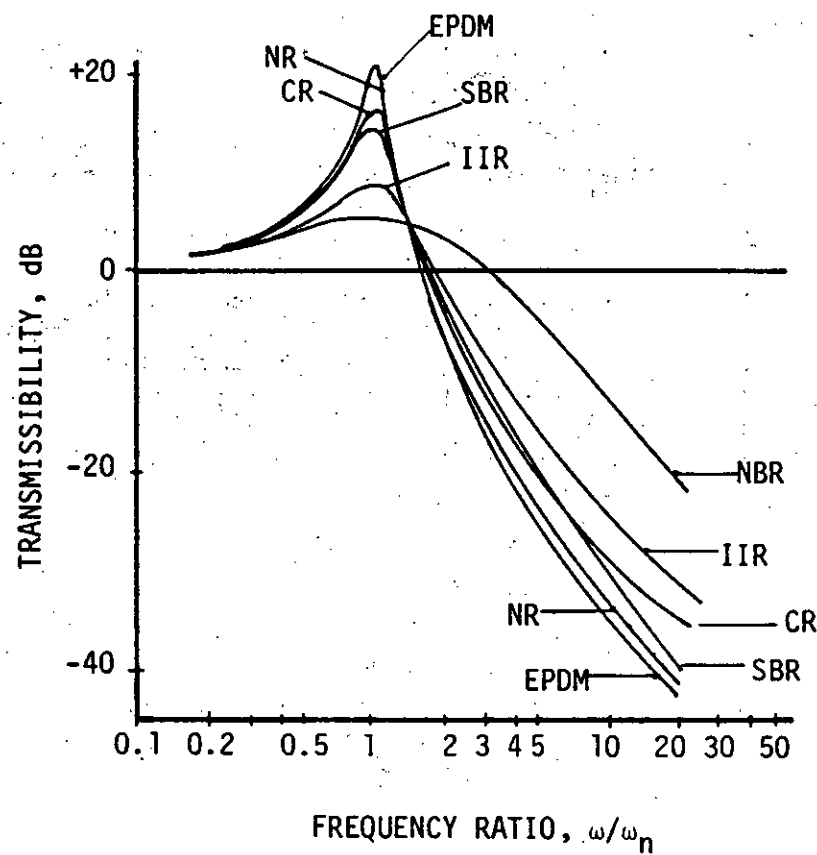


FIGURE 15. DEPENDENCE OF TRANSMISSIBILITY OF A SIMPLE LINEAR SYSTEM ON TYPE OF RUBBER USED FOR MOUNTING (33)

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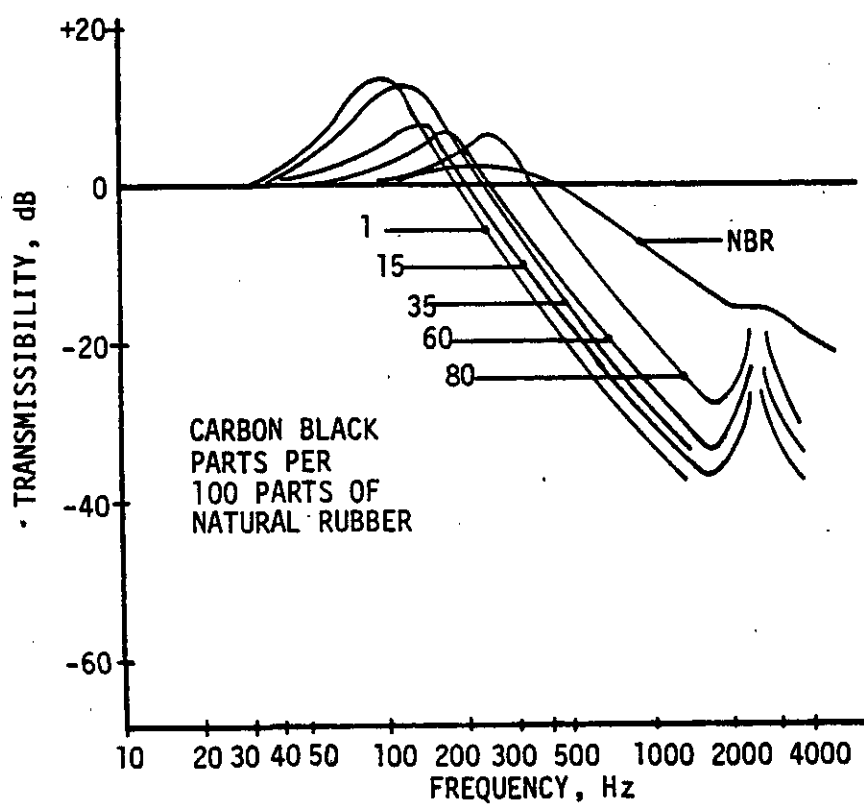


FIGURE 16. DEPENDENCE OF TRANSMISSIBILITY-FREQUENCY CURVES ON CARBON BLACK CONTENT OF NATURAL RUBBER (33)

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4.11.4 An appropriate unit for rate of creep is the percent creep per decade of time. This is nearly constant for viscoelastic (recoverable) creep; that is, it is nearly linear with the logarithm of the loading time. Creep caused by chemical changes or crystallization does not behave in this manner.

4.11.5 Creep in metals is important only under very high forces and at very high temperatures, where yielding occurs. Rubber, however, can creep under any force. If the mechanism is viscoelastic, there is no yielding or flow. Rubber under a given stress creeps fastest in tension, next fastest in shear, and slowest in compression.

4.11.6 Rubber usually exhibits only primary creep, which is linear with logarithmic time but at a continually decreasing rate with linear time. Creep that occurs at a constant rate with linear time is secondary, and that which accelerates with time is tertiary.

4.11.7 Creep modulus is defined as the ratio of the initial applied stress on a material to the creep strain, where the creep strain is defined as the total strain at any time caused by the applied stress. Creep at room temperature, often seen in uncured polymers of low crosslinking, is often called "cold flow".

4.11.8 In ASTM Standard D2990, seven stress levels are chosen to produce tensile failure in about 1, 10, 100, 300, 1000, and 3000 hours. The resulting plot of a "creep-rupture envelope" characterizes the ultimate load limit of the material. Although rubber is seldom used under such extreme forces, the method illustrates that tensile strength depends on loading time, and can fail from "static fatigue". Figure 17 shows characteristic creep curves, which are linear when plotted on a log-time scale, except for the failure phase when the stress is high enough to produce actual fracture.

4.11.9 Rubber continues to creep indefinitely under constant force but a practical equilibrium deformation can be reached at a given low temperature if the load is applied at a considerably higher temperature before cooling to the test temperature. Under such pseudo-equilibrium conditions the total deflection in a given time at high temperatures, that is, the creep rate is a higher percentage of the initial dimension. The temperature at which the creep rate of rubber is the highest percentage of the original deformation is near its glass transition temperature, T_g (see 7.2.3), because the initial deflection is so small.

4.11.10 Static creep rate of rubber increases with the stress level and decreases with increase in the state of cure and increased carbon black content. Figure 18 illustrates the effect of load and shows the progress of creep and recovery of a rubber of 40 Durometer A hardness at 80°F (27°C). The time dependence of recovery is seen to be very nearly the same as that of creep.

4.11.11 Typical shear creep curves for chloroprene and natural rubber are shown in Figure 19. Preconditioning by heating the specimens for a short time under strain reduced the creep rate.

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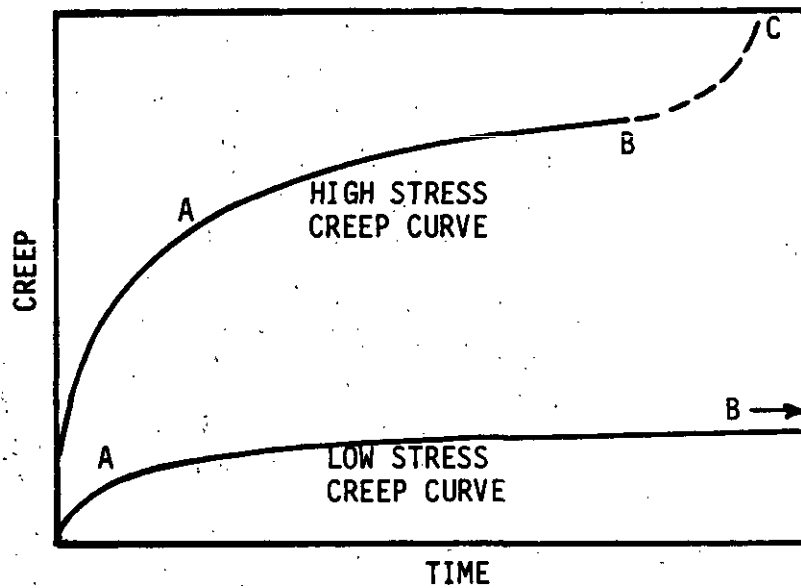
4.11.12 The creep discussed thus far has been under constant load. For linearly viscoelastic materials the creep under repeated application of force would always be less than that under the same load applied continuously. For some materials and conditions, however, the reverse is true. Figure 20, for example, shows creep rate as a function of carbon black content for three types of load application. The constant strain cycles were to 100 percent extension and the constant stress cycles at 2.3 MPa, each on a loading schedule of 10 seconds on and 10 seconds off. The static stress was also at 2.3 MPa. The dynamic tests show a strong dependence on filler content.

4.11.13 ASTM Standard D945 is a method for measuring dynamic creep in compression.

4.11.14 Creep is important in applications such as engine mountings since it influences the space relationships among various parts of the equipment. It is difficult to predict creep for a given application without resorting to simulated service tests because of the effect of such factors as the amount of strain, the temperature, and the changes in these two from vibration or cyclic loading. Results of tests under one set of conditions will not yield accurate prediction of creep under another set of conditions.

4.11.15 Short-term creep of a rubber article under a constant load will be significantly lower if the temperature is kept constant than if it is higher for a time during the test, then returned to its original value, as shown in Figure 21 which shows the effect for the different vulcanizates (NR and SBR). Long-term creep at a given temperature, therefore, can be predicted more accurately by short-term tests in which the temperature is raised for most of the loading time than by constant-temperature tests. This phenomenon is another manifestation of the equivalent effects of time and temperature on the deflection of rubber.

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ORIGIN TO A - INITIAL OR TRANSIENT PHASE
A TO B - STEADY-RATE PHASE
B TO C - FAILURE PHASE

FIGURE 17. CHARACTERISTIC CREEP CURVES (54)

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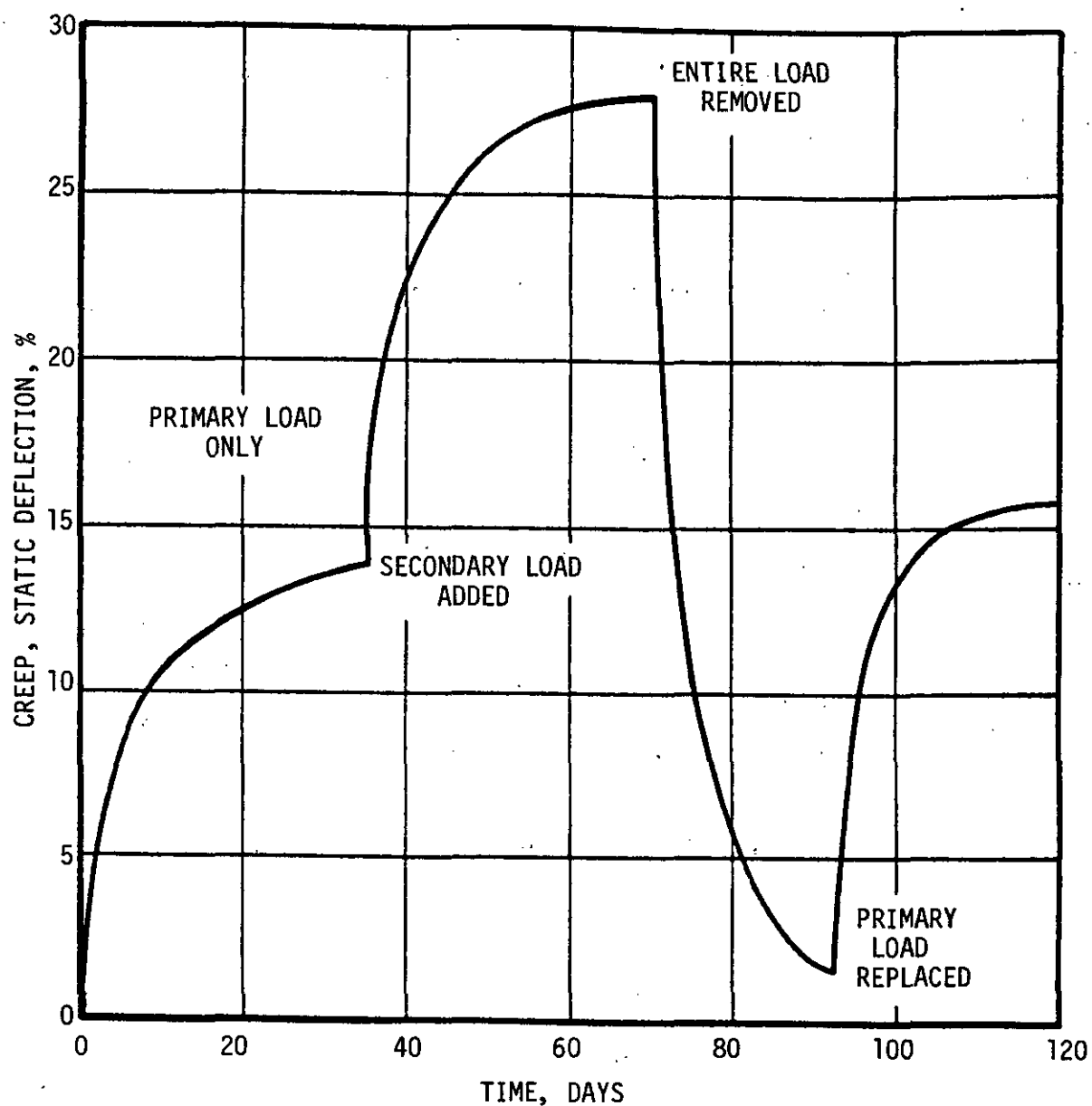


FIGURE 18. CREEP OF A 40 DUROMETER A HARDNESS RUBBER AT 80°F (27°C) AS A FUNCTION OF TIME FOR TWO DIFFERENT LOADS (48)

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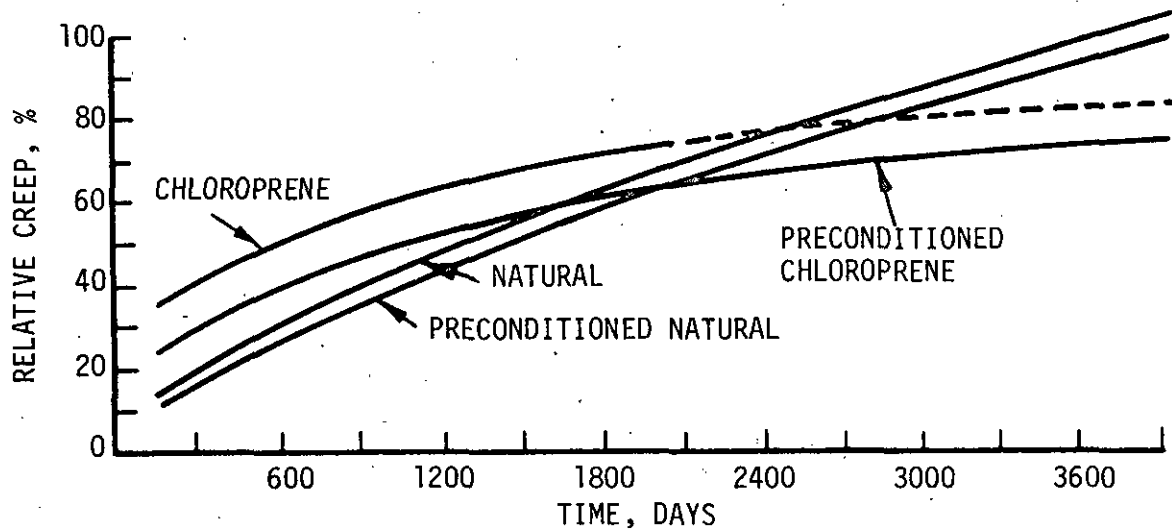


FIGURE 19. EFFECT OF PRECONDITIONING ON SHEAR CREEP OF NATURAL AND CHLOROPRENE RUBBER (47)

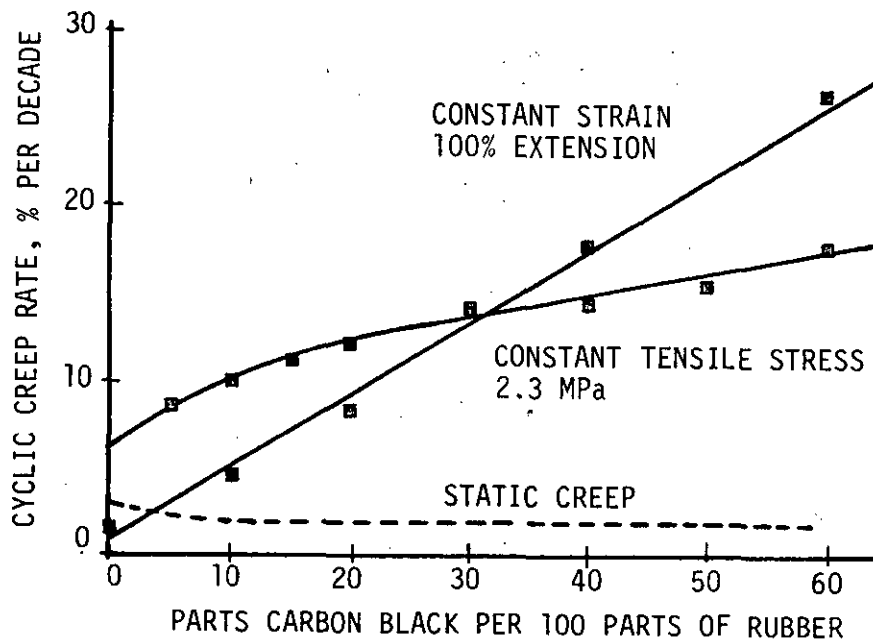


FIGURE 20. DEPENDENCE OF CREEP RATE ON CARBON BLACK CONTENT (27)

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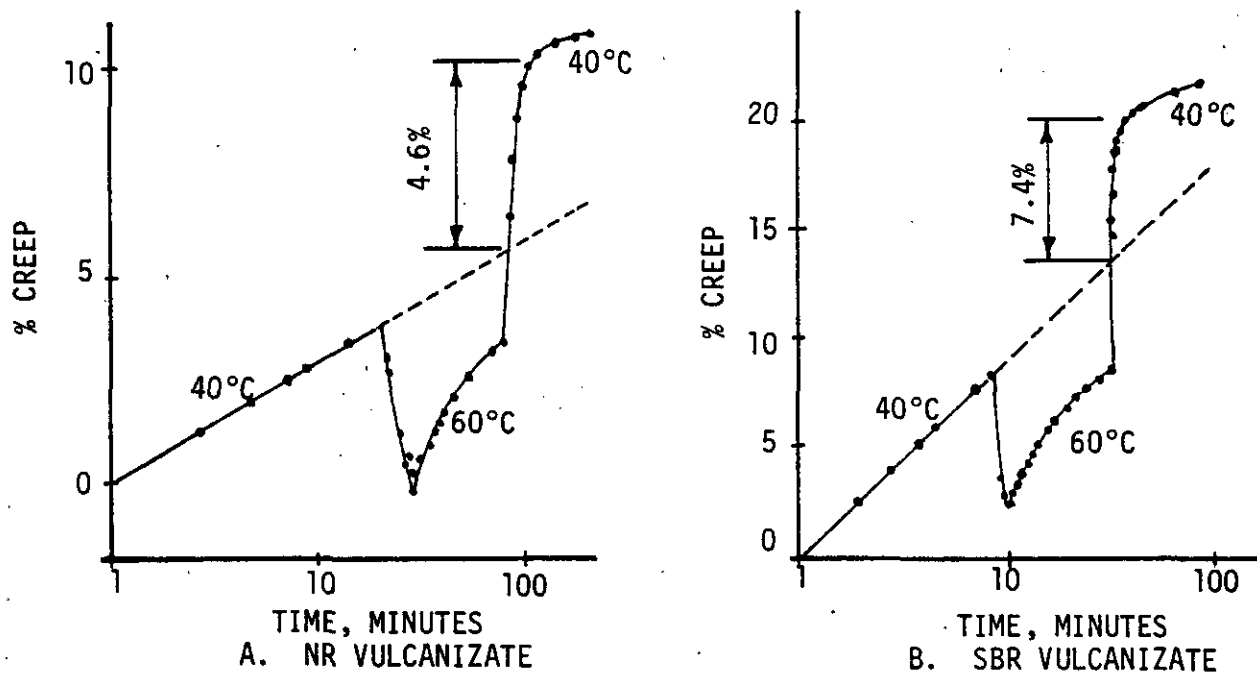


FIGURE 21. EFFECT OF A TEMPERATURE CYCLE STARTING AT 20 MINUTES ON THE CREEP OF NATURAL (NR) AND SBR RUBBERS (26)

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4.12 Stress Relaxation.

4.12.1 The stress relaxation of a rubber at any time after it has been deformed to a constant strain is simply the difference between its restoring stress at that time and its stress at a selected previous time, usually a specified short time after deformation. Whereas the quotient of the strain divided by the stress in a creep test is called compliance, the quotient of the stress divided by the strain in a stress relaxation test is called the stress relaxation modulus.

4.12.1.1 Compliance is not precisely the reciprocal of stress relaxation modulus because the materials are not ideally elastic, but the agreement is close enough for practical usage. Creep and stress relaxation are easily related mathematically for linearly viscoelastic materials, that is, those for which such viscoelastic properties are functions of time (or frequency) and temperature, but are independent of stress magnitude. A more complicated relationship has been developed for materials, such as most polymers, that are nonlinearly viscoelastic.

4.12.1.2 Creep compliance, $D(t)$, is defined as the time dependent response of a rubber (the time dependent strain, $\epsilon(t)$) per unit excitation (stress level, σ):

$$D(t) = \frac{\epsilon(t)}{\sigma} \quad \text{Eq. 12}$$

4.12.1.3 Conversely, the stress relaxation modulus, $E(t)$, is defined as:

$$E(t) = \frac{\sigma(t)}{\epsilon} \quad \text{Eq. 13}$$

4.12.1.4 Plots of $\log D(t)$ and $E(t)$ as functions of $\log t$ yield, for most elastomers, straight lines for times longer than a few seconds. The slopes of these lines are convenient measures for the stability of the mechanical properties with time.

4.12.1.5 For linearly viscoelastic materials, $D(t)$ and $E(t)$ values are independent of the level of excitation. Elastomers meet this condition only for shear up to moderate strains and for extension at strains smaller than 0.1. For linearly viscoelastic materials the slopes derived from stress-relaxation and creep plots are equal in magnitude but have opposite signs. Furthermore, slopes are proportional to the tangent of the loss angle in sinusoidal tests.

4.12.2 Most of the conditions that affect creep have an analogous effect on stress relaxation. The rate of each, for example, is increased by an increase in temperature. If there is no chemical change in the rubber, the rates depend on the difference between the test or service temperature and the glass transition temperature, T_g , (see 7.2.3), obtained under static conditions.

4.12.3 Stress relaxation caused by chemical changes such as chain scission is usually more important in a practical situation than is that due to physical effects alone. Both effects, and their relative contributions at different temperatures, can be determined in a single test. An example, on an

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EPDM vulcanizate, is shown in Figure 22, where the stress relaxation modulus is plotted as a function of time on a log-log scale. Curves obtained at the different temperatures were shifted parallel to the time axis until they formed a single continuous curve. The amount necessary to accomplish this is a consistent temperature-dependent quantity, a_T , which is called the WLF Shift Factor, after its developers, Williams, Landel, and Ferry. The solid line is a composite of results at different temperatures, but is equivalent to physical stress relaxation at the lowest test temperature for an enormously long time. Experimental data depart from this curve at temperatures where chemical effects become significant. Multipoint data such as this gives much more information for design usage than could be conveyed by any single point index such as "time for stress to decay to $1/e$ of its initial value at specified temperatures" (where $e = 2.71828$, the base for natural logarithms).

4.12.4 Maintenance of a given stress level is particularly important in a seal. If the fluid being sealed swells the rubber, the resulting stress increase can counteract the normal stress relaxation. Swelling is not necessarily desirable, however, since it weakens the rubber.

4.12.5 A stress relaxation curve of a modified SBR compressed in air and in ASTM No. 1, No. 2 and No. 3 oil at 70°C is given in Figure 23 where the ratio of stress relaxation to original stress is shown as a function of time. (See 7.3.1 for discussion of "ASTM oils".)

4.12.6 Any type of deformation might be used in creep or stress relaxation tests. ASTM Standard D1290 describes a stress relaxation test in compression, which is probably the most important type because seals usually operate in compression. The measurement of decay of sealing force with time is a very important design consideration but the widespread use of such tests has been inhibited by instrumental difficulties in holding a constant deflection and at the same time monitoring the force exerted by the specimen. There is no problem if a load cell can be used to monitor each specimen, but this becomes impractical when many specimens are to be tested over long periods of time.

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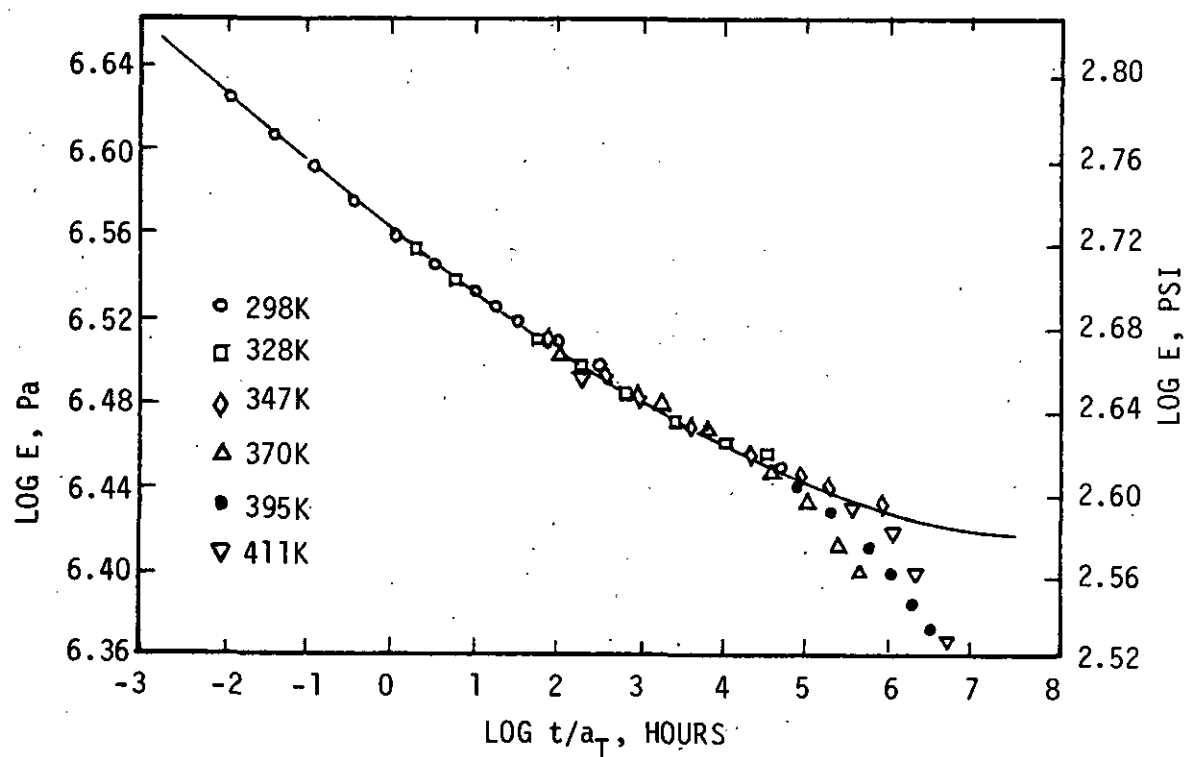


FIGURE 22. STRESS RELAXATION OF EPDM RUBBER (24)

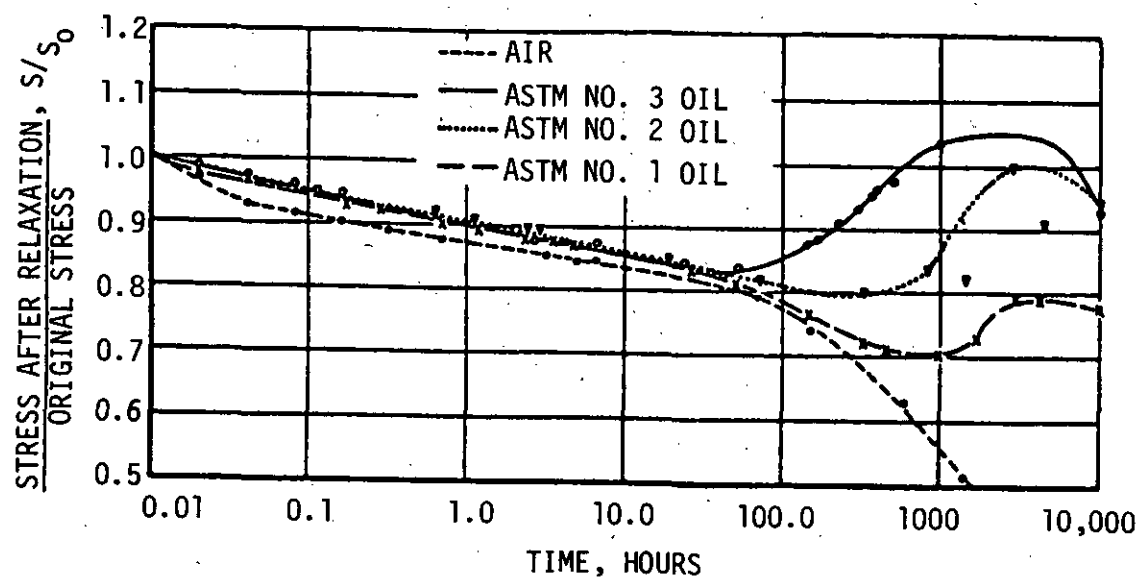


FIGURE 23. EFFECT OF FLUID ENVIRONMENT ON STRESS RELAXATION OF MODIFIED SBR AT 158°F (70°C) (10)

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4.13 Set.

4.13.1 The deformation that remains in a rubber after complete release of the force that produced the initial deformation is called "set". Due to practical considerations, such as distortion in the specimen and slack in the strain-indicating system, measurements of deformation at a small remaining force, rather than zero force, are often taken. If recovery stops short of being complete, the remaining deformation is often called "permanent set". Permanent set occurs in rubber primarily when chemical changes have occurred. Viscoelastic deformation is completely recoverable, and that maintained by crystallization can be recovered by increasing the temperature above the melting point of the crystals.

4.13.2 Compression set, permanent set, or loss in thickness after release of a deforming load is usually expressed as a percentage of the original height or thickness. Tensile set is expressed as a percentage of the original length, and shear set is expressed as a percentage of the original distance between the planes that were displaced parallel to each other. However, ISO Standard 815 for compression set and ISO Standard 2285 for tension set, use initial strain rather than initial thickness or length as the basis for calculating the percent of set, so the method of calculation must be stated.

4.13.3 Compression set is the factor most often used to characterize the ability of a rubber article to retain its elastic properties during prolonged deformation. Ideally the entire curve of recovery as a function of recovery time should be given, but comparisons after a given time are often used. In ASTM Standard D395 this time is taken as 30 minutes. Measurements are made after release from compression under constant force (Method A) or constant deflection (Method B).

4.13.3.1 Method A, Constant Force:

$$\text{Compression Set, percent} = \frac{t_0 - t_f}{t_0} \times 100 \quad \text{Eq. 14}$$

4.13.3.2 Method B, Constant Deflection:

$$\text{Compression Set, percent} = \frac{t_0 - t_f}{t_0 - t_s} \times 100 \quad \text{Eq. 14}$$

where

t_0 = original thickness

t_f = final thickness

t_s = constant thickness during compression

4.13.3.3 Any specifications that are made for compression set should require the test method that produces the deformation most like the type of compression to be encountered by the part in service.

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4.13.3.4 In either Method A or Method B the deflection is static, so the results do not necessarily characterize the test material under dynamic conditions.

4.13.4 Figure 24 shows the compression set of six types of rubber at each of four temperatures. Far different results might be obtained on different compounds of these polymers or on specimens having different states of cure.

4.13.5 Compression set is often used to evaluate resistance to deterioration of rubber at high temperature. Such deterioration may occur by either additional crosslinking, which binds the rubber into its deflected position or by chain scission, which reduces its force of recovery. These changes are permanent.

4.13.6 Compression set may be used as a quality control test method to evaluate state of cure. An undercured specimen will have unduly large set.

4.13.7 Another use for static set tests is to evaluate low temperature behavior of rubber. Recovery may be slow because of the decreased thermal energy of the molecular segments or because crystallization has locked the specimen into its deflected position. Unless crystallization occurs, however, complete recovery would eventually take place, as shown by the curve of Figure 25 for a natural rubber compound that had been deflected in shear at room temperature, then allowed to recover at each of a series of temperatures. Shifting of the resulting curves gave a master curve that represents the equivalent recovery behavior at -76°F (-60°C).

4.13.8 Set can cause a seal to leak, but usually the more appropriate property to measure is stress relaxation. However, no direct correlation can be found in most cases between compression set and creep or stress relaxation behavior at small stress or strain.

4.13.9 Compression set has been referred to as a gradual loss of seal memory, which reduces the force required to maintain a seal; it is therefore a common cause of leakage of seals and is considered the most important physical property for evaluating toroid-shaped O-ring seal performance. Test data show that compression set decreases rapidly as deflection increases, often reaching an optimum point of minimum set before increasing with increasing deflection. Each rubber compound and shape exhibit a unique set of values when determined on either O-rings or flat-faced standard test buttons, as described in ASTM Standard D1414 for O-rings and ASTM Standard D395 for standard test buttons. See Figure 26a for effect of shape (O-ring and test button) and Figure 26b for effect of specimen thickness (or diameter). These test data also support the rules of thumb often used in O-ring design: seal deflection should be about 25 percent, never less than 10 percent; and seal cross section should be as large as possible for the available space. Seals designed by these rules achieve longer service life, especially at low pressures, where only the memory of the rubber maintains the sealing force.

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4.13.10 A long-time evaluation of O-ring seals, based on each of several polymers, was conducted to establish, if possible, reliable predictions of extended service life of such a seal from short time compression set testing. This factor is important, as some seals are required to function without leakage for long times at elevated temperatures. The variable of the effects of the fluid being sealed on the characteristics of the polymer was ignored for this test, conducted in dry air, since it would mask the effects of the compression set test results. Effects of fluids on the various polymers are discussed in 4.22 and 7.3. Figure 27 shows 90 percent compression set curves for several rubber polymers as a function of temperature and time. The constant compression set of 90 percent of the deflection was chosen as the common factor in this comparison, as it is the highest set for which sealability could reasonably be expected. Tests were conducted on 0.139 inch (3.5 mm) cross-section O-rings at 25 percent deflection and in accordance with the procedure defined in ASTM Standard D1414.

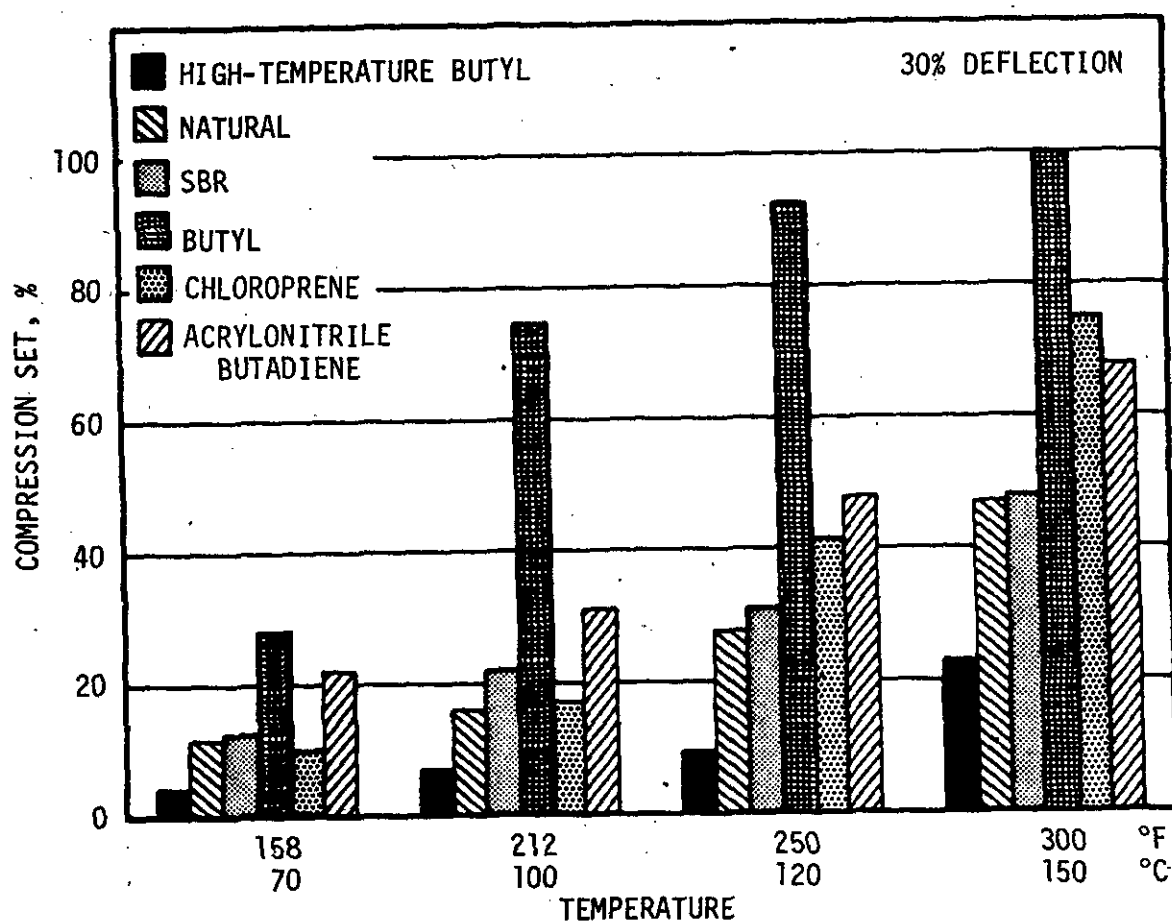


FIGURE 24. COMPRESSION SET AS A FUNCTION OF TEMPERATURE (62)

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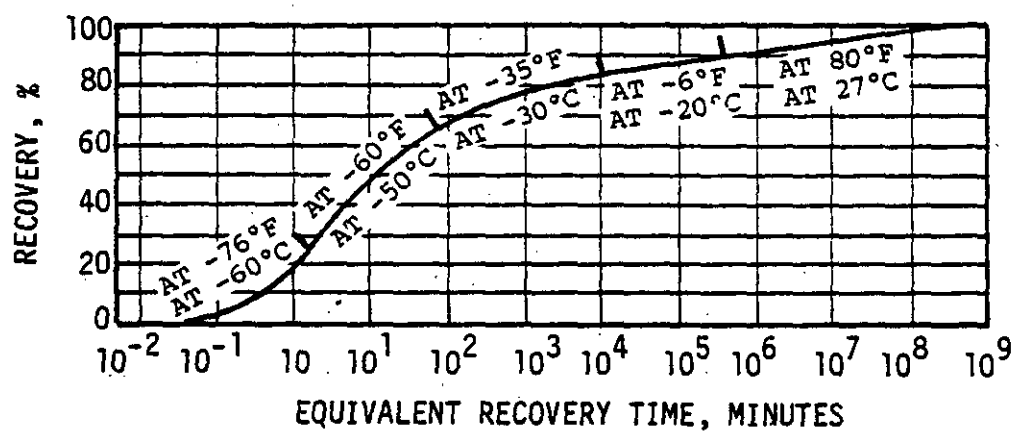


FIGURE 25. EQUIVALENT EFFECTS OF TIME AND TEMPERATURE ON RECOVERY FROM EQUILIBRIUM SHEAR DEFORMATION OF A NATURAL RUBBER VULCANIZATE (19)

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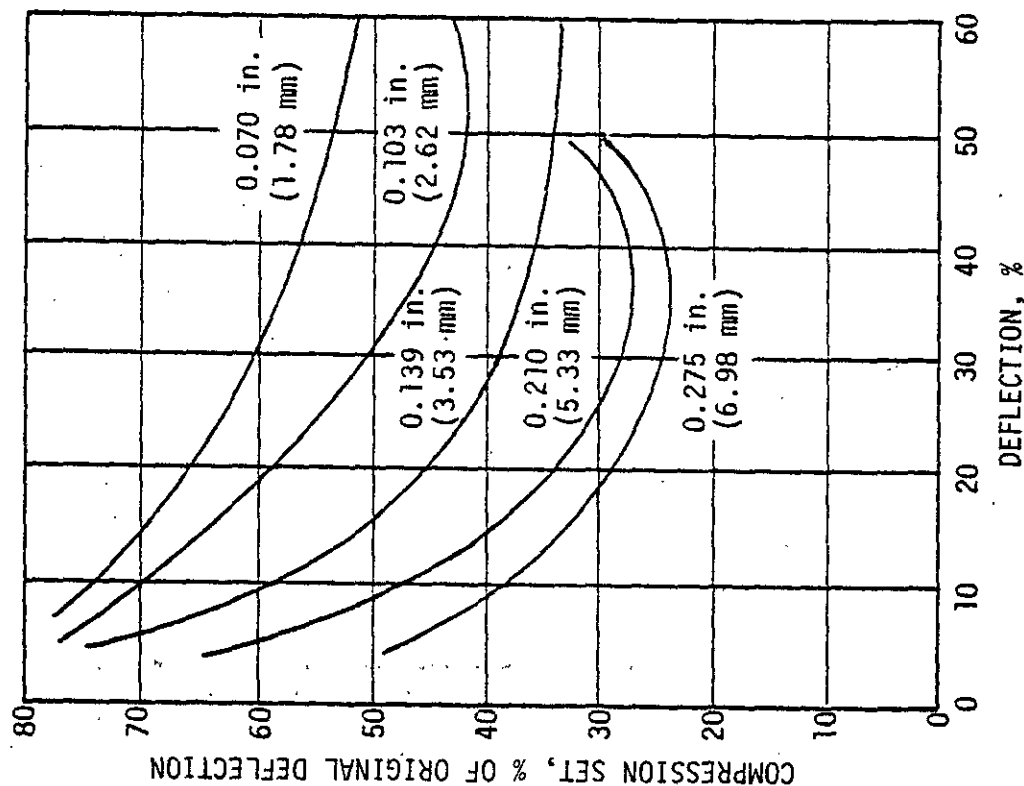


FIGURE 26a. SHAPE COMPARISON

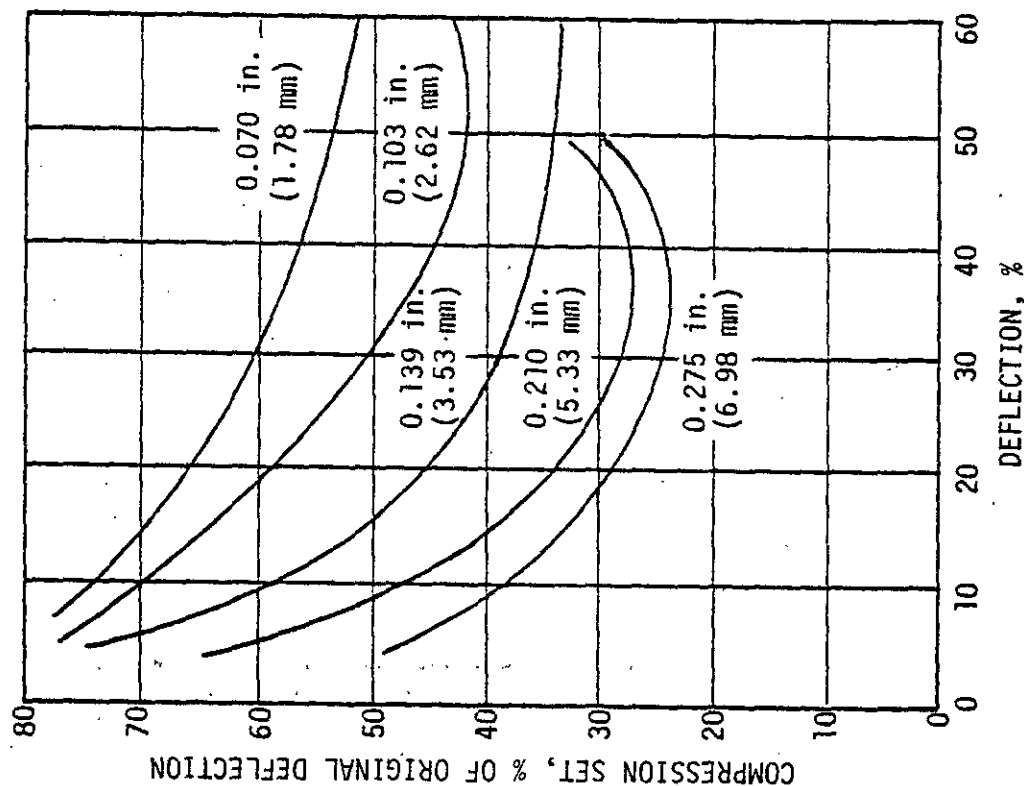


FIGURE 26b. THICKNESS COMPARISON

FIGURE 26. COMPRESSION SET AS A FUNCTION OF DEFLECTION (8)

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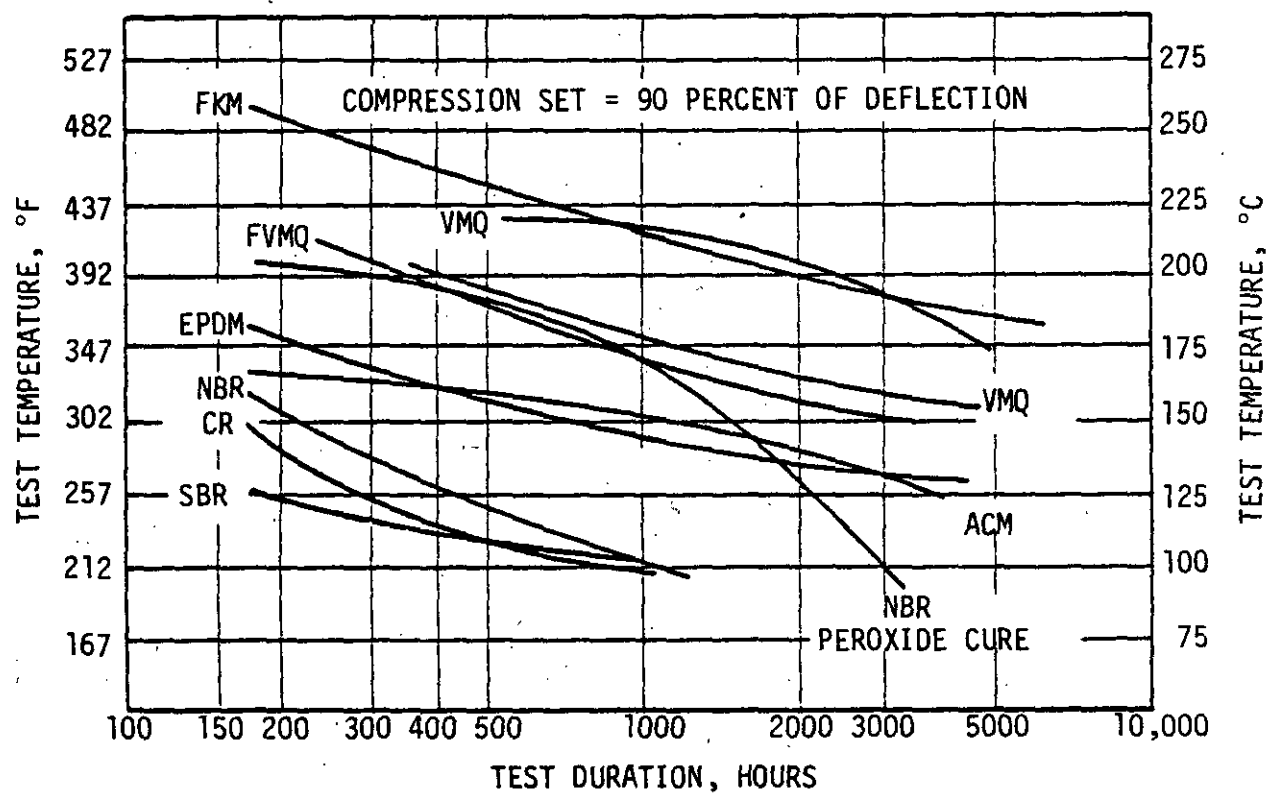


FIGURE 27. COMPRESSION SET OF O-RING SEALS AS FUNCTIONS OF TIME AND TEMPERATURE (40)

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4.14 Thermal Expansion.

4.14.1 The coefficient of linear expansion, e , of rubber is 10 to 100 times that of metals, as shown by typical values in Table VII. Values for other rubbers are given in the applicable Data Sheets in Appendix C. When a dimension L_0 at temperature T_0 is known, its value, L_1 , at temperature T_1 is given by:

$$L_1 = L_0 [1 + e (T_1 - T_0)]$$

Eq. 16

4.14.2 Volume changes with temperature in an analogous manner; the coefficient of volume expansion is very close to 3 times the linear expansion.

4.14.3 In a rubber article that operates at constant extension, such as a belt, the major effect of thermal expansion or contraction is to change the force exerted by that article. This is seldom an important amount.

4.14.4 An article such as a shaft seal that operates under constant compressive deflection can expand or contract only laterally, so the coefficient of volume expansion becomes the operative constant. Since the volume coefficient is three times the linear coefficient, dimensional stability could become important.

4.14.5 A part that operates at constant compressive or shear deflection, and in which the rubber is bonded to metal, can respond to temperature-induced dimensional changes only by becoming distorted at the free surfaces. One inherent danger in this situation is that there may be high strain gradients, and localized strains might become high enough to induce unacceptable susceptibility to ozone attack.

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TABLE VII. LINEAR THERMAL EXPANSION OF TYPICAL ELASTOMERS AND COMMON ALLOYS (49)

Material	Coefficient of Linear Expansion		
		in./in.-°F	m/m-°C
Vulcanized Rubber			
Silicone	VMQ	103 x 10 ⁻⁶	185 x 10 ⁻⁶
Polychlorotrifluorethylene	CFM	83 x 10 ⁻⁶	149 x 10 ⁻⁶
Fluorocarbon	FKM	77 x 10 ⁻⁶	139 x 10 ⁻⁶
Chloroprene	CR	76 x 10 ⁻⁶	137 x 10 ⁻⁶
Acrylonitrile Butadiene	NBR	62 x 10 ⁻⁶	112 x 10 ⁻⁶
Alloy			
Aluminum Alloy, 2017		13.0 x 10 ⁻⁶	23 x 10 ⁻⁶
Stainless Steel, Type 302		9.6 x 10 ⁻⁶	17 x 10 ⁻⁶
Mild Steel		6.7 x 10 ⁻⁶	12 x 10 ⁻⁶
Low Expansion Nickel		0.6 x 10 ⁻⁶	1 x 10 ⁻⁶

4.14.6 Rubber in general, and especially rubber that is adhered to metal, might also become unacceptably distorted by differential shrinkage from mold curing temperature to operating temperature. Here again, the volume coefficient of thermal expansion is operative. The rubber will shrink more than the metal. An adjustment in mold shape could be made so that the product has the desired size and shape at its operating temperature. Actually, in curing any rubber product that has very small tolerances, it may not be satisfactory to assume that the vulcanizate will have the same size and shape as that of the mold cavity. An approximate rule is to make mold dimensions larger than those of the required item by about 1.5 percent. The shrink rate will vary from compound to compound; the range is often from 1 to 2.5 percent.

4.14.7 Dimensions and retractive forces of deformed rubber products are functions of the Joule effect (see 4.17) as well as of thermal expansion or contraction.

4.15 Heat Transport and Exchange.

4.15.1 The rate of heat transport through a material by vibration of its molecules or movement of free electrons is its thermal conductivity. The rate of heat exchange at the surface is a function of its film transfer coefficient for conduction or convection and of its emissivity for radiation. The rubber compounder can offer a greater range of conductivity than of surface exchange values.

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4.15.2 Thermal conductivity, or more properly the coefficient of thermal conductivity, is the time rate of transfer of heat through a unit thickness across a unit area of material for a unit difference in temperature. At thermal equilibrium, that is, when the temperature at any point in the material is constant with time, conductivity is the property that controls heat transfer. For a flat slab in which the heat flows perpendicular to the faces, the coefficient of thermal conductivity, k , becomes:

$$k = \frac{qL}{At(T_1 - T_2)} \quad \text{Eq. 17}$$

where

q = quantity of heat transported

L = specimen thickness

A = specimen area

t = time

T_1 = temperature of face 1

T_2 = temperature of face 2

4.15.2.1 In Inch-Pound system of measure, k is expressed as Btu·in./hr·ft²·deg F.

4.15.2.2 In SI metric, k is expressed as W/mk.

4.15.3 The total conductivity of a compound or composite is usually taken to be the sum of the products of the conductivity of each component by its volume fraction when all components have conductivities in the same range. This is not a good approximation when conductivities differ greatly as for steel cords in a tire where the ratio may be 150 to 1. Conductivity along the cord will exceed that transverse to it. There is evidence that carbon black may produce some of the same effect because rubber samples having poor carbon black dispersion may show conductivities that differ from those on samples having good dispersion. Different types of carbon black also affect the thermal conductivity of the rubber in which they are dispersed, perhaps because of their structure or "chaining" effect. Figure 28 shows this effect as well as the much greater influence of temperature on the thermal conductivity of reinforced compounds (filled with carbon black) than on gum compounds (without carbon black).

4.15.4 Compounding of rubbers for greater hardness can increase their thermal conductivity by as much as 30 percent, mostly because the k -value of the added material is higher than that of the polymer. One carbon black, for example, has a coefficient of 0.86 W/mk. The coefficients for some of the common types of rubber, each containing about 50 parts of carbon black per hundred parts of rubber, are given in Table VIII. These were not all from the same reference, and values quoted by different observers vary widely.

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4.15.5 The rate of thermal conductivity of solid rubber is between those of good insulating materials such as cork and those of ceramics such as brick, glass, or marble. Cellular rubber, however, is a good insulator because of its structure. The processability of unvulcanized rubber is promoted by its low conductivity; it remains hot, and therefore plastic, long after milling or sheeting. The same property, however, is troublesome in curing thick pieces in molds because portions near the mold surfaces heat up and cure first, making the attainment of a uniform state of cure very difficult. There is a counteracting effect from the exothermic heat of vulcanization, which is very small in soft rubber, but may be large enough in hard rubber to destroy the article because that heat generated in the interior cannot escape rapidly enough.

4.15.6 Low conductivity may likewise be either an advantage or a disadvantage in the use of rubber products. Truck and automobile tires can and do fail from overheating due to hysteretic losses; the heat cannot escape fast enough. No significant improvement can be made by compounding changes; even doubling the low conductivity would still be insufficient. Although SBR may have slightly higher conductivity than natural rubber, the advantage is not sufficient to offset the greater heat generated in SBR. Rubber insulation in power lines and electrical machinery often fails because it cannot dissipate heat quickly enough, the heat being generated by overload currents. Conversely, the low thermal conductivity of rubber is desirable in gaskets for refrigerator doors or air conditioned spaces where thermal insulation is desired.

4.15.7 Thermal diffusivity measures the change in temperature per unit volume of a substance produced by the quantity of heat that flows in a unit time across a unit area of a layer of the substance of unit thickness with a unit temperature difference between its faces. It is the property that determines the transient temperature distribution in the absence of heat generation and convection. So, thermal diffusivity, α , is related to the thermal conductivity, k , by the equation:

$$k = \alpha \rho C_p \quad \text{Eq. 18}$$

where

ρ = the density of the material

C_p = the heat capacity of the material under constant pressure conditions (see 4.16)

C_p = the volumetric heat capacity

4.15.8 The two thermal transport quantities differ in fundamental significance and in applicability: (1) thermal conductivity determines rate of heat flow through a material, thermal diffusivity determines rate of heat flow into or out of it; (2) conductivity deals with transfer of heat energy, diffusivity with temperature change; (3) conductivity relates to steady-state conditions, diffusivity to transient conditions. Conductivity is important for insulation, diffusivity for rates of heating up or cooling down as during vulcanization of a rubber article.

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4.15.9 Hardly any thermal diffusivity data for rubber exists. Of course could be calculated from thermal conductivity values when the density and specific heat are known, as shown in Equation 18, but values for thermal conductivity coefficient are very imprecise. For example, there is a spread of nearly 300 percent in reported values of k for gum natural rubber. Both k and α of rubber are very dependent on the temperature of measurement as well as on the polymer and its compounding. Figure 29 shows representative effects of temperature on the thermal diffusivity of natural rubber containing various carbon blacks.

4.15.10 The surface heat transfer coefficient is analogous to the thermal conductivity, except that the resistance to heat flow is provided by factors other than material thickness, so it is sometimes called a film transfer coefficient. Its value is given by h : (See Eq. 17 for legend).

$$h = \frac{q}{At(T_1 - T_2)} \quad \text{Eq. 19}$$

where T_1 and T_2 represent the temperatures of the two materials at the interface. If the heat transfer is perfect, then $T_1 = T_2$ and h becomes infinite. Often any value of h above 6000 W/m²K is regarded as infinite. It has little if any dependence on the composition of rubber but varies widely with surface roughnesses and with fluid velocity if the heat transfer is between a rubber and a gas or liquid. Typical values are given in Table IX, but in any particular case, heat transfer coefficient, h , should be regarded as a quantity to be determined experimentally. These heat transfer considerations become important in determining curing times for rubber compounds, especially when a mold cannot be used. As shown in Table IX, a fluid bed gives better transfer than does air. In a fluid bed the rubber is surrounded by tiny balls or microballoons, which are often made of glass. They support the uncured rubber without unduly deforming it.

4.15.11 The thermal emissivity of a material surface, or its numerically equal absorptivity, must be considered if radiative heat exchange is to be calculated. This quantity, represented by e , is the dimensionless ratio of the radiative or absorptive efficiency of the surface to that of a black body. Thermal emissivity for rubber is quite high at about 0.94, but the departure from unity may be significant in at least two circumstances. One is in the measurement of surface temperature by infrared radiography where emissivity must be used to correctly interpret the instrument reading. The second is in determining heat balance equations where all of the heat exchange must be accounted for.

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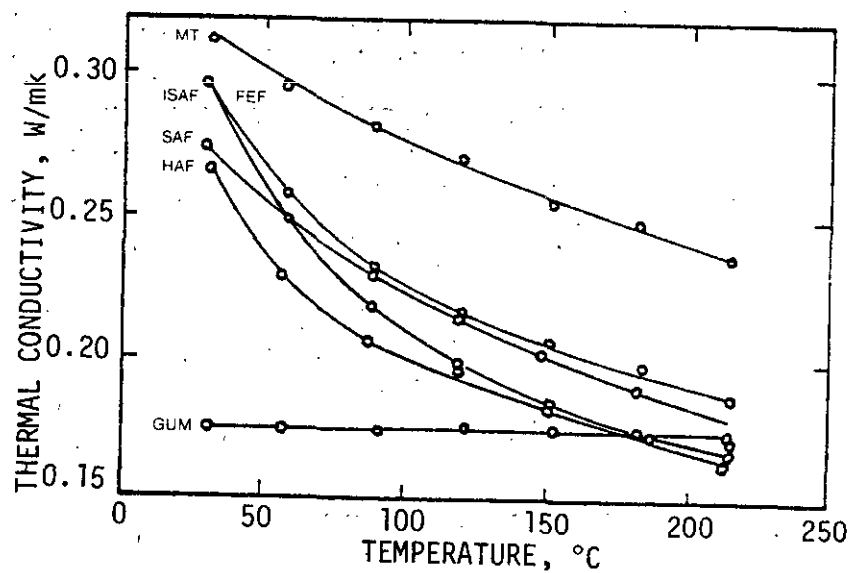


FIGURE 28. THERMAL CONDUCTIVITY OF NATURAL RUBBER WITH 60 PARTS CARBON BLACK PER 100 PARTS RUBBER (38)

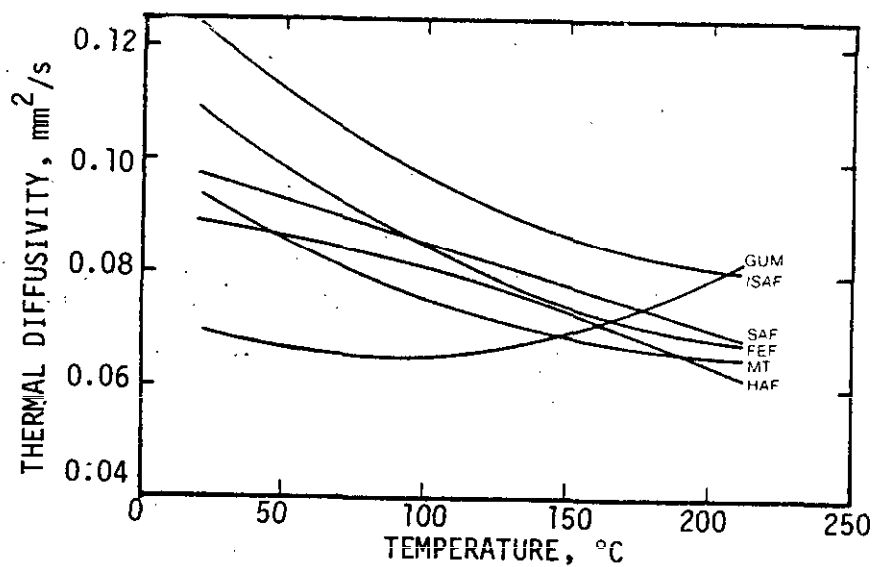


FIGURE 29. THERMAL DIFFUSIVITY OF NATURAL RUBBER WITH 60 PARTS CARBON BLACK PER 100 PARTS RUBBER (38)

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TABLE VIII. HEAT CAPACITY AND THERMAL CONDUCTIVITY OF
SEVERAL TYPES OF RUBBER WITH 50 PARTS
CARBON BLACK FOR EACH 100 PARTS OF RUBBER (85)

Rubber		Heat Capacity, C_p		Thermal Conductivity	
		Btu/lb.°F	kJ/kg·K	But.in./hr.ft ² .°F	W/mk
Chloroprene	CR	0.41-0.43	1.7-1.8	1.46	0.21
Natural	NR	0.36	1.50	1.94	0.28
Styrene- Butadiene	SBR	0.36	1.50	2.08	0.30
Water		1.00	4.2	47.1	6.8

TABLE IX. TYPICAL HEAT TRANSFER COEFFICIENTS (66)

System	Heat Transfer Coefficient, h	
	Btu/hr.ft ² .°F	W/m ² .°K
Condensing Steam	∞	∞
Rubber Mold	∞	∞
Heating or Cooling		
with water	49 to ∞	280 to ∞
with air	0.8 to 8	4.5 to 45
Fluid Bed	19	110

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4.16 Heat Capacity.

4.16.1 The terms "heat capacity" and "thermal capacity" are often used in an engineering sense to mean the total amount of heat required to raise the temperature of a system by 10°F or 1°C . They are also used in the material properties sense as the amount of heat required to raise a unit mass of material by one degree. Current usage appears to favor restricting "heat capacity" to a material property with units $\text{cal/g}^{\circ}\text{C}$ (J/kgK) and to discard "specific heat" which was defined as the number of calories of heat required to raise the temperature of one gram of a material by 1°C or the number of Btu required to raise the temperature of one pound of the material by 10°F . This also had the same numerical value as the nondimensional ratio of the amount of heat required to raise the temperature of a body by x° to the heat required to raise the temperature of an equal mass of water by x° .

4.16.2 The heat capacity, C_p , of a gas held at constant pressure is different from the heat capacity, C_v , of the same gas held at constant volume. Rubber is not very sensitive to this variable, but the C_p value is the one that is usually given. Rubber is a bit more sensitive to the analogous thermodynamic variables of stress and strain. The heat capacity C_F at constant tension is not exactly the same as the heat capacity C_L of the same material at constant length. The heat capacity of rubber is less at about 100 percent extension than at either higher or lower values.

4.16.3 The heat capacity of rubber is affected more by temperature than it is by either hydrostatic or linear constraints. Table X shows the heat capacity of some common rubbers at 77°F (25°C) and the formula that gives the effect of temperature. Except for the butyl rubber the temperature effect is nearly linear. A side effect of temperature is observed if the rubber crystallizes. This gives a fairly marked change in heat capacity.

4.16.4 The heat capacity of a rubber compound is very nearly equal to the sum of the heat capacities of its components, and is practically unaffected by vulcanization. Heat capacities of butadienes polymerized at high temperature are somewhat lower than those polymerized at low temperature.

4.16.5 Differences in heat capacity between different polymers or compounds have little practical consequence in rubber engineering. Heat capacity differences can have a slight effect on the rate of temperature build-up from hysteresis or external heating and must be considered in thermal analyses that involve transient heating conditions. In the case of automobile tires, for example, a low rate of temperature rise means that the tire is operating longer at low temperatures where energy losses are higher. In operations at thermal equilibrium, however, heat capacity is no longer a factor.

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TABLE X. HEAT CAPACITY OF COMMON RUBBERS (86)

Rubber	Heat Capacity Referred to 25°C, J/kgK
Acrylonitrile Butadiene	NER 1970 + 2.83(t-25)
Butadiene (hi cis)	BR 1854 + 2.98(t-25)
Butadiene (low temp.)	BR 1963 + 3.05(t-25)
Butyl	IIR 1947 + 4.37(t-25) + 2.24x10 ⁻³ (t-25) ²
Natural Rubber	NR 1917 + 3.44(t-25)
Styrene Butadiene	SBR 1930 + 3.21(t-25)
Water	4200 (minimum at 34°C)

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4.17 The Joule Effect.

4.17.1 In contrast to the behavior of most engineering materials, rubber gives off heat when it is deformed and absorbs heat when it recovers. This property, called the Gough-Joule, or simply the Joule effect, is also responsible for the unique reaction of deformed rubber to externally applied heat. In the case of a rubber article such as a motor mount that supports a constant load, the Joule effect acts to decrease the deformation when the temperature is raised. A static seal that operates at constant deformation tends to exert greater retractive force at higher temperatures. These reactions oppose those of thermal expansion or contraction, so the net effect of a temperature increase depends upon the initial deformation. There is no Joule effect at zero deformation. For each type of rubber there exists a deformation above which the Joule effect predominates and below which the thermal expansion or contraction predominates. For rubber in tension this point is called the thermoelastic inversion extension and is about 13 percent for gum natural rubber.

4.17.2 The Joule effect can be quantified by determining the temperature rate of change of strain at constant stress $(\frac{\partial \epsilon}{\partial T})_{\sigma}$ and the analogous temperature rate of change of stress at constant strain $(\frac{\partial \sigma}{\partial T})_{\epsilon}$. These values vary linearly with stress and strain respectively, but the quotients of Joule effect at constant stress divided by the stress $(\frac{\partial \epsilon}{\partial T})_{\sigma} / \sigma$ and that at constant strain divided by the strain $(\frac{\partial \sigma}{\partial T})_{\epsilon} / \epsilon$ are invariant for a given rubber. Typical values for each of these quantities are given in Table XI. All of the values are more sensitive to hardness of the vulcanizate, as determined by carbon black content, than to the base polymer. This is shown by comparing the differences between the two compounds of natural rubber with those between the different polymers.

4.17.3 The relationship of Joule effect to hardness or modulus can be extended by noting that the ratio of the Joule effect at constant strain to that at constant stress at a given temperature is equal to the tangent modulus at that temperature.

4.17.4 Measurement or application of Joule effect requires thermodynamic equilibrium. Any creep or stress relaxation that occurs during the time interval of measurement introduces an error, one that may overwhelm the effect. For example, the stress in a specimen held at a given elongation is directly proportional to the absolute temperature because of the Joule effect. The customary stress-strain test, however, shows a much lower stress at higher temperatures. This is because the rubber is far from thermodynamic equilibrium in the stress-strain test. Another interference with rigorous Joule effect behavior is the chemical degradation that may occur in a specimen that is held in a deformed state long enough to reach equilibrium.

4.17.5 The Joule effect could be used to convert heat energy into mechanical energy, and this has been done in the Wiegand pendulum. The probability of practical application to a heat motor seems small, however, because the low thermal conductivity of rubber causes the heat interchange of rubber with its surroundings to be too slow.

4.17.6 Although the Joule effect is usually insignificant, it can sometimes have a spectacular effect.

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4.17.6.1 A rubber torsion spring for an automobile might cause the vehicle to ride much higher from the road in summer than in winter.

4.17.6.2 A seal tightly fitted to a rotating shaft may become tighter as a result of the conversion of frictional energy to heat. This effect may increase until complete failure of the seal occurs. Although O-ring seals have been used for rotating seals, the applications are highly restricted. Low speeds, in fluid media that do not swell the rubber much, and using a light squeeze, are typical limitations. Mechanical seals designed for rotating shafts or rotary shaft lip-type seals ("oil" seals) should be used wherever possible.

TABLE XI. JOULE EFFECTS FOR BASIC TYPES OF RUBBER (20)

Rubber		Constant Stress, σ	Constant Strain, γ	$\left(\frac{\partial \gamma}{\partial T}\right)_{\sigma}$	$\left(\frac{\partial \sigma}{\partial T}\right)_{\gamma}$
				σ	γ
		OC-1	OC-1	OC-1, kPa-1	kPa · OC-1
Acrylonitrile					
Butadiene	NER	0.84×10^{-3}	0.11	0.34	1.63
Butyl	IIR	1.50×10^{-3}	0.13	0.61	1.56
Chloroprene	CR	1.20×10^{-3}	0.14	0.49	1.68
Natural, carbon black					
50 pphr	NR	0.15×10^{-3}	0.09	0.06	5.38
Natural, gum	NR	1.67×10^{-3}	0.10	0.66	1.34
Styrene Butadiene	SBR	1.39×10^{-3}	0.16	0.57	2.74

(Shear stresses of 90 to 248 kPa, shear strains of 0.14 to 0.37, reference temperatures 0 to 20°C).

4.18 Friction.

4.18.1 The apparent contact area between two objects in relative motion is much larger than the true contact area unless the surfaces are very deformable or exceptionally smooth. Asperities support the load and may therefore develop very high temperatures during sliding. The opposing asperities of two metals may weld to each other and the breaking of these welds contributes much to the frictional force. In sliding on ice the asperities of the ice melt, thereby reducing the friction. Rubber deforms by flattening its own asperities, by conforming to those of the opposing surface, and by forming "waves of detachment" at the interface. These properties lead to two important distinctions in frictional response between rubber and most other engineering materials: (1) The rubber area at the interface increases with load until contact is essentially complete; frictional force increases concomitantly because it is proportional to true contact area, and (2) rubber deformation transforms mechanical force into hysteretic heating, thus making

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friction at least partly a viscoelastic process. Rubber therefore does not obey the classical laws of friction unless it is either so heavily loaded against the opposing surface that contact is nearly complete, or it is so hard that it doesn't deform and therefore acts like a rigid solid. In either of these cases the frictional force becomes independent of load. This behavior is illustrated in Figure 30.

4.18.2 Although it is far from being a constant, the resistance of rubber to sliding on another surface is usually expressed as a "coefficient" of friction, or more accurately the nondimensional quotient of the frictional force divided by the loading force. The coefficient is actually dependent on almost every imaginable variable, for example, load, velocity, temperature, and surface roughness, and its dependence on sliding velocity is particularly interesting in that the maximum is neither at zero speed nor at a very high speed.

4.18.2.1 For tires sliding on wet pavement the maximum coefficient has been reported as occurring at speeds between 0.01 m/s and 0.5 m/s. Figure 31 illustrates such a peak obtained in laboratory tests. The other, and perhaps most important, point demonstrated by this figure is that curves of coefficients of friction as functions of velocity, obtained over a wide range of temperatures, can be combined into a master curve by the WLF transform method (See 4.12.3). Since viscoelastic stress-strain behavior can be treated similarly, friction again appears to be a viscoelastic phenomenon.

4.18.2.2 However, the loading force usually becomes more important than the coefficient of friction. For example, the squeeze force of an O-ring in a rod gland is so great a factor that the resistance force to move the rod is lowered by substituting a softer (lower Durometer) O-ring in a component despite the higher coefficient of friction of the softer rubber compound. The dimensions of interference and the shape factor are dominating characteristics.

4.18.3 There is no general agreement on the theory of rubber friction, including the question as to whether or not a true "static" friction exists or if it is even a valid concept. Neither can the proportion of friction ascribable to adhesion and that due to hysteresis be clearly distinguished. The base polymer seems to affect rubber friction more on fairly rough surfaces than on smooth surfaces because of the hysteretic effect. Table XII shows some values for the coefficient of friction of automobile tires obtained in tests for wet cornering traction. Although butyl rubber had the highest value at 30 mph (48 km/h), it became lower than the SBR at 37 mph (60 km/h). Some rubbers, such as the silicones, have inherently low friction.

4.18.4 Rubber differs from rigid materials in its response to lubrication. Two types of lubrication are usually considered: boundary and fluid film or hydrodynamic. In boundary lubrication, the frictional force is a function of the properties of the contacting solids and of the lubricant. For hard materials the force is essentially independent of the lubricant viscosity and of the speed. In hydrodynamic lubrication, friction is dependent on bulk properties of the lubricant, mainly viscosity. Frictional force is dependent on the shear properties of the film, which is several times thicker than the height of the asperities. Rubber adds a third type of lubrication, or rather one that is intermediate between boundary and hydrodynamic. This has been called elastohydrodynamic. It is a condition in which elastic surface

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deformation adds to the hydrodynamic forces. In boundary lubrication the asperities are in contact; in hydrodynamic they are separated; in elasto-hydrodynamic they are separated but deformed by the force transmitted by the lubricant. This may be the reason that friction of rubber on lubricated shafts increases with increased shaft roughness as shown in Figure 32. Friction of unlubricated rubber usually decreases with increase in roughness of the opposing surface because of the decrease in area, but in lubricated sliding, the friction is largely due to elastic losses in rubber so the determining factor is not the actual area of contact.

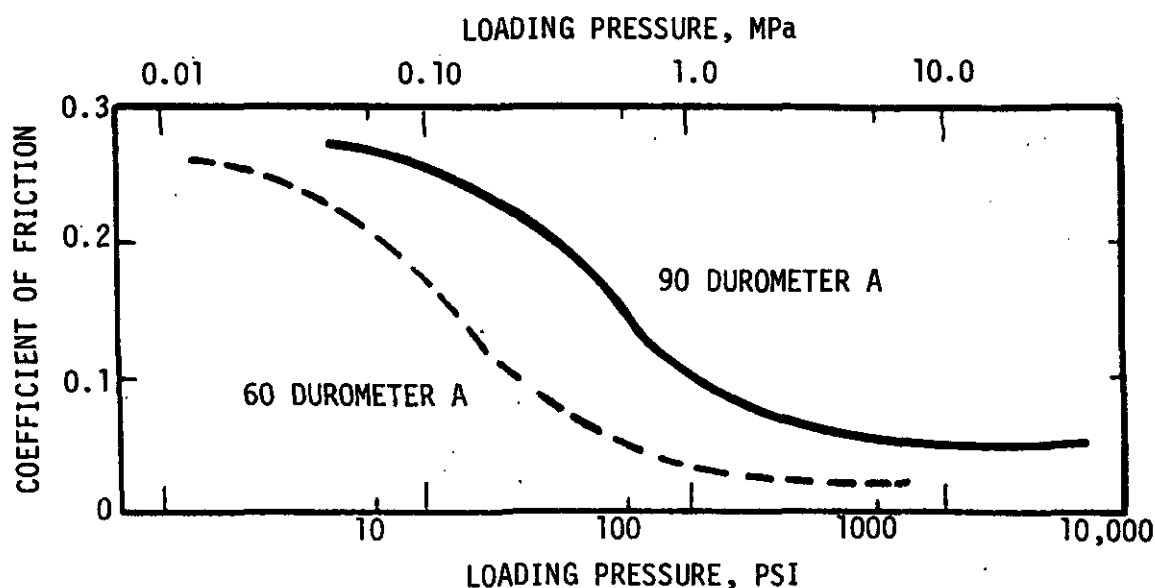
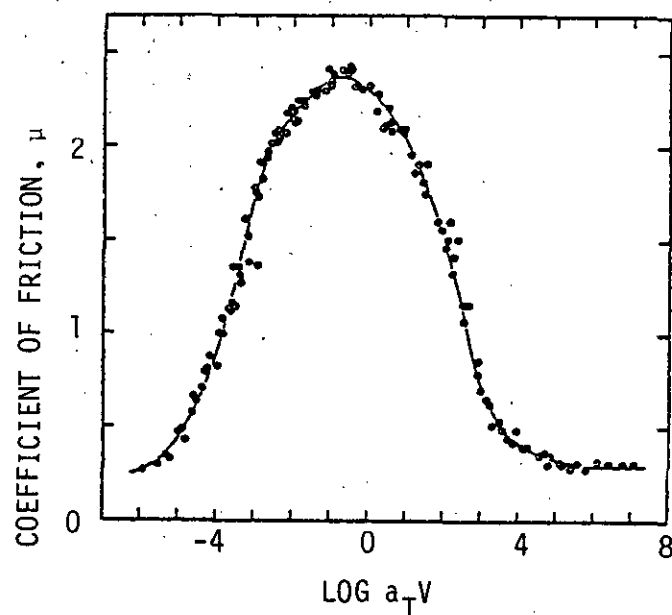


FIGURE 30. VARIATION OF RUBBER FRICTION WITH PRESSURE, MAN-MADE RUBBER LUBRICATED WITH OIL ON SMOOTH STEEL SURFACE (25)

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μ = FRICTIONAL FORCE/LOADING FORCE

a_T = WLF SHIFT FACTOR (SEE 4.12.3)

FIGURE 31. MASTER CURVE FOR COEFFICIENT OF FRICTION OF ACRYLONITRILE BUTADIENE (NBR) RUBBER AT 68°F (20°C) (36)

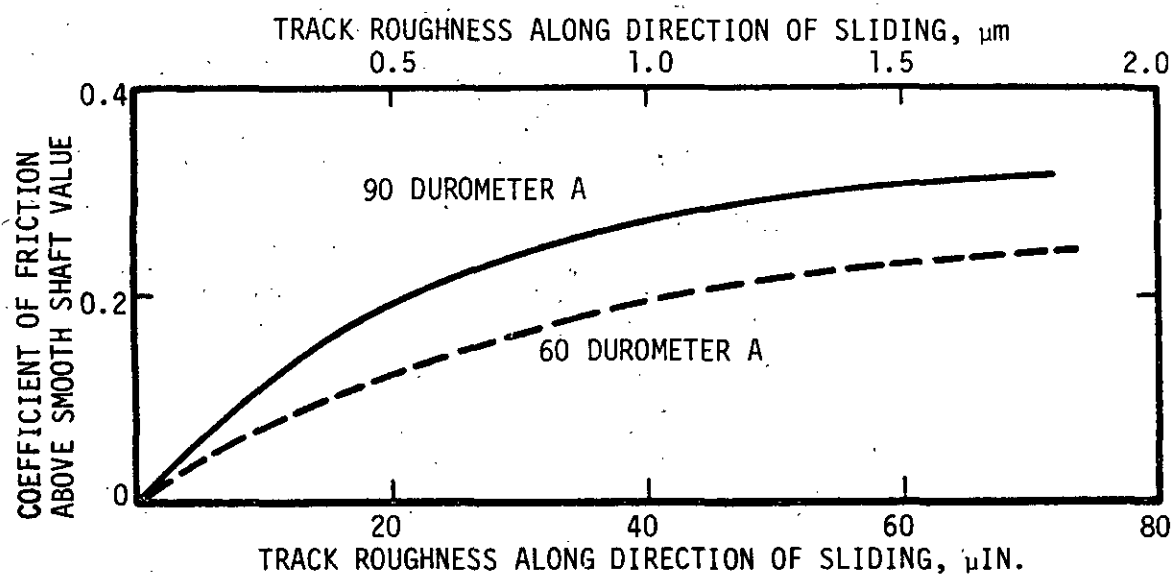


FIGURE 32. INCREASE OF RUBBER FRICTION DUE TO SHAFT ROUGHNESS, MAN-MADE RUBBER LUBRICATED WITH OIL (25)

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TABLE XII. EFFECT OF TREAD POLYMER ON COEFFICIENT OF FRICTION OF TIRES CORNERING AT VARIOUS SPEEDS ON WET PAVEMENT (79)

TIRE TREAD POLYMER		COEFFICIENT OF FRICTION, μ at Speed, mph (km/h)			
		30 (48)	40 (64)	50 (80)	60 (97)
Butadiene	BR	0.32	0.29	0.26	0.22
Butadiene/Styrene					
Butadiene	BR/SBR	0.38	0.34	0.30	0.25
Butyl	IIR	0.59	0.48	0.37	0.25
Natural	NR	0.45	0.38	0.31	0.23
Styrene Butadiene	SBR	0.55	0.49	0.43	0.36

4.19 Specific Gravity. Specific gravity normally has no engineering value in designing with rubber, but is useful in quality control during the manufacture of rubber articles. To obtain the properties required for a specific rubber application, it is necessary to "compound" the rubber by adding reinforcing fillers, plasticizers, vulcanizing agents, and anti-oxidants to the elastomer. Once the composition is ascertained, a certain specific gravity is exhibited. The specific gravity of a carbon black filled rubber compound should not vary, lot-to-lot, or batch-to-batch, by more than ± 0.02 units; a silicone rubber compound, which uses nonblack fillers should not vary more than ± 0.03 units. Many material specifications use specific gravity as a quick method of determining if an error has been made in compounding a specified rubber.

4.20 Abrasion Resistance.

4.20.1 No single test can be used to characterize abrasion resistance of rubber because so many variables can affect the results. This property should therefore not be used as a general quality index for rubber. An abrasion requirement should not be part of a specification unless the validity of the designated test to the application has been established. Even service tests may be misleading. For example, both the absolute and relative wear ratings of tire treads are definitely related to the severity of operating conditions. In evaluating tire wear rate and tread life, the same tires run under different conditions may be entirely different in rank order. Since service tests may yield contradictory results, it is not surprising that the general validity of laboratory tests is questionable.

4.20.2 Because abrasion resistance of such items as tires, footwear, and conveyor belt coverings is so important, many laboratory tests have been devised for abrasability of rubber as a material and as a component of product. Three mechanisms of wear have been recognized: cutting and gouging, fatigue, and chemical action. All three may occur in a given article at different times, but fatigue has been given the most attention with cut growth

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being considered the principal mechanism at ordinary levels of energy input. At higher levels of available tearing energy, above approximately 0.114 ft-lb per sq in. (20 kJ/m²) cut growth is replaced by catastrophic tearing.

4.20.3 Cut growth type of wear appears to be reproduced by repeatedly scraping a blade across the rubber surface. The resultant effect is illustrated in Figure 33, where crack growth is assumed to occur at points P and Q. P is the reentrant angle in the undeformed abrasion pattern, and Q represents a similar element deformed by the blade. The blade, in moving in the direction shown by F, has passed over the point P and increased the depth of cut under the partially detached flap. The blade is shown stretching another flap thereby producing a downwardly directed tearing force at Q. Repeated scrapings over the same area produces a pattern of ridges perpendicular to the direction of abrasion. In steady-state operation the quantity of rubber abraded can be related quantitatively to the frictional force and the crack growth characteristics of the rubber. Good agreement with experiment is found for noncrystallizing rubbers, but not for crystallizing rubbers, such as NR. The ASTM Standard D2228 for the Pico Abrader is based on the scraping blade.

4.20.4 Abrasion rate is higher if the force cycles are always in the same direction than if they are varied, as shown in Figure 34. Some rubber articles might be designed to use this property to advantage. Automobile tires with both cornering and traction forces seldom show an abrasion pattern unless they have been slid or spun for a long distance.

4.20.5 Rapid abrasion is promoted by high temperatures or oxidation which reduces tearing resistance of rubber and by movement on sharp surfaces which abrade by cutting or gouging. Contour maps of the United States have been made that show areas of high and low average tire wear ratings as determined by the sharpness of road surface aggregates. The Pico test, however, is very insensitive to blade sharpness because the blade does not cut the rubber. Its tearing force is obtained by friction.

4.20.6 Abrasion rate is also affected by the impurities present on the rubber surface. Those may fill in between surface asperities, thereby reducing their cutting action; they may reduce the frictional force of an asperity on the rubber; they may prevent abraded rubber from smearing on the surface; or they may take an active part in the abrasion process, perhaps by supporting the partially disengaged lip of torn rubber. A carefully specified powder is used in the Pico test.

4.20.7 Although high frictional forces promote high wear rates, rubber sliding on another surface can develop appreciable frictional force without being abraded at all. This can happen if the forces at the rear of the waves of detachment are insufficient to tear the rubber, or if the frictional force is developed elastohydrodynamically.

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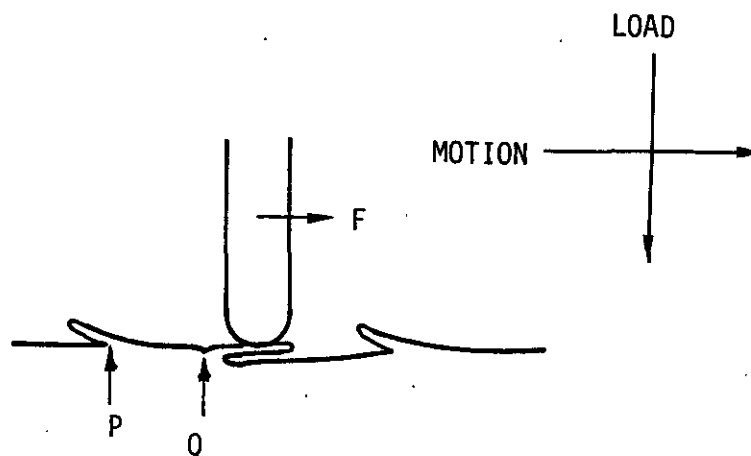


FIGURE 33. SCHEMATIC DIAGRAM OF ABRASION PATTERN AND ITS DEFORMATION BY A BLADE (SEE 4.20.3) (77)

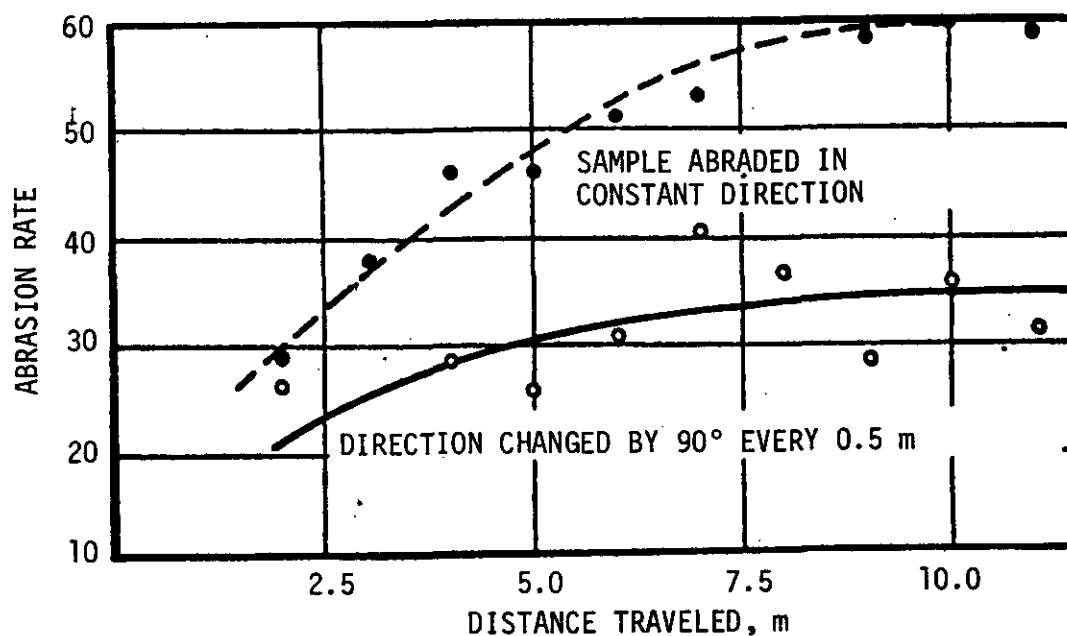


FIGURE 34. EFFECT OF CHANGE OF DIRECTION ON RATE OF ABRASION (70)

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4.21 Tear Resistance.

4.21.1 The tear resistance of rubber is strongly affected by stress distribution, by speed of stretching, and by the shape and size of the specimen. Specifications for rubber often require the use of ASTM Standard D624 test method for evaluating tear strength, using either Die C or Die B; specimen configuration in ISO Standard R34 is equivalent to Die B. All tear tests have a low degree of interlaboratory reproducibility due to specimen preparation techniques and sharpness of dies used, as well as the accuracy of the nick applied to Die B. Generally, Die C is preferred over Die B in specifications developed in the United States, based on an unpublished survey conducted in 1972. Tear strength in pounds or newtons per unit test piece is reported in ISO Standard R34, while ASTM Standard D624 also permits units of force per unit thickness (lbf/in. or N/m). This usage assumes that tearing force is proportional to thickness, which is not strictly true; neither is it independent of thickness.

4.21.2 Results obtained in a test can be regarded as a measure of the tear resistance only under the conditions of the particular test, and not necessarily having a relation to service value. Additional service tests should be made under simulated service conditions to obtain a true tear resistance index for each case. Man-made rubbers, except polyurethane, have substantially poorer tear resistance than natural rubber. Those polymers which crystallize upon extension usually have a high tear resistance and a "knotty" torn surface. Addition of reinforcing fillers (for example, carbon black) improves tear resistance markedly.

4.22 Fluid Resistance

4.22.1 Certain fluids are absorbed into rubber and cause it to swell, soften, and lose strength. The three effects usually occur at the same time, although the extent of each may vary. The method generally used for determining the effect of fluids is ASTM Standard D471, which also defines some standardized test fluids used in evaluation of these characteristics. A more specific discussion of fluid resistance is contained in 7.3.

4.22.2 Resistance of a rubber to damage by a fluid is determined by immersion tests of specimens under specified conditions in specified fluids, usually oils, fuels, solvents, or water. Test conditions are likely to differ from actual service conditions in at least two ways. First, in actual service, the component may not be subjected to complete immersion, but rather to splashing or spilling, in which case weathering or ozone resistance may be more important than fluid resistance. Secondly, rubber is generally stressed when it is exposed to a fluid. Test data have only comparative value and cannot be applied directly to service conditions.

4.22.3 If the rubber contains a plasticizer or other compounding ingredients which are soluble in the immersion fluid, these ingredients will eventually be extracted. If the volume of material leaving the rubber exceeds that of the fluid entering it, the rubber will shrink. If this happens to a rubber seal, leakage may occur. This characteristic, together with compression set, is especially troublesome to seals. At the same time, plasticizers which were added to the rubber to improve low temperature capabilities may be leached and low temperature sealing performance is impaired, contributing to further leakage.

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4.22.4 Some rubber compounds, and this is typical of seal materials, exhibit increase in hardness with sometimes concurrent increase of tensile strength, usually associated with shrinkage. Compounds that resist damage by aircraft fuel exhibit still another characteristic, swelling severely at times, which is usually associated with the aromatic content of the fuel, and then shrinking upon drying. Both of these behaviors are due to plasticizer and inherent solubles leaving the rubber during fluid exposure. These conditions are greatly accelerated by high temperature exposure and frequent sequences of exposure and drying out.

4.22.5 The resistance of a rubber to damage by a fluid decreases with increasing temperature. If the recommended service temperature is exceeded, a fluid that would not normally affect a rubber may become destructive. Chemical reactions increase and permanent damage may occur. In addition, the fluid may start to break down, creating different chemicals and adding to the compatibility problem.

4.22.6 Some fluids affect rubber chemically, whether they swell the rubber or not. Oxidizing fluids are examples. One form of degradation would be hardening and cracking of the rubber; other rubbers may be softened (often referred to as reversion) and reduced to a sticky mass. Obviously, fluids that cause these reactions should be avoided; in the fluid resistance tables in 7.3, reactions coded "fair", "poor", "dissolved" characterize this type of reaction.

4.22.7 Another consideration is the time between exposures. If the fluid is able to evaporate during nonexposed intervals and there is no extraction or leaching of plasticizers, little or no permanent damage may result.

4.22.8 Finally, whether swelling alone is indicative of a failure depends on the application. It is, however, most important that the rubber be allowed to increase in volume without restraint so that an increase in stress level is avoided. An example of utilizing the plasticizing effects of a fluid is the compounding for petroleum fuel resistant seals, by not plasticizing a rubber to achieve low temperature performance, as the seal would not be subject to low temperature exposure unless the system was wet with the fuel. In this case, the fuel plasticizes the rubber, causing increase in volume and improving the low temperature flexibility. However, when the fuel system is nonfunctional, such as during an overhaul, the seals dry but usually do not shrink below their original volume significantly, so the system does not leak when fuel is again applied.

4.23 Dynamic Properties

4.23.1 Three classes of dynamic properties are associated with rubber or rubber products:

- (1) Engineering Properties relate to a specific structure and depend on its geometry as well as its composition.
- (2) Material Properties are independent of structure geometry and, theoretically, of the test apparatus.

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- (3) Technological Properties depend on both specimen geometry and the test apparatus. These indices can seldom be used in further calculations.

4.23.2 There are, furthermore, three types of properties that can be listed under each of these classes:

- (1) Storage (Elastic) Properties which depend on the input magnitude but not its rate. The full response takes place immediately and there is no loss.
- (2) Loss (Viscous) Properties which depend on the input rate but not its magnitude. There is no immediate response, and the energy required is all transformed into heat.
- (3) Combination Properties result from some algebraic combination of the storage and loss properties.

4.23.3 The commonly used terminology and symbolism for each class and type of property are listed in Table XIII.

4.23.4 The engineering properties most commonly used to describe the dynamic behavior of a structure are its spring constant, K , and its dampings constant, C . Their use assumes that the viscoelastic response can be represented by a model having a spring for the elastic component and a dashpot for the viscous component. The force, F , exerted on such a structure at any time during a deformation cycle, assuming no inertial effects, is:

$$F = Kx + C\dot{x}$$

Eq. 20

The elastic component, Dx , is proportional to x , the magnitude of deformation, and the viscous component, $C\dot{x}$, is proportional to \dot{x} , the rate of deformation.

4.23.5 The constants K and C are properties of a defined engineering structure.

4.23.6 There are only two basic dynamic properties. The different representations have arisen from either the mathematical model, the test machine, or the desired application. Each representation has certain limitations. Consider, for example, the use of material properties to describe stress-strain behavior in tension.

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TABLE XIII. CLASSIFICATION OF TERMS AND SYMBOLS DESCRIBING DYNAMIC PROPERTIES OF RUBBER PRODUCTS (18)

Dynamic Property	Material Property (In Tension) ^{1/}	Engineering Property	Technology Property
Storage Properties	Young's modulus E Storage modulus E' Storage compliance $D' = E' / E \times 2$	Spring Constant, K	Hardness Stress at 300 percent elongation Energy input
Loss Properties	Viscosity, Loss Modulus E" Loss Compliance $D'' = E'' / E \times 2$	Damping Constant, C	Hysteresis Temperature Build-up Damping
Combination Properties	Complex modulus $E^* = E' + iE''$ Loss tangent $\tan \delta = E'' / E'$	Material Time Constant, C/K Log Decrement	Loss Ratio, or Specific Damping capacity Hysteresis/input Rebound Resilience

^{1/} Analogous properties
in shear, where G is
used rather than E.

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4.23.6.1 Assume linear viscoelasticity and sinusoidal wave input, then

$$\sigma = E' \epsilon_0 + E'' \epsilon_0 \quad \text{Eq. 21}$$

where

σ = stress

E' = storage modulus

E'' = loss modulus

ϵ_0 = cyclic amplitude

Note that E' and E'' are undefined unless these assumptions are justified.

4.23.6.2 Assume linear viscoelasticity and a Voight (Kelvin) model such as that shown in Figure 35; the stress-strain equation becomes:

$$\sigma = E \epsilon + \eta \dot{\epsilon} \quad \text{Eq. 22}$$

Where

E = Young's modulus

η = viscosity

ϵ = strain

$\dot{\epsilon}$ = rate of strain

Note that this representation requires a model, but not sinusoidal cycles.

4.23.6.3 Assume linear viscoelasticity, a Voight model, and sinusoidal wave input, then $E' = E$ and $E'' = \eta \omega$; the stress-strain equation becomes

$$\sigma = E \epsilon_0 + \eta \omega \epsilon_0 \quad \text{Eq. 23}$$

where

$\omega = 2 \pi$ (cyclic frequency)

4.23.7 Some combination properties that include these forms are obtained by representing the storage modulus, E' , on the abscissa (real axis) and the loss modulus, E'' , on the ordinate (imaginary axis) of a vector diagram such as that shown in Figure 36. The following relationships are evident from the geometry of the diagram, with analogous relations for the shear moduli G' , G'' , and G^* :

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$$E^* = E' + iE''$$

Eq. 24

where

$$i = \sqrt{-1}$$

$$E'^2 = \sqrt{E'^2 + E''^2}$$

Eq. 25

$$\tan \delta = E''/E'$$

Eq. 26

4.23.8 Loss modulus is usually decreased slightly as the modulus of a rubber is increased by increasing its primary molecular weight or crosslink density. Increased filler loading causes an increase in storage modulus and a larger increase in loss modulus. Filler loading does not influence the location of the maximum loss modulus relative to the glass transition temperature, but it may decrease the magnitude of that maximum.

4.23.9 The most significant effect of varying the nature of the polymer is to move the modulus-frequency curve parallel to the frequency axis. Alternatively this may be considered as moving the modulus-temperature curve parallel to the temperature axis. The curve moves in the direction of lower frequency or higher temperature as the polymer becomes more polar, where a polar material is defined as one whose molecules contain atomic groups that are electrically unsymmetrical, having positive and negative poles. Among the common types of rubber the polarity increases in the following order; natural rubber and butyl rubber, styrene-butadiene rubber, polychloroprene, acrylonitrile-butadiene rubber. However, polyvinyl chloride (PVC) is much more polar than any of these.

4.23.10 Table XIV gives a summary of effects of vulcanization and additives on dynamic properties.

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TABLE XIV. SUMMARY OF EFFECTS OF VULCANIZATION AND ADDITIVES
ON DYNAMIC PROPERTIES (33)

Property	Region	Vulcanization	Plasticiser	Filler
In-phase component of complex dynamic modulus, G'	Rubbery	Increase, plateau lengthened, Fig. 38A, B and D	Decrease	Large increase, plateau lengthened, Fig. 38C
	Glassy	Little effect	Slight decrease	Increase Fig. 38C
Out-of-phase component of complex dynamic modulus, G''	Rubbery	Increase Fig. 38A and B	Increase	Increase, Fig. 38C
	Glassy	Little effect Fig. 38C	Increase	Increase,
Tangent of the phase angle, $G''/G' = \tan \delta_G$	Rubbery	Increase	Decrease	Increase
	Glassy	Decrease	Decrease	Increase
	Transition	Peak lowered and broadened	Peak lowered and broadened (at high plasticiser content peak may be raised again	Peak lowered and broadened

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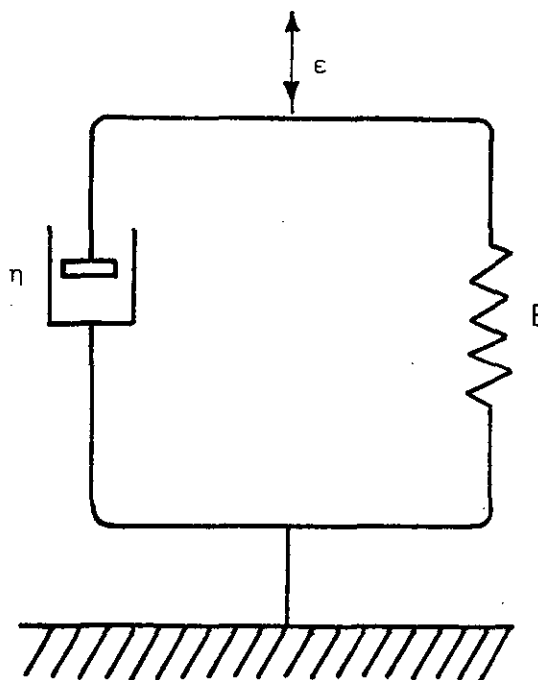


FIGURE 35. VOIGHT MODEL OF SPRING AND DASHPOT TO REPRESENT ELASTIC AND VISCOUS PARTS OF VISCOELASTIC DEFORMATION (SEE 4.23.6.2) (18)

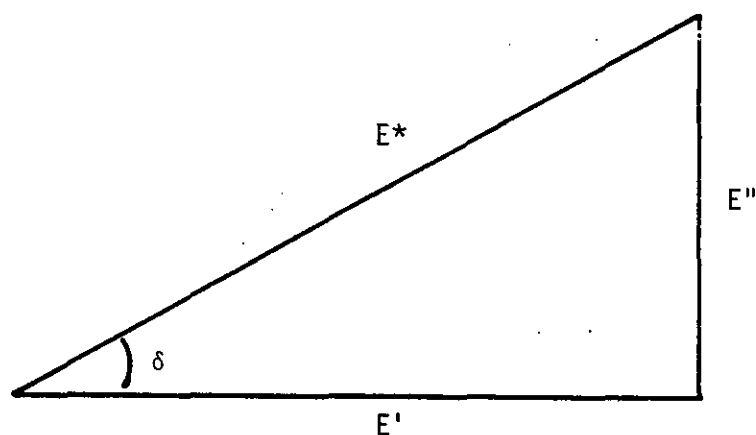


FIGURE 36. VECTOR DIAGRAM FOR RELATION BETWEEN COMPLEX MODULUS (E^*) AND ITS IN-PHASE (E') AND OUT-OF-PHASE (E'') COMPONENTS (18)

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4.24 Tests for Dynamic Properties

4.24.1 Forced vibration in both nonresonant and resonant conditions, free vibration, and impact rebound are all used to characterize dynamic responses of rubber and rubber products. Apparent values for a given index may differ from one type of test to another, or even between different tests on a given apparatus if conditions or methods have been changed. So the specification of a certain dynamic modulus, for example, is insufficient unless the details of apparatus, method, and condition are also specified. A standard test should be used if possible, not only for details of procedure but also for the information that is usually given on precision and significance of results. Even standard tests should be read carefully for scope, interferences, caveats and, especially, for any choices that need to be made. Some standard methods include the statement that they are not suitable for use in material or procurement specifications.

4.24.2 Nonresonant Forced Vibration The International Draft Standard for forced vibration measurements, ISO Standard DIS4664, does not specify any particular apparatus. It does require forced sinusoidal displacement cycles in shear. $\tan \delta$ and G^* are measurable. Each should be reported as a function of temperature, frequency, and strain amplitude. This requirement emphasizes the insufficiency of point data for design purposes, especially that for dynamic properties. Determination of functional relationships over the expected service range of temperature, frequency, and strain amplitude gives more information than would tests at the range limits only, in that they also give values throughout the normal operating range. This would permit, for example, construction of a three-dimensional graph or surface that shows the response at any combination of variables.

4.24.2.1 ASTM Standard D2231 is a Recommended Practice for Rubber Properties in Forced Vibration of either resonant or nonresonant type. It defines many terms associated with dynamic properties and divides them into classes: (a) applying to any periodic motion, (b) applying to sinusoidal motion, and (c) applying to nonsinusoidal motion. Cycles of constant strain amplitude rather than constant stress amplitude are recommended, as is the use of standard test temperatures. Necessary characteristics of test machines are listed, such as flat frequency response, essentially no drift, simple calibration check, adequate sensitivity, and temperature-compensated transducers. Where hysteresis loops are used, there must be identical (or zero) phase shift in the x-axis and y-axis circuits.

4.24.2.2 Nonresonant systems are usually powered by servohydraulics. Frequencies can be as high as 500 hertz and low amplitudes and dynamic forces up to 500,000 lbf (2MN), also at low amplitudes. These wide ranges, and the choice of wave shape, are important reasons why nonresonant forced vibration is more widely used than the other types. Other reasons include reproducibility of input force or amplitude regardless of specimen stiffness and the versatility of test machines, some of which can also be used for measuring temperature rise or fatigue.

4.24.3 Resonant Forced Vibration. Any rubber specimen with or without added mass has a natural or resonant frequency of vibration determined by the dimensions and viscoelastic properties of the rubber, the total inertia of the system, and the mode of deformation. If constant force-amplitude cycles are

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applied to the rubber and the frequency varied, the resulting deformation cycles will have a maximum value when the applied frequency equals the resonant frequency of the specimen.

$$\text{Resonant frequency, } f_R = \sqrt{\frac{S'}{m}} \quad \text{Eq. 27a}$$

$$\text{Deformation Amplitude, at resonance, } A_R = \frac{F}{S''} \quad \text{Eq. 27b}$$

where

S' = in-phase component of stiffness

m = mass of vibrating system

F = applied force amplitude

S'' = out-of-phase component stiffness

4.24.3.1 Alternatively, the mass can be varied in a constant-frequency system to obtain resonance. From S' and S'' , the moduli G' , G'' , and G^* can be calculated.

4.24.3.2 Both dynamic modulus and $\tan \delta$ are strongly dependent on test frequency, as shown in Figures 37 and 38 respectively. These are master curves obtained by shifting curves obtained at various temperatures along the frequency axis to represent behavior at the stated reference temperatures. Maxima in the $\tan \delta$ curves occur at about the same frequency as the maximum slopes in modulus curves. This would be the glass transition frequency at the reference temperature.

4.24.3.3 A more common concept is the glass transition temperature; that is, the temperature, at the reference frequency, at which the molecular segments no longer respond fully (See 7.2.3). Figure 39 shows that the loss tangent ($\tan \delta$) is a maximum at this temperature and that the storage modulus curve is steepest here.

4.24.4 Free Vibration In free vibration tests the rubber specimen forms the spring in a mechanical system with inertia chosen so that a damped oscillation of the desired frequency results from release of a deformation. Deformations in compression, shear, torsion, tension, or torsion plus extension have been used. A common instrument of this type is the Yerzley Oscillograph, described in ASTM Standard D945, which yields a trace of the type shown in Figure 40. The average ratio of heights of successive oscillations, such as $(A_3/A_2 + A_4/A_3)/2$ gives the "Yerzley Resilience". This value would normally differ from rebound resilience because the strain is more uniformly distributed and at a much lower deformation rate. The natural frequency of vibration, f , measured from such a trace can be used to calculate the effective dynamic modulus, K , from the formulas noted below, where I is the moment of inertia of the system. The range of frequency of this system is small, extending up to only a few hertz.

$$K_C = 210 I f^2 \text{ (Compression)} \quad \text{Eq. 28}$$

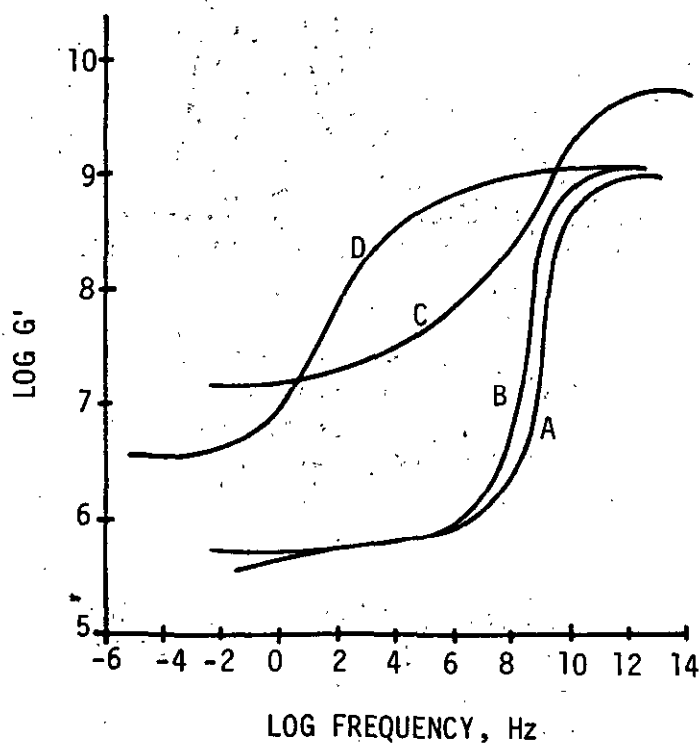
$$K_X = 105 I f^2 \text{ (Shear)} \quad \text{Eq. 29}$$

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4.24.4.1 Some form of torsion pendulum is the most widely used free vibration test. Three methods are standardized in ISO Standard 4663; they cover a much lower range of frequency than do the forced vibration tests. Normal ranges are 0.1 to 10 hertz at strains of less than 0.05 percent in shear. The methods are primarily intended for determining transition temperatures by measuring modulus and damping as functions of temperature; they may not be sufficiently accurate for determination of moduli.

4.24.4.2 An objection to any free vibration method is that amplitude is not maintained. A calculated modulus which depends on the amount of specimen deformation is thus not consistent from one material to another.

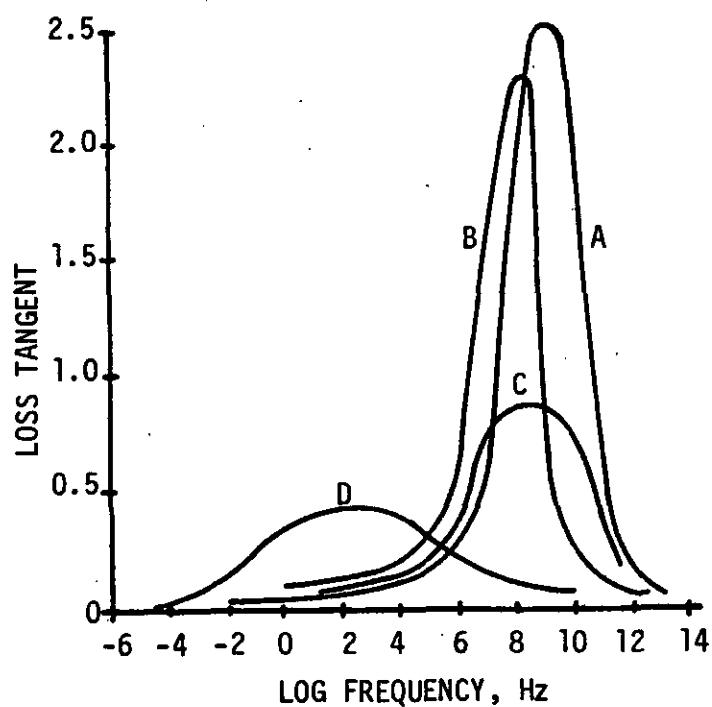
4.24.4.3 Rebound tests (resilience) were described in 4.9 and other dynamic properties in 4.6 on Dynamic Modulus. Still others, such as logarithmic decrement, natural frequency, forced vibration with damping, transmissibility, torsional vibration, and designing for shock and vibration are discussed in Section 6.



- A = UNVULCANIZED, AT 0°C
- B = GUM VULCANIZATE, AT 0°C
- C = VULCANIZATE CONTAINING
CARBON BLACK, AT 0°C
- D = EBONITE, AT 60°C

FIGURE 37. COMPOSITE CURVES OF DEPENDENCE OF DYNAMIC MODULUS (G') ON FREQUENCY FOR NATURAL RUBBER (33)

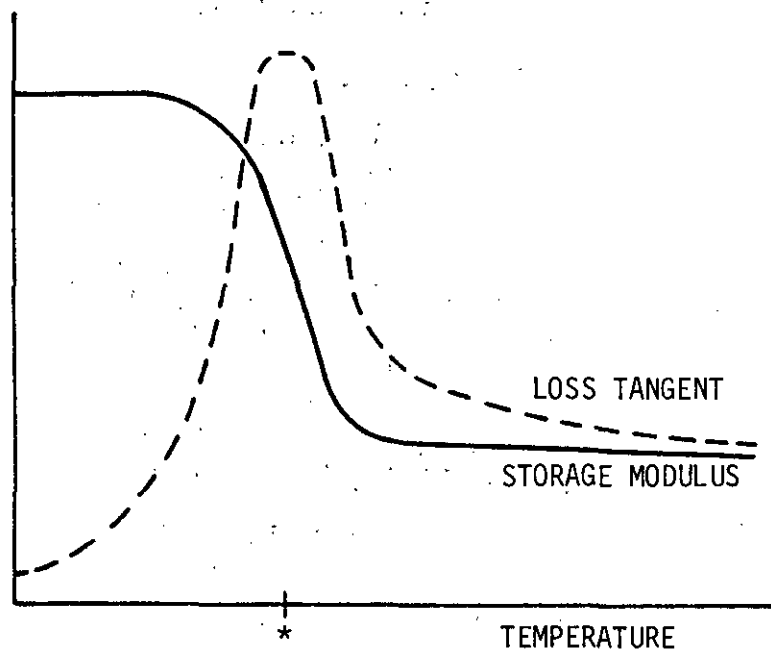
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A = UNVULCANIZED, AT 0°C
B = GUM VULCANIZATE, AT 0°C
C = VULCANIZATE CONTAINING
CARBON BLACK, AT 0°C
D = EBONITE, AT 60°C

FIGURE 3E. COMPOSITE CURVES OF LOSS TANGENT
AS A FUNCTION OF FREQUENCY (33)

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* THIS POINT CORRESPONDS APPROXIMATELY WITH THE GLASS TRANSITION TEMPERATURE. FOR NATURAL RUBBER THIS IS ABOUT -99°F (-73°C) (See 7.2.3)

FIGURE 39. GENERAL RESPONSE OF VULCANIZATES TO TEMPERATURE CHANGE AT LOW FREQUENCY (7)

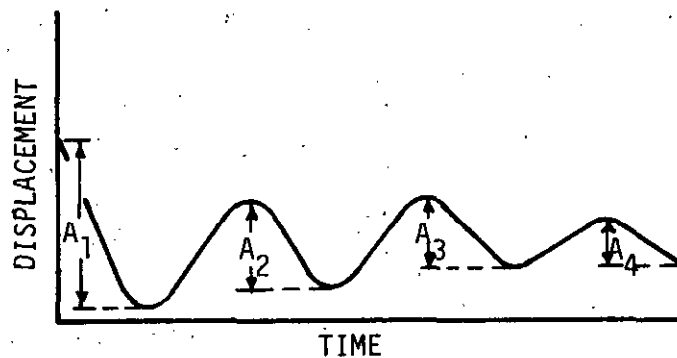


FIGURE 40. A TYPICAL DAMPED OSCILLATION CURVE (18)

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5. DESIGNING WITH RUBBER

5.1 General Design Considerations

5.1.1 Elastomeric materials used with a view to their areas of strength and weakness offer many advantages over metals for certain engineering applications. For example, used as a spring: (1) Rubber is able to store considerably more energy per unit volume than are metals; (2) Rubber has higher inherent damping characteristics. These reduce the effect of suddenly applied loads, and obviate the need for external dashpot damping devices which are likely to produce high peak forces in the system; (3) Rubber does not corrode; (4) Lubrication maintenance is not required; and (5) Failures in rubber components nearly always occur gradually.

5.1.2 Limitations on elastomer use are generally environmental, as rubber properties are affected by temperature, by contact with solvents and oils, and by exposure to ozone and to radiation. However, selection of the proper elastomer for a particular application can largely overcome these limitations. Data to aid in such selection are given in 7.1 through 7.13, and 10.1.

5.1.3 The engineer designing components from rubber must have maximum information on the conditions to which the rubber parts will be subjected during their working life. Necessary data include: maximum loads, normal working loads, permissible and desirable deflections, vibratory conditions, shock loads, and the desired life expectancy of the component.

5.1.4 To promote long life, stresses should be kept within recommended low limits. As with other engineering materials, highly stressed components become subject to fatigue failure, as fatigue life is predominantly a function of strain in the body. The design stresses for the rubber suspension system components of an LVT tank indicate static stresses of 75 psi (0.5 MPa), and 220 psi (1.5 MPa) at bump excursion conditions. The suspension system was designed for a 100-hour life, but actual life experienced was 150 service hours. Newer military designs report using similar design stresses and obtaining longer life by designing for a smaller stress range. In passenger cars, suspension design stresses are 120 psi (0.8 MPa) and, in bus suspensions, designs are for 75 psi (0.5 MPa) empty and 105 psi (0.7 MPa) at a fully seated load. If strains are calculated on the basis of a uniform stress distribution, a corrective factor should be applied to compensate for surface irregularities and section changes. Discontinuities, such as occur in a bonded assembly, must be so designed that flared edges at the interface provide a low strain gradient.

5.1.5 In practice, dynamic failure of rubber springs always occurs progressively; the interval between the start of failure and complete failure occupies a considerable portion of the fatigue life. This is an advantage of a rubber spring over a steel spring, in that sudden catastrophic failure rarely occurs.

5.1.6 Rubber volume is affected by temperature changes, and is subject to swelling by oils. The volume compressibility of rubber is so low that it can be considered negligible. Consequently, large compressive stresses may be induced in rubber where the part is confined in rigid surroundings unless adequate provisions are made for such volume expansions. Such allowances must be made for rubber seals and other components that must function at a wide range of temperatures.

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5.1.7 The question of "how the rubber is to be loaded" depends on the application. In most cases, there is a choice between application in tension, shear, or compression. The choice should be made in accordance with the best utilization of the material. Where large production quantities are involved, the economic aspects of minimum rubber volume are major considerations. Other factors are determined by load-deflection characteristics, space allotment, and other available design data.

5.1.8 The following section presents design data for use of rubber in shear, compression, and tension. It covers discussion of rubber applications, stress-strain curves, design equations, and includes design examples. The design equations are based on theory of small strains typical for rigid materials, where Hooke's law of proportionality of stress to strain applies. The stress-strain curves presented are average curves and considerable deviation, as a result of variations in compounding, can be expected when components designed with the aid of these data are tested. Among the reasons for requiring approximate solutions is the lack of a suitable theory for macroscopic behavior. Such theories exist but are not adaptable in practice, and therefore do not constitute practical design tools.

5.2 Stress-Strain Relationship in Shear Sandwiches

5.2.1 Rubber stressed in shear is usually bonded between two parallel metal plates and the force is applied in the plane of one plate and in a direction parallel with it. An elementary form of such rubber sandwich is shown in Figure 41; Figure 42 shows a balanced design of a double sandwich. The second design also incorporates a means for limiting the deflection.

5.2.2 For rubber, the shear strain must be defined in terms of the ratio of the linear deformation in the direction of load application to the thickness, d/t . This ratio represents the tangent of the shear angle, which itself is conventionally used if dealing with rigid materials elastically deformed in shear. Because of the nonlinear load-deflection characteristics of elastomeric materials, the deflection resulting from an applied load is best obtained from the empirical curves presented in Figures 43 and 44 for various hardness grades. The curves are usable directly after the stress has been determined. This is done by dividing the imposed load by the acting shear area (either single or double shear area depending on whether a single or double sandwich is being designed). Similarly, the load associated with a specific deflection can be found.

5.2.3 Figure 43 presents curves for hardness levels from 30 to 80 Durometer A. These have been determined from natural rubber and chloroprene samples and are only applicable to these elastomers. However, they should provide a good approximation for other types of rubber. A separate shear stress-strain curve for polyurethanes is presented in Figure 44. The limit-lines for maximum deflection are experimentally determined. They should not be used without prior consideration of other factors such as shape and possible stress concentration inherent in the design, the bond strength, the effect of creep on bottoming, clearance, and the life expectancy. Note that softer compounds and intermittent loads allow greater deflections.

5.2.4 There are at least two advantages to using rubber in shear. Rubber possesses greater deformation capability in shear than in compression, and the shear load-deflection behavior is more nearly linear than compression load-deflection behavior. The linear behavior allows a better design estimate of the performance of shear-loaded components than components loaded in compression.

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5.2.5 The calculated deflections in Table XV clearly show the difference in shear and compression deformation of a one-inch (25.4-mm) rubber cube subjected to a 50-pound (222-N) load. For the softest compounds, the ratio of deflections obtainable in shear and compression is 8:1. Energy absorbed during shear and compression loading is approximately in the same 8:1 ratio.

5.2.6 Where larger deflections are desired, two sandwiches may be used in series (Figure 45). The total deflection is then the sum of the individual deflections for the load applied. Such a sandwich makes it possible to use small d/t ratios, which assure unit performance according to shear theory predictions. However if more than two sandwiches are used, instability is likely to result. Furthermore, the use of sandwich structures has the advantage that the unit is considerably stiffer in a direction perpendicular to the shear load.

5.2.7 Many variations from the basic shapes (shown in Figures 41, 42 and 45) are used. By altering the pad depth or the load area so that one or both vary along the width, desirable load deflection characteristics may be achieved. Deflection characteristics of some basic configurations have been tabulated in Figures 46 through 48, but many others are feasible.

5.2.8 Figures 46 through 48 include equations for spring rate, shear stress, and rubber volume. Symbols used in these figures are as follows:

- A = Shear Area, sq. in. (mm^2),
- F = Load, lb (N),
- G = Modulus of elasticity in shear, psi (MPa),
- K_L = Nominal linear spring rate, lb/in. (N/mm),
- K_T = Nominal torsional spring rate, lb-in./deg ($\text{N}\cdot\text{m}/\text{rad}$),
- L = Length, in. (mm),
- R = Radius, in. (mm),
- S_L = Linear shear stress, psi (MPa),
- S_T = Torsional shear stress, psi (MPa),
- V = Volume of rubber, cu in. (mm^3),
- ϕ = Shear strain angle, deg (rad)
- θ = Torsional deflection, deg (rad)

5.2.9 Observe that all formulas use the modulus of elasticity which is assumed to have a constant slope and to pass through the origin. The modulus curves in Figure 49 have been developed by taking tangents along points on the stress-strain curve. They do not pass through the origin, and the curve shows that the modulus is not constant. Therefore, results obtained by using values from the curves will be approximate. A more accurate, though time consuming, method is to use an analytical expression, such as that in Eq. 30, for the stress-strain relationship.

5.2.10 For many rubbery materials the modulus in extension is different from that in compression. One of the reasons for this difference is that the cross-sectional area is decreased as tension increases. It is often found that the modulus derived from the true stress (the tension force divided by the deformed

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cross-sectional area) vs. strain curve is nearly independent of strain and also agrees closely with that determined from compression experiments.

5.2.11 The deformed cross-sectional area is given by the undeformed one divided by the extension ratio (L/L_0) in uniform extension of incompressible materials such as elastomers.

TABLE XV. DEFLECTION IN SHEAR AND COMPRESSION

Hardness, Durometer A	Deflection in Shear	Deflection in Compression	Ratio
	Inch	Inch	
30	1.6	0.2	8
40	0.9	0.14	6.5
50	0.6	0.08	7.5
60	0.4	0.08	5
70	0.3	0.06	5
80	0.08	0.04	2
	mm	mm	
30	40.6	5.1	8
40	22.9	3.6	6.5
50	15.2	2.0	7.5
60	10.2	2.0	5
70	7.6	1.5	5
80	2.0	1.0	2

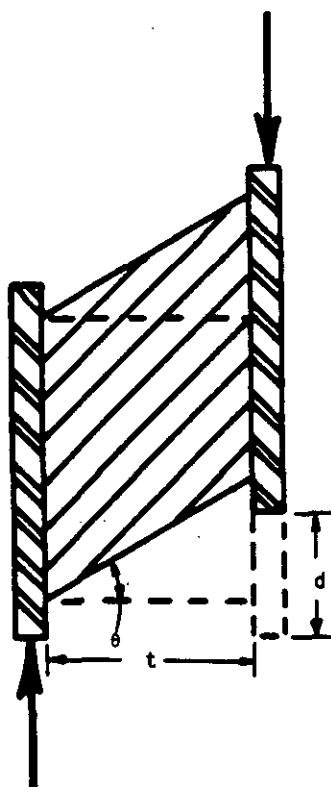


FIGURE 41. SINGLE SHEAR SANDWICH (64)

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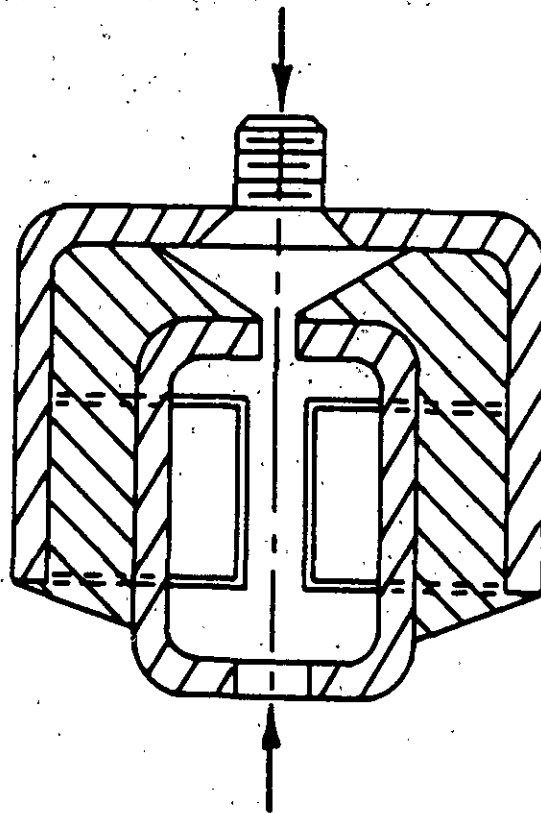
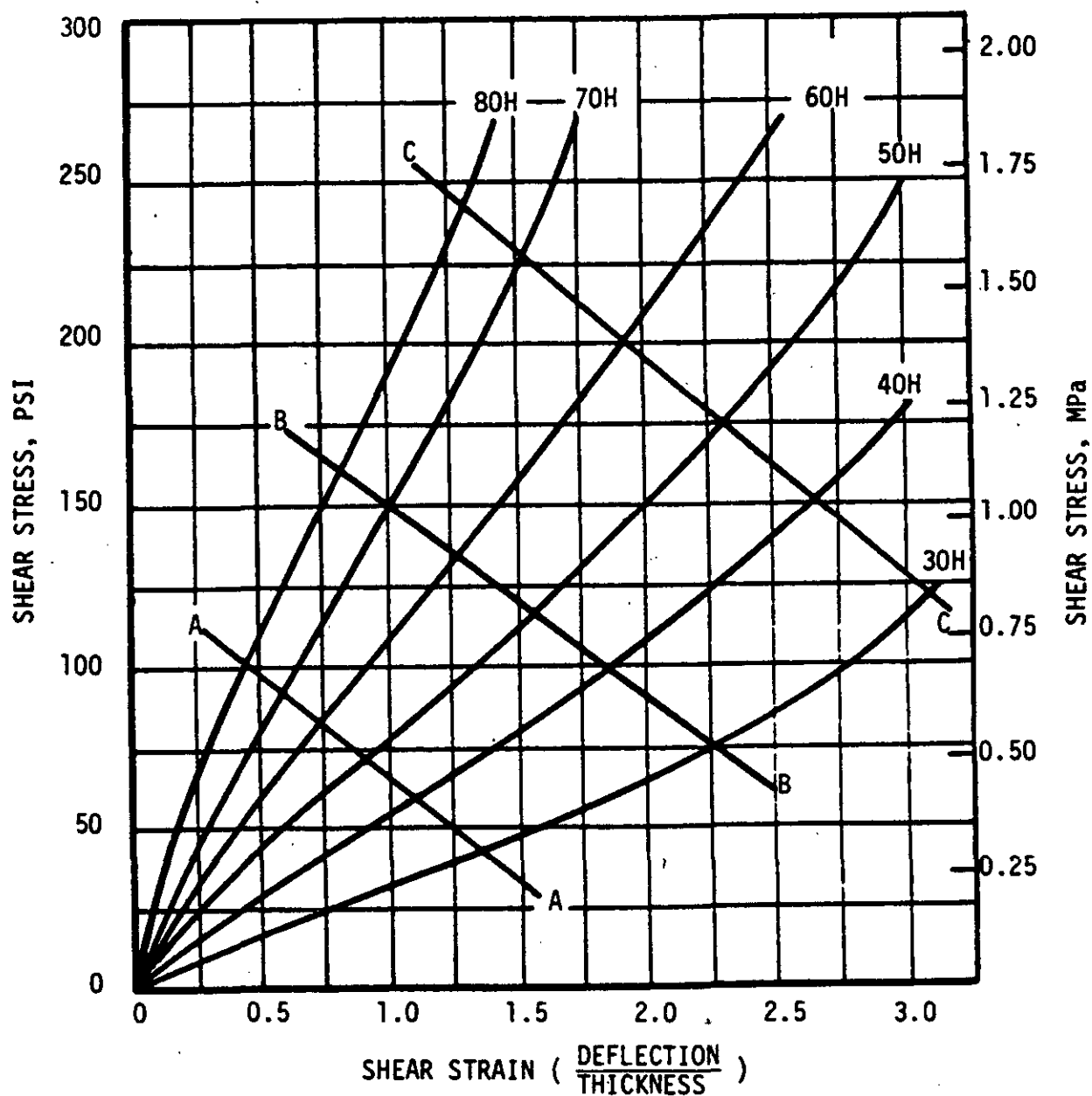


FIGURE 42. BALANCED DOUBLE SHEAR SANDWICH (64).

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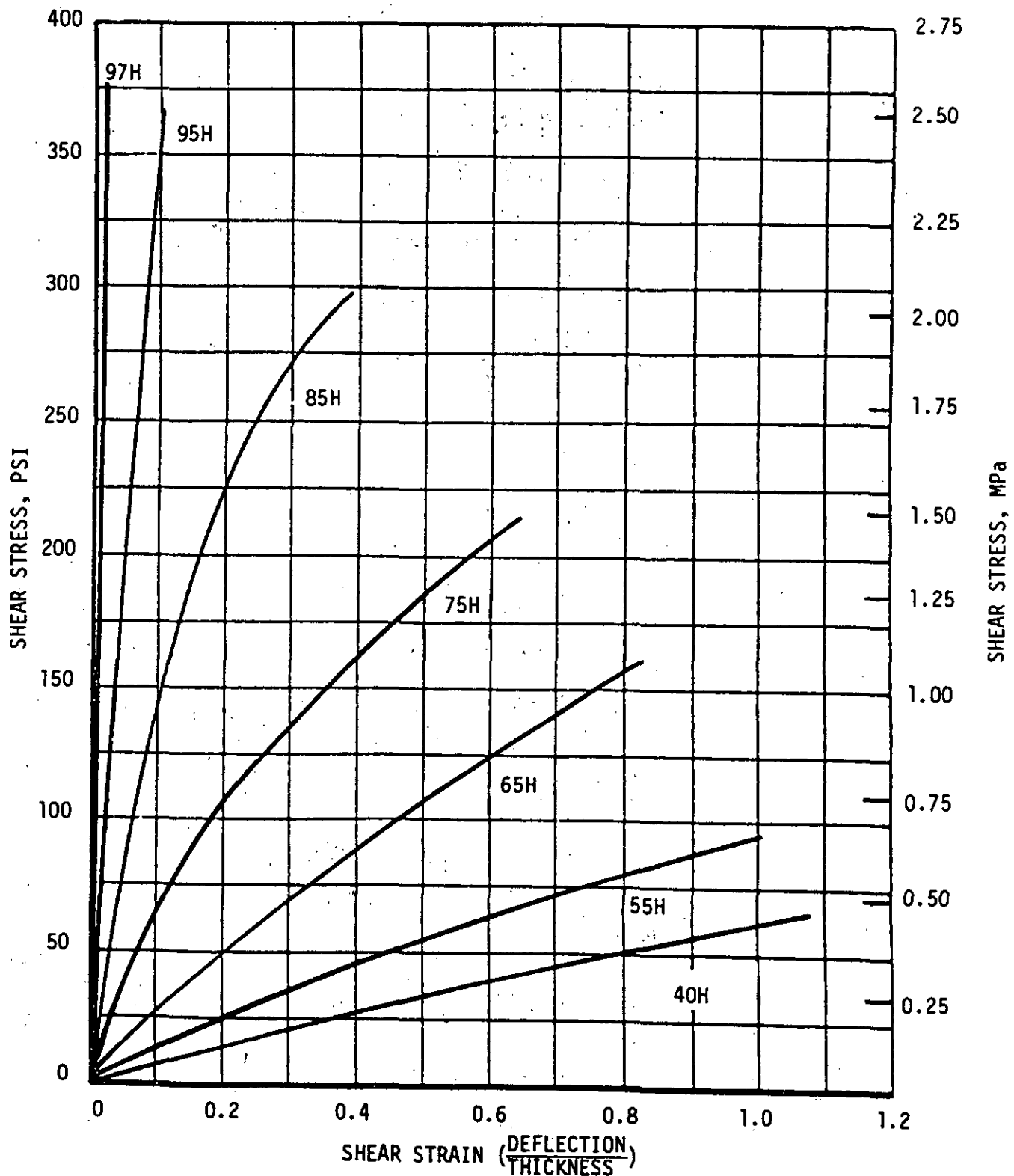


	LINEAR SHEAR MOVEMENT	ROTATIVE SHEAR MOVEMENT
LIMITS FOR CONTINUOUS OR FREQUENT LOADING	LINE A--A	LINE B--B
LIMITS FOR OCCASIONAL LOADING	LINE B--B	LINE B--B

H REPRESENTS DUROMETER A HARDNESS

FIGURE 43. SHEAR STRESS-STRAIN CURVES FOR NATURAL AND CHLOROPRENE RUBBERS (37)

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H REPRESENTS DUROMETER A HARDNESS

FIGURE 44. SHEAR STRESS-STRAIN CURVES
FOR POLYURETHANE RUBBER (30)

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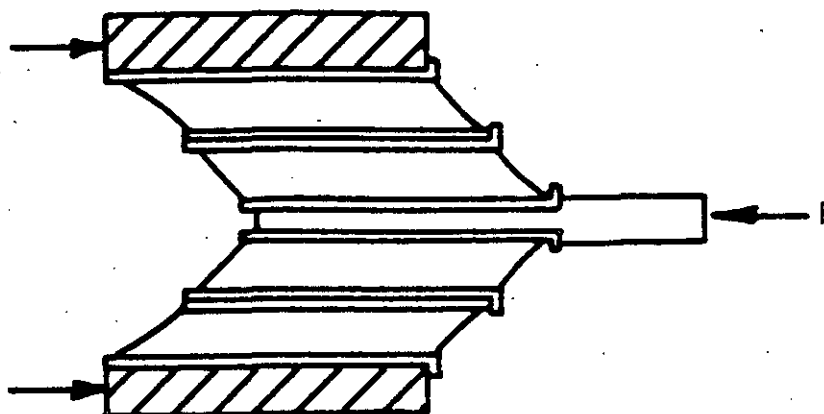


FIGURE 45. TWO SHEAR SANDWICHES IN SERIES, BALANCED DESIGN (64)

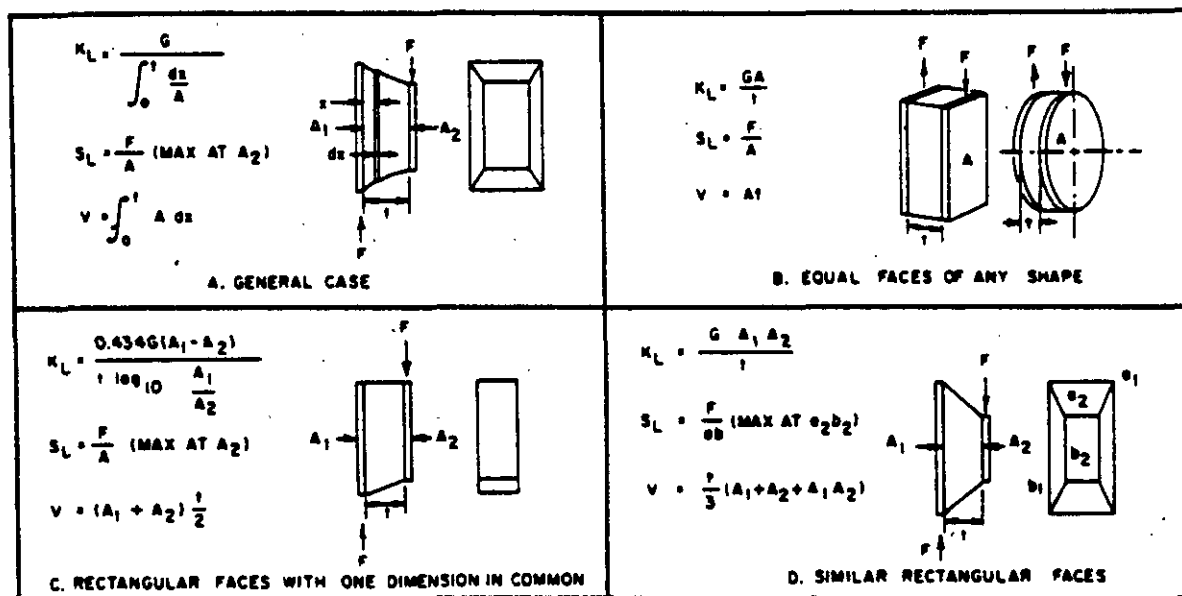


FIGURE 46. PLANE SHEAR SANDWICHES (37)
(See 5.2.8 for legend)

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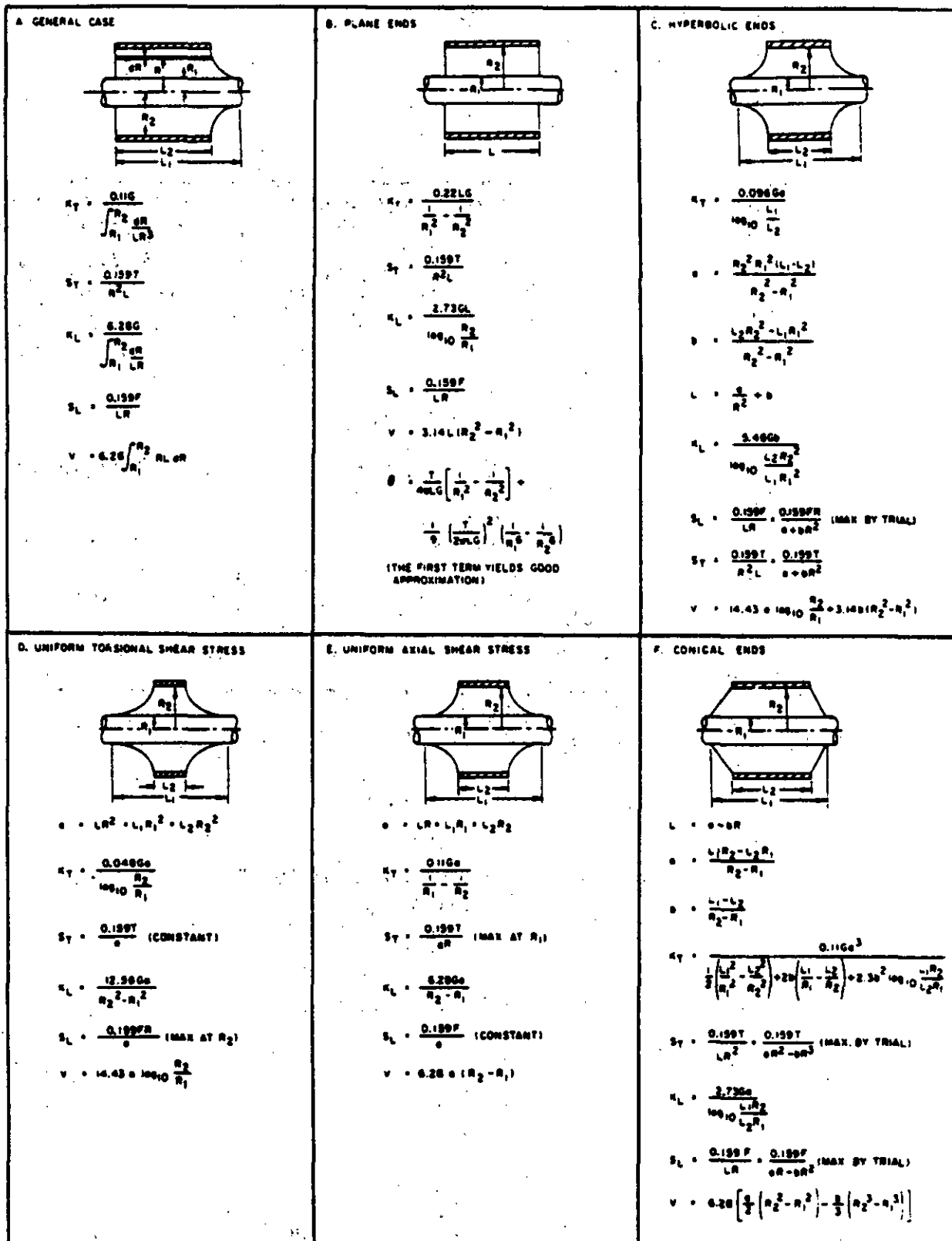


FIGURE 47. BUSHINGS UNDER AXIAL AND TORSIONAL SHEAR (37)
(See 5.2.8 for legend)

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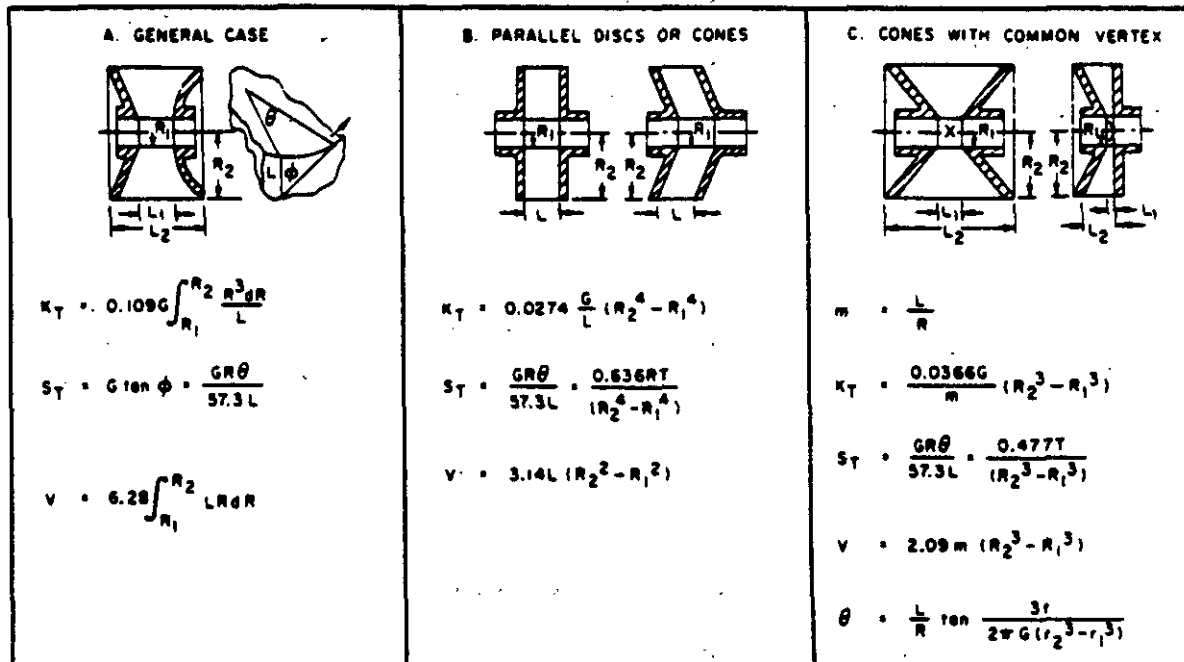


FIGURE 48. DISK TYPE SHEAR UNITS (37)
(See 5.2.8 for legend)

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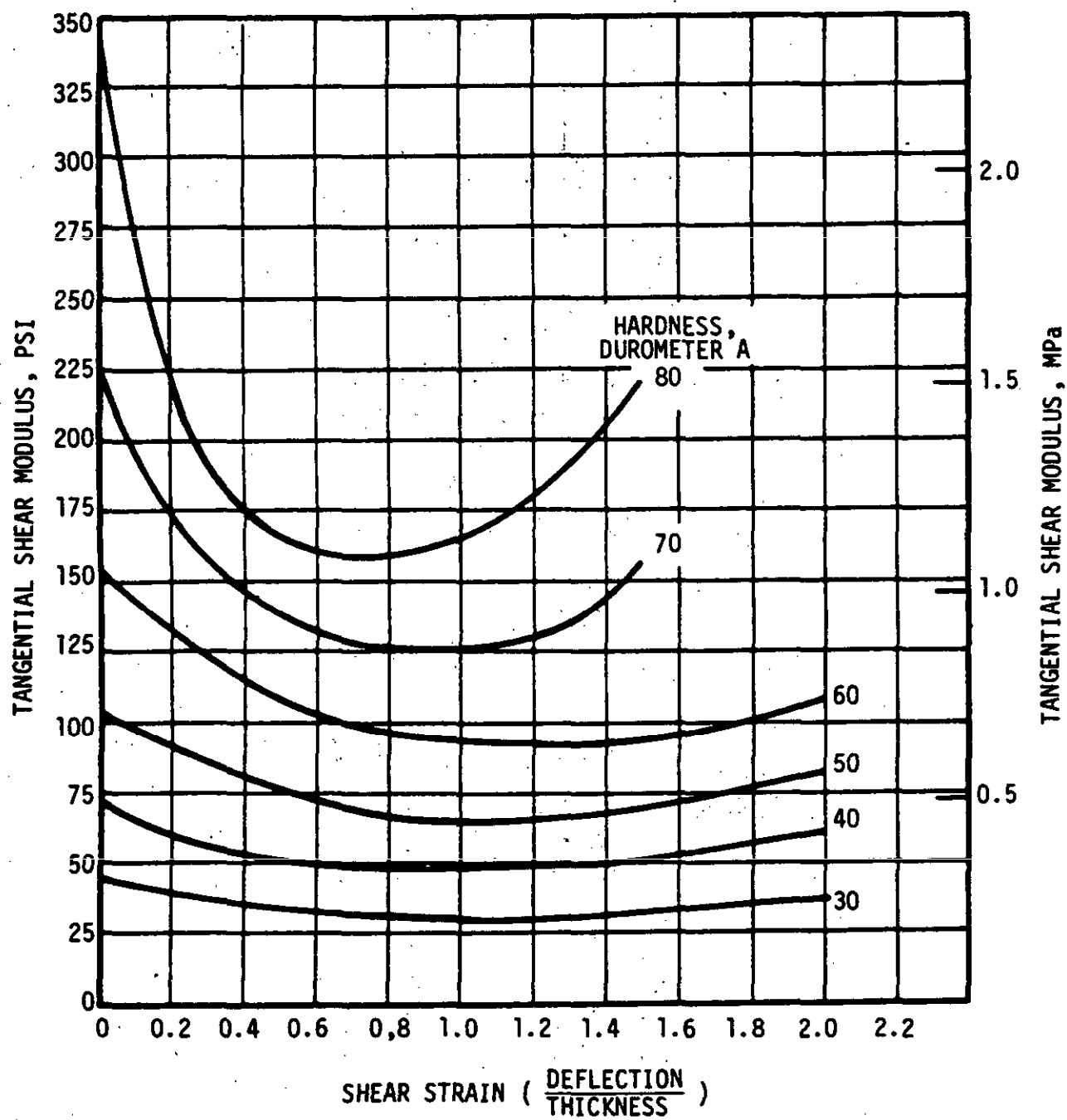


FIGURE 49. STATIC TANGENT SHEAR MODULUS (37)

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5.3 Equations for Determining Static Shear Modulus. By Equation 30, a realistic shear modulus is determined which can be used in calculating the properties of shear sandwiches. This equation was developed from empirical stress-strain curves.

$$d/t = D = a_1 S + a_2 S^2 + a_3 S^3 \quad \text{Eq. 30}$$

where,

D = the deflection per unit thickness

S = the stress

$a_1 a_2 a_3$ = constants listed in Table XVI

5.4 Radial Loading of Bushings. When a bushing is loaded in a radial direction (Figure 50), the top part of it will be in compression and the bottom part in tension. Treating the bushing as a compression member with a modified shape factor, the following empirical method of calculating shape factor has been proposed.

$$\text{Load Area} = 3/2 \text{ rubber ID} \times \text{length} \quad \text{Eq. 31}$$

$$\text{Bulge Area} = 2/3 \text{ area of free ends} + 2/3 (\text{OD-ID}) \times \text{length} \quad \text{Eq. 32}$$

The force deflection characteristics are then determined from the shape factor curves (see Eq. 33 in 5.6.2).

5.5 Design Recommendations for Shear Sandwiches.

5.5.1 Shear sandwiches should be designed so the free sides are initially inclined and become square when fully deflected. The application of a shearing force will then put the bonded surface in compression, rather than in tension where it may be subjected to peeling effects.

5.5.2 If the thickness of the sandwich exceeds 25 percent of the lateral dimension, the deformation is a combination of shear and bending. The bending deformation reduces the predicted shear stiffness and has to be analyzed using the standard equations for the bending of beams. The stiffness of a shear sandwich is decreased by an increased compression for the reasons given in 5.11.2.

5.5.3 Shear sandwiches should be installed with an initial compression of 10 to 15 percent. This decreases the stiffness only slightly and provides additional support for the bonded surfaces.

5.5.4 Shock loads should be allowed to develop stresses no greater than 50 psi (0.3 MPa).

5.5.5 Bond stresses on torsional bushings are highest on the inner shell and should not exceed 100 to 120 psi (0.7 to 0.8 MPa). Stress concentrations are also more influential at this point, and should be minimized by the application of shaped end contours.

5.5.6 Torsion bushings are usually made with an outer split shell as shown in Figure 51. This prevents shrinkage stresses from being set up after molding, permits some compression of the bushing upon installation, and affords additional support to the bonded surface. Rubber less than 50 Durometer A hardness is not recommended for use in torsion springs.

5.5.7 Torsion springs may be applied in series. If a common shaft is used, the spring rates are additive, the stiffness of the combination is that of the sum of the two springs.

5.6 Compression Design

5.6.1 For rubber in compression, the stress-strain relationship depends not only on the mechanical properties of the material, but also on the shape of the piece and in particular on the relative sizes of the loaded and free rubber areas. Since rubber is virtually incompressible, compression in one direction results in extension in the other two principle directions, the effect of which is bulging of the free sides. Free bulging is particularly promoted in parts having relatively large perimeters which act in a softer fashion, that is, deflecting more under equal load than a piece having the same loaded area but a shorter perimeter (square shape).

5.6.2 The bulging of a bonded rubber block is due to the fact that rubber is incompressible. This bulging gives rise to an internal pressure which contributes to the load carrying capacity of the block. The relations between this pressure, the properties of the rubber, and the shape of the block have been derived theoretically. This theory predicts that bonded rubber blocks have the same stress-strain properties in compression irrespective of size as long as they have the same shape factor for a given geometry. The shape factor is defined as:

$$\text{Shape Factor} = \frac{\text{One Loaded Area}}{\text{Total Free Area}} \quad \text{Eq. 33}$$

5.6.3 The geometry (form of cross-section) of the block affects the stress-strain properties to a lesser extent. As a first approximation this effect may be ignored.

5.6.4 Bubbles inside the rubber block or holes in the plates which permit additional bulging away from the free surfaces reduce the shape factor significantly, thus the stiffness of the blocks. The pertinent areas are indicated in Figure 52.

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5.6.5 Figures 53 through 58 present the stress-strain curves for natural rubber. Shape factor values on each curve are for use with the rubber of the hardness range indicated. The stress values, plotted as the dependent variable, are in the conventional psi (MPa) units. Strain, on the other hand, is not in the usual in./in. (mm/mm) units; rather, it is in terms of percent of compression of the original, unloaded rubber thickness. These curves may be used with reasonable success for other rubber types with the exception of the polyurethanes and polysulfides. Similar curves for the polyurethanes are presented in Figures 59 through 62. Figure 63 shows compressive stress-strain curves for polysulfide rubber of various hardnesses. The natural rubber curves (Figures 53 through 58) indicate stress limits for continuous loading as well as for occasional load application. These curves are only applicable to rubber sandwiches in which the rubber is prevented from spreading on the loaded surfaces. This is done either by the usual rubber-to-metal bonding or by corrugation in the rubber-metal contact surfaces. In addition, the curves are limited to sandwich construction with parallel loaded surfaces.

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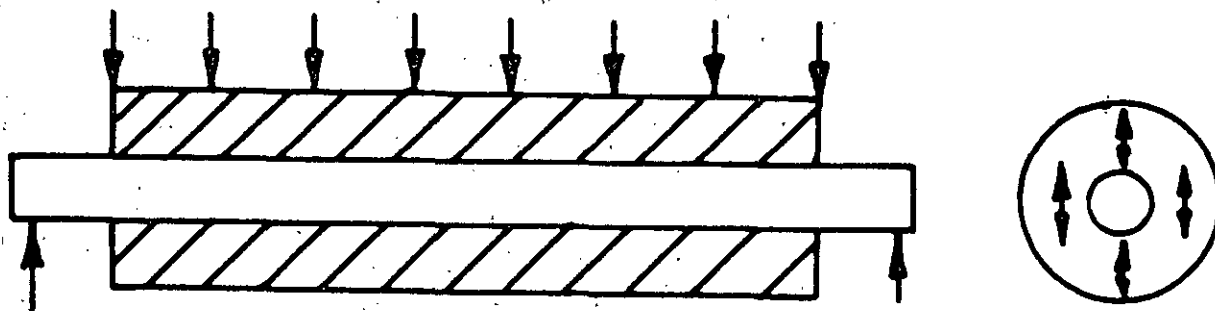


FIGURE 50. BUSHING UNDER RADIAL LOADING

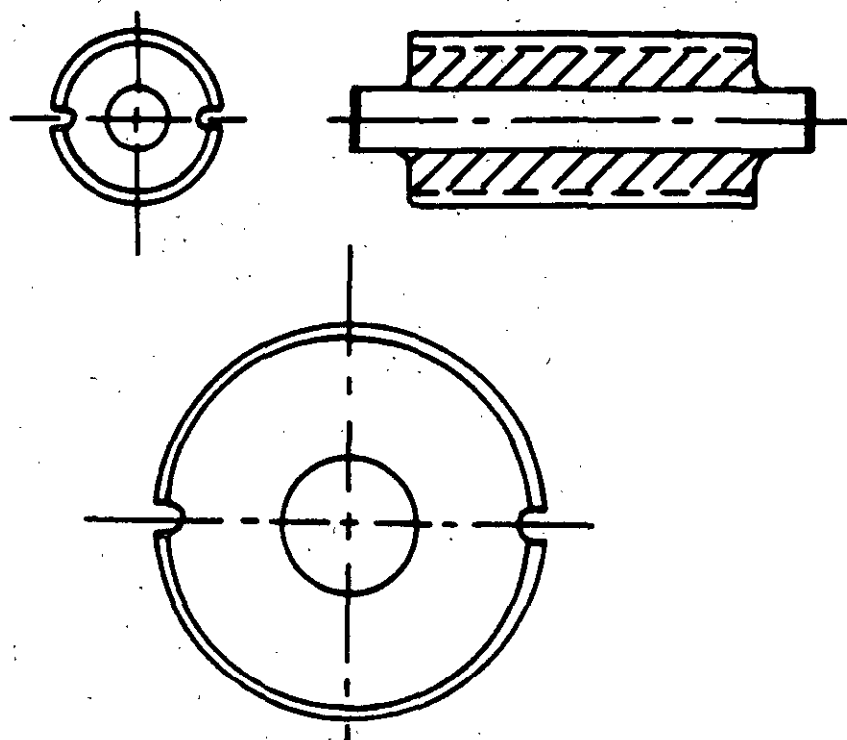


FIGURE 51. RUBBER BUSHING WITH SPLIT OUTER SHELL (55)

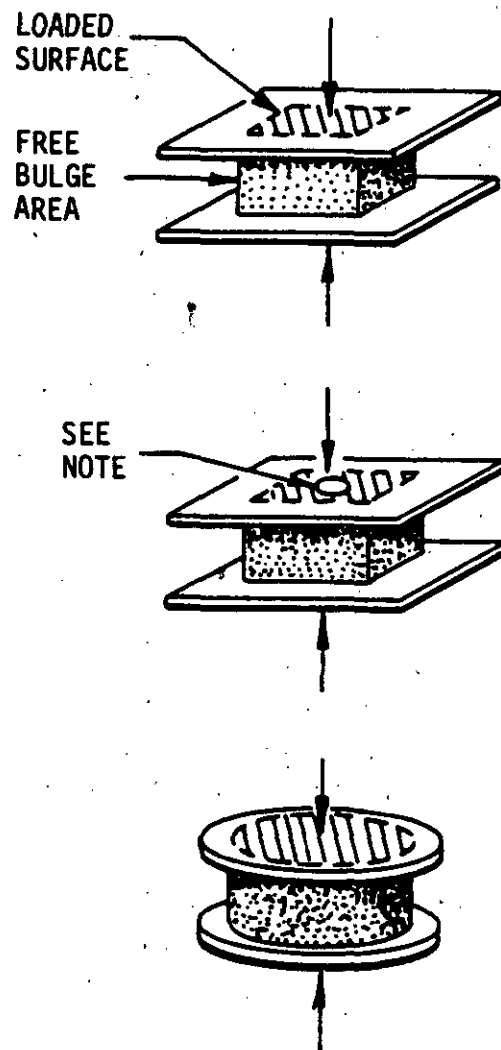
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TABLE XVI. CONSTANTS FOR SHEAR-STRESS-STRAIN EQUATION^{1/}

Hardness, Durometer A	a ₁	a ₂	a ₃
30	3.174 x 10 ⁻²	2.890 x 10 ⁻⁵	-6.645 x 10 ⁻⁷
40	1.577 x 10 ⁻²	6.745 x 10 ⁻⁵	-3.565 x 10 ⁻⁷
50	1.0225 x 10 ⁻²	4.552 x 10 ⁻⁵	-1.648 x 10 ⁻⁷
60	7.701 x 10 ⁻³	2.192 x 10 ⁻⁵	-6.151 x 10 ⁻⁸
70	4.644 x 10 ⁻³	2.491 x 10 ⁻⁵	-6.970 x 10 ⁻⁸
80	2.527 x 10 ⁻³	2.523 x 10 ⁻⁵	-5.497 x 10 ⁻⁸

^{1/}See 5.3 and Equation 30

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NOTE: The hole reduces the shape factor significantly more than would be accounted for by subtracting the hole's area from that of the plate.

FIGURE 52. COMPRESSION SANDWICHES

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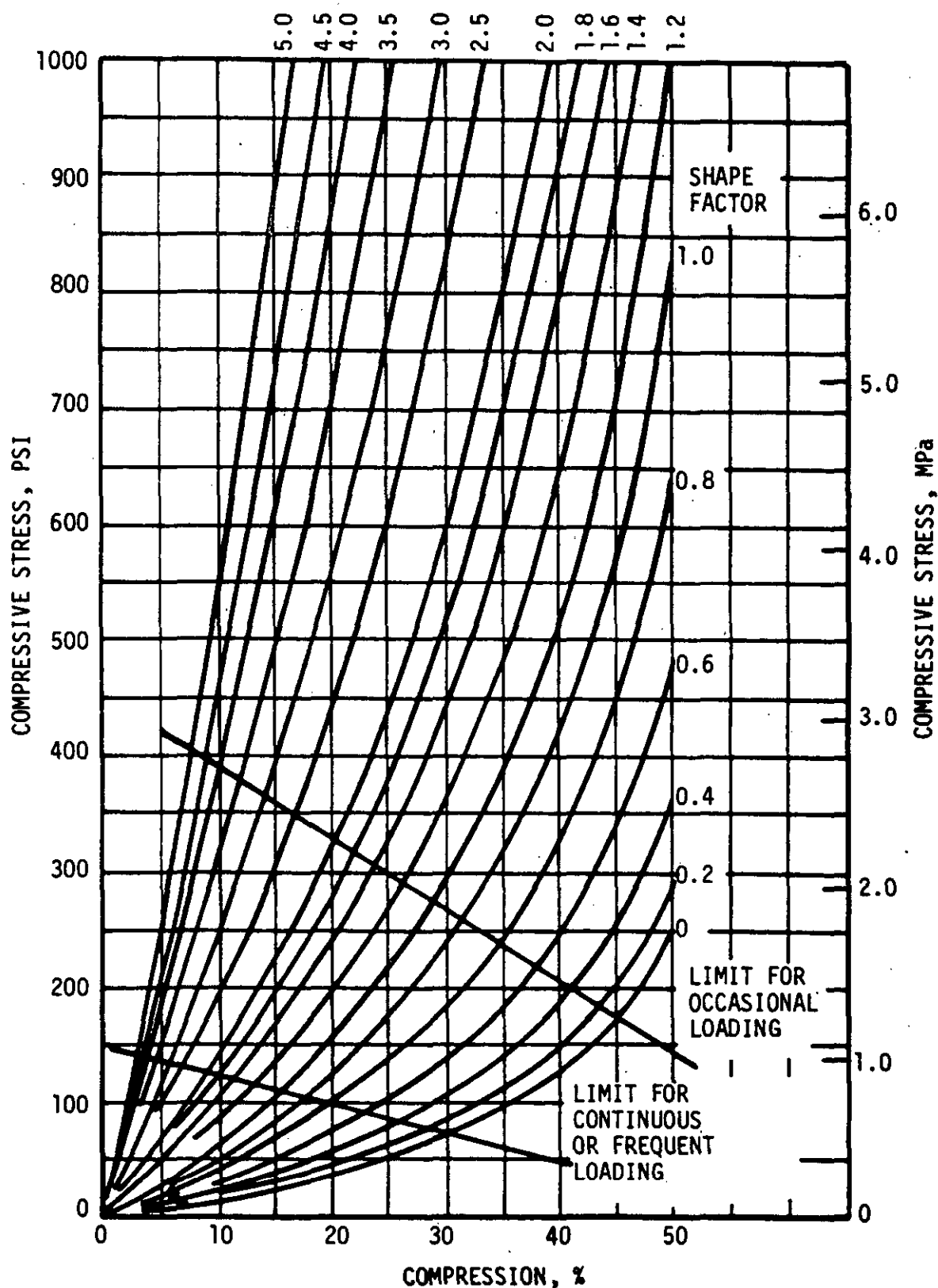


FIGURE 53. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 30 DUROMETER A NATURAL RUBBER (37)

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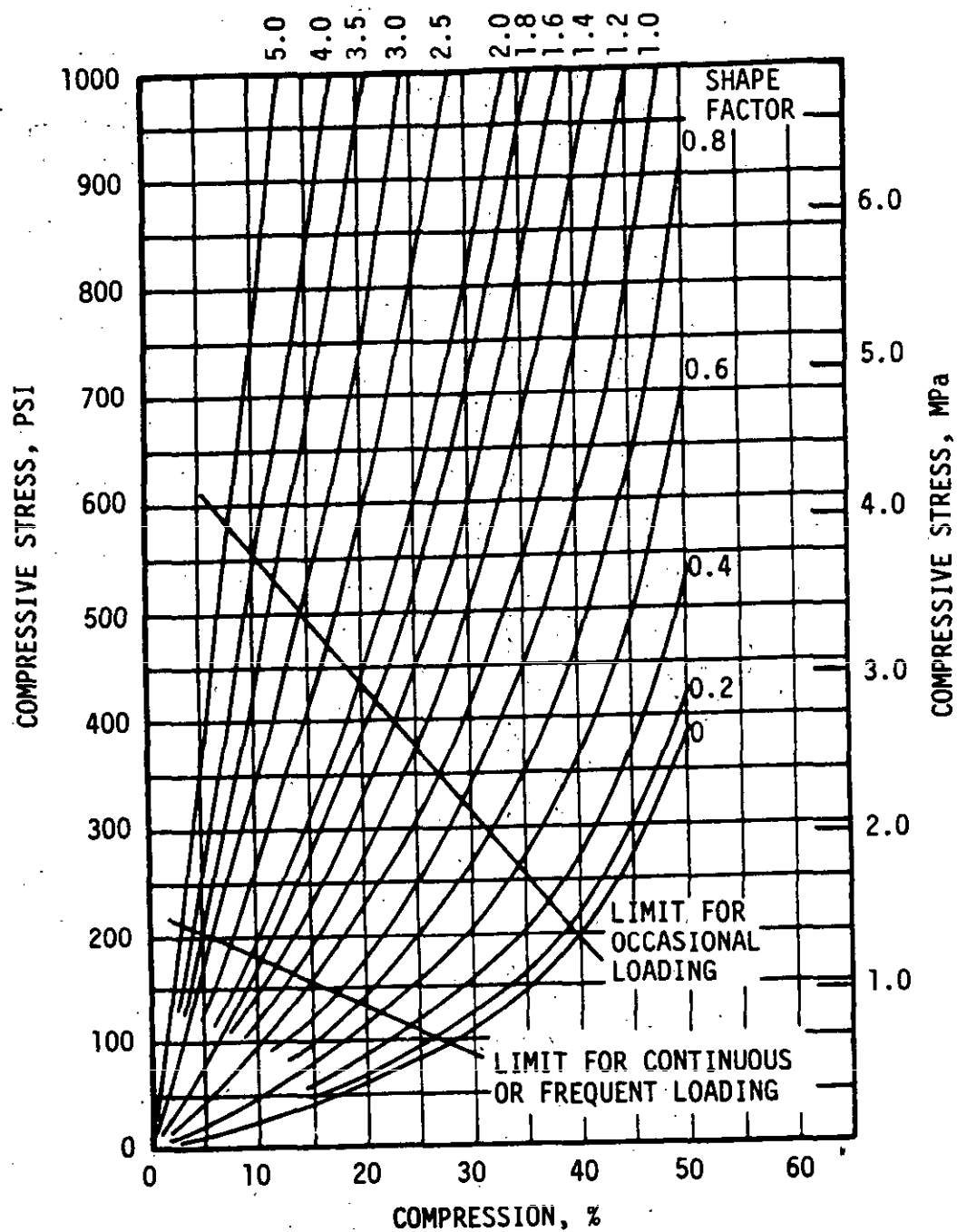


FIGURE 54. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 40 DUROMETER A NATURAL RUBBER (37)

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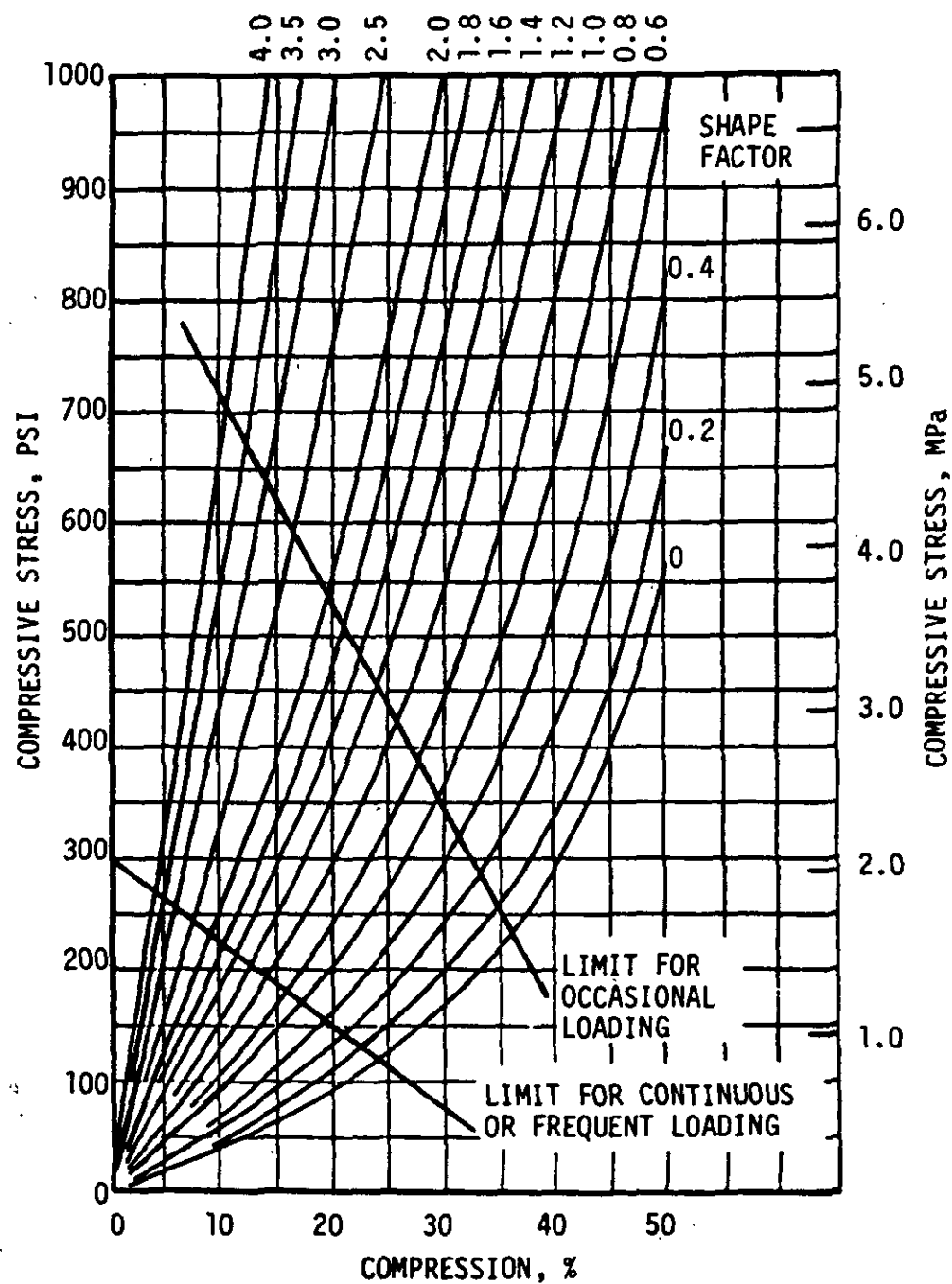


FIGURE 55. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 50 DUROMETER A NATURAL RUBBER (37)

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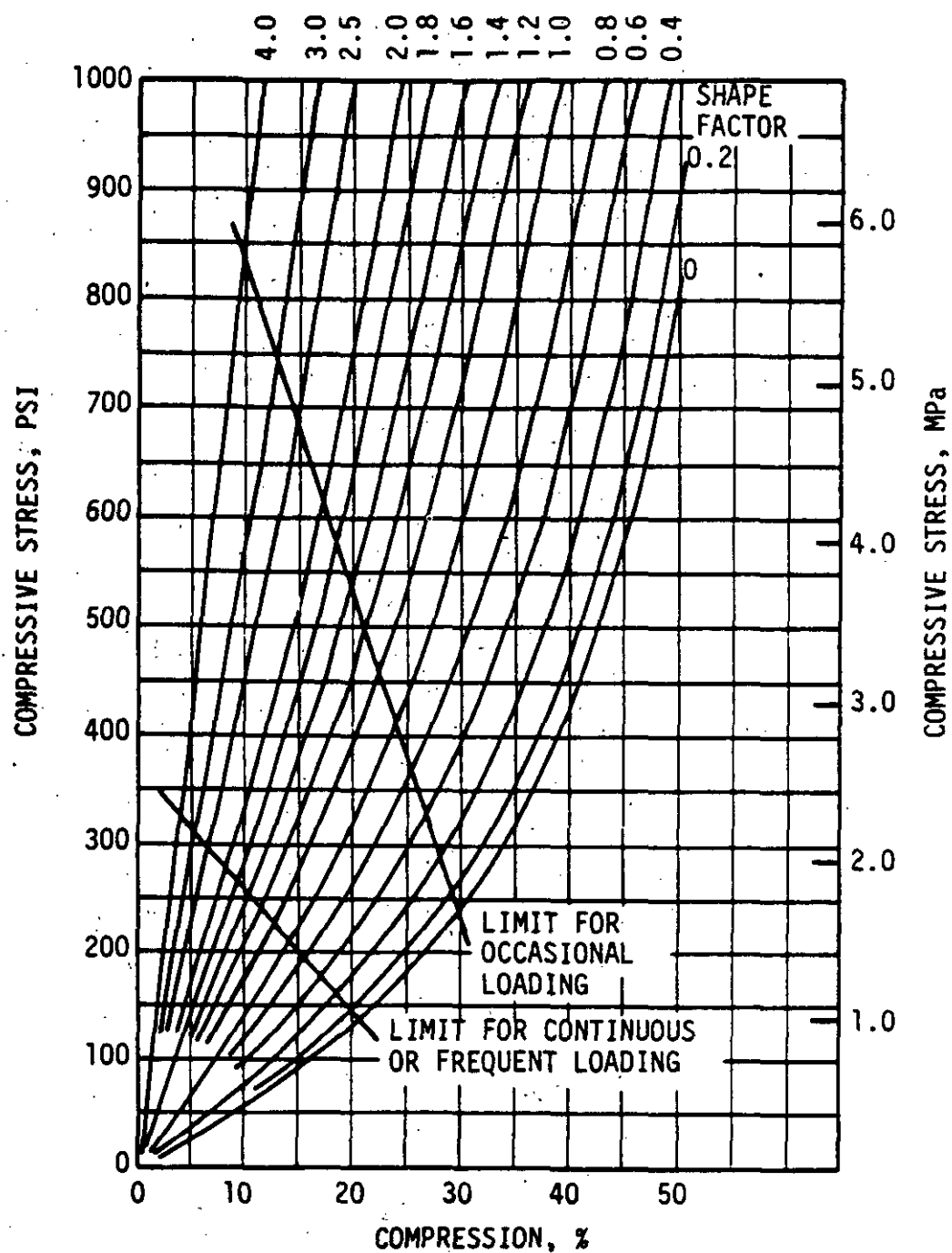


FIGURE 56. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 60 DUROMETER A NATURAL RUBBER (37)

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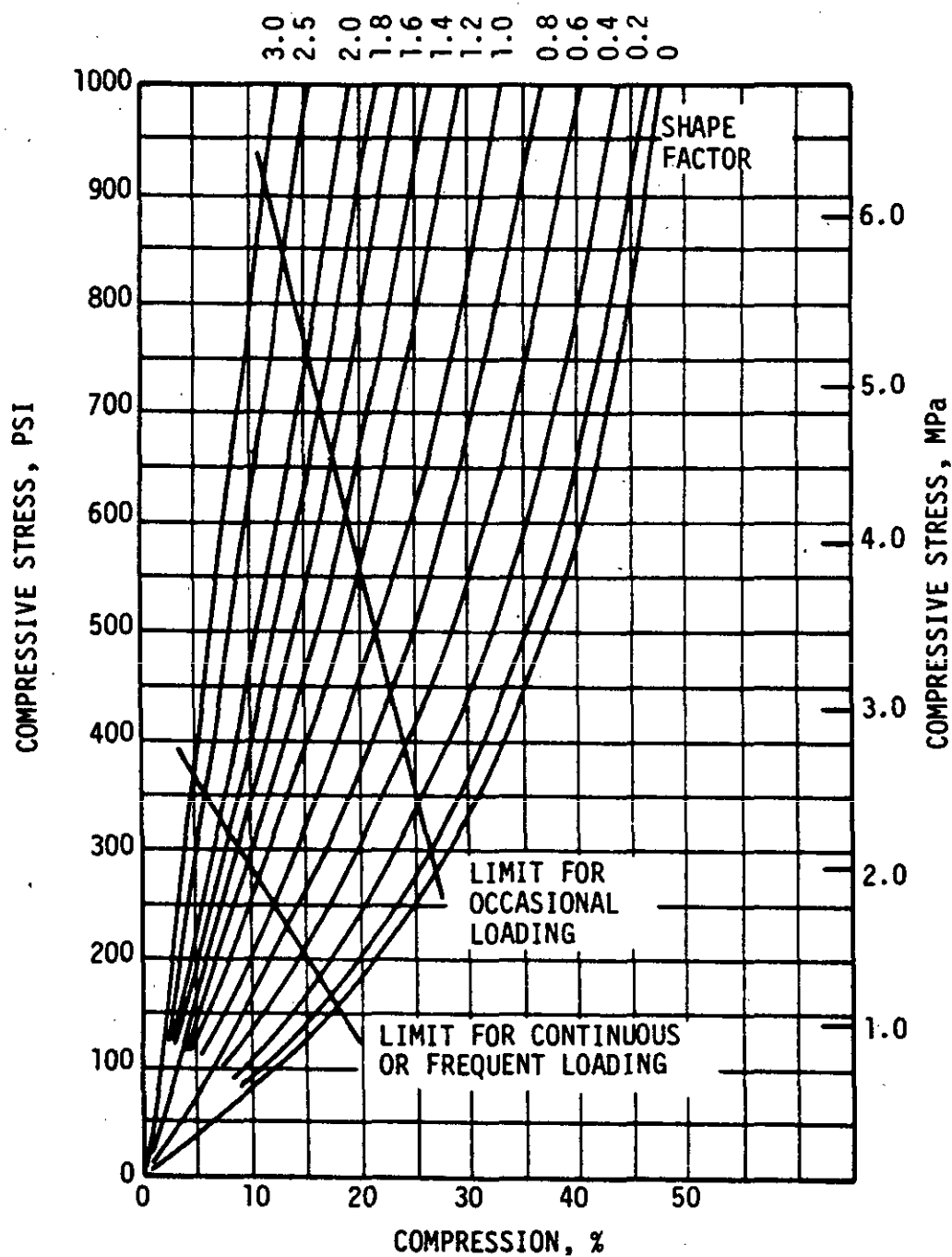


FIGURE 57. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 70 DUROMETER A NATURAL RUBBER (37)

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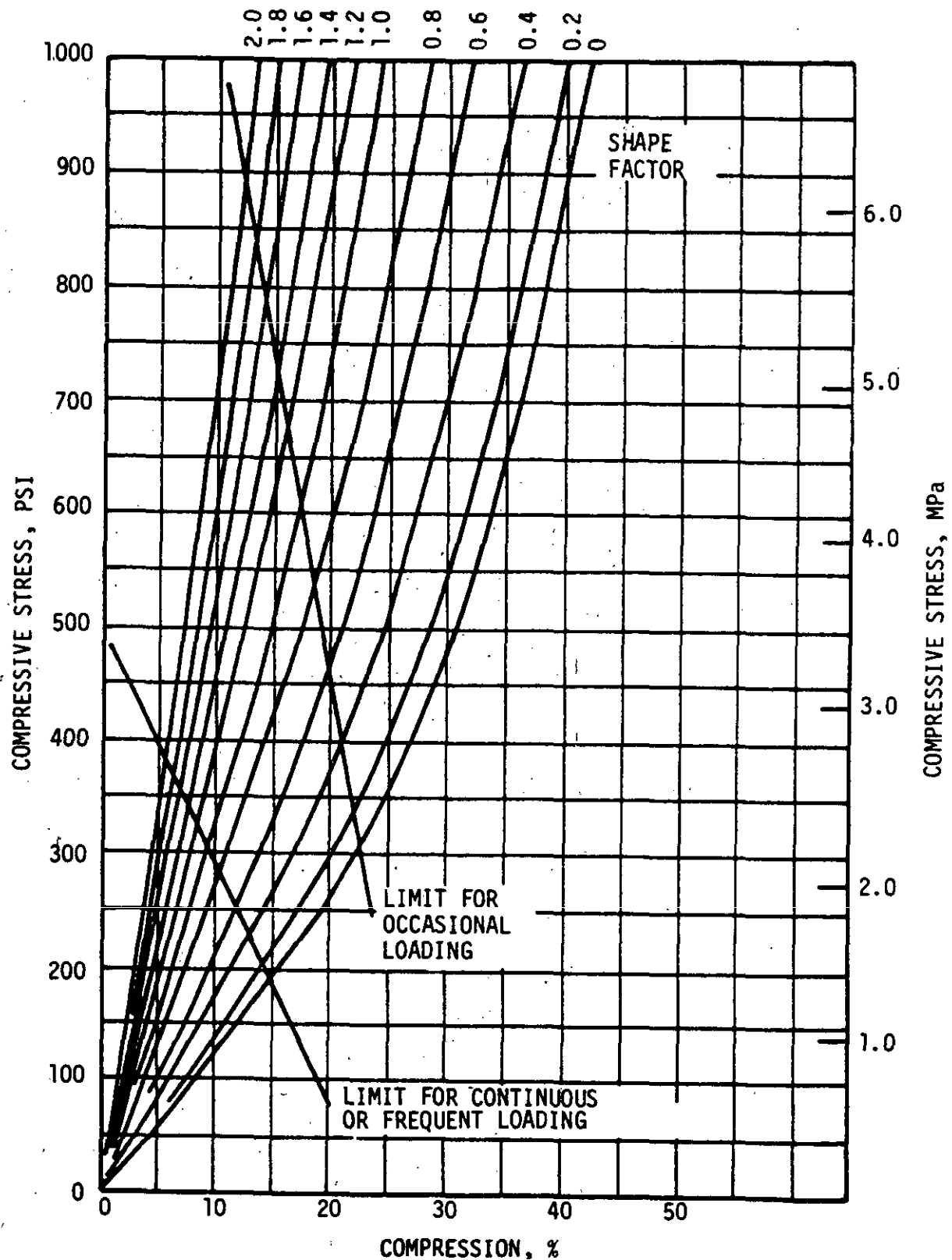


FIGURE 58. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 80 DUROMETER A NATURAL RUBBER (37)

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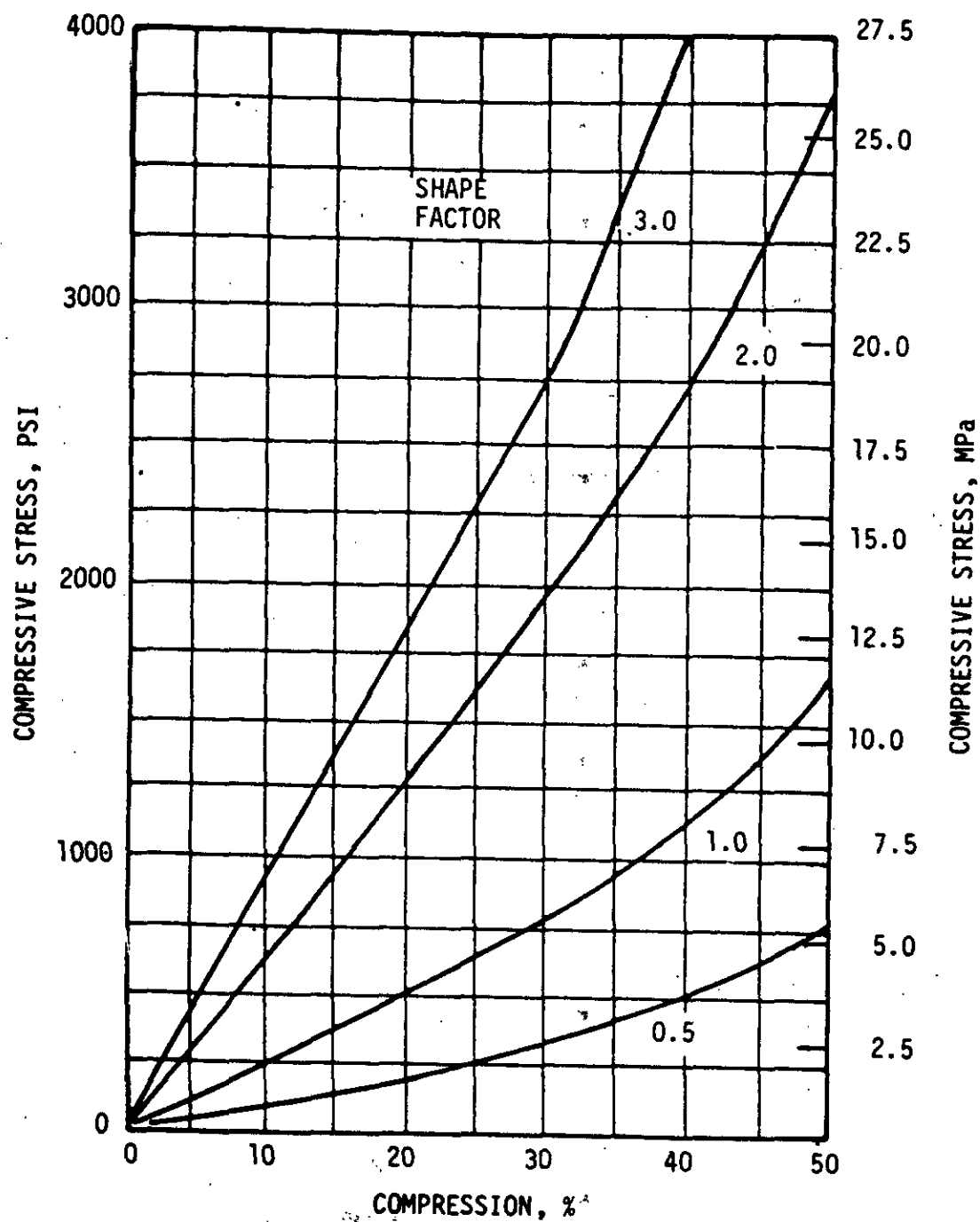


FIGURE 59. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 60 DUROMETER A POLYURETHANE RUBBER (30)

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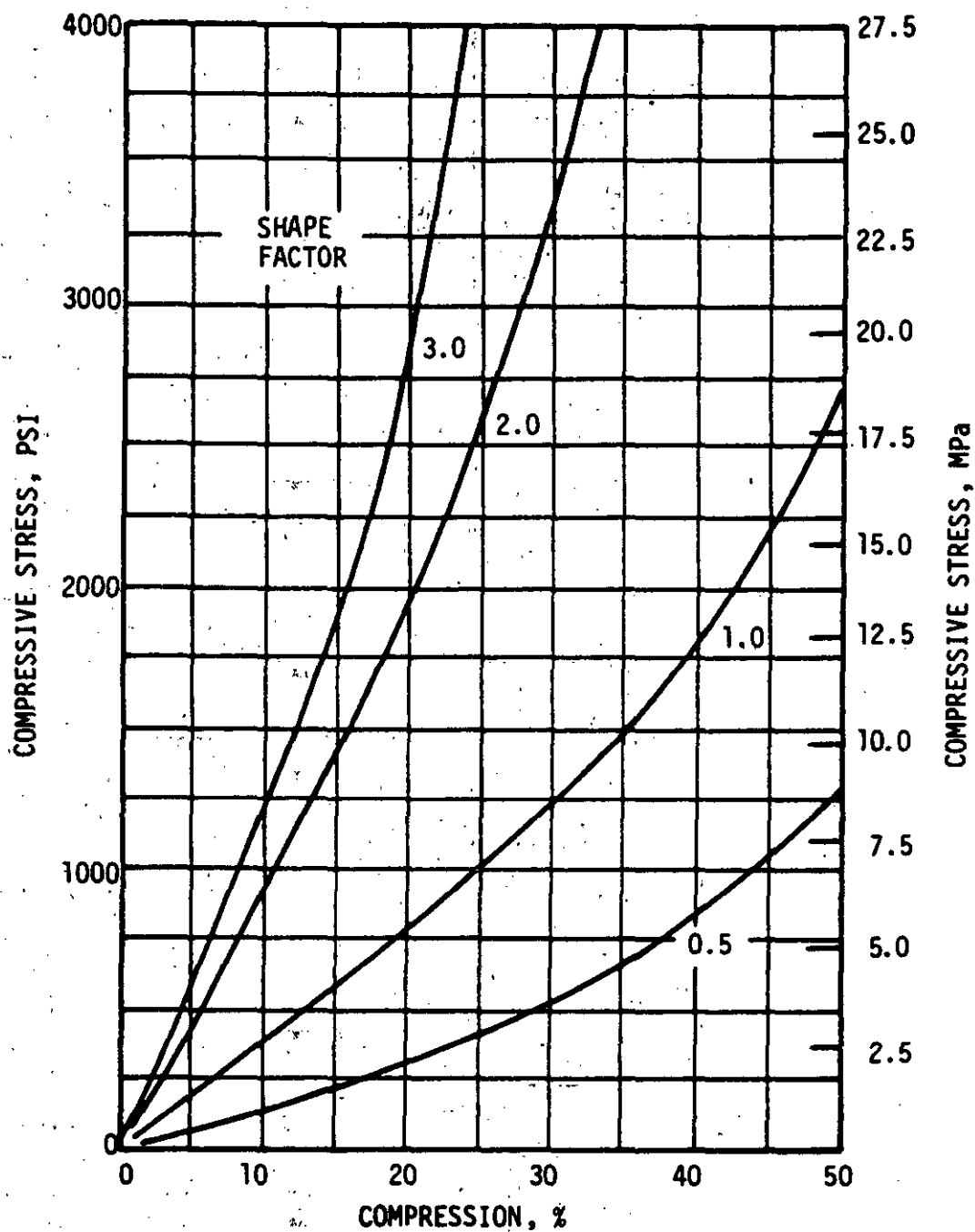


FIGURE 60. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 70 DUROMETER A POLYURETHANE RUBBER (30)

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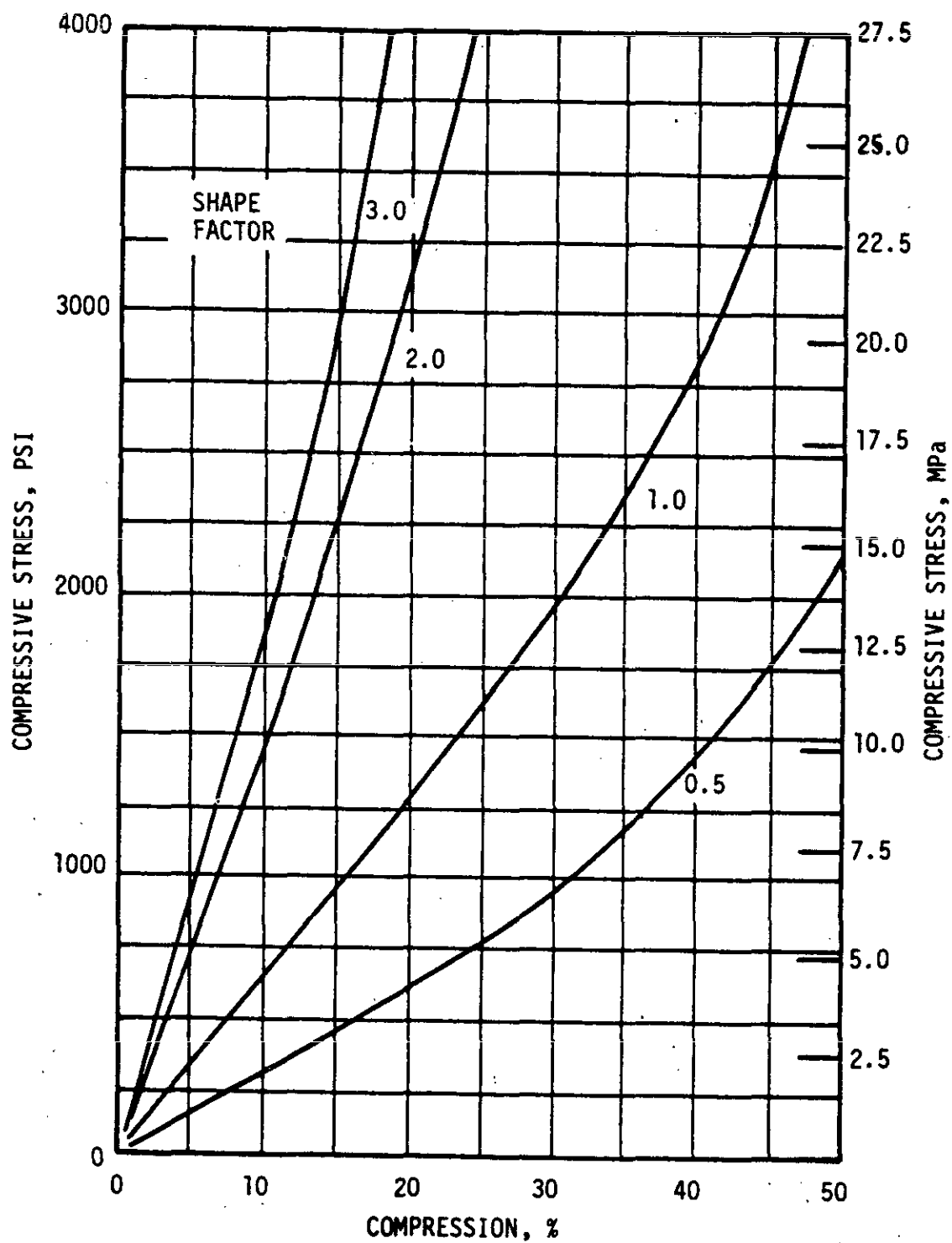


FIGURE 61. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 80 DUROMETER A POLYURETHANE RUBBER (30)

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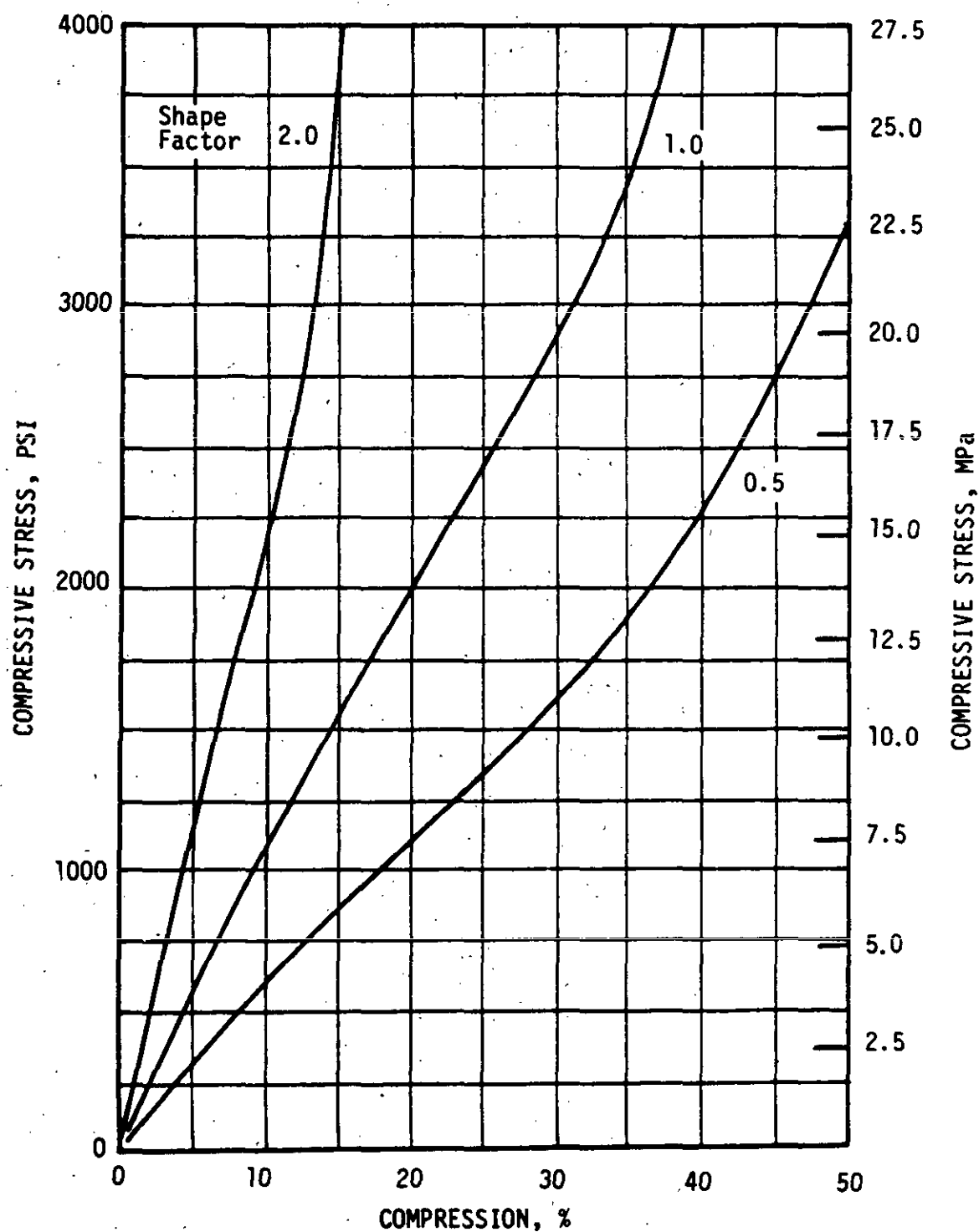


FIGURE 62. SHAPE FACTOR AND COMPRESSION STRESS-STRAIN CURVES, BONDED 90 DUROMETER A POLYURETHANE RUBBER (30)

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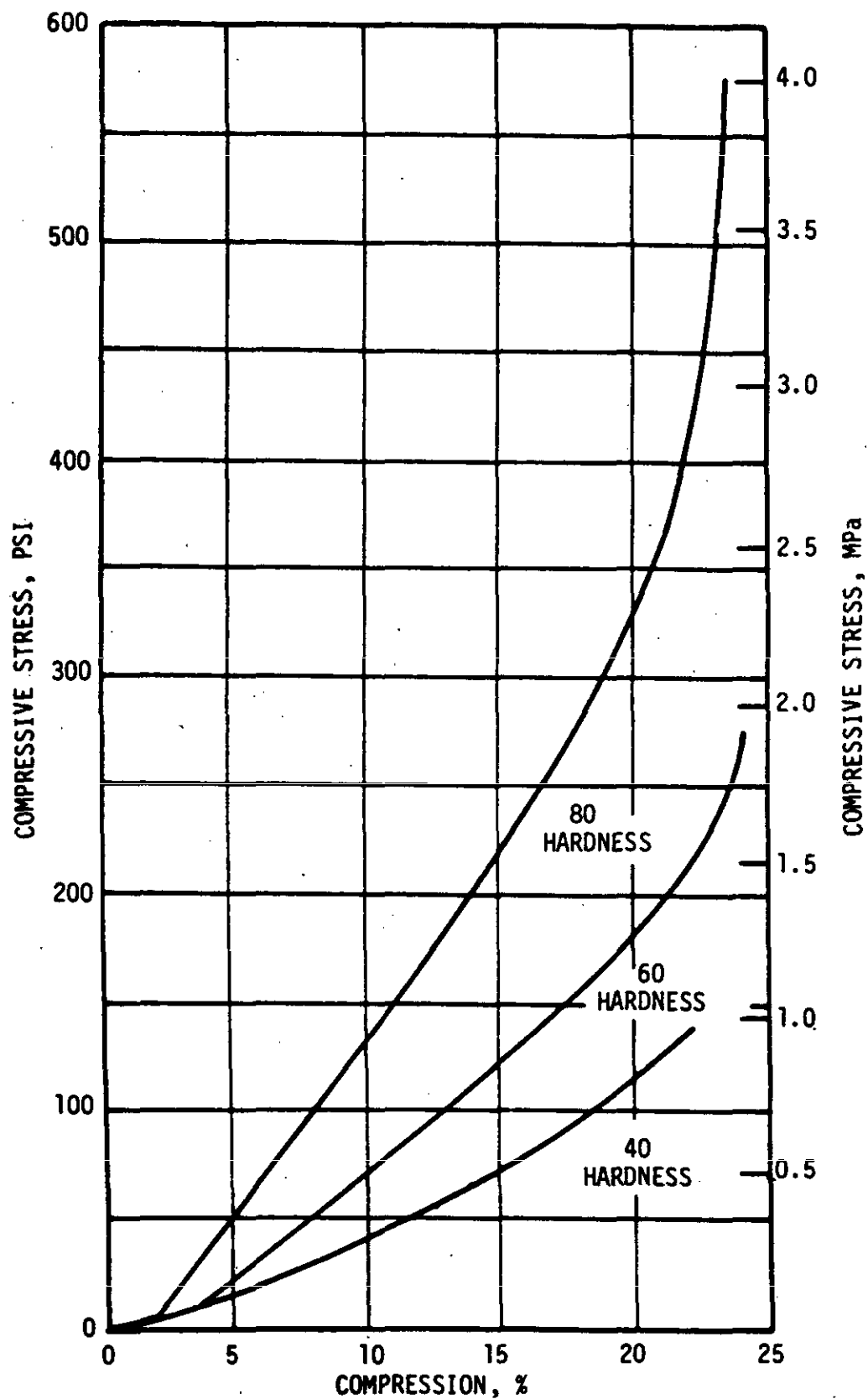


FIGURE 63. COMPRESSION STRESS-STRAIN CURVES FOR VARIOUS HARDNESSES OF POLYSULFIDE RUBBER (76)

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5.7 Compound Sandwiches

5.7.1 The load deflection characteristics of a rubber compression block may be altered by breaking up the thickness into several sandwiches in series as shown in Figures 64 and 65. Using Equation 33 in 5.6.2, the example in Figure 64 has a shape factor of:

in inches	in millimetres
$\frac{2 \times 2}{4(2 \times 1)} = 0.5$	$\frac{50 \times 50}{4(50 \times 25)} = 0.5$

whereas Figure 65 consists of two sandwiches, each having a shape factor of:

in inches	in millimetres
$\frac{2 \times 2}{4(2 \times 0.5)} = 1.0$	$\frac{50 \times 50}{4(50 \times 12.5)} = 1.0$

5.7.2 A double sandwich made from a 50 Durometer A rubber compound has a higher load limit, 180 psi (1.24 MPa) versus 150 psi (1.03 MPa), for a single sandwich. The deflection at 150 psi (1.03 MPa) would be about 2 x 13 percent of 0.5 in. (12.5 mm) or 0.13 in. (3.3 mm) for the single sandwich versus 20 percent of 1.0 in. (25.4 mm) or 0.20 in. (5.1 mm) for the double sandwich. Not surprisingly, the single sandwich acts softer. One important application of multiple sandwich construction occurs when the sandwich is loaded in compression as well as shear. If the dimensions of a single compression sandwich exceed the desirable proportion of thickness to depth in shear (design limit is 1/4), the multiple sandwich construction can provide a convenient solution.

5.8 Other Sandwich Configurations. A double-acting combination of two compression pads (see Figure 66), having both rubber pads under initial compression, is sometimes used.

5.8.1 The equilibrium condition for this construction is stated in the equation.

$$K_1 d = W = K_2 d \quad \text{Eq. 34}$$

where

K_1 and K_2 = the respective spring rates

d = the deflection

W = the weight

5.8.2 The deflection, d , resulting from a force, F , applied to the system is a function of the sum of the two spring rates.

$$d = \frac{F}{K_1 + K_2} \quad \text{Eq. 35}$$

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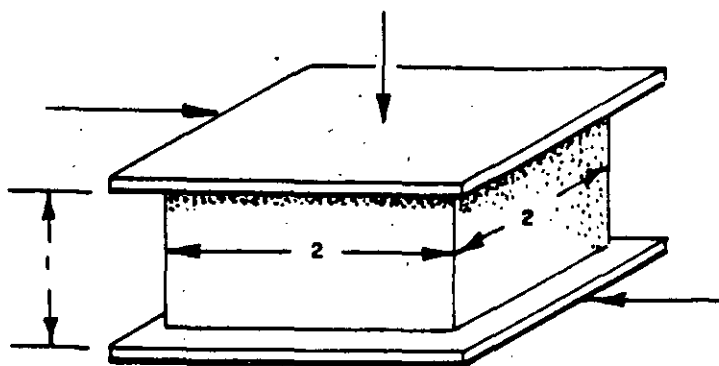
5.9 Sandwich Construction with Sides Nonperpendicular to Base

5.9.1 For shapes in which free surfaces are not parallel to the direction of load application, adjustments in the shape factor must be made. For shapes where sides are inclined to the vertical up to an angle of 30° , the shape factor may be calculated with the loaded surface areas being taken as the arithmetic mean of the large and small areas. Shapes with sides of greater inclination act softer (more deflection for equivalent load) than straight-sided shapes having the same shape factor. This behavior is noted in Figure 67 where typical load curves for 10 and 20 percent deflections are shown as a function of the cosine of the angle of inclination. At 45° , the 20 percent deflection line shows a reduction in stiffness of nearly 50 percent. Sides with slopes greater than 60° are not practical, as instability is introduced at such angles.

5.9.2 Compression sandwiches should be limited to thickness to 2 inches (50 mm), as thicker sections create manufacturing problems. In addition, the smallest transverse dimension should be at least equal to the thickness.

5.10 Design Procedure for Sandwich Configurations. The design of a component requires a knowledge of the total load to be supported and the deflection which is permissible. Using a mid-range hardness, for example 50 Durometer A as a starting point, assume first a load area so that the maximum stress will be within acceptable limits. The shape factor is now determined, and from it, a large number of design configurations are possible. The selection depends on space limitations. If the loads are too high so that no design is possible within the load limits imposed by the 50 Durometer A chart (see Figure 55), values among the harder rubber materials should be sought. It is best to try to fit a design in the middle hardness range, so that if the design turns out to be either too stiff or too soft when manufactured and tested, adjustment in the compound hardness may be made and the design need not be altered.

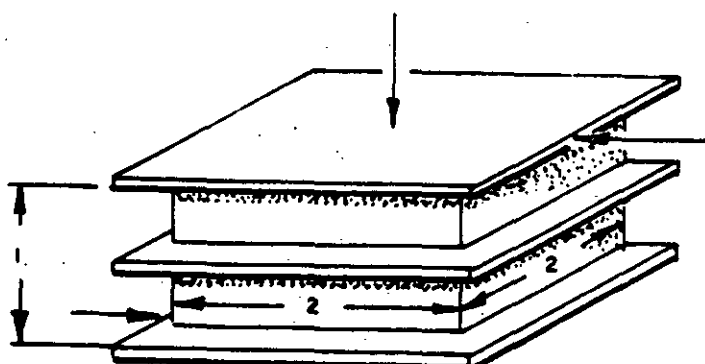
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If shear loading in horizontal direction is also required, the thickness (1 in.) is excessive in proportion to lateral dimensions.

FIGURE 64. SIMPLE COMPRESSION SANDWICH

Inch	mm
1	25
2	50



Better stability than single sandwich if subjected to additional shear loads.

FIGURE 65. DOUBLE COMPRESSION SANDWICH

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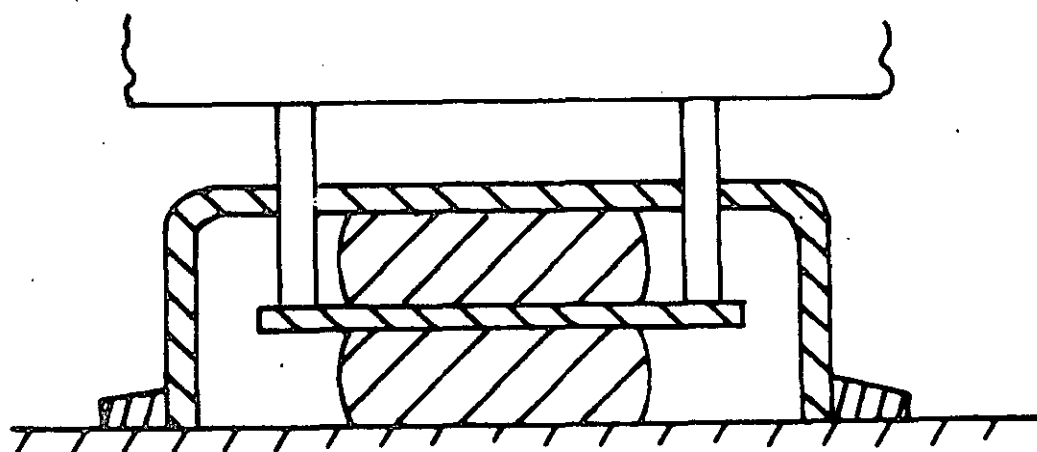


FIGURE 66. DOUBLE ACTING COMPRESSION SANDWICH

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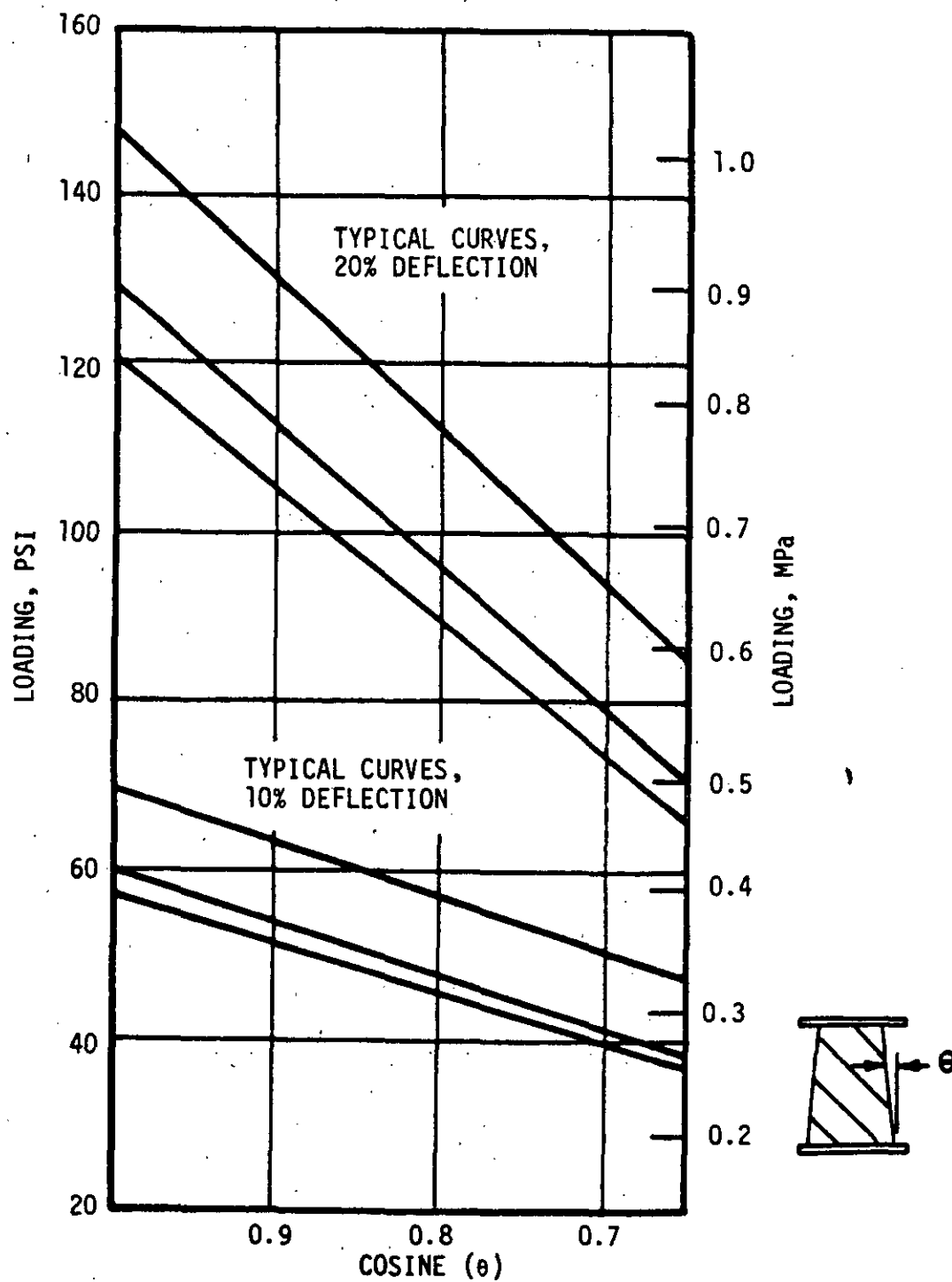


FIGURE 67. VARIATION OF LOAD REQUIRED FOR 10% AND 20% DEFLECTION AS A FUNCTION OF ANGLE FORMED BY SIDES WITH BASE (64)

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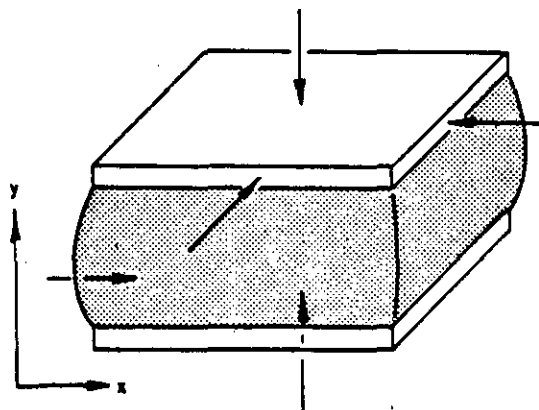


FIGURE 68. COMPRESSION SANDWICH WITH
ADDITIONAL SHEAR LOADING

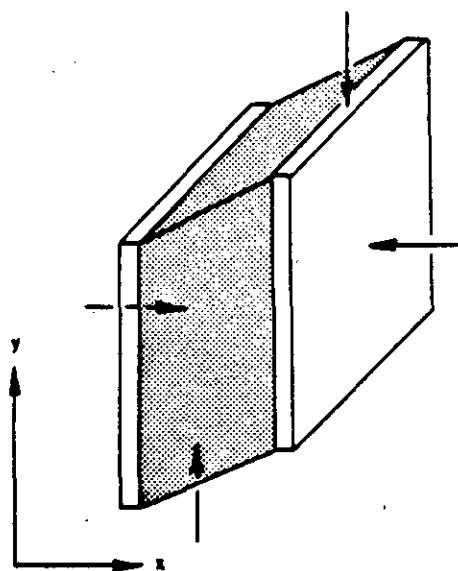


FIGURE 69. SHEAR SANDWICH WITH ADDITIONAL
COMPRESSION LOADING

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5.11 Multidirectional Properties of Rubber Sandwiches

5.11.1 A rubber sandwich possesses flexibility along all three major axes. However, different load-deflection characteristics apply. A sandwich in which a compressive load is imposed on the mounting may also be subject to lateral deflections in both x and y directions which load it in shear. The lateral stiffness in both directions would be the same for the same length and width. A sandwich which is loaded predominantly in shear has different deflection characteristics along the two major axes. Along one axis, lateral deflection will cause compression loading, and on the other, shear loading (Figures 68 and 69). In this case, the preferred orientation of such a mount must be in accordance with the characteristics of the mounting equipment chosen.

5.11.2 Static compression of a sandwich affects its shear stiffness because of three effects: (a) the bulging increases the effective area of the sample in shear, thus reduces the shear stress; (b) the compression decreases the height of the sample, the shear strain thus increases for a given shear deformation; and (c) in a sheared block, the compressive force has a vector component in the direction of the shear force.

5.11.3 Many of the commercial isolators do not employ elemental shapes for which design equations have been presented here. Approximations to complex shapes can be made by dividing them into simpler shapes which can be calculated by foregoing methods. The combination of their effects, with appropriate considerations of whether the parts act in series or in parallel, will provide a means for determining dimensions of an initial prototype. Characteristics can then be accurately determined by experimental means.

5.12 Energy Absorption by a Sandwich. To determine energy absorption characteristics, the area under the load-deflection-shape factor curve can be used either by superimposing a grid system and counting the squares, or by determining the areas by means of a planimeter. The shape factor curves are also useful to determine energy absorbed during deflecting.

5.12.1 For example, to calculate the energy which can be absorbed during the first and the second half of the excursion of a mount, select a shape factor of 0.6 with 18 percent deflection so that the required height is 1.39 in. (35.3 mm) and the free surface area 6.660 sq. in. (4297 mm²).

5.12.2 Using the Inch-Pound units of measure.

5.12.2.1 Find the areas corresponding to 9 percent and 18 percent deflection under the 0.6 shape factor curve in Figure 55. The curve must be extended to the origin. Each large square has one side equal to 50 psi, the other side equal to 5 percent of 1.39, the total thickness, or 0.070 inch. Therefore, each square has a value of 50 x 0.070, or 3.5 pound-inches. When the total area is divided in this manner (see Figure 70), portions of the curve may be taken as straight lines without appreciable error.

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$$\text{Area ADE} = \frac{65 \times 0.09 \times 1.39}{2} = 4.1 \text{ lb-in./sq in.}$$

$$\text{Area EDBC} = 65 \times 0.09 \times 1.39 + \frac{85 \times 0.09 \times 1.39}{2} =$$

$$8.2 + 5.3 = 13.5 \text{ lb-in./sq in.}$$

5.12.2.2 The total energy absorbed during compression is found by multiplying by the mount area as follows:

$$4.1 \times 6.66 = 27 \text{ lb-in. during the first half-stroke}$$

$$13.5 \times 6.66 = 90 \text{ lb-in. during the second half-stroke}$$

$$\text{Total energy absorbed during entire stroke} = 117 \text{ lb-in.}$$

5.12.3 Using the SI units of measure.

5.12.3.1 Find the areas corresponding to 9 percent and 18 percent under the 0.6 shape factor curve in Figure 55. The curve must be extended to the origin. Each large square has one side equal to 0.34 MPa, the other side equal to 5 percent of 35.3 mm, the total thickness, or 1.76 mm. Therefore, each square has a value of 0.34×1.76 , or 0.60 MPa-mm. When the total area is divided in this manner (see Figure 70), portions of the curve may be taken as straight lines without appreciable error.

$$\text{Area ADE} = \frac{0.45N}{m^2} \times \frac{0.09}{2} \times 35.3 \text{ mm} = 0.71 \text{ N}\cdot\text{mm}/m^2 = 0.00071 \text{ N}\cdot\text{m}/m^2$$

$$\text{Area EDBC} = 0.45N \times 0.09 \times 35.3 \text{ mm} + \frac{0.59N}{m^2} \times \frac{0.09}{2} \times 35.3 \text{ mm} =$$

$$0.00142 + 0.00095 = 0.00237 \text{ N}\cdot\text{m}/m^2$$

5.12.3.2 The total energy absorbed during the compression, 13.2 J, is found by multiplying the energy absorbed during each half stroke by the area of the mount, as follows:

during the first half-stroke:

$$0.00071 \text{ N}\cdot\text{m}/m^2 \times 4297 \text{ mm}^2 = \frac{0.00071}{1,000,000} \times 4297 = 3.05 \text{ N}\cdot\text{m} = 3.05 \text{ J}$$

during the second half-stroke:

$$0.00237 \text{ N}\cdot\text{m}/m^2 \times 4297 \text{ mm}^2 = \frac{0.00237}{1,000,000} \times 4297 = 10.18 \text{ N}\cdot\text{m} = 10.18 \text{ J}$$

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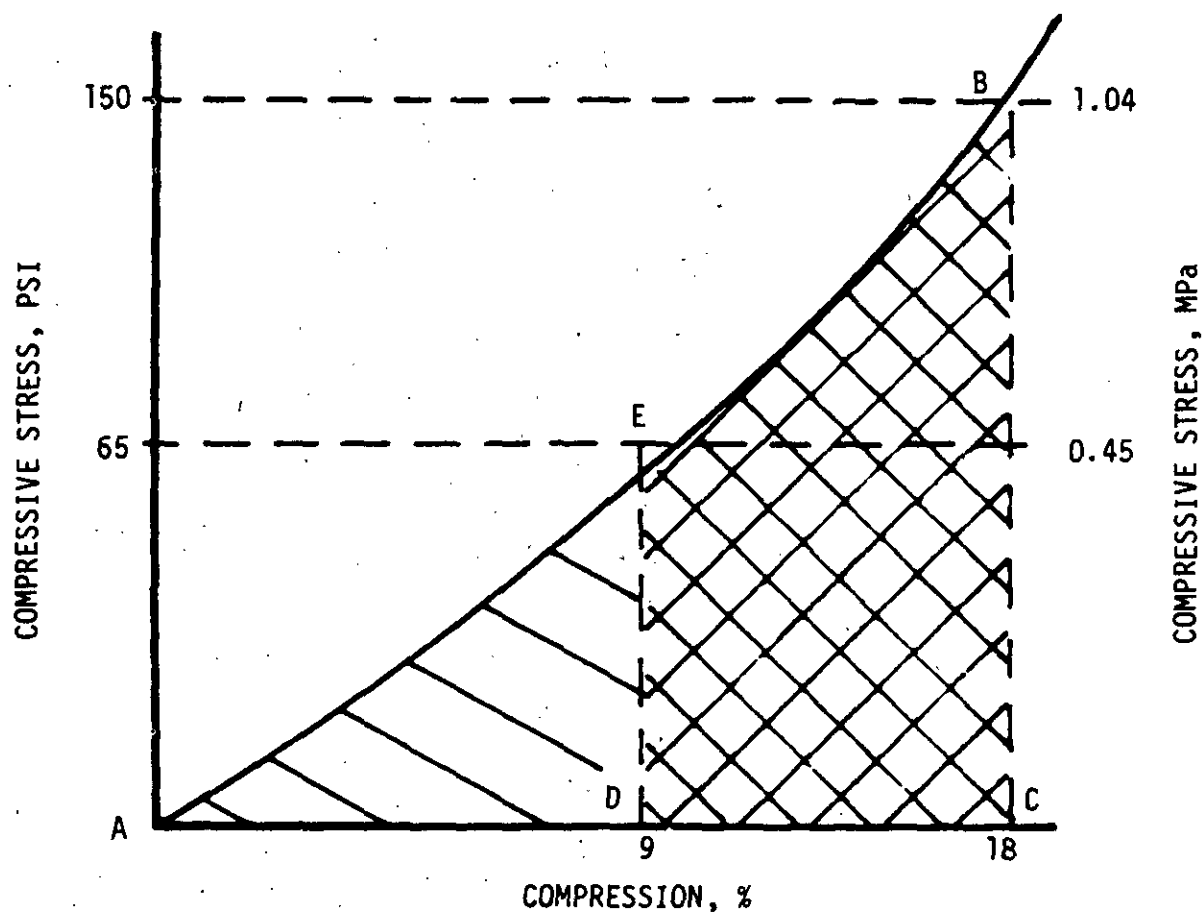


FIGURE 70. SHAPE FACTOR CURVE, 0.6 SHAPE FACTOR (37)

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5.13 Stress-Strain Properties

5.13.1 The predominant advantage of using rubber in tension lies in its great extensibility. Ultimate elongation, to the point where breaking occurs, can reach up to 900 percent so that relatively large motion can be accommodated. While the tensile strength of high grade rubber may be 5000 psi (35 MPa) or greater, authorities recommend the following limitations on design stress, which are conservative ratings based on considerations other than tensile strength:

Hardness Durometer A	Design Stress, max	
	psi	MPa
50	50	0.34
65	60	0.45
Over 65	75	0.52

5.13.2 The reluctance to use rubber in tension undoubtedly is largely due to its relatively low tear strength. Tearing of rubber in tension is caused by edge effects, and failure of a rubber in tension will most likely be a tear failure. In addition, weathering or degradation due to ozone or other atmospheric contaminants causes small edge-cracks that become stress risers and cause failure in tearing. Selection of an elastomer for a tensile application should be made from those polymers having above-average tear strength and weather resistance. Another deterrent from tension application is the lack of suitable end connections. Bonded surfaces perform poorly under tension and are subject to peeling.

5.13.3 A typical stress-strain curve for rubber in tension is shown in Figure 71. From the figure, the maximum design elongation would be approximately 80 percent for a 30 Durometer A hardness rubber loaded at 50 psi (0.34 MPa). However, weather resistance should be considered, with a suggested maximum elongation of 20 percent, as effects of weathering increase greatly at higher elongations, especially on thin sections or edges. Very little data based on experience with rubber in tension have been accumulated. Therefore, applications where current design recommendations are exceeded should be noncritical and life requirements should not be high.

5.13.4 Because of the infrequent use of rubber in tension and relatively low design stresses, the tensile properties of rubber are of little interest to the designer. They are, of course, of interest to the compounder as an indicator for quality control. For this reason, the designer should not be tempted to use the high strength of a compound as a selection criterion even though this property is prominently stated in elastomer data sheets.

5.13.5 The technically most interesting part of the tensile stress-strain curve is the small strain modulus, because it is the same as the small strain compressive modulus. The zero strain modulus is most easily obtained by plotting the true stress (the tensile force divided by the deformed sample area) against strain. This plot is quite often close to a straight line so that the slope for small strains can be determined quite accurately. The modulus thus obtained is equal to the one obtained from the nominal tensile stress-strain curve and also to the small strain compressive modulus.

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5.13.6 The shear modulus may also be obtained from the small strain tensile modulus from the relation:

$$\text{Shear modulus} = \text{tensile modulus}/3$$

This relation is strictly done only for incompressible materials such as unfilled elastomers but is still an excellent approximation for highly filled compounds.

5.13.7 Torsional assemblies made from elastomers are quite rare (aside from concentric bushings where the elastomer is loaded in simple shear, not in torsion). The torsional deformation of a rubber column (for example, a cylinder) is accompanied by an extension of its outer layers and a compression of the inner ones. Furthermore, bonding to make parts is difficult since the maximum shear stress is on the outside of the column. Compressive preloading of torsion bars and stress-concentration relieving increased dimensions at the bonding surfaces can overcome these problems. The torsional stiffness of rubber bars can be calculated from the equations derived from the classic linear theory of elasticity as long as the maximum torsional strains (at the outside of the column) do not exceed 15 percent.

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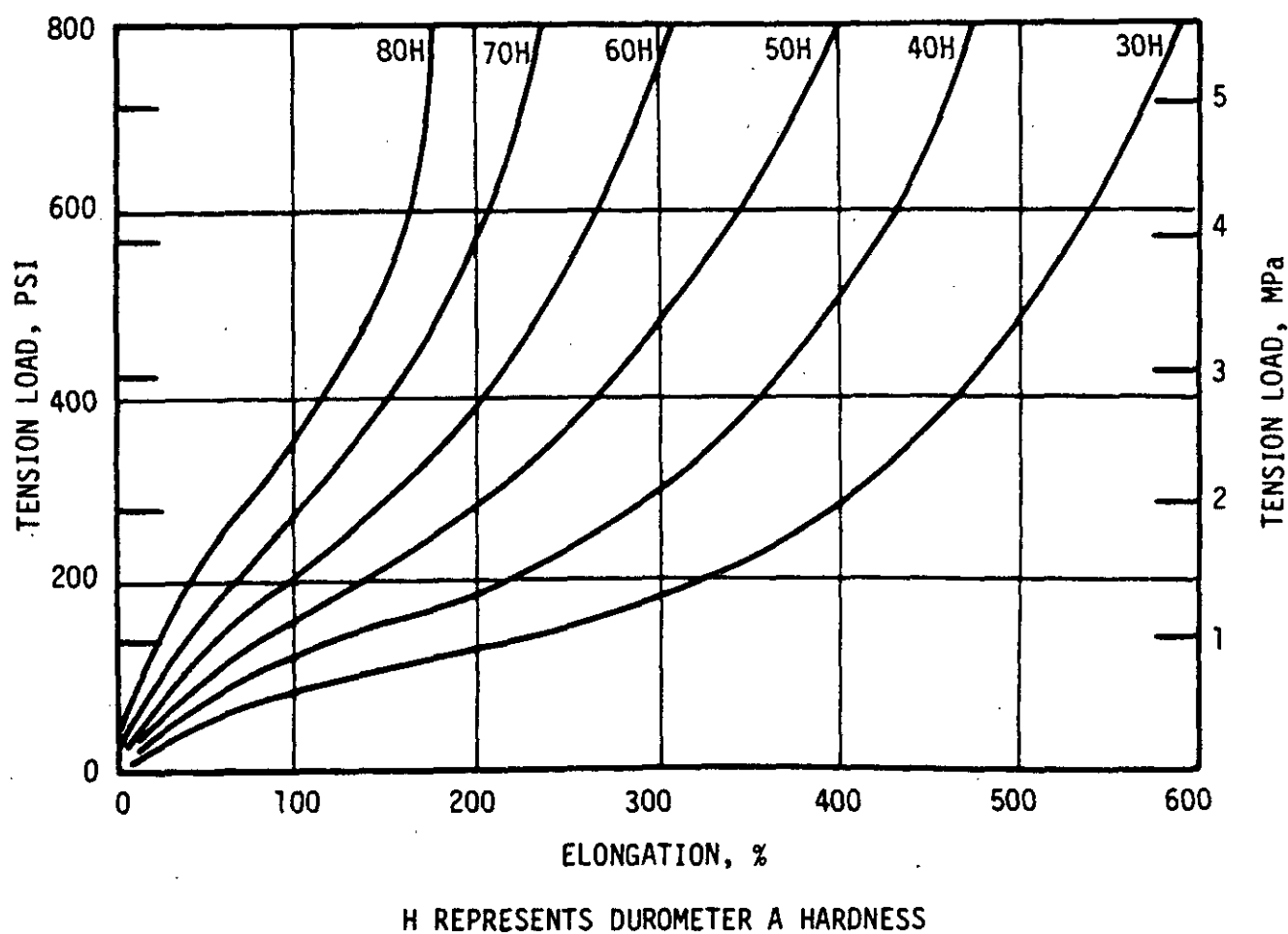


FIGURE 71. TYPICAL STRESS-ELONGATION CURVES FOR NATURAL RUBBER IN TENSION (54)

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6. ISOLATION OF VIBRATIONS AND SHOCKS

6.1 General Considerations.

6.1.1 One of the important applications of rubber is in vibration isolators. The function of a vibration isolator is to reduce the transmission of forces by reflecting vibrational energy back to its source. This is attained by maintaining the natural frequency of vibration of the system low with respect to the frequency of the disturbance. The disturbing forces may be generated externally, and it is necessary to protect the mounted system from them. Or a periodically generated force within the system requires isolation so it will not be transmitted to its full intensity to the environment.

6.1.2 Unless a body is rigidly restrained in one or more directions, it has six degrees of freedom; that is, it is free to move by translation in three directions along the x, y, and z axes as well as rotate about each axis. An example of a maximum freedom suspension is shown in Figure 72. Such a body has six natural frequencies. However, when rotation does not occur about the center of gravity, coupling occurs and the motions are no longer independent. Nevertheless, each vibration must be examined separately.

6.1.3 Vibration systems can be categorized as: (1) free vibration, (2) free vibration with damping, (3) forced vibration without damping, and (4) forced vibration with damping.

6.1.4 The free vibration system can be illustrated as an ideal mass-spring system (Figure 73) which, if started by an initial motion--such as pulling a weight down and releasing it, would vibrate ad infinitum about its initial position. However, in every physical system, the inherent friction that is experienced as damping (Figure 73b) inhibits such continuing motion so that, in effect, the amplitude decreases with each oscillation until the first position is resumed.

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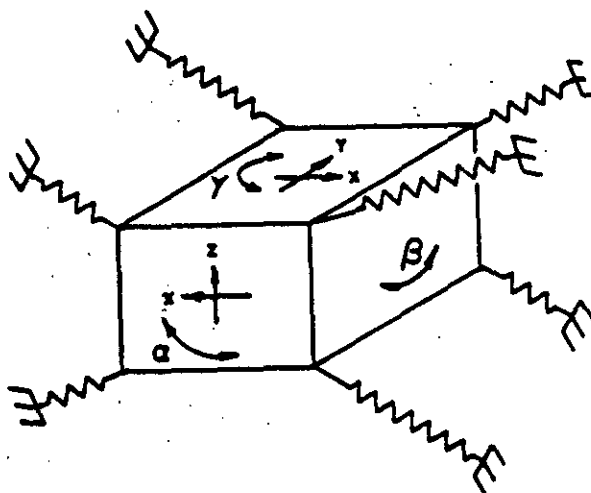
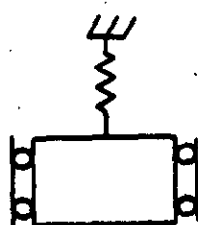
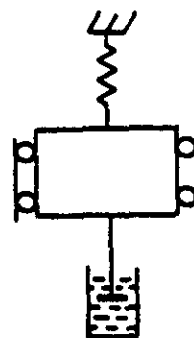


FIGURE 72. SIX DEGREES OF FREEDOM OF BODY
SUSPENDED FROM EIGHT POINTS



a. Idealized



b. With Damping

FIGURE 73. MASS-SPRING SYSTEM

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6.2 Damping of Vibratory Motion in Rubber.

6.2.1 In rubber, the damping is closely proportional to the velocity. It approaches viscous damping. The decrease of amplitude of a vibrating mass resulting from damping can be stated as a logarithmic function termed logarithmic decrement. This is the logarithm of the constant ratio of the amplitude of two successive cycles. The shape of the periodic oscillation curve and its envelope, which is the curve of the logarithmic decrement L_d , is shown in Figure 74, the magnitude of L_d is determined in Equation 36.

$$L_d = \log \frac{a_1}{a_2} = \log \frac{a_2}{a_3} \text{ etc.} = \log \frac{a_n}{a_{n+1}} \quad \text{Eq. 36}$$

6.2.2 During the vibratory motion the period of each oscillation (or the reciprocal, frequency) can be considered, for all practical purposes, to remain nearly constant.

6.3 Natural Frequency.

6.3.1 The natural frequency of a spring-mounted system with a single degree of freedom and a linear spring rate can be determined with the static deflection of the spring-mounted mass is known. Equations 37 and 38 apply to a system without damping.

6.3.1.1 Natural frequency, ω_n , of the system in radians per second is determined by Equation 37.

$$\omega_n = \sqrt{K \frac{g}{W}} \quad \text{Eq. 37}$$

6.3.1.2 Natural frequency, f_n , of the system in cycles per minute is determined by Equation 38.

$$f_n = \frac{188}{\sqrt{d}}$$

where

K = the slope of the load-deflection curve at the point about which the vibration occurs, lb/in. (kg/mm)

g = the acceleration due to gravity, 386 in./sec² (9804 mm/sec²)

W = the dead weight of the component, lb (kg)

d = the static deflection caused by the weight, in. (mm)

6.3.1.3 Damping factors have negligible effects on the frequency of free vibration and need not enter into the calculations. Data obtained in using Equations 37 and 38 are given in Figures 75 and 76, respectively.

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6.3.2 The static deflection resulting from dead weight and static forces, such as belt pull, or other reactions, can best be determined for viscoelastic materials with the aid of stress-strain curves for compression mountings (Figures 53 to 63).

6.3.2.1 An initial determination must be made as to the number of mounts used for support, so that the specific load per mount can be obtained. Also, assumptions must be made as to load area and thickness of each mount so that the chart may be entered at the correct stress level. The unit deflection corresponding to this unit stress can then be read directly from the chart.

6.3.2.2 In the case of compression mounts, the percent unit deflection is indicated as percent original rubber thickness, t , so that actual deflection, d , is equal to

$$d = \frac{\% \text{ compression deflection} \times t}{100}$$

Eq. 39

6.3.3 The formula for natural frequency, Equation 37, shows that this frequency will decrease as the weight, W , increases if K remains constant. The K of a shear mount is essentially constant at different deflections; however, the K of a compression mount rises as deflection increases. At higher deflections, K will rise almost in proportion to W , so the natural frequency of a compression mount, although decreasing initially as W increases, will eventually approach a constant value as W continues to rise.

6.3.4 The static spring rate (tangent to load-deflection curve) is close to the dynamic spring rate in the case of a natural rubber mount, and therefore may be used to calculate an approximate natural frequency.

6.3.5 The resilient elements of many mounts are so shaped that they deflect under load in neither simple shear nor simple compression, but in a combination of these modes and often with some tension due to bending. The behavior of these mounts cannot be calculated from the stress-strain curves given in this handbook.

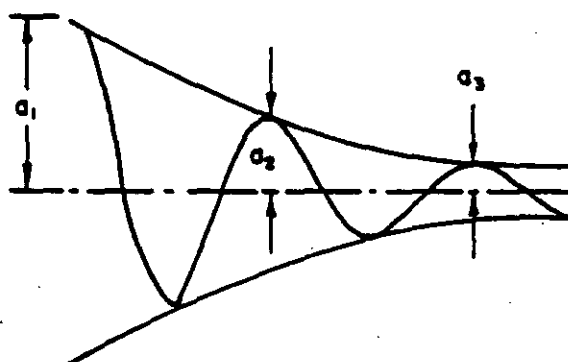


FIGURE 74. DECAY OF VIBRATORY OSCILLATIONS

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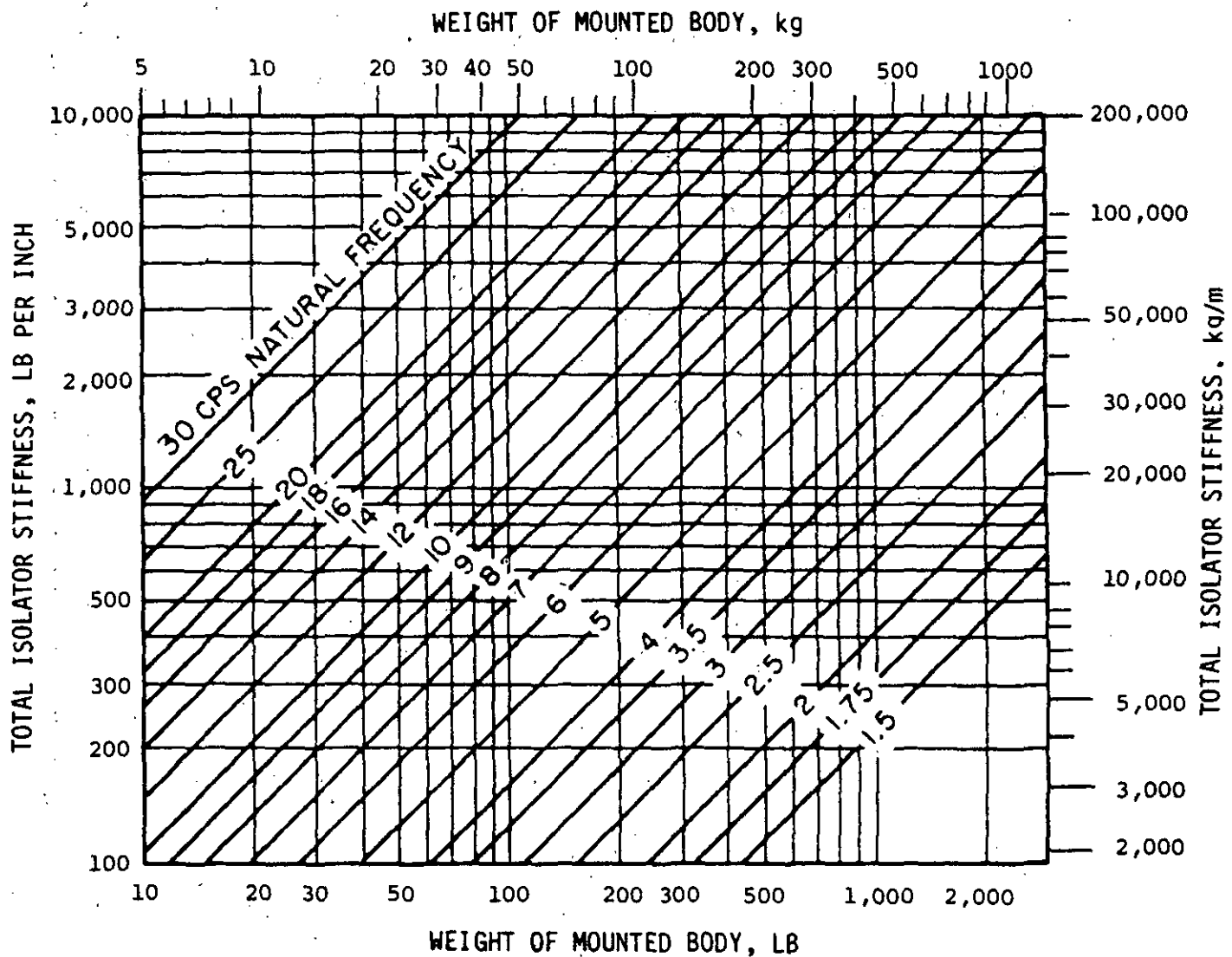


FIGURE 75. NATURAL FREQUENCY OF A LINEAR SINGLE-DEGREE-OF-FREEDOM SYSTEM AS A FUNCTION OF WEIGHT OF MOUNTED BODY AND TOTAL ISOLATOR STIFFNESS (22)

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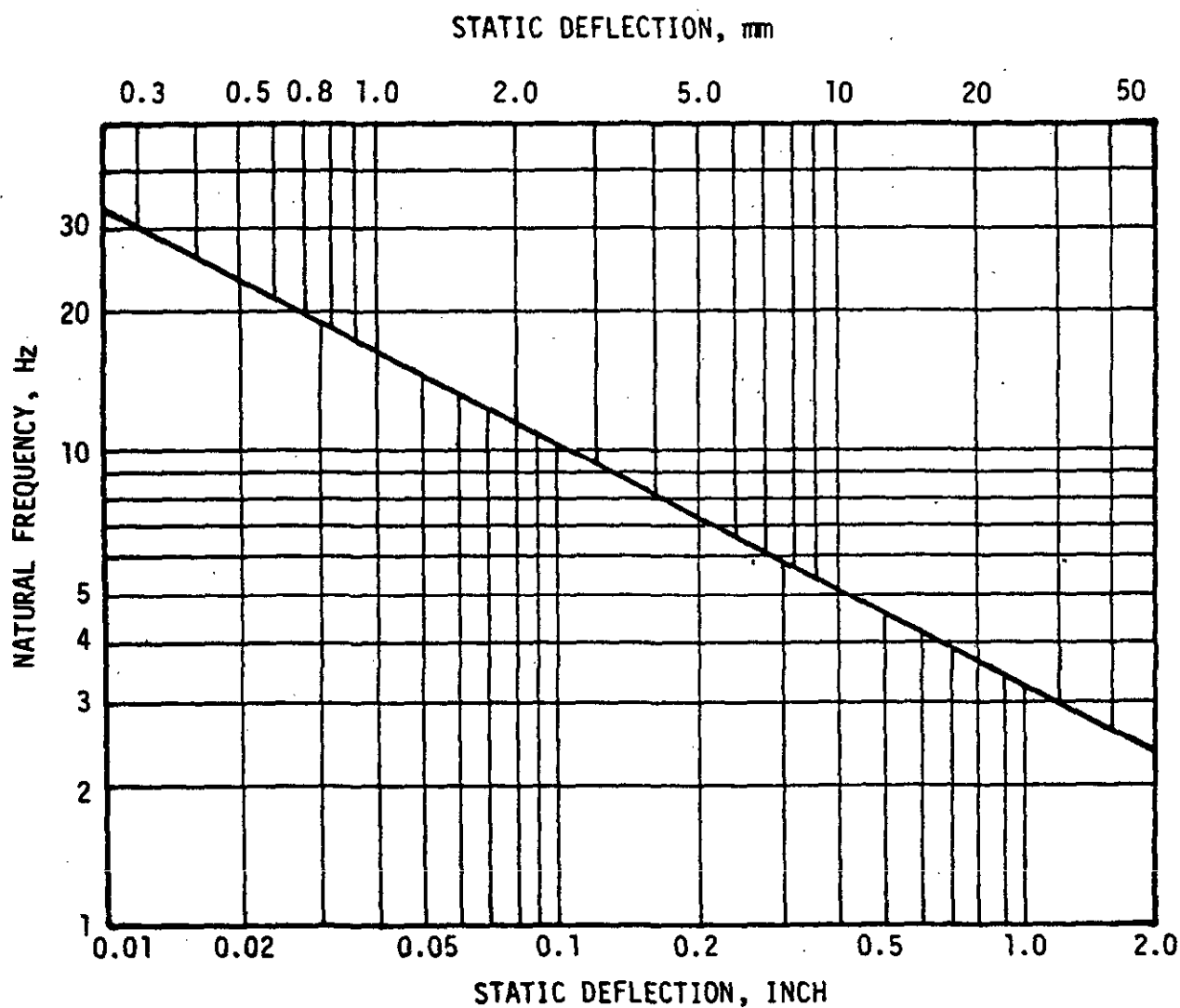


FIGURE 76. RELATIONSHIP BETWEEN NATURAL FREQUENCY AND STATIC DEFLECTION, LINEAR, SINGLE-DEGREE-OF-FREEDOM SYSTEM (22)

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6.4 Forced Vibration with Damping.

6.4.1 The designer is generally faced with the problem of a forced vibration system with damping. The force exerted on or generated within the system has periodically repetitive magnitude and, generally, a fixed frequency. The source of the disturbance may be an imbalance in a rotating element or reciprocating mass. The maximum force caused by an imbalance in a rotating element is found by the equation:

$$F = \frac{W}{g} r \omega^2 \quad \text{Eq. 40}$$

where

W = the unbalanced weight, lb (kg)

r = the radius at which the imbalance occurs, in. (mm)

ω = the circular frequency, rad/s

g = the acceleration due to gravity, 386 in./sec² (9804 mm/s²)

6.4.1.1 Using Equation 40, an unbalanced weight of one-tenth pound located at a radius of 12 in. on an 1800-rpm motor results in a maximum force of

$$\frac{0.1}{386} \times 12 \times \frac{1800 \times 2\pi}{60}^2 = 110 \text{ lbf}$$

6.4.1.2 Using Equation 40, an unbalanced weight of 0.045 kg located at a radius of 300 mm on an 1800-rpm motor results in a maximum force of

$$\frac{0.045}{9804} \times 300 \times \frac{1800 \times 2\pi}{60}^2 = 50 \text{ kg} = 490 \text{ N}$$

6.4.2 Torsional vibration of long shafts may result from fluctuating load conditions. Depending on mounting locations, some modes of vibration may couple and result in secondary excitations. The coupling of such modes may be minimized if the mounting is near the center of gravity of the mounted mass. Figure 77 shows an idealized single-degree-of-freedom system with damping having a rotating excitation force, as from an unbalanced rotor element. The rpm of the motor represents the frequency of the disturbing force; its magnitude is the product of the unbalanced weight and the square of the angular velocity. The differential equation of motion for a system influenced by a periodic disturbing force and also affected by damping is

$$\frac{W}{g} \ddot{x} = W - (W + KX) - CX + P \sin \omega t \quad \text{Eq. 41}$$

where

W - (W + KX) represents the force function of a free vibration system,

CX represents the viscous damping function (damping force proportional to the velocity), and

$P \sin \omega t$ represents the external disturbance assumed to be a periodic oscillating force with sinusoidal characteristics.

6.4.3 From the solution of Equation 41, the maximum amplitude of the vibration may be obtained in the form:

$$X_d = \frac{P}{K} \frac{1}{\sqrt{\left[1 - \frac{\omega_f^2}{\omega_n^2}\right]^2 + \left[2 \frac{c}{c_{cr}} \frac{\omega_f}{\omega_n}\right]^2}} \quad \text{Eq. 42}$$

where

P = the disturbing force (for example, the centrifugal force of a rotating element)

K = the dynamic spring rate which can be taken as the slope of the dynamic force deflection curve at the point of static deflection. (Since such curves are not available except in special cases, a correction factor, varying from 1.2 to 3.0, must be applied to the static rate to compensate for dynamic stiffness)

ω = the rate of vibratory motion, radians per second, and c/c_{cr} is the damping ratio

X_d = the dynamic deflection. The factor P/K could be interpreted as X_{st} , the deflection which would result if the disturbing force acted statically.

Then, the factor

$$\frac{1}{\sqrt{\left[1 - \frac{\omega_f^2}{\omega_n^2}\right]^2 + \left[2 \frac{c}{c_{cr}} \frac{\omega_f}{\omega_n}\right]^2}} \quad \text{Eq. 43}$$

is the magnification factor of this (hypothetical) static deflection.

6.4.4 The magnification factor depends on the ratio of ω_f/ω_n ; that is, the ratio of the forced frequency to the natural frequency without damping, as well as on the ratio c/c_{cr} where c represents the actual damping energy and c_{cr} the critical damping energy, lb-sec/in. (kg-sec/mm). The influence of both ratios is shown in Figure 78. Transmissibility is the percentage of force transmitted through the isolation system and is mathematically expressed by the ratio:

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Eq. 43

$$\frac{\sqrt{1 + \left[2 \frac{c}{c_{cr}} \frac{\omega_f}{\omega_n} \right]^2}}{\sqrt{\left[1 - \frac{\omega_f^2}{\omega_n^2} \right]^2 + \left[2 \frac{c}{c_{cr}} \frac{\omega_f}{\omega_n} \right]^2}}$$

6.4.5 Figure 78 shows that when the natural frequency is the same as the impressed frequency, a condition known as resonance exists. The force transmitted builds up to a very high magnitude, and reaches infinity for the hypothetical case of zero damping. When the impressed frequency is less than $\sqrt{2}$ times the natural frequency, the force transmitted is always larger than the impressed force. The effect of damping, as shown by the curves, is most beneficial in the region where resonance is approached. Above the frequency ratio of the $\sqrt{2}$, higher damping actually results in higher transmissibility values. Some damping will be necessary if the system is subjected to resonance conditions for any appreciable time during starting and stopping of the disturbance. Accepted values of frequency ratio, ω_f/ω_n , for effective isolation are of the order of 2.5 to 4 or greater if a soft spring system is permissible. The limitation is usually imposed by the available clearance space. The damping parameter used in Figure 78 is the ratio of actual to critical damping. Critical damping is the minimum damping required to inhibit oscillatory motion, where viscous friction is so large that the body displaced by the periodic disturbing force creeps back to its equilibrium position. Typical inherent material damping ratios c/c_{cr} are indicated in Table XVII. Where more damping is required, such devices as dashpots or electromagnetic devices must be incorporated in the system.

6.4.6 Since the logarithmic decrement may be experimentally determined by measuring the amplitude of two successive cycles (See Figure 74), it is convenient to calculate the actual damping ratio in a given isolator by the following formula for small damping ratios:

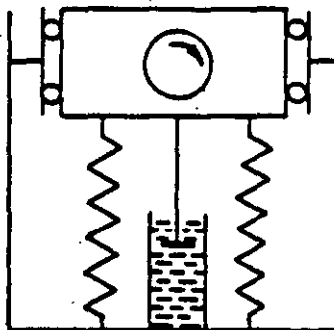
Eq. 44

$$L_d = \log \frac{a_2}{a_1} = \frac{2\pi \frac{c}{c_{cr}}}{\sqrt{1 - \left(\frac{c}{c_{cr}} \right)^2}} \approx 2\pi \frac{c}{c_{cr}}$$

TABLE XVII. TYPICAL VALUES FOR DAMPING RATIO

Material	$\frac{c}{c_{cr}}$ Ratio
High-damping Elastomers	0.12
60 Durometer A Rubber	0.08
30 Durometer A Rubber	0.02
Steel	0.005

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**FIGURE 77. SCHEMATIC REPRESENTATION OF A SYSTEM
CONTAINING A ROTATING MASS MOUNTED ON
ISOLATION PADS WHICH PROVIDE DAMPING**

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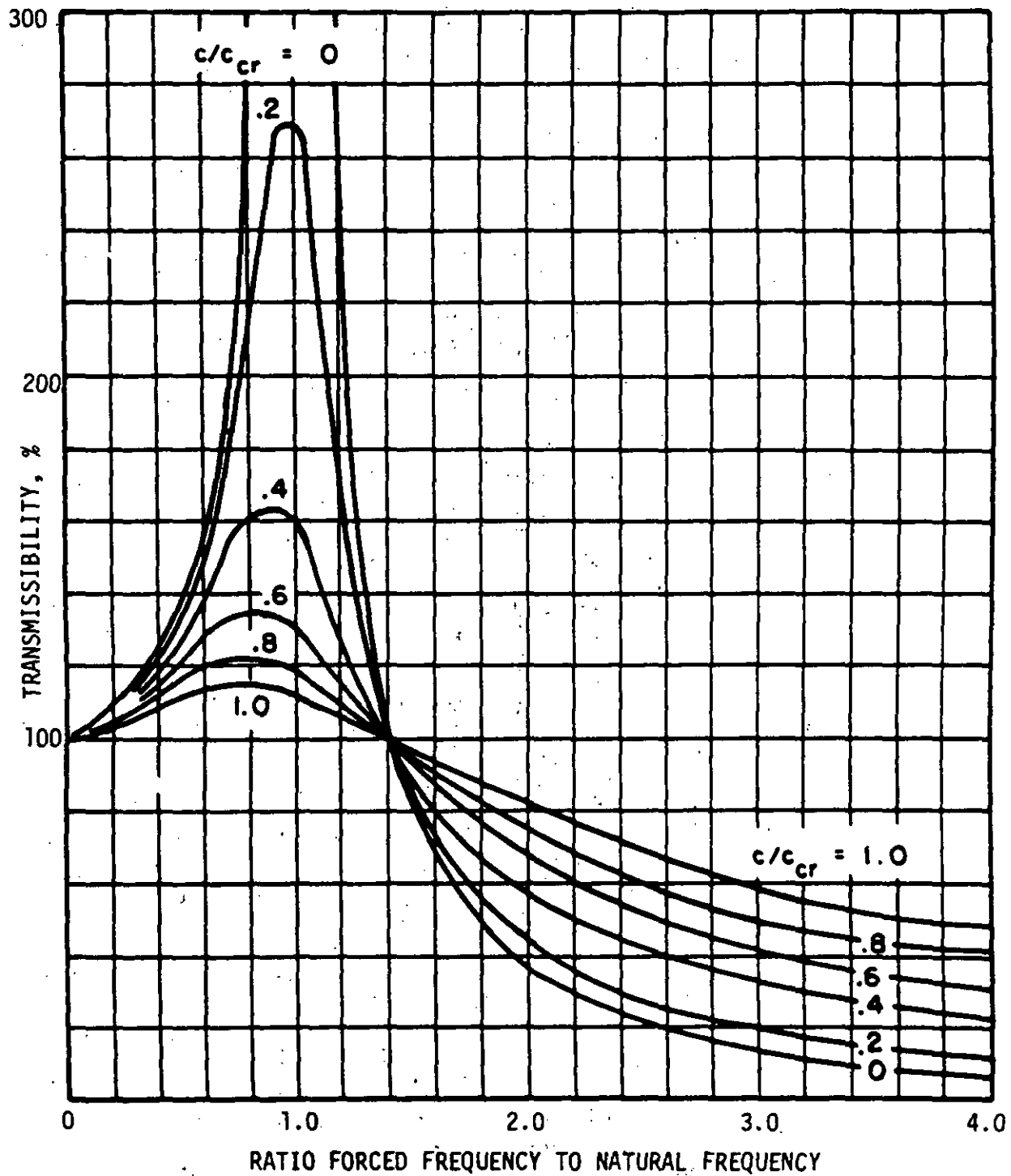


FIGURE 78. TRANSMISSIBILITY OF VIBRATORY DISTURBANCE AS A FUNCTION OF THE FREQUENCY RATIO AND DAMPING RATIO (37)

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6.5 Design Example, A Vibration Mount.

6.5.1 A truck-mounted motor-generator-compressor weighing 3000 lb (1360 kg) is to be supported by four sandwich type shear mountings. These mountings are so oriented that accelerations and decelerations of the vehicle will be resisted by the mounts acting in compression; that is, the faces of the sandwich are to be perpendicular to the major axis of the vehicle. Rotational speed of the motor generator unit is 900 rpm. It is considered that vertical impact during travel will be absorbed by the truck tires and the vehicle suspension system. At least 75 percent of the disturbing vibratory forces must be isolated; that is, the transmissibility is to be 25 percent.

6.5.2 From the transmissibility curve (Figure 78) assume a ratio of $c/c_{cr} = 0.05$. The ratio of forced to natural frequency must be $f/f_n = 2.5$ so that the natural frequency of the system must be $900/2.5 = 360$ rpm or 6 hertz.

6.5.3 From Figure 76, a static deflection of 0.3 in (7.6 mm) is indicated. Some preliminary assumptions must now be made: (1) type of rubber selected, (2) hardness of rubber selected, and (3) geometric design of the mount.

6.5.4 The type of rubber selected must be suitable to the application and compatible with environmental conditions. Application to a motor-mount requires a low compression-set stock of medium strength with good bondability to metal. Oil resistance is not a primary consideration.

6.5.5 A land vehicle operates over a broad ambient temperature range, from -65° to $+160^{\circ}\text{F}$ (-55° to $+70^{\circ}\text{C}$). The upper temperature requirement necessitates careful selection of a material which does not become brittle and stiffen excessively. In addition to having to function in the temperature range, the outdoor exposure requires resistance to ozone, weather, and ultraviolet light.

6.5.6 The following selection procedure is recommended. Figure 1, a guide to useful range of commercial elastomers, shows that the following polymers are possible candidates on the basis of temperature suitability and weather resistance: butyl, chlorosulfonated polyethylene, chloroprene, polyurethanes, and silicones.

6.5.7 Investigating each of these elastomers by analyzing the individual data sheets in Appendix C, the following data are obtained:

6.5.7.1 Butyl. Excellent damping, low compression set, excellent ozone resistance, good adhesion to metal, high low-temperature stiffness from 0° to $+20^{\circ}\text{F}$ (-18° to -7°C), brittle point from -40° to -54°F (-40° to -48°C) which may be lowered by the addition of plasticizers, and moderate cost.

6.5.7.2 Chloroprene. Good ozone and weathering resistance, adhesion to metal is good, but stiffens in the range of -20° to $+10^{\circ}\text{F}$ (-30° to -12°C).

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6.5.7.3 Chlorosulfonated Polyethylene. Adequate low temperature properties if specially compounded, but has poor resistance to ultraviolet, and is not generally used for vibration mountings.

6.5.7.4 Polyurethanes. High strength, high ozone resistance, high damping characteristics although somewhat less so than butyl, and higher cost.

6.5.7.5 Silicones. Excellent low temperature and ozone resistance, lower strength and tear resistance than competing polymers, and higher cost. Useful in small instrument mountings with light loads.

6.5.8 From the pertinent characteristics discussed above, it appears that butyl rubber or polyurethane rubber are suited for the application. Calculation procedures for butyl and polyurethane rubber sandwich are shown below.

6.5.9 Butyl Rubber.

6.5.9.1 Considering a 50 Durometer A butyl rubber compound from the shear stress-strain curves shown in Figure 43 (see 5.2.3), it is observed that a 70 psi (0.48 MPa) stress is permissible for continuous or frequent loading, which results in a static deflection, d/t , ratio of 0.9. Since the required deflection is 0.3 in. (7.6 mm), the thickness of the rubber must be:

$$t = \frac{0.3}{0.9} = 0.33 \text{ in.}$$

$$t = \frac{7.6}{0.9} = 8.4 \text{ mm}$$

6.5.9.2 To obtain adequate stability of the rubber-to-metal bond, a rubber thickness of 0.375 in. (9.5 mm) should be selected. At assembly, the sandwich is to be compressed to an installation thickness of 0.33 in. (8.4 mm). The height of the sandwich should be at least four times the thickness, so that 1.50 in. (38 mm) is the minimum height. Since there are four pads, each pad must carry one-fourth of the total load of 3000 lb or 750 lb (1360 kg or 340 kg) and a total area of 10.5 sq in. (6775 mm²) is required to obtain a 70 psi (0.48 MPa) stress. An approximately square design 3 in. (75 mm) in depth and 3.5 in. (89 mm) in width would be satisfactory. The total volume of the butyl pad would be 3.5 x 0.375 x 3, or 4 cu in. (89 x 9.5 x 75, or 63 412 mm³). Static deflection of the unit will be 0.9 x 0.33, or 0.30 in. (0.9 x 8.4, or 7.6 mm). Considering clearance requirements to prevent bottoming, an allowance of an additional 20 percent for creep should be made, at least 0.5 in. (12.7 mm).

6.5.10 Polyurethane Rubber.

6.5.10.1 Considering a 65 Durometer A polyurethane rubber compound from the shear stress-strain curves shown in Figure 44, it is observed that a somewhat higher stress of 100 psi (0.69 MPa) is acceptable because of the high strength of the rubber polymer. The corresponding d/t ratio is 0.47. Therefore the thickness of the rubber must be:

$$t = \frac{0.30}{0.47} = 0.63 \text{ in.}$$

$$\left(t = \frac{7.60}{0.47} = 16 \text{ mm} \right)$$

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6.5.10.2 A nominal thickness of 0.68 in. (17.5 mm) rubber pad should be manufactured and compressed to an installed thickness of 0.63 in. (16 mm) at assembly. The maximum height of the sandwich should then be 4×0.63 or approximately 2.5 in. (4×16 or approximately 64 mm). The area of each pad supporting 750 lb (340 kg) would be 7.5 sq. in. (4840 mm²), resulting in a width of 3 in. (75mm). Volume of the polyurethane pad would be $0.68 \times 2.5 \times 3$, or 5.15 cu. in. ($17.3 \times 63.5 \times 76.2$ or 83 709.5 mm³). It will be noted that this volume is greater than that of the butyl rubber pad.

6.5.11 The two sandwiches should be made and tested under dynamic conditions at low temperature. A final selection can then be made.

6.5.11.1 In order to assure adequate clearance to prevent bottoming, the dynamic deflection which occurs as a result of incompletely balanced masses, that is, an unbalanced motor and generator rotor, must be taken into account.

6.5.11.2 To determine the dynamic deflection due to the disturbance, the magnitude of the imbalance must be either known or assumed. Assuming an unbalanced weight of 0.1 lb. (45 g) at a radius of 12 in. (300 mm), the dynamic deflection would be (Equation 42, See 6.4.3):

$$x_d = \frac{P}{K} \times \frac{1}{\sqrt{\left[1 - \frac{\omega_f}{\omega_n}\right]^2 + \left[2 \frac{c}{c_{cr}} \frac{\omega_f}{\omega_n}\right]^2}}$$

$$\frac{\omega_f}{\omega_n} = 2.5 \text{ and } \frac{c}{c_{cr}} = 0.05$$

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6.5.11.3 The nominal rate K is the load divided by the deflection, or

$$\frac{750 \text{ lb}}{0.3 \text{ in}} = 2500 \text{ lb/in.} \quad \left(\frac{340 \text{ kg}}{7.6 \text{ mm}} = 45 \text{ kg/mm} \right)$$

$$\frac{P}{K} = \frac{\frac{0.1 \times 12}{386} \times \left[\frac{900}{60} \times 2\pi \right]^2}{2500} = 0.012 \text{ in.}$$

$$\left(\frac{P}{K} = \frac{\frac{0.045 \times 300}{9804} \times \left[\frac{900}{60} \times 2\pi \right]^2}{45} = 0.30 \text{ mm} \right)$$

6.5.11.4 The magnification factor equals (See 6.4.3):

$$\frac{1}{\sqrt{[1 - (2.5)^2]^2 + [0.1 (2.5)]^2}} = \frac{1}{\sqrt{27.56 + 0.06}} = \frac{1}{5.26} = 0.19$$

$$X_d = 0.012 \times 0.19 = 0.0023 \text{ in.} \quad (X_d = 0.30 \times 0.19 = 0.058 \text{ mm})$$

6.5.11.5 The dynamic deflection turns out to be only 0.0023 in. (0.058 mm).

6.6 Torsional Vibration. The deflection caused by torsional vibration is found by means of an expression similar to that for linear vibration. The magnification factor is the same as used previously.

$$\theta_d = \frac{M}{K} \times \frac{1}{\sqrt{\left[1 - \left(\frac{\omega_f}{\omega_n} \right)^2 \right]^2 + \left[2 \frac{c}{c_{cr}} \left(\frac{\omega_f}{\omega_n} \right) \right]^2}} \quad \text{Eq. 45}$$

where

M = the torsional moment of the disturbing force

K = the torsional spring rate

θ_d = the angular deflection in radians

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6.7 Shock Mount Design.

6.7.1 The purpose of a shock-mounting system is to absorb the energy of sudden impact, and return it gradually over a comparatively long period of time. The meaning of "sudden" is defined, in this case, as a change of velocity taking place within a period of time small in comparison with the natural period of the system. The energy can be absorbed only if work is done on the shock absorber by deflecting it against the force of stiffness of the rubber. The energy thus absorbed is equal to $\int F \delta d$, which, for a linear spring, is equal to $1/2 Kd^2$, where K is the spring rate and d the total deflection.

6.7.2 In design for shock mountings, the nonlinear characteristics of rubber are much more significant than in vibration-mount design. The reason for this is that greater deflections are required for shock mounting. The nonlinearity can be an asset. When unusually great shock loads are experienced, the progressive stiffening of the rubber isolator limits acceleration forces to values smaller than could be expected from a linear rate spring which is forced to bottom.

6.7.3 The maximum shock load on the mass of a simple mass-spring system can be determined from Equation 46, which can be solved with the aid of Figures 79 and 80, correction chart for nonlinear shock absorbers for determining transmitted maximum accelerations. An isolator thickness is assumed, and the correction factor is then determined.

$$a = (\Delta V)\omega$$

Eq 46

where

a = maximum acceleration,

(ΔV) = impact velocity change, and

ω = natural frequency of the mass spring.

6.7.4 To determine maximum deflection, the maximum impact force is determined by the formula

$$F = \frac{aW}{g}$$

Eq 47

where

a = acceleration due to impact, ft/sec² (m/s²)

g = acceleration due to gravity, 32 ft/sec² (9.8 m/s²)

W = weight of mounted component, lb (kg)

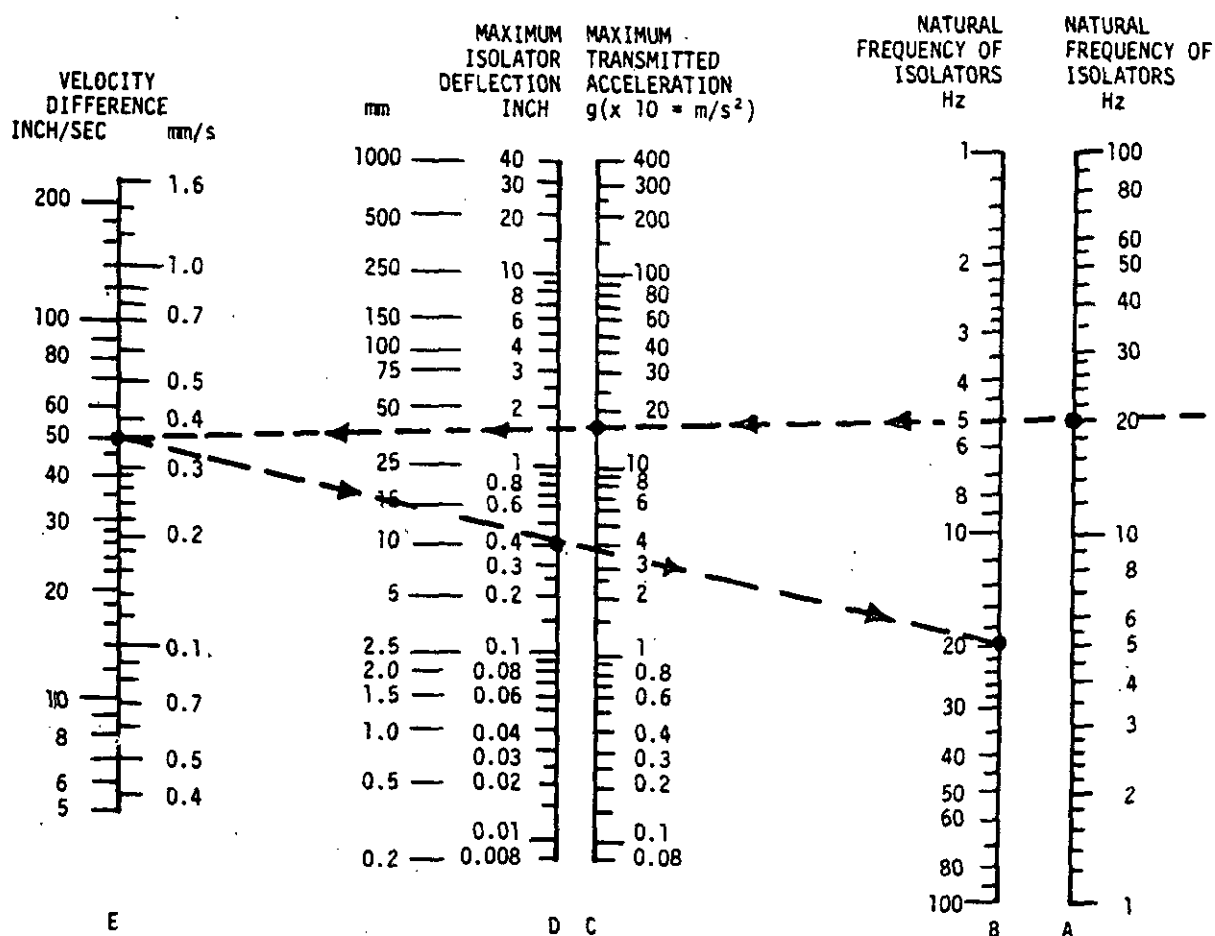
For any specific mount, the deflection is then obtained from the stress-strain curve.

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6.7.5 Single-degree-of-freedom systems, for which equations are presented, are only a small fraction of the cases encountered by the engineer. For solutions to more complicated problems, the reader is referred to any one of the standard texts on vibration. Nevertheless, the scarcity of data regarding the pertinent properties of natural and synthetic rubbers, and the mathematical complications which arise in nonlinear theory make it necessary to follow initial calculations with an experimental approach. Whenever possible, commercially produced mountings, which abound in sufficient varieties to suit many applications, should be employed. For such mountings, the manufacturer can often supply better performance data, based on test results, than can be obtained by theoretical design.

6.7.6 The perfect stress-strain curve for shock absorption would be a straight line plateau parallel to the strain axis. This type of curve is found for large cell elastomeric foams and long slender rubber columns which can undergo buckling (the struts of a compressed foam also deform in a buckling mode.) However, in both cases the load carrying capacity per unit volume of material is quite low. Analytical methods for predicting accurately the response of buckling of elastomeric columns have not been developed. The equations developed for perfectly elastic materials are poor approximations at best.

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This nomograph can be used to determine two of four factors in a shock mount system. If the natural frequency and the velocity difference (initial-final velocity) of the system subjected to shock is known, enter the nomograph at Scale A (20 Hz) and connect the straight line with the given or assumed value on Scale E, for example, 50 inch/sec (3.5 mm/s). The intersection with Scale C will show the maximum acceleration sustained, 16 g (160 m/s²). Connect the point on Scale E, 50 inch/sec (3.5 mm/s), by a straight line with the value of natural frequency on Scale B (20 Hz) will give the isolator deflection on the intersect with Scale D. The order of operation may be either A-C-E-D-B as shown as shown by arrows and intersection dots or in the reverse order B-C-E-D-A.

FIGURE 79. NOMOGRAPH FOR DETERMINING ACCELERATION AND DEFLECTION OF A SYSTEM SUBJECTED TO SHOCK (23)

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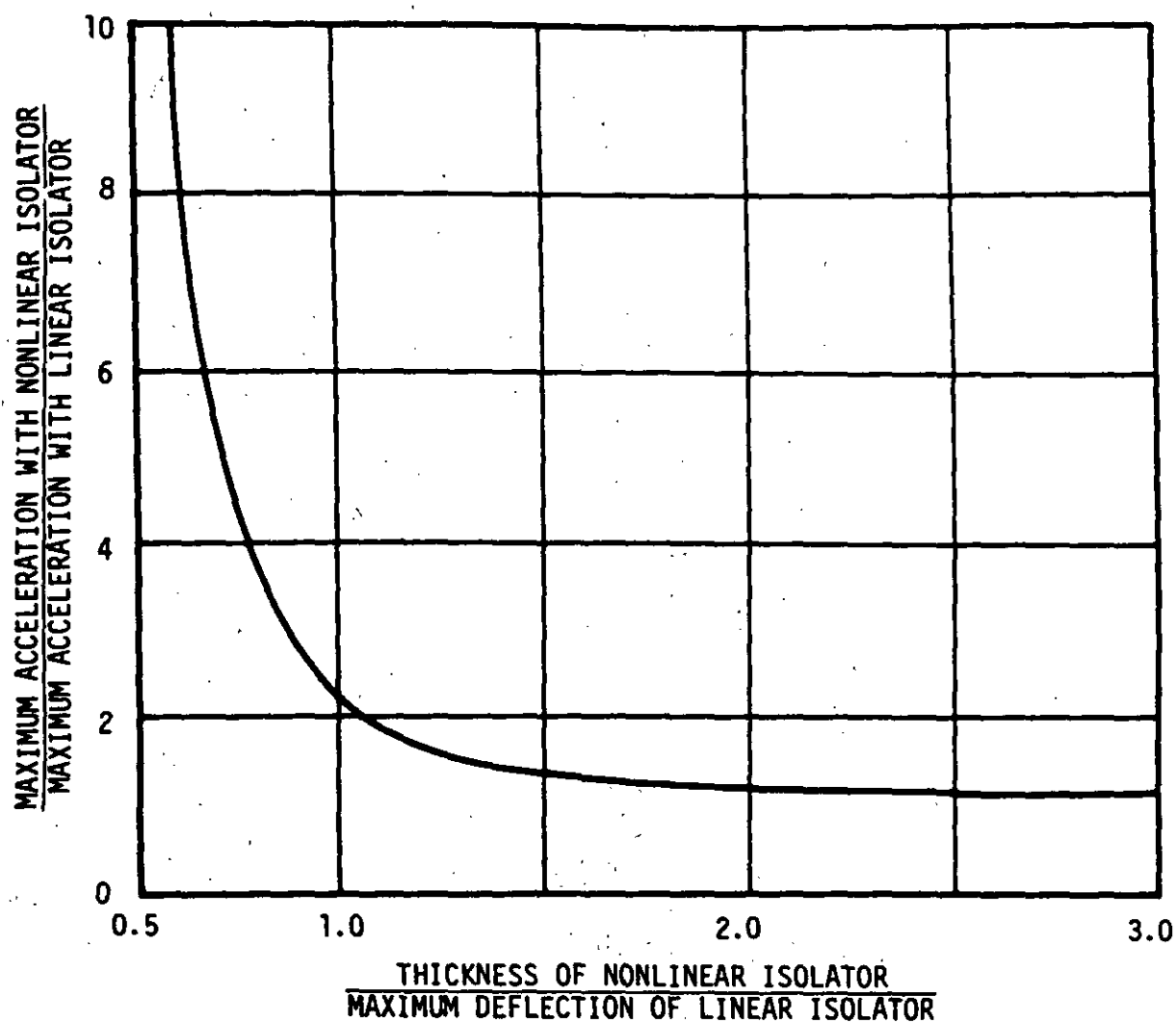


FIGURE 80. CHART FOR DETERMINING TRANSMITTED MAXIMUM ACCELERATION FOR NONLINEAR ISOLATORS (22)

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7. Rubber Under Special Environmental Conditions

7.1 High Temperature Characteristics

7.1.1 When rubber is exposed to elevated temperatures in the presence of oxygen, two possible mechanisms become effective. The polymer chain may break down (reversion), resulting in a lower modulus and an increase in ultimate elongation. In other elastomers, the reverse occurs; continued cross-linking results in higher moduli and lower ultimate elongations. At the same time, other processes which favor degradation are also accelerated. For instance, deterioration by oxidation proceeds at an increased rate.

7.1.2 The deterioration of rubber at elevated temperatures is determined by test from stress-strain measurements (generally in tensile tests), from compression-set characteristics, and from the behavior of the material in contact with fluid. In actual service, such properties as hardness, resilience, modulus, permeability to gases and liquids may be factors determining the usefulness of the rubber.

7.1.3 At elevated temperatures, the tensile strength of all elastomers decreases. After aging at elevated temperatures, some compounds show an increase in hardness and a decrease in flexibility. This is due to volatilization of plasticizers and oxidative embrittlement. Exceptions are the butyl rubbers and polyurethanes which experience softening at temperatures in the 400°F (200°C) range. Silicone rubber and fluoroelastomers maintain their original hardness best. Figure 81 compares the tensile strength, elongation, and hardness of a natural and a silicone rubber aged in air at 400°F (200°C).

7.1.4 To determine the maximum temperature to which a rubber component can be exposed, the considered application and the result which aging will have on the effectiveness of the rubber in this application must be examined. Whether or not the exposure is to dry heat, or whether exposure at elevated temperatures to fluids is expected, will determine temperature limitations.

7.1.5 Perhaps most important in the design of a rubber-containing component is allowance of adequate volume around the rubber for thermal expansion. Because rubber is virtually incompressible, high stresses result if thermal expansion is prevented. In applications where rubber is exposed to fluids and subject to consequent swelling, additional space for expansion must be allowed. This is particularly important since the rate of degradation of rubber is directly proportional to the magnitude of the stress. Consequently, at elevated temperatures where lowered overall properties are generally encountered, this effect is serious. A design that permits reductions in the amplitude and frequency of dynamic strains at elevated temperatures, compared to allowable amplitude and frequency levels at room temperature should result in longer service life. There are indications that thin sections are more adversely affected during elevated temperature exposure than are heavier sections.

7.1.6 Table XVIII shows the tensile and elongation properties of several rubber compounds before and after heat-aging at temperatures ranging from 73°F to 550°F (23°C to 288°C). In Table XIX, the elastomers are

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arranged in order of decreasing temperature at which 25 percent of loss of room temperature tensile strength results from heat-aging for eight hours. A typical natural rubber loses 25 percent of its strength after eight hours of exposure at 300°F (150°C).

7.1.7 When rubber is tested at elevated temperatures, the tensile strength is less than at room temperature. Table XX lists some elastomers and the temperature at which they lose 50 percent of the original room temperature tensile strength.

7.1.8 Changes in hardness, recorded after preheating and aging for one hour and eight hours, are recorded in Table XXI. Note that the hardness was not measured at the elevated temperature, but at room temperatures after the specimen had cooled to room temperature; therefore these values represent a residual effect of elevated temperature exposure.

7.1.9 The changes in tear strength are noted in Table XXII, which shows that chloroprene and natural rubber retain their capacity best in this respect.

7.1.10 The bar graph in Figure 82 is primarily presented to show the temperature-aging effect on tensile strength of several rubber types. Observe that when aging is not a factor, butyl rubber shows the greatest retention of tensile strength. However, the tensile strength after eight hours at 400°F (200°C) is below 500 psi (3.45 MPa) for the most heat resistant rubber in the group.

7.1.11 Heat-aging also affects elongation as shown in Figure 81.

7.1.12 Air permeability increases with increases in temperature, as discussed in 7.5.1.

7.1.13 An important factor in compounding elastomers for high temperature resistance is the use of reinforcement other than carbon black. However, such compounds may be difficult to process and fabricate, and conditions of high purity must be observed in their manufacture. Silicone rubber compounds usually do not use carbon black as reinforcement.

7.1.14 Rubber compounds may be grouped by characteristic behavior at elevated temperatures in three categories:

7.1.14.1 Rapid loss of strength with temperature increase:

- Natural Rubber (NR)
- Polyurethane Rubber (AU, EU)
- Chloroprene Rubber (CR)
- Styrene Butadiene Rubber (SBR)
- Acrylonitrile Butadiene Rubber (NBR)

7.1.14.2 Lower Percent loss of strength with increasing temperatures:

- Silicone Rubber (VMQ, PVMQ, FVMQ)
- Polysulfide Rubber (T)
- Fluorocarbon Rubber (FKM, FFKM)

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7.1.14.3 Sharp drop in tensile properties in the temperature range from 200 to 250°F (95 to 120°C), with a much smaller loss with further temperature rise:

Fluorocarbon Rubber (FKM)

Polychlorotrifluoroethylene Rubber (CFM)

7.1.15 Fluorocarbon rubbers, silicone rubbers, and fluorosilicone rubbers offer the greatest attraction as flexible materials of construction where prolonged exposure to oxidation, ozone, sunlight, and other adverse environmental conditions occur at high temperatures. Certain butyl or chlorobutyl compounds deserve examination for selected applications where the rubber is not exposed continuously to high temperatures (400°F (200°C) maximum). At very high temperatures, some fluorocarbon rubbers and silicone rubbers offer serviceability for brief periods. For example: at 500°F (260°C) vinylidene fluoride/hexafluoropropylene, methyl vinyl silicone, and methyl phenyl silicone are serviceable for 28 days. At 600°F (315°C) they are serviceable only for 72 hours. At 700°F (370°C) vinylidene fluoride/hexafluoropropylene alone remains usable for several hours, and at 800°F (425°C), for only 10 minutes.

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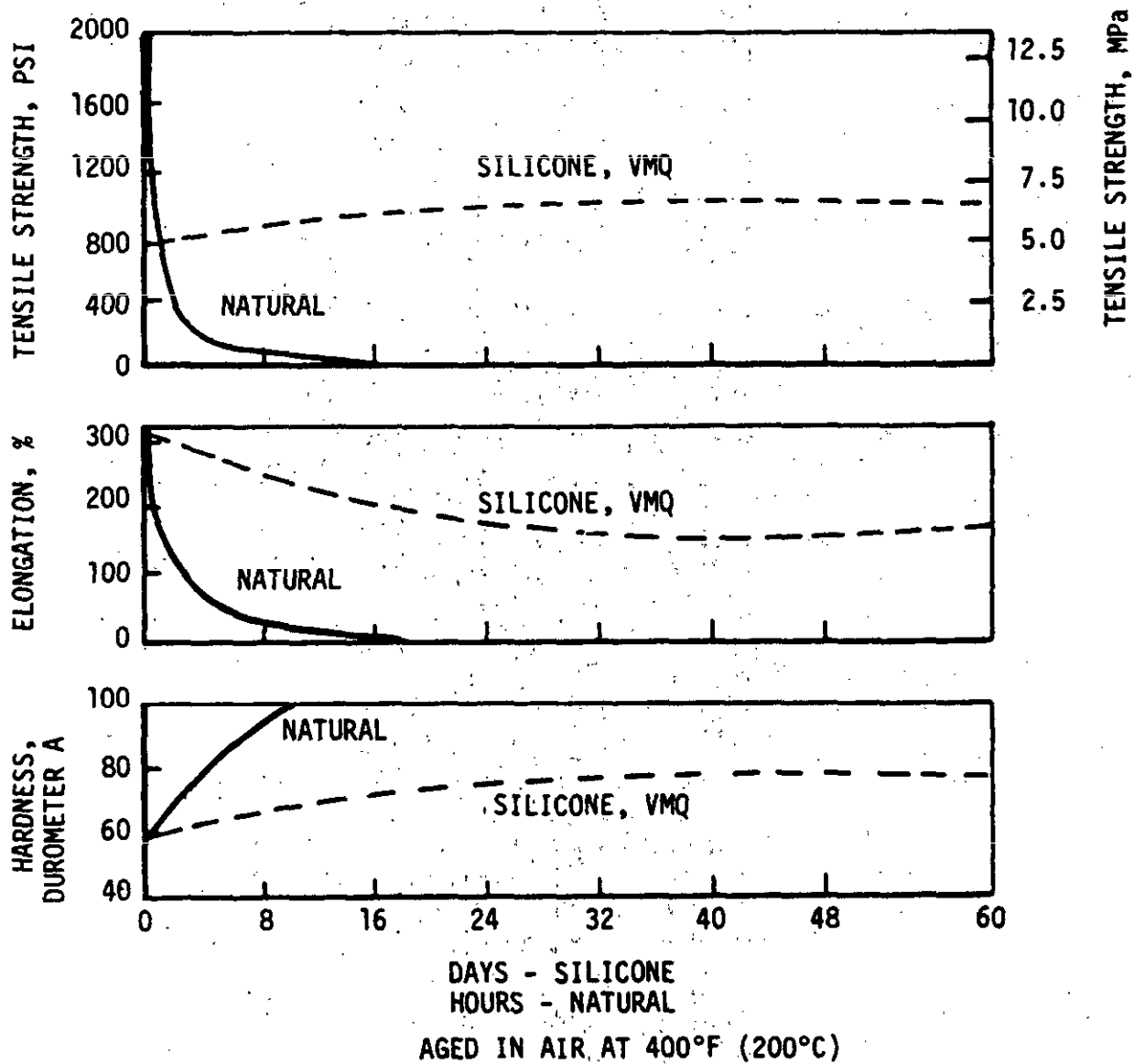


FIGURE 81. THE EFFECT OF HIGH TEMPERATURE AGING ON TENSILE STRENGTH, ELONGATION, AND HARDNESS, SILICONE (VMQ) AND NATURAL RUBBER (NR) (53)

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TABLE XVIII SUMMARY OF TENSILE PROPERTIES OF ELASTOMER COMPOUNDS
AT ELEVATED TEMPERATURES BEFORE AND AFTER HEAT AGING (73)

Rubber			Unaged								Aged 8 Hours							
			Tested at Temperature Shown, °F								Tested at Temperature Shown, °F							
			73	200	250	300	350	400	450	500	550	200	250	300	350	400	450	500
Acrylonitrile Butadiene ^b	NBR	T	2500	860	700	640	440	230	160	100	---	925	630	410	300	130	160	---
		E	300	140	120	100	70	40	20	10	---	170	80	80	20	20	10	---
Butyl ^c Phenol dialcohol cure	IIR	T	2050	1550	1320	1140	940	790	600	440	---	1470	1270	850	500	360	---	---
		E	440	330	340	260	200	150	120	100	---	330	300	180	120	90	---	---
Sulfur Cure		T	2325	1170	930	750	710	640	440	---	---	1240	730	600	410	---	---	---
		E	400	270	210	190	210	260	330	---	---	200	140	160	230	---	---	---
Sulfur plus Quinone Cure		T	1925	860	690	500	380	290	170	---	---	870	520	400	260	---	---	---
		E	360	210	190	170	130	100	120	---	---	200	130	100	110	---	---	---
Chloroprene ^d	CR	T	3550	1920	1570	1410	1320	770	380	215	---	1980	1680	1020	330	180	---	---
		E	480	360	320	320	350	100	30	10	---	320	240	100	20	10	---	---
Chlorosulfonated Polyethylene ^e	CSM	T	2175	660	470	460	470	440	380	170	---	740	720	670	400	200	270	400
		E	260	160	60	50	50	100	80	10	---	100	60	40	20	20	10	20
Fluorocarbon ^c (Kel-F 3700 [®])	CFM	T	2650	710	---	500	---	420	250	410	440	900	---	---	---	280	500	300
		E	300	130	---	100	---	90	50	80	---	120	---	---	---	70	110	90
Fluorocarbon ^c (Kel-F 5500 [®])	CFM	T	1775	340	300	230	---	165	---	150	---	370	190	220	---	160	---	155
		E	390	400	320	230	---	190	---	160	---	380	310	220	---	160	---	190
Fluorocarbon ^{c,d}	FDM	T	1200	450	345	225	210	225	165	---	---	475	360	265	215	140	135	---
		E	160	90	60	60	50	50	50	---	---	90	70	60	10	40	50	---
Fluorocarbon ^e (Viton A [®])	FDM	T	1625	440	---	260	---	180	180	150	90	420	---	---	---	200	200	110
		E	230	150	---	100	---	70	80	70	60	140	---	---	---	80	70	90
Methyl Phenyl Vinyl Silicone C.f.g	PMVQ	T	1650	960	---	720	---	430	390	350	310	870	---	660	---	410	390	290
		E	580	390	---	330	---	240	200	190	180	390	---	340	---	220	180	160
Methyl Vinyl Silicone C.f.g	VMQ	T	1000	830	---	500	---	480	280	330	270	760	---	560	---	420	340	270
		E	300	190	---	130	---	110	70	80	70	200	---	130	---	110	80	60
Natural ^b	NR	T	3850	2980	2460	1530	770	500	270	20	---	2730	800	690	400	125	---	---
		E	480	500	480	400	520	500	300	10	---	480	180	440	260	80	---	---
Polyacrylate ^b	ACM	T	1825	1330	940	630	610	495	460	370	290	1090	840	610	580	330	370	50
		E	370	240	200	160	150	100	100	60	20	180	120	100	80	20	20	20
Polysulfide ^b	EDT	T	1350	800	690	550	210	30	---	---	---	740	580	200	---	---	---	---
		E	240	180	140	120	110	50	---	---	---	140	120	60	---	---	---	---
Polyurethane ^b		T	5775	3220	2320	1260	1090	750	---	---	---	3450	2110	1340	580	100	---	---
		E	420	310	300	190	180	160	---	---	---	310	280	250	300	160	---	---
Polyurethane ^c		T	4240	1970	1320	810	690	515	380	---	---	1550	1180	800	530	240	65	---
		E	360	240	210	140	110	110	200	---	---	210	200	140	140	130	110	---
Polyurethane ^c (Adiprene C [®])	EU	T	4650	1130	580	280	270	60	---	---	---	770	470	290	30	---	---	---
		E	480	220	140	60	80	160	---	---	---	120	70	80	70	---	---	---
Styrene Butadiene ^b	SBR	T	3475	1680	1190	890	590	260	200	140	---	1625	990	270	220	170	100	60
		E	530	300	250	180	160	100	40	30	---	240	140	30	20	60	10	20

NOTES: a. Tests: Tensile strength (T) in psi, and Elongation (E) % at break, measured at the temperatures shown. All samples, both aged and unaged, were allowed to come to equilibrium temperature prior to actual test.
b. Preheat period of 30 minutes used to bring test strips to test temperature.
c. Preheat period of 6 minutes used to bring test strips to test temperature.
d. Postcure: 24 hours at 300°F.
e. Postcure: 1 hour at 300°F; 1 hour at 250°F; 8 hours at 400°F.
f. Postcure: 1 hour at 300°F; 8 hours at 480°F.
g. Data based on compounds subsequently discontinued, current compounds exceed these values.

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TABLE XVIII-SI SUMMARY OF TENSILE PROPERTIES OF ELASTOMER COMPOUNDS
AT ELEVATED TEMPERATURES BEFORE AND AFTER HEAT AGING (73)

Rubber	a	Unaged								Aged 8 hours							
		Tested at Temperature Shown, °C								Tested at Temperature Shown, °C							
		23	95	120	150	175	200	230	260	290	95	120	150	175	200	230	260
Acrylonitrile Butadiene ^b	NBR	T 17.2	5.93	4.83	4.41	3.03	1.58	1.10	0.69	---	6.38	4.34	2.83	2.07	0.90	1.10	---
		E 300	140	120	100	70	40	20	10	---	170	80	80	20	20	10	---
Butyl ^c	IR	T 14.1	10.7	9.10	7.86	6.48	5.45	4.14	3.03	---	10.1	8.76	5.86	3.45	2.48	---	---
Phenol dialcohol cure		E 440	330	340	260	200	150	120	100	---	330	300	180	120	90	---	---
Sulfur Cure		T 16.0	8.07	6.41	5.17	4.90	4.41	3.03	---	---	8.55	5.03	4.14	2.83	---	---	---
		E 400	270	210	190	210	260	330	---	---	200	140	160	230	---	---	---
Sulfur plus Quinone Cure		T 13.3	5.93	4.76	3.45	2.62	2.00	1.17	---	---	6.00	3.58	2.76	1.79	---	---	---
		E 360	210	190	170	130	100	120	---	---	200	130	100	110	---	---	---
Chloroprene ^b	CR	T 24.5	13.2	10.8	9.72	9.10	5.31	2.48	1.48	---	13.6	11.6	7.03	2.28	1.24	---	---
		E 480	360	320	320	350	100	30	10	---	320	240	100	20	10	---	---
Chlorosulfonated Polyethylene ^b	CSM	T 15.0	4.55	3.24	3.17	3.24	3.03	2.62	1.17	---	5.10	4.96	4.62	2.76	1.38	1.86	2.76
		E 260	160	60	50	50	100	80	10	---	100	60	40	20	20	10	20
Fluorocarbon ^c (Kal-F 3700 [®])	CFM	T 18.3	4.90	---	3.45	---	2.90	1.72	2.83	3.03	6.20	---	---	---	1.93	3.45	2.07
		E 300	130	---	100	---	90	50	80	90	120	---	---	---	70	110	90
Fluorocarbon ^c (Kal-F 5500 [®])	CFM	T 12.2	2.34	2.07	1.58	---	1.14	---	1.03	---	2.55	1.31	1.52	---	1.10	---	1.07
		E 390	400	320	230	---	190	---	160	---	380	310	220	---	160	---	190
Fluorocarbon ^{c,d}	FRM	T 8.27	3.10	2.38	1.55	1.45	1.55	1.14	---	---	3.27	2.48	1.83	1.48	0.96	0.93	---
		E 160	90	60	60	50	50	50	---	---	90	70	60	10	40	50	---
Fluorocarbon ^e (Viton A [®])	FRM	T 11.2	3.03	---	1.79	---	1.24	1.24	1.03	0.62	2.90	---	---	---	1.38	1.38	0.76
		E 230	150	---	100	---	70	80	70	60	140	---	---	---	80	70	50
Methyl Phenyl Vinyl Silicone ^{c,f,g}	PMV	T 11.4	6.62	---	4.96	---	2.96	2.69	2.41	2.14	6.00	---	4.55	---	2.83	2.65	2.00
		E 580	390	---	330	---	240	200	190	180	390	---	340	---	220	180	160
Methyl Vinyl Silicone ^{c,f,g}	VMQ	T 6.89	5.72	---	3.45	---	3.31	1.93	2.28	1.86	5.24	---	3.86	---	2.90	2.34	1.86
		E 300	190	---	130	---	110	70	80	70	200	---	130	---	110	80	60
Naturel ^b	NR	T 26.5	20.5	17.0	10.5	5.31	3.45	1.86	0.14	---	18.8	5.52	4.76	2.76	0.86	---	---
		E 480	300	480	400	320	500	300	70	---	480	180	640	260	80	---	---
Polyacrylate ^b	ACH	T 12.6	9.17	6.48	4.34	4.20	3.41	3.17	2.55	2.00	7.52	5.79	4.20	4.00	2.28	2.55	0.34
		E 370	240	200	160	150	100	100	60	20	180	120	100	80	20	20	20
Polysulfide ^b	EOT	T 9.31	5.52	4.76	3.79	1.45	0.21	---	---	---	5.10	4.00	1.38	---	---	---	---
		E 240	180	140	120	110	50	---	---	---	140	120	60	---	---	---	---
Polyurethane ^b		T 39.8	22.2	16.0	8.69	7.52	5.17	---	---	---	23.8	14.5	9.24	4.00	0.69	---	---
		E 420	310	300	190	180	160	---	---	---	310	280	250	300	160	---	---
Polyurethane ^c		T 29.2	10.8	9.10	5.58	4.76	3.55	2.62	---	---	10.7	8.14	5.52	3.65	1.65	0.45	---
		E 360	240	210	140	110	110	200	---	---	210	200	140	140	130	110	---
Polyurethane ^c (Adiprene C [®])	EU	T 32.1	7.79	4.00	1.79	1.86	0.41	---	---	---	5.31	3.24	2.00	0.21	---	---	---
		E 480	220	140	60	80	160	---	---	---	120	70	80	70	---	---	---
Styrene Butadiene ^b	SBR	T 24.0	11.6	8.20	6.14	4.07	1.79	1.38	0.96	---	11.2	6.62	1.86	1.52	1.17	0.69	0.41
		E 530	300	250	180	160	100	40	30	---	240	140	30	20	60	10	20

NOTES: a. Tests: Tensile strength (T) in MPa, and Elongation (E) % at break, measured at the temperatures shown. All samples, both aged and unaged, were allowed to come to equilibrium temperature prior to actual test.

b. Preheat period of 30 minutes used to bring test strips to test temperature.

c. Preheat period of 6 minutes used to bring test strips to test temperature.

d. Postcure: 24 hours at 150°C.

e. Postcure: 1 hour at 150°C; 1 hour at 175°C; 8 hours at 200°C.

f. Postcure: 1 hour at 150°C; 8 hours at 250°C.

g. Data based on compounds subsequently discontinued, current compounds exceed these values.

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TABLE XIX. SHORT-TERM HEAT AGING OF ELASTOMER COMPOUNDS (13)

Elastomer		Temperature ^a	
		OF	OC
Vinylidene fluoride/ hexafluoropropylene		530	270
Methyl silicone	MC	450	230
High strength silicone	PVMQ	450	230
Chlorotrifluoroethylene/ vinylidene fluoride	CFM	450	230
Methyl vinyl silicone	VMQ	430	220
Fluorinated silicone	FVMQ	430	220
Isobutylene/isoprene	IIR/IR	410	210
Ethyl acrylate/chloroethyl vinyl ether		390	200
Chlorosulfonated polyethylene	CSM	370	185
Poly 1, 1 dihydroperfluoro butyl acrylate		370	185
Chlorinated isobutylene/isoprene	CIIR/IR	350	175
Brominated isobutylene/isoprene	BIIR/IR	340	170
Polychloroprene	CR	330	165
Styrene butadiene	SBR	310	155
Acrylonitrile butadiene	NBR	310	155
Acrylonitrile butadiene/acrylic acid		310	155
Polyurethane		310	155
Natural Rubber	NR	300	150

^a Temperature at which compounds retained 75 percent of original tensile strength, tested at room temperature after 8 hours exposure to elevated temperature.

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TABLE XX. TEMPERATURES AT WHICH ELASTOMERS RETAIN 50 PERCENT
OF ORIGINAL TENSILE STRENGTH AT TEST TEMPERATURE (13)

Elastomer		Temperature	
		°F	°C
Methyl silicone	MQ	450	230
Methyl vinyl silicone	VMQ	450	230
High strength silicone	PVMQ	350	175
Brominated isobutylene/isoprene	BIIR/IR	300	150
Chlorinated isobutylene/isoprene	CIIR/IR	270	130
Isobutylene/isoprene	IIR/IR	270	130
Styrene butadiene	SBR	240	115
Natural Rubber	NR	230	110
Polychloroprene	CR	210	100
Polyurethane		200	95
Acrylonitrile butadiene/ acrylic acid		200	95
Acrylonitrile butadiene	NBR	200	95
Chlorosulfonated polyethylene	CSM	200	95
Fluorinated silicone	FVMQ	190	90
Poly 1, 1 dihydroperfluoro butyl acrylate		180	80
Vinylidene fluoride/ hexafluoropropylene	FKM	180	80
Chlorotrifluoroethylene vinylidene fluoride	CFM	170	70

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TABLE XXI HARDNESS OF RUBBER AFTER HEAT AGING IN AIR FOR ONE AND EIGHT HOURS, TESTED AT ROOM TEMPERATURE (13)

Rubber		Original	Exposure Temperature							
			Exposure Time 1 Hour				Exposure Time 8 Hours			
			200°F (95°C)	300°F (150°C)	400°F (200°C)	500°F (260°C)	200°F (95°C)	300°F (150°C)	400°F (200°C)	500°F (260°C)
Hardness, Durometer A ^a										
Acrylonitrile Butadiene	NBR	70	69	72	75	78	72	80	79	84
Butyl	IIR	66	65	65	70	72	65	70	70	-
Butyl	IIR	55	52	55	43	-	55	52	20	-
Butyl	IIR	57	53	56	41	-	55	62	35	-
Chloroprene	CR	68	70	72	73	90	70	74	83	90
Chlorosulfonated Polyethylene	CSM	74	74	75	76	74	74	75	87	-
Fluorocarbon	FKM	67	60	60	60	60	60	60	60	55
Fluorocarbon (Viton A®) ^b	FKM	72	70	67	62	68	69	65	64	70
Methyl Phenyl Vinyl Silicone ^c	PVMQ	52	52	52	52	52	53	52	54	54
Methyl Vinyl Silicone ^c	VMQ	51	51	50	50	48	50	50	52	51
Natural Rubber	NR	68	69	68	59	-	70	67	72	-
Polyacrylate (Acrylon EA-5®)	ACH	76	75	75	77	81	78	-	80	86
Polyacrylate (Hycar 4021®)	ACH	74	72	74	75	82	77	77	80	96
Polyacrylate (Vyram, M-5400®)	ACH	68	70	71	d	d	70	78	d	d
Polysulfide	EDT	67	69	68	-	-	64	66	-	-
Polyurethane		65	65	67	62	-	66	66	-	-
Polyurethane		62	62	64	56	e	63	63	e	e
Polyurethane (Adiprene C®)	EU	67	66	66	e	e	68	58	e	e
Styrene Butadiene	SBR	65	66	68	67	66	67	68	66	66

^a Test blocks were allowed to rest 12 hours or more at room temperature after preheating or aging period before Durometer hardness was measured.

^b Postcure: 4 hr at 300°F (150°C); 8 hr at 350°F (175°C); 8 hr at 400°F (200°C).

^c Postcure: 4 hr at 300°F (150°C); 8 hr at 350°F (175°C); 8 hr at 400°F (200°C); 4 hr at 480°F (250°C).

^d Too brittle.

^e Melted.

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TABLE XXII. TEAR STRENGTH OF ELASTOMER COMPOUNDS
AT ELEVATED TEMPERATURES (13)

Rubber		Test Temperature				
		730F (230C)	2000F (950C)	3000F (1500C)	4000F (2000C)	5000F (2600C)
		Tear Strength, lb per in. (N/mm)				
Acrylonitrile						
Butadiene	NBR	228 (40)	98 (17)	63 (11)	49 (8.6)	18 (3.2)
Butyl	IIR	332 (58)	195 (34)	165 (29)	72 (13)	35 (6.1)
Butyl	IIR	234 (41)	163 (28)	137 (24)	91 (16)	-
Butyl	IIR	166 (29)	100 (18)	70 (12)	25 (4.4)	-
Chloroprene	CR	696 (122)	323 (56)	218 (38)	101 (18)	13 (2.3)
Chlorosulfonated						
Polyethylene	CSM	256 (45)	56 (9.8)	36 (6.3)	19 (3.3)	16 (2.8)
Fluorocarbon		118 (21)	34 (6.0)	16 (2.8)	11 (1.9)	6 (1.0)
Fluorocarbon	CFM					
(Kel-F 3700)		134 (23)	69 (12)	38 (6.6)	24 (4.2)	-
Fluorocarbon	FKM					
(Viton A)		179 (31)	62 (11)	23 (4.0)	4 (0.7)	-
Methyl Phenyl Vinyl						
Silicone	PVMQ	187 (33)	83 (14)	54 (9.4)	42 (7.4)	-
Methyl Vinyl						
Silicone	VMQ	68 (12)	39 (6.8)	32 (5.6)	18 (3.2)	-
Natural Rubber	NR	864 (151)	362 (63)	311 (54)	204 (36)	-
Polyacrylate	ACM					
(Acrylon EA-5)		216 (38)	109 (19)	58 (10)	60 (10)	26 (4.6)
Polyacrylate	ACM					
(Hycar 4021)		226 (40)	117 (20)	65 (11)	37 (6.5)	18 (3.2)
Polyacrylate	ACM					
(Vyram, N-5400)		194 (34)	70 (12)	50 (7.0)	14 (2.5)	-
Polysulfide	T	218 (38)	182 (32)	148 (26)	12 (2.1)	-
Polyurethane		308 (54)	155 (27)	101 (18)	92 (16)	-
Polyurethane		214 (37)	79 (14)	45 (7.9)	32 (5.6)	-
Polyurethane	EU					
(Adiprene C)		211 (37)	68 (12)	33 (5.8)	20 (3.5)	-
Styrene						
Butadiene	SBR	304 (153)	192 (34)	114 (20)	50 (10)	19 (3.3)

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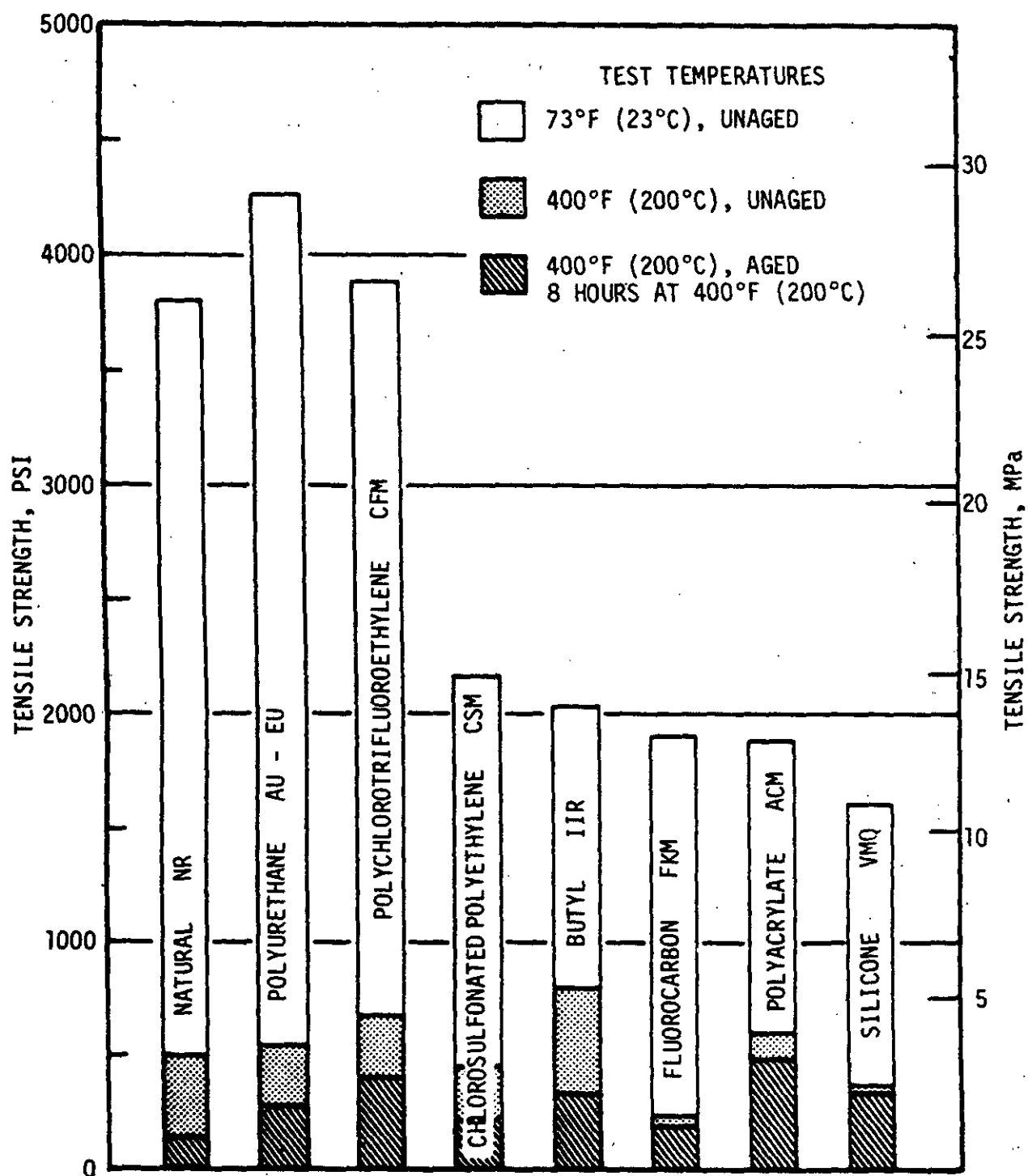


FIGURE 82. TENSILE STRENGTH OF AGED AND UNAGED ELASTOMERS (9)

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7.2 Low Temperature Characteristic

7.2.1 The elastic properties of rubber undergo important changes when the material is exposed to low temperature environments. For low-temperature rubber applications, the effects of greatest concern include changes in flexibility, changes in compression-set characteristics, the occurrence of brittleness, the state in which the rubber no longer performs as a highly resilient material, and the loss of sealability or the ability to reseal as in an O-ring application. In most cases these "lost" attributes are regained with the return to room temperature, provided the rubber part has not been physically damaged during the low temperature exposure.

7.2.2 As the temperature decreases from room temperature, some rubbers, especially natural rubber, man-made isoprene, and chloroprene, undergo first-order transition, which is associated with crystallization and is enhanced by deformations. Crystallization may require a period ranging from hours to weeks or even months exposure to low temperature, and is accompanied by increased stiffness, increased hardness, and changes in volume, coefficient of thermal expansion, and specific heat. The crystallization rate increases with increasing strain, and with increasing rate of strain, that is, the rate of load application. Some compounds show rapid increase of modulus within the first 20 hours of low-temperature exposure, remaining nearly constant afterward. Others show continued increase over the entire period of exposure. A Navy installation in the Arctic Circle conducted tests over a period of one year during which the temperature remained below -20°F (-30°C) for more than three months. They found that natural rubber stocks showed an increase of 40 points hardness over laboratory results obtained at -20°F (-30°C). Chloroprene stocks were 10 points harder under the same conditions.

7.2.3 All rubbers undergo a secondary transition at some temperature, which is known as the "glass transition temperature", T_g . This is the temperature at which a polymer changes from a glassy to a rubbery state as the temperature is raised. Thermal motion of major segments of the backbone chain begin here as the temperature is raised.

7.2.3.1 Various methods of measurement are used to determine T_g of polymers. One common method is to determine the temperature dependence of the specific volume. Using this method, the T_g is the temperature at which the volume temperature curve changes slope (See Figure 83). The heat capacity, H , of a polymer varies with temperature and is also used to estimate the T_g . When the heat capacity, H , is plotted against temperature, as in Figure 84, there is a discontinuity at the glass transition temperature, T_g . A plot of loss tangent ($\tan \delta$) as a function of temperature shows a pronounced peak at the T_g , as shown in Figure 39. (See 4.24.3.3.)

7.2.3.2 The T_g is important because it may determine the suitability of a polymer for specific uses. For a polymer to serve as a useful rubber rather than a plastic at room temperature, the T_g must be well below room temperature. For example, the T_g for polyisoprene (natural rubber) is about -92°F (-70°C), that of styrene butadiene, SBR, is about -60°F (-50°C), while the polybutadienes, BR, exhibit T_g values as low as -150°F (-100°C) and the methyl phenyl silicones, PMQ and PVMG, have T_g values as low as about -190°F (-120°C):

7.2.3.3 Three parameters affect the T_g values of a vulcanizate: plasticizer content; molecular weight of the polymer, and the degree of crosslinking. Plasticizers (low molecular weight, nonvolatile compounds) are often added to a polymer to make it more flexible or easier to process by lowering the T_g . (See Figure 85.) Experimental results on some polymers also show that as the molecular weight increases, the T_g rises. When a polymer is crosslinked by a method that introduces no foreign group (as by irradiation), the specific volume of the polymer decreases linearly with the number of crosslinks, provided the crosslinking density is not too high. The specific volume of polyisoprene (NR) at 20°C is, for example, 1.104 cm^3g^{-1} when the polymer contains 2×10^{20} crosslinks per gram. Increase in density restricts segmental motion and raises the range of temperatures in which the glass transition occurs. The value of T_g increases linearly with the number of crosslinks, provided by crosslinks are not too numerous. The T_g of linear polyisoprene increases 6°C for every increase of 10^{20} crosslinks per gram. When the density of crosslinks is very high, the glass transition occurs over a broad range of temperatures and it is difficult to assign a single value to T_g .

7.2.3.4 As the temperature of a vulcanizate is reduced through the T_g range, changes occur in behavior of a vulcanizate, such as increase in stiffness and hardness. Resilience initially decreases, but then increases with continuing decline in temperature. (See 4.9.4 and Figure 13.)

7.2.4 Second-order transitions usually take place quite rapidly and within a small temperature range. They are preceded by substantial changes in elastic properties. The temperature at which a state of brittleness occurs varies with elastomer compounding and test conditions. Plasticizers can affect the stiffening of rubber compounds. Some plasticizers lower the brittle point; some raise it. Some of the plasticizers which lower the brittle point are not completely soluble in the rubber at low temperatures, and will gradually come out of the solution if the rubber is held at these temperatures. If this happens, the rubber becomes stiffer and its brittle point rises.

7.2.5 The changes in elastic properties at low temperatures have been described in a number of ways. One criterion is the stiffening point, the temperature at which Young's modulus reaches 10,000 psi (69 MPa). Comparative criteria relate the degree of stiffness at low temperature to that at room temperature. These are noted in terms such as T_5 or T_{10} ; that is, the temperature at which the rubber becomes 5 times or 10 times as stiff as it is at room temperature.

7.2.6 In Table XXIII, the temperature at which similar changes in modulus occur in various rubbers, determined dynamically at two different frequencies, is presented. T_a represents the temperature at which the modulus of elasticity is increased by 20 percent, and T_{10} the temperature at which the rubber increases its room temperature stiffness ten times.

7.2.7 In Figure 86, a tensile stress-strain curve for SBR at various temperatures from +75°F (+24°C) to -76°F (-59°C) is presented. Figure 87 presents Young's modulus versus exposure time at three equilibrium temperatures. Figure 88 shows the ratio of stress required at the indicated temperature to that required to produce the same elongation at room

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temperature. Table XXIV summarizes the brittle temperature ranges of six elastomers. Figure 89 represents compression-recovery characteristics of a natural rubber, an SBR, and a silicone rubber as a function of temperature. The compression set of the silicone remains nearly constant over a wide range of temperatures (5 to 15 percent).

7.2.8 Low temperature flexibility may be improved by the addition of certain plasticizers to the compound. However, this is usually at the sacrifice of other properties such as tear and abrasion resistance, and bondability. Continuous contact with fuels, which normally causes a limited degree of swelling, will also lower the brittle temperature, as is shown in Table XXV for chloroprene and nitrile rubbers immersed in fuels for thirty days.

7.2.9 Design considerations for low-temperatures are as follows: (1) Lowest temperature during operation or in transit, (2) Longest duration of exposure time to this low temperature, (3) Temperature of long time exposure, (4) Rate of loading, (5) Service application (vibration or shock isolation, fuel container), (6) Highest temperature exposure, (7) Environmental conditions (fuel, oil oxidation).

7.2.10 The interrelation between plasticizer and crystallization effects and the mechanical properties is complex and cannot be predicted. It is necessary, therefore, to determine the dynamic or static properties as a function of temperature using conventional test methods. Each type of product should be evaluated by a specific test procedure that relates low temperature behavior to the expected serviceability of that product.

7.2.10.1 Rubber parts, such as bellows, dust covers, hoses, and door seals, that are exposed to atmospheric weathering, would be evaluated by the brittleness test, ASTM Standard D2137 (formerly ASTM Standard D746 and ASTM Standard D736), the Young's modulus test, ASTM Standard D797, and the torsional stiffness test, ASTM Standard D1053, or combination of two or more of these.

7.2.10.2 Packings or seals designed to operate immersed in fluids would be evaluated by temperature retraction or elastic recovery test, ASTM Standard D1329. The "TR-10" value of ASTM Standard D1329, which correlates directly to low temperature static O-ring sealing, would be approximately 150°F (80°C) above the temperature at which an O-ring will maintain a static seal, independent of type of rubber or fluid. This relationship is dependent on sufficient compatibility of the rubber and the fluid, and reasonable resistance of the rubber to compression set. In the TR Test, the characteristic "snap back" of an elastomer at room temperature becomes "crawl back" at low temperatures. An elastomer sample is stretched, usually approximately 50 percent, and then cooled well below the glass transition temperature, T_g , to become a rigid frozen plastic column which does not recover at all upon release. The released sample is heated at a fixed rate (10°F or 1°C per minute) and the percent retraction versus temperature curve is plotted. Figure 90 shows a typical temperature retraction curve for elastomers that do not crystallize. Figure 91 shows a typical TR curve for a strongly crystallizable elastomer; the sag indicates the range of temperatures over which the crystallites were melting out, and the amount of departure from the typical sigmoid curve is an indication of the degree of crystallinity. The complete TR curve can be used

directly by a designer to note the degradation of elastomeric recovery with dropping temperature. The TR-10 point is often used as a go-no-go value in material specifications for elastomers to be used in seals and represents the temperature where 10 percent retraction occurs for a specimen at low elongation, such as 50 percent. The designer would be well advised to become proficient using TR-10 data in O-ring design.

7.2.10.3 Seals and tires would be evaluated by low temperature set, ASTM Standard D1229, or by a combination of set and stiffness. The low temperature compression set test measures the lack of elastic recovery from compression, whereas the temperature retraction test (7.2.10.2) measures the same phenomenon, but, in tension. In ASTM Standard D1229 tests, a rubber button is compressed at room temperature between metal plates to a deformation set by spacers, then placed in a cold chamber. After 22 or 94 hours, the sample is released from compression and allowed to recover for 30 minutes while still in the cold temperature. The amount the sample fails to recover from deformation is the cold set, expressed in percent. As the rubber approaches the plastic state, as testing at progressively lower temperatures indicates, the cold set approaches 10 percent. The meaning for pneumatic O-ring service becomes immediately apparent. If the test is conducted at the optimum crystallization temperature of the rubber, the set after 94 hours may be grossly higher than after 22 hours. If the crystallization continues to an asymptotic condition, the cold set will exceed 100 percent. This "shrinkage" is due to the more ordered state of a partly crystalline as compared to an amorphous elastomer. The implication to sealing power is apparent: any shrinkage of a seal is usually considered decidedly undesirable. This test should be used in development testing and should not be used for routine quality tests of material specifications.

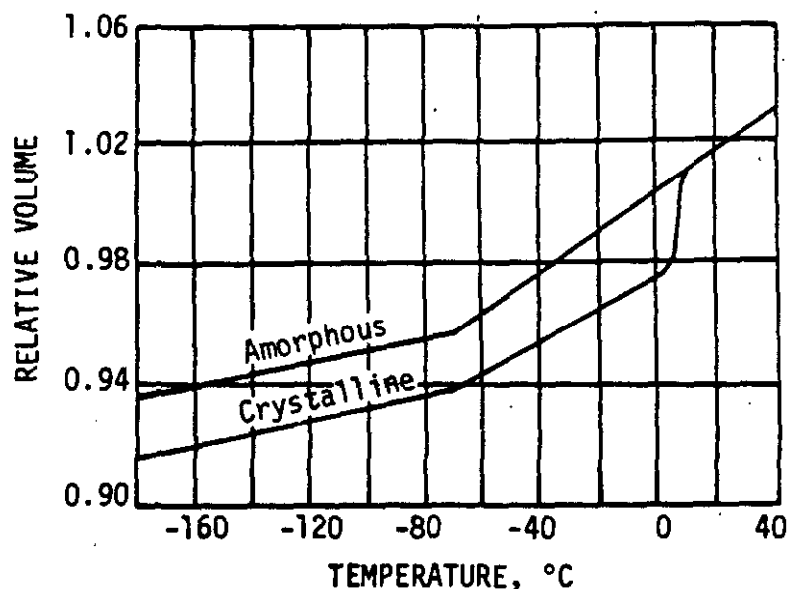


FIGURE 83. VOLUME BEHAVIOR OF RUBBER NEAR THE GLASS TRANSITION TEMPERATURE, T_g (12)

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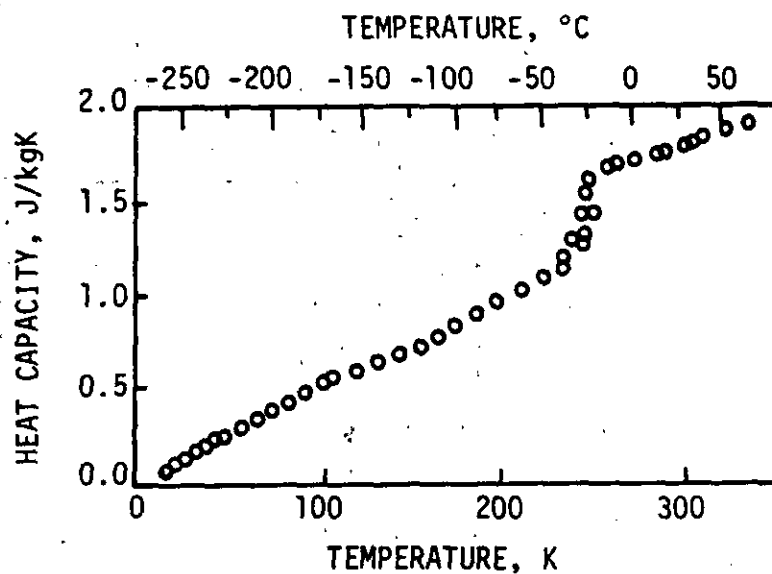
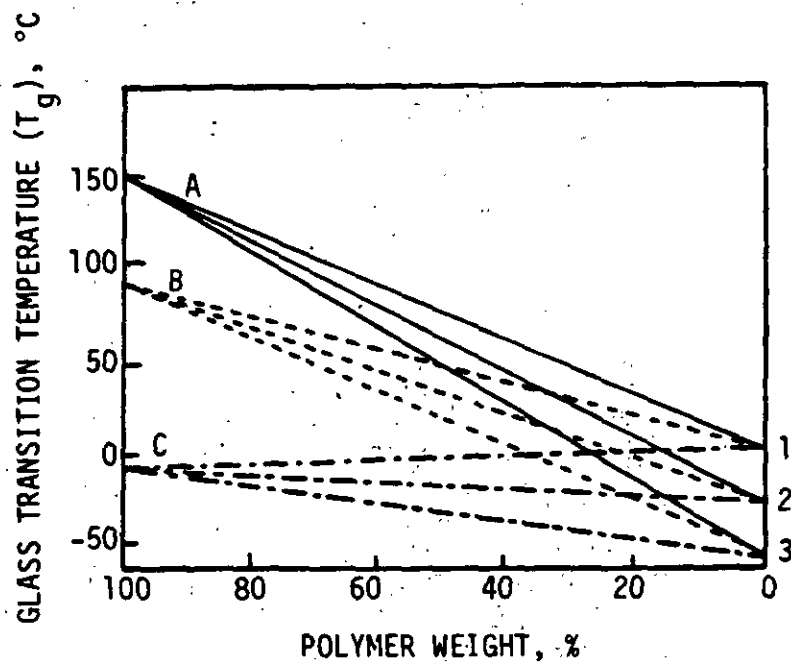


FIGURE 84. TEMPERATURE DEPENDENCE OF THE HEAT CAPACITY OF AN SBR COPOLYMER (56)



- A - POLYSTYRENE-ACRYLONITRILE COPOLYMER
- B - POLY(VINYL ACETATE)
- C - POLYCHLOROPRENE
- 1 - DIMETHYLCYCLOHEXYL ADIPATE
- 2 - TRICRESYL PHOSPHATE
- 3 - DI-n-HEXYL PHTHALATE

FIGURE 85. EFFECT OF DIFFERENT PLASTICIZERS ON THE GLASS TRANSITION TEMPERATURE, T_g , OF THREE POLYMERS (56)

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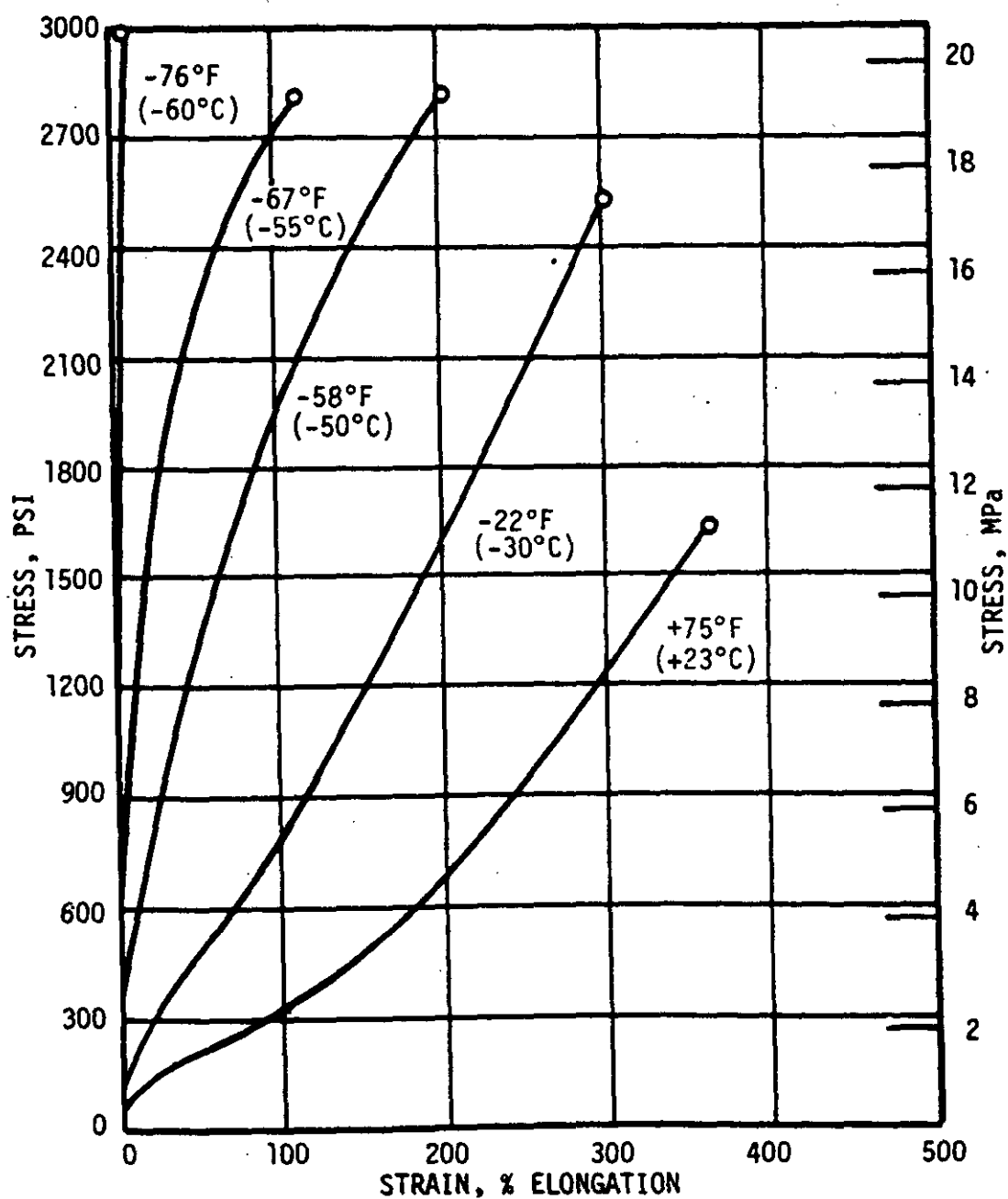


FIGURE 86. STRESS-STRAIN CURVES AT VARIOUS TEMPERATURES FOR SBR RUBBER (61)

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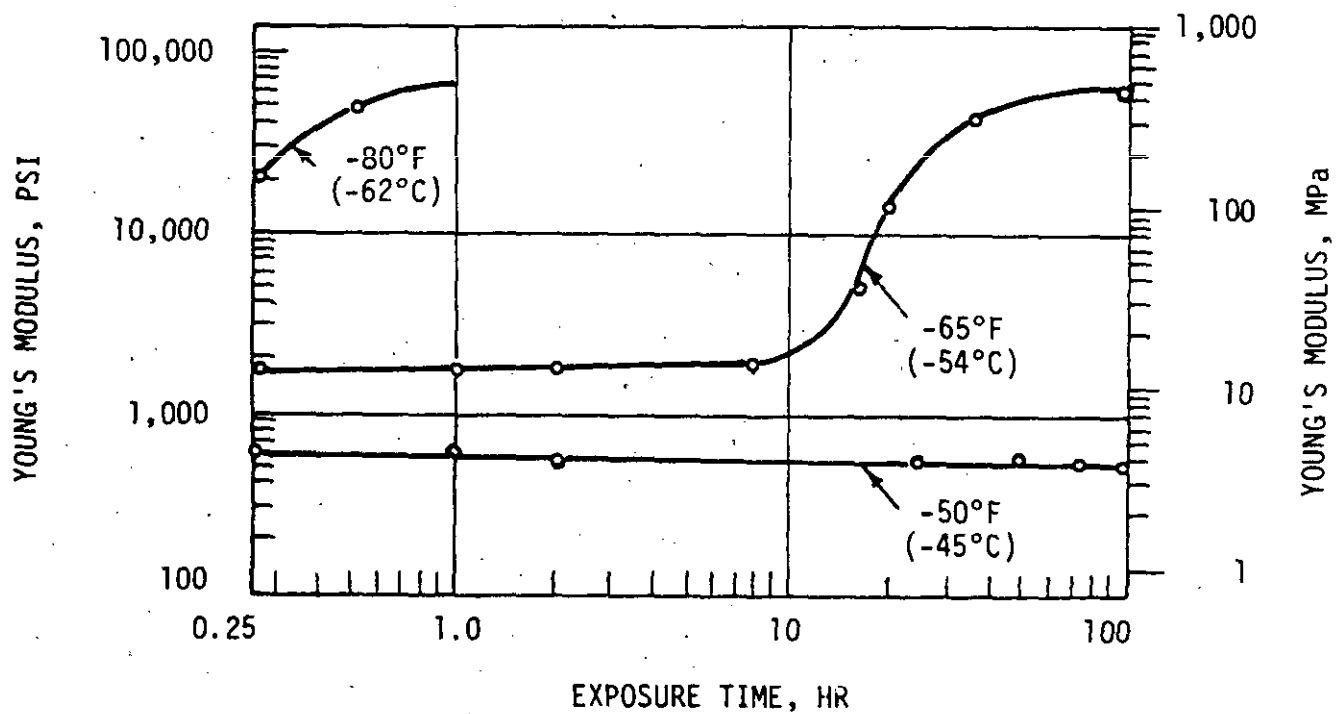


FIGURE 87. YOUNG'S MODULUS VS EXPOSURE TIME AT LOW TEMPERATURE, DIMETHYL SILICONE RUBBER (MQ) (15)

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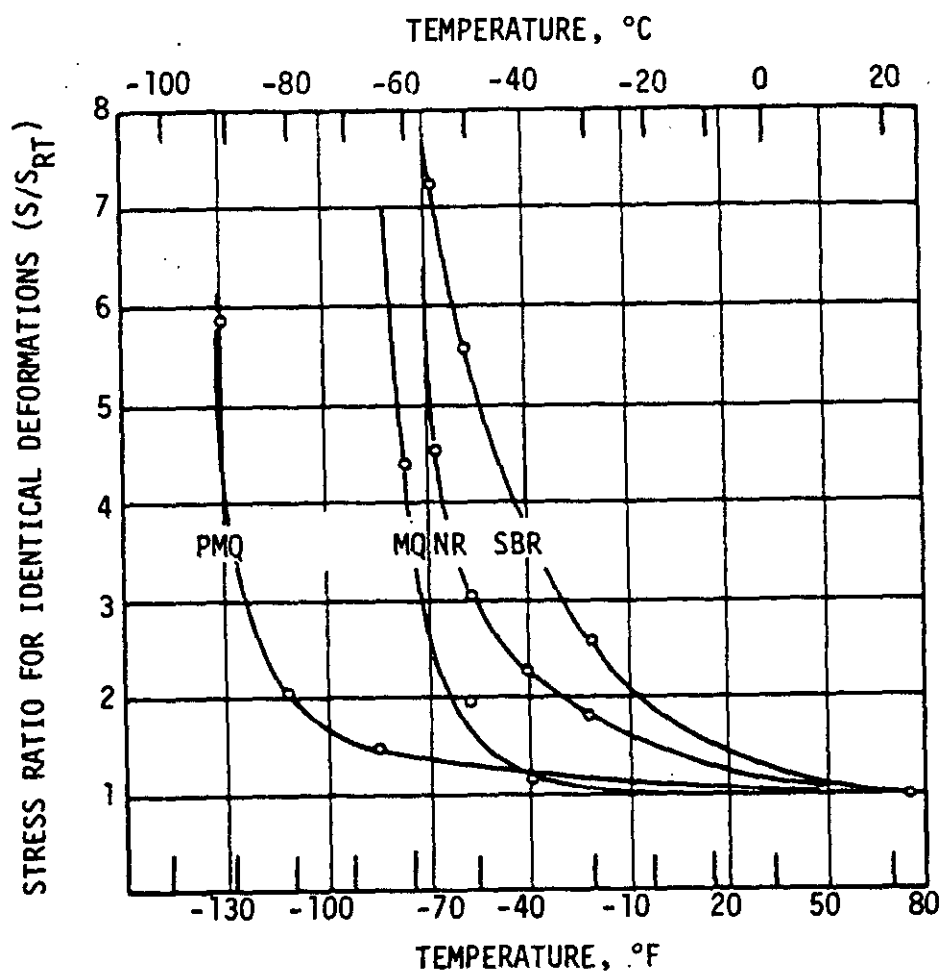


FIGURE 88. STRESS RATIO VS TEMPERATURE FOR SILICONE, NATURAL, AND SBR RUBBER (61)

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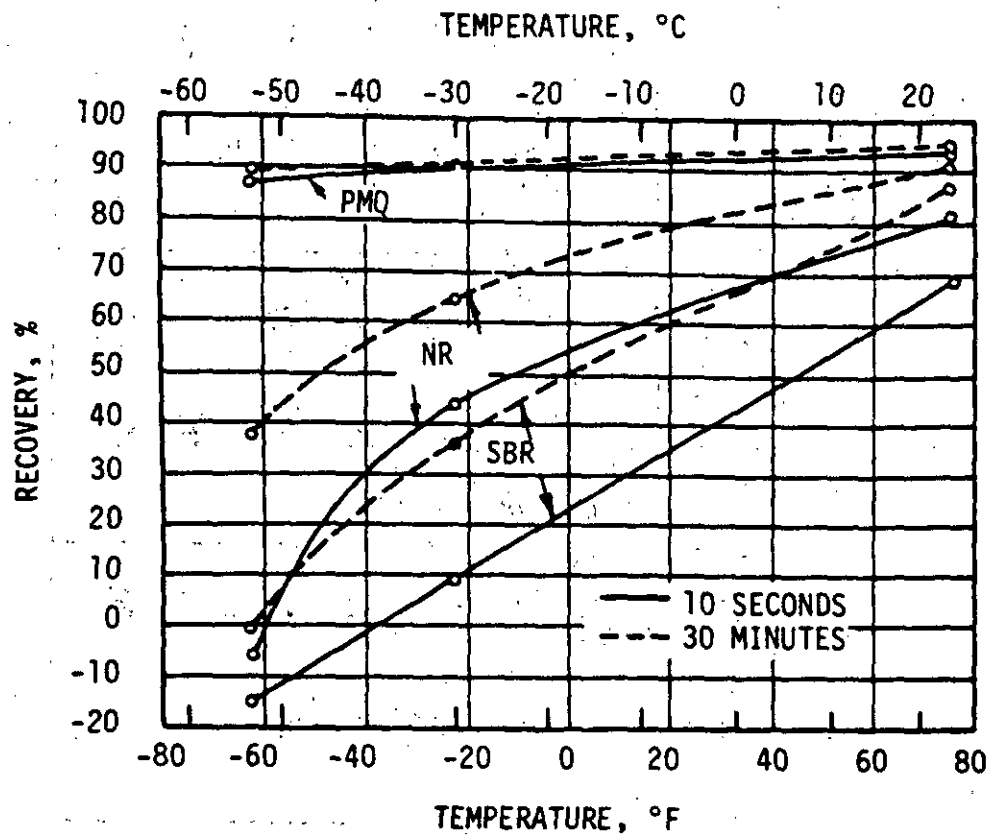


FIGURE 89. RECOVERY FROM COMPRESSION AT VARIOUS TEMPERATURES, DETERMINED 10 SECONDS AND 30 MINUTES AFTER RELEASE, SILICONE (PMQ), NATURAL (NR), AND SBR RUBBER (61)

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TABLE XXIII. CHANGES IN ROOM TEMPERATURE MODULUS OF ELASTICITY AT LOW TEMPERATURES, DETERMINED AT TWO FREQUENCIES

Rubber	10 cpm Frequency		1000 cpm Frequency	
	T _a Modulus Increase by 20% °F °C	T ₁₀ Modulus Increase 10 Times °F °C	T _a Modulus Increase by 20% °F °C	T ₁₀ Modulus Increase 10 Times °F °C
Acrylonitrile Butadiene (70/30)	+32 0	-3 -19	+68 +20	+32 0
Butyl	+14 -10	-22 -30	+86 +30	+50 +10
Chloroprene	+5 -15	-31 -35	+41 +5	+5 -15
Silicone, Low Temperature	-76 -60	-122 -86	---	---
Natural	-40 -40	-76 -60	-4 -20	-32 -36
Styrene Butadiene (75/25)	-4 -20	-40 -40	+32 0	-4 -20

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TABLE XXIV. BRITTLE TEMPERATURE RANGE OF BASIC RUBBER TYPES (52)

Rubber		Brittle Temperature	
		°F	°C
Acrylonitrile Butadiene	NBR	-20 to -60	-30 to -50
Acrylonitrile Butadiene, Low Swell	NBR	+10 to -40	-12 to -40
Butyl	IIR	-55 to -65	-48 to -54
Chloroprene	CR	-20 to -70	-30 to -57
Natural	NR	-60 to -70	-50 to -57
Silicone	VMQ	-90 to -112	-68 to -80
Silicone, Low Temperature	PMW PVMQ	-160 to -180	-107 to -118
Styrene Butadiene	SBR	-60 to -70	-50 to -57

TABLE XXV. BRITTLE TEMPERATURES AFTER 30-DAY FUEL IMMERSION, CHLOROPRENE AND ACRYLONITRILE BUTADIENE RUBBERS (52)

	Brittle Temperature					
	Chloroprene		Acrylonitrile Butadiene		Acrylonitrile Butadiene Low Swell	
	°F	°C	°F	°C	°F	°C
Original	-32	-35	-17	-27	+8	-13
After Immersion in the Following Fuels						
Isooctane	-60	-50	-32	-35	+6	-14
Gasoline	-87	-66	-42	-41	-5	-21
Gasoline with Aromatics	-107	-77	-107	-77	-63	-53

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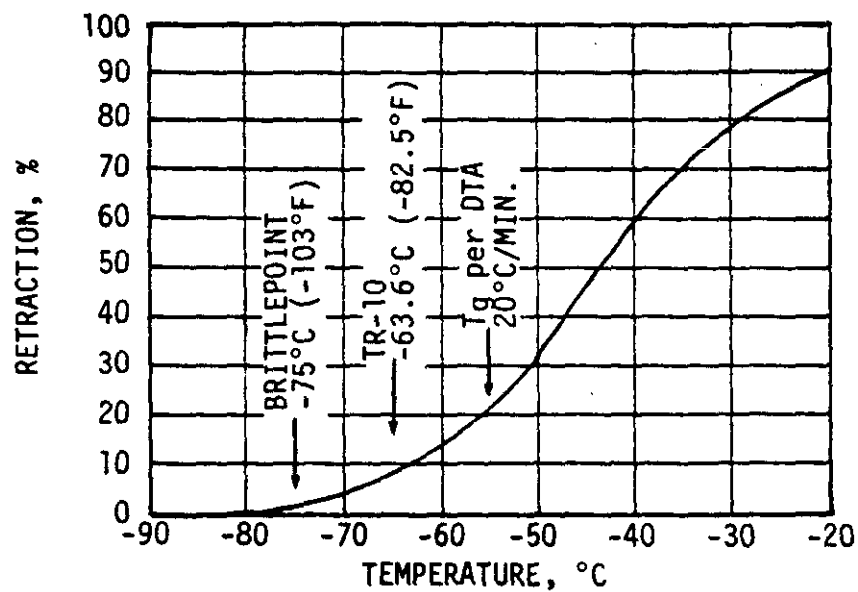


FIGURE 90. RELATIONSHIP BETWEEN GLASS TRANSITION, T_g , TEMPERATURE RETRACTION, TR-10, AND BRITTLEPOINT FOR A SPECIFIC ETHYLENE-PROPYLENE, EPM, RUBBER COMPOUND, AS SHOWN ON A COMPLETE TEMPERATURE RETRACTION CURVE (28)

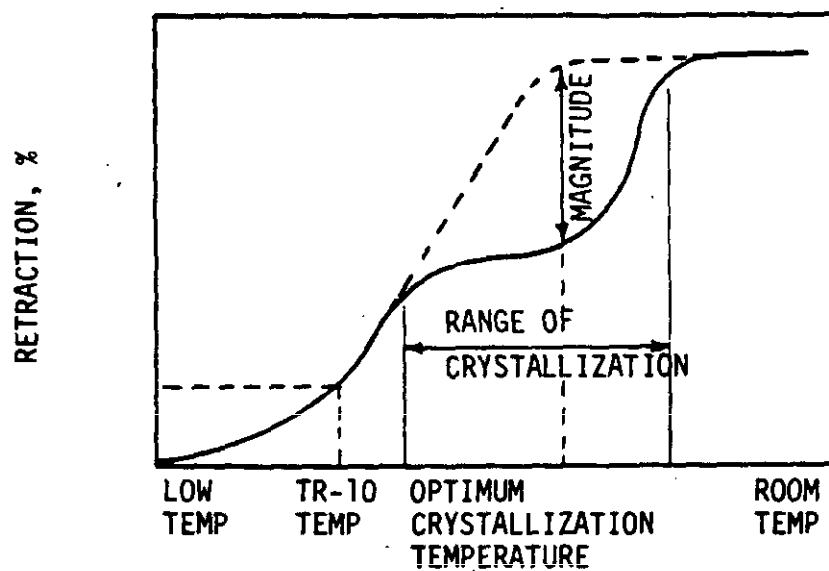


FIGURE 91. TEMPERATURE RETRACTION CURVE FOR A STRONGLY CRYSTALLIZABLE ELASTOMER (28)

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7.3 Fluid Resistance

7.3.1 The fluid resistance of rubber is characterized by the degree of swelling which occurs in the presence of the fluid. The smaller the swelling or volume growth, the greater the resistance to the particular fluid. Swelling is an important consideration from two standpoints. First, the ensuing volume increase must be accommodated, and second, the effects of deterioration of physical properties resulting from the interaction of the fluid and the rubber must be considered. Swelling is not necessarily associated with destructive effects. Although some liquids will swell a rubber compound as much as 200 percent or more, the properties of the rubber may remain essentially unchanged upon evaporation of the liquid. On the other hand, some fluids have a slow deteriorating influence, causing irreversible and permanent damage. Typical curves for loss in tensile strength, elongation, and hardness for nitrile rubber as a function of percent volume swell are shown in Figures 92 through 94. The curves have similar shapes for all rubbers affected by fluids. Actual values must be determined for the compound with the fluid to which it will be exposed during service. Considerable testing has been performed by the rubber polymer manufacturers and rubber compounders, in a seemingly endless variety of fluids and test conditions, as noted in the data sheets (Appendix C). Much more data is published in the brochures of these rubber manufacturers. Tables XXVI through XXVIII summarize the changes in elastomers as a result of immersion in various fluids at the temperatures and for the times specified. Some of the fluids shown in Table XXVI and elsewhere, herein, are standardized reference fluids used in the evaluation of rubber polymer behavior and are defined as follows:

- ASTM Oil No. 1 - Generally considered to be representative of high aniline point petroleum-base lubricating oils and defined in ASTM Standard D471. Used as a reference fluid for engine oils that exert low swelling effects on most elastomer vulcanizates, and is therefore considered representative of the least severe oils encountered in automotive service applications.
- ASTM Oil No. 2 - Generally considered to be more representative of petroleum-base lubricating oils used in engines and defined in ASTM Standard D471. Since No. 1 and No. 3 Oils are representative of the extremes encountered in lubricating oils, No. 2 Oil is not as frequently used as a test fluid.
- ASTM Oil No. 3 - Generally considered to be representative of low aniline point petroleum-base lubricating oils and defined in ASTM Standard D471. Used as reference fluid for oils that produce severe swelling effects on most elastomer vulcanizates, and is therefore considered representative of the most severe petroleum-base oils encountered in service applications. Sometimes used as a polymer identifier in material specifications.
- ASTM Oil No. 5 - This oil came into being as a substitute for Oil No. 1, when the latter became unavailable and is defined in ASTM Standard D471. Oil No. 5 is not in general use, as a new source for Oil No. 1 diminished the need for a substitute oil.

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- ASTM Ref. Fuel A - Defined in ASTM Standard D471 and Federal Specification TT-S-735, Type I, as 100 percent isooctane, and is used as a reference fuel for gasoline with no aromatic content.
- ASTM Ref. Fuel B - Defined in ASTM Standard D471 and Federal Specification TT-S-735, Type III, as isooctane 70 percent and toluene 30 percent, and is used as a reference fluid for petroleum fuel with aromatic content, such as jet engine fuel.
- ASTM Ref. Fuel C - Defined in ASTM Standard D471 as isooctane 50 percent and toluene 50 percent and is used as a reference fluid for automotive gasoline.
- ASTM Ref. Fuel D - Defined in ASTM Standard D471 as isooctane 60 percent and toluene 40 percent and is used as a reference fluid for automotive gasoline.
- ASTM Service Fluid No. 100 - Defined in ASTM Standard D471 as ASTM Oil No. 1 with a chlorosulfonated additive.
- ASTM Service Fluid No. 101 - Defined in ASTM Standard D471 as di-2-ethyl hexyl sebacate with 0.5 mass percent phenothiazine. Used as a reference fluid for evaluating elastomers in diester oil and nonflammable-nonpetroleum hydraulic oil at temperatures up to 500°F (260°C).
- AMS 3020 - "Oil, Reference, for "L" Stock Rubber Testing", was developed to provide a standardized test fluid for high aniline point petroleum-base hydraulic oil commonly referenced as "red hydraulic fluid" and supplied to Military Specification MIL-H-5606.
- AMS 3021 - "Fluid, Reference, for Testing Diester (Polypol) Resistant Materials", was developed to provide a standardized test fluid for diester lubricating oil supplied to Military Specification MIL-L-7808.
- SAE Phosphate Ester Standard Test Fluid No. 1A - Defined in several AMS specifications for fluorosilicone and butyl rubber seals for use in evaluating resistance to phosphate ester hydraulic fluids.
- SAE Ester Test Fluid No. 2 - Defined in several AMS specifications for fluorosilicone, fluorocarbon, and butyl rubber seals for use in evaluating resistance to diester oils of the MIL-L-7808 type up to 400°F (200°C). Should be replaced by AMS 3021.

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7.3.2 Where rubber components are utilized to contain fluids, the permeability of the rubber with respect to the fluid becomes important. Permeability can be considered to occur in three stages. First, the fluid is absorbed on one side of the rubber; second, the fluid permeates the rubber and reaches the opposite surface; and third, the liquid evaporates into the air from the opposite surface. The permeability of rubber to organic fluids increases logarithmically with temperature.

7.3.3 Fluid resistance depends primarily on the type of rubber polymer, but within some classes of polymers, swell percentages can vary greatly. This is especially true for nitrile rubbers, which are used extensively for petroleum oil and fuel applications. NBR rubber is a copolymer of acrylonitrile and butadiene, which can range in polymer ratio from 20 to 50 percent acrylonitrile. The higher the acrylonitrile content the greater the resistance to swelling in hydrocarbon fluids. At the same time, the ratio affects the low temperature properties; the higher the butadiene content, the better the low temperature properties. This relationship is shown in Figure 95 and is also noted in several tables (70/30 means 70 percent butadiene and 30 percent acrylonitrile). "Low Swell" nitrile indicates a high acrylonitrile content.

7.3.4 Polysulfide and fluorocarbon rubbers have excellent resistance to gasoline and petroleum-base oils. The fluorocarbons have better physical properties and withstand much higher temperatures than the polysulfide rubbers, but are more expensive. Perfluorocarbon rubber is designed for even higher temperatures and more severe conditions, but it is also much more expensive. Other rubbers which have good resistance to these fuels and have good physical properties are nitrile, polyacrylate, polyurethane, fluorosilicone, phosphonitrilic fluoroelastomer, and one type of chloroprene rubbers. Other types of chloroprene and silicone rubbers have fair resistance to the fuels. Polyacrylate, fluorosilicone, and fluorocarbon rubbers are also suitable for use in hot oils. Ethylene-propylene and butyl rubber should be used for polar fluids such as acetone, methyl ethyl ketone, hydrazine and phosphate esters, and not for hydrocarbon service. The hydrocarbon fluid resistant polymers generally do not do as well in these polar fluids.

7.3.5 The use of plasticizers in the rubber compound should be carefully controlled, especially where sealing of petroleum fuels will be required. Plasticizers will be dissolved from the rubber compound, and replaced by a component of this fuel. This is particularly evident in low temperature applications as discussed in 7.2.8. One approach to overcome this problem with acrylonitrile butadiene O-rings in aircraft fuel systems is to compound the rubber with little or no temperature plasticizer, as the seals will not be required to exhibit low temperature performance until after thoroughly wetted with the fuel. In this case, the component of the fuel plasticizes the rubber, swells it within the limits for which it was designed, and achieves the low temperature performance in the "wet" condition. Upon drying, as during overhaul, the seals will shrink from their swollen plasticized condition, but not below their original size, as there has been no extraction of their plasticizer. In this way, leaks in the system are avoided.

7.3.6 The additives used in compounded petroleum oils and greases, such as transmission fluids, and in water-antifreeze solutions, may affect the rubber even if the polymer is resistant to the base fluid. It would be best, therefore, to evaluate the rubber in the actual material to be used and at the applicable service temperature before establishing a design.

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7.3.7 For hot water service the best rubber is ethylene propylene, followed by butyl rubber. In other polymer groups, a limited number of compounds are suitable for hot water service; among these are specific silicone rubbers, chloroprene, chlorosulfonated polyethylene, natural, and nitrile rubbers. Prolonged tests have shown that polyurethanes, polysulfides, and the polyacrylates are adversely affected and should not be used. See the individual Data Sheets in Appendix C for more specific information.

7.3.8 With the liquid propellants extensively used in missile power plants, a limited number of elastomers are suitable. In general, the oxidizer has a much more deleterious effect than the fuel itself. The undesirable effects on elastomers, due to exposure to hydrazine-type fuels and nitrogen tetroxide (an oxidizer), are shown in Table XXVII.

7.3.9 The effects on butyl and silicone rubber compounds of exposure in 50:50 unsymmetrical dimethylhydrazine (UDMH) and hydrazine are shown in Figures 96 and 97. Tensile strength and hardness after exposure up to 8 weeks are shown in Figure 96, while weight gains in percent and linear swelling are shown in Figure 97. The proprietary "Butyl A" compound, prepared specifically for this type of application, exhibits the best resistance to this fuel. "Butyl C" represents an average for two commercial butyl compounds. Further tests indicate that 80 percent of the strength and elongation have been retained after eight months exposure to a 100 percent UDMH, a 50:50 percent mixture of the two, and 100 percent mono methyl hydrazine.

7.3.10 The effects on fluorosilicone and fluorocarbon rubbers of exposure in nitrogen tetroxide are shown in Figures 98 through 100. Tensile strength and hardness after exposure up to 4 hours are shown in Figure 98, while elongation and weight gain are shown in Figure 99. The changes in tensile strength, hardness and weight of fluorosilicone in nitrogen tetroxide exposure up to 8 weeks are shown in Figure 100. Fluorosilicone appears to be the best among those shown. For diaphragms and seals, a lamination of fabric and fluorosilicone has been among the more successful products, with the fabric providing most of the strength and the fluorosilicone the sealing.

7.3.11 The usefulness of various rubber types in acids and alkali is shown in Table XXVIII.

7.3.12 New polymers have been developed in the last few years that are becoming more widely used, but data are not yet available to integrate them into the figures and tables shown herein. Two of these polymers exhibit specialized characteristics and are shown in the applicable Data Sheet in Appendix C.

7.3.12.1 Phosphonitrilic Fluoroelastomer, "PNF", is classified in ASTM Standard D1418 as "FZ". This polymer has $-P=N-$ in the polymer chain and performs quite similarly to fluorosilicone, but with better overall dynamic properties, such as abrasion resistance and flexure fatigue; its applications will not be too different from FVMQ. PNF exhibits good wear and extrusion resistance in seals and slightly different fluid resistance characteristics that are being further evaluated. See Data Sheet No. 18.

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7.3.12.2 Perfluorocarbon Elastomer, tetrafluoroethylene perfluoromethylvinylether plus a cure site monomer is really a rubber, but its chemical resistance ranges between that of fluorocarbon rubber and polytetrafluoroethylene plastic. This polymer, Kalrez, is identified as ASTM Class FFKM, perfluorocarbon, and is available only from the manufacturer as finished parts. See Data Sheet No. 15. Primary applications are where conditions are so severe that other rubbers are marginal or nonfunctional. It is reported to be quite expensive.

7.3.13 Developments in 1980, of dynamic O-ring seals for fluid compatibility, indicate leading candidates for use in nonflammable hydraulic fluid systems for 4000 psig (27,600 kPag) systems with service temperatures up to 600°F (315°C) to be phosphonitrilic fluoroelastomer (FZ) (Polyphosphazene, PNF), chlorinated polyethylene (CM), and ethylene propylene (EPM), along with FKM type fluorocarbon (Viton GLT) and fluorosilicone (FVMQ) elastomers.

7.3.14 Alcohol blends with gasoline for automobile propulsion with reduced emissions are becoming more widely used, especially in heavy smog producing areas. The effect of alcohol/gasoline blends on the volume of rubber seals is shown in Figure 101, for 20 days exposure in a 42 percent aromatic fuel containing varying amounts of methanol and ethanol.

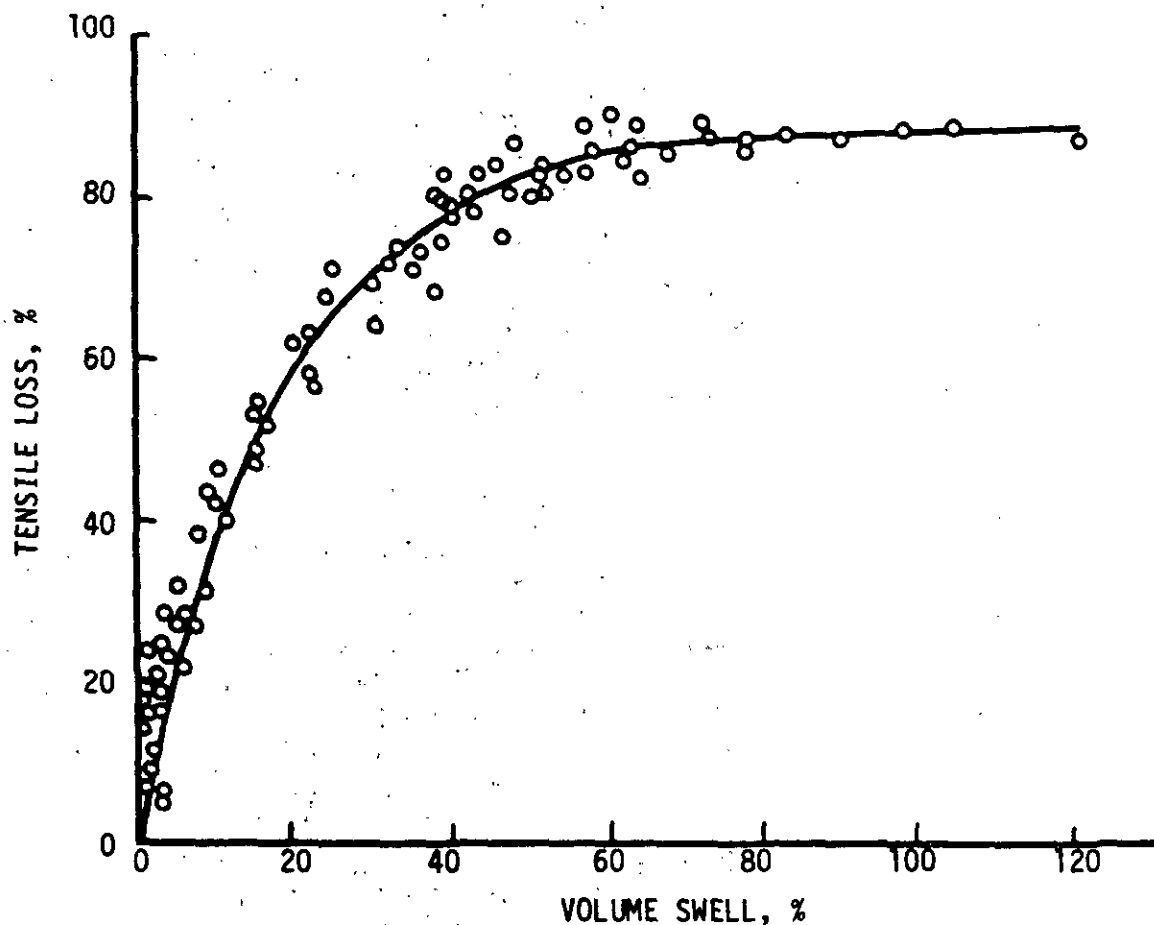


FIGURE 92. VOLUME SWELL AND TENSILE STRENGTH LOSS OF ACRYLONITRILE BUTADIENE COMPOUNDS IN VARIOUS FLUIDS (83)

MIL-HDBK-149B

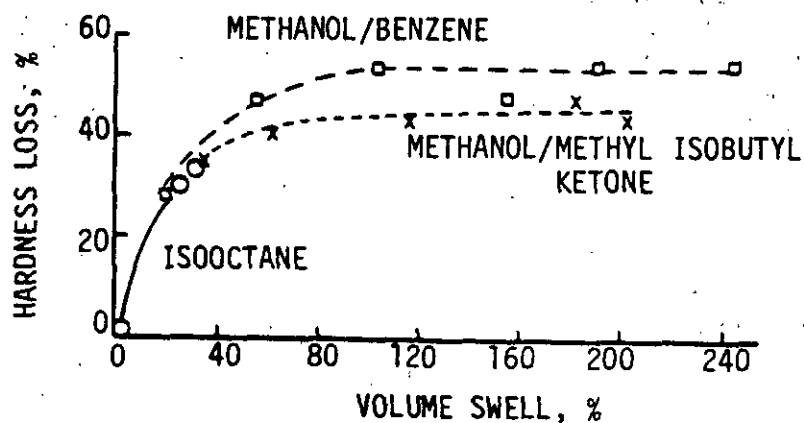


FIGURE 93. VOLUME SWELL AND HARDNESS LOSS OF ACRYLONITRILE BUTADIENE RUBBER IN VARIOUS FLUIDS (83)

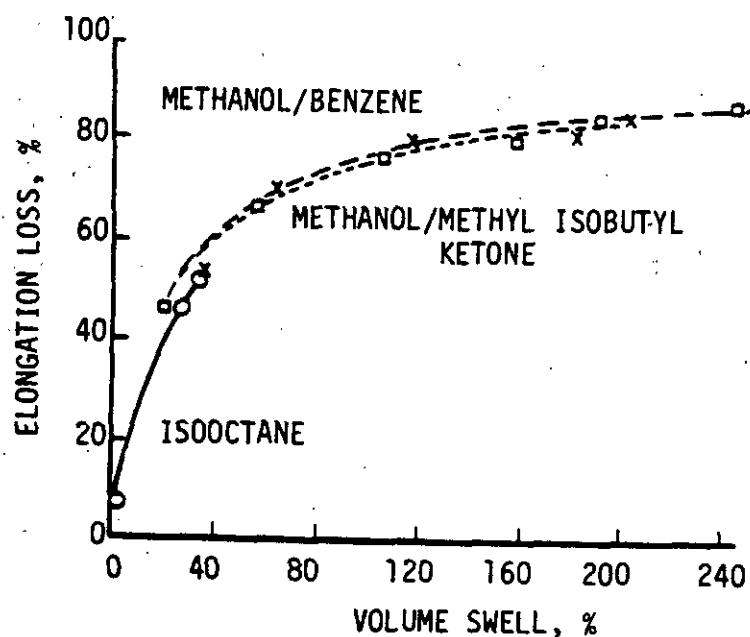


FIGURE 94. VOLUME SWELL AND ELONGATION LOSS OF ACRYLONITRILE BUTADIENE RUBBER IN VARIOUS FLUIDS (83)

MIL-HDBK-149B

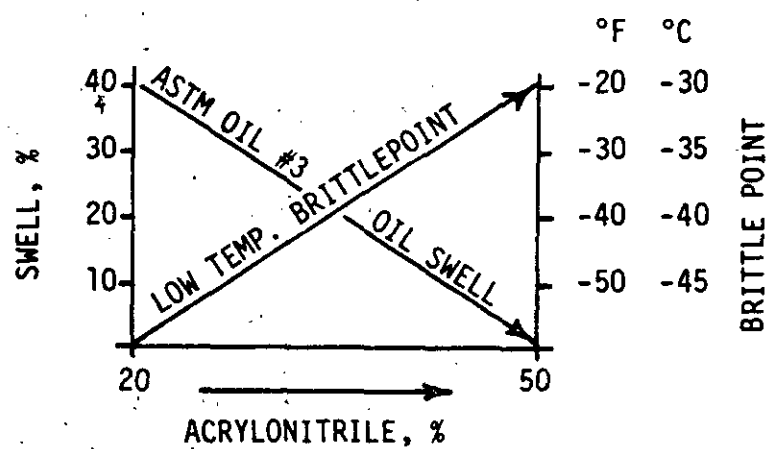


FIGURE 95. EFFECT OF ACRYLONITRILE CONTENT
IN ACRYLONITRILE BUTADIENE RUBBER (42)

MIL-HDBK-149B

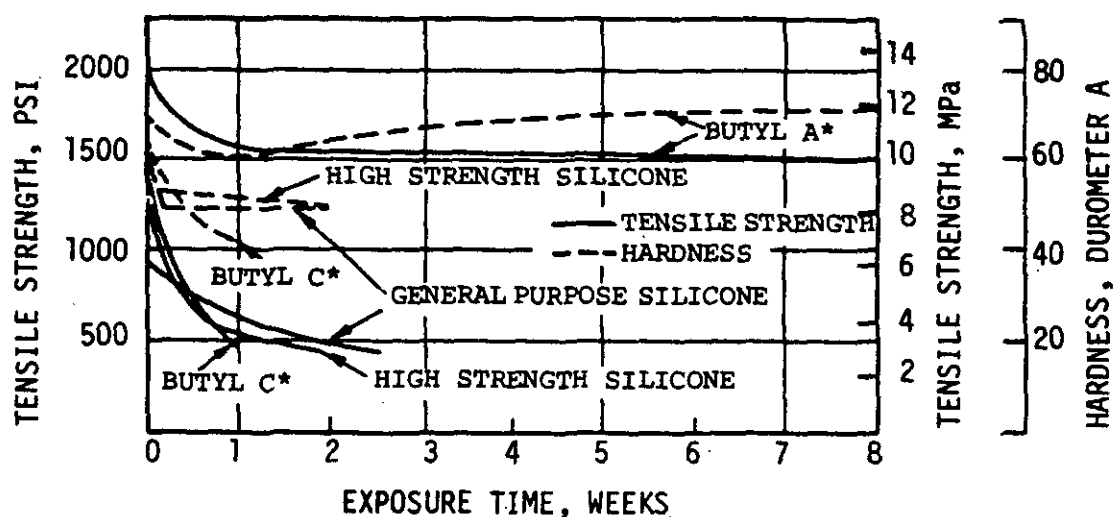


FIGURE 96. TENSILE STRENGTH AND HARDNESS VS EXPOSURE TIME OF BUTYL AND SILICONE RUBBER IN 50:50 UDMH AND HYDRAZINE (*See 7.3.9) (57)

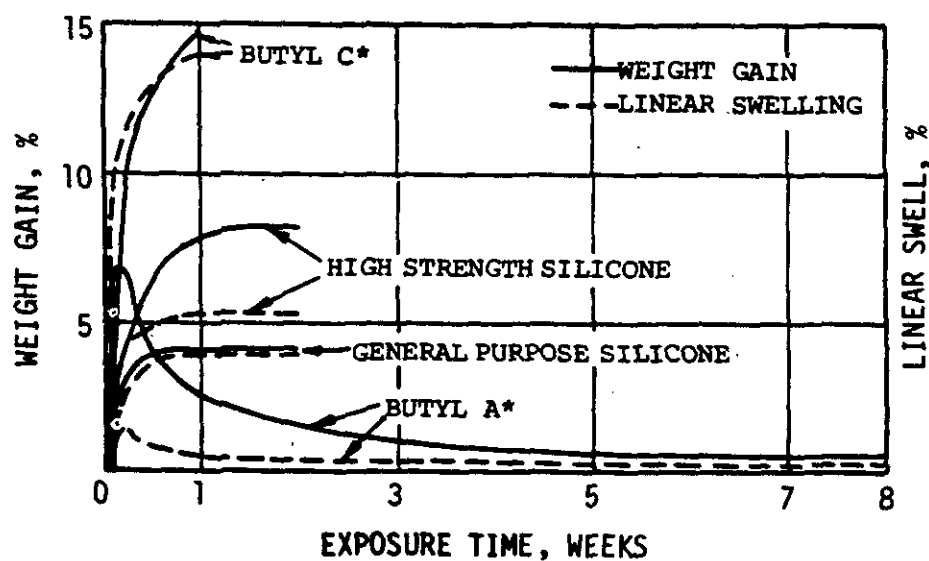


FIGURE 97. WEIGHT GAIN AND LINEAR SWELLING VS EXPOSURE TIME OF BUTYL AND SILICONE RUBBER IN 50:50 UDMH AND HYDRAZINE (*See 7.3.9) (57)

MIL-HDBK-149B

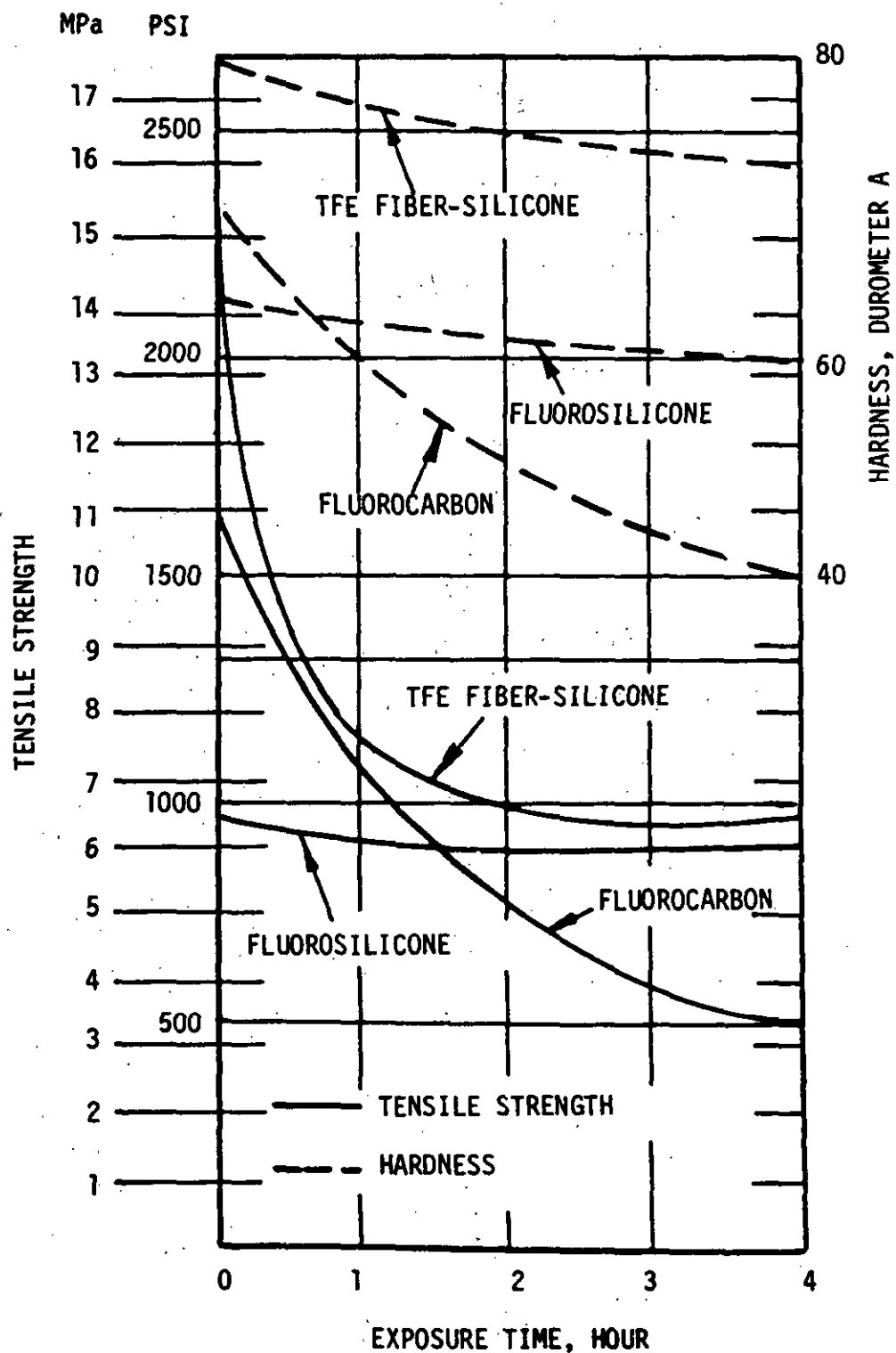


FIGURE 98. TENSILE STRENGTH AND HARDNESS VS EXPOSURE TIME IN NITROGEN TETROXIDE (57)

MIL-HDBK-149B

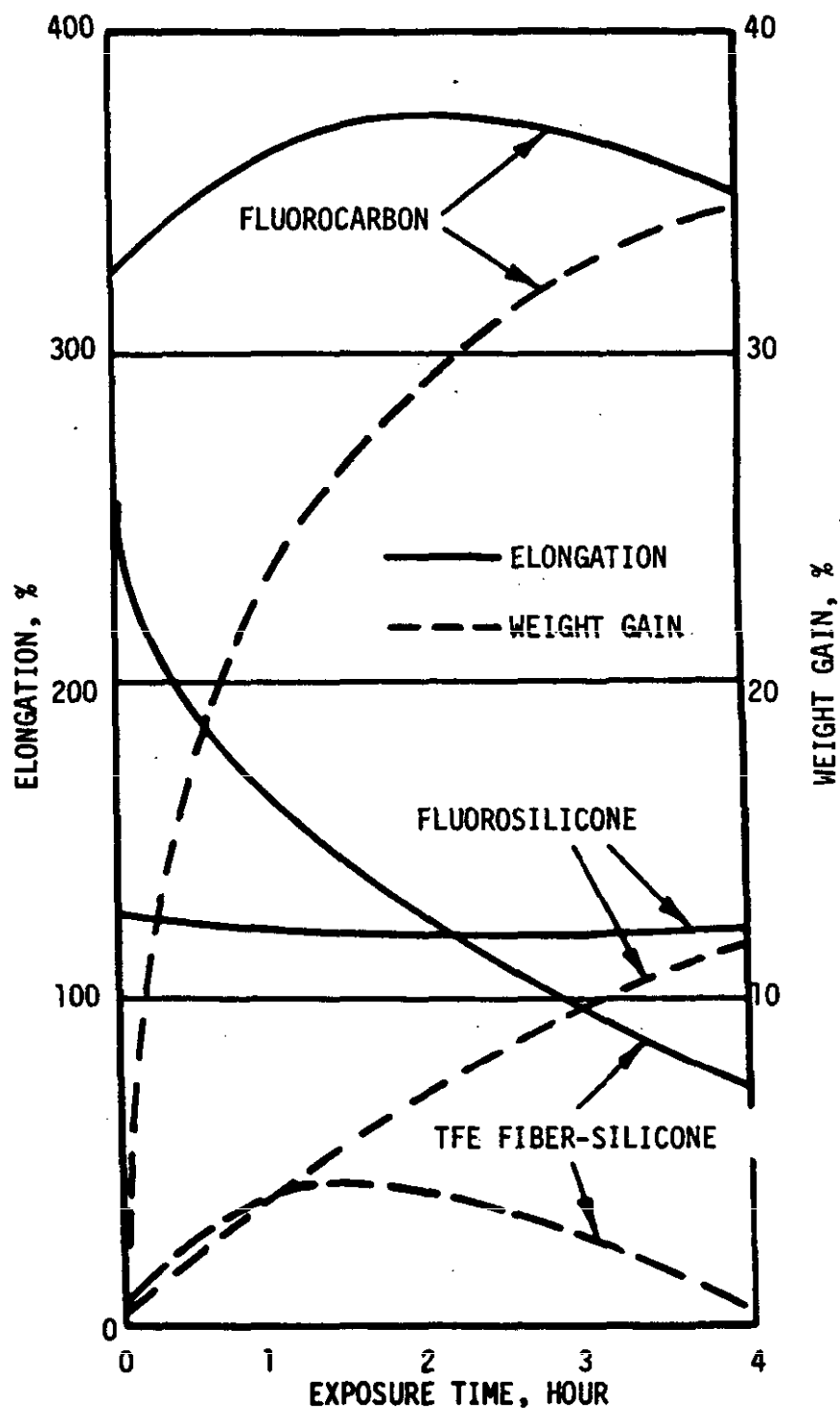


FIGURE 99. WEIGHT GAIN AND LINEAR SWELLING VS EXPOSURE TIME IN NITROGEN TETROXIDE (57)

MIL-HDBK-149B

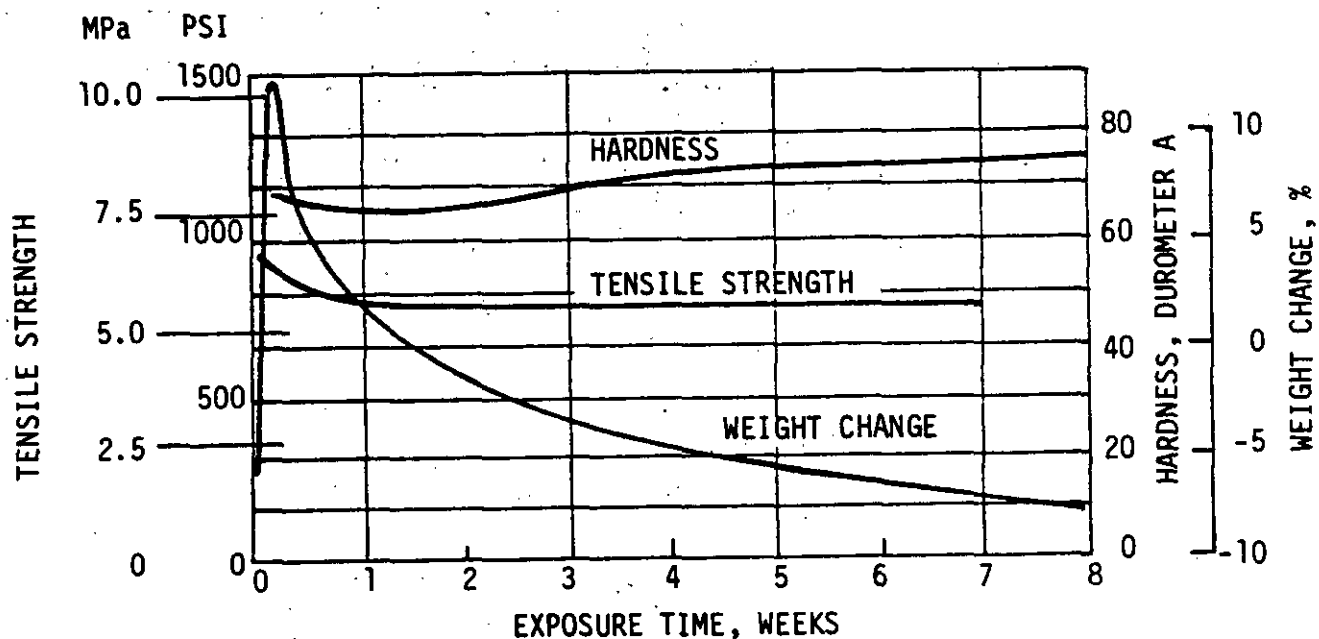
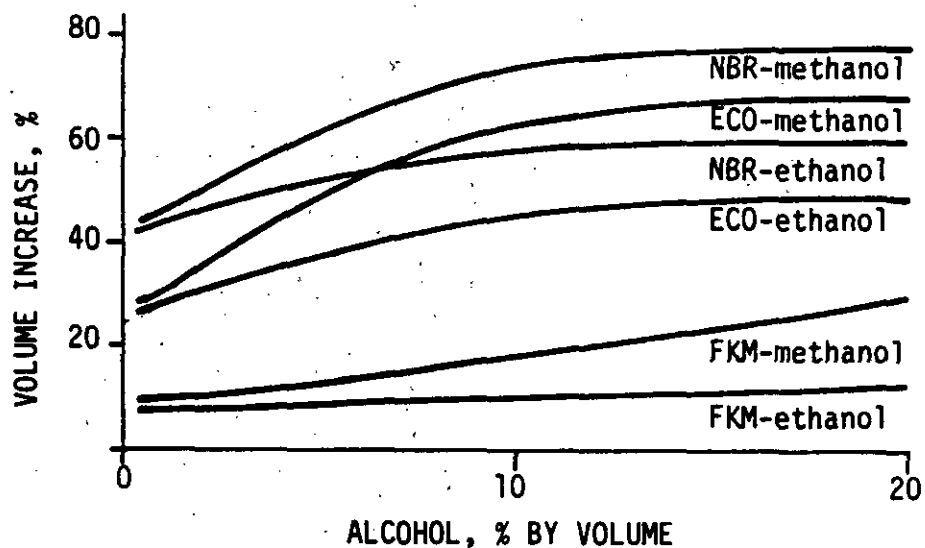


FIGURE 100. WEIGHT CHANGE, TENSILE STRENGTH, AND HARDNESS OF FLUOROSILICONE VS EXPOSURE TIME IN NITROGEN TETROXIDE (57)



Base Fuel: Gasoline with 42% aromatic content
 Exposure: 20 days at 70°F (21°C)

FIGURE 101. EFFECT OF ALCOHOL-GASOLINE BLENDS ON ELASTOMERS (74)

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS

Fluid	Exposure			Change in Properties,			Change in Hardness
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points
	°F	°C					
ACRYLONITRILE BUTADIENE, LOW ACRYLONITRILE							NBR
ASTM No. 1 Oil	212	100	70 hrs	+5	-10	+15	+3
ASTM No. 3 Oil	212	100	70 hrs	+42	-25	+11 to -30	-5 to -12
ASTM Ref Fuel A	75	23	70 hrs	+4	-10	-16	-6
ASTM Ref Fuel B	75	23	70 hrs	+28	-40	-35	-13
Aromatic Fuels SR6	75	23		+30	-31	-27	-22
Aromatics	168	76		+130			
Carbon Tetrachloride	75	23	168 hrs	+58			
Diester Lube	212	100	70 hrs	+16	-50	-54	-7
Ethylene Glycol	300	150	70 hrs	+4	-4	-12	-5
Gasoline	75	23	90 days	+6			
Hydraulic Oil	75	23	90 days	-3			
JP4	75	23	70 hrs	+8	-25	-25	-6
Skydrol 500®	212	100	70 hrs	+190	-90	-75	-30
Vegetable and Animal Oil	75	23	90 days	-2			
Water	75	23	90 days	-10	-10	-15	-1
BUTYL							IR
Aromatic Fluids	77	25			Poor to Fair		
ASTM Oils 1, 2, 3					Poor		
Ethylene Glycol					Excellent		
Freon 21®					Poor		
Gasoline					Poor		
Skydrol®	212	100	70 hrs	+9.6	-10	-20	-30
Toluene					Poor		
Vegetable and Mineral Oil	77	25			Excellent		
CHLOROPRENE							CR
ASTM No. 3 Oil	212	100	70 hrs	+65	-53	-40	-17
ASTM Ref Fuel A	75	23	70 hrs	+16	-36	-18	-6
ASTM Ref Fuel B	75	23	70 hrs	+62	-61	-34	-15
Ethyl and Methyl Alcohol	75	23	70 hrs	+3	-23	-7	-5

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness	
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points	
	°F	°C						
CHLOROPRENE (continued)								CR
Ethylene Glycol	212	100	70 hrs	-3	-13	-22	+1	
JP4	75	23	70 hrs	+46	-54	-31	-15	
Skydrol 500®	212	100	70 hrs	+151	-83	-54	-33	
Water	212	100	70 hrs	+16	-46	-37	-5	
CHLOROSULFONATED POLYETHYLENE								CSM
Acetone	70	21	14 days	+20	Moderate Effect			
Carbon Tetrachloride	70	21	14 days	+150	Severe Effect			
Gasoline	70	21	14 days	+50	Severe Effect			
JP4	70	21	14 days	+100	Severe Effect			
MIL-L-7808 Diester Lube	70	21	14 days		Moderate Effect			
SAE 10 Oil	70	21	14 days	+3	Little or No Effect			
SAE 10 Oil	158	70	14 days	+11	Moderate Effect			
Tributyl Phosphate	70	21	14 days	+100	Moderate Effect			
Vegetable and Mineral Oil	70	21	14 days		Little or No Effect			
Water	200	95	14 days		Little or No Effect			
Xylene	70	21	14 days	+200	Severe Effect			
EPICHLOROHYDRIN COPOLYMER								ECO
Acetone	75	23	7 days	+100	-21	-48	-23	
ASTM Fuel A	75	23	7 days	+2	+1	-8	-1	
ASTM Fuel B	75	23	7 days	+19	-5	-20	-9	
ASTM No. 3 Oil	75	23	7 days	+2	+4	-8	-9	
Dibutyl Phthalate	75	23	7 days	+80	-31	-50	-31	
Ethyl Acetate	75	23	7 days	+95	-33	-56	-21	
Ethylene Glycol	75	23	7 days	+2	+5	+12	-4	
Freon 113®	75	23	7 days	+7	-1	-2	-5	
Kerosene	75	23	7 days	+2	0	-6	-10	
Linseed Oil	75	23	7 days	0	0	+8	-7	

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties,			Change in Hardness
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points
	°F	°C					
EPICHLOROHYDRIN COPOLYMER (continued)							ECO
Methanol	75	23	7 days	+19	-9	-20	-10
Oleic Acid	75	23	7 days	+5	+2	-20	-9
Olive Oil	75	23	7 days	0	+4	+4	0
Perchloroethylene	75	23	7 days	+28	-3	-20	-15
Pine Oil	75	23	7 days	+24	-9	-20	-19
Texamatic Fluid®	75	23	7 days	+2	+4	0	-2
Toluene	75	23	7 days	+95	-32	-52	-19
Turpentine	75	23	7 days	+8	-12	-12	-4
Wagner Brake Fluid	75	23	7 days	+49	-18	-36	-23
Water	75	23	7 days	+1	+8	+20	-7
EPICHLOROHYDRIN HOMOPOLYMER							CO
Acetone	75	23	7 days	+105	-32	-61	-19
ASTM Fuel A	75	23	7 days	0	-5	-3	-3
ASTM Fuel B	75	23	7 days	+14	-8	-42	-4
ASTM No. 3 Oil	75	23	7 days	0	+6	-8	0
Dibutyl Phthalate	75	23	7 days	+62	-43	-44	-31
Ethyl Acetate	75	23	7 days	+131	-42	-50	-18
Ethylene Glycol	75	23	7 days	0	0	-11	+2
Freon 113®	75	23	7 days	0	+12	-22	+2
Kerosene	75	23	7 days	0	+4	-17	+1
Linseed Oil	75	23	7 days	0	-4	-20	0
Methanol	75	23	7 days	+8	-8	-67	-9
Oleic Acid	75	23	7 days	0	-3	0	+1
Olive Oil	75	23	7 days	0	+4	0	+2
Perchloroethylene	75	23	7 days	+11	-7	-36	-5
Pine Oil	75	23	7 days	0	-10	-17	-4
Texamatic Fluid®	75	23	7 days	0	+7	-6	+1
Toluene	75	23	7 days	+96	-32	-50	-17
Turpentine	75	23	7 days	0	-3	-8	+1
Wagner Brake Fluid	75	23	7 days	+65	-34	-39	-16
Water	75	23	7 days	0	-1	0	-1

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness	
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points	
	°F	°C						
ETHYLENE PROPYLENE DIENE MODIFIED								EPDM
ASTM No. 1 Oil	212 75	100 23	72 hrs 12 mo	+129 +144	-47 -47	-54 -56	-34 -29	
ASTM No. 3 Oil	212 75	100 23	72 hrs 12 mo	+216 +212	-61 -57	-67 -66	-35 -29	
Benzaldehyde	212 75	100 23	72 hrs 12 mo	+26 +31	-15 -19	-20 -25	-13 -12	
Dioctyl Phthalate	212 75	100 23	72 hrs 12 mo	+40 +10	-12 +9	-17 +4	-18 -6	
Water	212 75	100 23	72 hrs 12 mo	+1 +1	+6 +8	+2 +9	+2 +3	
Ethyl Alcohol	212 75	100 23	72 hrs 12 mo	-1 -0.1	+8 +7	+5 +8	-4 +2	
Ethyl Ether	212 75	100 23	72 hrs 12 mo	+97 +108	-58 -62	-62 -60	-28 -25	
Hexane	212 75	100 23	72 hrs 12 mo	+178 +194	-63 -68	-70 -69	-30 -28	
Lard	212 75	100 23	72 hrs 12 mo	+64 +32	-30 -16	-33 -21	-26 -15	
Methyl Ethyl Ketone	212 75	100 23	72 hrs 12 mo	+16 +10	-17 -1	-21 -3	-12 -6	
Perchloroethylene	212 75	100 23	72 hrs 12 mo	+207 +104	-76 -58	-60 -51	-40 -30	
Skydrol 500®	212 75	100 23	72 hrs 12 mo	+10 +1	-0.2 +10	+1 +3	-4 -1	
Toluene	212 75	100 23	72 hrs 12 mo	+218 +179	-77 -62	-70 -67	-35 -30	
FLUOROCARBON (VITON®)								FKM
ASTM No. 1 Oil	300	150	7 days					
ASTM No. 3 Oil	300	150	7 days	+2.3	-5	0	-1	
ASTM Ref Fuel A	75	23	3 days	0				
ASTM Ref Fuel B	75	23	7 days	+2.5	+7	0	+1	
Carbon Tetrachloride	75	23	7 days	+1.3	-15	-17	+2	
Diester Lube	400	200	7 days	+9.3	-29	-2	-3	
Gasoline	75	23	28 days	+4				
JP4	450	230	28 days	+1.6				
Red Fuming Nitric Acid	75	23	7 days	+22.9				

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points
	°F	°C					
FLUOROCARBON (VITON®) (continued)							FKM
Skydrol®	212	100	28 days	+270			
Transmission Fluid, Type A	212	100	7 days	+1.5	-23	-21	-1
Tributyl Phosphate	212	100	7 days	+375			-39
Vegetable and Animal Oil	75	23	7 days	+4	-10	-2	-5
FLUROSILICONE							FVMQ
Acetone	75	23	168 hrs	+180			
ASTM No. 1 Oil	300	150	70 hrs	0	0		-4
ASTM No. 3 Oil	300	150	70 hrs	+5	-25	-10	-5
ASTM Ref Fuel A	75	23	70 hrs	+15	-40	-30	-5
ASTM Ref Fuel B	77	25	48 hrs	+20	-50	-20	-6
Carbon Tetrachloride	77	25	48 hrs	+20	-30	-20	-5
JP4	77	25	70 hrs	+10	-35	-20	-5
MIL-L-7808 Diester Lube	300	150	70 hrs	+8	-9	-24	-8
Phosphate Ester Hydraulic Fluid	250	120	70 hrs	+11			-17
Skydrol 500®	250	120	70 hrs	+28	-80		-26
Xylene	75	23	168 hrs	+20	-45	-35	-10
METHYL VINYL SILICONE							VMQ
ASTM No. 1 Oil	300	150	70 hrs	+8	-10	-15	-5
ASTM No. 1 Oil	300	150	168 hrs	+10	-36	+8	-9
ASTM No. 3 Oil	300	150	70 hrs	+80	-40	-25	-15
Diester Oils	350	175	168 hrs	+25			
MIL-L-7808 Diester Lube	350	175	70 hrs	+25	-97	-49	-25
Tricresyl Phosphates	350	175	70 hrs	+10			
Water	212	100	70 hrs	+3	-18	-15	-5
Water Based Hydraulic Fluid	70	21	70 hrs	+10			
ASTM Ref Fuel A	70	21	70 hrs	+140	-75	-50	-15
JP4	70	21	70 hrs	+200	-70	-60	-20

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness	
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points	
	°F	°C						
PERFLUOROELASTOMER								FFKM
ASTM No. 1 Oil	375	190	120 hrs	+0.6	0	-11	+5	
ASTM No. 3 Oil	375	190	120 hrs	+3.7	-14	-8	+3	
Stauffer Blend 7700 ®	302	150	14 days	+4	+23	+14	-2	
Turbine Engine Oil, MIL-L-23699B, Type II	400	205	70 hrs	+1	-4	-23	+2	
	400	205	168 hrs	+3.5	-3	+10	0	
	500	260	70 hrs	+8.5	0	0	+1	
	500	260	168 hrs	+10.5	0	+8	+3	
Skydrol 500 ®	250	120	168 hrs	+2	+33	0	-3	
Acetone	73	23	168 hrs	+1	-27	0		
Benzene	73	23	168 hrs	+1.3	-20	0		
Carbon Tetrachloride	73	23	168 hrs	+3.2 weight	-25	0		
Chlorobenzene	73	23	168 hrs	+1				
Cyclohexane	73	23	168 hrs	+1				
Ethanol	73	23	168 hrs	0				
Ethyl Acetate	73	23	168 hrs	+1.2 weight	-27	0		
Hexane	73	23	168 hrs	+1				
Methyl Ethyl Ketone	73	23	168 hrs	+1				
Nitrobenzene	73	23	168 hrs	+1				
Perchloroethylene	73	23	168 hrs	+2				
Steam	450	230	14 days	+22	-20	+225		
	550	290	14 days	+22	-25	+230		
Tetrahydrofuran	73	23	168 hrs	+1				
Toluene	73	23	168 hrs	+1				
PHOSPHONITRILIC FLUOROELASTOMER								FZ
ASTM No. 1 Oil	73	23	166 hrs	0	-12	-14	+1	
	300	150	166 hrs	0	-15	-7	+1	
ASTM No. 3 Oil	73	23	166 hrs	0	-4	-7	+1	
	300	150	166 hrs	+2	-16	-14	-2	
ASTM Ref Fuel A	73	23	166 hrs	+6	-26	0	-8	
	200	95	166 hrs	+13	-29	-18	-10	

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness	
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points	
	°F	°C						
PHOSPHONITRILIC FLUOROELASTOMER								FZ
ASTM Ref Fuel B	73	23	166 hrs	+11	-31	-14	-7	
	212	100	166 hrs	+16	-23	-22	-7	
Aviation 100	73	23	166 hrs	+12	-22	0	-12	
	180	80	166 hrs	+15	-28	-9	-12	
Jet Reference Fuel	73	23	166 hrs	+11	-33	-9	-12	
	190	90	166 hrs	+15	-25	-9	-12	
JP4	73	23	166 hrs	+4	-22	-14	-4	
	230	110	166 hrs	+9	-12	-14	-4	
JP8	73	23	166 hrs	+2	-24	-14	-4	
	300	150	166 hrs	+8	-19	0	-4	
JP10	73	23	166 hrs	+2	-36	-21	-3	
	300	150	166 hrs	+10	-21	0	-9	
Jet Fuel A	73	23	166 hrs	+2	-10	0	-5	
	300	150	166 hrs	+10	-21	0	-9	
Arctic Diesel Fuel	73	23	166 hrs	+2	-5	0	-6	
	300	150	166 hrs	+10	-24	+9	-13	
Stauffer Blend 7700 [®] AMS 3021	73	23	166 hrs	+4	-14	-14	-12	
	300	150	166 hrs	+29	-46	-21	+14	
Anderol 774 [®]	73	23	166 hrs	+6	-11	-7	-2	
	300	150	166 hrs	+22	-38	-14	-11	
MIL-L-7808	73	23	166 hrs	+3	-17	-14	-5	
	300	150	166 hrs	+15	-38	+7	-20	
MIL-L-23699	73	23	166 hrs	+3	-7	-7	-6	
	300	150	166 hrs	+11	-36	0	0	
Grease, Lithium Lithium Based	300	150	166 hrs	+2	-22	-14	-1	
MIL-H-5606B	73	23	166 hrs	+1	-7	-7	0	
	275	135	166 hrs	+4	-4	-7	-3	
MIL-H-83282A	73	23	166 hrs	+1	-6	-7	0	
	275	135	166 hrs	+2	-5	0	-2	
Skydrol 500B4 [®]	73	23	166 hrs	+154	-63	-21	-9	
Brayco Micronic 762 [®] Hydraulic Fluid	73	23	166 hrs	+0.4	-15	0	-3	
	275	135	166 hrs	+3	-9	+11	-7	
Silicone Brake Fluid, MIL-B-46176	300	150	166 hrs	+32	-51	0		

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points
	°F	°C					
PHOSPHONITRILIC FLUOROELASTOMER (continued)							FZ
Dowtherm J®	73	23	166 hrs	+6	-10	-16	-10
	300	150	166 hrs	+12	-24	-9	-10
Monsanto Coolant 25R®	73	23	166 hrs	+1.2	0	+8	-3
	212	100	166 hrs	+1.2	0	+8	-6
Acetone	73	23	166 hrs	+166	-76	-36	-14
Benzene	73	23	166 hrs	+14	-26	0	-11
	180	80	166 hrs	+15	-37	-9	-12
Ethyl Acetate	73	23	166 hrs	+167	-79	-43	-11
Ethylene Glycol	73	23	166 hrs	+2	-14	-14	0
	300	150	166 hrs		Degraded		
Methylene Chloride	100	38	166 hrs	+15	-40	-14	-7
						-21	
Tetrachloroethylene	73	23	166 hrs	+8	-20	+9	-12
	250	120	166 hrs	+15	-18	-9	-11
Tetrahydrofuran	73	23	166 hrs	+153	-69	-36	-12
Toluene	73	23	166 hrs	+13	-29	-14	-10
	230	110	166 hrs	+19	-31	-14	-10
Trichloroethylene	73	23	166 hrs	+11	-35	-21	-8
	190	90	166 hrs	+16	-26	-14	-8
Xylene	73	23	166 hrs	+13	-19	+9	-14
	280	138	166 hrs	+19	-17	+9	-16
POLYACRYLATE							ACM
ASTM No. 1 Oil	212	100	70 hrs	0	+10	-20	+10
ASTM No. 3 Oil	212	100	70 hrs	+7	-20	-35	+10
ASTM Ref Fuel A	75	23	24 hrs	+1	-9	-3	0
ASTM Ref Fuel B	75	23	24 hrs	+45	-75	+43	-10
Ethylene Glycol	212	100	70 hrs		Disintegrated		
Hypoid Oil	300	150	70 hrs	+5	-75	+43	-10
SR-6 Oil	75	23	168 hrs	+50	-50	-20	-20
Toluene	158	70	168 hrs	+300	-70	-70	-50
Vegetable and Mineral Oil	212	100	70 hrs	0	0		-4
Water	75	23	168 hrs	+16	-50	+15	-25

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TABLE XXVI. FLUID RESISTANCE OF ELASTOMERS (Continued)

Fluid	Exposure			Change in Properties, %			Change in Hardness
	Temperature		Time	Volume	Tensile Strength	Elongation	Durometer A Points
	°F	°C					
POLYSULFIDE	EOT						
ASTM No. 1 Oil	80	27	30 days	-4	-5 ^a	-20 ^a	-4 ^a
ASTM No. 3 Oil	80	27	30 days	-2	-18 ^a	-33 ^a	-15 ^a
ASTM Ref Fuel A	80	27	30 days	+2	0 ^a	0 ^a	-20 ^a
ASTM Ref Fuel B	80	27	30 days	+10			
Carbon Tetrachloride	80	27	30 days	+46			
Ethylene Glycol	80	27	30 days	+2			
Gasoline	80	27	30 days	+3			
JP4	80	27	30 days	+1			
Mineral Oil	80	27	30 days	-2			
Skydrol [®]	80	27	30 days	+24			
Toluene	80	27	30 days	+70			
Vegetable Oil	80	27	30 days	0			
Water	80	27	30 days	+5			
POLYURETHANE							
ASTM No. 1 Oil	75	23	168 hrs	-1			0
ASTM No. 3 Oil	75	23	168 hrs	+3			0
ASTM Ref Fuel A	75	23	168 hrs	0			0
Carbon Tetrachloride	75	23	168 hrs	+62			0
Cotton Seed Oil	75	23	168 hrs	0			-5
Ethylene Glycol	75	23	168 hrs	+2	Complete Disintegration		
Hot Water	130	54	65 days				-2
JP4	75	23	168 hrs	+3			-3
Mineral Oil	75	23	168 hrs	0			-25
Skydrol [®]	75	23	168 hrs	+80			-10
Tricresyl Phosphate	75	23	168 hrs	+41			-20
Xylene	75	23	168 hrs	+39			

a 70 hours at 212°F (100°C).

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TABLE XXVII. REACTION OF VARIOUS RUBBERS TO HYDRAZINE AND NITROGEN TETROXIDE EXPOSURE (57)

Rubber		Hydrazine-Type Fuel	Nitrogen Tetroxide
Acrylonitrile Butadiene	NBR	Softens, swells gummy	Dissolves
Butyl, Resin Cured	IIR	Very resistant	Disintegrates
Chloroprene	CR	Blisters, swells	Blisters, dissolves
Chlorosulfonated Polyethylene	CSM	-	Swells excessively
Ethylene Propylene Diene Modified	EPDM	Very resistant	Disintegrates
Fluorocarbon, Kel-F	CFM	Blisters, becomes tacky	Swells, becomes tacky
Fluorocarbon, Viton A	FKM	Embrittles, flakes	Swells excessively
Fluorosilicone	FVMQ	Dissolves	Limited satisfactory performance
Methyl Vinyl Silicone	VMQ	Softens, loses properties	Hardens, disintegrates
Polysulfide	EOT	Disintegrates	-

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TABLE XXVIII. USE OF RUBBER IN ACIDS AND ALKALI AT ROOM TEMPERATURE

Rubber		Acid						Alkali	
		Hydrochloric conc. dil.		Sulfuric conc. dil.		Nitric fuming dil.*		Phosphoric	Sodium Hydroxide conc. dil.
Acrylonitrile Butadiene	NBR	C	OK	C	OK	NG	NG	NG	OK C
Butyl	IIR	OK	OK	C	OK	C	OK	OK	OK OK
Chloroprene	CR	C	OK	C	OK	NG	C	C	OK OK
Chlorosulfonated Polyethylene	CSM	NG	C	C	OK	NG	C	OK	OK OK
Ethylene Propylene Diene	EPDM	OK	OK	C	OK	C	OK	OK	OK OK
Fluorocarbon	FKM	C	OK	C	OK	C	C	OK	OK C
Fluorosilicone	FVMQ	NG	OK	NG	OK	NG	OK	C	OK NG
Methyl Vinyl Silicone	VMQ	OK	C	NG	OK	NG	C	C	C NG
Natural	NR	NG	OK	C	OK	NG	C	C	OK C
Perfluoro-elastomer	FFKM	OK	OK	OK	OK	OK	OK**	OK	OK OK
Phosphonitrilic Fluoroelastomer	FZ	NG	C	NG	C	NG	C	NG	C OK
Polysulfide	EOT	NG	OK	NG	OK	NG	C	NG	OK OK
Polyurethanes	AU,EU	NG	NG	NG	NG	NG	NG	NG	NG NG
Styrene Butadiene	SBR	NG	OK	NG	OK	NG	C	NG	OK C

Legend: OK - Suitable

*26%

NG - Not suitable

**70%

C - Use with caution, preferably after service tests

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7.4 Effects of Heat and Humidity (Hydrolysis)

7.4.1 The combination of high atmospheric temperatures and high humidity is usually of little concern to rubber designers and engineers, because natural and most man-made rubbers are quite resistant to such conditions. Polyester urethane rubbers, AU, however, are a notable exception, many of them breaking down rapidly in hot, humid atmospheres. At temperatures above about 120°F (50°C) and in the presence of high humidity, polyester urethanes hydrolyze by scission of main chain ester groups. The result is reversion of the rubber to a tar-like mass. Below about 120°F (50°C) and again in the presence of high humidity, the breakdown is evidence by cracking followed by gradual softening. Both types of hydrolytic degradation usually occur in less than one year of exposure outdoors.

7.4.2 A short term laboratory test method has been developed for use in the evaluation of the hydrolytic stability of vulcanized rubber. Useful primarily in identifying the poor hydrolytic stability of polyester urethanes, the test method should prove invaluable for use with all newly developed polymers whose hydrolytic stability is suspect.

7.4.3 The method is ASTM Standard D3137, "Standard Test Method for Rubber Property - Hydrolytic Stability". Tensile dumbbell specimens are exposed to the influence of humid environments under definite conditions of temperature, humidity, and time. The resulting hydrolytic degradation is determined by measuring the change in tensile strength after exposure over distilled water. Exposure time and temperature are 96 hours and 185°F (85°C), respectively. The test method recommends that dumbbell specimens also be exposed to dry heat in an air oven (ASTM Standard D573) for 96 hours at 185°F (85°C). This latter procedure aids in distinguishing between the effects of hydrolysis and those due to heat aging.

7.4.4 The data shown in Table XXIX resulted from tests of eighteen rubber compounds using ASTM Standard D3137. The compounds are all based on commercially available polymers and standard recipes. The tests were conducted at 180°F (82°C) which was the test temperature specified in the original version of ASTM Standard D3137. The currently specified temperature is 185°F (85°C) but the data of Table XXIX are valid because no significant differences were noted when tests were performed at the two temperatures.

7.4.5 Of the eighteen compounds tested, all but the two based on polyester urethanes are, from years of experience, known to be stable to hydrolysis. The results of the tests over water verify this fact. The changes in tensile strength of all but the polyester urethanes range from +8 to -15 percent. Changes of this magnitude are not considered to be significant because they are within the range of values attributed to the reproducibility of the tensile test. Two compounds exhibited significant losses in tensile strength after exposure over water, suggesting that these two polyester urethane (AU) compounds would deteriorate rapidly in humid climates.

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TABLE XXIX. HYDROLYTIC STABILITY OF ELASTOMERS (32)

Rubber	Over Water ASTM D3137 4 days at 82°C Tensile Strength Change, %	Air Oven ASTM D573 4 days at 82°C Tensile Strength Change, %	Outdoor Exposure in Panama Rain Forest	
			Tensile Strength Change, %	Exposure Time Months
Acrylonitrile Butadiene				
High Acrylonitrile				
Chlorobutyl	NBR	- 7	--	--
Chloroprene	CIIR	+ 7	- 6	77
Chlorosulfonated	CR	+ 3	-11	72
Polyethylene	CSM	+ 5	--	--
Epichlorohydrin	ECO	- 4	+13	72
Copolymer				
Ethylene Propylene	EPM	+ 8	-15	77
Terpolymer	FKM	-10	-18	77'
Fluorocarbon	FVMQ	- 8	--	--
Fluorosilicone	VMQ	+ 7	- 5	77
Methyl Vinyl Silicone				
Methyl Vinyl Silicone	VMQ	- 7	--	--
High Strength	NR	- 8	--	--
Natural	ACM	+ 3	--	--
Polyacrylate	BR	- 9	-67	77
Polybutadiene	AU	-37	-40	21*
Polyester Urethane	AU	-69	-83	15*
Polyester Urethane	EU	-14	-27	60
Polyether Urethane	T	-15	--	--
Polysulfide	SBR	- 5	-36	77
Styrene Butadiene				

*Exposed in Outdoor, Open Sun Exposure Site in Panama.

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7.4.6 All eighteen compounds were also tested after a four-day exposure in a circulating air oven at 180°F (82°C). This was done to be certain that any large changes in tensile strength noted after the exposure over hot water were due to hydrolysis rather than to heat alone. The results given in the column headed "Air Oven" of Table XXIX show that none of the eighteen compounds deteriorated significantly because of heat aging. Thus, the 37 and 69 percent losses in the tensile strengths of the polyester urethane compounds were due to hydrolysis and not to heat alone.

7.4.7 Eleven compounds of Table XXIX were exposed outdoors in Panama to determine whether correlation existed between the results of the four-day test over water and results from long-term outdoor exposure. Average climatological data for the exposure period were as follows: temperature 79°F (26°C); relative humidity 94 percent; annual precipitation of 148 inches (3759 mm) of water. As indicated by the data, four compounds suffered significant losses in tensile strength after outdoor exposure in Panama. Two of these compounds, based on SBR and polybutadiene, did not deteriorate significantly during the accelerated test. This apparent lack of correlation is explained by the fact that these compounds are known to undergo fairly rapid oxidative aging outdoors. Thus, these losses in strength of the SBR and polybutadiene compounds during Panama exposure are due to oxidation and not to hydrolysis. The two polyester urethane compounds deteriorated rapidly in Panama as well as in the accelerated test over water, proving that the deterioration was due to hydrolysis.

7.4.8 Experience with ASTM Standard D3137 has shown that a rubber compound will resist hydrolysis after years of outdoor exposure in hot, humid climates if it loses no more than 30 percent of its original tensile strength during the four-day test over water.

7.5 Permeability

7.5.1 Gas Permeability

7.5.1.1 The permeability of an elastomer to gases, particularly air, is of interest where rubber components are required to maintain gases under pressure at room as well as elevated temperatures. Such applications occur in bladders used to contain a pressurized gas, and in mechanical seals which must prevent leakage and pressure loss. Aside from the loss of pressure, the deterioration of the rubber caused by the permeating gases, particularly oxygen, is of concern.

7.5.1.2 Permeability is expressed as the volume of gas, corrected to standard conditions (0°C, 760-mm mercury) which permeates a specimen of one square centimetre area, one centimetre thickness in one second. For low permeability, a rubber should contain maximum loading of filler and minimum loading of plastidizer. Laminar type fillers are most suitable for retarding permeability. Table XXX presents the air permeability rates for the major elastomer groups at five temperatures. The absence of data for the higher temperatures indicates that many of the elastomers had deteriorated beyond the point of being able to test them.

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TABLE XXX. AIR PERMEABILITY OF VARIOUS ELASTOMERS (34)

Elastomer		Permeability x 10 ⁷ (a)				
		75°F (23°C)	175°F (79°C)	250°F (120°C)	350°F (175°C)	400°F (200°C)
Acrylonitrile Butadiene	NBR	0.13	0.8	2.2	6.6	---
Butyl	IIR	0.02	0.32 - 0.46	1.3 - 1.8	5.6 - 6.1	10
Carboxylic Acrylonitrile Butadiene Copolymer (Hycar 1072®)	XBNR	---	2.4 - 2.6	2.3 - 6.2	7.1 - 14	---
Chloroprene	CR	0.10	0.98 - 1.7	2.6 - 3.0	7.3	---
Chlorosulfonated Polyethylene	CSM	0.72	0.73	2.3	6.2	---
Epichlorohydrin Copolymer	ECO	0.20	---	8.7	---	---
Epichlorohydrin Homopolymer	CO	0.01	---	3.6	---	---
Fluorocarbon (Kel-F 3700®)	CFM	---	0.8	3.4	15.6	---
Fluorocarbon	FKM	1.5	9.6	24	49	---
Fluorocarbon (Viton A®)	FKM	---	0.88	3.7	14.6	---
Methacrylate		---	---	---	---	16.3
Methyl Vinyl Silicone	VMQ	11 - 33	35 - 47	---	69 - 113	74
Natural Rubber	NR	0.49	4.4	7.1	20.7	26.2
Polyacrylate (Acrylon EA-5®)	ACM	0.16	1.5	3.7	10.2	---
Polyacrylate (Hycar 4021®)	ACM	0.19	1.8	4.8	9.4	---
Polyacrylate (Vyram®)	ACM	0.007	0.24	0.56	5.1	---
Polysulfide	EOT	0.02	0.37	1.6	melted	---
Polyurethane Polyester Type	AU	0.05	0.97	3.1	7.1	melted
Polyurethane Polyether Type (Adiprene C®)	EU	---	2.3	3.8	16.6	---
Styrene Butadiene	SBR	0.25	2.9	4.7	15.4	---

NOTE: (a) Permeability is expressed in cubic centimetres of air (corrected to standard conditions) per second which would permeate through one square centimetre of vulcanizate one centimetre thick with one atmosphere of pressure difference.

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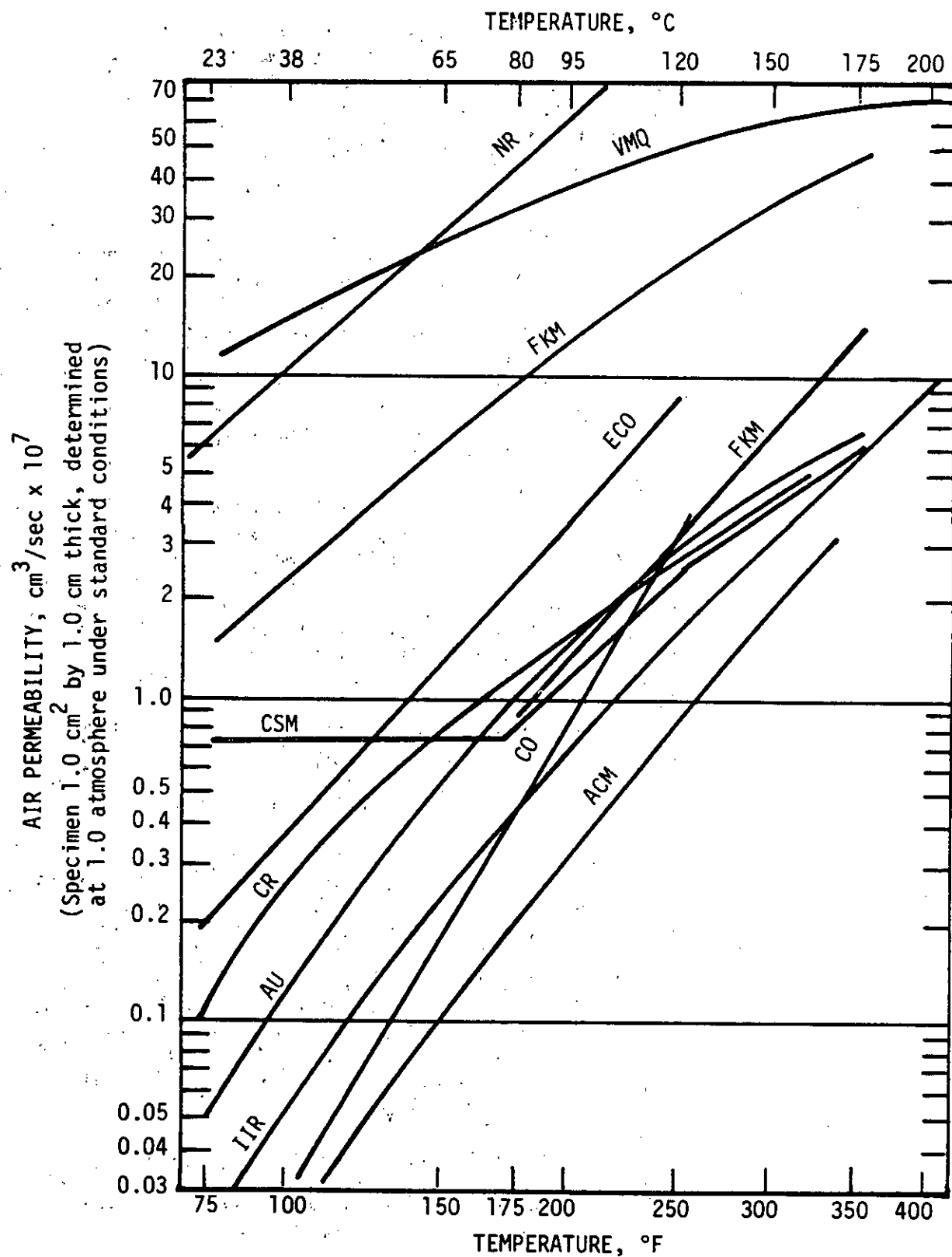


FIGURE 102. AIR PERMEABILITIES OF ELASTOMERS AT ELEVATED TEMPERATURES (34)

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7.5.1.3 Figure 102 presents permeability temperature curves for six elastomers and shows tht polyacrylate (Vyram) and butyl rubber have the lowest permeability rates. At room temperature, the permeability of silicone (VMQ) rubber is 1000 times greater than that of butyl. This is reduced to 20 times at 400°F (200°C). The permeability of butyl, polyurethane, and silicone (VMQ) rubbers to nitrogen is substantially the same as for air.

7.5.2 Water Vapor Permeability.

7.5.2.1 Rubber frequently serves as a barrier between moist environments and personnel or materiel that would suffer if exposed to water vapor. Rubber coatings or rubber coated fabrics are used in the fabrication of tents and tarpaulins. Rubber covers and cocoons see use as moisture barriers for sensitive components such as engines, electric motors, and even entire automotive vehicles, aircraft, and locomotives. The rubber diaphragm in a gas accumulator of a gun recoil mechanism is not only a barrier between nitrogen gas and recoil fluid but also retards the movement of water vapor that might be mixed with gas.

7.5.2.2 The most important factors to consider in selecting or developing a rubber compound having low water vapor permeability are the polymer type, and amount and type of filler and the plasticizer or process oil content. Polymer type is very important. As a broad generalization for unfilled polymers, the more polar the polymer, the lower the permeability will be. This is so because activation energies for diffusion increase with increasing polymer polarity. Table XXXI shows the water vapor transmission rates (WVTR) for rubber compounds based on commercially available polymers. The relationship between high polymer polarity and low permeability is not strictly borne out by the data of Table XXXI. Differences in state of cure may account for some of the discrepancies, others may be due to varying degrees of interaction between polymer and carbon black. The high permeabilities of the polysulfide, polyurethane, silicone, and polyacrylate-based compounds may be due to the relatively poor hydrolytic stability of these polymers.

7.5.2.3 The effects of filler type, size, and amount on the permeability of an EPDM-based compound are shown in Table XXXII. The compound was cured with sulfur, Altax , and methyl tuads. The first portion of Table XXXII shows that large size carbon black particles are more effective in reducing the water vapor transmission rate than are the smaller particles. The middle portion of the table shows the effectiveness of some white fillers in lowering the WVTR. The last portion of the table shows the effect of the lamellar filler mica on WVTR. Here again, the larger the particle size, the lower the permeability. The plate-like mica particles are so effective because their shape aids in blocking the diffusion of water vapor.

7.5.2.4 Caution should be exercised in employing fillers to reduce the water permeability of a rubber compound. As shown in Table XXXIII, increasing amounts of mica added to an EPDM compound bring about decreases in tensile strength and elongation, increases in hardness and compression set, and detract from flexibility at low temperatures.

7.5.2.5 The use of plasticizers and oils in a rubber compound increases the WVTR, as indicated in Table XXXIV. This effect is true for both paraffinic and napthenic process oils as well as for most rubber plasticizers.

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TABLE XXXI. WATER VAPOR TRANSMISSION RATE (WVTR) OF FUEEEL COMPCUNDS
BASED ON VARIOUS POLYMERS IN INCREASING ORDEF (17)

Polymer Type		WVTR grams H ₂ O/24 hr (Note 1)
Butyl	IIR	0.03
Chlorobutyl	CIIR	0.03
Low Density Polyethylene Plastic		0.05
Ethylene Propylene Copolymer	EPM	0.16
Chlorosulfonated Polyethylene	CMS	0.18
Ethylene Propylene Diene	EPDM	0.19
Fluoroelastomer	FKM	0.24
Chloroprene	CR	0.57
Natural Rubber	NR	0.58
Styrene Butadiene	SBR	0.73
Epichlorohydrin	CO	0.86
Butadiene/Acrylonitrile 80/20	NBR	1.4
Butadiene/Acrylonitrile 60/40	NBR	1.6
Polysulfide	EOT	3.4
Polyether urethane	EU	3.7
Polyester urethane	AU	5.5
Dimethyl phenyl siloxane	PMQ	6.5
Polyacrylate (acrylic ester)	ACM	7.3

Note 1. Determined in accordance with ASTM Standard E96, Procedure E,
Specimen: 100 sq. in. (64,516 mm²) surface area, 0.030 in.
(0.76 mm) thick.

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TABLE XXXII. EFFECT OF FILLERS ON THE WVTR OF AN EPDM RUBBER COMPOUND (82)

Filler (Note 1)	Diameter, mu, (m)		WVTR (Note 2), grams H ₂ O/24 hr
SAF carbon black	20		0.29
FEF carbon black	45		0.23
FT carbon black	150		0.20
MT carbon black	300		0.20
Hi Sil 233	-		0.34
Ground Quartz	-		0.21
Titanox	-		0.21
Silica microballoons	-		0.20
Teflon powder	-		0.19
Laminar	-		0.18
Dixie clay	-		0.16
Talcum powder	-		0.12
	mesh	m	
Mica	5	4750	0.19
Mica	20	850	0.15
Mica	50	300	0.12
Mica	160	95	0.10
Mica	325	45	0.11

Note 1. All fillers were used at the 50 pphr level.

Note 2. WVTR was determined in accordance with ASTM Standard E96, Procedure E.

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TABLE XXXIII. FORMULATION AND PROPERTIES OF ETHYLENE PROPYLENE TERPOLYMER RUBBER (EPDM) FILLED WITH CARBON BLACK AND MICA (82)

Formulation	Parts (by weight)					
	100	100	100	100	100	100
Norde1 1040®	100	100	100	100	100	100
Stearic Acid	1	1	1	1	1	1
FEF Carbon Black	50	50	50	50	50	50
Mica, 160 mesh (95 µm)	0	10	20	30	40	50
Zinc Oxide	5	5	5	5	5	5
Sulfur	0.5	0.5	0.5	0.5	0.5	0.5
Altax®	1	1	1	1	1	1
Methyl Tuads	2	2	2	2	2	2
Property	Typical Values					
	2140 (14.8)	2100 (14.5)	2210 (15.2)	1810 (12.5)	1720 (11.8)	1530 (10.5)
Tensile Strength, psi (MPa)	890 (6.14)	1090 (7.52)	1000 (6.89)	1160 (8.00)	1195 (8.24)	1010 (6.96)
Modulus (300%), psi (MPa)	545	500	505	480	495	470
Elongation, %	66	70	74	75	77	79
Hardness, Durometer A	0.24	0.17	0.15	0.12	0.11	0.10
Water-Vapor Transmission Rate grams H ₂ O/24 hr 100 sq in. (64,516 mm ²) surface area 0.030 in. (0.76 mm) thick	16	21	21	24	25	27
Compression Set, Method B 22 hr/158°F (70°C), %	-62 (-52.2)	-59 (-50.6)	-59 (-50.6)	-56 (-48.9)	-52 (-46.7)	-50 (-45.6)
Low-Temperature Flexibility, ASTM D1043, Temp. at which Young's Modulus is 10,000 psi, °F (69 MPa, °C)						

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TABLE XXIV. EFFECT OF PROCESS OIL ON THE WVTR OF ETHYLENE
PROPYLENE TERPOLYMER RUBBER (EPDM) (17)

Process Oil, parts by weight	WVTR grams H ₂ O/24 hr (Note 1)
0	0.20
20	0.23
40	0.25
60	0.27

Note 1. Determined in accordance with ASTM Standard E96,
Procedure E, Specimen: 100 sq in. (64,516 mm²) surface
area, 0.030 in. (0.76 mm) thick.

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TABLE XXXV. FORMULATION AND PHYSICAL PROPERTIES OF ETHYLENE PROPYLENE TERPOLYMER/BUTYL RUBBER BLENDS, EPDM/IIR (82)

Formulation	Parts (by weight)					
	100	75	50	25	0	
Nordel 1040 [®]	100	75	50	25	0	
Butyl 325 [®]	0	25	50	75	100	
Stearic Acid	1	1	1	1	1	
FEF Carbon Black	50	50	50	50	50	
Zinc Oxide	5	5	5	5	5	
Sulfur	0.5	0.5	0.5	0.5	0.5	
Altax [®]	1	1	1	1	1	
Methyl Tuads	2	2	2	2	2	
Properties	Typical Values					
	2140 (14.8)	1870 (12.9)	2030 (14.0)	1750 (12.1)	1720 (11.8)	
Tensile Strength, psi (MPa)	890 (6.14)	990 (6.82)	1330 (9.17)	1100 (7.58)	1340 (9.24)	
Modulus (300%), psi (MPa)	545	535	450	460	380	
Elongation, %	66	68	65	67	68	
Hardness, Durometer A	0.23	0.14	0.08	0.06	0.04	
Water-Vapor Transmission Rate grams H ₂ O/24 hr						
100 sq in. (64,516 mm ²) surface area						
0.030 in. (0.76 mm) thick						
Compression Set, Method B 22 Hr/158°F (70°C), %	16	13	12	12	19	
Low-Temperature Flexibility, ASTM D1043, Temp. at which Young's Modulus is 10,000 psi, °F (69 MPa, °C)	-62 (-52.2)	-61 (-51.7)	-61 (-51.7)	-60 (-51.1)	-54 (-47.8)	

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7.5.2.6 Butyl rubber (IIR) exhibits the lowest permeability of all rubber polymers but it is somewhat difficult to process, especially by injection molding. By blending EPDM with IIR, improved processability can be achieved with only a slight increase in permeability, as shown in Table XXXV for three blends.

7.6 Electrical Insulation Applications.

7.6.1 Rubber used in electrical service must not only be able to meet electrical requirements but must withstand, for a reasonable life period, the environmental conditions existing under service conditions. This means that frequently the choice of rubber will be as dependent on mechanical as on the electrical conditions. For instance, where oil is likely to be present in the environment, an oil resistant rubber is required. At high temperatures, silicones or fluorosilicones will be required. Abrasion resistance is required in wire and cable insulation that is subjected to chafing during installation and dragging on the ground. Low water-absorption characteristics are desirable since water absorption lowers insulation properties and dielectric strength.

7.6.2 Electrical properties of primary importance are insulation resistance, dielectric strength, volume resistivity, and dielectric constant.

7.6.2.1 Dielectric strength indicates resistance of the material to voltage breakdown expressed in volts/mil (or V/mm), and is a function of several parameters such as thickness of insulation, temperature, and time of voltage application. Dielectric strength increases nearly linearly with wall thickness, but wide variations exist between various compounds of a base polymer. Dielectric strength is usually determined in accordance with ASTM Standard D149. The maximum stress occurs at the surface of the insulation. The electrical stress at any point, P , in the insulation is given by the formula:

$$S = \frac{V}{2.303r \log_{10} \frac{D}{d}} \quad \text{Eq. 48}$$

where

S = the stress in V/mil (V/mm) at a point P

V = the voltage across insulation, volts

r = the distance of P from the cylindrical axis, mils (mm)

d = the ID of insulation

D = the OD of insulation

7.6.2.2 Insulation resistance denotes resistance of flow of current through the insulation, usually measured for direct current only and in accordance with ASTM Standard D257. The direct current insulation resistance, expressed in ohms of a single conductor cable of length, L , is calculated by the formula

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$$R = \frac{K}{2L} \log_e \frac{D}{d}$$

Eq. 49

where

K = the specific resistance, ohm-cm

d = the diameter of conductor

D = the OD of insulation

L = the length of cable, cm

7.6.2.3 The dielectric constant, denoting electrostatic capacitance, is a dimensionless property which expresses the ability of an insulation to hold an electrostatic charge compared with that of air. The capacitance value of a cm length of an insulated wire is

$$C = \frac{K}{2 \log_e \frac{D}{d}}$$

Eq. 50

where

K = the specific resistance, ohm-cm

C = the dielectric constant

D = the OD of insulation

d = the diameter of conductor

7.6.3 The highest degree of suitability for electrical engineering applications is found in materials having this combination of properties: high dielectric strength, high resistivity, low dielectric constant, and low power factor. The difficulty of selecting elastomers for electrical applications is similar to that encountered in the selection for mechanical applications; no single rubber offers clearly outstanding properties in all respects. Sometimes materials with inferior electrical properties may even have to be chosen because severe mechanical or chemical requirements predominate. Table XXXVI shows electrical properties for seven elastomers. The change in dielectric constant resulting from water immersion is shown in Figure 103. Figures 104 and 105 show the values of some electrical properties of silicone rubber. Electrical properties, as well as other properties, can be varied widely by use of various fillers and additives. The dielectric constant can be varied rather easily from about 2.7 up to 5.0 and higher; the power factor can be varied from 0.0005 to 0.1 or more by compounding.

7.7 Electrically Conductive Rubber

7.7.1 Although rubber is considered an insulating material, any polymer can be made to have limited electrical conduction characteristics by the addition of carbon black or metallic particles. While carbon is a good conductor, the

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dispersion of carbon black in the rubber prevents the formation of a really continuous electrical path. To provide electrically conductive compounds, special forms of carbon black, such as ASTM Standard D1765, No. 472 or acetylene carbon black, are used. These form long clusters which lower the resistivity of the rubber. Such rubbers are harder and have lower tensile strength than nonconductive compounds. Minimum practical hardness is 60 Durometer A. The resistivity of such rubber varies from 1 to 5 ohm-cm in sheet and film form, and from 10 to 10^6 ohm-cm in molded products. Conductive silicone rubber compounds have been developed with a resistivity range of 10 to 10^5 ohm-cm and with general properties similar to those of conventional silicones.

7.7.2 Control of the exact resistivity is almost impossible as the magnitude of variation from one batch to another is as high as 200 percent. Therefore, specifications of sheets must be tied to resistivity rather than in dimensional terms. For highly conductive (5 to 10 ohm-cm) rubbers, a 10 percent variation can be expected. Greater variations are experienced for products with lower resistivities.

7.7.3 The resistance of conductive rubber increases under stress and is roughly proportional to it. This holds true for compression or tension. Swelling in conductive rubber resulting from solvent or oil action also increases the resistivity.

7.7.4 Conductive rubbers are used to prevent accumulation of static electric charges on equipment used in explosive atmospheres and for flexible heating surfaces. For the dissipation of static electric charges, resistivity ranges from 10^2 to 10^6 ohm-cm are appropriate. Static charges are usually characterized by high voltages so that a highly conductive path is not essential.

7.7.5 Specially compounded rubbers have been developed that utilize metallic particles to produce the conductance. The best that can be obtained with rubbery materials is about 10^{-3} ohm-centimeters.

TABLE XXXVI. TYPICAL ELECTRICAL CHARACTERISTICS OF RUBBERS

Rubber	Water Absorption		Dielectric Constant at 60 Hz	Power Factor $\tan \delta$	Insulation Resistance ohm-cm	Dielectric Strength	
	mg/in. ² 7 days	(mg/cm ²) 55 days				V/mil	V/mm
Acrylonitrile Butadiene NBR	---	---	3.0	---	---	100 - 300	3,935 - 11,800
Butyl IIR	15 (2.3)	20 - 30 (3.1 - 4.6)	5.0	5	75,000	450	17,715
Chloroprene CR	---	---	8.7	High	100	400 - 600	15,750 - 23,625
Fluorocarbon FKM	---	3.5 (0.5)	6.2	0.11 - 0.12	---	---	---
Methyl Vinyl Sillicone VMQ	---	---	3.0 - 3.4	0.50 - 0.80	5,000	450	17,715
Natural NR	10 (1.6)	12 (1.8)	2.8 - 6.0	5	20,000	400 - 600	15,750 - 23,625
Styrene Butadiene SBR	20 (3.1)	---	3.2 - 5.0	5	2,000	500 - 700	19,685 - 27,560

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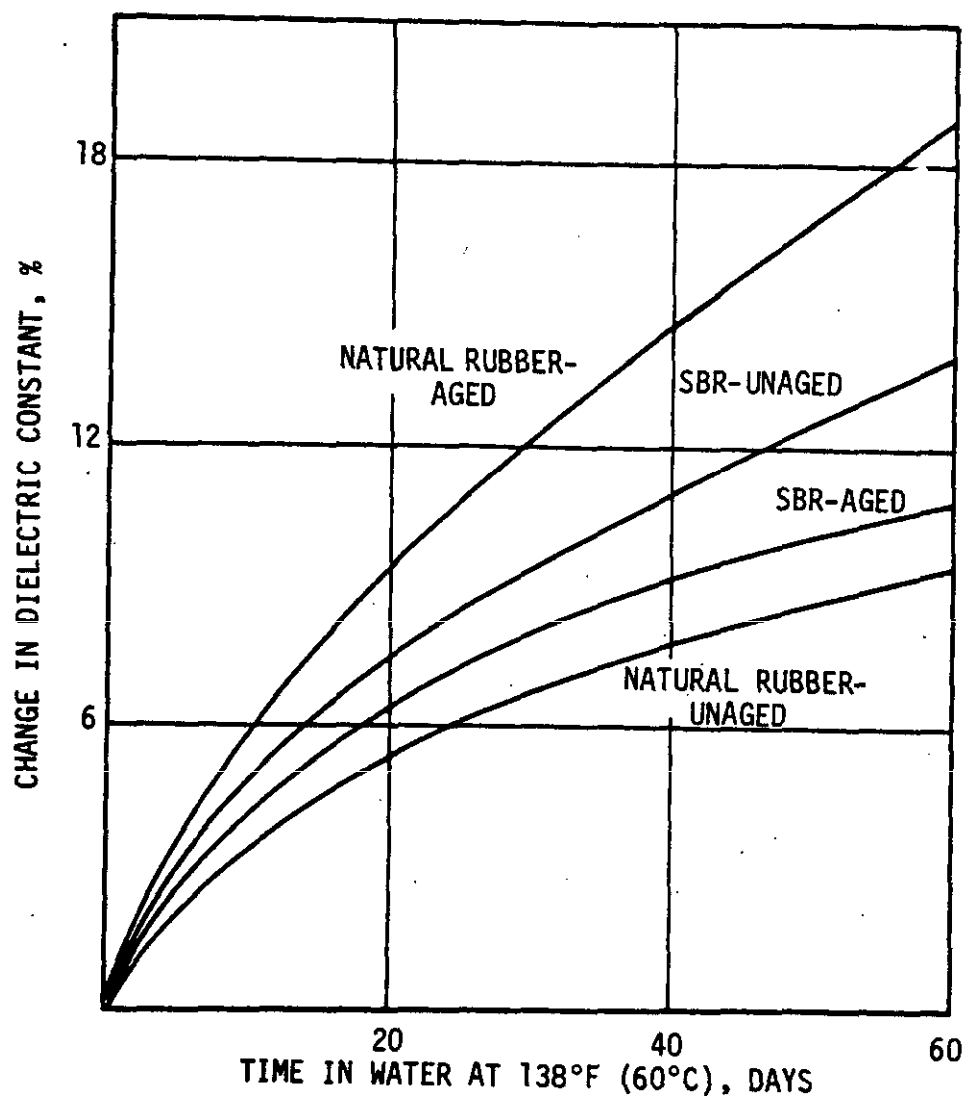


FIGURE 103. CHANGE IN DIELECTRIC CONSTANT ON AGED AND UNAGED NATURAL AND SBR RUBBERS IN WATER (54)

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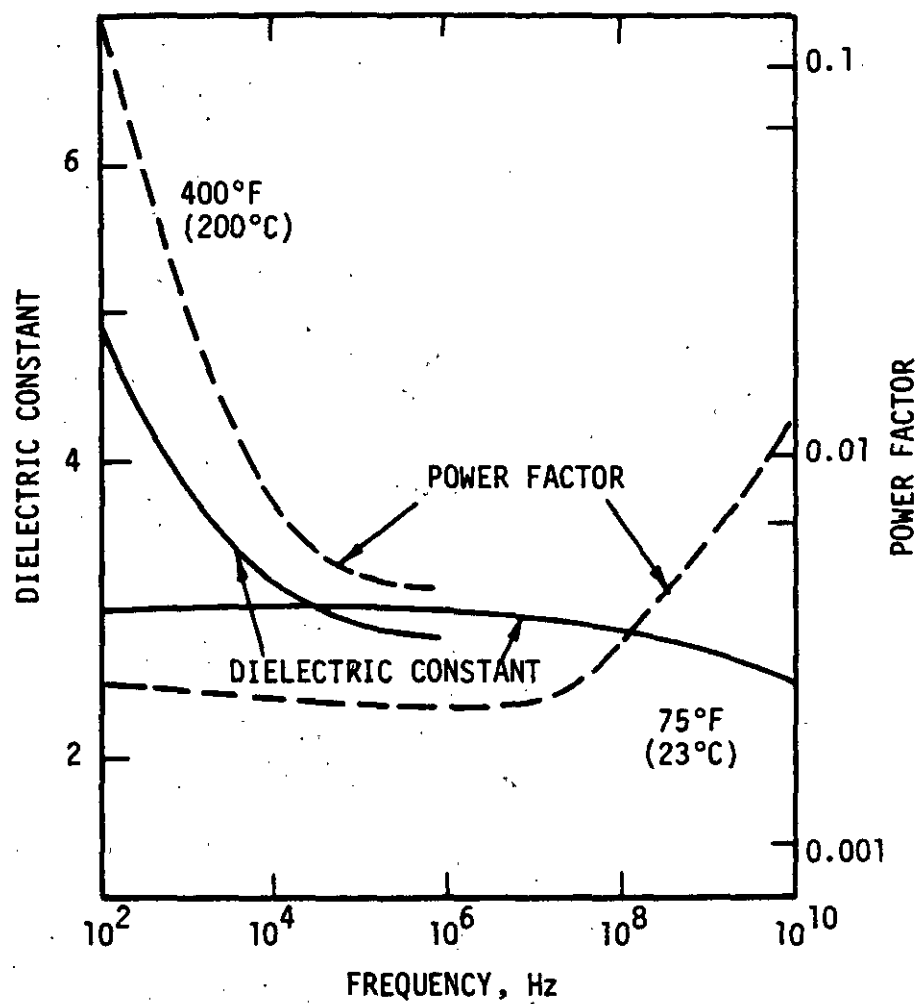


FIGURE 104. DIELECTRIC CONSTANT AND POWER FACTOR AS A FUNCTION OF TEMPERATURE AND FREQUENCY, SILICONE RUBBER, VMQ (53)

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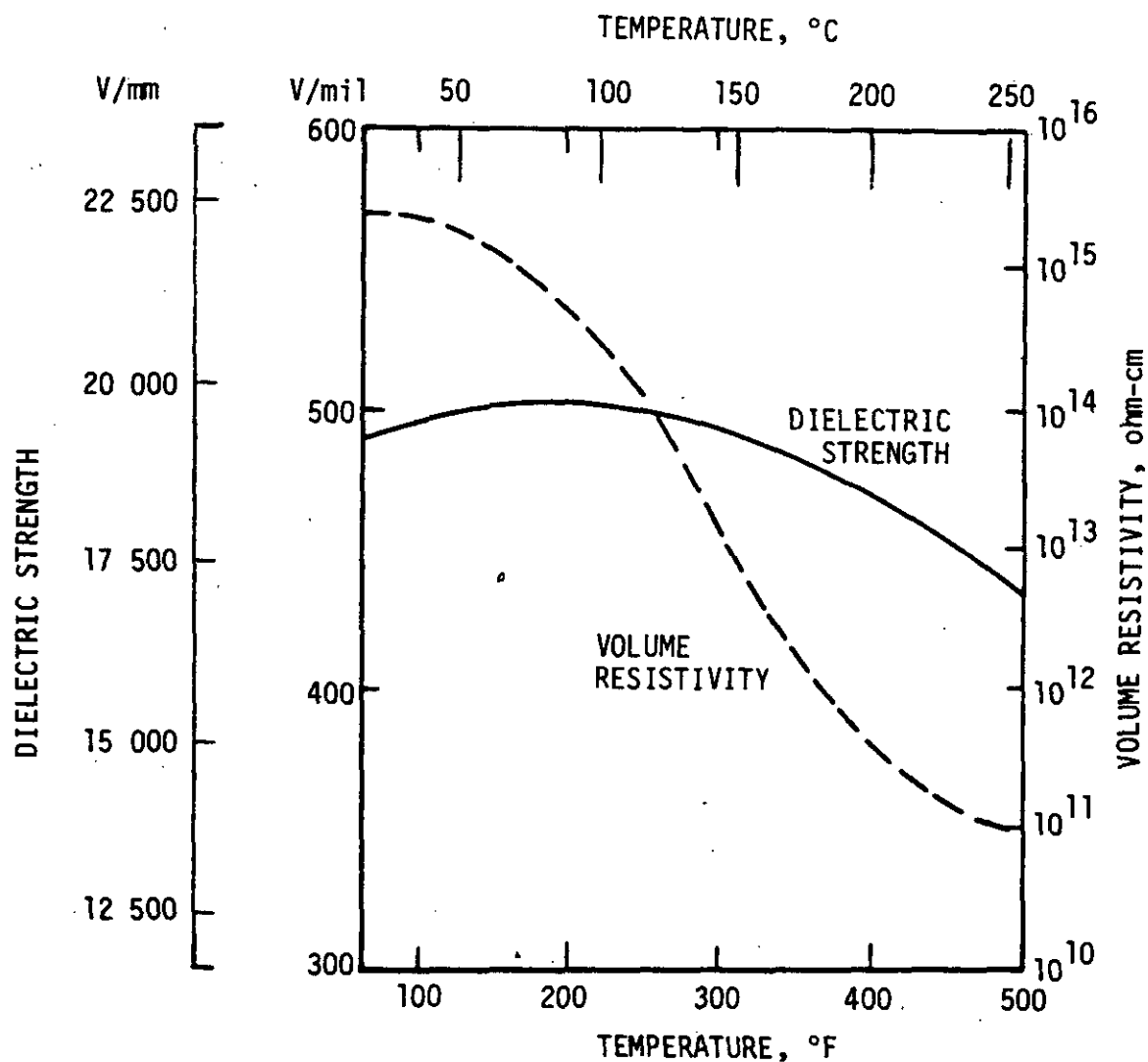


FIGURE 105. DIELECTRIC STRENGTH AND VOLUME RESISTIVITY AS A FUNCTION OF TEMPERATURE, SILICONE RUBBER, VMQ (53)

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7.8 Ozone Effects

7.8.1 Many elastomers, when strained and exposed to the atmosphere, exhibit cracking to various degrees. The principal cause for deterioration is atmospheric oxygen, ozone, and airborne pollutants, especially in larger cities or areas subject to smog. The reaction of rubber with molecular oxygen is slow and results in oxidation of the carbon atoms of the elastomer. The more severe attack by ozone produces deeply penetrating fissures causing serious damage. Ozone exercises this deleterious effect only when rubber is under a tensile stress. The orientation of the cracks is such that they cross the axis of the tensile stress at 90°. There are indications that, under dynamic stress conditions, the rate of ozone absorption increases manyfold over that occurring under plain stress conditions. At low ozone concentrations with rubber in a relaxed state, an ozonized film quickly formed on the surface provides an effective barrier against further reaction. The degree and the rate of deterioration are largely controlled by the concentration of ozone in the atmosphere, the stress in the rubber, the rubber composition, and the temperature of exposure. Ozone concentration varies with geographic location, altitude, and time, and is reported in parts per million (ppm) by the atmosphere control agencies in many countries. The average measured quantity of ozone is 0.02 to 0.07 ppm of atmosphere, by volume, although concentrations as high as 0.90 ppm have been recorded. The California air quality standard for ozone is 1-hour average concentration equal to or greater than 0.10 ppm (1/10 of a part of ozone per million parts of air, or 1 part ozone in 10 million parts of air). The Federal air quality standard is 0.12 ppm. Ozone content reported in the Los Angeles basin varied from 0.02 to 0.43 during the high smog summer months of 1979. A first stage smog alert is 0.20 ppm ozone; second stage is 0.35 ppm; while a third stage is 0.50 ppm. A world average summer day would be approximately 0.05 ppm. Ozone resistance of rubber is evaluated by procedures in ASTM Standard D1149, generally utilizing an ozone concentration of 0.50 ppm of air in the test chamber.

7.8.2 The rubber types most inherently resistant to ozone attack are:

- chlorosulfonated polyethylene, CSM
- ethylene propylene copolymer, EPM
- ethylene propylene diene modified, EPDM
- propylene oxide, GPO
- silicone, PMQ, PVMQ, VMQ
- fluorosilicone, FVMQ
- fluorocarbon, FKM
- perfluorocarbon, FFKM
- polychlorotrifluoroethylene, CTFM
- phosphonitrilic fluoroelastomer, FZ

7.8.3 Rubbers which can be compounded to become ozone resistant (resist cracking with long time exposure to concentrations up to 0.50 ppm and strains up to 30 percent) are:

- bromobutyl, BIIR
- butyl, IIR (uncontaminated by other rubber types)
- chloroprene, CR
- polyurethanes, AU & EU

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7.8.4 Rubbers requiring special antiozonants to achieve protection from ozone attack in order of decreasing effectiveness:

styrene butadiene, SBR
acrylonitrile butadiene, NBR
natural, NR, and isoprene, IR

7.8.5 The ozone resistance of some rubbers decreases with temperature increase. Figure 106 shows curves of temperatures versus time-to-crack for chloroprene, butyl, SBR, and natural rubber. In accelerated ozone tests (high ozone concentration) on specimens elongated 50 percent and 100 percent at 77°F (25°C) and at -48°F (-45°C), the time necessary to produce a crack was measured. Natural rubber required 90 minutes at -48°F (-45°C) versus three minutes at 77°F (25°C). In chloroprene and butyl rubber, no cracks developed at -48°F (-45°C), whereas at 77°F (25°C), cracks developed after periods ranging from 5 to 23 minutes. At higher temperatures, butyl rubbers, which are relatively ozone resistant at room temperatures, apparently lose the protective antiozone quality. At 130°F (54°C) they become slightly more resistant than natural rubber, which shows a flat crack-time-temperature curve. Compounds protected from ozone attack at room temperature with certain waxes, however, will be rapidly attacked by ozone at low temperatures where the wax does not give a protective film.

7.8.6 The means presently available for obtaining ozone resistance in rubber may be classified as follows:

- (1) Selection of polymer having inherent ozone resistance
- (2) Proper compounding, high-set and low-modulus compounds, chemical antiozonants
- (3) Application of physical barriers, such as wrapping, painting with ozone-resistant rubber, plastics, chemicals, and waxes
- (4) Installation and storage at low stress levels. If storage in the unstressed state is not possible, minimize stresses by supporting the rubber, using large coil diameters, and avoiding kinking or folds. If necessary, store particularly susceptible parts in closed containers, with controlled atmosphere.

7.8.7 The effects of ozone should be considered in designating the rubber polymer for each part, as storage and installation may be an ozone-hazard period, while the service environment may be free from ozone hazard. A good example would be the fuel-resistant rubber cushions on line clamps to be installed inside fuel tanks on aircraft; nitrile fuel-resistant cushions have weather-cracked during installation prior to fueling of the tank. Once fuel was applied to the tank, the cushions were protected from ozone by the fuel; however, installation stresses prior to fuel immersion caused cracking of the thin cushion flanges from exposure to the atmosphere of the manufacturing area. A choice was necessary between optimum fuel resistance of the cushions for the fuel immersed service and the ozone resistance of the cushions for the ozone-hazard period prior to service.

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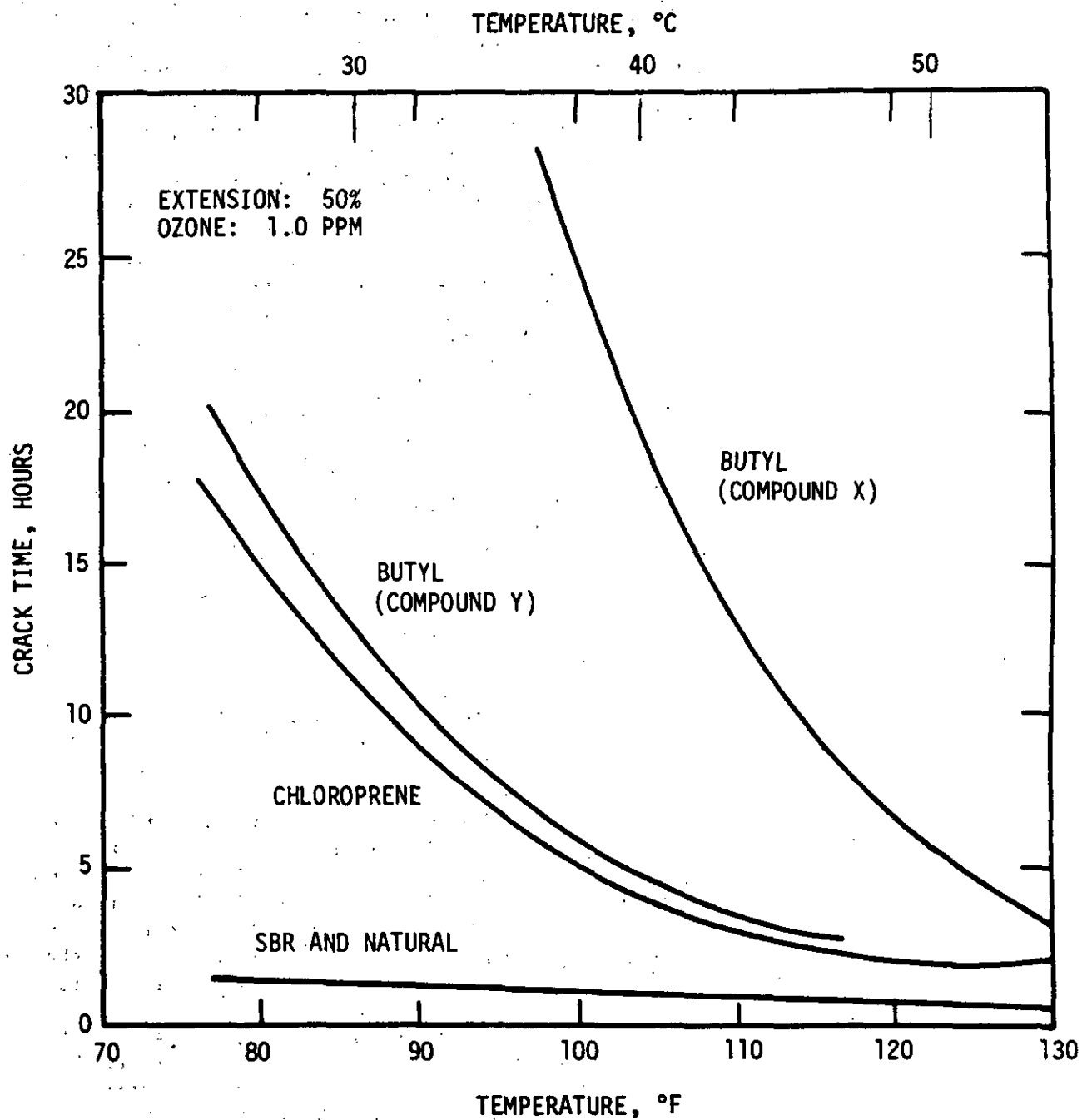


FIGURE 106. EFFECT OF TEMPERATURE ON OZONE RESISTANCE, BUTYL, CHLOROPRENE, SBR, AND NATURAL RUBBER (29)

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7.9 Radiation Effects

7.9.1 Modern technical applications of rubber include many cases where radiation is encountered. Major sources of radiation are radioactive materials, nuclear reactors, high energy accelerators, and the atmosphere. The latter becomes an important source at high altitude environments.

7.9.2 The major types of radiation are X-rays, alpha rays, beta rays, and gamma rays. Natural radioactive materials are sources of alpha particles, which are helium nuclei with a double positive charge; beta particles, which are negatively charged electrons; and gamma rays, which are electromagnetic waves of photons having no charge and negligible mass. The energy of a charged particle is transferred to the medium through which it is moving by several mechanisms: ionization, atomic displacements and thermal. The charge of the particle and its energy primarily determine the depth of penetration.

7.9.3 Quantitative radiation exposure is measured in the following units:

Roentgen units (gamma or X-rays) (coulomb per kilogram, C/kg)

$$= 5.4 \times 10^7 \text{ MeV/gram in air } [r \times (2.58 \times 10^{-4}) = \text{C/kg}]$$

(0.87 rad in air, or 0.96 rad in tissue)

Rads = $6.25 \times 10^6 \text{ MeV/gram}$ [rad $\times (1 \times 10^{-2}) = \text{gray, Gy}$]
 = 100 ergs of energy per gram of absorber
 (0.01 Gy of energy per gram of absorber)

Rem = absorbed dose (rads or Gy) $\times QF$
 where: $QF = 1$ for X-rays, electrons, and positrons
 $= 10$ for particles, fast neutrons, and
 protons up to 10 MeV
 $= 20$ for heavy recoil nuclei

7.9.4 The effects of irradiation are diverse, and not always harmful. Irradiation can change the atomic structure of elastomers, causing atom displacement, chain breakdown, or crosslinking. Indirect effects are caused by altering the composition of the atmosphere and specifically increasing ozone concentrations which have increased deleterious effects on elastomers. Gamma rays can vulcanize rubber; such vulcanized products are more heat stable than similar sulfur-containing compounds vulcanized by conventional methods.

7.9.5 Among changes caused by radiation affecting rubber performance are changes in hardness, elongation, tensile strength, stress-strain properties (modulus), and crack-formation. Characteristic changes, with increasing radiation dosage in the above properties for specific elastomer groups, are given in Table XXXVII and Figures 107 through 109.

7.9.6 Composite comparative tests have been made on the damage effects of radiation on different elastomers. The bar graph on Figure 110 allows a general estimate of the utility of various polymers in radiation environments. From the chart, note that all rubbers except the butyl group retain substantial utility at low exposure and that the natural rubber, SBR, and polyurethane group retain limited use even at high exposure. Fluorocarbons have been used in atomic reactors for their high heat resistance, while some

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ethylene propylene compounds have proven best for the combination of water and radiation exposure. EPDM compounds were not available when the data for Figure 110 was collected, but a bar for EPDM would be similar to NBR, and perhaps a little better. Although polyurethane ranks high on the chart, these compounds should be used cautiously because of limitations on high temperatures, water resistance, and compression set resistance.

7.10 Very Low Vacuum Exposure Effects

7.10.1 The effect of vacuum exposure on elastomers has become important with space applications. From tests on specimens subjected to vacuum as low as 10^{-6} mm. Hg (0.1 mPa), a number of conclusions can be drawn.

- (1) Ingredients, such as plasticizers, antioxidants, and antiozonants having relatively high vapor pressure, are lost during vacuum exposure. As a consequence, the rubbers lose flexibility at low temperature, and oxidation and ozone resistance diminishes.
- (2) Loss of strength is not experienced. Room temperature stress-strain properties are not affected appreciably.
- (3) Loss of oxidation resistance does not affect the elastomer until it is brought back to normal atmospheric conditions.
- (4) When vacuum exposure is accompanied by high temperature, degradation is accelerated, and it is somewhat worse than under conditions of air exposure at the same temperature.

7.10.2 Effect of vacuum exposure on high-temperature elastomers can be summarized as follows. The high-temperature tensile strength of silicone rubber, VMQ, after vacuum exposure is equal or superior to that after air-oven exposure. There is no significant change in other properties. The high-temperature tensile strength of fluorocarbons and fluorosilicones is also equal to the original after vacuum exposure. Greater stiffness results but no other pronounced changes are noted.

7.10.3 To subject rubber specimens to combined vacuum and ultraviolet radiation exposure, simulated conditions of high altitude and sunlight have been produced in a test chamber. The resulting damage of severe cracking is a surface phenomenon. Initial indications are that the effective damage will be a function of material thickness, the heavier sections losing a smaller percentage of their functional capability.

7.10.4 Rubber compounds for use in space applications must not contain any constituent that would "outgas". The presence of equipment with optical lenses is a concern, where the free gas could dull or obscure the optical surfaces. Material specifications for these rubber compounds usually contain special outgassing requirements to ensure suitability of the compound for the application.

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TABLE XXXVII. EFFECTS OF RADIATION ON HARDNESS, TENSILE STRENGTH, AND ELONGATION (65)

Rubber	Dosage		Hardness Change %	Tensile Strength Change %	Elongation Change %
	Roentgen	C/kg			
Acrylonitrile Butadiene NBR					
Hycar 1002 B1® (Black Compound)	5,000,000	1,290	+ 2	+ 11	- 6
	100,000,000	25,800	+42	+ 7	- 81
	300,000,000	77,400	+92	+374	- 92
HW B17®	5,000,000	1,290	+ 3.9	- 6	- 21
	100,000,000	25,800	+55	+139	- 88
	300,000,000	77,400	+96	+972	- 99
Butyl IIR					
PR 907-70®	5,000,000	1,290	0	- 7	- 5
	60,000,000	15,480	-40	-100	+ 2
Hycar 2202®	5,000,000	1,290	- 3	- 32	- 8
	60,000,000	15,480	-20	- 88	- 27
Fluorocarbon CFM					
Kel-F®	5,000,000	1,290	- 6	+ 27	- 10
	60,000,000	15,480	-10	- 36	- 14
Fluorocarbon FKM					
Viton A4®	5,000,000	1,290	+11	- 22	- 55
	100,000,000	25,800	+13	+ 8	- 94
Methyl Vinyl Silicone VMQ	5,000,000	1,290	+22	+ 10	- 38
	100,000,000	25,800	+74	- 0.4	- 90
VMQ	5,000,000	1,290	+ 2	+ 9.1	- 40
	100,000,000	25,800	+11	+ 62.1	- 80
Natural NR					
NWB14® (Brown)	5,000,000	1,290	+ 4	- 17	- 22
	100,000,000	25,800	+24	- 23	- 67
	1,000,000,000	258,000	+94	+171	-100
TK1/1®	5,000,000	1,290	0	- 1	- 7
	100,000,000	25,800	+ 9	- 74	- 67
	1,000,000,000	258,000	+41	- 61	- 96
Polyether Urethane EU					
Adiprene CI®	5,000,000	1,290	- 1	+ indetermin.	- 10
	100,000,000	25,800	-12	- 53	- 57
Chemigun XSL®	5,000,000	1,290	- 3	- 5.9	0
	100,000,000	25,800	-20	- 79	- 58

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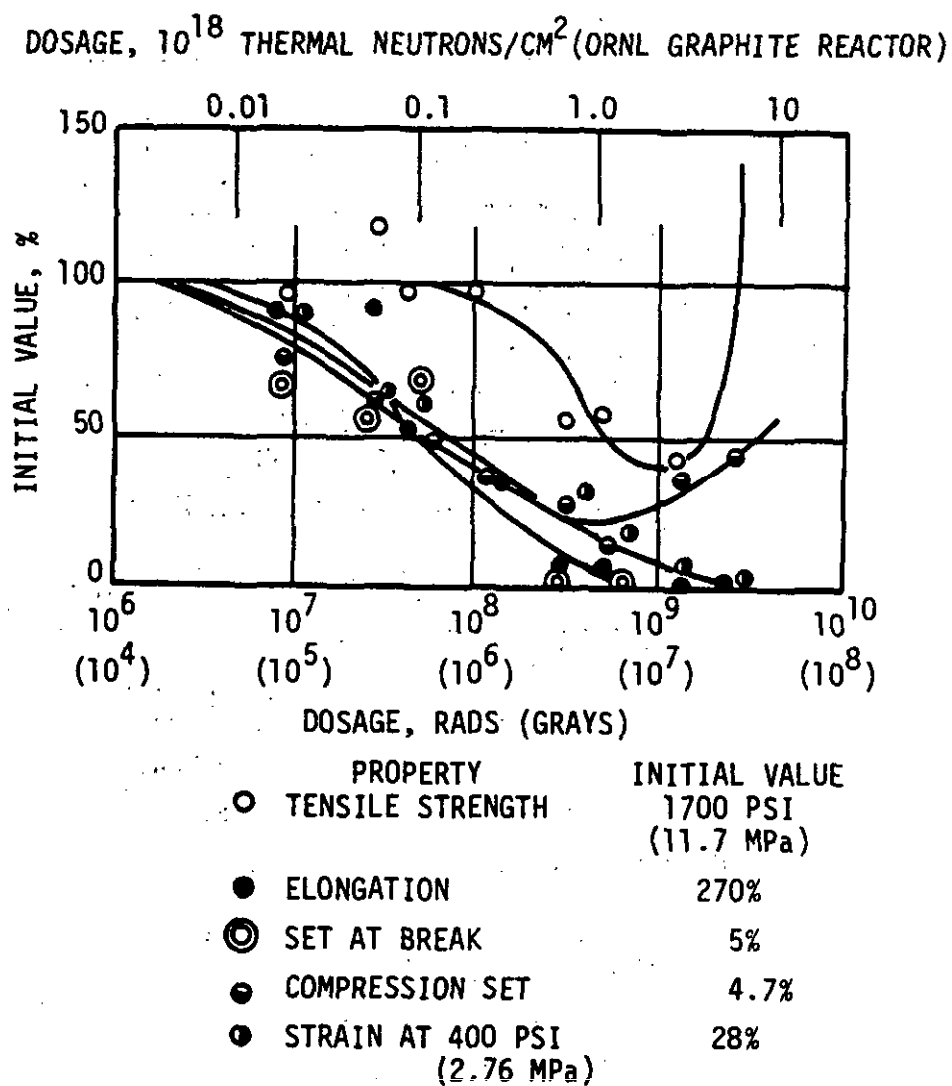


FIGURE 107. QUANTITATIVE CHANGES IN PHYSICAL PROPERTIES OF STYRENE BUTADIENE RUBBER, SBR, AS A FUNCTION OF RADIATION DOSAGE (21)

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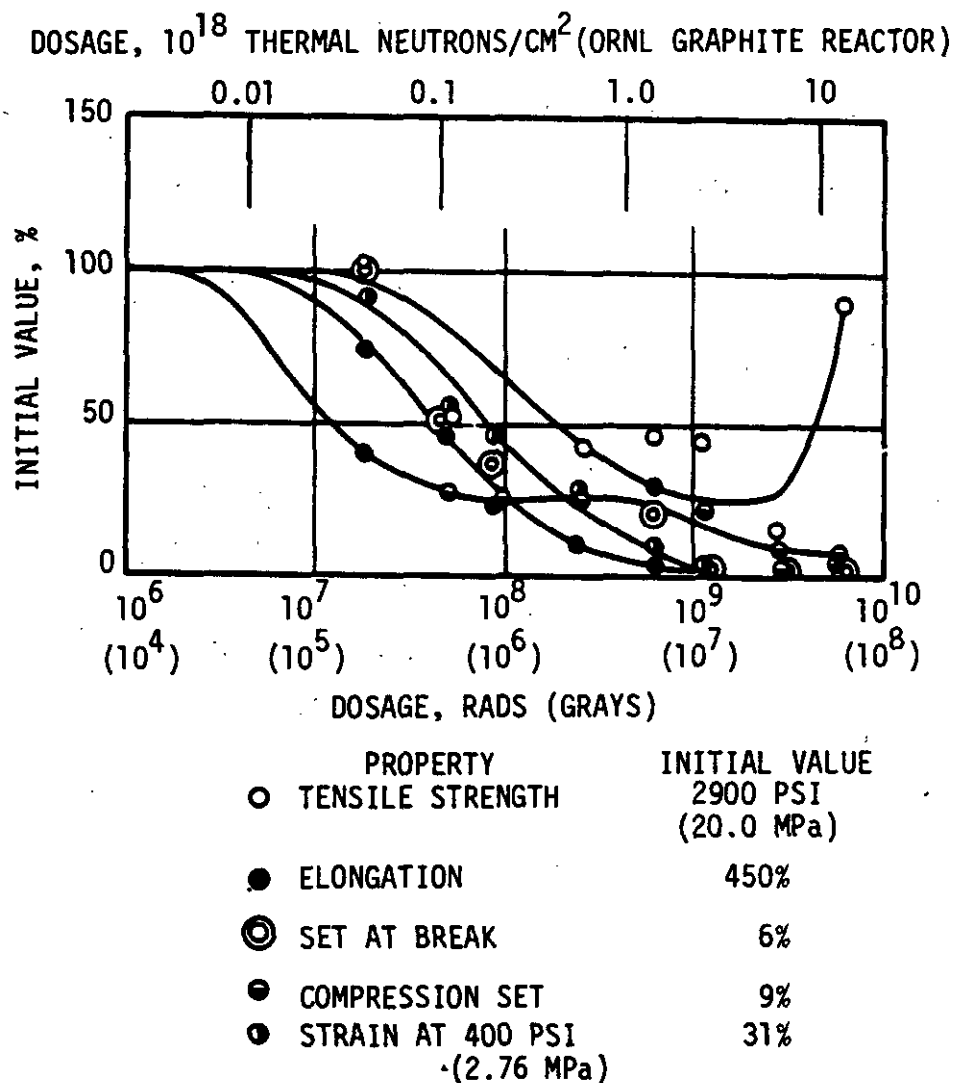


FIGURE 108. QUANTITATIVE CHANGES IN PHYSICAL PROPERTIES OF CHLOROPHRENE RUBBER, CR, AS A FUNCTION OF RADIATION DOSAGE (21)

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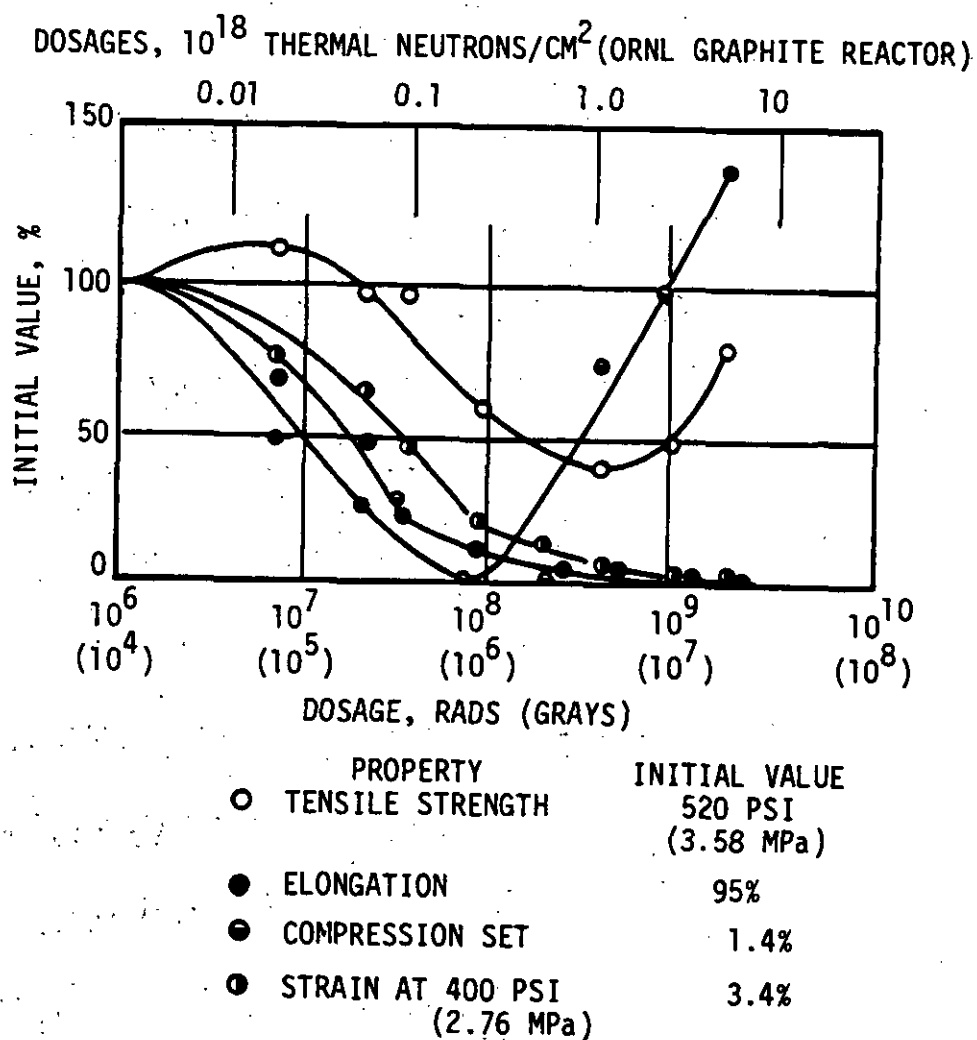


FIGURE 109. QUANTITATIVE CHANGES IN PHYSICAL PROPERTIES OF METHYL VINYL SILICONE RUBBER, VMQ, AS A FUNCTION OF RADIATION DOSAGE (21)

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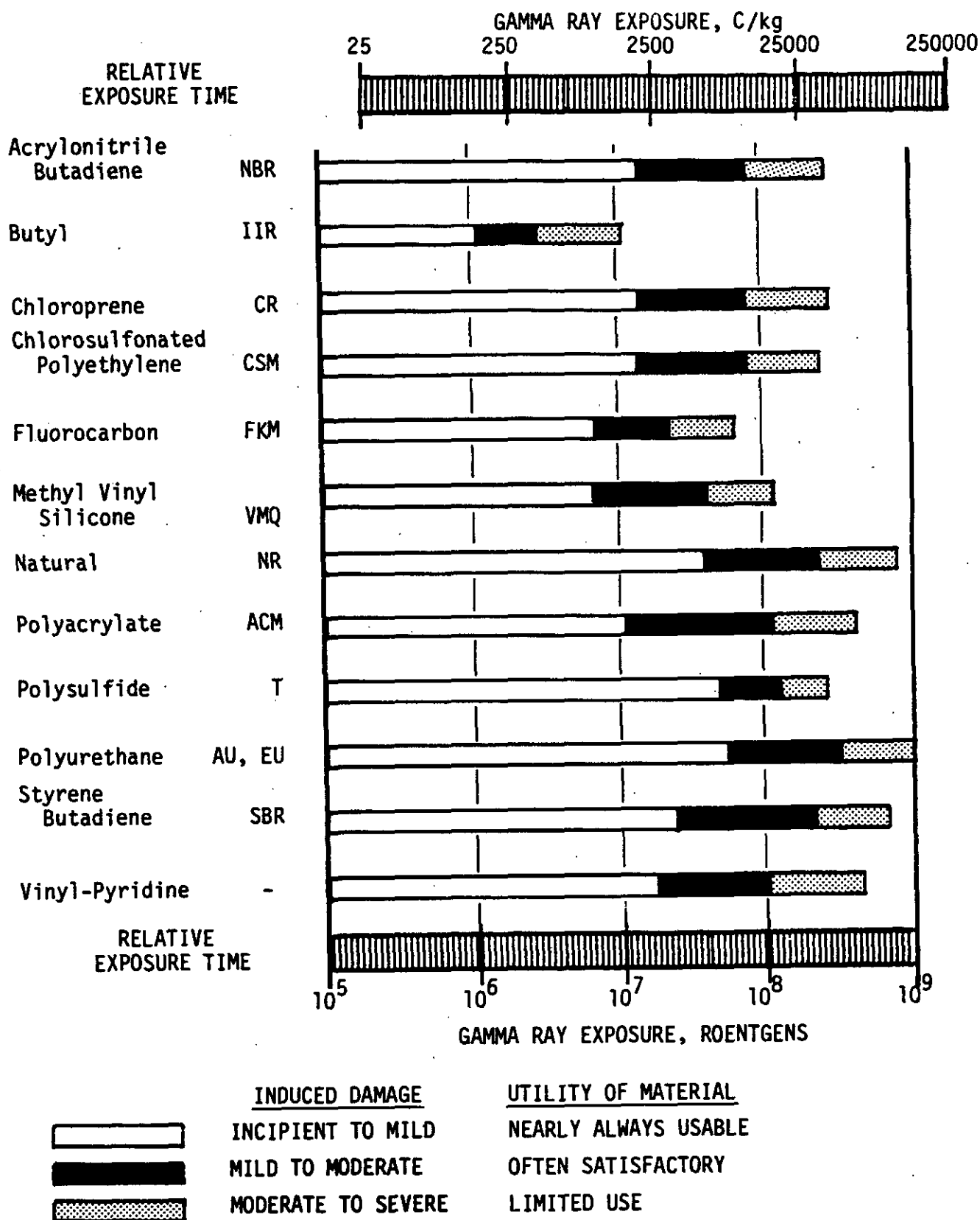


FIGURE 110. OVERALL SUITABILITY OF RUBBER POLYMERS AS A FUNCTION OF GAMMA RAY EXPOSURE LEVEL (39)

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7.11 Effects of Rubber on Environment

7.11.1 Odor in rubber is relative and not as easily described as most other characteristics. It can range from faint to strong, and from pleasant to offensive. When odor is a factor, polymers which have been prepared with the greatest care are usually selected. The odors which usually prevail in rubber are caused by their various components, or by material added to them in processing. Additives which are relatively odorless should, if possible, be used in compounding. A small percentage of deodorant may even be added to the mixture. SBR, nitrile, chloroprene, and silicone rubbers usually present no odor problem. Polysulfide, on the other hand, is generally not used where a strong odor is undesirable. A compound which is odorless under ordinary conditions may develop an offensive odor when kept in a tightly closed container. There are no standard rules to evaluate compounds for odor, but a number of practical tests exist. One of these is to seal a test piece of any thickness and approximately 1 by 2 inches (25 by 50 mm) in a glass jar at room temperature for about six hours, and judge the odor upon opening the jar. Objectionable residual odors may sometimes be counteracted by subjecting the compound to circulating air at moderately elevated temperatures. In automotive or industrial applications, odor is usually not a problem. In food handling applications, odor and taste imparted to food products may be a serious problem, which would require selection of rubber polymers based primarily on these factors.

7.11.2 Staining means the tendency of rubbers to discolor paint, lacquer, enamel, and other finishes, or to tarnish high-finish metal surfaces when rubbers are placed in contact with them. ASTM Standard D925 is the test normally used. The stain caused by the rubber, which is usually caused by an ingredient added to the polymer for some purpose, can be a contact stain or a migratory stain. The contact stain is confined to the contact area. The migratory stain spreads from the contact area. Ultraviolet light accelerates migratory stain.

7.11.3 In testing for stain, the actual finish surface should be used in the test. Any residual solvent in an organic coating can make the stain worse. These solvents tend to evaporate with extended aging, therefore, any test panels for evaluation of residual solvent action should be used within two months of being coated.

7.11.4 Staining characteristics may be eliminated or reduced by the use of specially prepared rubber and the proper selection of compounding ingredients.

7.11.5 Corrosion of metal surfaces from contact with rubber is usually not a serious problem; staining or discoloration of metal surfaces is usually not objectionable. However, some compounding ingredients or residual unreacted curing agents may cause corrosion under high humidity or in confined spaces, such as in electrical equipment potted with rubber insulation. Material specifications for rubber compounds often require "no corrosion" but allow staining or discoloration; test procedures for evaluation of corrosion are not usually specified, as conditions of use vary so greatly. If a corrosion resistant rubber is required, it should be evaluated by simulated-part or test-sandwich exposure to the anticipated service condition.

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7.12 Fungus Resistance. When rubber is used in any warm damp environment, it must resist attack by fungus, mold, or mildew. Most man-made rubbers are not nutrient to fungus and are not generally attacked by such organisms. Some natural rubber compounds may contain varying amounts of protein not reacted during vulcanization, and may become subject to fungus attack. Antifungicidal agents may need to be added to uncured or partially cured rubbers used in adhesives or similar applications.

7.13 Flammability

7.13.1 All rubber polymers will burn to some extent, although some are slow to ignite and burn rather slowly. Special compounding may be required to pass standardized tests developed for evaluating flammability of materials. Results of flammability tests are no indication of behavior of a polymer under actual fire conditions.

7.13.2 Products of combustion are generally unpleasant odors, and are usually hazardous.

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8. RUBBER IN SPECIAL APPLICATIONS

8.1 Mountings and Springs

8.1.1 A great number of "standard" or "off-the-shelf" rubber isolators or mountings have been developed for a wide range of applications. The designer should check commercial sources for such products before designing special parts. Rubber mountings of various types and the conditions under which they are employed are illustrated and described in Figures 111 through 117.

8.1.2 Rubber torsion springs consist of a cylindrical sandwich having an inner and an outer shell, usually consisting of split sections, with the rubber bonded to both shaft and shell. Such springs are well suited for vehicle suspension systems. Either the shaft or the shell is held in a fixed position while the nonstationary side rotates under load. Such a spring and a typical application of it are shown in Figure 118. An application of the torsion spring to a wheel suspension is shown in Figure 119.

8.1.3 Such torsion mounts can be applied to a wide range of uses and are most advantageous where they can function both as a spring and as a locating means, forming their own bearings. This enables the rubber to absorb some impact in every direction. No lubrication is required, problems associated with bearings and bearing seals are eliminated, and the noise level is reduced because it is damped out by the rubber. Figure 120 shows a typical curve of torque versus angular deflections (windup). In Table XXXVIII, hysteresis and elastic properties of suggested rubber types for engine mountings are listed.

8.1.4 A different type of torsion spring is shown in Figure 121. In this spring, multiple rubber cylinders are contained between an inner and outer shell which may either have a square, triangular, or any other polygonal cross sectional shape. No adhesive bond is present between the rubber and metal parts. In operation, the elastic members roll and are deformed in compression. Coaxial multiple spring arrangements may be designed to increase the deflection.

8.1.5 Triangular springs have maximum angular deflection characteristics of slightly less than 60° , whereas quadratic shapes have a practical maximum of 42° . Characteristic load deflection curves are shown in Figures 122 and 123. Such curves are applicable to all springs which have the same size ratios; that is, the same relationship of the rubber diameter, the cross-flats dimension of the inner and outer tube. For the sake of stability, the length of the spring should be several times the diameter, the appropriate ratio depending on the application. For coupling application, a 3:1 ratio is sufficient.

8.2 Rubber-Mounted Wheels for Rail Vehicle

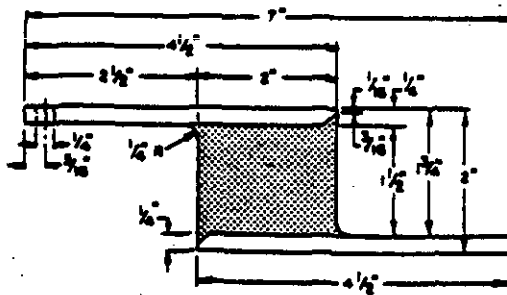
8.2.1 Figure 124 shows rubber-mounted wheels with the elastic mounting incorporated in the wheel itself. While these design examples are for application on rail vehicles, certain other uses such as on tanks and chain sprocket mountings are possible.

MIL-HDBK-149B

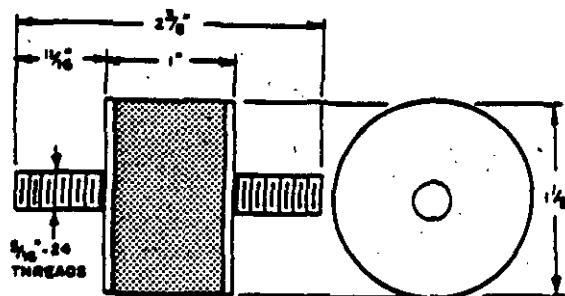
8.2.2 In Figure 124a and b, a T-ring to which rubber has been vulcanized places a shear loading on the rubber. In Figure 124c, the rubber ring is placed in compression. Because of wheel rotation, the shear stresses in Figure 124a and b are reversed stresses, and consequently should be kept small, such as approximately 20 psi (138 kPa). Figure 124d shows an application in which mounting of the rim is through cylindrical rubber plugs. The force distribution of vertical static and dynamic forces, and horizontal shear forces resulting from brake applications are indicated. In addition, they also incur transverse forces where the mounting is in vehicles, due to negotiation of curves.

8.2.3 The work done in deflecting the rubber is reflected in a power loss. For this particular application, a resistance equal in amount to 7-1/2 percent of the rolling resistance of a rail vehicle has been calculated. Of importance, in such applications, is the selection of rubber with a small permanent set so that out-of-roundness is held to a minimum after a period of idleness during which the rubber is loaded in one direction.

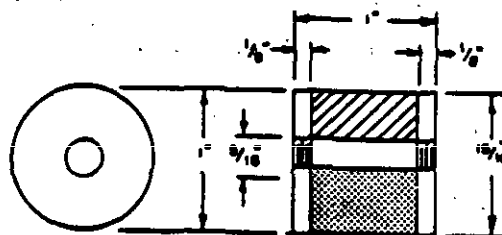
MIL-HDBK-149B



Rubber hardness, Durometer A: 40.

Maximum recommended load in vertical shear:
80 lb per inch of length.
(14 N/mm of length)Deflection at this load: 1.0 inch.
(25.4 mm)Minimum disturbing frequency at this
deflection: 470 cycles per minute.
For frequencies of 550 cycles per minute
or higher, recommended load is
60 lb per inch (10.5 N/mm).Maximum recommended load in compression:
250 lb per inch of length.
(44 N/mm of length)Deflection at this load: 0.312 inch.
(7.9 mm)Minimum disturbing frequency at this
deflection: 850 cycles per minute.

Rubber Hardness, Durometer A: 40.

Maximum recommended load in shear:
30 lb (135 N).Minimum disturbing frequency at this
load: 1,000 cycles per minute.Maximum recommended load in compression:
125 lb (555 N).Deflection at this load: 0.175 inch.
(4.45 mm)Minimum disturbing frequency at this
deflection: 1,250 cycles per minute.

Rubber hardness, Durometer A: 40.

Maximum load in vertical shear:
10 lb (45 N).Deflection at this load: 0.156 inch.
(4.0 mm)Minimum disturbing frequency at this
deflection: 1,200 cycles per minute.Maximum recommended load in compression:
25 lb (110 N).Deflection at this load: 0.063 inch.
(1.60 mm)Minimum disturbing frequency at this
deflection: 1,750 cycles per minute.

Dimensions

Inch Millimetres

1/16	0.063	1.59
1/8	0.125	3.18
3/16	0.188	4.76
1/4	0.250	6.35
5/16	0.312	7.94
11/16	0.688	17.46

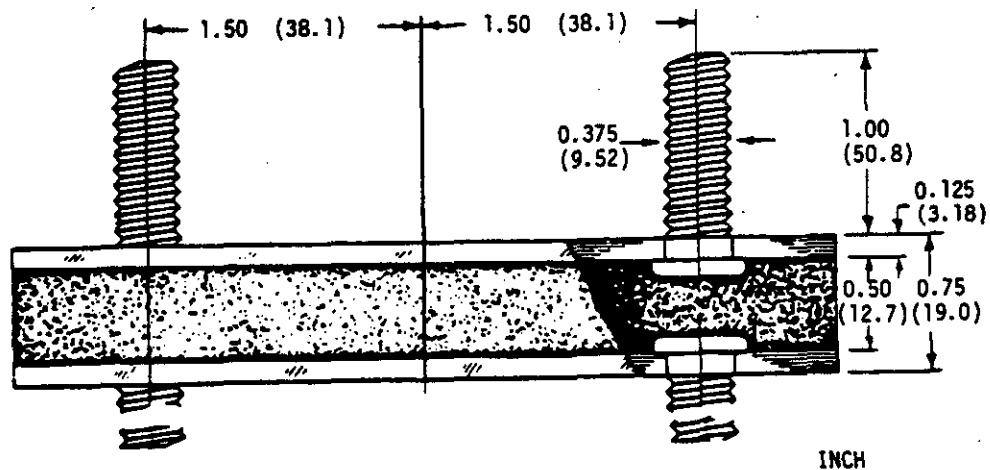
Dimensions

Inches Millimetres

1	1.00	25.4
1 1/2	1.50	38.1
1 3/4	1.75	44.4
2	2.00	50.8
2 3/8	2.375	60.3
2 1/2	2.50	63.5
4 1/2	4.50	114.3
7	7.00	177.8

FIGURE 111. SHEAR OR COMPRESSION-TYPE MOUNTINGS (16)

MIL-HDBK-149B



Rubber durometer hardness, 40.

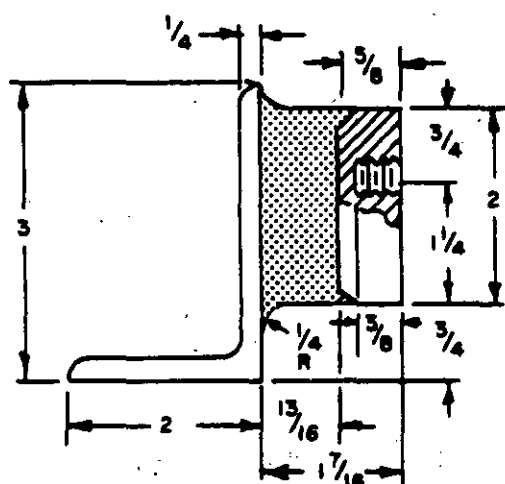
Deflection in shear at 400-pound (1779-N) load, 0.17 inch (4.3 mm).

Minimum disturbing frequency at this deflection, 1000 cycles per minute.

For use at disturbing frequencies of 1200 cycles and over, load should be reduced to 300 to 350 pounds (1335 to 1560 N) for each mounting.

FIGURE 112. SHEAR-TYPE RUBBER MOUNTING SANDWICH BETWEEN TWO STEEL PLATES (16)

MIL-HDBK-149B

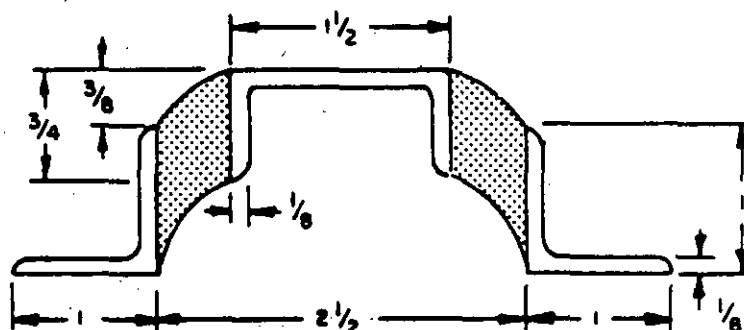


Rubber hardness, Durometer A: 40.

Maximum recommended load:
75 lb per inch of length.
(13 N/mm of length)

Deflection at this load: 0.5 inch.
(12.7 mm)

Minimum disturbing frequency at this
deflection: 600 cycles per minute.



Rubber hardness, Durometer A: 45.

Maximum recommended load:
50 lb per inch of length.
(8.7 N/mm of length)

Deflection at this load: 0.188 inch.
(4.75 mm)

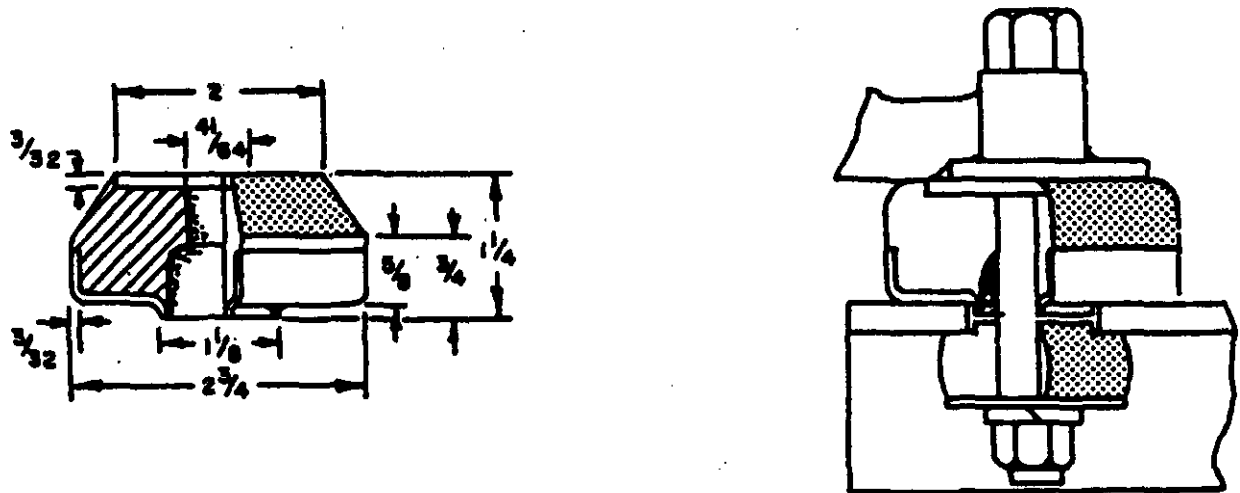
Minimum disturbing frequency at this
deflection: 1,000 cycles per minute.

For frequencies of 1,200 cycles per
minute and over, loading should be
reduced to 40 lb per inch (7.0 N/mm)
of length.

Dimensions		
Inches		Millimetres
1/8	0.125	3.18
1/4	0.250	6.35
3/8	0.375	9.52
5/8	0.625	15.88
3/4	0.750	19.05
13/16	0.812	20.64
1	1.00	25.4
1 1/4	1.25	31.8
1 7/16	1.44	36.5
1 1/2	1.50	38.1
2	2.00	50.8
2 1/2	2.50	63.5
3	3.00	76.2

FIGURE 113. SHEAR-TYPE RUBBER MOUNTINGS (16)

MIL-HDBK-149B



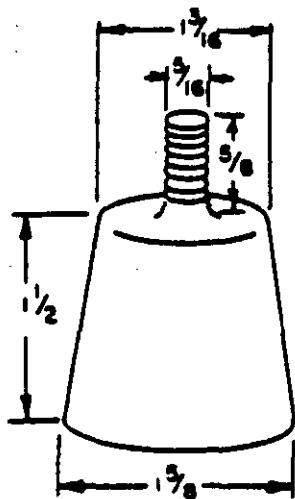
Designed particularly to isolate internal-combustion engines against torsional vibration at frequencies from 1,200 cycles per minute and upward.

Normally the larger metal-encased rubber part is of 40 Durometer A hardness; the smaller rubber part is of 60 Durometer A hardness.

	Dimensions	
	Inches	Millimetres
	3/32	0.094 2.38
	5/8	0.625 15.88
	41/64	0.641 16.27
	3/4	0.750 19.05
1	1/8	1.125 28.6
1	1/4	1.25 31.8
2		2.00 50.8
2	3/4	2.75 69.8

FIGURE 114. TWO-PART COMPRESSION-TYPE RUBBER VIBRATION INSULATOR (16)

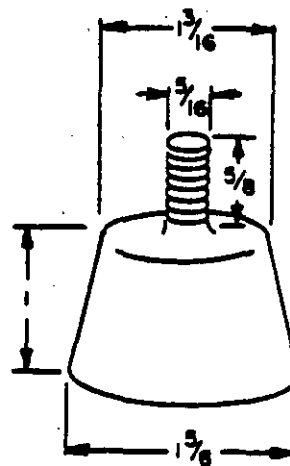
MIL-HDBK-149B



Maximum recommended load: 132 pounds.
(590 N)

Maximum deflection at this load: 0.188 inch.
(4.8 mm)

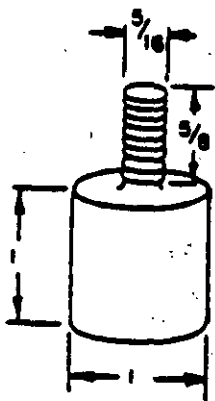
Minimum disturbing frequency at this
deflection: 1,200 cycles per minute.



Maximum recommended load: 180 pounds.
(800 N)

Maximum deflection at this load: 0.156 inch.
(4.0 mm)

Minimum disturbing frequency at this
deflection: 1,200 cycles per minute.



Maximum recommended load: 60 pounds.
(270 N)

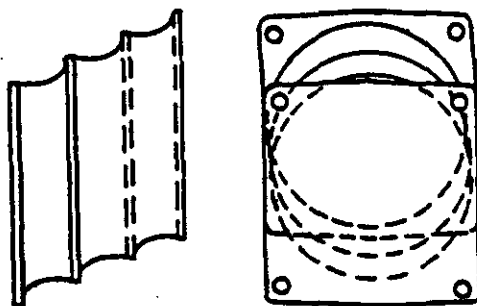
Maximum deflection at this load: 0.125 inch.
(3.2 mm)

Minimum disturbing frequency at this
deflection: 1,350 cycles per minute.

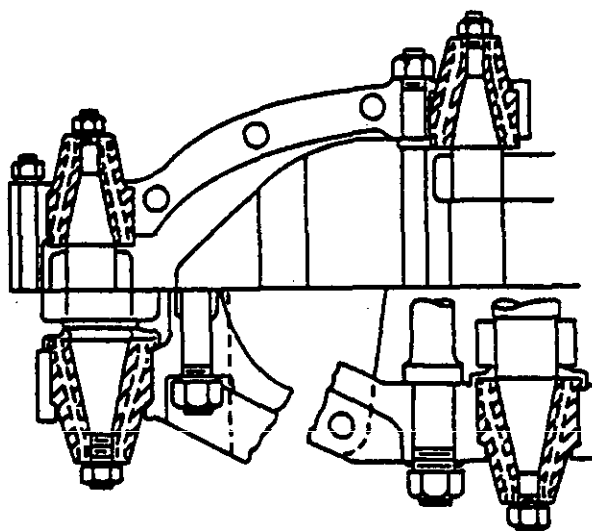
	Dimensions	
	Inches	Millimetres
5/16	0.312	7.94
5/8	0.625	15.88
1	1.00	25.4
1 3/16	1.18	30.2
1 1/2	1.50	38.1
1 5/8	1.62	41.3

FIGURE 115. THREE COMPRESSION-TYPE RUBBER MOUNTINGS (16)

MIL-HDBK-149B



a. Detail of Rubber Spring for Independent Front Suspension of Bus.



b. Heavy Duty Conical Bushes to a Link Type Suspension

FIGURE 116. EXAMPLES OF SPECIAL VEHICLE MOUNTS (68)

MIL-HDBK-149B

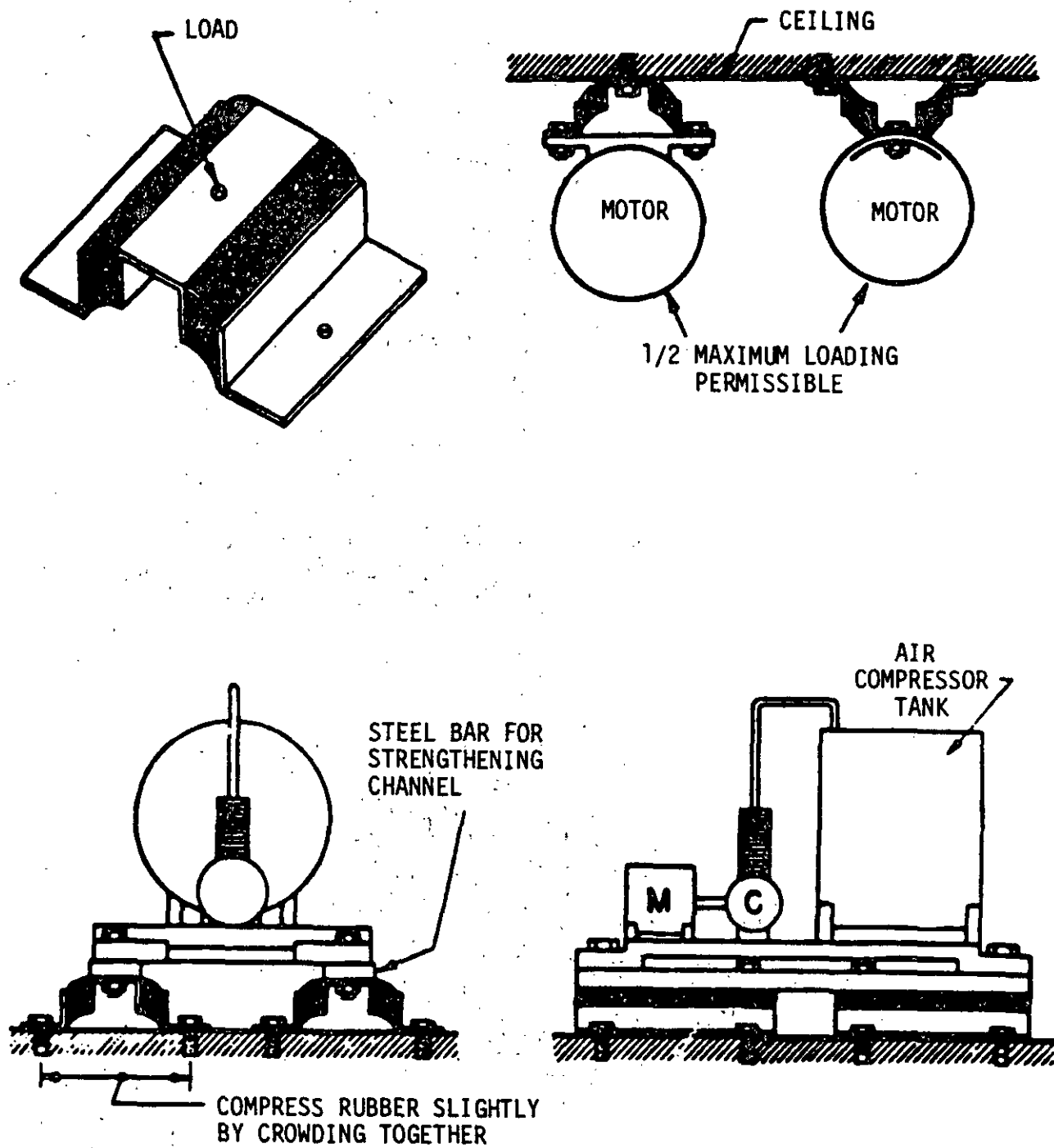


FIGURE 117. TYPICAL WAYS OF EMPLOYING RUBBER VIBRATION ISOLATORS (16)

MIL-HDBK-149B

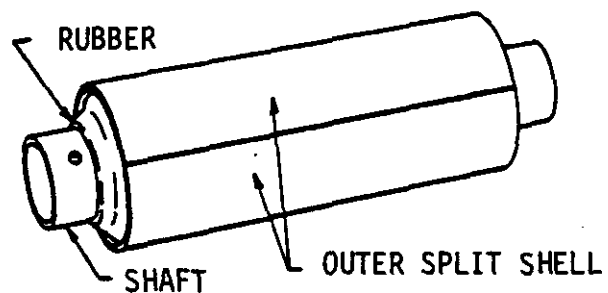


FIGURE 118. TORSILASTIC RUBBER SPRING CONSISTING OF A CYLINDER OF SOFT RUBBER BONDED TO A TUBULAR STEEL SHAFT AND AN OUTER SPLIT SHELL (16)

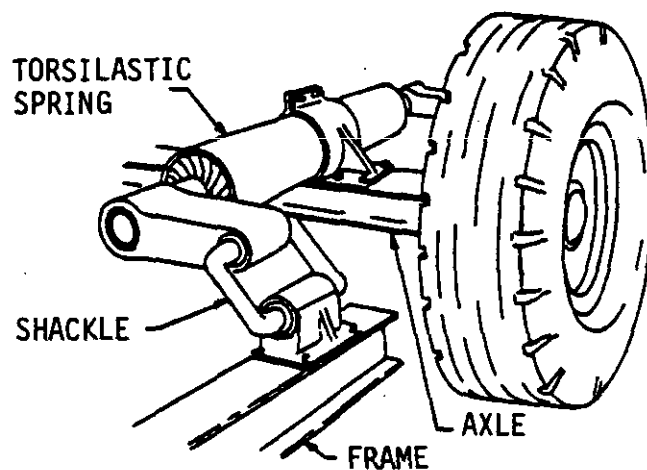
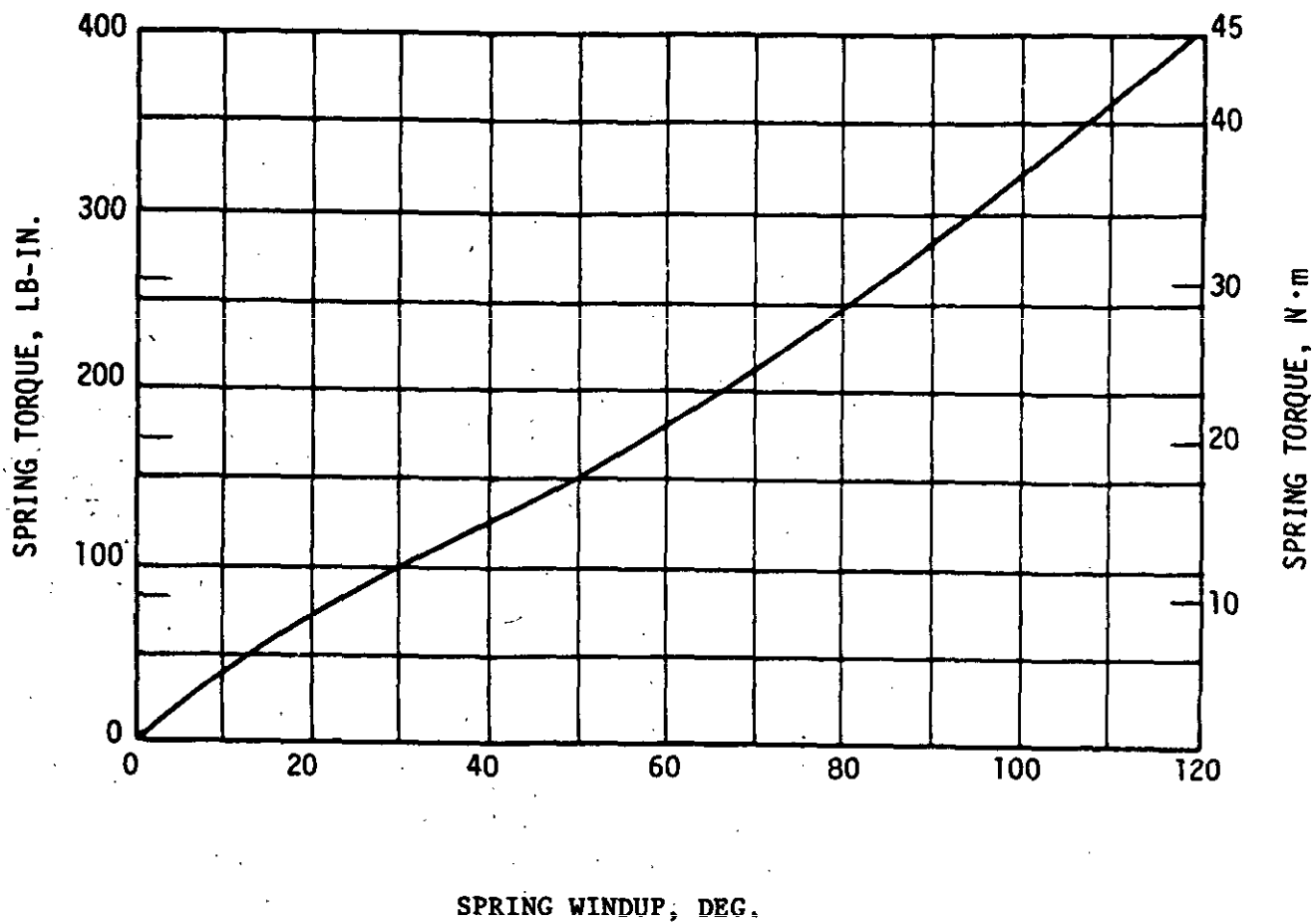


FIGURE 119. TORSILASTIC RUBBER SPRING AS USED ON A MODERN BUS (16)

MIL-HDBK-149B



SPRING DIMENSIONS: 1.1 inch ID x 0.50 in. ID x 3.1 in. LG
27.9 mm ID x 12.7 mm ID x 78.7 mm LG

FIGURE 120. SPRING WINDUP VS TORQUE (53)

MIL-HDBK-149B

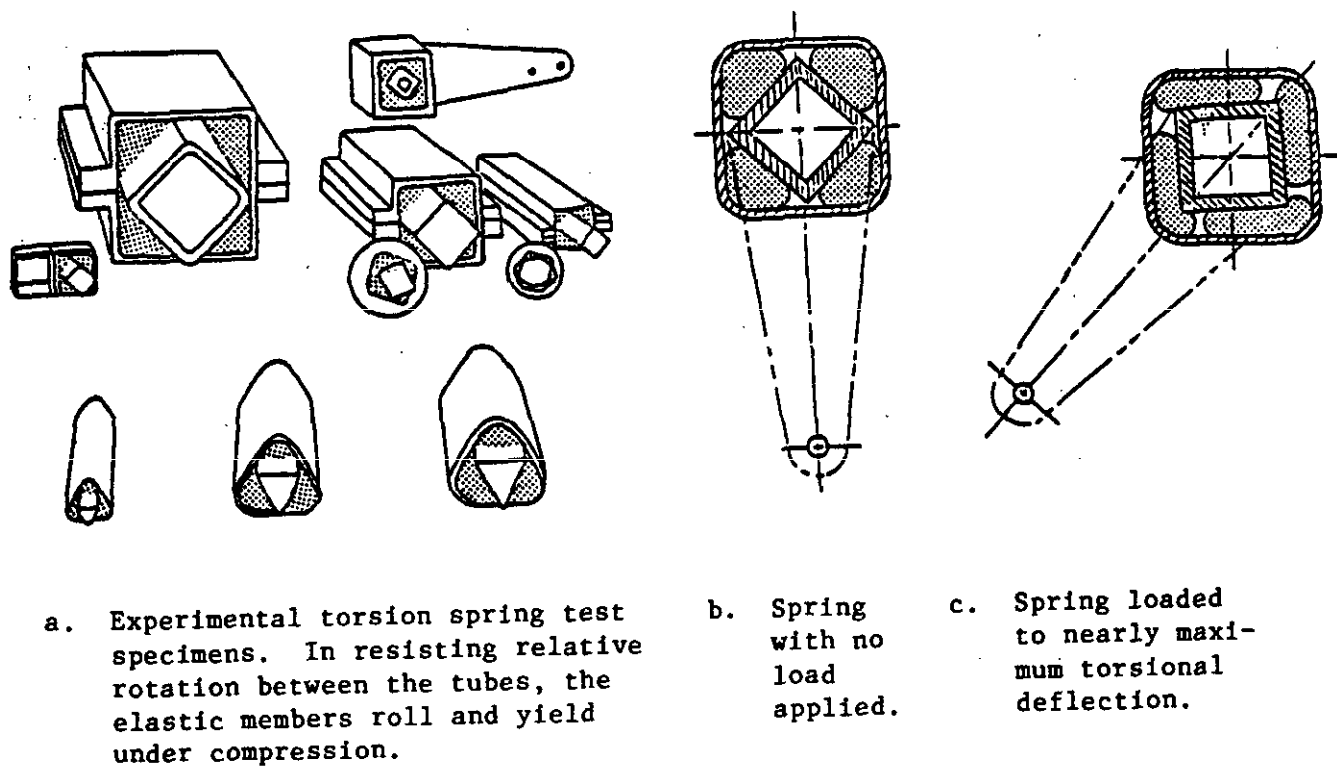
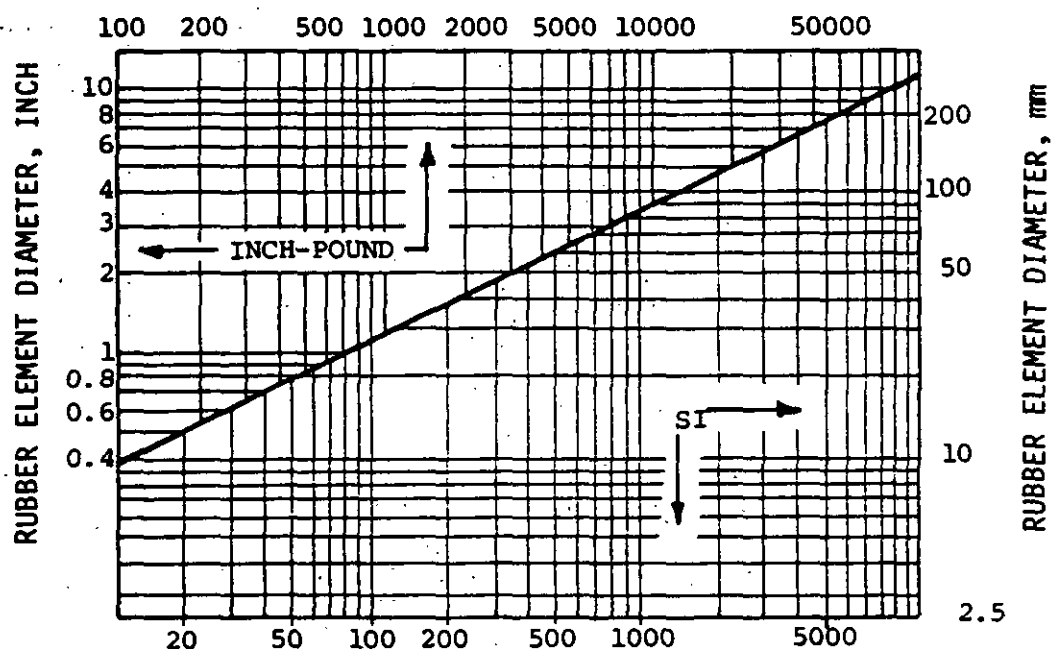


FIGURE 121. FOUR-SIDED TORSION SPRING OF TYPICAL NEIDHART CONSTRUCTION (45)

MIL-HDBK-149B

ULTIMATE DESIGN LOAD PER INCH OF RUBBER LENGTH, LB-IN.



ULTIMATE DESIGN LOAD PER 25 mm OF RUBBER LENGTH, N·m

FIGURE 122. FOUR-SIDED SPRING - RELATIONSHIP BETWEEN THE RUBBER DIAMETER SIZE AND THE MAXIMUM TORQUE LOAD OR LOAD AT 42° DEFLECTION, FOR EACH ONE INCH (25 mm) OF RUBBER SPRING ELEMENT LENGTH (45)

MIL-HDBK-149B

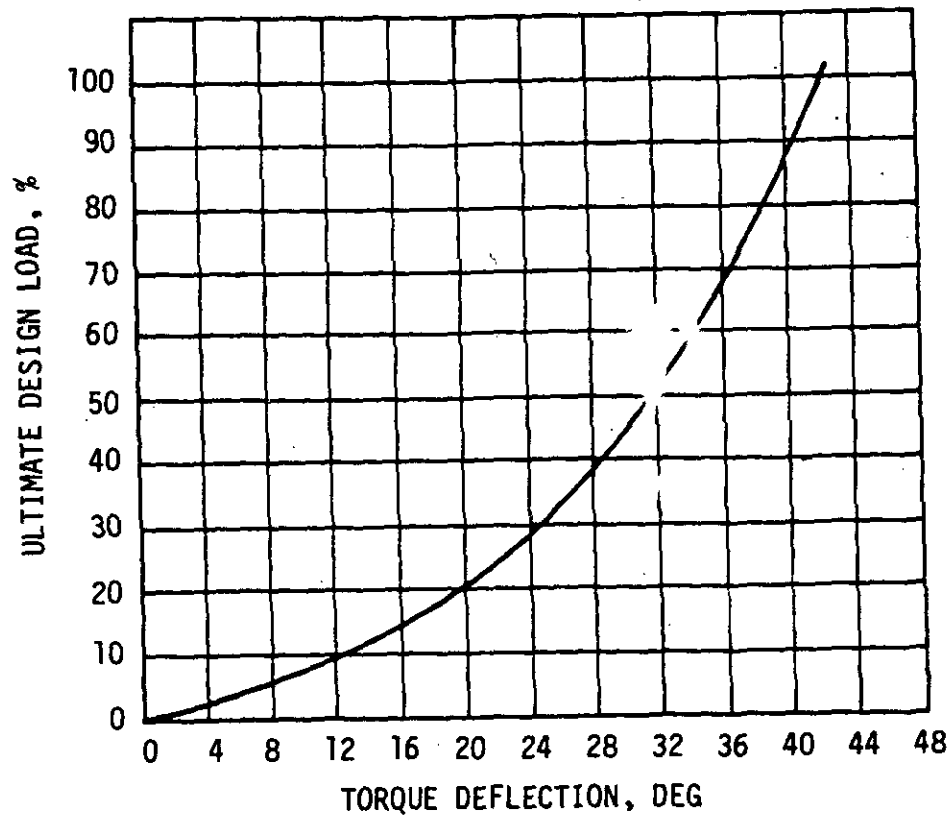


FIGURE 123. TYPICAL TORQUE DEFLECTION CURVE FOR A QUADRATIC TORSION SPRING (45)

MIL-HDBK-149B

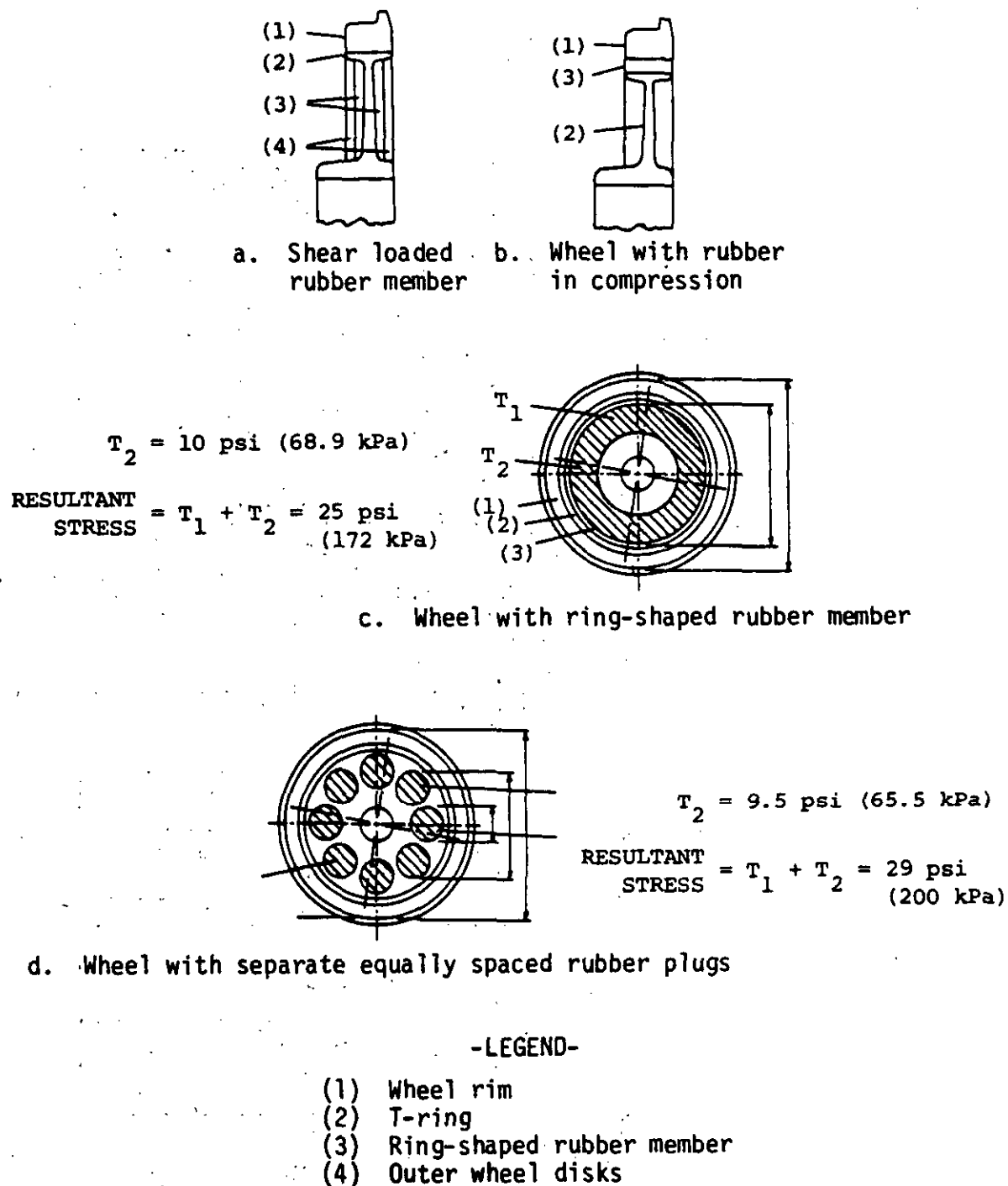


FIGURE 124. VEHICLE WHEELS WITH BUILT-IN SHOCK MOUNTS (46)

MIL-HDBK-149B

TABLE XXXVIII. HYSTERETIC AND ELASTIC PROPERTIES OF RUBBER TYPES SUGGESTED FOR ENGINE MOUNTINGS (63)

Rubber	Temperature °F	Dynamic Modulus psi	Internal Friction kilopoises	Relative Energy Absorption	
				Constant Strain ft-lb/min.	Constant Stress ft-lb/min.
40 Durometer A Hardness					
Acrylonitrile NBR Butadiene	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	83.4	4.15	71.5	1003
	212	57.5	2.58	44.5	1345
Butyl IIR	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	57.5	3.72	64.0	1930
	212	62.2	1.05	18.1	468
Chloroprene CR	-4	Resonance mass too high to measure			
	32	138.3	13.70	236.0	1230
	122	76.2	1.72	29.6	510
	212	69.2	1.62	28.0	585
Natural NR	-4	136.0	17.00	293.0	1583
	32	85.5	4.70	81.0	1101
	122	62.0	1.26	19.4	504
	212	64.5	0.81	14.0	346
Styrene SBR Butadiene	-4	Resonance mass too high to measure			
	32	295.0	22.30	384.0	441
	122	139.5	0.85	101.0	520
	212	70.3	3.00	51.7	1041
50 Durometer A Hardness					
Acrylonitrile NBR Butadiene	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	277.0	14.30	246.2	321
	212	145.6	7.00	120.6	565
Butyl IIR	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	119.6	3.22	55.5	388
	212	120.4	1.02	16.4	328
Chloroprene CR	-4	Resonance mass too high to measure			
	32	495.0	59.50	1003.0	420
	122	143.0	4.40	76.0	372
	212	119.6	3.72	64.0	447
Natural NR	-4	300.0	39.60	682.0	756
	32	137.0	9.40	162.0	861
	122	92.6	1.93	33.2	386
	212	90.4	1.18	20.4	250
Styrene SBR Butadiene	-4	Resonance mass too high to measure			
	32	483.0	32.40	558.0	239
	122	163.0	6.25	108.0	407
	212	99.8	3.02	52.0	520

MIL-HDBK-149B

TABLE XXXVIII. (Continued)

Rubber	Temperature °F	Dynamic Modulus psi	Internal Friction kilopoises	Relative Energy Absorption	
				Constant Strain ft-lb/min.	Constant Stress ft-lb/min.
60 Durometer A Hardness					
Acrylonitrile NBR Butadiene	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	310.2	16.50	276.4	225
	212	207.0	7.12	150.6	285
Butyl IIR	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	388.5	17.85	308.0	204
	212	252.3	7.14	123.2	193
Chloroprene CR	-4	Resonance mass too high to measure			
	32	554.0	59.50	1003.0	336
	122	212.5	5.10	88.0	195
	212	175.0	4.05	69.8	228
Natural NR	-4	Resonance mass too high to measure			
	32	406.0	23.80	410.0	249
	122	210.0	4.88	84.3	201
	212	170.0	2.51	43.3	150
Styrene SBR Butadiene	-4	Resonance mass too high to measure			
	32	Resonance mass too high to measure			
	122	359.1	14.27	246.1	190
	212	196.0	7.28	125.7	327

TABLE XXXVIII-SI. HYSTERETIC AND ELASTIC PROPERTIES OF RUBBER
TYPES SUGGESTED FOR ENGINE MOUNTINGS (63)

Rubber	Temperature °C	Dynamic Modulus MPa	Internal Friction Pa·s	Relative Energy Absorption	
				Constant Strain N·m/min.	Constant Stress N·m/min.
	40 Durometer A Hardness				
Acrylonitrile NBR Butadiene	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	0.58	415	96.9	1360
	100	0.40	258	60.3	1824
Butyl IIR	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	0.40	372	86.7	2617
	100	0.42	105	24.5	634
Chloroprene CR	-20	Resonance mass too high to measure			
	0	0.95	1370	320.0	1668
	50	0.52	172	40.1	691
	100	0.48	162	38.0	793
Natural NR	-20	0.94	1700	397.0	2146
	0	0.59	470	110.0	1493
	50	0.43	126	26.3	683
	100	0.44	81	19.0	469
Styrene SBR Butadiene	-20	Resonance mass too high to measure			
	0	2.03	2230	521.0	598
	50	0.96	85	137.0	705
	100	0.48	300	70.0	1411

MIL-HDBK-149B

TABLE XXXVIII-SI (Continued)

Rubber	Temperature °C	Dynamic Modulus MPa	Internal Friction Pa·s	Relative Energy Absorption	
				Constant Strain N·m/min.	Constant Stress N·m/min.
50 Durometer A Hardness					
Acrylonitrile NBR Butadiene	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	1.56	1430	333.8	435
	100	1.00	700	163.5	766
Butyl IIR	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	0.82	322	75.2	526
	100	0.83	102	22.2	445
Chloroprene CR	-20	Resonance mass too high to measure			
	0	3.16	5950	1360.0	569
	50	0.94	440	103.0	504
	100	0.82	372	87.0	606
Natural NR	-20	2.07	3960	925.0	1025
	0	0.94	940	219.6	1167
	50	0.64	193	45.0	523
	100	0.62	118	27.6	339
Styrene SBR Butadiene	-20	Resonance mass too high to measure			
	0	3.33	3240	756.5	324
	50	1.12	625	146.4	552
	100	0.69	302	70.5	705
60 Durometer A Hardness					
Acrylonitrile NBR Butadiene	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	2.14	1650	374.7	305
	100	1.43	712	204.2	386
Butyl IIR	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	2.68	1785	417.6	276
	100	1.74	714	167.0	262
Chloroprene CR	-20	Resonance mass too high to measure			
	0	3.82	5950	1360.0	456
	50	1.46	510	119.3	264
	100	1.21	405	94.6	309
Natural NR	-20	Resonance mass too high to measure			
	0	2.80	2380	555.9	338
	50	1.45	488	114.3	272
	100	1.17	251	58.7	203
Styrene SBR Butadiene	-20	Resonance mass too high to measure			
	0	Resonance mass too high to measure			
	50	2.48	1427	333.7	258
	100	1.35	728	170.4	443

MIL-HDBK-149B

8.3 Couplings

8.3.1 Numerous types of flexible couplings for rotating shafts can be devised employing rubber either in compression or in shear.

8.3.2 The noise-damping characteristics of rubber are particularly advantageous in such applications, as they allow gear noise and torsional vibration occurring in the transmission system to be isolated from the vehicle. They are capable of absorbing shock loads, and permit a limited amount of misalignment.

8.3.3 Some torsion spring designs can, of course, often be utilized as couplings, but couplings usually require a much stiffer action than torsion springs. Most frequently, for high-torque applications, rubber is used in compression between metallic elements of the input and output member of the coupling. An example of a flexible coupling is shown in Figure 125.

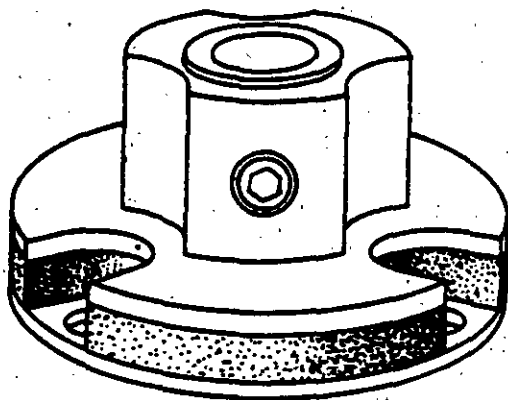


FIGURE 125. EXAMPLE OF FLEXIBLE COUPLING (50)

MIL-HDBK-149B

8.4 Seals and O-rings

8.4.1 O-rings are most effective as static seals or on reciprocating shafts or pistons. The commercial availability of O-rings produced in various sizes and rubber compounds usually obviates the necessity for special designs.

8.4.2 For rotating service, O-rings have a relatively high leakage rate and short life; oil seals of the rotary lip type with garter springs, and mechanical seals with graphite shear faces are preferred in such applications.

8.4.3 For satisfactory O-ring operation, the following principles must be observed:

8.4.3.1 The rubber compound must be compatible with the fluid to be sealed and must have adequate tensile and torsional strength.

8.4.3.2 The O-ring must be under initial compression.

8.4.3.3 The O-ring groove cross sectional area must be great enough to allow for volume swell and thermal expansion of the rubber, which is approximately 18 times that of steel.

8.4.3.4 Surfaces on which the O-ring slides must be smooth, free from sharp edged grain structure, but not too smooth, 10 to 20 microinches (0.25 to 0.50 μ) is recommended.

8.4.3.5 A lead chamber of 10 to 20° should be provided where necessary so that the O-ring will not be damaged during installation. In addition, the size of bosses over which the O-ring must be stretched during installation should not require extensive stretching of the O-ring as very small cuts or cracks in the O-ring may become failure points in service.

8.4.4 Figure 126 shows the use of O-rings in a few static and dynamic arrangements. Manufacturers of O-rings and hydraulic system components publish outstanding catalogs showing the proper use of O-rings. Military Specification MIL-G-5514 has established basic design parameters and most hydraulic systems designs utilize these criteria. More recent parameters based on considerable experience and reflecting the International Standardization activities are compared with MIL-G-5514 parameters in Table XXXIX. Note that MIL-G-5514 shows only one percentage of squeeze for both dynamic and static O-rings.

8.4.5 Figure 127 gives O-ring seal groove design formulas.

8.4.6 Two interesting sealing arrangements have been developed and patented by the British Hydromechanics Research Association for shafts which have excessive eccentric motion. With such eccentricities, the leakage rates are greatly increased. To overcome this, sealing is accomplished on a centered sleeve which is supported by an additional bearing. The sleeve has sufficient clearance from the shaft to accommodate the eccentricities. In Figure 128a, the sleeve rotating with the shaft is centered by a bearing surface on the housing. A lip seal rides on the centered sleeve, and a static O-ring seal prevents leakage through the sleeve-shaft clearance.

MIL-HDBK-149B

TABLE XXXIX. NOMINAL SQUEEZE OF O-RINGS (41)

C-ring Cross Section Nominal		Squeeze, Percent				
		MIL-G-5514	International Standard		Static Seal	
Inch	Millimetres		Hydraulic Rod Seals	Pneumatic		
0.070	1.80	18.75	17.2	11.8	18.5	
0.103	2.65	13.00	14.5	9.6	16.9	
0.139	3.55	11.75	12.85	8.1	16.2	
0.210	5.30	10.90	11.45	7.6	15.7	
0.275	7.00	12.75	11.35	7.45	14.3	
Piston Seals						
					Radial	Axial
0.070	1.80	18.75	20.0	15.0	21.4	26.0
0.103	2.65	13.00	17.6	13.0	20.0	24.0
0.139	3.55	11.75	16.0	11.2	19.3	21.0
0.210	5.30	10.90	14.7	11.0	18.7	20.5
0.275	7.00	12.75	14.35	10.5	17.3	17.5

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8.4.7 In Figure 128b, the sleeve is constrained to rotate concentrically by an antifriction bearing while being supported by a bonded seal in a floating arrangement. With these arrangements, eccentricities of 0.020 in. (0.51 mm) at 2000 rpm, or 0.006 in. (0.15 mm) at 4000 rpm can be tolerated.

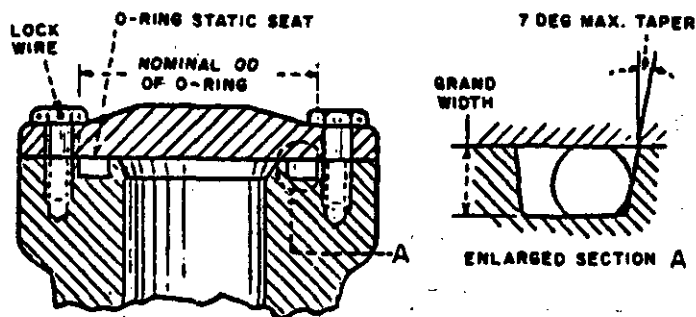
8.4.8 Probably the most common dynamic seal for vacuum application is the Wilson Shaft Seal shown in Figure 129. The holes in the rubber gaskets are approximately two thirds the shaft diameter.

8.4.9 For high vacuum applications, the general practice is to use double seals, allowing for some gas leakage out of the inner seal which is then pumped out. Examples and brief descriptions are shown in Figure 130.

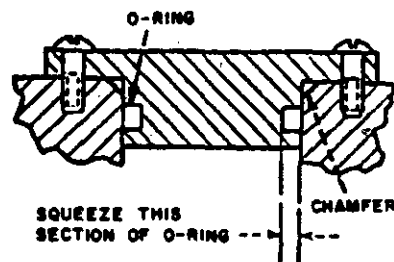
8.4.10 The atmospheric pressure allowed through the pump out, and the resilience of the rubber maintain the sealing force on the inner seal. Permanent set of the rubber portion of the seal does not affect the sealing ability. A soap film across the pump out will check the sealing ability of the inner seal, and a vacuum across the pump out will check leaking until repairs can be made.

8.4.11 The effectiveness of this type of seal depends upon careful design and installation which should include: (1) a smooth shaft; (2) proper lubrication; and (3) proper compression--too much compression can cause the seal to be cut or extruded, or both.

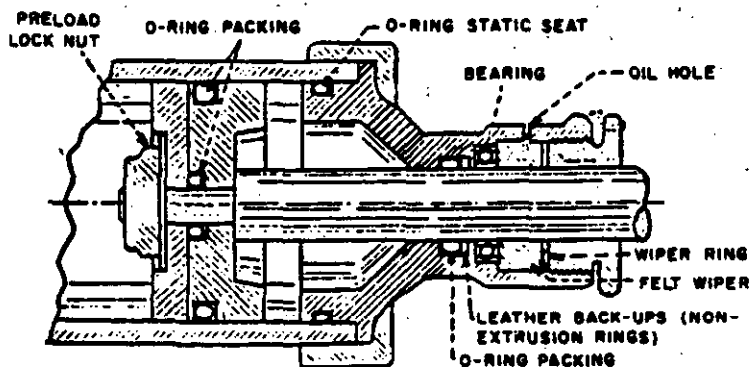
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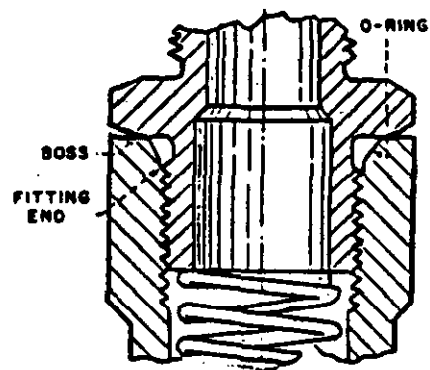
SUGGESTED FACE SEAL O-RING APPLICATION. In this case, the rectangular shape groove is employed. The gland width should be less than the O-ring cross section width to provide compression or diametral squeeze of the O-ring. The nominal outside diameter of the O-ring indicates the outside diameter of the circular groove as machined in the metal part to which the end cap is bolted.



HOLE PLUG SEAL, with the O-ring contained in the groove in the plug, being squeezed between the bottom of the groove and the wall of the holed part. The corner of the hole entrance should be chamfered to prevent pinching, cutting, or otherwise damaging the O-ring on installation.



USE OF BACK-UPS OR ANTIEXTRUSION RINGS with rubber O-rings for effective running seals under high pressure (1500 to 3000 psig [10,340 to 20,685 kPag]). The back-up rings prevent excessive extrusion of the O-ring into clearance gaps between piston and cylinder wall and between piston rod and its housing. O-rings are also shown without back-ups in two static seal applications. Note O-ring in piston assembly for sealing at a three-part junction.



STATIC SEAL application, showing a valve end connection. The O-ring is contained in an irregular cavity, which, of course, must bear the proper relationship to the volume of the O-ring.

FIGURE 126. DYNAMIC AND STATIC SEAL APPLICATIONS (75)

MIL-HDBK-149B

A. Radial Stretch

$$d_3 = d_4 - 2d_2 \left(\frac{100 - a}{100} \right) + k_1$$

B. Radial Compress

$$d_6 = d_5 + d_2 \left(\frac{100 - a}{100} \right) + k_2$$

C. Axial - Pressure Out

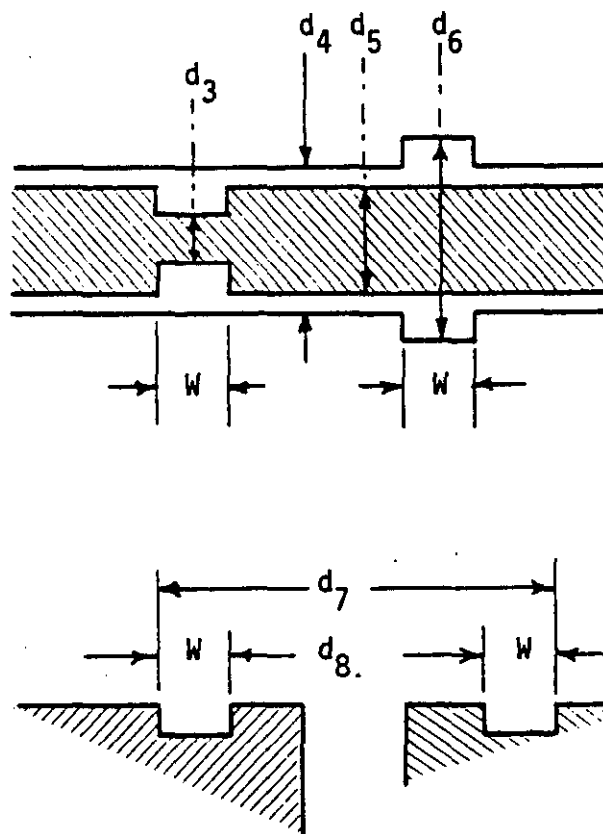
$$d_7 = d_1 + 2d_2 + \left(\frac{a}{100} \right) d_2$$

D. Axial - Pressure in (Vacuum)

$$d_8 = d_1 + \left(\frac{a}{100} \right) d_2$$

E. Groove Width (W)

$$W = \left(\frac{100 + a}{100} \right) d_2 + X$$



Legend:

d_1 = O-ring inside diameter

d_2 = O-ring cross section diameter

d_3 to d_8 = As shown in sketches

k_1 = Correction of cross section-stretch (ID)

k_2 = Correction of cross section-compress (ID)

W = Groove width

X = Variable added to establish volume of the void (25 to 40%)

a = Squeeze, percent

To establish k : d_2 can be estimated as being changed half of the percentage that the core diameter of the O-ring changes.

Example: If the core diameter change is 4 percent,
then $k = 0.02 d_2$

FIGURE 127. O-RING SEAL GROOVE DESIGN FORMULAS (41)

MIL-HDBK-149B

B

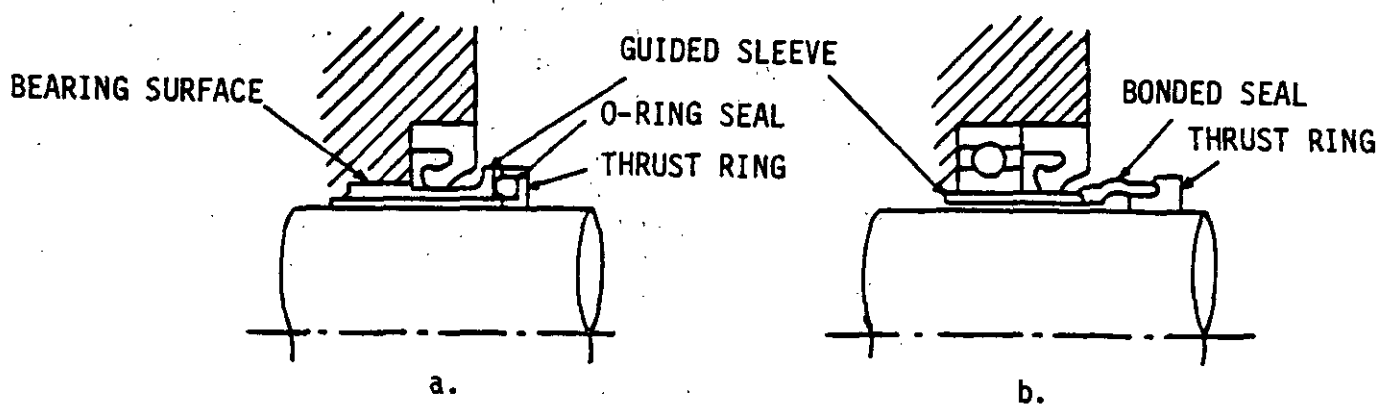


FIGURE 128. CENTERED-SLEEVE ARRANGEMENTS FOR REDUCING SHAFT WHIP (72)

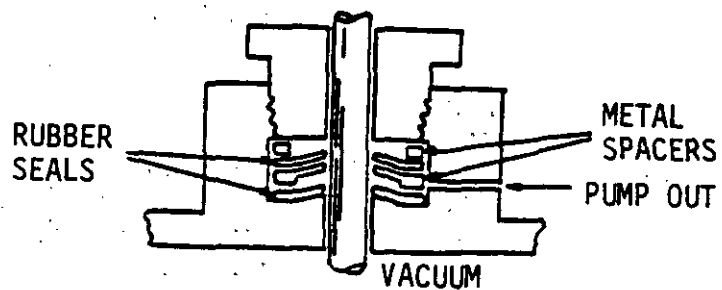
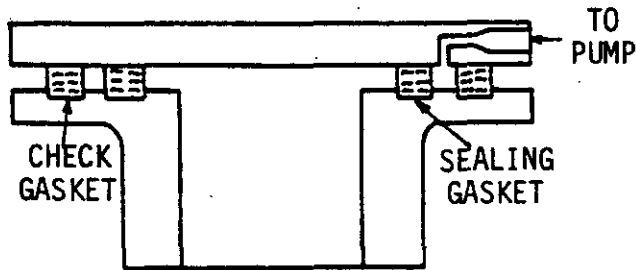
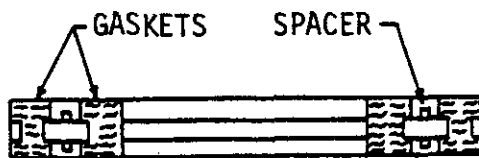


FIGURE 129. WILSON TYPE VACUUM SHAFT SEAL (80)

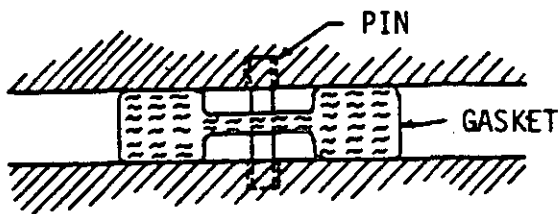
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The flange and plate arrangement utilizes two concentric gaskets. The inner gasket constitutes the primary seal, while the outer gasket provides a means of checking the inner gasket and is an emergency seal upon the failure of the primary seal. A soap film across the pumpout will be drawn inward by a leaking primary seal. A vacuum across the pumpout temporarily arrests leaks.



The seal configuration is similar in the use of two gaskets. In it the rubber is bonded to a metal spacer ring. A port drilled in one of the flanges into the intergasket space provides a means of leak check and emergency sealing.



The "Dumbbell" all rubber gasket is designed for sealing without grooves in the flanges. Pins through the web portions of the seal position it during assembly.

FIGURE 130. EXAMPLES OF GASKET TYPE SEALS FOR HIGH VACUUM APPLICATIONS (80)

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8.5 Gaskets. Only general parameters for gaskets will be discussed here, as Military Standardization Handbook, MIL-HDBK-212, covers nonmetallic gaskets in considerable depth.

8.5.1 The function of a gasket is to provide a material which can flow into the surface irregularities of mating areas which require sealing. To accomplish this function, the gasket material must be under pressure, requiring that the joint be tightly bolted or otherwise held together. The gasket material must, of course, be resistant to the fluid or gas it is intended to seal. For oil, the nitrile rubber group offers the best gasket material (within its temperature limit) available to date. They have low solubility, low swell, retain tensile properties well after oil penetration, and have an operating temperature range of -60 to +300°F (-50 to +150°C).

8.5.2 Among other low-cost rubbers, chloroprene seals well against nonaromatic gasolines, air, water, and refrigerant gases.

8.5.3 Irregular surfaces call for use of softer compounds with light bolt loadings, whereas heavily bolted sections should have smoother flange surfaces, harder gaskets, and thicker metal flanges.

8.5.4 Gasketing practices are as follows:

8.5.4.1 Gaskets should be partially or totally confined although flat, thin gaskets need not be recessed.

8.5.4.2 Compressive stresses in the range of 600 to 1200 psi (4 to 8 MPa) give best results for flat sections.

8.5.4.3 Round or square section gaskets should be compressed 30 to 40 percent of their original thickness.

8.5.4.4 If the possibility of overcompression exists, solid stops should be provided.

8.5.4.5 Any parts which are to be compressed by rotating parts should be lubricated prior to installation.

8.5.4.6 Overcompression combined with "cold flow" or set may cause deflection of flanges around the bolts and result in bowing between bolts, which may produce leaks. Bolt size and spacing, flange thickness and width, and gasket hardness and thickness must all be considered in establishing a design.

8.5.5 Figure 131 illustrates the effect of the hardness of rubber on the compressive load required to deflect the rubber 20 percent of its original thickness.

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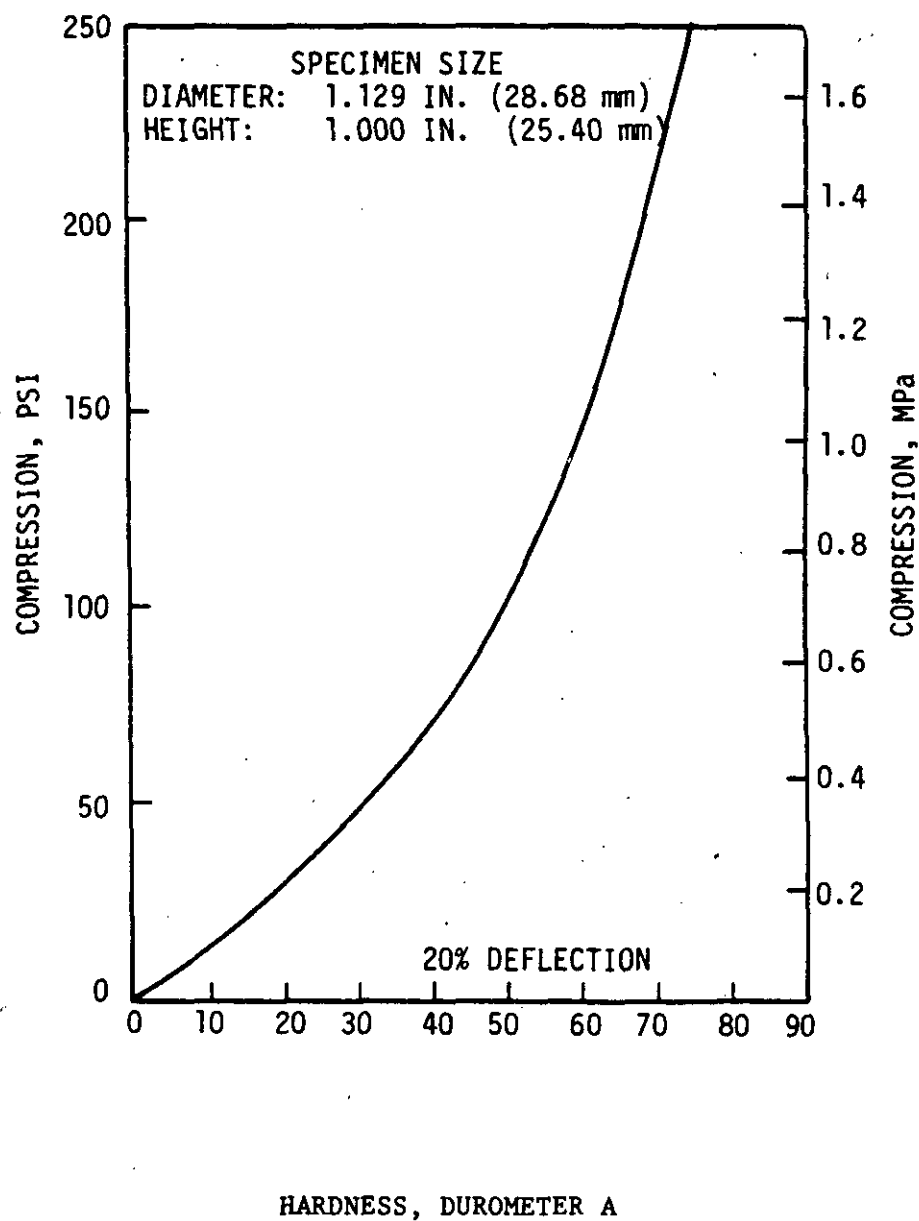


FIGURE 131. EFFECT OF HARDNESS ON THE COMPRESSION REQUIRED TO PRODUCE 20% DEFLECTION (37)

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9. MAJOR FABRICATION METHODS

9.1 Processing

9.1.1 Raw natural rubber of the Hevea type is obtained from a latex, not a sap, which occurs in special vessels of certain trees and other plants. The rubber polymer is coagulated from the aqueous serum in which it is obtained, then dried and mixed with additives to get a uniform material that will have useful properties after it is vulcanized. Guayule rubber is produced by pulverizing the entire desert shrub in which it occurs, then separating the polymer from the pulp; there is no latex. Most of the naturally-occurring resins are then removed, leaving only 2 - 6 parts of resin per 100 parts of polymer. The resulting product, which is chemically very much like Hevea rubber, can be treated in nearly the same manner as Hevea rubber. Man-made rubbers are polymerized from petroleum derivatives called petrochemicals. Rubbers from any source are shaped by means such as calendering, molding, or extrusion before vulcanization. A process diagram for rubber goods is shown in Figure 132.

9.1.2 The vulcanizing process requires the addition of a curing agent, usually sulfur, and the application of heat, to change the molecular structure of the rubber. During vulcanization, the following changes occur:

- (1) The long chains of the rubber molecules become crosslinked by reactions with the vulcanizing agent to form three-dimensional structures. This reaction transforms a soft weak plastic-like mastic into a strong elastic product.
- (2) The rubber loses its tackiness, becomes insoluble in most solvents, and is more resistant to deterioration normally caused by heat, light, and aging processes.

9.1.3 Properties of the basic types of rubber can be further enhanced by compounding the elastomer with various fillers and reinforcing agents. However, improvements in certain desirable properties by such compounding techniques frequently results in deterioration of other characteristics, for example, resilience. Therefore, performance should be determined by testing prototype components under conditions closely simulating actual service conditions.

9.2 Molding Methods

9.2.1 Molded rubber products are formed and vulcanized in a mold under the simultaneous application of pressure and heat. Three processes are in general use:

- a. Compression molding
- b. Transfer molding
- c. Injection molding

9.2.2 To compression mold, unvulcanized compounded rubber blanks having the correct weight are prepared to the approximately correct shape, placed in one part of the mold, and forced into final shape by the pressure of the press pushing the two or more parts of the mold together. To transfer mold, a rubber

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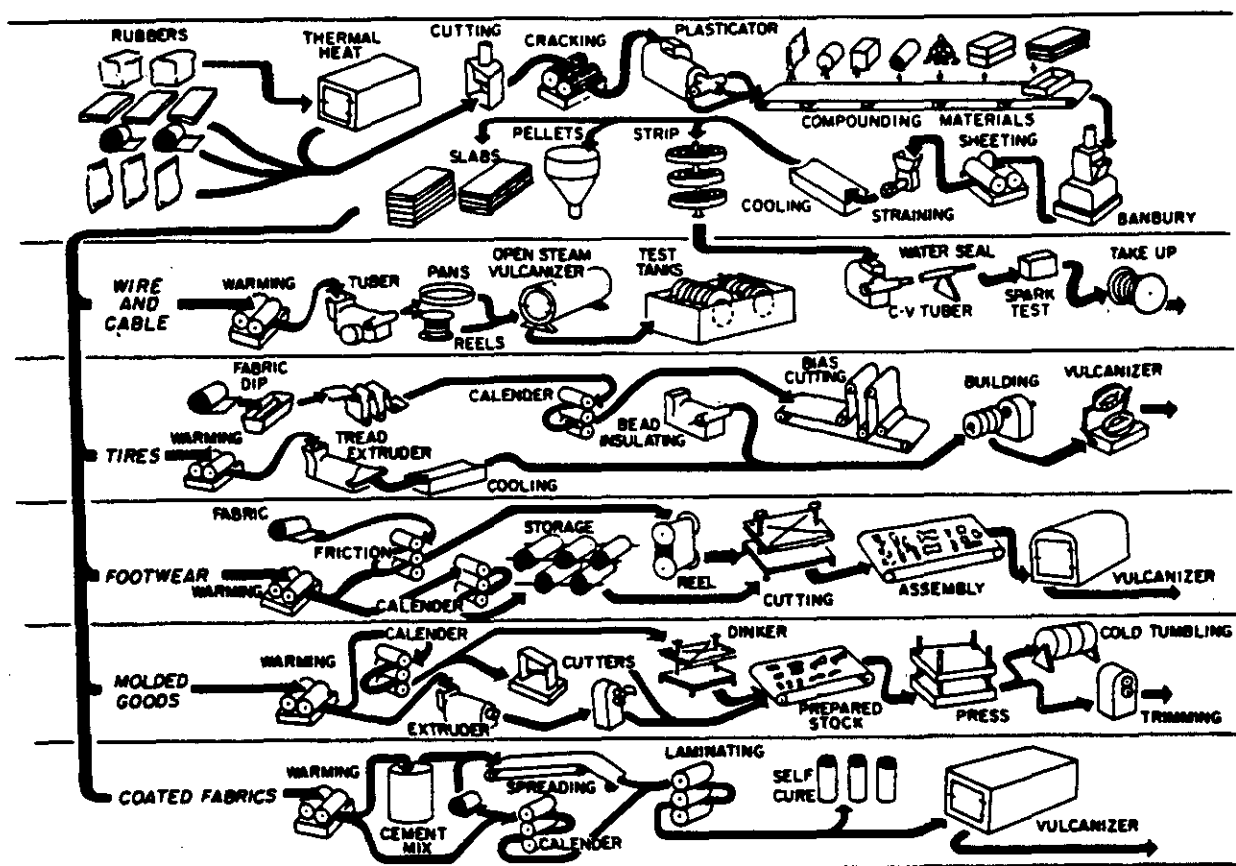


FIGURE 132. TYPICAL FLOW DIAGRAMS FOR RUBBER GOODS MANUFACTURE (84)

MIL-HDBK-149E

blank is loaded into a transfer cavity and forced by a ram to flow through runners into the mold cavities. Usually the force on the ram is the force of the closing press, although it can be a separate hydraulic system. To injection mold, a screw mechanism is used to heat the rubber and reduce its viscosity. A ram (which frequently is the locked screw mechanism) then forces the rubber through narrow runner passages into the cavities. Transfer molding gives lower curing time than compression molding, and injection molding gives lower cure times than transfer molding.

9.2.3 The favorable features of molding a product include: uniformity, close tolerance, good finish, and almost unlimited adaptability to contour design.

9.2.4 Molding as a production method has these disadvantages: high cost of mold equipment, cost of finished parts probably higher than an extruded part, and the parts produced per day are limited by the number of cavities in the mold.

9.3 Mold Design. For volume production of simple parts, multiple cavity molds are used. Complicated parts requiring metal inserts for molding cavities or holes into the rubber part generally require single cavity molds. Parts having simple geometrical shapes with cavities along one axis only can utilize simple two-piece molds, a portion of the cavity being shaped in each half. The part designed with holes or cavities in more than one direction, or with geometry not permitting the mold to be opened in the direction of the axis of a single cavity, necessitates the use of either inserts such as plugs or mandrels or a multisectional mold. A compression molding die and a transfer-injection molding die are shown in Figure 133.

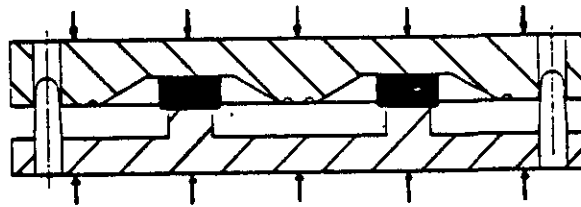
9.4 Molded Product Design Considerations

9.4.1 The design of a molded rubber product greatly affects its final cost. After the functional requirements have been met, a design review should be made by molding experts. Often, improvements facilitating manufacture to a considerable extent while affecting function little, if at all, can be made.

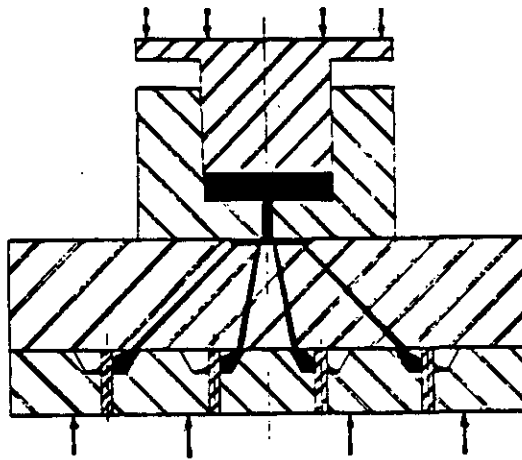
9.4.2 To illustrate how design can result in more economical methods of manufacture, Figure 134 shows two designs for a simple mount in which rubber is bonded to a metal plate.

9.4.3 Note that in the improved Design B of Figure 134, the sides of the rubber part are tapered to allow easy extraction from the mold. The metal insert is flat, making positioning in the die cavity simpler. This also promotes easier stripping from the mold cavity by allowing formation of a flash strip which permits unloading of all the cavities of the mold in one operation. A sheared tab can be bent down. Design A of Figure 134 allows rubber to flow into the cavity provided for the tab, covering it completely. The material would fill the hole and subsequently have to be removed. With the tab in its flat position, a pin in the cavity enters this hole and prevents its being filled.

MIL-HDBK-149B



a. Compression mold



b. Injection mold

FIGURE 133. RUBBER MOLDS (37)

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9.4.4 Wall thickness ranges from 0.005 to 12 inches (0.13 to 300 mm) are possible within molded parts. Furthermore, uniformity of wall thickness is not generally essential. However, great differences in wall thickness are not desirable in a specific part because of the difference in vulcanization time required for the various section thicknesses. The mechanical properties of such parts can never be optimum since the thin sections will be over-vulcanized (reversion or hardening) and the thick sections under-vulcanized.

9.4.5 A draft from $1/2$ to 1° should be provided in the mold. The flexibility of rubber makes it possible to mold undercuts in the rubber part, if, during withdrawal, the rubber can be deformed and displaced into cavities created by the removal of plugs or mandrels. Because of the noncompressibility of rubber, solid rubber components with external undercuts must be made in a split mold.

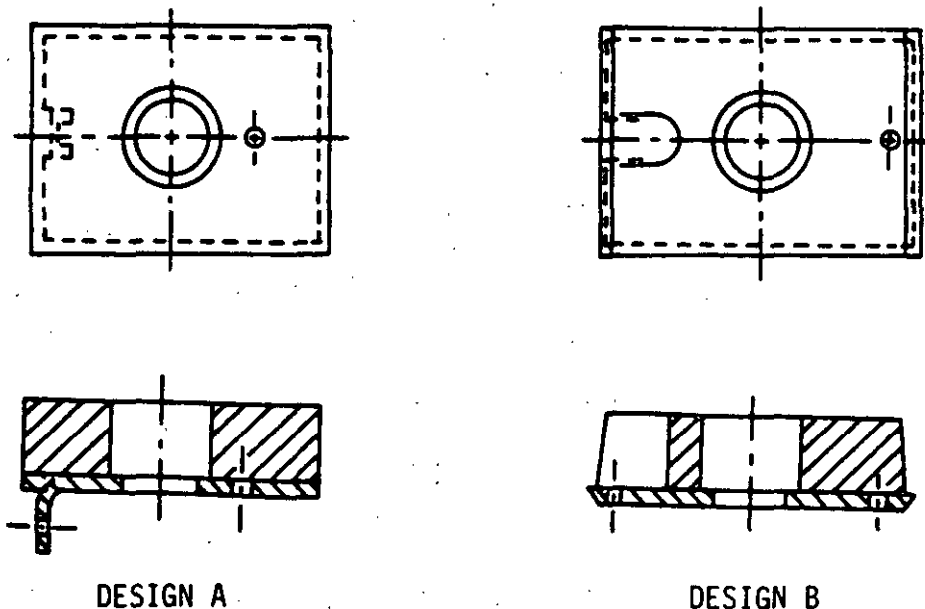


FIGURE 134. MOTOR MOUNTING PAD DESIGNS (51)

9.4.6 Flash, the ridge of the material which overflows from the cavity or mold during molding, occurs at the mold parting line. A part must be designed so that the parting line and the flash which is produced there occur at the least objectionable area. If possible, it should be located at the largest cross-sectional area perpendicular to the direction of mold opening to facilitate part extraction. In finishing requirements, maximum allowable flash should be specified and requirements for over-finishing should be avoided to limit cost. When the part is of such a design that there is a tendency for it to stick to the mold, a heavy flash may be desirable to

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facilitate removal from the mold. Flash may be trimmed after the part emerges from the mold by means of a die (precision method), by buffing, or by tumbling. When buffing, an abrasion wheel is used to remove the flash. Tumbling requires that the parts be placed in a rotating drum, often with an abrasive compound, and often at temperatures sufficiently low to increase stiffness. The rubber parts rub and fall on each other, which abrades or breaks the flash.

9.4.7 Rubber shrinks appreciably on cooling to room temperature after vulcanization. This shrinkage allowance is made by providing an enlarged mold cavity. The actual amount depends on the curing temperature and the difference in thermal coefficients between the rubber and the mold material. Shrinkage varies from 0.6 percent for a given chloroprene compound, to as much as 5 percent for certain silicones. On metal bonded parts, shrinkage will be unidirectional as the surface in contact with the metal is restricted. Normally, shrinkage occurs over areas which are not bonded. On drawings, no shrinkage allowance should be made on dimensions. The rubber molder will estimate the amount of shrinkage to be expected, based on the specified compound and will allow for it when preparing the mold.

9.4.8 Surface finish may be varied from bright and glossy to one that presents a dull appearance. The finish of the mold, as well as the type mold release agent used, affects the product's finish. Polished and chrome-plated molds produce a glossy finish, whereas abrasive-blasted mold surfaces yield satin or semi-rough finishes. The surface appearance is also affected by compounding, especially the kind and amount of carbon black or other fillers.

9.4.9 In addition, wherever possible, extremely sharp edges and corners should be avoided in rubber parts. A radius, no matter how slight, is preferred anywhere except at the cut end of an extrusion. Sharp edges are likely to feather, and entrapped air may make the edge jagged as a result of pitting. A 0.031-inch (0.79-mm) minimum radius is recommended. However, occasionally the omission of a radius requirement on a simple cylindrical or torrodial shape will convert a molded part to a less expensive part that can be cut from an extrusion.

9.4.10 Improved methods of vulcanization have, in many cases, made direct attachment possible, and have eliminated mounting holes, bolts, and metal flanges. When mounting holes are necessary, care should be taken not to place them too near each other or the edge. Mounting bolts or screws can occasionally be made an integral part of the rubber piece by curing the rubber to the metal. A molded part may be attached to a machine by molding a groove which will permit it to be snapped into a hole or around a disk-like member. A pertinent example of such a design is a grommet. Male or female threaded inserts should be avoided, as the excess rubber must be cleaned from the threads after molding. A single large insert allows easier and less costly production than two smaller ones. Prepositioning in the mold is facilitated if the projecting end of the insert is of simple geometric shape. A draft of one° minimum for surfaces perpendicular to the parting line is advisable on parts more than 0.5 inch (13 mm) thick. Figure 135 illustrates good and bad design examples.

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9.5 Extrusion

9.5.1 Many rubber products in use and required for various applications have complex cross sections. If these parts have surfaces parallel to the longitudinal axis, they are generally fabricated by extrusions. The process of extrusion uses a rotating tube screw to force a rubber compound through an extruding die having an aperture shaped to produce the desired cross section. This shaped material is placed in a steam chamber for curing or vulcanization. Almost any shape can be extruded, provided all contours are parallel to the longitudinal axis of the die.

9.5.2 General merits of this manufacturing process include: low setup and die costs; minimum waste or scrap, therefore, low finished part cost; can be cut to length to form endless gaskets economically; and is the cheapest method for mass production of small parts, such as washers, spacers, and bushings.

9.5.3 Unfavorable factors to be considered in design are: moderately large tolerances required; Durometer hardness limited to 40 minimum and 95 maximum; diameter usually limited to 4.5 inches (115 mm) maximum; and some shape design limitations.

9.5.4 The extrudate swells when leaving the die, depending upon the type of elastomer, the amount of fillers, the extrusion speed, and the slope of the die. Thin sections generally swell less than thick sections, that is, the shape of the extrudate is different from that of the die. It is therefore important that large differences in cross-sectional area are avoided during the design of the extrudate.

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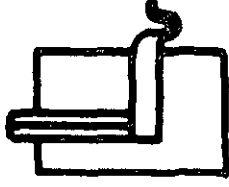


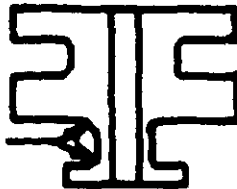
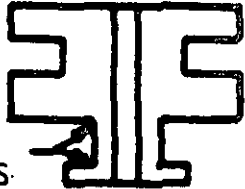
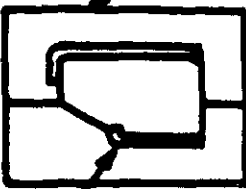
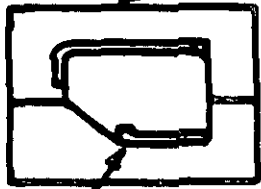
	GOOD	POOR
To facilitate molding, avoid holes or slots in two directions.		
To facilitate holding and prepositioning of insert in mold, provide projecting ends with standard geometrical shapes.	HOLE FOR PIN TO LOCATE INSERT IN MOLD 	
To prevent peeling under shear load, provide generous fillets and overhang of inserts where practicable.	INSERT OVERHANG FILLET 	
To prevent failure caused by concentration of stress at sharp internal corners, use fillets.	FILLETS 	SHARP CORNERS 
To prevent cocking of parts during molding, design mold to hold parts securely.	MOLD PART HELD SECURELY BY MOLD 	MOLD PART NOT HELD SECURELY BY MOLD 

FIGURE 135. SOME FACTORS INVOLVED IN DESIGN OF RUBBER PARTS, PANEL A

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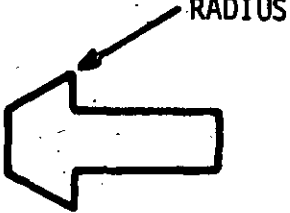
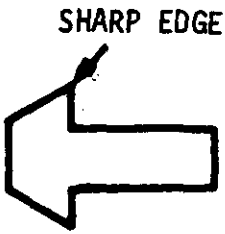
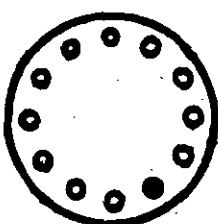
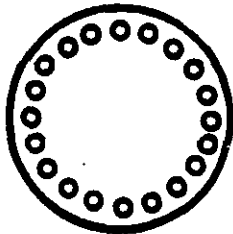
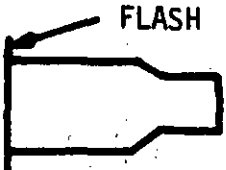
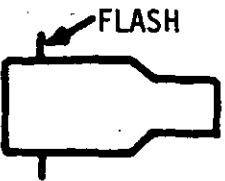
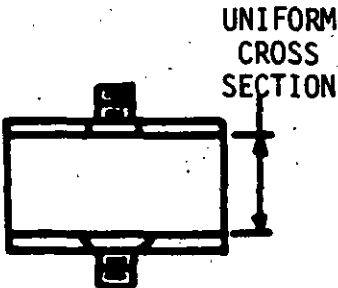
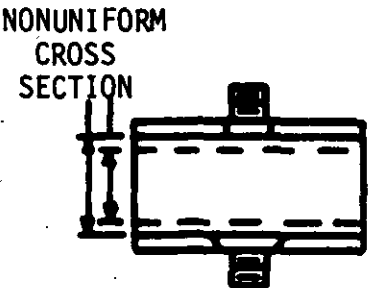
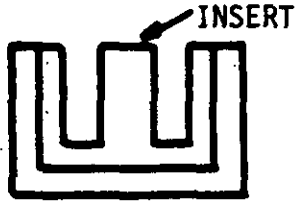
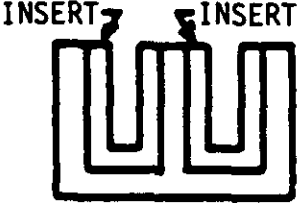
	GOOD	POOR
To prevent feathering and pitting, avoid sharp edges.		
To prevent tearing at mounting holes, keep holes well spaced and away from edges.		
To facilitate trimming of flash, locate flash groove at edges.		
To ensure uniform distribution of tensile load at bonding surfaces, keep rubber cross section uniform.		
To simplify molding and decrease costs, avoid multiple inserts.		

FIGURE 135. SOME FACTORS INVOLVED IN DESIGN OF RUBBER PARTS, PANEL B

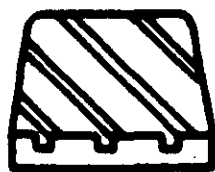
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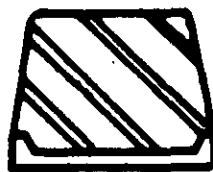
Stresses are over-concentrated on the edges of the insert. Edges and corners have not been rounded off.



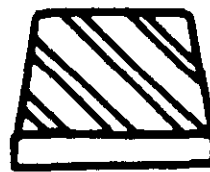
The insert has been reversed and more uniform application of stresses has been achieved. The corners have been rounded off to prevent cutting.



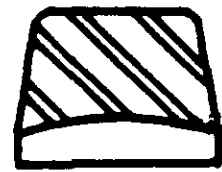
A.



B.



C.



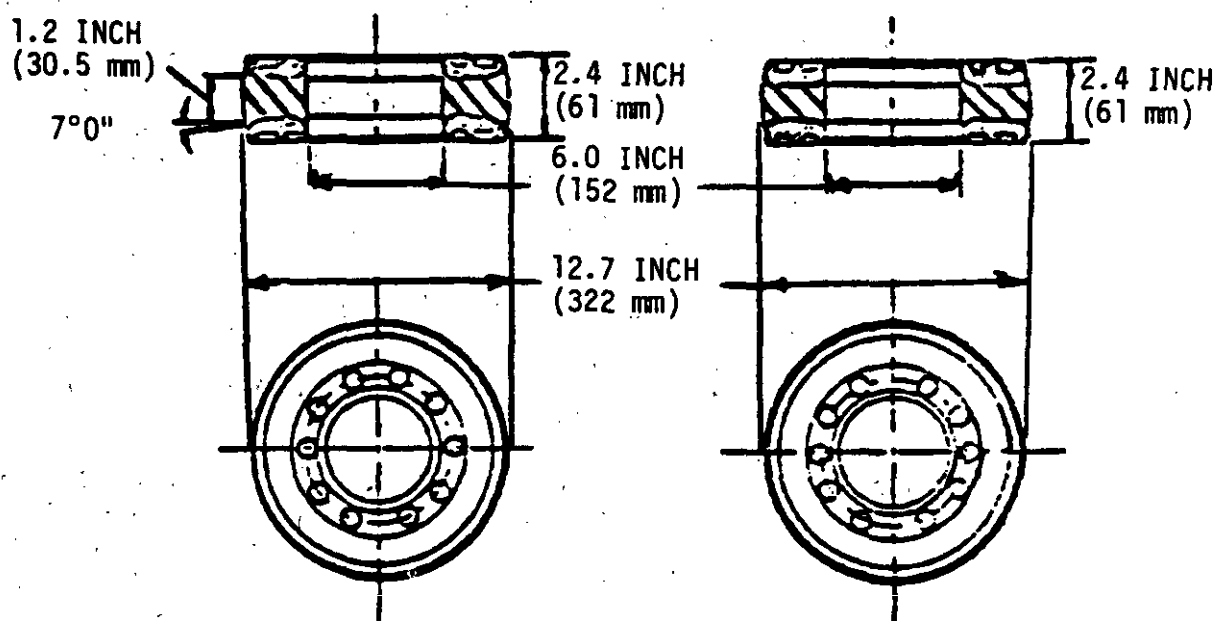
D.

Design Sequence for a Solid Tank Tire:

- A. Dovetails and serrations unnecessary; merely complicate cleaning.
- B. Local stress concentrations were found to occur in the corners of the rim shoulder causing separation.
- C. Shoulders removed.
- D. Improved design with major causes of bond failure eliminated.

FIGURE 135. SOME FACTORS INVOLVED IN DESIGN OF RUBBER PARTS, PANEL C

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The bonded metal plates of the coupling have been modified so that under a given stress the strain remains constant over the whole rubber section from the center out to the periphery.

The parallel bonded faces of the coupling apply progressively greater strains on the rubber section from the center to the periphery for the same amount of angular movement.

FIGURE 135. SOME FACTORS INVOLVED IN DESIGN OF RUBBER PARTS, PANEL D

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9.6 Extruded Product Design Considerations.

9.6.1 To reduce distortion during vulcanization, extrusions should be designed with one side flat, if possible. Wall thicknesses should be reasonable since thin wall sections sag during vulcanization.

9.6.2 Since extrusion dies are developed for a specific rubber compound and compensate for extrusion swell, any major change in compound hardness or rubber type will likely require a die revision or a new die. Different rubber compounds extruded from the same die will usually result in different sized, but generally the same shaped, extruded product.

9.6.3 The manner in which the extruded shape is cured, in coils or in straight lengths, may affect its usefulness in the application intended. A rubber product manufacturer will cure extrusions in loose coils, unless the purchaser requests curing in straight lengths.

9.6.3.1 A certain amount of curvature will result in the final product after curing in coils. If this curvature is objectionable, the purchaser should specify "Extrude and cure in straight length - do not coil". The greatest length that can be cured straight without coiling is approximately 14 feet (4.5 m), although specialty items may be made in much longer lengths.

9.6.3.2 Tubing cured in large diameter coils may not be truly round in cross section, especially if the diameter/wall thickness ratio is small. If ovality, as noted in some procurement specifications, is a requirement for a circular cross-section part, such as a tube to be used as an air seal, curing should be in straight lengths on mandrels or poles to preserve the ovality.

9.6.4 The term "extrudability" describes the perfection to which a compounded rubber can be extruded. Extrudability is a function of the physical properties of the rubber which are determined by chemical structure and material compounding, cross-section variations and complexity, and length of the uncured piece.

9.6.5 In general, hard rubbers allow closer tolerances and thinner cross sections than do soft rubbers. Compounds with higher tensile strengths require greater tolerances than do low tensile strength compounds. Natural, SBR, chloroprene, NBR, butyl, and silicone rubbers all can be compounded to extrude a variety of satisfactory cross sections.

9.6.6 A uniformly thick cross section can be better extruded in softer material than can a cross section that varies from thick to thin. If a section is irregular in shape, support of the section during cure may be necessary. Thin cross sections cannot be handled in straight lengths over 60 inches (1500 mm) and still be held to close tolerances. Uniform tolerances can be held over the entire length of the extrusion, if the design of the cross section is such that the product can be coiled during cure.

9.6.7 It is difficult to generalize the effects of the many factors on the extrusion of rubber products. As guides in planning extrusion products, several of these factors have been related in chart form. These extrudability charts can be used in several ways. If one of the factors related by the charts is given for a specific extrusion, the charts show the limitations that factor places on the nature of the extrusion. If more than one factor is

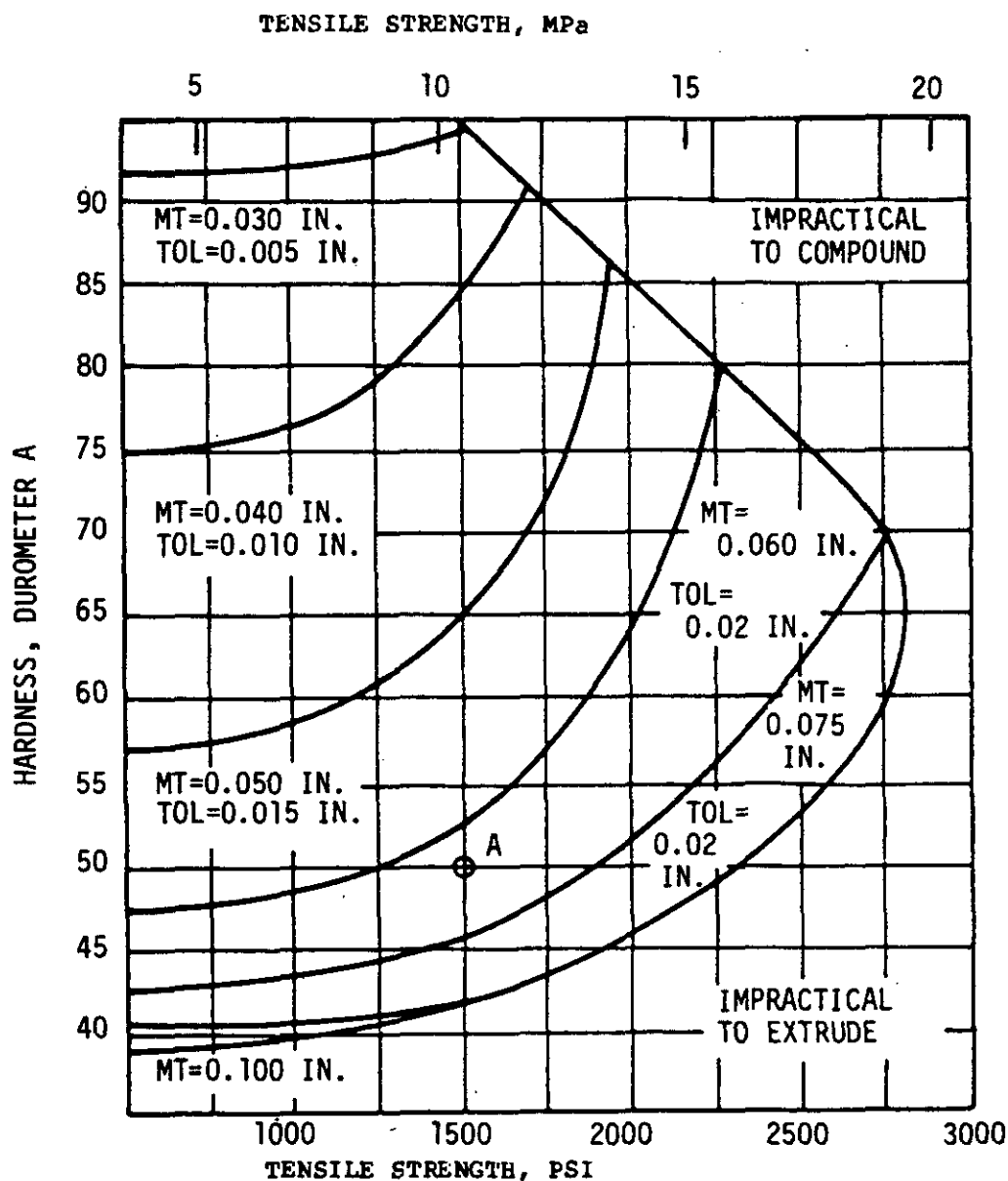
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given, the charts show how the relationship of the factors will affect the nature of the extrusion. Figure 136 relates hardness, tensile strength, and tolerance limits to the minimum practical uniform thickness that can be extruded satisfactorily. The areas enclosed by the curved lines are the limits for the specifications designated within the areas. If any of the factors on the chart are given for a product, the extrudability of the product can be found. For example, if a material must meet the specifications of 50-Durometer A hardness, 1,500 psi (10.3 MPa) tensile strength (point A on the chart), the product can be extruded with a minimum thickness of 0.060 inch (1.52 mm) and with a thickness tolerance of plus or minus 0.020 inch (0.51 mm). If tensile strength and hardness specifications fall outside the longest curve, the product is impractical to extrude. Figure 137 relates hardness, tensile strength, and tolerance in extrusions with nonuniform cross sections that have a great variation in section thickness. This chart can be used to find the tolerance for an extruded cross section of given hardness and tensile strength. For example, if the material has the specifications of 50-Durometer A hardness, 1,500 psi (10.3 MPa) tensile strength (point A on the chart), it can be extruded with a tolerance of plus or minus 0.020 inch (0.51 mm) as well.

9.6.8 Two facts are apparent from Figures 136 and 137. First, the absolute minimum hardness for extrusion in nonuniform thin sections is higher (45 Durometer A) than for extrusions of uniform thickness (37 Durometer A). The minimum hardness of 45 Durometer A would be covered by a specification of 50 plus-or-minus-5 Durometer A, and is interpreted to mean that 50 is the minimum hardness that should be specified. This condition exists because of the higher swell characteristics of softer materials and the difficulty encountered in attempting to build an extruding die to produce thin and thick sections immediately adjacent to one another. The second significant fact is that the closer tolerances, indicated for higher hardness and relatively lower tensile materials, are in line with the thinner extrusions permissible in these same physical ranges.

9.6.9 Orientation occurs during flow of the elastomer through the extrusion die. Most of this built-in stress relaxes rather rapidly, even though smaller amounts are still present after vulcanization. Extrudates have the tendency, therefore, to shrink even over long time spans.

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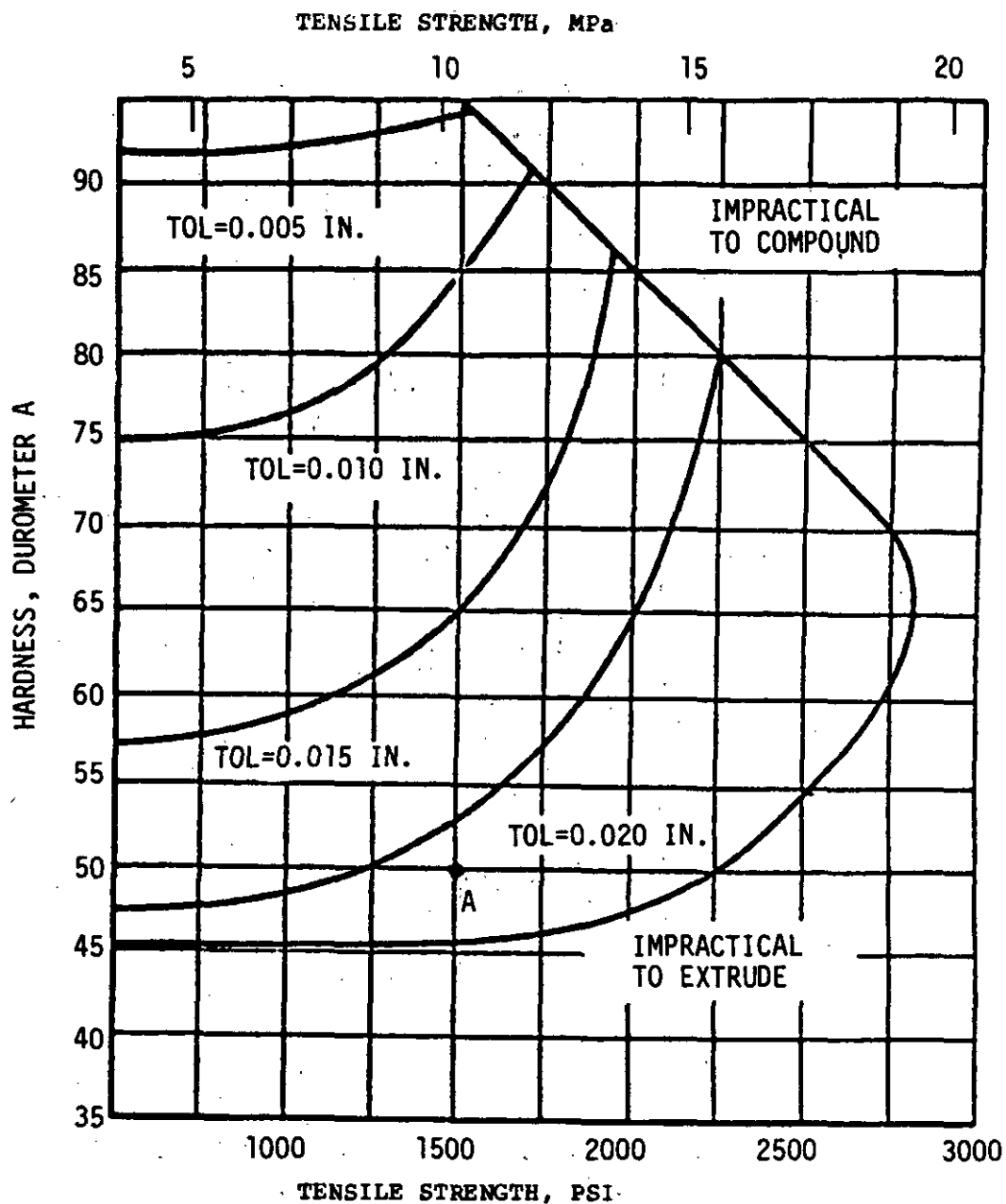
MT = MINIMUM THICKNESS

TOL = TOLERANCE LIMITS

inch	mm	inch	mm
0.005	0.13	0.040	1.02
0.010	0.25	0.050	1.27
0.015	0.38	0.060	1.52
0.020	0.51	0.100	2.54
0.030	0.76		

FIGURE 136. EXTRUSION TOLERANCES AS A FUNCTION OF HARDNESS, TENSILE STRENGTH, AND THICKNESS OF RUBBER SECTION (SEE 9.6.7 FOR EXAMPLE)

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TOL = TOLERANCE LIMITS

inch	mm
0.005	0.13
0.010	0.25
0.015	0.38
0.020	0.51

FIGURE 137. EXTRUSION TOLERANCES AS A FUNCTION OF HARDNESS AND TENSILE STRENGTH FOR NONUNIFORM CROSS SECTIONS (SEE 9.6.7 FOR EXAMPLE)

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9.7 Calendering.

9.7.1 Calendering is the process in which raw rubber stocks are fed through a series of steel cylinders parallel-mounted in a vertical bank. The space between rolls can be adjusted accurately so as to build up proper gage. After the sheet stock has been run through the calender, it is vulcanized in a hot room or cured in long vulcanizing presses. This sheet stock can be stamped or punched into practically any desired shape, provided top and bottom surfaces are flat.

9.7.2 A special case of calendering is the technique whereby a fabric is coated with a film of rubber. The fabric and sheeted rubber are passed through rolls to effect the permanent lamination. The character and quantity of the coating applied is governed by the setting, temperature, and speed ratio of the rolls.

9.7.3 The advantages of calendering are: substantial daily production, uniformity of finished parts, nominal initial set-up charges, low cost per unit, no quantity too large or too small, great flexibility of design and materials, minimum time before commencing production, and usually many stock dies available which can be utilized without amortization expense.

9.7.4 Disadvantages to be considered are: articles must be flat on both sides, and the wastage of material if the article has large cut-out sections.

9.8 Rubber-to-Metal Bonding.

9.8.1 Rubber can be bonded to most metals with good results. Lead, nickel plate, and cadmium form only poor to fair direct bonds with rubber. Bonding is necessary in applications such as mounts and couplings where rubber is used in shear or tension, and is optional when rubber is used in compression pads. In the latter case, bonding is the best method of retaining control over the stress-strain relationship. When, for instance, an adhesive bond does not exist in a sandwich application, the surface of the rubber in contact with the metal will spread out in accordance with the frictional conditions of the surface. Metal inserts must also be bonded to the rubber.

9.8.2 Design of a bonded assembly should consider a number of factors, relating mostly to avoiding localized areas of high stress. Sharp corners and edges should be avoided. Projecting lips, tending to restrict the flow of rubber under stress, should be eliminated. Acute angles formed by the rubber around inserts should be avoided. Cross sections of the same general thickness range should be used to reduce variations in the state of cure. The stresses in the rubber should be uniformly distributed insofar as possible, (for example, cylindrical assemblies loaded in torsion). Large external fillets or radii should be designed.

9.8.3 The oldest method of bonding rubber to metal utilizes the ability of brass to form a chemical union with the rubber. Metal parts are brass-plated with a 70/30 or 80/20 copper-zinc alloy, coated with a liquid rubber bonding agent and then vulcanized. Brass plating is expensive and is not satisfactory in all cases. For an effective bond, the specific brass alloy must be tailored to the rubber compound. In recent years, bonding agents effective without brass plating have been developed. Such bonding agents are commercially available and must be selected to be compatible with the rubber

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as well as with the metal used. In some instances, a two-coat bonding agent is most effective, the primer being able to achieve a good bond with the metal and the second coat with the rubber.

9.8.4 Bond strength tests are generally conducted in accordance with ASTM Specification D429. Method A is a tensile test, and Method B a 90-degree peel test. As bond strengths have improved with better manufacturing procedures and materials, Method A has frequently resulted in failure in the rubber itself, and actual bond strength could not be determined. Hence, Method B is becoming the preferred test method. In Table XL, some comparative values of tensile bond strength are indicated when the rubber was bonded directly to brass.

TABLE XL. COMPARATIVE BOND STRENGTH OF
VARIOUS POLYMERS TO BRASS

Rubber	24-Hour Strength	30-Day Accelerated Aging	12-Month Shelf Life
Tensile Strength, psi			
Natural	998	922	680
Chloroprene	702	658	137
SBR	398	594	267
Butyl	426	618	700
Tensile Strength, MPa			
Natural	6.88	6.36	4.69
Chloroprene	4.84	4.54	0.94
SBR	2.74	4.10	1.84
Butyl	2.94	4.26	4.83

9.8.5 Failure stresses vary naturally with the mode of loading.

9.8.5.1 The following are some average ultimate bond strength values which are achievable either by bonding to brass directly or with intermediary bonding agents to other metals.

	psi	MPa
Tension:	600 - 1500	4.14 - 10.34
Shear:	800 - 1200	5.52 - 8.27
Compression:	2000 - 5000	13.79 - 34.47

9.8.5.2 It is recommended that design stresses be held within the following limits:

	psi	MPa
Tension:	150	1.03
Shear:	150	1.03
Compression:	750	5.17

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9.8.6 Failure in rubber-bonded-to-metal articles generally results from: stress concentrations caused by poor design, metallic corrosion at the bonding layer, rubber deterioration by solvents, oils, or gases, and peeling in shear loaded parts.

9.8.7 Metal parts molded into rubber should not be knurled. Surfaces should be machined smooth. In some cases, grit or shot blasting, or acid-etching the metal surface improves the bond. Surfaces must always be clean and nonporous, as porosity allows cleaning agents to remain and gradually destroy bond quality. Nonporous cast surfaces need not be machined before bonding. Aluminum or aluminum alloys are best prepared by treating them with chemical solutions which will produce polar surfaces.

9.8.8 Figure 135 illustrates good and poor practices in rubber-to-metal bonding.

9.9 Tolerances.

9.9.1 Dimensional variations on finished rubber parts occur mainly because of shrinkage variation and mold design.

9.9.2 All rubber shrinks to some extent after molding. The mold designer and rubber compounder must estimate the amount of shrinkage and incorporate this allowance into the mold-cavity size. Shrinkage varies with type of compound, rubber batch variance, cure time, temperature, and pressure. As a result, even using a mold built to anticipate shrinkage, an inherent variability remains which must be covered by adequate dimensional tolerance.

9.9.3 Molds are designed and built to varying degrees of precision. The mold designer attempts to get the highest amount of precision and mold life per dollar of mold cost. With any type of mold, the mold builder must have some tolerance, and therefore each cavity will have some variance from the others. For molds requiring high precision, the design and machining work is performed accordingly. Consequently, the cost of such a mold is higher than for one having less rigorous requirements. In addition to cavity variations, the accuracy of mold "register" must be considered. In a simple two-plate mold, register is the parallel fit between the halves of the mold when closed. In simple molds, the register is usually obtained by sturdy dowel pins and bushings. If tolerances are too tight on dimensions affected by the register, the wear on dowel pins creates the need for frequent mold maintenance. For parts requiring close register, greater precision is obtained by other types of mold construction such as self-registering cavities. The dimensional variations on finished rubber parts must be taken into consideration by the specification of realistic tolerances for each dimension.

9.9.4 To arrive at an acceptable method of showing dimensions and tolerances on molds, the terms "fixed" and "closure" dimensions must be defined and understood. Fixed describes those dimensions parallel to the parting line (see Figure 138). In a simple wheel with half the wheel formed in each half of the mold and the flash line around the OD, the CD and the hub diameter are fixed dimensions. Holes formed by solid pins will usually be included in this classification. Fixed dimensions are not affected by flash-thickness variations. Closure dimensions are those dimensions at right angles

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to the mold parting line or to parting lines of major mold sections. The thickness of the wheel (Figure 138) is a closure dimension.

9.9.5 These dimensions are affected by flash thickness variation. In addition to the shrinkage, mold-maker's tolerance, trim and finish methods, and a number of other factors affect closure dimensions. Among these are flow characteristics, weight and shape of the raw stock, and types of flash grooves or other relief devices. While closure dimensions are affected by flash thickness variation, they are not necessarily related to basic flash thickness. If a manufacturer plans to machine or die-trim a part, the mold is planned with an artificial flash, which is thicker than if hand-flashing or tumble-trim is to be employed. Thus, parts purchased from two sources may have different basic flash thickness at the parting line and yet both meet drawing dimensions.

9.9.6 There is usually a logical place for the mold designer to locate the parting line for best dimensional control. If the product design limits this location, an alternate mold construction, which may limit the tolerance control on the part or increase the cost of the mold, is required.

9.9.7 As a guide for the designer, the Rubber Manufacturers Association (RMA) has set up tolerance schedules for molded and extruded rubber parts. The four RMA classes, the basis of the schedules, are defined in Table XLI. Economy dictates that the widest possible tolerance be selected. If one tolerance class is used exclusively for a part, the appropriate drawing designation (that is, A1, A2, A3, G1, or M1) can be used in place of individual dimension tolerances. Table XLI lists the general dimensional tolerances for molded products. Tolerances for extruded parts are given in Table XLII (cross-sectional dimensions), Table XLIII (cut-length dimensions), Table XLIV (mandrel-cured tubing dimensions), and Table XLV (ground-surface tubing dimensions). Table XLVI lists general dimensional tolerances for extruded parts made from silicone, polyacrylate, fluoroelastomer, and other post cured rubber compounds.

9.9.8 In establishing realistic tolerances for extrusions, the elastomers have been divided into two groups, and a tolerance schedule compiled for each. In general, Group 1 includes compounds with hardness of 55 Durometer A or higher. Group 2 includes compounds difficult to extrude and are frequently in the hardness ranges less than 55 Durometer A.

9.9.9 Ovality tolerances of extruded tubing, which normally require curing in straight lengths, are 10 percent of the nominal diameter in sizes up to and including 0.500 inch (12.70 mm), and 15 percent in larger sizes. Ovality tolerances are normally applicable to wall thicknesses 0.063 inch (1.60 mm) or over, and are computed from the difference between the minor and major axis diameter measurements, taken at the same transverse plane on the tube, expressed as a percentage of the nominal diameter, measured either on the inside diameter, ID, or outside diameter, OD. Ovality tolerances were established for aircraft tubing and are shown in the SAE Aerospace Material Specifications on rubber materials.

9.9.10 The concentricity of surfaces are specified as total indicator runout (T.I.R.) in decimals. Where close tolerances are required, it may be advantageous or even necessary to specify greater tolerances for molding, and then to specify the close tolerances after grinding, allowing sufficient stock for this operation. Cases to be considered include:

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- (1) Concentricity of all cylindrical surfaces formed by the same mold part (dimensions "A" and "B", Figure 139b).
- (2) Concentricity of all cylindrical surfaces formed by mating mold parts (surfaces "C" and "A", or "C" with "B", Figure 139b).
- (3) Concentricity of all surfaces of a metal insert (Figure 139c).
- (4) Concentricity of metal with metal surfaces (surfaces "A" and "B", Figure 139c).
- (5) Concentricity of metal with rubber surfaces (surfaces "A" and "B", Figure 139c).

9.9.11 An angular tolerance of one degree should be specified for unground parts, and squareness should be specified in the same manner. The angle specified is to be measured either from a convenient axis, or one of the surfaces (Figure 139e).

9.9.12 Flatness should be specified as deviation from the true plane. For unground molded surfaces, a 0.010-inch (0.25-mm) tolerance is realistic. For ground surfaces, this can be tightened to 0.005 inch (0.13 mm).

9.9.13 Parallelism tolerance should be specified for short distances on an overall basis or, for long parts, as a deviation per specified length; for example, parallel within 0.030 inch (0.76 mm) or parallel within 0.050 inch per foot (4.17 mm/m). These figures represent reasonable commercial tolerances (Figure 139a).

9.9.14 An understanding of manufacturing procedures is helpful in understanding the applicable dimensional tolerances and avoiding unnecessarily close control, which increases part costs considerably. A typical example is the requirement for mandrel-cured and subsequently surface-ground extruded tubing. When it becomes necessary to hold the tubing round and to close tolerances, a mandrel of the proper size must be inserted in the inside diameter of the tubing before vulcanizing. This limits the length of the tubes. The shrinkage that occurs after removal from the mandrel causes the inside diameter to be less than the mandrel size or, in other words, tolerances are always minus with no plus, as shown in Table XLIV. This means that tubes vulcanized on standard mandrels will have an inside diameter less than standard. If a standard inside diameter is necessary for tubing, then special oversize mandrels are required. These specially ground oversize mandrels are costly and many times can be avoided through understanding of the problem and proper consideration for tolerances. The designer should indicate what type of surface would be required on the outside diameter of tubing, such as surface ground, cloth-wrapped or as-extruded surface. Any tube that has to have close tolerances on the outside diameter will generally have a ground surface. Cloth wrapping aids in maintaining a round shape and is used when the rubber compound is soft and may sag in curing; an imprint of the cloth wrapping will be on the outside surface. If the type of surface is not indicated, the rubber fabricator will assume that an as-extruded surface will be acceptable.

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9.9.15 Standard thickness tolerances for molded cellular, open cell sponge and closed cellular rubber are shown in Table XLVII, while width and length tolerances are shown in Table XLVIII. Note that the four-class designation is shown in these Rubber Manufacturers Association tolerance tables.

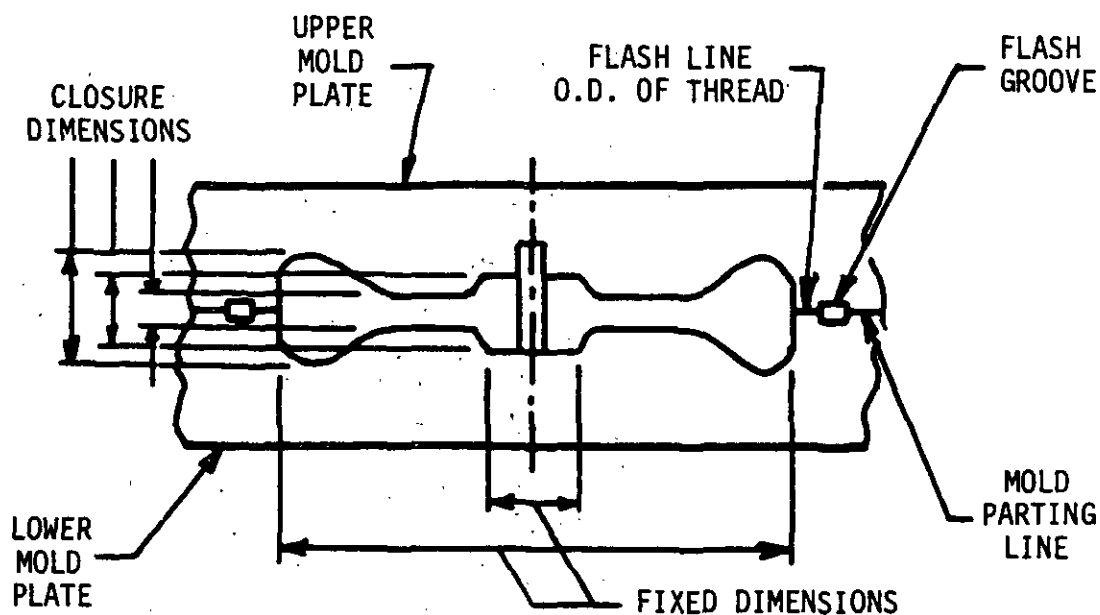
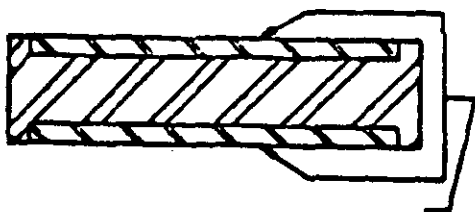
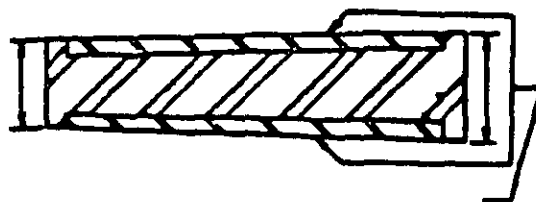


FIGURE 136. NOMENCLATURE FOR DIMENSIONAL TOLERANCES OF MOLDED PRODUCTS (67)

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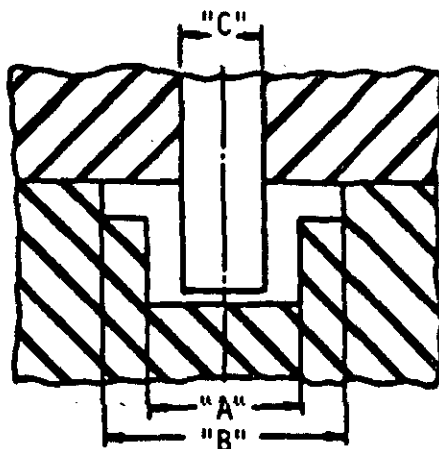
SKETCH 1



SKETCH 2

Example: In Sketch 1, the plates of the sandwich mount are parallel. In Sketch 2, they are not. On such a part approximately 8 inches square (200 mm square), parallelism to within 0.030 inch (0.76 mm) can be expected.

(a)



Rubber Parts with no Metal Inserts

- a. All diameters formed by the same piece of the metal mold will be concentric within 0.010 inch (0.25 mm) T.I.R. (Total Indicator Runout).

Example: Diameter "A" will be concentric with Diameter "B" within 0.010 inch (0.25 mm) T.I.R.

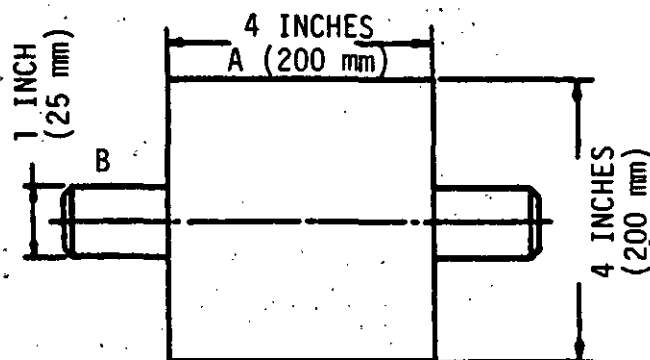
- b. Other diameters will be concentric within 0.030 inch (0.76 mm) T.I.R.

Example: Diameter "A" or "B" will be concentric with Diameter "C" within 0.030 inch (0.76 mm) T.I.R.

(b)

FIGURE 139. PARALLELISM, CONCENTRICITY, AND SQUARENESS (67)

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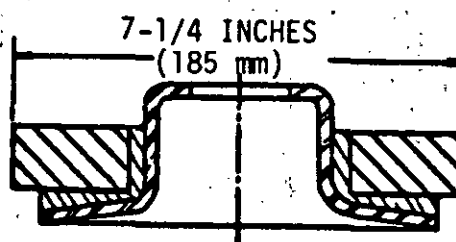
Rubber Parts with Metal Inserts

Rolls

Outside surface "A" will be concentric with shaft "B" within 0.030 inch (0.76 mm) T.I.R. plus the metal tolerance if the shaft is unground.

Note: Parts may be ground to considerably closer tolerances.

(c)



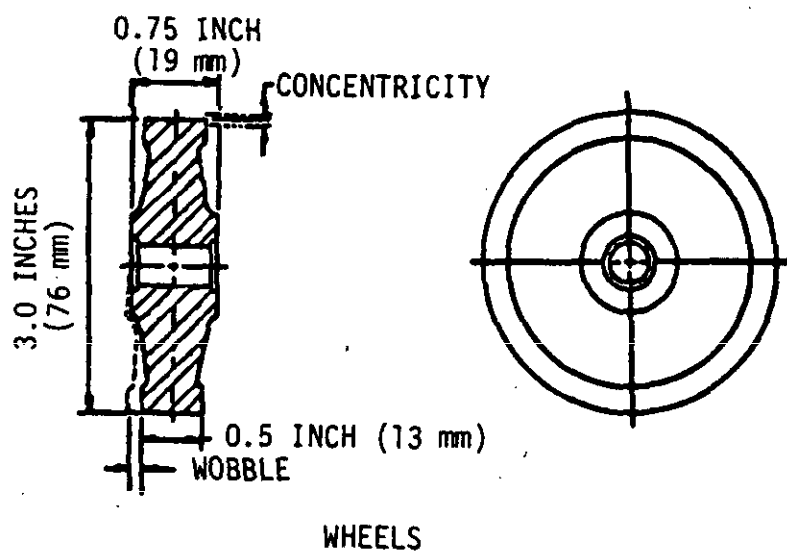
VIBRATION DAMPERS

Concentricity may be within 0.035 inch (0.89 mm) T.I.R. This type of part requires more control than is usually used on other commercial products.

(d)

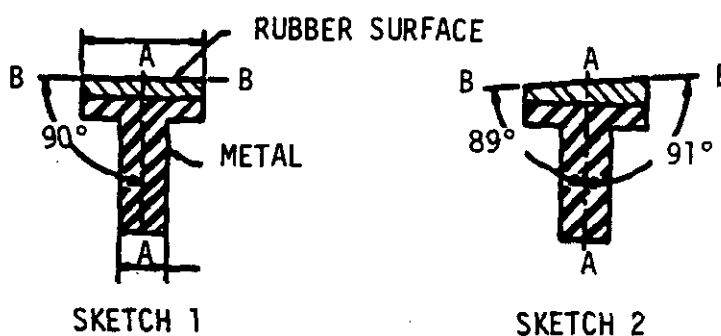
FIGURE 139. PARALLELISM, CONCENTRICITY, AND SQUARENESS (continued)

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On similar wheel, having an outside diameter of 3 inches (76 mm), concentricity within 0.030 inch (0.76 mm) and wobble within 0.030 inch (0.76 mm) can be expected.

(e)



Rubber-to-Metal Part

In Sketch 1, rubber surface B-B is square with axis A-A as the angle is true 90 degrees. Sketch 2 indicates the same example with the 1 degree tolerance exaggerated.

Note: This type of part requires closer control than is usually normal with commercial parts.

(f)

FIGURE 139. PARALLELISM, CONCENTRICITY, AND SQUARENESS (continued)

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Table XLI. Standard dimensional tolerances - molded solid rubber products
Rubber Manufacturers Association (RMA) (69)

Dimensions Inches	Tolerances, Inch					
	RMA Drawing Designation A1		RMA Drawing Designation A2		RMA Drawing Designation A3	
	High Precision	Fixed	Precision	Fixed	Commercial	Noncritical
Up to 0.400, incl	+0.004	+0.005	+0.006	+0.008	+0.008	+0.013
Over 0.400 - 0.630, incl	+0.005	+0.006	+0.008	+0.010	+0.010	+0.016
Over 0.630 - 1.000, incl	+0.006	+0.008	+0.010	+0.013	+0.013	+0.020
Over 1.000 - 1.600, incl	+0.008	+0.010	+0.013	+0.016	+0.016	+0.025
Over 1.600 - 2.500, incl	+0.010	+0.013	+0.016	+0.020	+0.020	+0.032
Over 2.500 - 4.000, incl	+0.013	+0.016	+0.020	+0.025	+0.025	+0.040
Over 4.000 - 6.300, incl	+0.016	+0.020	+0.025	+0.032	+0.032	+0.050
Over 6.300 and over	No High Precision above 6.30 inches		To find fixed dimensional tolerances multiply dimension by 0.42		To find fixed dimensional tolerances multiply dimension by 0.52	To find fixed dimensional tolerances multiply dimension by 0.82

Table XLI-SI. Standard dimensional tolerances - molded solid rubber products
rubber manufacturer association (RMA) (69)

Dimensions Millimetres	Tolerances, Inch					
	RMA Drawing Designation A1		RMA Drawing Designation A2		RMA Drawing Designation A3	
	High Precision	Fixed	Precision	Fixed	Commercial	Noncritical
Up to 10.00, incl	+0.10	+0.13	+0.16	+0.20	+0.20	+0.32
Over 10.00 - 16.00, incl	+0.13	+0.16	+0.20	+0.25	+0.25	+0.40
Over 16.00 - 25.00, incl	+0.16	+0.20	+0.25	+0.32	+0.32	+0.50
Over 25.00 - 40.00, incl	+0.20	+0.25	+0.32	+0.40	+0.40	+0.63
Over 40.00 - 63.00, incl	+0.25	+0.32	+0.40	+0.50	+0.50	+0.80
Over 63.00 - 100.00, incl	+0.32	+0.40	+0.50	+0.63	+0.63	+1.00
Over 100.00 - 160.00, excl	+0.40	+0.50	+0.63	+0.80	+0.80	+1.25
Over 160.00 and over	No High Precision over 160 mm		To find fixed dimensional tolerances multiply dimension by 0.42		To find fixed dimensional tolerances multiply dimension by 0.52	To find fixed dimensional tolerances multiply dimension by 0.82

Notes to Tables XLI and XLI-SI

Drawing Designation A1 is the tightest tolerance classification and indicates a high precision rubber product. Such products require expensive molds, fewer cavities per mold, costly in-process controls and inspection procedures. It is desirable that the exact method of measurement is agreed upon between manufacturer and customer, as errors in measurement may be large in relation to the tolerance. Some materials, particularly those requiring post curing, do not lend themselves to Drawing Designation "A1" tolerances.

Drawing Designation A2 tolerances indicate a precision product. Molds must be precision machined and kept in good repair. While measurement methods may be simpler than Drawing Designation A1, careful inspection will usually be required.

Drawing Designation A3 tolerances indicate a "commercial" product and will normally be used for most products.

Drawing Designation A4 tolerances apply to products where dimensional control is noncritical and secondary to cost.

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TABLE XLII. STANDARD CROSS SECTIONAL TOLERANCES - EXTRUDED RUBBER PARTS
RUBBER MANUFACTURERS ASSOCIATION (RMA)^{1/} (69)

Dimensions	RMA Class A Drawing Designation A High Precision	RMA Class 1 Drawing Designation A1 Precision	RMA Class 2 Drawing Designation A2 Commercial	RMA Class 3 Drawing Designation A3 Noncritical
Inches	Group 1 Compound Tolerances, Inch ^{2/}			
Up to 0.100, incl ^{3/}	±0.008	±0.010	±0.013	±0.016
Over 0.100 - 0.160, incl	±0.010	±0.013	±0.016	±0.020
Over 0.160 - 0.250, incl	±0.013	±0.016	±0.020	±0.025
Over 0.250 - 0.400, incl	±0.016	±0.020	±0.025	±0.032
Over 0.400 - 0.630, incl	±0.020	±0.025	±0.032	±0.040
Over 0.630 - 1.000, incl	±0.025	±0.032	±0.040	±0.050
Over 1.000	Multiply Dimension by 0.0225	Multiply Dimension by 0.0275	Multiply Dimension by 0.0350	Multiply Dimension by 0.0450
Inches	Group 2 Compound Tolerances, Inch ^{4/}			
Up to 0.100, incl ^{3/}	±0.010	±0.013	±0.016	±0.020
Over 0.100 - 0.160, incl	±0.013	±0.016	±0.020	±0.025
Over 0.160 - 0.250, incl	±0.016	±0.020	±0.025	±0.030
Over 0.250 - 0.400, incl	±0.020	±0.025	±0.030	±0.040
Over 0.400 - 0.630, incl	±0.025	±0.030	±0.040	±0.050
Over 0.630 - 1.000, incl	±0.032	±0.040	±0.050	±0.063
Over 1.000	Multiply Dimension by 0.0275	Multiply Dimension by 0.0350	Multiply Dimension by 0.0450	Multiply Dimension by 0.0550

TABLE XLII-SI. STANDARD CROSS SECTIONAL TOLERANCES - EXTRUDED RUBBER PARTS,
RUBBER MANUFACTURERS ASSOCIATION (RMA)^{1/} (69)

Dimensions	RMA Class A Drawing Designation A High Precision	RMA Class 1 Drawing Designation A1 Precision	RMA Class 2 Drawing Designation A2 Commercial	RMA Class 3 Drawing Designation A3 Noncritical
Millimetres	Group 1 Compound Tolerances, mm ^{2/}			
Up to 2.50, incl ^{3/}	±0.20	±0.25	±0.32	±0.40
Over 2.50 - 4.00, incl	±0.25	±0.32	±0.40	±0.50
Over 4.00 - 6.30, incl	±0.32	±0.40	±0.50	±0.63
Over 6.30 - 10.00, incl	±0.40	±0.50	±0.63	±0.80
Over 10.00 - 16.00, incl	±0.50	±0.63	±0.80	±1.00
Over 16.00 - 25.00, incl	±0.63	±0.80	±1.00	±1.25
Over 25.00	Multiply Dimension by 0.0225	Multiply Dimension by 0.0275	Multiply Dimension by 0.0350	Multiply Dimension by 0.0450
Millimetres	Group 2 Compound Tolerances, mm ^{4/}			
Up to 2.50, incl ^{3/}	±0.25	±0.32	±0.40	±0.50
Over 2.50 - 4.00, incl	±0.32	±0.40	±0.50	±0.63
Over 4.00 - 6.30, incl	±0.40	±0.50	±0.63	±0.80
Over 6.30 - 10.00, incl	±0.50	±0.63	±0.80	±1.00
Over 10.00 - 16.00, incl	±0.63	±0.80	±1.00	±1.25
Over 16.00 - 25.00, incl	±0.80	±1.00	±1.25	±1.60
Over 25.00	Multiply Dimension by 0.0275	Multiply Dimension by 0.0350	Multiply Dimension by 0.0450	Multiply Dimension by 0.0550

^{1/} - Tolerances for outside diameter (OD), inside diameter (ID), wall thickness, width, height, and general cross sectional dimensions of extrusions.

^{2/} - In general Group 1 compounds are harder or more firm, with Durometer A Hardness of 55 or higher.

^{3/} - General cross sectional dimensions below 0.040 inch or 1.00 mm are impractical.

^{4/} - In general Group 2 compounds are softer, with Durometer A Hardness of less than 55, and include the more difficult to extrude compounds.

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TABLE XLIII. STANDARD CUT-LENGTH TOLERANCES - EXTRUDED PARTS,
RUBBER MANUFACTURERS ASSOCIATION (RMA) (69)

Length			RMA Class 1 Drawing Designation L1 Precision	RMA Class 2 Drawing Designation L2 Commercial	RMA Class 3 Drawing Designation L3 Noncritical
Inches			Group 1 Compound Tolerances, Inch ^{1/}		
	Up to	4.000, incl.	+0.040	+0.063	+0.100
Over	4.000 -	6.300, incl.	+0.050	+0.080	+0.125
Over	6.300 -	10.000, incl.	+0.063	+0.100	+0.160
Over	10.000 -	16.000, incl.	+0.080	+0.125	+0.200
Over	16.000 -	25.000, incl.	+0.100	+0.160	+0.250
Over	25.000 -	40.000, incl.	+0.125	+0.200	+0.315
Over	40.000 -	63.000, incl.	+0.160	+0.250	+0.400
Over	63.000 -	100.000, incl.	+0.200	+0.315	+0.500
Over	100.000 -	160.000, incl.	+0.250	+0.400	+0.630
Inches			Group 2 Compound Tolerances, Inch ^{2/}		
	Up to	4.000, incl.	+0.050	+0.080	+0.125
Over	4.000 -	6.300, incl.	+0.063	+0.100	+0.160
Over	6.300 -	10.000, incl.	+0.080	+0.125	+0.200
Over	10.000 -	16.000, incl.	+0.100	+0.160	+0.250
Over	16.000 -	25.000, incl.	+0.125	+0.200	+0.315
Over	25.000 -	40.000, incl.	+0.160	+0.250	+0.400
Over	40.000 -	63.000, incl.	+0.200	+0.315	+0.500
Over	63.000 -	100.000, incl.	+0.250	+0.400	+0.630
Over	100.000 -	160.000, incl.	+0.315	+0.500	+0.800

1/- In general Group 1 compounds are harder or more firm, with Durometer A hardness of 55 or higher.

2/- In general Group 2 compounds are softer, with Durometer A hardness of less than 55, and include the more difficult to extrude compounds. Special consideration should be given to extremely soft compounds and high tensile strength compounds.

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TABLE XLIII-SI. STANDARD CUT-LENGTH TOLERANCES - EXTRUDED PARTS,
RUBBER MANUFACTURERS ASSOCIATION (RMA) (60)

Length	RMA Class 1		RMA Class 2		RMA Class 3	
	Drawing		Drawing		Drawing	
	Designation		Designation		Designation	
	L1	L2	L3			
Precision	Commercial	Noncritical				
Millimetres	Group 1 Compound Tolerances, mm ^{1/}					
Up to 100.00, incl.	+1.00	+1.60	+2.50			
Over 100.00 - 160.00, incl.	+1.25	+2.00	+3.15			
Over 160.00 - 250.00, incl.	+1.60	+2.50	+4.00			
Over 250.00 - 400.00, incl.	+2.00	+3.15	+5.00			
Over 400.00 - 630.00, incl.	+2.50	+4.00	+6.30			
Over 630.00 - 1000.00, incl.	+3.15	+5.00	+8.00			
Over 1000.00 - 1600.00, incl.	+4.00	+6.30	+10.00			
Over 1600.00 - 2500.00, incl.	+5.00	+8.00	+12.50			
Over 2500.00 - 4000.00, incl.	+6.30	+10.00	+16.00			
Millimetres	Group 2 Compound Tolerances, mm ^{2/}					
Up to 100.00, incl.	+1.25	+2.00	+3.15			
Over 100.00 - 160.00, incl.	+1.60	+2.50	+4.00			
Over 160.00 - 250.00, incl.	+2.00	+3.15	+5.00			
Over 250.00 - 400.00, incl.	+2.50	+4.00	+6.30			
Over 400.00 - 630.00, incl.	+3.15	+5.00	+8.00			
Over 630.00 - 1000.00, incl.	+4.00	+6.30	+10.00			
Over 1000.00 - 1600.00, incl.	+5.00	+8.00	+12.50			
Over 1600.00 - 2500.00, incl.	+6.30	+10.00	+16.00			
Over 2500.00 - 4000.00, incl.	+8.00	+12.50	+20.00			

1/- In general Group 1 compounds are harder or more firm, with Durometer A hardness of 55 or higher.

2/- In general Group 2 compounds are softer, with Durometer A hardness of less than 55, and include the more difficult to extrude compounds. Special consideration should be given to extremely soft compounds and high tensile strength compounds.

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TABLE XLIV. STANDARD MANDREL-CURED TOLERANCES - EXTRUDED TUBING,
RUBBER MANUFACTURERS ASSOCIATION (RMA) (69)

Specified Dimensions		RMA Class 1 Drawing Designation M1 Precision			
		Group 1 Compounds		Group 2 Compounds	
		Tolerances, Inch			
Dimensions, Inch		Tolerances, Inch			
Up to	0.400, incl.	+0,	-0.016	+0,	-0.020
Over 0.400 -	0.630, incl.	+0,	-0.020	+0,	-0.025
Over 0.630 -	1.000, incl.	+0,	-0.025	+0,	-0.032
Over 1.000 -	1.600, incl.	+0,	-0.032	+0,	-0.040
Over 1.600 -	2.500, incl.	+0,	-0.040	+0,	-0.050
Over 2.500 -	4.000, incl.	+0,	-0.050	+0,	-0.063

Dimensions, mm		Tolerances, mm			
Up to	10.00, incl.	+0,	-0.40	+0,	-0.050
Over 10.00 -	16.00, incl.	+0,	-0.50	+0,	-0.63
Over 16.00 -	25.00, incl.	+0,	-0.63	+0,	-0.80
Over 25.00 -	40.00, incl.	+0,	-0.80	+0,	-1.00
Over 40.00 -	63.00, incl.	+0,	-1.00	+0,	-1.25
Over 63.00 -	100.00, incl.	+0,	-1.25	+0,	-1.60

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TABLE XLV. STANDARD GROUND-SURFACE TOLERANCES - EXTRUDED TUBING, RUBBER MANUFACTURERS ASSOCIATION RMA^{1/} (69)

Inside Diameter	RMA Class 1	RMA Class 2
	Drawing	Drawing
	Designation	Designation
	G1	G2
	Precision	Commercial
Inch	Group 1 Compound Tolerances, Inch ^{2/}	
0.20 and larger	0.005	0.010
Inch	Group 2 Compound Tolerances, Inch ^{3/}	
0.20 and larger	0.010	0.020
mm	Group 1 Compound Tolerances, mm ^{2/}	
5.00 and larger	0.12	0.25
mm	Group 2 Compound Tolerances, mm ^{3/}	
5.00 and larger	0.25	0.50

- ^{1/-} If it becomes necessary to hold the outside diameter of extruded mandrel cured tubing to closer tolerances than normal manufacturing methods will permit, as shown in Table XLIV, this can be accomplished by surface grinding the part if the part has an inside diameter of 0.20 inch (5.0 mm) or more. This surface grinding is done by rotating the part on a mandrel against an abrasive, such as an abrasive stone or abrasive paper, sometimes called "lathe grinding". The drawing should specify inside diameter or outside diameter, wall thickness, and outside finish, classified as rough, smooth, or fine.
- ^{2/-} In general Group 1 compounds are harder or more firm, with Durometer A hardness of 55 or higher.
- ^{3/-} In general Group 2 compounds are softer, with Durometer A hardness of less than 55, and include the more difficult to extrude compounds.

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TABLE XLVI. STANDARD DIMENSIONAL TOLERANCES - EXTRUDED PARTS MADE FROM SILICONE, POLYACRYLATE, FLUCROELASTOMER, AND OTHER POST CURED RUBBER COMPOUNDS, RUBBER MANUFACTURERS ASSOCIATION (RMA) (69)

Dimensions	RMA Class 1	RMA Class 2
	Drawing	Drawing
	Designation	Designation
	SIL-A1	SIL-A2
	Precision	Commercial
Inches	Tolerances, Inch	
Up to 0.100, incl	+0.008	+0.010
Over 0.100 - 0.160, incl	+0.012	+0.013
Over 0.160 - 0.250, incl	+0.016	+0.020
Over 0.250 - 0.400, incl	+0.025	+0.032
Over 0.400 - 0.630, incl	+0.040	+0.050
Over 0.630 - 1.000, incl	+0.063	+0.080
1.000 and over	Consult	Consult
	Fabricator	Fabricator
Millimetres	Tolerances, mm	
Up to 2.50, incl	+0.20	+0.25
Over 2.50 - 4.00, incl	+0.30	+0.32
Over 4.00 - 6.30, incl	+0.40	+0.50
Over 6.30 - 10.00, incl	+0.63	+0.80
Over 10.00 - 16.00, incl	+1.00	+1.25
Over 16.00 - 25.00, incl	+1.60	+2.00
25.00 and over	Consult	Consult
	Fabricator	Fabricator

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TABLE XLVII. STANDARD THICKNESS TOLERANCES - MOLDED CELLULAR RUBBER - OPEN CELL SPONGE, DIE CUT, SHEET OR STRIP; AND CLOSED CELL MOLDED CELLULAR RUBBER, RUBBER MANUFACTURERS ASSOCIATION (RMA) (69)

	FMA Class 1	RMA Class 2	RMA Class 3	RMA Class 4
	Drawing	Drawing	Drawing	Drawing
Thickness	Designation	Designation	Designation	Designation
	ATH 1	ATH 2	ATH 3	ATH 4
	High Precision	Precision	Commercial	Noncritical
Inches	Tolerances, Inch			
Up to 0.1250, incl	+0.0125	+0.016	+0.020	+0.025
Over 0.1250 - 0.2500, incl	+0.016	+0.20	+0.025	+0.0315
Over 0.2500 - 0.5000, incl	+0.020	+0.025	+0.0315	+0.040
Over 0.5000 - 1.0000, incl	+0.025	+0.315	+0.040	+0.050
Over 1.0000 - 2.0000, incl	+0.0315	+0.040	+0.050	+0.055
Over 2.0000	+2%	+2.5%	+3%	+3.5%
Millimeters	Tolerances, mm			
Up to 3.15, incl	+0.32	+0.40	+0.50	+0.63
Over 3.15 - 6.30, incl	+0.40	+0.50	+0.63	+0.80
Over 6.30 - 12.50, incl	+0.50	+0.63	+0.80	+1.00
Over 12.50 - 25.00, incl	+0.63	+0.80	+1.00	+1.25
Over 25.00 - 50.00, incl	+0.80	+1.00	+1.25	+1.50
Over 50.00	+2%	+2.5%	+3%	+3.5%

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TABLE XLVIII. STANDARD LENGTH AND WIDTH TOLERANCES - MOLDED CELLULAR RUBBER - OPEN CELL SPONGE, DIE CUT, SHEET OR STRIP; AND CLOSED CELL MOLDED CELLULAR RUBBER, RUBBER MANUFACTURERS ASSOCIATION (RMA) (69)

Dimension		RMA CLASS 1 ^{1/} Drawing Designation High Precision	RMA Class 2 Drawing Designation Precision	RMA Class 3 Drawing Designation Commercial	RMA Class Drawing Designation Noncritical
		Tolerances, Inch			
Inches		Tolerances, Inch			
Up to	0.250, incl	+0.010	+0.016	+0.025	+0.040
Over 0.250 -	0.500, incl	+0.016	+0.025	+0.040	+0.063
Over 0.500 -	1.000, incl	+0.025	+0.040	+0.063	+0.080
Over 1.000 -	2.000, incl	+0.040	+0.063	+0.080	+0.100
Over 2.000 -	4.000, incl	+0.063	+0.080	+0.100	+0.125
Over 4.000 -	8.000, incl	+0.080	+0.100	+0.125	+0.160
Over 8.000 -	16.000, incl	+0.100	+0.125	+0.160	+0.200
Over 16.000 -	32.000, incl ^{2/}	+0.125	+0.160	+0.200	+0.240
Over 32.000 -	64.000, incl	+0.4%	+0.5%	+0.63%	+0.8%
Over 64.000 -	128.000, incl	+0.8%	+1.0%	+1.25%	+2.0%
Over 128.000		+1.6%	+2.0%	+2.5%	+3.0%
Millimetres		Tolerances, mm			
Up to	6.30, incl	+0.25	+0.40	+0.63	+1.00
Over 6.30 -	12.50, incl	+0.40	+0.63	+1.00	+1.60
Over 12.50 -	25.00, incl	+0.63	+1.00	+1.60	+2.00
Over 25.0 -	50.0, incl	+1.0	+1.6	+2.0	+2.5
Over 50.0 -	100.0, incl	+1.6	+2.0	+2.5	+3.2
Over 100.0 -	200.0, incl	+2.0	+2.5	+3.2	+4.0
Over 200.0 -	400.0, incl	+2.5	+3.2	+4.0	+5.0
Over 400.0 -	800.0, incl ^{2/}	+3.2	+4.0	+5.0	+6.2
Over 800.0 -	1600.0, incl	+0.4%	+0.5%	+0.63%	+0.8%
Over 1600.0 -	3200.0, incl	+0.8%	+1.0%	+1.25%	+2.0%
Over 3200		+1.6%	+2.0%	+2.5%	+3.0%

^{1/} - Class 1 tolerances are not recommended for softer grades of cellular rubber, below 9 psi or 63 kPa compression-deflection.

^{2/} - Accurate measurement of larger lengths is difficult because these materials stretch and compress easily. Where close tolerances are required on long lengths, a specific technique of measurement should be agreed upon by purchaser and manufacturer.

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10. THE PHYSICAL PROPERTIES OF ELASTOMERS

10.1 Factors Influencing the Selection of an Elastomeric Compound

10.1.1 The selection of a particular rubber compound for a specific application is complicated by the number of elastomers available and the many ways that each can be compounded. Different compounds are available to fill the broad range of chemical, mechanical, and electrical properties required. Among the additives used are reinforcing ingredients to increase tensile strength and resistance to abrasion, fillers to decrease cost, and antiozonants to inhibit ozone deterioration. Other common additives are antioxidants, plasticizers, and curing agents.

10.1.2 The physical properties of elastomers are markedly dependent on temperature, and each elastomer has a definite useful temperature range. Progressively lower temperatures promote changes in performance from leatherlike, to boardlike, and then to a brittle material condition. At higher temperatures, rubber loses its elasticity and becomes plastic; tensile strength decreases and ultimate elongation decreases. Over long periods of time, if the temperature is high enough, thermal decomposition may take place. Most types of rubber, while having comparatively high strength at ordinary temperatures, lose a considerable portion of it at elevated temperatures.

10.1.3 Chemical attack may seriously compromise or destroy the physical properties of the elastomer. The resistance to chemicals, oxidation by air or ozone, weathering, aging, all vary widely among rubbers. Some chemicals, especially oils and solvents, do not attack rubber chemically but are absorbed so that the rubber becomes swollen and weak.

10.1.4 Physical properties of the most common elastomers are provided in the applicable data sheets in Appendix C.

10.2 Reclaimed Rubber

10.2.1 Reclaimed rubber may be derived from any of the man-made rubbers or from natural rubber.

10.2.2 In the reclaiming process, the treatment of scrap vulcanized rubber with heat and chemical agents regenerates the rubber to a plastic state. This occurs because a break in the crosslinked rubber molecule is developed as the scrap is depolymerized. A shorter chain structure is produced with additional double bonds that are readily available for further sulfur crosslinkage as the reclaim is used.

10.2.3 The chief reason for using reclaimed rubber is the economy of processing realized from faster mixing using less power, faster extrusion, and faster calendaring. Shrinkage in the uncured state, as well as during cure, is decreased. Curing time is reduced. The raw material (scrap) is low in cost. The addition of reclaimed stock makes compounds easier to handle during processing.

10.2.4 Vulcanizates made from reclaimed rubber have neither the strength nor the abrasion resistance of new rubber. Nevertheless, the reduced cost of

the raw material makes it attractive for applications where the requirements are less demanding or as an expensive extender for new rubber.

10.3 Cellular Rubber

10.3.1 Unlike rubber in its conventional state, cellular rubber has the characteristic of volume compressibility. This is due to a large number of more-or-less uniformly distributed air or gas pockets. The natural skin of cellular rubber is smooth in conformance with the surfaces of mold in contact with the rubber during vulcanization. Cellular rubber compounds are manufactured in sheet, strip, or special shapes. Man-made rubber compounds are available for application where oil resistance is required. Cellular rubber has considerably softer load-deflection characteristics than does conventional rubber. Problems in controlling the amount of voids creates wide variation in stiffness, so that the rational utilization of this material in engineering applications is difficult.

10.3.2 The cells of foam rubber are produced by blowing or whipping air through the liquid latex prior to vulcanization, resulting in an open-celled structure.

10.3.3 In sponge or cellular rubber, gasifying substances, such as sodium bicarbonate, are incorporated into the rubber mixture, which is then placed in a mold of a size larger than the rubber to be vulcanized. As these substances become gases, the vulcanized shape fills the cavity producing the porous structure with open, interconnected or closed cells.

10.3.4 Expanded rubbers have a closed-celled structure which is produced by subjecting the compound to a high pressure gas such as nitrogen or chloro-fluorocarbons, which causes a portion of the gas to dissolve in the rubber. When the gas pressure is lowered, the volume expands forming a closed-cell cellular structure.

10.3.5 Cellular rubber is manufactured in a number of grades reflecting polymer types and load-deflection characteristics. The American Society for Testing and Materials has established several standards on cellular rubbers manufactured from natural rubber, man-made rubbers, and some plastic materials that exhibit rubber-like properties in cellular form.

10.3.5.1 Latex foam rubber is described in ASTM Standard D1055, which defines eleven grades of cored product, ranging in load/deflection for 25 percent deflection from 5 to 90 lbf per 50 in.² (0.7 to 12.5 kPa per 325 cm²), and six uncured grades from 11 to 150 lbf per 50 in.² (1.5 to 20.8 kPa per 325 cm²). While originally established for natural rubber foam, several man-made polymers are produced to these same load/deflection criteria.

10.3.5.2 Sponge and expanded rubber are described in ASTM Standard D1056, which defines six grades of open-cell sponge, ranging in compression/deflection for 25 percent deflection from 0.5 to 24 psi (3.5 to 168 kPa), in three types of rubber polymers, nonoil resistant, low-swell oil resistant, and medium-swell oil resistant. Five grades of expanded, closed-cell general purpose rubber are defined in compress/deflection grades from 2 to 24 psi (14 to 168 kPa) compression/deflection for 25 percent deflection.

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10.3.5.3 Flexible cellular urethane foam is described in ASTM Standard D3490 covering five grades ranging from 20 to 90 lbf (89 to 400 N) to produce 25 percent deflection using a 50 in.² (325 cm²) pressure foot.

10.3.5.4 Flexible cellular materials made from vinyl chloride polymers and copolymers are described in ASTM Standard D1565 for open-cell foam, and in ASTM Standard D1667 for closed-cell sponge. While generally regarded as a "flexible plastic," polyvinyl chloride cellular products exhibit similar behavior to rubber foam and sponge materials, and are mentioned here for this reason only.

10.3.6 Representative load deflection curves indicating the stress-strain behavior of two cellular elastomers, polyester urethane, AU, foam, and rubber foam, are shown in Figure 140. Shown are two sequential loading curves and the first unloading curve which is indicative of the hysteresis effect. The knee of the polyurethane foam curves is typical for that material and suggests a change in cell structure at that point, about 6 to 10 percent deflection.

10.3.7 Some properties of elastomeric foams are given in Table XLIX. Since foams are compressible in contrast to unexpanded elastomers, the bonding of rigid plates does not effect their apparent modulus as described in 5.6.

10.3.8 Tolerances for thickness, width, and length of molded cellular rubber are shown in Tables XLVII and XLVIII.

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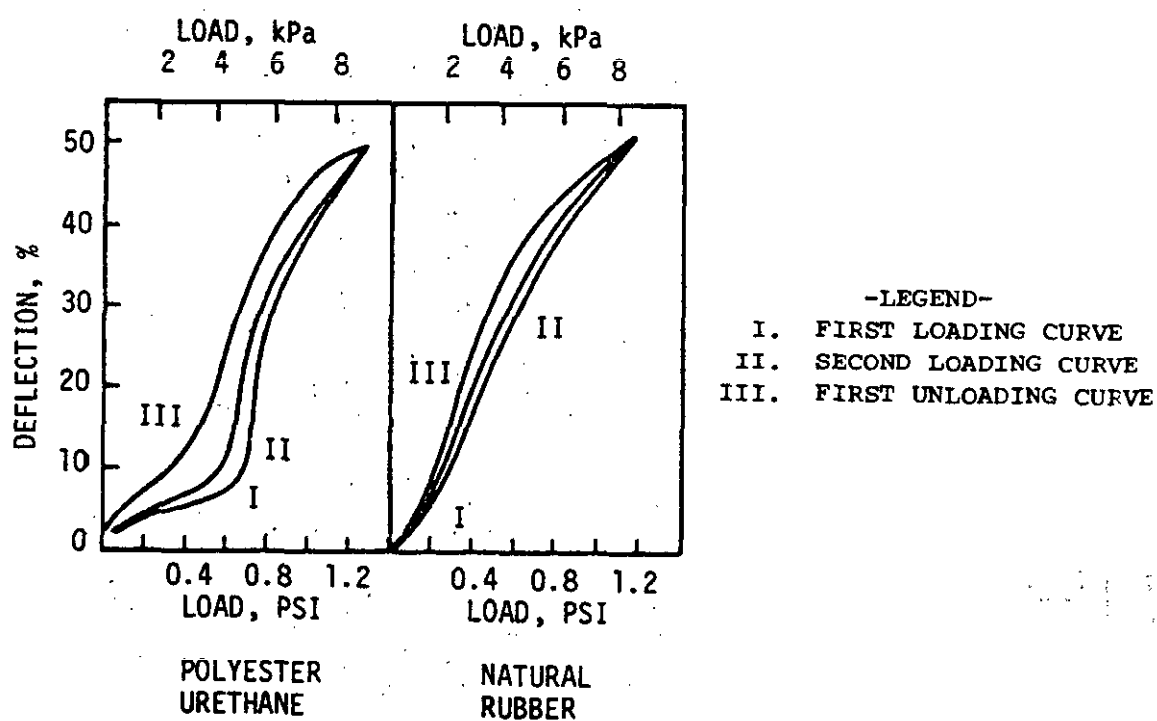


FIGURE 140. STRESS-STRAIN BEHAVIOR OF FOAMS OF
POLYESTER URETHANE AND NATURAL RUBBER (43)

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TABLE XLIX. PROPERTIES OF FOAM RUBBERS

Property	Acrylonitrile Butadiene	NBR	Chloroprene	CR	Polyurethane	Styrene Butadiene	SBR
Density, lb per cu ft	10 - 25		10 - 30		2.5	4.5	
Thermal Conductivity, Btu-ft/hr-ft ² -°F	0.021 - 0.025		0.021 - 0.029		0.02	0.018	
Tensile Strength, psi	40		20 - 100		12 - 20	80	
Maximum Recommended Service Temperature, °F	210		180		300	160	
Hardness Range of Soft to Firm, Durometer A	7 - 20		7 - 20		7 - 20	7 - 20	

TABLE XLIX-SI. PROPERTIES OF FOAM RUBBERS

Property	Acrylonitrile Butadiene	NBR	Chloroprene	CR	Polyurethane	Styrene Butadiene	SBR
Density, kg/m ³	160 - 400		160 - 480		40	72	
Thermal Conductivity, W/m-K	0.036 - 0.043		0.036 - 0.050		0.035	0.031	
Tensile Strength, MPa	0.28		0.14 - 0.69		0.08 - 0.14	0.55	
Maximum Recommended Service Temperature, °C	100		80		150	70	
Hardness Range of Soft to Firm, Durometer A	7 - 20		7 - 20		7 - 20	7 - 20	

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10.4 Molding of Foam Rubber Components

10.4.1 Molds used for foam rubber are of much lighter construction than those used for solid rubber parts, since the internal pressure is kept low. Any material which can stand the curing temperature, except copper or brass which would cause discoloration, can be used in foam rubber mold construction. Foaming is caused either chemically, through release of a gas from the composition, or mechanically, blowing air into the rubber. For vulcanization, the mold is generally placed in an open steam autoclave. Foam rubber is also available in extruded sections.

10.4.2 Cellular rubber products have found extensive application as a cushioning for both personnel and mechanical components. Primary applications are in seat cushions, back rests, molded door seals, and in the packaging of components for shipment; and damping pads for unloading sensitive materials. Because of their excellent insulating properties, they also provide thermal protection. By profiling the shape to provide cavities into which the displaced rubber can deform much softer stress-strain behavior can be achieved than that predicted by the basic characteristics of the material.

10.5 Room Temperature Vulcanizing Compounds (RTV)

10.5.1 Occasionally, an elastomeric component is made for experimental purposes, for prototypes, or short production runs. For such purposes, RTV compounds which cure at ordinary room temperature are well suited because vulcanizing equipment is not required and molds can be made economically from easily worked wood or aluminum. The materials must be mixed with a curing agent before they will set. Two materials developed for such purposes are the RTV silicones and the RTV polyurethanes. These materials do not develop the full mechanical properties offered by the conventionally vulcanized rubbers.

10.5.2 RTV polyurethanes have a temperature range from -40° to 300°F (-40° to 150°C); are resistant to dilute acids, most solvents, oils, aromatic fuels; and are impervious to sunlight and salt water. Resistance to oxidation is high. Polyurethane RTV can be molded to another piece of the same material without special equipment, forming a smooth joint with tensile strength equal to that of the material itself.

10.5.3 RTV silicones have a temperature range of -65° to 400°F (-55° to 200°C) and up to 600°F (315°C) for short time (40-hr.) exposure. For electrical applications, the properties in Table L are pertinent. Storage life of uncured material is 3 months maximum at 80°F (27°C), 6 months at 40°F (4°C). RTV silicones experience less than 0.2 percent shrinkage in molding and have good solvent and ozone resistance at elevated temperatures. Hardness is 50 + 15 Durometer A. Specific gravity is 1.5 to 2. They can be bonded to aluminum and stainless steel.

10.5.4 RTV compounds lend themselves readily to sealing between irregular surfaces after assembly, the potting of electrical components, and molds for plastic components (an existing plastic part can be utilized as a master). Gaskets in some difficult-to-seal applications have successfully been replaced with RTV "formed-in-place" gaskets.

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TABLE L. PROPERTIES OF RTV SILICONES PERTINENT TO ELECTRICAL APPLICATIONS

Property	Color		
	Off-White	Red	Red
Tensile Strength, psi	230	270	325
Elongation, %	250	380	400
Brittle Point, °F	-100	-100	-100
Dielectric Strength, V/mil	460	550	500
Dielectric Constant, 100 Hz	2.60	3.02	2.84
1,000,000 Hz	2.50	2.91	2.86
Dissipation Factor, 100 Hz	0.01	0.01	0.009
1,000,000 Hz	0.003	0.0042	0.004

TABLE L-SI. PROPERTIES OF RTV SILICONES PERTINENT TO ELECTRICAL APPLICATIONS

Property	Color		
	Off-White	Red	Red
Tensile Strength, MPa	1.58	1.86	2.24
Elongation, %	250	380	400
Brittle Point, °C	-75	-75	-75
Dielectric Strength, V/mm	18,110	21,650	19,685
Dielectric Constant, 100 Hz	2.60	3.02	2.84
1,000,000 Hz	2.50	2.91	2.86
Dissipation Factor, 100 Hz	0.01	0.01	0.009
1,000,000 Hz	0.003	0.0042	0.004

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10.6 Cost

10.6.1 Most interesting to engineers, always forced to face the hard facts of economics, is the cost picture. Published cost per pound (kg) of a polymer or a rubber compound can be misleading due to the wide variance in specific gravity of the materials and the wide diversity of shape, form, and complexity of parts. The cost comparisons shown in Tables LI and LI-SI are for rough evaluation of cost only, as production factors can vary the final costs considerably. These tables have been organized to compare basic costs per mass-volume, the product of cost per unit mass for equal volume. A pound-volume (kg-volume) represents the volume occupied by one pound (kg) of a rubber polymer adjusted to a specific gravity of 1.0, giving a cost comparison on an equal volume basis.

10.6.2 In both tables, the costs are approximate, based on Spring 1979 values. For more exact costs each supplier of these products should be consulted. For comparative purposes, a comparable high-quality-level rubber compound cost is shown in the fourth column; again, consult the supplier. The silicone rubber values represent the cost of a typical compound supplied by the manufacturer, rather than the cost of the polymer.

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TABLE LI. COSTS

RUBBER		POLYMER Cost/lb	POLYMER SPECIFIC GRAVITY	POLYMER Cost/lb-vol	TYPICAL COMPOUND Cost/lb-vol
Acrylonitrile- Butadiene	NBR	\$ 0.73	0.98	\$ 0.72	\$ 0.61
Acrylonitrile- Butadiene- Vinyl Blend	-	0.73	1.06	0.77	0.67
Bromobutyl	BIIR	0.63	0.93	0.59	0.52
Butyl	IIR	0.54	0.92	0.50	0.44
Butyl-High Temp	IIR	0.54	0.92	0.50	0.50
Carboxylic Elastomer	XNBR	0.79	1.00	0.79	0.65
Chlorobutyl	CIIR	0.58	0.92	0.53	0.49
Chloroprene	CR	0.81	1.23	1.00	0.78
Chlorosulfonated Polyethylene	CSM	1.05	1.10	1.16	1.01
Epichlorohydrin Copolymer	CO	1.64	1.27	2.08	1.92
Epichlorohydrin Homopolymer	ECO	1.67	1.36	2.27	2.00
Ethylene- Propylene Copolymer	EPM	0.60	0.86	0.52	0.42
Ethylene- Propylene- Diene Mod.	EPDM	0.65	0.85	0.55	0.40
Fluorocarbon	FKM	12.00	1.82	21.84	17.50
Fluorosilicone	FVMQ	25.00	1.42	35.50	35.50
Methyl Vinyl Silicone	VMQ	2.50	1.20	3.00	3.00

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TABLE LI. COSTS (Continued)

RUBBER		POLYMER Cost/lb	POLYMER SPECIFIC GRAVITY	POLYMER Cost/lb-vol	TYPICAL COMPOUND Cost/lb-vol
Methyl Vinyl Silicone Hi-Tensile	VMQ	\$ 5.00	1.20	\$ 6.00	\$ 6.00
Natural	NR	0.69	0.92	0.63	0.51
Perfluoro- Elastomer	FFKM	-	2.0 - 2.2	sold as parts only	20 to 50 times FKM
Phosphonitrilic Fluoroelastomer	FZ	45.00	1.85 (Compound 70 H)	sold as compound only	83.25
Polyacrylate	ACM	1.57 - 2.25	1.09	1.71 - 2.45	1.00 - 1.50
Polyisoprene	IR	0.66	0.91	0.60	0.51
Polyurethane	AU,EU	1.75	1.06	1.86	2.00
Propylene Oxide	GPO	1.47	1.01	1.48	1.06
Styrene Butadiene	SBR	0.45	0.93	0.42	0.34

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TABLE LI-SI. COSTS

RUBBER		POLYMER Cost/kg	POLYMER SPECIFIC GRAVITY	POLYMER Cost/kg-vol	TYPICAL COMPOUND Cost/kg-vol
Acrylonitrile- Butadiene	NBR	\$ 1.61	0.98	\$ 1.58	\$ 1.34
Acrylonitrile- Butadiene- Vinyl Blend	-	1.61	1.06	1.70	1.48
Bromobutyl	BIIR	1.39	0.93	1.30	1.15
Butyl	IIR	1.19	0.92	1.10	0.97
Butyl-High Temp	IIR	1.19	0.92	1.10	1.10
Carboxilic Elastomer	XNBR	1.74	1.00	1.74	1.43
Chlorobutyl	CIIR	1.28	0.92	1.17	1.08
Chloroprene	CR	1.78	1.23	2.20	1.72
Chlorosulfonated Polyethylene	CSM	2.31	1.10	2.56	2.22
Epichlorohydrin Copolymer	CC	3.61	1.27	4.58	4.23
Epichlorohydrin Homopolymer	ECO	3.68	1.36	5.00	4.40
Ethylene- Propylene	EPM	1.32	0.86	1.16	0.93
Ethylene- Propylene- Diene Mod.	EPDM	1.43	0.85	1.21	0.88
Fluorocarbon	FKM	26.43	1.82	48.10	38.55
Fluorosilicone	FVMQ	55.07	1.42	78.19	78.19
Methyl Vinyl Silicone	VMQ	5.51	1.20	6.60	6.60

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TABLE LI-SI. COSTS (Continued)

RUBBER		POLYMER Cost/lb	POLYMER SPECIFIC GRAVITY	POLYMER Cost/lb-vol	TYPICAL COMPOUND Cost/lb-vol
Methyl Vinyl Silicone Hi-Tensile	VMQ	\$11.01	1.20	\$13.22	\$13.22
Natural	NR	1.52	0.92	1.38	1.12
Perfluro- Elastomer	FFKM	-	2.0 - 2.2	sold as parts only	20 to 50 times FKM
Phosphonitrilic Fluoroelastomer	FZ	99.12	1.85 (Compound 70 H)	sold as compound only	183.37
Polyacrylate	ACM	3.46 - 4.96	1.09	3.77 - 5.40	2.20 - 3.30
Polyisoprene	IR	1.45	0.91	1.32	1.12
Polyurethane	AU,EU	3.85	1.06	4.10	4.40
Propylene Oxide	GPO	3.24	1.01	3.26	2.33
Styrene Butadiene	SBR	0.99	0.93	0.92	0.75

Custodians:

Army - MR
Navy - SH
Air Force - 99

Preparing activity:

Army - MR

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APPENDIX A

ACKNOWLEDGMENTS

This appendix includes cited literature references, coded from figure, table, and text citations by "(1)". Some figures and tables have not been changed from the previous issue of this handbook; others have been redrawn, modified by addition of SI (metric) units of measure or addition of new technical data, rearranged in order, or corrected, as necessary. Each figure or table is so coded in the listing below.

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Fig. 116

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- 69 Rubber Products Handbook, Molded, Extruded, Lathe Cut, Cellular, Rubber Manufacturers Association, 4th Edition Manuscript, 1981. (All replotted)

Table XLI

p. 278

Table XLI-SI

p. 278

Table XLII

p. 279

Table XLII-SI

p. 279

Table XLIII

p. 280

Table XLIII-SI

p. 280

Table XLIV

p. 282

Table XLV

p. 283

Table XLVI

p. 284

Table XLVII

p. 285

Table XLVIII

p. 286

- 70 Schalamach, A., Friction and Abrasion of Rubber, Vol. I (1957-58). (Reprinted by special permission from Elsevier Publ. Co., Amsterdam, Netherlands)

Fig. 34 (Modified)

p. 78

- 71 Schmulak, Ralph P. Transactions of the Society of Automotive Engineers, Vol. 68, 1960. (Reprinted by special permission)

Table III (Replotted, SI and additional rubbers added)

p. 15

- 72 Scientific Lubrication, September 1958. (Reprinted by special permission from Scientific Publications)

Fig. 128

p. 250

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- 73 Smith, Properties of Elastomers up to 550°F,
Rubber World, January 1959.

Table XVIII (Replotted)

p. 195

Table XVIII-SI (Derived from Table XVIII)

p. 195

- 74 Stevens, R. D., Specialty Elastomers, Seventeenth Annual Lecture Series, Co-sponsored by The Akron Rubber Group, Inc., and the University of Akron, Dept. of Special Programs, Contribution No. 374, Table 49.

Fig. 101 (Redrawn)

p. 184

- 75 Synthetic Rubber O-Rings, Carlotta, Prod. Eng., June 1951.

Fig. 126 (Modified, SI added)

p. 248

- 76 Thiokol Chemical Corporation, Trenton, New Jersey.
Private Communication.

Fig. 63 (SI added)

p. 119

- 77 Thomas, A.G., Factors Affecting the Strength of Rubbers,
J. Polym. Sci., Polymer Symposium No. 48, Fig. 4, P. 145,
1974.

Fig. 33 (Modified from Fig. 4)

p. 78

- 78 Transactions of the Institute of Marine Engineers, Vol. 65,
No. 10, October 1953. (Reprinted by special permission from
the Institute of Marine Engineers)

Fig. 2

p. 17

- 79 Veith, A. G., Measurement of Wet Cornering Traction of
Tires, Rubber Chem. and Technol., 44, p. 262, Table III,
1971. (Reprinted by permission from Rubber Chem Technol,
Journal of the Rubber Division, Am. Chem. Society)

Table XII (Replotted, inch/pound units added)

p. 76

- 80 WADC Report TR 56-272, Part V.

Fig. 129

p. 250

Fig. 130

p. 251

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- 81 What is KALREZ, Bulletin E-19829, E-09000, and Private Communication, E. I. duPont de Nemours & Co. (Inc.)

Table XXVI	(Data extracted from)	p. 185
Table XXVIII	(Data extracted from)	p. 195
Data Sheet No. 15	(Data extracted from)	p. C40

- 82 Williams, John A., Development of Elastomers Having Low Water Vapor Transmission Rate, Weapons Laboratory Report No. RE-TR-71-58, Rock Island Arsenal, 1971.

Table XXXII	p. 203
Table XXXIII	p. 204
Table XXXV	p. 206

- 83 Wilson, Grefis, and Montermoso, Effect of Swelling on Properties of Elastomers, Rubber World, October 1958.

Fig. 92	p. 178
Fig. 93 (Modified)	p. 179
Fig. 94 (Modified)	p. 179

- 84 Winspear, R. T. Vanderbilt Rubber Handbook, 1958. (Reprinted by special permission of R. T. Vanderbilt Co., Inc.)

Fig. 132	p. 255
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- 85 Wood, Lawrence A., Physical Constants of Different Rubbers, Rubber Chem. and Technol., 49, p. 189, 1976. (Reprinted by permission from Rubber Chem Technol, Journal of the Rubber Division, Am. Chem. Society)

Table VIII (Data extracted from)	p. 68
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- 86 Wood, Lawrence A. and Bekkedahl, Norman, Specific Heat of Natural Rubber and Other Elastomers Above the Glass Transition Temperature, Rubber Chem. and Technol, 41, p. 564, 1968.. (Reprinted by permission from Rubber Chem Technol, Journal of the Rubber Division, Am. Chem. Society)

Table X (Adapted from)	p. 70
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APPENDIX B

SPECIFICATIONS AND STANDARDS

1. Government. The following Government specifications and standards are typical of those available from governmental agencies. The titles are descriptive of the contents of the listed documents. There are additional specifications and standards for rubber products, listed in the Department of Defense Index of Specifications and Standards (DODISS) which are applicable to specific parts or components, such as belts, boots, gaskets, hoses, insulators, mounts, packings, and seals. See 1.7 and 2.2 for further discussion of specifications and standards.

1.1 Specifications.1.1.1 Federal

TT-S-735	Standard Test Fluids, Hydrocarbon
ZZ-R-710	Rubber Gasket Material, 35 Durometer Hardness
ZZ-R-765	Rubber, Silicone
ZZ-R-768	Rubber for Mountings, (Unbonded-Spool and Compression Types)

1.1.2 Military

MIL-R-900	Rubber Gasket Material, 45 Durometer Hardness
MIL-P-2693	Packing Material, Cold Storage Door Gasketing, Nonwatertight
MIL-R-2765	Rubber Sheet, Strip, Extruded and Molded Shapes, Synthetic, Oil Resistant
MIL-R-2778	Rubber Sheet, Solid, Unvulcanized, High Graphite, Gasket Use, Symbol 2352
MIL-S-2912	Synthetic Rubber Compound, Acid and Oil Resistant (For Lining Battery Compartments on Submarines)
MIL-D-2921	Disk, Rubber, Cellular, Hard
MIL-R-3065	Rubber, Fabricated Parts
MIL-C-3133	Cellular Elastomeric Materials, Molded or Fabricated Parts
MIL-R-3533	Rubber, Synthetic, Sheet, Strip, and Molded
MIL-R-5001	Rubber Cellular Sheet, Molded and Hand Built Shapes, Latex Foam
MIL-G-5514	Gland Design, Packings, Hydraulic, General Requirements for Rubber, Cellular, Chemically Blown
MIL-R-6130	Rubber, Cellular, Chemically Blown
MIL-R-6855	Rubber, Synthetic, Sheets, Strips, Molded or Extruded Shapes
MIL-R-7362	Rubber, Synthetic, Solid, Sheet, Strip and Fabricated Parts, Synthetic Oil Resistant
MIL-P-11520	Preservative Coating, Rubber, For Rubber Surfaces
MIL-G-12803	Gasket Material, Non-metallic

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1.2 (continued)

MIL-R-14328	Rubber Sheet, Synthetic, Medium Soft, General Purpose Gasket Material (For Extreme Climatic Conditions)
MIL-R-15624	Rubber Gasket Material, 50 Durometer Hardness (Maximum)
MIL-R-20092	Rubber Sheets and Molded Shapes, Cellular, Synthetic Open Cell (Foamed Latex)
MIL-S-21923	Synthetic Rubber Compound, Butadiene-Styrene Type, Ozone Resistant, for Low Temperature Service
MIL-G-22050	Gasket and Packing Material, Rubber, For Use with Polar Fluids, Steam, and Air at Moderately High Temperatures
MIL-R-25988	Rubber, Fluorosilicone Elastomer, Oil- and Fuel-Resistant, Sheets, Strips, Molded Parts, and Extruded Shapes
MIL-R-45036	Rubber, Hard (Ebonite), Natural or Synthetic, Sheet, Strip, Rod,, Tubing, and Molded Parts
MIL-R-46089	Rubber, Sponge, Silicone, Closed Cell
MIL-R-46846	Rubber, Synthetic, Heat Shrinkable
MIL-R-47013	Rubber, Butyl, Special Grade
MIL-R-47211	Rubber, Silicone, Room Temperature Curing
MIL-R-51209	Rubbers, Synthetic, For Chemical Agent Compounding
MIL-R-60671	Rubber, Chlorinated, Natural, Power
MIL-R-81828	Rubber, Chlorosulfonated Polyethylene Elastomer, Sheet and Molded Shapes, Ozone Resistant
MIL-R-82635	Rubber Sheet, Butyl, Unvulcanized
MIL-R-83248	Rubber, Fluorocarbon Elastomer, High Temperature, Fluid and Compression Set Resistant
MIL-R-83283	Rubber, Silicone, High Strength Cabin Pressure Seal Material Diaphragm Type
MIL-R-83285	Rubber, Ethylene-propylene, General Purpose
MIL-R-83322	Rubber, Carboxy-nitroso, Nitrogen Tetroxide (N ₂ O ₄) Resistant
MIL-R-83397	Rubber, Polyurethane, Sheets, Strips, Molded Parts, and Extruded Shapes
MIL-R-83412	Rubber, Ethylene-propylene, Hydrazine Resistant
MIL-R-83485	Rubber Fluorocarbon Elastomer, Improved Performance at Low Temperature
MIL-H-83797	Hose, Rubber, Lightweight, Medium Pressure, Fuel and Oil Resistant

1.2 Standards1.2.1 Federal.

FED-STD-00160	Rubber Products, Definitions and Terms for Visible Defects of
FED-STD-162	Hose, Rubber, Visual Inspection Guide for
FED-STD-601	Rubber, Sampling and Testing (Formerly FED. TEST METHOD STD.) (Replaced by ASTM Standards, See Table LII).

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1.2.2 Military.

MIL-STD-177	Rubber Products, Terms for Visible Defects of
MIL-STD-190	Identification Marking of Rubber Products
MIL-STD-289	Visual Inspection Guide For Rubber Sheet (Material)
MIL-STD-297	Visual Inspection Guide For Hard Rubber (Ebonite) Items
MIL-STD-298	Visual Inspection Guide For Rubber Extruded Goods
MIL-STD-413	Visual Inspection Guide for Elastomeric O-Rings
MIL-STD-417	Classification System and Tests for Solid Elastomeric Materials (Inactive for New Design, See SAE J200 or ASTM D2000)
MIL-STD-670	Classification System and Tests for Cellular Elastomeric Materials
MIL-STD-1573	Age Control of Age-sensitive Elastomeric Material

1.3 Military Handbooks .

MIL-HDBK-212	Gasket Materials (Nonmetallic)
MIL-HDBK-695	Rubber Products, Shelf Storage Life

2. Industry. The following industry specifications and standards represent a large body of documents prepared by technical societies and technical associations, as noted, to procure and test rubber and rubber containing materials. Technical society specifications and standards are available from the organizations noted below and are generally available for reference from libraries. They are also distributed among technical groups and using Federal agencies. Many industry specifications and standards have been approved for Government use and are so listed in the Department of Defense Index of Specifications and Standards (DODISS). For the latest revision of an individual document, consult the applicable industry index or the DODISS. See 1.7 and 2.2 for further discussion of specifications and standards.

2.1 Society of Automotive Engineers, Inc. 400 Commonwealth Drive, Warrendale, PA 15096

2.1.1 Aerospace Material Specifications (AMS)

AMS 2810	Identification and Packaging, Elastomeric Products
AMS 2817	Packaging and Identification, Preformed Packings
AMS 3020	Oil, Reference, for "L" Stock Rubber Testing
AMS 3021	Fluid, Reference, For Testing Diester (Polyol) Resistant Material
AMS 3022	Reference Fluid for Testing Hydrocarbon Fuel Resistant Materials, 10% Aromatic Content
AMS 3193	Silicone Rubber Sponge, Closed Cell, Medium, Extreme Low Temperature
AMS 3194	Silicone Rubber Sponge, Closed Cell, Firm, Extreme Low Temperature
AMS 3195	Silicone Rubber Sponge, Closed Cell, Medium
AMS 3196	Silicone Rubber Sponge, Closed Cell, Firm
AMS 3197	Sponge, Chloroprene, Rubber, Soft
AMS 3198	Sponge, Chloroprene, Rubber, Medium
AMS 3199	Sponge, Chloroprene, Rubber, Firm

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2.1.1 (continued)

AMS 3200	Nitrile Rubber, Petroleum Base Hydraulic Fluid Resistant, 55-65
AMS 3201	Nitrile Rubber, Dry Heat Resistant, 35-45
AMS 3202	Nitrile Rubber, Dry Heat Resistant, 55-65
AMS 3204	Synthetic Rubber, Low Temperature Resistant, 25-35
AMS 3205	Synthetic Rubber, Low Temperature Resistant, 45-55
AMS 3207	Chloroprene Rubber, Weather Resistant, 25-35
AMS 3208	Chloroprene Rubber, Weather Resistant, 45-55
AMS 3209	Chloroprene Rubber, Weather Resistant, 65-75
AMS 3210	Chloroprene Rubber, Electrical Resistant, 65-75
AMS 3212	Nitrile Rubber, Aromatic Fuel Resistant, 55-65
AMS 3213	Nitrile Rubber, Aromatic Fuel Resistant, 75-85
AMS 3214	Synthetic Rubber, Aromatic Fuel Resistant, 35-45
AMS 3215	Nitrile Rubber, Aromatic Fuel Resistant, 65-75
AMS 3216	Fluorocarbon Rubber, Fuel and Oil Resistant, 70-80
AMS 3220	Synthetic Rubber, General Purpose, Fluid Resistant, 55-65
AMS 3222	Synthetic Rubber, Hot Oil Resistant - High Swell, 45-55
AMS 3226	Nitrile Rubber, Hot Oil and Coolant Resistant - Low Swell, 45-55
AMS 3227	Nitrile Rubber, Hot Oil and Coolant Resistant - Low Swell, 55-65
AMS 3228	Nitrile Rubber, Hot Oil and Coolant Resistant - Low Swell, 65-75
AMS 3229	Nitrile Rubber, Hot Oil Resistant - Low Swell, 75-85
AMS 3232	Asbestos and Synthetic Rubber Sheet, Hot Oil Resistant
AMS 3237	Butyl Rubber, Phosphate Ester Resistant, 35-45
AMS 3238	Butyl Rubber, Phosphate Ester Resistant, 65-75
AMS 3239	Butyl Rubber, Phosphate Ester Resistant, 85-95
AMS 3240	Chloroprene Rubber, Weather Resistant, 35-45
AMS 3241	Chloroprene Rubber, Weather Resistant, 55-65
AMS 3242	Chloroprene Rubber, Weather Resistant, 75-85
AMS 3243	Chloroprene Rubber, Flame Resistant, 55-65
AMS 3244	Chloroprene Rubber, Flame Resistant, 65-75
AMS 3248	Synthetic Rubber, Phosphate Ester Resistant, Ethylene Propylene Type, 55-65
AMS 3249	Ethylene Propylene, Hydrazine-Base-Fluid Resistant, 75-85
AMS 3250	Synthetic Rubber and Cork Composition, General Purpose, Soft
AMS 3251	Synthetic Rubber and Cork Composition, General Purpose, Medium
AMS 3252	Synthetic Rubber and Cork Composition, General Purpose, Firm
AMS 3260	Synthetic Rubber, Ethylene Propylene Terpolymer, General Purpose, 45-55
AMS 3270	Chloroprene Rubber Sheet, Cotton Fabric Reinforced, Weather Resistant
AMS 3273	Chloroprene Rubber Sheet, Nylon Fabric Reinforced, Weather Resistant

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2.1.1 (continued)

AMS 3274	Nitrile Rubber Sheet, Nylon Fabric Reinforced, Fuel Resistant
AMS 3301	Silicone Rubber, General Purpose, 35-45
AMS 3302	Silicone Rubber, General Purpose, 45-55
AMS 3303	Silicone Rubber, General Purpose, 55-65
AMS 3304	Silicone Rubber, General Purpose, 65-75
AMS 3305	Silicone Rubber, General Purpose, 75-85
AMS 3307	Silicone Rubber, Low Compression Set, Non-Oil Resistant, 65-75
AMS 3315	Silicone Rubber Sheet, Glass Fabric Reinforced
AMS 3320	Silicone Rubber Sheet, Glass Fabric Reinforced, Heat and Weather Resistant, 60-80
AMS 3325	Fluorosilicone Rubber, Fuel and Oil Resistant, 55-65
AMS 3326	Fluorosilicone Rubber, Fuel and Oil Resistant, 50-65
AMS 3327	Fluorosilicone Rubber, High Temperature Fuel and Oil Resistant, 70-80
AMS 3332	Silicone Rubber, Extreme Low Temperature Resistant, 15-30
AMS 3334	Silicone Rubber, Extreme Low Temperature Resistant, 35-45
AMS 3335	Silicone Rubber, Extreme Low Temperature Resistant, 45-55
AMS 3336	Silicone Rubber, Extreme Low Temperature Resistant, 55-65
AMS 3337	Silicone Rubber, Extreme Low Temperature Resistant, 65-75
AMS 3338	Silicone Rubber, Extreme Low Temperature Resistant, 75-85
AMS 3345	Silicone Rubber, 1000 psi (6.9 MPa) Tensile Strength, 45-55
AMS 3346	Silicone Rubber, 1000 psi (6.9 MPa) Tensile Strength, 55-65
AMS 3347	Silicone Rubber, 1200 psi, High Modulus, 45-55
AMS 3348	Silicone Rubber, 1150 psi (7.93 MPa) Tensile Strength, High Resiliency, 25-35
AMS 3349	Silicone Rubber, 1100 psi (7.58 MPa) Tensile Strength, High Resiliency, 65-75
AMS 3356	Silicone Rubber, Lubricating Oil and Compression Set Resistant, Electrical Grade, 55-65
AMS 3357	Silicone Rubber, Lubricating Oil and Compression Set Resistant, 65-75
AMS 3358	Silicone Potting Compound, Elastomeric, Two Part, General Purpose, 80-180 Poise Viscosity
AMS 3359	Silicone Potting Compound, Elastomeric, Two Part, General Purpose, 200-400 Poise Viscosity
AMS 3360	Silicone Potting Compound, Elastomeric, Two Part, General Purpose, 200-600 Poise Viscosity
AMS 3361	Silicone Potting Compound, Elastomeric, Two Part, General Purpose, 150-400 Poise Viscosity
AMS 3362	Silicone Rubber Compound, Room Temperature Vulcanizing, 15,000 Centipoises Viscosity, 35-55

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2.1.1 (continued)

AMS 3363	Silicone Rubber Compound, Room Temperature Vulcanizing, 50,000 Centipoises Viscosity, 30-45
AMS 3364	Silicone Rubber Compound, Room Temperature Vulcanizing, 50,000 Centipoises Viscosity, Short Pot Life, 35-55
AMS 3365	Silicone Rubber Compound, Room Temperature Vulcanizing, 35,000 Centipoises Viscosity, Durometer, 40-55
AMS 3366	Silicone Rubber Compound, Room Temperature Vulcanizing, 55,000 Centipoises Viscosity, 55-70
AMS 3367	Silicone Rubber Compound, Room Temperature Vulcanizing, 1,200,000 Centipoises Viscosity, 55-70
AMS 3368	Silicone Resin - Elastomeric, Transparent, Elevated Temperature Cure
AMS 3369	Silicone Resin - Elastomeric, Opaque, Elevated Temperature Cure
AMS 3370	Silicone Resin - Elastomeric, Transparent, Room Temperature Cure
AMS 3371	Silicone Resin - Elastomeric, Opaque, Room Temperature Cure
AMS 3372	Silicone Resin - Elastomeric, High Tear Strength, Elevated Temperature Cure
AMS 3386	Hose, Synthetic Rubber, Aircraft Fueling, Textile Reinforced, Collapsing
AMS 3387	Hose, Synthetic Rubber, Aircraft Fueling, Textile Reinforced, Noncollapsing
AMS 3388	Hose, Synthetic Rubber, Aircraft Fueling, Single Wire Braid Reinforced, Noncollapsing
AMS 3389	Hose, Synthetic Rubber, Aircraft Fueling, Double Wire Braid Reinforced, Noncollapsing
AMS 7260	Rings, Packing, Synthetic Rubber, Fuel and Low Temperature Resistant, 70-80
AMS 7263	Rings, Sealing, Butyl Rubber, Phosphate Ester Hydraulic Fluid Resistant, 85-95
AMS 7266	Rings, Sealing, Fluorosilicone Rubber, General Purpose, High Temperature, Fuel and Oil Resistant, 65-75
AMS 7267	Rings, Sealing, Silicone Rubber, Heat Resistant Low Compression Set, 70-80
AMS 7268	Rings, Sealing, Silicone Rubber, Low Compression Set, Non-Oil Resistant, 65-75
AMS 7269	Rings, Sealing, Silicone Rubber, Low Outgassing, Space and Vacuum Service, 45-55
AMS 7270	Rings, Sealing, Synthetic Rubber, Fuel Resistant, 65-75
AMS 7271	Rings, Sealing, Synthetic Rubber, Fuel and Low Temperature Resistant, 60-70
AMS 7272	Rings, Sealing, Synthetic Rubber, Synthetic Lubricant Resistant, NBR Type, 65-75
AMS 7273	Rings, Sealing, Fluorosilicone Rubber, High Temperature Fuel and Oil Resistant, 70-80
AMS 7274	Rings, Sealing, Synthetic Rubber, Oil Resistant, 65-75
AMS 7276	Rings, Sealing, Fluorocarbon Rubber, High-Temperature-Fluid Resistant, Very-Low-Compression-Set, FKM Type, 70-80

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2.1.1 (continued)

AMS 7277	Rings, Sealing, Synthetic Rubber, Phosphate Ester Hydraulic Fluid Resistant, Butyl Type, 70-85
AMS 7278	Rings, Sealing, Fluorcarbon Rubber, High-Temperature-Fluid Resistant, 70-80
AMS 7279	Rings, Sealing, Fluorcarbon Rubber, High-Temperature-Fluid Resistant, 85-95
AMS 7280	Rings, Sealing, Fluorcarbon Rubber, High-Temperature-Fluid Resistant, Low Compression Set, FKM Type, 70-80

2.1.2 Aerospace Standards (AS)

AS 568	Aerospace Size Standard for O-Rings
AS 871	Manufacturing and Inspection Standards for Preformed Packings (O-Rings)

2.1.3 Aerospace Information Reports (AIR)

AIR 851	O-Ring Tension Testing Calculations
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2.2 American Society for Testing and Materials (ASTM), 1916 Race St., Philadelphia, PA 19103

ASTM D69	Friction Tape for General Use for Electrical Purposes
ASTM D119	Rubber Insulating Tape, Low Voltage
ASTM D296	Rubber-Lined Fire Hose with Woven Jacket
ASTM D297	Rubber Products - Chemical Analysis
ASTM D380	Rubber Hose, Testing
ASTM D395	Rubber Property - Compression Set Tests
ASTM D412	Rubber Properties in Tension
ASTM D413	Rubber Property - Adhesion to a Flexible Substrate
ASTM D429	Rubber Property - Adhesion to Rigid Substrates
ASTM D430	Rubber Deterioration - Dynamic Fatigue
ASTM D454	Rubber Deterioration by Heat and Air Pressure
ASTM D471	Rubber Property - Effect of Liquids
ASTM D518	Rubber Deterioration - Surface Cracking
ASTM D530	Hard Rubber Products, Testing
ASTM D531	Rubber Property - Pusey & Jones Indentation
ASTM D571	Testing Automotive Hydraulic Brake Hose
ASTM D572	Rubber Deterioration by Heat and Oxygen Pressure
ASTM D573	Rubber - Deterioration in an Air Oven
ASTM D575	Rubber Properties in Compression
ASTM D622	Rubber Hose for Automotive Air and Vacuum Brake System, Testing
ASTM D624	Rubber Property - Tear Resistance
ASTM D639	Battery Containers Made from Hard Rubber or Equivalent Materials, Testing
ASTM D746	Brittleness Temperature of Plastics and Elastomers by Impact
ASTM D750	Rubber Deterioration in Carbon-Arc or Weathering Apparatus, Recommended Practice
ASTM D751	Coated Fabrics, Testing

2.2 (continued)

ASTM D792	Specific Gravity and Density of Plastics by Displacement
ASTM D797	Rubber Property - Young's Modulus at Normal and Subnormal Temperatures
ASTM D814	Rubber Property - Vapor Transmission of Volatile Liquids
ASTM D832	Rubber Conditioning for Low Temperature Testing
ASTM D865	Rubber Deterioration by Heating in a Test Tube
ASTM D925	Rubber Property - Staining of Surfaces (Contact, Migration, and Diffusion)
ASTM D945	Rubber Properties in Compression or Shear
ASTM D991	Rubber Property - Volume Resistivity of Electrically Conductive and Antistatic Products
ASTM D1050	Rubber Insulating Line Hose
ASTM D1053	Rubber Property - Stiffening at Low Temperature Using a Torsional Wire Apparatus
ASTM D1055	Flexible Cellular Materials - Latex Foam
ASTM D1056	Flexible Cellular Materials - Sponge or Expanded Rubber
ASTM D1081	Rubber Property - Sealing Pressure
ASTM D1084	Viscosity of Adhesives
ASTM D1149	Rubber Deterioration - Surface Ozone Cracking in a Chamber (Flat Specimen)
ASTM D1171	Rubber Deterioration - Surface Ozone Cracking Outdoors or Chamber (Triangular Specimen)
ASTM D1229	Rubber Property - Compression Set at Low Temperature
ASTM D1329	Rubber Property - Retraction at Low Temperatures (TR Test)
ASTM D1349	Rubber - Standard Temperatures and Atmospheres for Testing and Conditioning, Recommended Practice (See 1.7.5)
ASTM D1390	Rubber Property - Stress Relaxation in Compression
ASTM D1414	Rubber O-Rings, Testing
ASTM D1415	Rubber Property - International Hardness
ASTM D1418	Rubber and Rubber Latices - Nomenclature, Recommended Practice for (See 1.4.4 and 1.7.5)
ASTM D1456	Rubber Property - Strain Testing at Constant Load
ASTM D1460	Rubber Property - Change in Length During Liquid Immersion
ASTM D1565	Flexible Cellular Materials - Vinyl Chloride Polymers and Copolymers (Open-Cell Foam)
ASTM D1566	Rubber, Definition of Terms Relating to
ASTM D1630	Rubber Property - Abrasion Resistance (NBS Abrader)
ASTM D1646	Rubber from Natural or Synthetic Sources - Viscosity and Vulcanization Characteristics (Mooney Viscometer)
ASTM D1667	Flexible Cellular Materials - Vinyl Chloride Polymers and Copolymers (Closed-Cell Sponge) (See 10.3.5.4)
ASTM D1765	Carbon Blacks Used in Rubber Products, Classification System for
ASTM D1780	Creep Tests of Metal-to-Metal Adhesives, Recommended Practice for Conducting
ASTM D1817	Rubber Chemicals - Density
ASTM D1871	Rubber Property - Adhesion to Single-Strand Wire

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2.2 (continued)

ASTM D2000	Rubber Products in Automotive Applications, Classification System for (See 1.7.5 and Table LIII)
ASTM D2137	Rubber Property - Brittleness Point of Flexible Polymers and Coated Fabrics
ASTM D2228	Rubber Property - Abrasion Resistance (Pico Abrader)
ASTM D2230	Rubber Property - Extrudability of Unvulcanized Compounds
ASTM D2231	Rubber Properties in Forced Vibration, Recommended Practice
ASTM D2240	Rubber Property - Durometer Hardness
ASTM D2632	Rubber Property - Resilience (Vertical Rebound)
ASTM D2663	Rubber Compounds - Dispersion of Carbon Black
ASTM D2707	Hard Rubber in Tension, Test
ASTM D2934	Rubber Seals - Compatibility with Service Fluids
ASTM D2990	Tensile, Compressive, and Flexural Creep and Creep Rupture of Plastics
ASTM D3137	Rubber Property - Hydrolytic Stability
ASTM D3157	Rubber from Natural Sources - Color, Testing
ASTM D3182	Rubber - Materials, Equipment, and Procedure for Mixing Standard Compounds and Preparing Standard Vulcanized Sheets, Recommended Practice (See 1.7.5)
ASTM D3183	Rubber - Preparation of Pieces for Test from Other Than Standard Vulcanized Sheets, Recommended Practice (See 1.7.5)
ASTM D3184	Rubber - Evaluation of NR (Natural Rubber) (See 1.7.5)
ASTM D3185	Rubber - Evaluation of SBR (Styrene-Butadiene Rubber) Including Mixtures with Oil (See 1.7.5)
ASTM D3186	Rubber Evaluation of SBR (Styrene-Butadiene Rubbers) Mixed with Carbon Black or Carbon Black and Oil (See 1.7.5)
ASTM D3187	Rubber - Evaluation of NBR (Acrylonitrile-Butadiene Rubbers) (See 1.7.5)
ASTM D3188	Rubber - Evaluation of IIR (Isobutene-Isoprene Rubbers) (See 1.7.5)
ASTM D3189	Rubber - Evaluation of Solution BR (Polybutadiene Rubber) (See 1.7.5)
ASTM D3190	Rubber - Evaluation of General Purpose CR (Chloroprene Rubbers)
ASTM D3191	Carbon Black in SBR (Styrene-Butadiene Rubber) - Recipe and Evaluation Procedures (See 1.7.5)
ASTM D3192	Carbon Black in NR (Natural Rubber) Recipe and Evaluation Procedures (See 1.7.5)
ASTM D3389	Coated Fabrics - Abrasion Resistance (Rotary Platform, Double-Head Abrader)
ASTM D3490	Flexible Cellular Materials - Bonded Urethane Foam
ASTM D3738	Rubber - Coated Cloth Hospital Sheeting
ASTM D3767	Rubber - Measurement of Dimensions
ASTM E96	Water Vapor Transmission of Materials in Sheet Form
ASTM F36	Compressibility and Recovery of Gasket Materials
ASTM F104	Classification System for Nonmetallic Gasket Materials
ASTM F607	Adhesion of Gasket Materials to Metal Surfaces, Test for

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2.2 (continued)

ASTM G21 Determining Resistance of Synthetic Polymeric Materials to Fungi, Recommended Practice

2.3 International Standardization Organization (ISO) Standards (available in USA from American National Standards Institute (ANSI), 1430 Broadway, New York, NY 10018). Standards cited in the text are shown.

R 34 Determination of Tear Strength of Vulcanized Natural and Synthetic Rubbers (Crescent Test Piece)

ISO 48 Vulcanized Rubbers - Determination of Hardness (Hardness between 30 and 85 IRHD)

ISO 815 Vulcanized Rubber - Determination of Compression Set Under Constant Deflection at Normal and High Temperatures

ISO 1382 Rubber, Vocabulary

ISO 1400 Vulcanized Rubbers of High Hardness (85 to 100 IHRD) - Determination of Hardness

ISO 1818 Vulcanized Rubbers of Low Hardness (10 to 35 IHRD) - Determination of Hardness

ISO 2285 Vulcanized Rubbers - Determination of Tension Set Under Constant Elongation at Normal and High Temperatures

ISO 3601/1 O-rings - Part 1: Inside Diameters, Cross-Sections, Tolerances, and Size Identification Code

DIS 4662 Rubber, Vulcanized - Rebound Resilience - Determination

DIS 4663 Rubber, Vulcanized - Low Temperature Dynamic Behavior (Torsion Pendulum) - Determination

DIS 4664 Rubber, Vulcanized - Dynamic Properties (Forced Sinusoidal Shear Strain), for Classification Use - Determination

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APPENDIX E

TABLE LII. FED-STD-601 REPLACEMENT BY ASTM STANDARDS

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 1000 - Preparation of Materials and Samples			
Separation of rubber from other materials	1011	D3183	
Buffing	1111	D3183	
Composite sample for chemical analysis	1211	D297	8
Group 2000 - Geometrical Measurements			
Geometrical measurements, general	2001	D3767	
Thickness, micrometer, flat foot	2011	D3767	8.1 (Method A)
Thickness, micrometer, spherical foot	2021	D3767	8.2 (Method A1)
Thickness, optical	2031	D3767	11 (Method D)
Thickness, magnetic gage	2041	D3767	
Width, narrow units	2111	D3767	11 (Method D)
Width, scale or tape	2121	D3767	10 (Method C)
Diameter, optical	2211	D3767	11 (Method D)
Diameter, scale or tape	2221	D3767	9&10 (Method B&C)
Diameter, circumference method	2231	D3767	9 (Method B)
Circumference, outer wire or thread	2311	D3767	
Circumference, diameter, optical	2321	D3767	11 (Method D)
Circumference, scale	2331	D3767	
Circumference, inner, mandrel	2341	D3767	12 (Method E)
Circumference, outer, tape	2351	D3767	10 (Method C)
Circumference, diameter, scale or tape	2361	D3767	10 (Method C)
Length	2411	D3767	10 (Method C)
Group 3000 - Rheological Tests			
Hardness, durometer	3021	D2240	
Calibration of durometer	3025	D2240	
Hardness, plastometer	3031	D531	
Hardness, ASTM hardness number	3041	None <u>1/</u>	
Hardness, indentometer	3051	None <u>1/</u>	
Plastic flow	3111	None <u>1/</u>	
Sealing pressure	3211	D1081	
Compression set	3311	D395	Method B
Compression and recovery	3321	None <u>1/</u>	
Compressibility and recovery, gasket materials	3331	F36	
Resilience, oscillograph	3411	D945	Part C
International hardness of vulcanized rubber	3061	D1415	

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 4000 - Tension Tests			
Tension Tests, general	4001	D412	
Tensile strength	4111	D412	
Calibration of tension testing machine	4116	D412	
Elongation, ultimate	4121	D412	
Tensile stress	4131	D412	
Strain	4141	D1456	
Tear resistance, crescent and angle	4211	D624	
Tear resistance, strip	4221	None <u>1/</u>	
Strength of splice	4311	None <u>1/</u>	
Tension set	4411	D412	
Group 5000 - Thermal Tests			
Conditioning of materials for low temper- ature testing, general	5111	D832	
Flexibility, bending beam, low- temperature	5211		
Brittleness, low-temperature, motor-driven apparatus	5311	D2137	
Brittleness, low-temperature, solenoid- actuated apparatus	5321	D2137	
Compression set, low-temperature	5411	D1229	
Hardness, durometer, low-temperature	5511	D2240	
Hardness, indentometer, low-temperature	5521	None <u>1/</u>	
Hardness, plastometer, low-temperature	5531	D746	
Stiffness, torsional, low-temperature	5611	D1053	
Hose, flexibility, low-temperature	5711	None <u>1/</u>	
Stiffness, torsional, low-temperature, gaseous medium	5612	D1053	
Group 6000 - Liquid Treatment Tests			
Liquid treatment tests, general	6001	D471	1-8
Tensile strength and elongation immed- iately after immersion in liquids	6111	D471	14
Tensile strength and elongation, liquid immersion, after recovery	6121	D471	14
Change in volume, liquid immersion	6211	D471	14
Change in thickness immediately after immersion in liquid	6231	D471	11

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 6000 (continued)			
Change in thickness, liquid immersion			
after recovery	6241	None <u>1</u> /	
Change in weight, liquid immersion . . .	6251	D471	9, 12, 13
Change in laminated materials, liquid			
immersion	6311		
Hose, change in adhesion, liquid			
immersion	6411	D380	
Hose, change in diameter, liquid exposure	6421	None <u>1</u> /	
Extraction, organic solvent	6511	D471	
Resistance to boiling water	6611	D471	
Extraction, boiling water	6621	D471	
Change in weight, water immersion . . .	6631	None <u>1</u> /	
Resistance to phenol	6711	D3738	9.7
Group 7000 - Accelerated Aging Tests			
Accelerated aging tests, general	7001		
Oxygen pressure test	7111	D572	
Air pressure test	7211	D454	
Air heat test, air heating medium . . .	7221	D573	
Air heat test, liquid heating medium . .	7231	D865	
Test-tube heat-aging test	7241	D865	
Resistance to light	7311	D750	
Sterilization steam	7411	D3738	9-10
Resistance to steam, digestion method . .	7421	D380	19
Resistance to steam, rack method	7431	D380	18
Group 8000 - Adhesion Tests			
Friction, general	8001	None <u>1</u> /	
Friction, machine method	8011	D413	
Friction, dead-weight method	8021	D413	
Adhesion, rubber to metal	8031	D429	Method B
Adhesion, coating to fabric	8211	D751	39-42
Adhesion, seams (seam strength)	8311	D751	50
Group 9000 - Electrical Tests			
Volume resistivity	9111	D991	
Electrical resistance of casters	9211	None <u>1</u> /	

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 10000 - Hydrostatic Tests			
Bursting strength, straight specimen	10011	D380	14.1
Bursting strength, curved specimen	10021	D380	14.2
Air leakage	10111	D622	5
Proof pressure	10211	D380	12,13,15.1,15.2
Hold test, straight specimen	10221	D380	
Hold test, curved specimen	10231	None <u>1/</u>	
Elongation or contraction	10311	D380	15.1,15.1.1,15.2
Expansion, circumference	10321	D380	15.1, 15.1.5
Twist	10331	D380	15.1, 15.1.2
Warp	10341	D380	15.1, 15.1.3
Rise	10351	D380	15.1, 15.1.4
Kink	10361	D380	15.1, 15.4
Coated fabrics, hydrostatic resistance	10511	D751	35-38
Group 11000 - Hard Rubber			
Hard rubber, general	11001	D530	
Tensile strength, hard rubber	11011	D2707	
Elongation, hard rubber	11021	D2707	
Flexural strength, hard rubber	11041	None <u>1/</u>	
Deflexion, hard rubber	11051	None <u>1/</u>	
Cold flow, hard rubber	11121	D530	
Impact resistance, hard rubber, general	11211	None <u>1/</u>	
Impact resistance, hard rubber, cantilever	11221	D530	4.1.5 &
		D256	Method A
Impact resistance, hard rubber, simple beam	11231	D530	4.1.5 &
		D256	Method B
Impact resistance, hard rubber, variable size ball	11241	D639	
Impact resistance, hard rubber, fixed size ball	11251	None <u>1/</u>	
Impact resistance, battery containers	11261	D639	35-40
Softening point, hard rubber	11311		
Bulge test, battery containers	11321	D639	41-47
Weight change, hard rubber in battery acid	11411	D639	19-26
Dimensional changes, hard rubber in battery acid	11421	D639	19-26
Penetration, acid, hard rubber	11431	None <u>1/</u>	
Voltage withstand, battery containers	11521	D639	54-59

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 12000 - Cellular Rubber			
Cellular rubber, general	12001	D1056	1-4
Geometrical measurements, cellular rubber, general	12005	D1056	15
Length, cellular rubber	12011	D1056	15
Width, cellular rubber	12021	D1056	15
Thickness, cellular rubber	12031	D1056	15
Diameter, cellular rubber	12041	D1056	15
Flexing endurance, cellular rubber	12111	D1055	24-26
Indentation, cellular rubber	12121	D1055	20-23
Compression set, cellular rubber	12131	D1055	17-19
Compression resistance, cellular rubber, oscillograph	12141	D945	
Compression deflection, cellular rubber	12151	D1056	18-21
Air heat test, cellular rubber	12211	D1055	15-16
Deflection at low temperature, cellular rubber	12221	D1055	27-30
Air pressure test, cellular rubber	12231	D1055	15-16
Oil immersion test, cellular rubber	12311	D1056	25-30
Water absorption, cellular rubber	12411	D1056	31-33
Group 13000 - Tape			
Tape, general	13001	D69	1-5
Breaking strength, friction tape	13011	D69	9.1
Tensile strength, insulating tape	13021	D119	16
Elongation, insulating tape	13031	D119	16
Adhesion, friction tape	13111	D69	19.1
Adhesion, insulating tape	13121	D69	19.2
Fusion, insulating tape	13131	D119	18
Tackiness, friction tape	13141	D69	20
Tackiness, insulating tape	13151	D119	19
Pinholes, friction tape	13211	D69	22
Dielectric strength, friction tape	13311	D69	23
Dielectric strength, insulating tape	13321	D119	17
Sulfure, friction tape	13411	None <u>1/</u>	
Group 14000 - Miscellaneous Physical Tests			
Specific gravity, hydrostatic	14011	D792	
Specific gravity, pycnometer	14021	D792	
Abrasion	14111	D1630	
Corrosion of metal by rubber	14211		

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 1500 - Chemical Analysis of Synthetic Rubber Compounds			
Chemical analysis of synthetic rubber			
compounds, general	15001	D297	5-1
Identification of synthetic rubber	15011	D297	Appendix X2
Polychloroprene rubber	15111	D297	53
Acrylonitrile rubber	15211	D297	54
Styrene rubber	15311	D297	56
Polysulfide rubber (thioplasts)	15411		
Polyisobutylene rubber	15511	D297	55
Carbon black	15811	D297	38
Phosphate plasticizer, fusion method	15821		
Phosphate plasticizer, sodium method	15825		
Group 16000 - Chemical Analysis of Rubber Compounds and Packings			
Chemical analysis of rubber compounds,			
general	16001	D297	
Preliminary examination of sample for			
test	16011	D297	9
Rubber content, general	16101	D297	51
Rubber content, indirect method	16111	D297	10 & 12
Rubber content, direct method	16121	D297	52
Sulfur, general	16201	D297	26 & 27
Sulfur, free	16211	D297	28
Sulfur in extract	16221	D297	29
Sulfur zinc - nitric acid method	16231	D297	Appendix X1
Sulfur, fusion method	16241	D297	31
Sulfur, inorganic, antimony present	16251	None <u>1/</u>	
Sulfur, inorganic, antimony absent	16261	D297	32
Extractable materials, general	16301		
Extract, total	16311	D297	20
Extract, acetone	16321	D297	18
Extract, chloroform	16331	D297	19
Extract, alcoholic potassium hydroxide	16341	D297	21
Extract acetone, unsaponifiable	16351	D297	22
Extract, waxy hydrocarbons	16361	D297	23
Extract, mineral oil	16371	D297	24
Fillers, general	16401	None <u>1/</u>	
Fillers, mineral oil	16411	None <u>1/</u>	
Fillers, paranitrotoluene-orthodichloro- benzene	16421	None <u>1/</u>	

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TABLE LII. (continued)

FEDERAL TEST METHOD STANDARD NO. 601		ASTM TEST METHOD	
TITLE	NUMBER	NUMBER	SECTION
Group 16000 (continued)			
Fillers, ash method	16431	D297	34
Free carbon	16511	D297	37
Glue	16521	D297	9.1.6 & 39
Fibrous materials, mineral oil	16531	None <u>1/</u>	
Fibrous materials, paranitrotoluene- orthodichlorobenzene	16535	None <u>1/</u>	
Chemical analysis of packings, general .	16601	None <u>1/</u>	
Packings, rubber compound and rubber hydrocarbon	16611	None <u>1/</u>	
Packings, lubricant, graphite absent . .	16621	None <u>1/</u>	
Packings, lubricant, graphite present . .	16625	None <u>1/</u>	
Packings, lubricant, organic solvent soluble, and graphite	16627	None <u>1/</u>	
Packings, metal and fibrous materials, mineral oil	16631	None <u>1/</u>	
Packings, metal and fibrous materials, paranitrotoluene-orthodichlorobenzene .	16635	None <u>1/</u>	
Packings, fillers in rubber compound, mineral oil	16641	None <u>1/</u>	
Packings, fillers in rubber compound, paranitrotoluene-orthodichlorobenzene .	16645	None <u>1/</u>	
Packing, asbestos	16651	None <u>1/</u>	
Packings, chemically combined water, asbestos	16661	None <u>1/</u>	

1/The word "None" indicates that the test method has been cancelled because it is no longer referenced in any Federal or Military specification, and there is no comparable ASTM test method.

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APPENDIX B

TABLE LIIT. OUTLINE OF SAE J200 - ASTM D2000
FOR NATURAL AND SYNTHETIC RUBBER COMPOUNDS (6)

Typical Line Call-out = 2BC515A14EO34F17 = Specification for Rubber

BASIC SUFFIX

Expands to: 2 B C 5 15 A 1 4 EO 3 4 F 1 7

-400°C (-400°F)

ASTM D2137, Method A, Para. 9.3.2,
3 minute exposure

LOW TEMPERATURE

-1000°C (2120°F)

ASTM D471, Oil No. 3, 70 hr

FLUID RESISTANCE

-1000°C (2120°F)

ASTM D573, 70 hr

HEAT RESISTANCE

TENSILE STRENGTH, 1500 psi, (10.5 MPa), minimum

HARDNESS, 50 Durometer A, +5

CLASS, indicates degree of oil resistance

TYPE, indicates temperature of basic heat aging

GRADE, indicates a particular set of suffix requirements, as
explained in ASTM D2000

BASIC REQUIREMENTS

TYPE designation establishes the temperature of basic heat aging. This shall produce not more than 30 percent tensile strength change, not more than 50 percent loss in elongation, and not more than +15 points hardness change. CLASS designation establishes the volume change in ASTM Oil No. 3 after 70 hours at the temperature of aging for that type, but not over 150°C (300°F).

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TABLE LIII. (continued)

TYPE BY TEMPERATURE

A	70°C (160°F)
B	100°C (212°F)
C	125°C (260°F)
D	150°C (300°F)
E	175°C (350°F)
F	200°C (400°F)
G	225°C (440°F)
H	250°C (480°F)
J	275°C (525°F)

CLASS BY VOLUME SWELL

A	no requirement
B	140 percent, maximum
C	120 percent, maximum
D	100 percent, maximum
E	80 percent, maximum
F	60 percent, maximum
G	40 percent, maximum
H	30 percent, maximum
J	20 percent, maximum
K	10 percent, maximum

SUFFIX REQUIREMENTS

The SUFFIX LETTER designates that an additional test is required for some property, as shown below. The FIRST SUFFIX NUMBER establishes the test method by ASTM standard number, shown in ASTM D2000. The SECOND SUFFIX NUMBER establishes the test temperature as shown below.

SUFFIX LETTERS

SECOND SUFFIX NUMBER

Letter	Test Required	Test Temperature
A	Heat Resistance	11 275°C (525°F)
B	Compression Set	10 250°C (480°F)
C	Ozone or Weather Resistance	9 225°C (440°F)
D	Compression-Deflection Resistance	8 200°C (400°F)
EA	Aqueous Fluid Resistance	7 175°C (350°F)
EF	Fluid Resistance (Other than aqueous or lubricants)	6 150°C (300°F)
EO	Oil (lubricants) Resistance	5 125°C (260°F)
F	Low Temperature Resistance	4 100°C (212°F)
G	Tear Resistance	3 70°C (160°F)
H	Flex Resistance	2 38°C (100°F)
J	Abrasion Resistance	1 23°C (75°F)
K	Adhesion	0 Ambient, outdoor
M	Flammability Resistance	1 23°C (75°F)
N	Impact Resistance	2 0°C (32°F)
P	Staining Resistance	3 -10°C (15°F)
R	Resilience	4 -18°C (-0°F)
Z	Any special requirement, which shall be specified in detail	5 -25°C (-13°F)
		6 -35°C (-30°F)
		7 -40°C (-40°F)
		8 -50°C (-60°F)
		9 -55°C (-67°F)
		10 -65°C (-85°F)
		11 -75°C (-100°F)
		12 -80°C (-110°F)

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APPENDIX C

DATA SHEETS

The following data sheets describe the polymers and their attributes, and lists pertinent physical and mechanical properties of typical rubber compounds of the most commonly used elastomers. It must not, however, be assumed that from a given compound optimum values can be obtained for all the properties. For this reason, it should be again emphasized that in the final compound selection the aid of a rubber technologist is most valuable, and that prototype testing is necessary to obtain definite values for the behavior of the rubber after the part has been formed. Part geometry must be considered, along with expected part performance, in selecting a rubber compound for a specific application in a specific atmosphere or environment.

The data sheets are not uniform with respect to the properties as the availability of data from the manufacturers of different rubbers was not standardized. The application of metric units required duplication of some tables and charts, which are identified as "SI", Systeme Internationale, and are based on standard conversion tables, such as ASTM Standard E380, "Standard for Metric Practice," and SAE Recommended Practice, SAE J916, "Rules for SAE Use of SI (Metric) Units."

The physical and mechanical properties shown herein have been extracted from manufacturer's technical literature. See Table I and the Trade Name Index in Appendix D for product identification and manufacturer's names.

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APPENDIX C

INDEX OF DATA SHEETS

DATA SHEET NUMBER	RUBBER POLYMER	PAGE
1	ACRYLONITRILE BUTADIENE, NBR	C-4
2	ACRYLONITRILE ISOPRENE, NIR.	C-9
3	BROMO BUTYL, BIIR.	C-11
4	BUTADIENE, BR.	C-13
5	BUTYL, IIR	C-15
6	CARBOXYLIC NITRILE BUTADIENE, XNBR	C-19
7	CHLORO BUTYL, CIIR	C-22
8	CHLOROPOLYETHYLENE, CM	C-24
9	CHLOROPRENE, CR.	C-26
10	CHLOROSULFONATED POLYETHYLENE, CSM	C-29
11	EPICHLORHYDRIN ELASTOMERS, CO & ECO.	C-31
12	ETHYLENE PROPYLENE COPOLYMER, EPM.	C-33
13	ETHYLENE PROPYLENE DIENE MODIFIED, EPDM.	C-34
14	FLUOROCARBON, CFM & FKM.	C-36
15	PERFLUOROELASTOMER, FFKM.	C-38
16	FLUOROSILICONE, FVMQ	C-40
17	NATURAL RUBBER, NR	C-43
18	PHOSPHONITRILIC FLUOROELASTOMER, FZ	C-46
19	POLYACRYLATE, ACM.	C-48
20	POLYURETHANE, AU & EU.	C-50
21	POLYSULFIDE, EOT	C-53
22	PROPYLENE OXIDE, GPC	C-56

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INDEX OF DATA SHEETS (continued)

DATA SHEET NUMBER	RUBBER POLYMER	PAGE
23	PYRIDINE BUTADIENE, PBR.	C-58
24	SILICONE RUBBER, PMQ, PVMQ, VMQ.	C-59
25	STYRENE BUTADIENE, SBR	C-63
26	STYRENE ISOPRENE, SIR.	C-66

MIL-HDBK-149E

DATA SHEET NO. 1

ASTM DESIGNATION

ACRYLONITRILE BUTADIENE

NBR

(NITRILE RUBBER)

General: Nitrile Rubber is a copolymer of butadiene and acrylonitrile. It is a special purpose rubber used commercially in molding, extruding, and calendering. The greater the acrylonitrile content, the greater the resistance to petroleum oils, fuels, and solvents. The greater the butadiene content, the greater the resilience and low temperature flexibility.

Notable Resistance Properties: Aliphatic hydrocarbons, hydroxyl compounds, and acids. Heat resistance in petroleum-based oils to 300°F (150°C), only fair ozone and weather resistance. The latter may be improved at sacrifice of oil resistance. Good resistance to petroleum solvents.

Notable Mechanical Properties: Good abrasion resistance. Good dry heat properties, 250°F (120°C).

Useful Temperature Range: -60° to +250°F (-50° to +120°C).

Electrical Properties: Not as good as other polymers.

Applications: Machinery parts, hose, gaskets, diaphragms, oil-well drilling equipment, shoesoles, solid tires, automotive equipment.

Identification: Burns readily - emits heavy smoke with very sickly, oily odor. Residue is a slightly tacky ash.

NOTES

Aging characteristics are poor without antioxidants especially in the presence of metallic peroxides and impurities. Evidence of deterioration is hardening and surface cracking. Nitrile rubber is, however, extremely responsive to protection by antioxidants. Cold flow is somewhat greater than for natural rubber.

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NBR

DATA SHEET NO. 1
(Continued)

PROPERTIES

Medium Acrylonitrile, General Purpose		
Properties	Hardness, Durometer A	
	50	60
Tensile Strength, psi	2500-3500	1800-4000
300% Modulus, psi	300-400	500-1700
Ultimate Elongation, %		
at Room Temperature	600-700	350-700
at 212°F		95-125
Compression Set, Method B, 70 hr at 212°F, %	15	20
Specific Gravity	1.2-1.3	1.2-1.3
Modulus of Elasticity, 0% Elongation, psi	300-550	400-550
Brittle Temperature, °F	-44 to -49	-20 to -30
Low Temperature Range for Rapid Stiffening, °F	+30 to -20	+30 to -10
Temperature at which Torsional Modulus is 10 times at 70°F, °F	-19 to -37	-10 to -37
Dynamic Modulus of Elasticity, psi		
at 122°F	277	310
at 212°F	145	207
Dynamic Fatigue Life*, Cycles x 10 ³	500-2500	3000
Resilience - Lupke Rebound, at 68°F, %	34-38	25-29
Coefficient of Thermal Expansion, in./in.-°F	10-12	
Dielectric Constant	15-20	15-20
Dielectric Strength, v/mil	230-280	250-280
Water Absorption, 70 hr at 212°F**, %	5-11	5-11
Power Factor		3.0-9.0
25% Reduction of Tensile Strength for 158°F Service, weeks	15-25	30
Vulcanization Shrinkage, %	2.0	1.7

Low Acrylonitrile, Low Temperature Nitrile Rubber					
Properties	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, psi	1230-1880	1270-2000	1250-2100	980-2270	1300-2600
30% Modulus, psi	400-450	860-960	330-400	280-300	
Ultimate Elongation, %	550-680	500-600	400-520	310-500	220-230
Compression Set,					
70 hr at 212°F, %	23-25	18-30	16-33	20-32	26-32
Tear Resistance, lb/in.	105	215	250	270	
Resilience, R.T., %	28-42	26-37	23-31	21-29	
Low Temperature					
Brittleness, °F	-40 to -80	-40 to -67	-40	-40	-40
Specific Gravity	1.10-1.13	1.19-1.30	1.15-1.40	1.20-1.46	1.23-1.40
Volume Change, 70 hr at 212°F in ASTM No. 3 Oil, %	23	29	33	36	23

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NBR

DATA SHEET NO. 1
(Continued)

PROPERTIES (Continued)

High Acrylonitrile, High Aromatic Solvent Resistance Nitrile Rubber					
Properties	Hardness, Durometer A				
	40	50	60	70	80
Low Temperature Brittleness, °F	-14 to -40	-7 to -37	-7 to -37	-3 to -34	-1 to -36
Volume Change, Iso-octane 168 hr at R.T., %	5-10	5-10	5-10	5-10	7-11

FOOTNOTES:

*Number of cycles after which flex-cracks become visible with pocket magnifier (approximately 10X).

**Immersion 1 week at 68°F.

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NBR

DATA SHEET NO. 1
(Continued)

PROPERTIES - SI

Medium Acrylonitrile, General Purpose		
Properties	Hardness, Durometer A	
	50	60
Tensile Strength, MPa	17.24-24.13	12.41-27.58
300% Modulus, MPa	2.07-2.76	3.45-11.72
Ultimate Elongation, %		
at Room Temperature	600-700	350-700
at 100°C		95-125
Compression Set, Method B, 70 hr at 100°C, %	15	20
Specific Gravity	1.2-1.3	1.2-1.3
Modulus of Elasticity, 0% Elongation, MPa	2.07-3.79	2.76-3.79
Brittle Temperature, °C	-42 to -45	-29 to -34
Low Temperature Range for Rapid Stiffening, °C	-1 to -29	-1 to -23
Temperature at which Torsional Modulus is 10 times at 20°C, °C	-23 to -38	-23 to -38
Dynamic Modulus of Elasticity, MPa		
at 50°C	1.91	2.14
at 100°C	1.00	1.43
Dynamic Fatigue Life*, Cycles x 10 ³	500-2500	3000
Resilience - Lupke Rebound, at 20°C, %	34-38	25-29
Coefficient of Thermal Expansion, mm/mm-°C	18-22	
Dielectric Constant	15-20	15-20
Dielectric Strength, N/mm	9055-11024	9843-11024
Water Absorption, 70 hr at 100°C**, %	5-11	5-11
Power Factor		3.0-9.0
25% Reduction of Tensile Strength for 70°C Service, weeks	15-25	30
Vulcanization Shrinkage, %	2.0	1.7

Low Acrylonitrile, Low Temperature Nitrile Rubber					
Properties	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, MPa	8.48-12.96	8.76-13.79	8.62-14.48	6.76-15.65	8.96-17.93
30% Modulus, MPa	2.76-3.10	5.93-6.62	2.28-2.76	1.93-2.07	
Ultimate Elongation, %	550-680	500-600	400-520	310-500	220-230
Compression Set, 70 hr at 100°C, %	23-25	18-30	16-33	20-32	26-32
Tear Resistance, N/m	18 375	22 575	26 250	28 350	
Resilience, R.T., %	28-42	26-37	23-31	21-29	
Low Temperature Brittleness, °C	-40 to -62	-40 to -55	-40	-40	-40
Specific Gravity	1.10-1.13	1.19-1.30	1.15-1.40	1.20-1.46	1.23-1.40
Volume Change, 70 hr at 100°C in ASTM No. 3 Oil, %	23	29	33	36	23

MIL-HDBK-149B

NBR

DATA SHEET NO. 1
(Continued)

PROPERTIES - SI (Continued)

Low Acrylonitrile, Low Temperature Nitrile Rubber					
Hardness, Durometer A					
Properties	40	50	60	70	80
Low Temperature Brittleness, °C	-25 to -40	-22 to -38	-22 to -38	-20 to -36	-17 to -38
Volume Change, Iso-octane 168 hr at R.T., %	5-10	5-10	5-10	5-10	7-11

FOOTNOTES:

*Number of cycles after which flex-cracks become visible with pocket magnifier (approximately 10X).

**Immersion 1 week at 20°C.

MIL-HDEK-149B

DATA SHEET NO. 2

ASTM DESIGNATION

ACRYLONITRILE-ISOPRENE

NIR

General: Acrylonitrile-Isoprene rubber has the same oil resistance as acrylonitrile butadiene rubber. It has advantages in some processing over acrylonitrile butadiene rubber in that it can be broken down somewhat like natural rubber and has a higher green strength. NIR is characterized with a high gum strength and a high permeability to gasses.

Notable Resistance Properties: Very good oil resistance. Does not "glaze" harden under friction as bad as NBR.

Notable Mechanical Properties: High gum tensile strength (over 3100 psi or over 21.37 MPa). Very good hot tear resistance. Highly impermeable to gasses. Can be made into compositions with hardnesses from very soft 20 Durometer A, to hard rubber (ebonite).

Useful Temperature

Range: -20° to +250°F (-30° to +120°C).

Applications: Oil resistant cut thread, oil resistant roll covering, oil resistant sponge, cork gasketting, ebonite and blends with NBR (for better cold resistance than NIR alone) and blends with polychloroprene. Used where better oil resistance of NBR is needed with better tack or gum tensile.

Unsuitable: For use with ketones such as acetone or aromatic solvents. Not suitable for low temperature applications, below -20°F (-30°C).

MIL-HDBK-149B

NIR

DATA SHEET NO. 2
(Continued)

POLYMER PROPERTIES

Composition	Acrylonitrile-isoprene polymer
Color	Light tan
Specific Gravity	0.98
Odor	None
Shelf Life	24 months

TYPICAL COMPOUND PROPERTIES

Hardness, Durometer A	62
Tensile Strength	3160 psi (21.79 MPa)
Elongation at Break	590%
Tear Strength	
Room Temperature	280 ppi (49,035 N/m)
250°F (120°C)	150 ppi (26,270 N/m)
Compression Set, ASTM D395, Method B	
70 hr at 212°F (100°C)	27%
Rebound Goodyear-Healey	40%
Low Temperature	
Brittle Point	-19°F (-28°C)
Aged in ASTM #3 oil, 70 hr at	
212°F (100°C)	
Hardness Change	+1
Tensile Change	-9%
Elongation Change	-17%
Volume Change	+7%
Aged in ASTM Fuel B, 70 hr at	
Room Temperature	
Hardness Change	-14
Tensile Strength Change	-45%
Elongation Change	-29%
Volume Change	+23%

MIL-HDEK-149B

DATA SHEET NO. 3

ASTM DESIGNATION

BROMO BUTYL RUBBER

BIIR

General: Bromo butyl is a butyl rubber which incorporates 1-3.5% bromine in the polymer. This accelerates curing (economy) and allows the modified butyl to be blended with other synthetics and natural rubber. Such mixtures reduce the gas permeability and increase the ozone resistance of natural rubber and SBR.

Notable Resistance Properties: Same as butyl, heat resistant to 350°F (175°C).

Notable Mechanical Properties: Retains tensile strength and elongation properties after heat aging; low compression set; low temperature flexibility; excellent dynamic properties; scorch safety; fast curing; long term intermediate heat stability, 350°F (175°C).

Electrical Properties: Equal or superior to unmodified butyl rubber.

Applications: Electrical insulators, curing bags, gaskets, tires.

Unsuitable: For direct immersion in petroleum fuels or lubricants.

Filler and Reinforcing Agents: HAF black compounds provide best ambient physical properties and their retention after aging; 50% part loading provides optimum results.

Useful Temperature Range: -50° to +350°F (-45° to 175°C).

MIL-HDEK-149E

BIIR

DATA SHEET NO. 3
(Continued)

PROPERTIES

Tensile Strength, R.T., psi	1150-2600
Tensile Strength 212°F, psi	500-1670
Elongation, R.T., %	230-940
Elongation 212°F, %	1000 + 210
300% modulus, R.T., psi	250-1000
300% modulus 212°F, psi	100-1420
Hardness, Durometer A	50-75
Tear Strength (crescent), R.T., lb/in.	90-360
Tear Strength (crescent), 212°F, lb/in.	37-300
Compression Set, %	
22 hr at 158°F	26-56
70 hr at 212°F	53-82
Ozone Resistance - 0.5 ppm	
100°F 50% extension, days to visible cracking	4-60

PROPERTIES - SI

Tensile Strength, R.T., MPa	7.65-17.93
Tensile Strength 100°C, MPa	3.45-11.51
Elongation, R.T., %	230-940
Elongation 100°C, %	1000 + 210
300% modulus, R.T., MPa	1.72-14.48
300% modulus 100°C, MPa	0.69-9.79
Hardness, Durometer A	50-75
Tear Strength (crescent), R.T., N/m	15,761-63,045
Tear Strength (crescent), 100°C, N/m	6,480-52,538
Compression Set, %	
22 hr at 70°C	26-56
70 hr at 100°C	53-82
Ozone Resistance - 0.5 ppm	
38°C 50% extension, days to visible cracking	4-60

MIL-HDBK-149B

DATA SHEET NO. 4

ASTM DESIGNATION

BUTADIENE RUBBER

BR

General: This rubber is used most frequently as a blend with other polymers. The biggest use is for tire tread. It does have other specialized uses.

Notable Resistance Properties: Low temperatures. It enhances the low temperature properties of the other polymers with which it is blended. When used alone it can be made to remain nonbrittle at -100°F (-73°C). Water resistant.

Notable Mechanical Properties: High resilience. High abrasion resistance. It improves the abrasion resistance and resilience of other polymers with which it is blended.

Applications: The major use of this is for tire tread rubber. Also used in low temperature gaskets, molded golf balls, molded products requiring low heat build-up and good abrasion resistance. High resilience mountings. Very low temperature applications.

Unsuitable: For items requiring oil resistance, unless as a minor component in a blend with an oil resistant polymer. For continuous use above 212°F (100°C).

MIL-HDEK-149B

BR

DATA SHEET NO. 4

(Continued)

POLYMER PROPERTIES

Specific Gravity	0.91
Appearance	Buff to Light Brown
Cis 4 Content	90% +

COMPOUND PROPERTIES

Tensile Strength, R.T., psi	1100 to 2900
(MPa)	(7.58 to 19.99)
Ultimate Elongation, %	300 to 600
Low Temperature Brittle Point, °F (°C)	Below -100 (-73)
Goodyear-Healy Rebound, %	About 60
National Bureau of Standards	
Abrasion Revolutions to 0.10 inch	
(2.5 mm) wear	151,300
Volume Change after 10 days in boiling water, %	1

MIL-HDBK-149B

DATA SHEET NO. 5

ASTM DESIGNATION

BUTYL RUBBER

IIR

General: Butyl rubber is a versatile general purpose nonoil resistant rubber, consisting mainly of two monomers, isobutylene and isoprene, which are made to react at the low temperature of -140°F (-96°C). Proportions of isoprene vary from low, for good ozone and chemical resistance, to higher proportions for achieving a tighter cure.

Notable Resistance Properties: Good resistance to ozone and weather, strong acids, salt solutions, alkalis, silicate and phosphate-type hydraulic fluids, alcohols, esters, ketones, animal and vegetable oils. Best rubber for resistance to dilute mineral acids.

Notable Mechanical Properties: Good abrasion resistance. Good tear resistance. Good heat resistance. High damping characteristics. Very low permeability to gases (8 times better than natural rubber). Only fair compression set characteristics.

Useful Temperature Range: -50° to +350°F (-45° to +175°C).

Electrical Properties: Excellent dielectric and insulation properties.

Applications: Inner tubes, hoses, shock absorbers, power cables, bellows, window seals, weather strip, conveyor belts, tractor tires, pedal pads, and engine components.

Unsuitable: For direct immersion in petroleum (mineral) fuels or lubricants. Not compatible with other polymers. Not flame resistant.

Fillers and Reinforcing Agents: Carbon blacks - increase modulus, radiation resistance, tear resistance. Talc - improved electrical characteristics.

Identification: Burns readily with tacky residue, melts; slow rebound characteristics.

MIL-HDBK-149B

IIR

DATA SHEET NO. 5
(continued)

NOTES

Butyl Rubber

Butyl rubber is suitable for extrusions, calendering, and molding.

High Temperature Butyl Rubber

Specially compounded butyl rubber which has been cured by resins or other specialized nonsulfur methods exhibits superior high temperature characteristics. It is manufactured in a hardness range of 45 to 80 Durometer A.

High temperature butyl compounds can be exposed to 350°F (175°C) for sustained periods, and compression set for these compounds at 300°F (150°C) is only one-fourth that of straight butyls, making the rubber suitable for gaskets and O-rings where compatible fluids are used.

High temperature butyl hose has withstood 450°F (230°C) superheated steam for one month. (No butyl will withstand wet steam.) It can withstand 50% nitric acid up to 150°F (66°C), and 350°F (175°C) dry heat for sustained periods.

Resistance to heat aging at 275°F (135°C) for 13 days:

Tensile strength - 50% of room temperature test value

Elongation - 55% of room temperature test value

Hardness - +12 Durometer A points from room temperature value

Compression set of high temperature butyl is superior to other butyls (see Figure 24).

MIL-HDBK-149B

IIR

DATA SHEET NO. 5
(continued)

PROPERTIES

General Purpose, Carbon Black Reinforced Butyl Rubber					
Properties	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, psi	1150-2000	590-3000	490-3200	480-3100	990-2400
Ultimate Elongation, %	680-840	400-810	400-800	260-750	190-620
100% Modulus, psi	60-250	90-260	80-500	140-810	320-1280
300% Modulus, psi	90-580	150-660	300-1000	300-1270	570-2080
Tear Strength, lb/in.	144-202	86-272	114-510	132-570	264-532
Specific Gravity	1.12-1.15	1.11-1.21	1.13-1.28	1.14-1.30	1.23-1.30
Compression Set					
22 hr at 158°F, %	13-19	11-21	14-22	14-30	13-32
Brittle Point, °F	-40 to -54				
Low Temperature Stiffness, °F	0 to +20				
Dynamic Fatigue Life, Cycles x 10 ³	>3000				
Linear Coefficient of Thermal Expansion, in./in.-°F	1.5-2.0 x 10 ⁻⁴				
Specific Heat	0.464				
Vulcanization Shrinkage, %	1.04	1.66	1.85		
Properties at 212°F	40	50	60	70	80
Tensile Strength, psi	110-580	110-610	260-1620	200-1420	250-1590
300% Modulus, psi	110-210	110-340	120-610	200-990	250-1270
Elongation, %	300-720	300-530	300-710	300-700	240-870
Tear Resistance, lb/in.	17-111	31-150	33-294	52-270	144-300
High-Damp Butyl Rubber					
Properties	Hardness, Durometer A				
	40	50	55		
Tensile Strength, psi	1580-1710	1820-2350	1610-1950		
Ultimate Elongation, %	695-780	630-680	580-635		
300% Modulus, psi	190-310	390-480	480-490		
Resilience at 77°F (Yerzley), %	43-61	54-63	54-58		
Relative Damping at 77°F (Yerzley), %	25-40	25-35	27-36		
Dynamic Modulus at 77°F (Yerzley), psi	545-650	680-800	918-950		
Resilience at 32°F (Yerzley), %	5.6-27	24-31	20-25		
Relative Damping at 32°F (Yerzley), %	61-63	57-64	62		
Dynamic Modulus at 32°F (Yerzley), psi	890-980	952-1149	1359		
Compression Set, Method B, 22 hr at 158°F, %	33-40	23-36	27-34		
Electrical Grade Butyl Rubber					
Hardness Range, Durometer A	55-75				
Tensile Strength, psi	975-1850				
300% Modulus, psi	275-700				
Ultimate Elongation, %	535-675				
Dielectric Constant	2.74 - 4.47				
Power Factor	0.37 - 5.0				
d.c. Resistivity, ohm-cm	2.0 - 6.1				
Dielectric Strength, v/mil	580-1400				
Water Absorption, 135°F - 19 days, mg/sq in.	10-28				

MIL-HDBK-149B

IIR

DATA SHEET NO. 5
(continued)

PROPERTIES - SI

General Purpose, Carbon Black Reinforced Butyl Rubber					
Properties	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, MPa	7.93-13.79	4.07-20.68	3.38-22.06	3.31-21.37	6.83-16.55
Ultimate Elongation, %	680-840	400-810	400-800	260-750	190-620
100% Modulus, MPa	0.41-1.72	0.62-1.79	0.55-3.45	0.97-5.58	2.21-8.83
300% Modulus, MPa	0.62-4.00	1.03-4.55	2.07-6.89	2.07-8.76	3.93-14.34
Tear Resistance at 25°C, N/m	25,218-35,376	15,061-47,634	19,964-89,315	23,117-99,822	46,233-93,167
Specific Gravity	1.12-1.15	1.11-1.21	1.13-1.28	1.14-1.30	1.23-1.30
Compression Set 22 hr at 70°C, %	13-19	11-21	14-22	14-30	13-32
Brittle Point, °C	-40 to -48				
Low Temperature Stiffness, °C	-18 to -7				
Dynamic Fatigue Life, Cycles x 10 ³	>3000				
Linear Coefficient of Thermal Expansion, mm/mm-°C	2.7-3.6 x 10 ⁻⁴				
Specific Heat	0.464				
Vulcanization Shrinkage, %	1.04	1.66	1.85		

Properties at 100°C	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, MPa	0.76-4.00	0.76-4.21	1.72-11.17	1.38-9.79	1.72-10.96
300% Modulus, MPa	0.76-1.45	0.76-2.34	0.83-4.21	1.38-6.83	1.72-8.76
Elongation, %	300-720	300-530	300-710	300-700	240-870
Tear Resistance, N/m	2,977-19,499	5,429-26,269	5,779-51,487	9,107-47,284	25,218-52,538

High-Damp Butyl Rubber			
Properties	Hardness, Durometer A		
	40	50	55
Tensile Strength, MPa	10.89-11.79	12.55-16.20	11.10-13.44
Ultimate Elongation, %	695-780	630-680	580-635
300% Modulus, MPa	1.91-2.14	2.69-3.31	3.31-3.38
Resilience at 25°C (Yerzley), %	43-61	54-63	54-58
Relative Damping at 25°C (Yerzley), %	25-40	25-35	27-36
Dynamic Modulus at 25°C (Yerzley), MPa	3.76-4.48	4.69-5.52	6.33-6.55
Resilience at 0°C (Yerzley), %	5.6 - 27	24-31	20-25
Relative Damping at 0°C (Yerzley), %	61-63	57-64	62
Dynamic Modulus at 0°C (Yerzley), MPa	6.14-6.76	6.56-7.92	9.37
Compression Set (Method B), 22 hr at 70°C, %	33-40	23-36	27-34

Electrical Grade Butyl Rubber	
Hardness Range, Durometer A	55-75
Tensile Strength, MPa	6.72-12.75
100% Modulus, MPa	1.90-4.83
Ultimate Elongation, %	535-675
Dielectric Constant	2.74-4.47
Power Factor	0.37 - 5.0
d.c. Resistivity, ohm-cm	2.0 - 6.1
Dielectric Strength, V/mm	22,834-55,118
Water Absorption, 57°C - 19 days, mg/cm ²	1.55-4.34

MIL-HDEK-149B

DATA SHEET NO. 6

ASTM DESIGNATION

CARBOXYLIC ACRYLONITRILE BUTADIENE

XNBR

General: Carboxylic elastomer is a medium high acrylonitrile copolymer which has been modified to include carboxylic groups in the polymer chain. It has high basic gum strength and high hardness without excessive loading. It is nonstaining.

Notable Resistance Properties: Maintains good physical properties at elevated temperatures, and has good low temperature characteristics, -50 to +400°F (-46° to 200°C).

Notable Mechanical Properties: Outstanding abrasion resistance, good tear resistance at 200°F (95°C).

Notable Chemical Properties: Good oil and fuel resistance.

Applications: Gaskets, O-rings, packings, pump parts, belting, solid tires, weather stripping, gun grips, and other mechanical goods.

Unsuitable: In aromatic solvents such as benzene, toluene, or xylene. In ketones such as acetone or methyl ethyl ketone.

MIL-HDBK-149B

XNBR

DATA SHEET NO. 6
(Continued)

POLYMER PROPERTIES

SPECIFIC GRAVITY 0.98

COMPOUND PROPERTIES

Properties	Hardness, Durometer A		
	60	70	80
Tensile Strength, psi	2340-2490	2640-2880	3680-3880
(MPa)	(16.13-17.17)	(18.20-19.86)	(25.37-26.75)
Ultimate Elongation, %	540-600	270-300	250-300
100% Modulus, psi	210-320	490-550	1350-1870
(MPa)	(1.45-2.21)	(3.38-3.79)	(9.31-12.89)
300% Modulus, psi	1300		2400-2500
(MPa)	(8.96)		(16.55-17.24)
Compression Set Method B, %			
70 hr at 212°F (100°C)	34	11	20
22 hr at 335°F (168°C)			70
Properties at 250°F (121°C)			
Tensile Strength, psi	980	840	2260
(MPa)	(6.76)	(5.79)	(15.58)
Ultimate Elongation, %	350	160	290
Tear Resistance, lb/in.	70	80	120
(N/m)	(12,259)	(14,010)	(21,015)
Ozone Resistance	No crack in 47 hr		
25 pphm at 120°F (49°C)	1 crack in 190 hr		
under 20% stretch			
Brittle Temperature, °F (°C)			-70 (-57)
T ₅ , °F (°C)			23 (-5)
Volume Change			
ASTM No. 1 Oil			
48 hr at 212°F (100°C)			0
ASTM No. 3 Oil			
48 hr at 212°F (100°C)	+25	+23	+17
70 hr at 350°F (177°C)	+25	+23	+14 - +21
Methyl Ethyl Ketone			
48 hr at room temperature			+143
Benzene			
48 hr at room temperature		+152	
Water			
70 hr at 212°F (100°C)	+7	+5	+12
Air Permeability (Standard			
Temperature and Pressure mils			
ft ³ /ft ² psi day x 10 ³)			0.273

MIL-HDEK-149B

XNBR

DATA SHEET NO. 6
(Continued)

COMPOUND PROPERTIES

Properties	Hardness, Durometer A		
	60	70	80
Dynamic Properties at 20%			
Deformation			
Static Modulus of Elasticity,			
psi			1520
(MPa)			(10.48)
Dynamic Modulus of Elasticity,			
psi			4480
(MPa)			(30.89)
Resilience, Yezley, %			67
Air Age 70 hr 250°F (121°C)			
Tensile Change, %	-58	-15	-19
Ultimate Elongation Change	-73	-50	-53
Hardness Change, Durometer			
A points	+3	+3	+3

MIL-HDBK-149B

DATA SHEET NO. 7

ASTM DESIGNATION

CHLORO BUTYL RUBBER

CIIR

General: Chloro butyl rubber is chemically similar to bromo butyl, and equally compatible with other rubbers. Because a wide variety of vulcanization methods are available, this rubber possesses a potentially wide range of physical properties expected of a good general purpose rubber, suitable for molding, extrusion, and calendering.

Notable Resistance Properties: Exceptional ozone resistance; can be blended with oil resistant rubbers such as nitrile and chloroprene. Good resistance to chemicals.

Notable Mechanical Properties: High tensile and tear strength with carbon black reinforcement, good adhesion to metals, low compression set, low gas permeability. Exhibits low temperature and damping properties similar to those of unmodified butyl rubber.

Useful Temperature Range: -50° to +350°F (-45° to +177°C)

Applications: Gaskets, couplings, ring seals, brake boots, vibration dampers, hoses, conveyor belts, liners and other products where only a small degree of oil resistance (splashing) is required.

Unsuitable: For direct immersion oil applications.

MIL-HDBK-149B

CIIR

DATA SHEET NO. 7
(Continued)

PROPERTIES

Properties	Hardness, Durometer A			
	40	50	60	70
Tensile Strength, psi	850-1450	1900-2750	1800-2600	1760-2630
Ultimate Elongation, %	870-895	645-745	480-715	420-620
300% Modulus, psi	250-280	720-790	875-1300	1000-1480
Tear Resistance, lb/in.	85-100	285-395	295-415	265-415
Compression Set				
70 hr at 212°F, %	Less than 20			
Abrasion Resistance	Slightly greater loss than conventional butyl			
Gas Permeability	Same as butyl			

PROPERTIES - SI

Properties	Hardness, Durometer A			
	40	50	60	70
Tensile Strength, MPa	5.86-10.00	13.10-18.96	12.41-17.93	12.13-18.13
Ultimate Elongation, %	870-895	645-745	480-715	420-620
300% Modulus, MPa	1.72-1.93	4.96-5.45	6.03-8.96	6.89-10.20
Tear Resistance, N/m	14,866-17,513	49,911-69,175	51,662-72,678	46,409-72,678
Compression Set				
70 hr at 100°C, %	Less than 20			
Abrasion Resistance	Slightly greater loss than conventional butyl			
Gas Permeability	Same as butyl			

MIL-HDEK-149B

DATA SHEET NO. 8

ASTM DESIGNATION

CHLOROPOLYETHYLENE

CM

General: Chlorinated polyethylene is the plastic, polyethylene, which has had chlorine inserted in varying amounts. When this is cross linked by peroxides or other means, it becomes a "rubber." It can easily be made in colors.

Notable Resistance Properties: Resists aromatic fuels in the same range as polychloroprene (in lower chlorine level polymers) to the same range as acrylonitrile butadiene (in higher chlorine level polymers). Resists strong mineral acids, strong bases, alcohols, organic acids including concentrated acetic acid. Weather and ozone resistant.

Notable Mechanical Properties: Hardness, Durometer A, can be varied from 55 to 95. Tensile to 3000 psi (20.68 MPa). Flexible down to -60°F (-50°C). Low resilience. Flame resilience. Good flex resistance.

Electrical Properties: Good insulator. Can be used directly over copper and can be adhered to metal conductors.

Useful Temperature Range: -60° to 350°F (-50° to 175°C)

Applications: Wire and cable covers and insulation, chemical hose.

Unsuitable: For high resilience applications.

MIL-HDBK-149B

CM

DATA SHEET NO. 8
(Continued)

POLYMER PROPERTIES

Specific Gravity	1.16 to 1.25 (Depending on chlorine content)
Form	Powder

TYPICAL PROPERTIES

Tensile	2700 psi (18.62 MPa)
Ultimate Elongation	350%
Hardness, Durometer A	70
Volume Change	
168 hr at 300°F (150°C)	+50 to +65%
Flammability	
Limiting oxygen	29% O ₂
Index ASTM D2863	
After Aging 168 hr	
in Air at 300°F (150°C)	
Tensile	2400 psi (16.55 MPa)
Ultimate elongation	300%

MIL-HCBK-149B

DATA SHEET NC. 9

ASTM DESIGNATION

CHLOROPRENE RUBBER

CR

- General:** Polychloroprene (Neoprene) is a general purpose synthetic made by emulsion polymerizing chloroprene. Chloroprene itself is prepared by reacting hydrogen chloride with monovinyl acetylene and acetylene.
- Notable Resistance Properties:** Good resistance to acids, gasoline, lube oils, animal and vegetable oils, oxidation, ozone, and weather.
- Notable Mechanical Properties:** High tensile strength, tear resistance, abrasion resistance, adhesion to metal and fabric, good rebound characteristics.
- Useful Temperature Range:** -50° to +250°F (-45° to +120°C)
- Electrical Properties:** Fair insulation, good dielectric strength.
- Applications:** Transmission belts, hoses, industrial tires, seals, O-rings, coating for metals, mechanical goods, and paint additive.
- Unsuitable:** For use where water absorption is a factor.
- Identification:** Does not support combustion, emits sharp odor while burning, residue after burning is black ash.

NOTES

Creep under compressive loads occurs mostly within the first 10 days. After that additional creep is slight.

For conservative design, compression-deflection of chloroprene should not exceed 15% uncompressed thickness, and shear deformation should be limited to 50% of the thickness.

Crystallization occurs in the 0° to 30°F (-18° to -1°C) temperature range, as evidenced by considerable stiffening. This does not imply a brittleness. Crystallization is reversible when the rubber is warmed.

Brittleness occurs at low temperature, -40° to -60°F (-40° to -50°C).

MIL-HDBK-149E

CR

DATA SHEET NO. 9
(Continued)

PROPERTIES

Properties	Hardness, Durometer A		
	40	50	65
Tensile Strength, psi	2800	2200	3400
300% Modulus, psi	150-300		650-1100
Ultimate Elongation, %	850-1050	750	550-750
Compression Set, Method B			
22 hr at 158°F, %	14	20	11
Specific Gravity	1.24	1.37	1.40
Modulus of Elasticity,			
0% Elongation, psi	200-400		400-700
Brittle Temperature, °F	-38 to -45	-38 to -45	-38 to -45
Low Temperature Range for Rapid			
Stiffening, °F	+10 to -20	+10 to -20	+10 to -20
Comparative Resilience (Natural			
Rubber = 100%), %			
at room temperature		95	
at 200°F		110	
Dynamic Modulus of Elasticity			
at 32°F	138	495	554
at 122°F	76	143	212
at 212°F	69	119	175
Dynamic Fatigue Life*,			
Cycles x 10 ³	3000		3000
Shear Modulus at 30%			
Deflection, psi			
158°F	64	97	120
70°F	65	107	127
0°F	69	145	153
Thermal Conductivity,			
Btu-in./ft ² ·h·°F	0.08	0.08	0.08
Coefficient of Thermal Expansion,			
in./in.-°F	11-12 x 10 ⁻⁵	11-12 x 10 ⁻⁵	11-12 x 10 ⁻⁵
Dielectric Strength, v/mil	350		350
Water Absorption, 168 hr at			
68°F, %	1.6 - 2.2		0.5 - 1.4
Power Factor, %	18 - 20	18 - 20	18 - 20
Time to 25% Red. of Tensile			
Strength for 158° Service,			
Weeks	25		20
Specific Heat	0.4 - 0.5		0.4 - 0.5
Vulcanization Shrinkage, %	2	1.6	1.7

FOOTNOTES: *Number of cycles after which flex-cracks become visible with pocket magnifier, approximately 10X.

MIL-HDBK-149B

CR

DATA SHEET NO. 9
(Continued)

PROPERTIES - SI

Properties	Hardness, Durometer A		
	40	50	65
Tensile Strength, MPa	19.30	15.17	23.44
300% Modulus, MPa	1.03-2.07		4.48-7.58
Ultimate Elongation, %	850-1050	750	550-750
Compression Set; Method B			
22 hr at 70°C, %	14	20	11
Specific Gravity	1.24	1.37	1.40
Modulus of Elasticity,			
0% Elongation, MPa	1.38-2.76		2.76-4.83
Brittle Temperature, °C	-39 to -43	-39 to -43	-39 to -43
Low Temperature Range for Rapid			
Stiffening, °C	-12 to -29	-12 to -29	-12 to -29
Comparative Resilience (Natural			
Rubber = 100%), %			
at room temperature		95	
at 95°C		110	
Dynamic Modulus of Elasticity			
at 0°C	138	495	554
at 50°C	76	143	212
at 100°C	69	119	175
Dynamic Fatigue Life*,			
Cycles x 10 ³	3000		3000
Shear Modulus at 30%			
Deflection, MPa			
70°C	0.44	0.67	0.87
21°C	0.45	0.74	0.88
-18°C	0.48	1.00	1.05
Thermal Conductivity, W/m·K	0.012	0.012	0.012
Coefficient of Thermal Expansion,			
mm/mm-°C	20-22 x 10 ⁻⁵	20-22 x 10 ⁻⁵	20-22 x 10 ⁻⁵
Dielectric Strength, v/mm	13,780		13,780
Water Absorption, 168 hr at			
20°C, %	1.6 - 2.2		0.5 - 1.4
Power Factor, %	18 - 20	18 - 20	18 - 20
Time to 25% Red. of Tensile			
Strength for 70°C Service,			
Weeks	25		20
Specific Heat	0.4 - 0.5		0.4 - 0.5
Vulcanization Shrinkage, %	2	1.6	1.7

FOOTNOTES: *Number of cycles after which flex-cracks become visible with pocket magnifier, approximately 10X.

MIL-HDEK-149B

DATA SHEET NO 10

ASTM DESIGNATION
CHLOROSULFONATED POLYETHYLENE

CSM

- General:** Chlorosulfonated polyethylene is produced by reacting polyethylene with chlorine and sulfur dioxide. Although it is difficult to process and somewhat higher in cost, it represents a special purpose elastomer with better high temperature characteristics and higher strength than chloroprene. It is producible in light colors.
- Notable Resistance Properties:** Outstanding resistance to acids and strong oxidizing agents such as sulfuric acid and hydrogen peroxide. Good resistance to nonoxidizing chemicals such as ethylene glycol, alkalis. Fair resistance to mineral oils, unaffected by ozone even at elevated temperature. Very good weather resistance and does not support combustion.
- Notable Mechanical Properties:** Relatively high strength, minimum practical hardness without plasticizers is 60-65 Durometer A, high modulus and stiffness, excellent abrasion resistance, good flex-life, suitable for molding, extrusion, or calendering.
- Useful Temperature Range:** -50° to +350°F (-45° to +175°C).
- Electrical Properties:** Intermediate between chloroprene and natural rubber.
- Applications:** Spark plug boots, weather stripping, tank lining, tarpaulin liners, colored mechanical goods for intermediate temperature service, acid hose, and gaskets for ozone generators.
- Unsuitable:** For direct contact with gasoline and aromatic solvents.

NOTES

White or colored chlorosulfonated polyethylene rubber has lower tensile strength, greater elongation, suffers more compression set and exhibits less heat resistance.

Black compounds are classified in accordance with their application:

Water and Chemical Resistance
Maximum Heat Resistance
Lead Free Systems

MIL-HDBK-149B

CSM

DATA SHEET NO. 10
(Continued)

PROPERTIES

Black Compounds

Hardness, Durometer A	60-95
Specific Gravity	1.12 - 1.28
Tensile Strength, psi	2400-3800
Elongation, %	200-560
Tensile Strength at 250°F, psi	500
Elongation at 250°F, %	60
100% Modulus, psi	500-1500
200% Modulus, psi	1800-3400
Stiffening Point, E = 10,000 psi, °F	-40
Brittleness Temperature, °F	-70
Compression Set (B), 70 hr at 158°F, %	Below 20 (after post cure)
D-C Resistivity, ohm-cm	10 ¹³
Power Factor, %	2 - 3
Dielectric Strength, v/mil	400-750
Volume Increase in ASTM No. 3 Oil, 70 hr at 212°F, %	60-65
Volume Increase in Water, 28 days at 158°F (Water Resistant Compound) %	2.5 - 4.4
Tear Resistance, lb/in.	145-260

PROPERTIES - SI

Black Compounds

Hardness, Durometer A	60-95
Specific Gravity	1.12 - 1.28
Tensile Strength, MPa	16.55 - 26.20
Elongation, %	200-560
Tensile Strength at 120°C, MPa	3.45
Elongation at 120°C, %	60
100% Modulus, MPa	3.45 - 10.34
200% Modulus, MPa	12.41 - 23.44
Stiffening Point, E = 68.95 MPa, °C	-40
Brittleness Temperature, °C	-57
Compression Set (B), 70 hr at 70°C, %	Below 20 (after post cure)
D-C Resistivity, ohm-cm	10 ¹³
Power Factor, %	2 - 3
Dielectric Strength, v/mm	15,748 - 29,528
Volume Increase in ASTM No. 3 Oil, 70 hr at 100°C, %	60-65
Volume Increase in Water, 28 days at 70°C (Water Resistant Compound), %	2.5 - 4.4
Tear Resistance, N/m	25,393 - 45,533

MIL-HDBK-149B

DATA SHEET NO. 11

ASTM DESIGNATION

EPICHLOROHYDRIN ELASTOMERS

CO, ECO

- General:** These elastomers can be homopolymers or copolymers of epichlorohydrin and ethylene oxide. The oil resistance is similar to nitrile; the low temperature flexibility, high temperature aging, and ozone resistance are superior to nitrile.
- Notable Resistance Properties:** Will stand 40 days at 257°F (125°C) or 10 days at 300°F (150°C) and still be quite usable. Very ozone resistant. Very resistant to oils; good resistance to perchloroethylene.
- Useful Temperature Range:** -25° to +300°F (-30° to +150°C).
- Applications:** Bushings, boots, tubing and other mechanical rubber parts which must resist heat up to 250°F (120°C) continuously and to 300°F (150°C) occasionally; also these same parts if exposed to oil and ozone. Since this is a higher priced polymer, its use is mainly where chloroprene or nitrile is not satisfactory.
- Unsuitable:** For exposure to aromatic solvents, such as toluene, concentrated acid at high temperatures, or liquid organic esters.

MIL-HDEK-149B

CO, ECO

DATA SHEET NO. 11
(Continued)

POLYMER PROPERTIES

Properties	Homopolymer, CO	Copolymer, CO
Specific Gravity	1.36	1.27
Chlorine Content, %	38.4	24

TYPICAL COMPOUND PROPERTIES

Properties	Homopolymer	Copolymer
Tensile, psi (MPa)	2300 (15.86)	1400-2200 (9.65-15.16)
Elongation, %	260	200-700
Hardness, Durometer A	60-80	50-70
Compression Set, ASTM D395, Method B 70 hr at 212°F (100°C), %	20	20
Aged in Air, 70 hr at 300°F (150°C)		
Tensile Change, %	-4	-21
Elongation Change, %	-24	-32
Hardness Change, Durometer A Points	+7	+3
ASTM No. 1 Oil, 70 hr at 300°F (150°C)		
Tensile Change, %	+11	+8
Elongation Change, %	-14	-28
Hardness Change, Durometer A Points	+7	+4
Volume Change, %	0	0
ASTM No. 3 Oil, 70 hr at 300°F (150°C)		
Tensile Change, %	0	-1
Elongation Change, %	-14	-20
Hardness Change, Durometer A Points	-3	-3
Volume Change, %	+4.5	+7.5
Volume Increase, ASTM Fuel B, 70 hr at room temperature, %	14	19
Brittle Point, ASTM D746, °F (°C)	-0 (-18)	-36 (-30)

MIL-HDEK-149B

DATA SHEET NO. 12

ASTM DESIGNATION

ETHYLENE PROPYLENE COPOLYMER

EPM

General: This is a man-made rubber, a linear copolymer of propylene and ethylene made by polymerizing alphaolefins with stereo-specific (Ziegler) catalysts. It is competitive with natural as well as with other man-made rubbers.

Notable Resistance Properties: Good resistance to acids, alkalis, hydraulic fluids, ozone, aging, and sunlight. Exhibits very poor flame resistance.

Notable Mechanical Properties: Compares well with natural rubber, SER, and has good low temperature mechanical properties, low hysteresis.

Electrical Properties: Good insulator.

Applications: General purpose, tires.

Unsuitable: For exposure to aromatic hydrocarbons and aliphatic hydrocarbons.

PROPERTIES

Specific Gravity, Base Polymer	0.85	
Specific Heat, Btu/lb-°F (J/kgK)	0.52 (0.002)	
Thermal Conductivity, Btu·in./ft ² ·hr·°F (W/m·K)	0.21 (0.030)	
Coefficient of Thermal Linear Expansion, in./in.-°F (mm/mm-°C)	10 ⁻⁴ (1.8 x 10 ⁻⁴)	
Hardness, Durometer A	60-65	
Tensile Strength, psi (MPa)	2400-4000 (16.55-27.58)	
Elongation at Break, %	400-500	
Dielectric Strength, v/mil (V/mm)	700 (27,560)	
Dielectric Constant	2.2	
Rebound, %		
at 60°F (16°C)	75-87	Similar to Natural Rubber
at 32°F (0°C)	83	Similar to Natural Rubber
at 15°F (-9°C)	4	Similar to Natural Rubber
at -40°F (-40°C)	20	Similar to Natural Rubber

MIL-HDEK-149B

DATA SHEET NO. 13

ASTM DESIGNATION

ETHYLENE PROPYLENE DIENE MODIFIED

EPDM

- General:** This is a copolymer of ethylene and propylene which has been modified by dienes to permit sulfur vulcanization. It is competitive in cost to natural rubber and styrene butadiene rubber.
- Notable Resistance Properties:** Nearly impervious to ozone, oxygen, and weathering. Very good resistance to heat and to steam up to 250 psi (1.72 MPa). Resistant to ethyl alcohol, aniline, 10% sodium hydroxide, and Skydrol 500. Resistant to ketones such as acetone or methyl ethyl ketone.
- Notable Mechanical Properties:** Resilience can be varied from 30% to 80% (ASTM Standard D945). Low temperature properties similar to natural rubber and, by special compounding, can be made flexible to -80°F (-62°C).
- Electrical Properties:** Good insulator. Dielectric constant of 3, power factor of less than 1% when suitably compounded. Suitable for high voltage application in wet or dry environments.
- Applications:** Weatherstrips, washing machine parts, engine and equipment mountings. Steam gaskets. Electrical wire and cable insulation and jacketing. Door seals. In tire sidewalls (as a blend). Sponge. Diaphragms and gaskets.
- Unsuitable:** For alipatic and aromatic hydrocarbons (petroleum oils and solvents). It is not flame resistant.

NOTES

Good abrasion resistance.

Retains 60 percent of tensile and elongation at 212°F (100°C).

Compression set is low and can be made very low by peroxide vulcanization at a sacrifice in other properties.

An easy processing material on conventional rubber making equipment.

MIL-HDEK-149B

EPDM

DATA SHEET NO. 13
(continued)

PROPERTIES

Tensile Strength	2000 to 3000 (13.79 to 20.68)
Elongation, %	300 to 500
Hardness, Durometer A	50 to 80
Tear, Die B, lb/in. (N/m)	200 to 260 (35,025 to 45,533)
Compression Set, ASTM D395, Method B, %	
22 hr at 158°F (70°C), %	16 - 35 (Lower with peroxide cure)
22 hr at 212°F (100°C), %	50 - 75 (Lower with peroxide cure)
After aging in air 70 hr at 212°F (100°C)	
Tensile Strength Change, %	0 to -10
Elongation Change, %	-5 to -30
Hardness Change, Durometer A points	+2 to +5

MIL-HDEK-149B

DATA SHEET NO. 14

ASTM DESIGNATION
CFM; FKM

FLUOROCARBON ELASTOMERS

- General:** Fluoro elastomers are synthetic polymers which contain varying proportions of fluorine (some more than 60 percent by weight), which imparts a high degree of resistance to many hot solvents and oils while retaining a fair proportion of room temperature strength characteristics after prolonged heat aging. Fabrication is easily accomplished by conventional equipment. Off-white color of gum elastomer makes possible a wide color choice.
- Notable Resistance Properties:** High temperature. Resistance to hot oils, lubricants, acids, low swelling in aliphatic and aromatic oils and chemicals, ozone and weathering. Does not support combustion.
- Notable Mechanical Properties:** Low temperature properties only moderately good. Rapid stiffening occurs at subzero temperatures but brittleness is not reached until -40°F (-40°C), low compression set.
- Electrical Properties:** Comparable with those of electrical grade vinyl chloride polymers, best for low-voltage, low-frequency where chemical and thermal stability are required.
- Applications:** Seals, diaphragms, insulators in applications where high temperature, plus fluids are encountered and where high cost is no deterrent.
- Unsuitable:** For exposure to organic acids, ketones, aldehydes, and highly polar fluids.

NOTES

Typical retention of strength after 28 days at 450°F (230°C) is 80 percent.

Typical retention of elongation after 28 days at 450°F (230°C) is 70 percent.

Typical retention of strength after 16 hours at 600°F (315°C) is 40 percent.

Typical retention of elongation after 16 hours at 600°F (315°C) is 45 percent.

400-hr exposure to ozone concentration of 10,000 ppm causes no cracking.

Low water absorption results in excellent retention of electrical properties.

Kel-F * is the only fluoroelastomer which should be considered for red fuming nitric acid (swells 64%).

Kel-F may be suitable for use with JP4 fuel up to 400°F (200°C) if it is not long term continuous exposure.

This section may be bent slowly without cracking at temperatures as low as -50°F (-46°C).

Good molding and extrusion characteristics with moderate care to prevent air entrapment since viscosity is higher than that of conventional polymers.

MIL-HDBK-149E

CFM; FKM

DATA SHEET NC. 14
(continued)

Time to brittleness:

Temperature, °F (°C)	400 (200)	450 (230)	500 (260)	550 (290)	600 (315)
Hours	2400	1000	100	72	24

*All references to Kel-F refer to the elastomer (copolymer of chlorotrifluoroethylene and vinylidene fluoride) not Kel-F plastic.

PROPERTIES

Fluorocarbon Elastomers, Fluorel - Viton - Kel-F

Properties	Hardness, Durometer A		
	60	70	80
Tensile Strength, psi (MPa)	2000 (13.79)	2000 (13.79)	2000 (13.79)
100% Modulus, psi (MPa)	300 (2.07)	500 (3.45)	700 (4.83)
Ultimate Elongation, %	200	175	150
Compression Set, 22 hr			
400°F (200°C) Method B, %	50	50	50
Specific Gravity	1.97	1.97	1.97
Brittle Temperature, °F (°C)	-30 to -50 (-34 to -46)	-30 to -50 (-34 to -46)	-30 to -40 (-34 to -40)
Tear Resistance, lb/in. (N/m)		180 (31 523)	
Abrasion Resistance, mg loss		31	
Dielectric Strength, v/mil (V/mm)		500-630 (19,685 - 24,803)	
Dielectric Constant		11.4	
Thermal Conductivity Btu-in./ft ² .h.°F(W/m.K)		1.25 (0.18)	
Oil Resistance, Swell in ASTM No. 3 Oil 7 days at 300°F (150°C), %		3-4	
Low Temperature Stiffness, T ₁₀ , Gehman Test, °F (°C)		+3 (-16)	
Mold Shrinkage, %		2	
Water Absorption at 77°F (25°C) (Kel-F), mg/in. ² (mg/cm ²)		3.5 (0.54)	

MIL-HDBK-149B

DATA SHEET NO. 15

ASTM DESIGNATION

PERFLUOROELASTOMER (81)

FFKM

- General:** Perfluorelastomers offer resistance to a very wide range of polar and nonpolar solvents and chemicals and also to high temperatures. The finished part cost ranges from 20 to 50 times that of a comparable part in a fluoroelastomer (FKM).
- Notable Resistance Properties:** Chemical and solvent resistance along with resistance to temperatures of 550°F (290°C) and occasional temperatures as high as 650°F (345°C).
- Notable Mechanical Properties:** Will retain 40% of sealing force after exposure to 400°F (200°C) in air for over 3 years.
- Useful Temperature Range:** 10° to 600°F (-12° to +315°C).
- Electrical Properties:** Excellent
 D. C. resistivity 5×10^{17} ohm-cm
 Dielectric Constant at 1000 Hz 4.9
 Dielectric Strength 450 volts/mil (17,717 V/mm)
- Applications:** O-rings for chemical seals and high temperature seals are the biggest application. Also used as "V" ring seals and gaskets. Before specifying a special part, the fabricator should be contacted to determine if it is possible to make the part.
- Caution:** Perfluoroelastomer parts should not be exposed to molten or gaseous alkali metals such as sodium, because a highly exothermic reaction could occur. Fully halogenated Freons (F11 , F12) and uranium hexafluoride cause considerable swell. At elevated temperatures above 212°F (100°C), service life can be significantly reduced in fluids containing high concentrations of some diamines, nitric acid, and basic phenol. KALREZ should be tested for suitability. Special compounds have been designated for use in oxidizing media and weak organic acids.

NOTES

Parts can easily be obtained from DuPont de Nemours & Co., as they are both polymer manufacturer and part fabricator.

MIL-HDBK-149E

FEKM

DATA SHEET NO. 15
(continued)

PROPERTIES

Specific Gravity	2.0 - 2.2
Linear Coefficient of Thermal Expansion	1.3×10^{-4} °F (2.3×10^{-4} °C)
Specific Heat (approximate), J/g	1
Hardness, Durometer A	70-90
Tensile Strength, psi (MPa)	1900-3000 (13-21)
Elongation at Break, %	120-160
Compression Set, ASTM D395 Method E,	
70 hr at 400°F (200°C), %	35 - 60
70 hr at 550°F (290°C), %	35 - 70
Brittle Point, °F (°C)	-40 (-40)

MIL-HDEK-149B

DATA SHEET NO. 16

ASTM DESIGNATION

FLUOROSILICONE RUBBER

FVMQ

- General:** The fluorosilicone rubbers combine a wide operating range with superior fluid and chemical resistance. They are used to their best advantage in applications where a high degree of resistance to petroleum and diester oils is required at low temperatures, and at temperatures up to 450°F (230°C).
- Notable Resistance Properties:** Excellent resistance to petroleum fuels, gasoline and JP4, diester oils, and ozone.
- Notable Mechanical Properties:** Excellent thermal stability and flexibility to -90°F (-70°C). Poor elastic recovery after long term exposure below -40°F (-40°C). Poor stress-strain properties, high mold shrinkage.
- Useful Temperature Range:** -90° to +450°F (-70° to +230°C).
- Applications:** Parts requiring combined low temperature flexibility and fuel resistance, such as fuel pump diaphragm, O-rings, seals, and brake cups.
- Unsuitable:** For exposure to unsymmetrical dimethyl hydrazine and red fuming nitric acids. Also, for general mechanical applications because of low strength and high cost.

NOTES

Extrusion of fluorosilicones is somewhat more difficult than other silicone rubbers. Most fluorosilicones can be calendered.

Toxic vapors are produced above 530°F (275°C).

Where occasional contact with solvents (splashing) is experienced, cost and manufacturing considerations make fluorosilicone-silicone blends appropriate.

MIL-HDEK-149B

FVMQ

DATA SHEET NO. 16
(continued)

PROPERTIES

Properties	Hardness, Durometer A				
	35	50	65	70	80
Tensile Strength, psi	700-900	800-1000	800-1000	800-1000	800-1000
Ultimate Elongation, %	250	200	200	150	140
Compression Set, 22 hr at 300°F, %	15	20	20	30	55
Compression Set, 70 hr at -40°F, %		60 (compares favorably with low temperature nitrile compression set)			
Tear Strength, lb/in.	50	70	80	100	110
Specific Gravity	1.38	1.40	1.41	1.44	1.46
Swell in ASTM No. 3 Oil, 77 hr at 300°F, %	+3	+5	+5	+3	+4
Swell in ASTM Reference Fuel B, 24 hr at 77°F, %	+30	+24	+17	+23	+23
Brittle Temperature, °F	-90	-90	-90	-90	-90
Stiffening Temperature, E = 10,000 psi, °F			-78		
Electric Strength, v/mil			350		
Dielectric Constant			6-7		
Volume Resistivity, ohm-cm			10 ¹³		
Volume Resistivity after 96 hr at 96% RH, 72°F			1.5 x 10 ¹²		
Linear Mold Shrinkage, %			4		

MIL-HDBK-149B

FVMQ

DATA SHEET NC. 16
(continued)

PROPERTIES -SI

Properties	Hardness, Durometer A				
	35	50	65	70	80
Tensile Strength, MPa	4.82-6.21	5.52-6.89	5.52-6.89	5.52-6.89	5.52-6.89
Ultimate Elongation, %	250	200	200	150	140
Compression Set, 22 hr at 150°C, %	15	20	20	30	55
Compression Set, 70 hr at -40°C, %		60 (compares favorably with low temperature nitrile compression set)			
Tear Strength, N/m	8,756	12,259	14,010	17,513	19,264
Specific Gravity	1.38	1.40	1.41	1.44	1.46
Swell in ASTM No. 3 Oil, 77 hr at 149°C, %	+3	+5	+5	+3	+4
Swell in ASTM Reference Fuel B, 24 hr at 250°C, %	+30	+24	+17	+23	+23
Brittle Temperature, °C	-68	-68	-68	-68	-68
Stiffening Temperature, 68.95 MPa, °C			-61		
Electric Strength, V/mm			13,780		
Dielectric Constant			6-7		
Volume Resistivity, ohm-cm			10 ¹³		
Volume Resistivity after 96 hr at 96% hr, 22°C			1.5 x 10 ¹²		
Linear Mold Shrinkage, %			4		

PROPERTIES - HIGH STRENGTH FLUOROSILICONE RUBBER

Properties	Hardness, Durometer A		
	50	60	70
Tensile Strength, psi (MPa)	1300 (8.96)	800-1000 (5.52-6.89)	800-1250 (5.52-8.62)
Elongation, %	450	200	150-210
Compression Set, %			
22 hr at 300°F (150°C)	15	20	15
70 hr at -40°F (-40°C)	no data	20	no data
Tear Strength, lb/in. (N/m)	155 (27,145)	80 (14,010)	90 (15,761)
Specific Gravity	1.46	1.45	1.49
Swell, %			
ASTM No. 3 Oil	+3	+4	+4
ASTM Reference Fuel B	+22	+21	+1

MIL-HDEK-149B

DATA SHEET NO. 17

ASTM DESIGNATION

NATURAL RUBBER

NR

General: Natural rubber, the latex of certain trees, must be blended with fillers and reinforcing agents to bring out maximum physical properties. The raw material, as the compounder obtains it is either smoked sheet or pale crepe. The latter is used for delicate colors and nonstaining applications. The light color products possess much lower mechanical properties than carbon black filled compounds.

Notable Resistance Properties: Resistant to strong and weak alkali, ketones, esters, and alcohol. Resistant to hydrochloric acid in all concentrations. Poor ozone and weather resistance.

Notable Mechanical Properties: Superior to most synthetics in strength, elongation, abrasion resistance, rebound, tear resistance, electrical resistance, and compression set.

Useful Temperature Range: -60° to +200°F (-50° to +95°C)

Electrical Properties: Superior to man-made rubbers.

Unsuitable: With gasoline, oil, copper, manganese or alloys containing manganese or copper. Concentrated sulfuric, nitric, and chromic acids.

Identification: Burns readily - emits odor, leaves tacky residue.

NOTES

Isoprene Rubber (Natural, Hevea) and Isoprene Rubber (Natural, Parthenium (Guayule)) are essentially equivalent.

Polyisoprene (man-made) is essentially the same as natural rubber..

MIL-HDBK-149B

NR

DATA SHEET NO. 17
(continued)

PROPERTIES

Properties	40	Hardness, Durometer A	
		50	60
	No Filler		25% Carbon black 10% Plasticizer
Tensile Strength, psi	3000-4000	3650	3000-4000
300% Modulus, psi	150-350		(700-1300
Ultimate Elongation, %	675-850	640	550-650
Compression Set, ASTM D395, Method B 22 hr at 158°F, %	15	12	10
Specific Gravity	0.96	1.11	1.12-1.2
Abrasion Resistance, mm ³ /kg	1.2-1.6		1.2-1.6
Modulus of Elasticity, 0% elongation, psi	140-290	340	400-600
Brittle Temperature, °F	-65	-65	-65
Low Temperature range for rapid stiffening, °F	-20 to -50	-20 to -50	-20 to -50
Dynamic Modulus of Elasticity, psi			
at -4°F	136	300	
at 32°F	85	137	406
at 122°F	62	92	210
at 212°F	64	90.4	120
Dynamic Fatigue Life*			
Cycles x 10 ³	600-800		130-150
Shear Modulus, psi	65	90	140
Thermal Conductivity, BTU-in./ ft ² -h-°F	0.08		0.18
Coefficient of Thermal Expansion, in./in.-°F	9-11 x 10 ⁻⁵		6.7 x 10 ⁻⁵
Dielectric Constant	2.6 - 2.8		
Dielectric Strength, v/mil	500-750	500-750	500-750
Water Absorption, 168 hr at 68°F, %	0.3 - 1.9		0.6 - 1.4
25% Reduction of Tensile Strength for 158°F Service, weeks	8		15
Specific Heat	0.4-0.5	0.4-0.5	0.4-0.5
Vulcanization Shrinkage, %	1.5	1.5	1.5
Critical Strain for Aging, %	10-20		

FOOTNOTE:

*Number of cycles after which flex-cracks visible with pocket magnifier,
approximately 10X.

MIL-HDEK-149B

NR

DATA SHEET NC. 17
(continued)

PROPERTIES - SI

Properties	40	Hardness, Durometer A	
		50	60
	No Filler		25% Carbon black 10% Plasticizer
Tensile Strength, MPa	20.68-27.58	25.17	20.68-27.58
300% Modulus, MPa	1.03-2.41		4.83-8.96
Ultimate Elongation, %	675-850	640	550-650
Compression Set, ASTM D395, Method B 22 hr at 70°C, %	15	12	10
Specific Gravity	0.96	1.11	1.12-1.2
Abrasion Resistance, mm ³ /kg	1.2-1.6		1.2-1.6
Modulus of Elasticity, 0% elongation, MPa	0.97-2.00	2.34	2.76-4.14
Brittle Temperature, °C	-65	-65	-65
Low Temperature range for rapid stiffening, °C	-29 to -46	-29 to -46	-29 to -46
Dynamic Modulus of Elasticity, MPa			
at -20°C	0.94	2.07	
at 0°C	0.59	0.94	2.80
at 50°C	0.43	0.63	1.45
at 100°C	0.44	0.62	0.82
Dynamic Fatigue Life*			
Cycles x 10 ³	600-800		130-150
Shear Modulus, MPa	0.45	0.62	0.97
Thermal Conductivity, BTU-in./ ft ² -h-°C	0.012		0.026
Coefficient of Thermal Expansion, mm/mm-°C	16-20 x 10 ⁻⁵		12 x 10 ⁻⁵
Dielectric Constant	2.6 - 2.8		
Dielectric Strength, v/mil	19,685- 29,528	19,685- 29,528	19,685- 29,528
Water Absorption, 168 hr at 20°C, %	0.3 - 1.9		0.6 - 1.4
25% Reduction of Tensile Strength for 70°C Service, weeks	8		15
Specific Heat	0.4-0.5	0.4-0.5	0.4-0.5
Vulcanization Shrinkage, %	1.5	1.5	1.5
Critical Strain for Aging, %	10-20		

FOOTNOTE:

*Number of cycles after which flex-cracks visible with pocket magnifier,
approximately 10X.

MIL-HDBK-149B

DATA SHEET NO. 18

ASTM DESIGNATION PHOSPHONITRILIC FLUOROELASTOMER (60)

FZ

General: Phosphonitrilic fluoroelastomers (PNF) combine generally tough and wear resistant properties with a wide temperature operating range and resistance to a broad range of fluids and chemicals. These elastomers are very versatile with excellent dynamic and static sealing; shock damping; and flex-fatigue resistant properties. They are flame resistant and do not support combustions; are readily processable (including calendaring) on conventional equipment; and provide excellent bonding to metal and fabric. Vulcanized parts have an indefinite shelf life.

Notable Resistance Properties: High temperature fluid resistance to jet fuels and gasolines; lubricants; hydraulic fluids; and brake fluids. Excellent resistance to anhydrous ammonia with low swell in aliphatic and aromatic hydrocarbon; aryl phosphate esters; silicate esters; and water/glycol mixtures. Liquid oxygen compatible. Excellent resistance to ozone and weathering. Fair resistance to hydrazine and nitrogen tetroxide N_2O_4 .

Notable Mechanical Properties: Good extrusion, dynamic chew and nibbling resistance; flex fatigue resistance; excellent shaft seal wear properties (dry and lubricated); low compression set; and very good shock damping properties over a wide temperature range. Available in a wide hardness range.

Useful Temperature Range: -90° to $+350^{\circ}F$ (-70° to $+175^{\circ}C$).

Electrical Properties: Fair to good electrical properties similar to fluorosilicone. Suitable for low voltage insulation, particularly low frequency applications where dielectric loss is minimal.

Applications: Dynamic and static seals, diaphragms, shock mounts, electrical jacketing or insulation in areas where fluid resistance and very low-to-high temperature ranges are encountered.

Unsuitable: For exposure to oxygenated solvents, ester base brake fluids, alkyl phosphate esters (that is, Skydrol 500), some acids, and highly polar fluids.

Cost: Approximately \$40 per lb (\$88/kg) for compounded formulations.

MIL-HDBK-149B

FZ

DATA SHEET NO. 18
(Continued)

PROPERTIES

Properties	Hardness, Durometer A				
	40	50	60	70	80
Tensile Strength, psi	1120	1240	1540	1530	1500
(MPa)	(7.72)	(8.55)	(10.62)	(10.55)	(10.34)
Modulus at 100% Elongation, %	230	600	660	1370	--
Ultimate Elongation, %	220	190	180	120	100
Compression Set, %					
70 hr at 300°F (150°C),					
ASTM D395, Method B, %	16	19	24	24	20
Tear Strength, lb/in. (N/m)				100-160 (17,513-28,020)	
Specific Gravity				1.85	
Swell in ASTM No. 1 Oil, %				-1	
Swell in ASTM No. 2 Oil, %				0	
Swell in ASTM No. 3 Oil, %				2	
Swell in ASTM No. 3 Oil, %				0	
166 hr at 300°F (150°C), %					
Swell in MIL-L-7608				15	
166 hr at 300°F (150°C), %					
Swell in MIL-L-23699				11	
166 hr at 300°F (150°C), %					
Swell in MIL-H-5606				4	
166 hr at 275°F (135°C), %					
Swell in MIL-H-83282				2	
166 hr at 275°F (135°C), %					
Swell in ASTM Reference					
Fuel A, %				6	
Swell in ASTM Reference					
Fuel B, %				11	
Swell in ASTM Reference					
Fuel C, %				12	
166 hr at 73°F (23°C), %					
Temperature Retraction,					
TR ₁₀ , °F (°C)				-69 (-56)	
Brittle Point, °F (°C)				-90 (-68)	
Mold Shrinkage, %				2	
Dielectric Constant				6-7	
Volume Resistivity, ohm-cm				10 ¹³	

MIL-HDBK-149B

DATA SHEET NO. 19

ASTM DESIGNATION

POLYACRYLATE

ACM

General: Polyacrylic rubber is a copolymer of acrylic acid ester and halogen-containing derivatives. It is chemically saturated which provides the basis for excellent aging characteristics.

Notable Resistance Properties: High degree of resistance to lubricants under extreme pressure and temperature to 350°F (177°C). Not affected by sulfur modified oils. Excellent storage life, excellent ozone resistance.

Notable Mechanical Properties: Low gas permeability, medium strength and elongation. Dry heat resistance to 400°F (200°C) intermittent operation. Poor low temperature properties.

Useful Temperature Range: -40° to +400°F (-40° to +200°C).

Applications: Recommended for O-rings in transmission cases, tank linings, belting, obtainable in white and pastel colors.

Unsuitable: Water, steam, or water soluble chemicals such as methanol or ethylene glycol. Decomposes in alkali medium, swells in acid solutions.

MIL-HDBK-149P

ACM

DATA SHEET NO. 19
(Continued)

PROPERTIES

Hardness Range, Durometer A	40 to 90
Elongation, %	100-400
Tensile Strength, psi (MPa)	500-2500 (3.45-17.24)
Requires post curing (or tempering) at 300° to 350°F (150° to 175°C) to obtain good compression set	
Plasticizer necessary to obtain low brittle temperature of -40°F (-40°C)	
Unplasticized stock has brittle temperature of +5°F (-15°C)	

60 DUROMETER A, COMPOUND

Properties	70°F (20°C)	Test Conditions	
		Aged 24 hr	
		212°F (100°C)	300°F (150°C)
Tensile Strength, psi	1340-1540	1550-1800	
(MPa)	(9.24-10.62)	(10.69-12.41)	
Ultimate Elongation, %	225-275	190-230	
Tear Resistance, lb/in. (N/m)	10 (1751)		
Static Modulus of Elasticity,			
20% Deformation, psi	725-825		
(MPa)	(5.00-5.69)		
Dynamic Modulus of Elasticity,			
20% Deformation, psi	1290-1440		
(MPa)	(8.89-9.93)		
Resilience, %	48-50		
Compression Set, ASTM D395,			
22 hr at 335°F (168°C), %			33-36
Brittle Temperature, °F (°C)	-12 (-24)	-19 (-28)	
Water Absorption, 7 days at			
212°F (100°C), %	85		
Air Permeability, Standard			
Temperature and Pressure,			
ft ³ mils/ft ² psi day x 10 ³	1.78		
Specific gravity	1.29		

MIL-HDBK-149B

DATA SHEET NO. 20

ASTM DESIGNATION

POLYURETHANE RUBBER

AU, EU

General: The polyurethanes constitute a large family of materials produced basically by combining diisocyanates with polyesters (AU) or polyethers (EU). Most types are cured without sulfur.

Notable Resistance Properties: Excellent resistance to alcohols, aliphatic solvents, ether, and most petroleum based fuels up to 250°F (120°C) only, edible fats and oils, and mixtures containing less than 80% aromatics; ozone, and oxygen.

Notable Mechanical Properties: High strength and shear resistance. Excellent resistance to abrasion and wear (3 times as resistant as natural or other rubbers). High damping characteristics, poor heat buildup characteristics.

Useful Temperature Range: -300 to +250°F (-20° to +120°C).

Electrical Properties: Of general magnitude as those of phenolics.

Applications: Energy absorbing devices, vibration dampers, mounting pads for machinery.

Unsuitable: In contact with esters and ketones and synthetic hydraulic oils (causes swelling). Concentrated acids and bases. Hot water and steam.

NOTES

Properly compounded urethane parts have been used in contact with liquid nitrogen.

Heat buildup caused by low thermal conductivity is comparatively great. This adversely affects abrasion resistance, friction properties, and service life. Designs should incorporate thin cross sections. When bonded to metal surfaces, relatively large bonding areas will aid in heat conduction from the rubber.

Polyurethanes of 50-H Durometer A have withstood ozone exposure of 0.5 ppm at 100°F (38°C) without the formation of noticeable cracks. Slight cracks have been noted in abnormally high concentrations of 100 ppm after 16 hours.

Damping characteristics are somewhat less than those of butyl, but greater than for other polymers.

C-50

MIL-HDBK-149B

AU, EU

DATA SHEET NO. 20
(Continued)

PROPERTIES

Properties	Hardness, Durometer A			
	55	65	75	85
Tensile Strength, psi	2500	3000	4500	4500
100% Modulus, psi	200	300	450	700
Ultimate Elongation, %	650	430	430	440
Compression Set, ASTM D395, Method A, 22 hr at 158°F, %	5	10	15	22
Specific Gravity	1.06	1.10	1.10	1.10
Tear Strength, Graves, lb/in.	150-180	175-280	225-375	400
Abrasion Resistance, ASTM D394, mg loss	37	100	145	170
Modulus of Elasticity 0% Elongation, psi	200		2000	
Brittle Temperature, °F	below -90	below -90	below -90	below -90
Low Temperature Range for Rapid Stiffening, °F	-10 to -30	-10 to -30	-10 to -30	-10 to -30
Bashore Rebound				
Resilience, %	50-80	50-80	50-80	50-80
Impact Resistance, ft/lb	107			
Kinetic Coefficient of Friction with Steel	0.5	0.4	0.20-0.03	
Specific Heat, Btu/lb	0.42-0.45			
Thermal Conductivity, Btu-in./ft ² ·h·°F	1.18-1.16	1.04	1.01	0.95
Coefficient of Thermal Expansion, in./in.-°F	0.77 - 1.22 x 10 ⁻⁴	1.04 - 1.4 x 10 ⁻⁴	1.02 - 1.35 x 10 ⁻⁴	0.97 - 1.27 x 10 ⁻⁴
Volume Resistivity at 75°F, ohm-cm	4.3 x 10 ¹¹	8.2 x 10 ¹²	4.8 x 10 ¹²	5 x 10 ¹¹
Power Factor, %				
at 75°F	2-9	5-8	8	5
at 150°F	6-9	6-12	6-14	4-10
at 212°F	7-20	8	4-6	4-17
Max. Useful Temperature, °F				
Dry	190-220	190-220	190-220	190-220
In Oil	250	250	250	250
Vulcanization Shrinkage, %	1.7	2.0	2.1	1.8

MIL-HDEK-149E

AU, EU

DATA SHEET NO. 20

(Continued)

PROPERTIES - SI

Properties	Hardness, Durometer A			
	55	65	75	85
Tensile Strength, MPa	17.24	20.68	31.03	31.03
100% Modulus, MPa	1.38	2.07	3.10	4.83
Ultimate Elongation, %	650	430	430	440
Compression Set, ASTM D395, Method A, 22 hr at 70°C, %	5	10	15	22
Specific Gravity	1.06	1.10	1.10	1.10
Tear Strength, Graves, N/m	26,269- 31,523	30,647- 49,036	39,404- 65,673	70,051
Abrasion Resistance, ASTM D394, mg loss	37	100	145	170
Modulus of Elasticity 0% Elongation, MPa	1.36		13.8	
Brittle Temperature, °C	below -68	below -68	below -68	below -68
Low Temperature Range for Rapid Stiffening, °C	-10 to -30	-10 to -30	-10 to -30	-10 to -30
Bashore Rebound Resilience, %	50-80	50-80	50-80	50-80
Impact Resistance	145			
Kinetic Coefficient of Friction with Steel	0.5	0.4	0.20-0.03	
Specific Heat, J/kg	976-1046			
Thermal Conductivity, W/m·K	0.170- 0.167	0.150	0.146	0.137
Coefficient of Thermal Expansion, mm/mm/°C	1.39 - 2.20 x 10 ⁻⁴	1.8 - 2.5 x 10 ⁻⁴	1.84 - 2.43 x 10 ⁻⁴	1.74 - 2.29 x 10 ⁻⁴
Volume Resistivity at 24°C, ohm-cm	4.3 x 10 ¹¹	8.2 x 10 ¹²	4.8 x 10 ¹²	5 x 10 ¹¹
Power Factor, %				
at 24°C	2-9	5-8	8	5
at 66°C	6-9	6-12	6-14	4-10
at 100°C	7-20	8	4-6	4-17
Max. Useful Temperature, °F				
Dry	190-220	190-220	190-220	190-220
In Oil	250	250	250	250
Vulcanization Shrinkage, %	1.7	2.0	2.1	1.8

MIL-HDEK-149B

DATA SHEET NO. 21

ASTM DESIGNATION

POLYSULFIDE RUBBER

EOT

General: Polysulfide rubber is a copolymer prepared from sodium tetrasulfide and ethylene dichloride or other organic halides. Physical properties are generally low. Thiokol is a polysulfide rubber.

Notable Resistance Properties: Excellent resistance to ketones, acetates, gasoline and aromatic fuel blends, exceptional ozone and weather resistance, and excellent aging characteristics.

Notable Mechanical Properties: Low tensile strength, poor heat resistance, highly impermeable to gases, water vapor.

Useful Temperature Range: -60° to +200°F (-50° to 95°C).

Electrical Properties: Useful potting compound where large temperature variation occurs.

Applications: Gasoline fuel hose, sealing putties, seals, packings, tank linings, sealants, and potting compounds for electrical equipment.

Unsuitable: For mechanical goods because of low strength and high cost.

Fillers and Reinforcing Agents: Carbon blacks, zinc sulfide, zinc oxide.

Identification: Strong characteristic sulfur odor.

MIL-HDBK-149B

ECT

DATA SHEET NO. 21
(Continued)

NOTES

Because of their high resistance to water and water vapor, and their good aging characteristics, special compounds are recommended:

As a putty for marine and aircraft (window, hatch, and fuel tank) applications which do not harden or crack, and can withstand vibrations.

As an impregnating agent for leather to impart to it limited moisture penetration without completely eliminating "breathing" ability.

As a potting compound for electrical equipment which must undergo severe temperature cycling, -65° to 300°F (-54° to 150°C)
(this does not imply mechanical strength in this temperature range).

Abrasion resistance is only half as good as that of typical tire stocks under dry conditions. Under oil conditions, abrasion resistance is superior to that of tire stock.

Thiokol-ST can be blended with chloroprene or nitrile to balance properties of strength and swelling in aromatics, fuels, esters, and ketones.

MIL-PLF-149F

ECT

DATA SHEET NO. 21
(Continued)

PROPERTIES

Properties	Hardness, Durometer A				
	40	50	60	70	80
Oil Resistant Application, -40° to +212°F					
Tensile Strength, psi	540	560	950	1200	1050
300° Modulus, psi	410	370	850		
Ultimate Elongation, %	420	420	320	260	150
Compression Set, 22 hr at 158°F, %	45	45	40	40	40
Specific Gravity			1.33 - 1.38		
Tear Resistance, lb/in.	80	80	100	200	150
Volume Swell in ASTM No. 3 Oil, %	+7	+7	+7	+7	+7
Low Temperature Stiffness, E = 10,000 psi, °F	-60	-60	-60	-60	-60
Aromatic Hydrocarbon Resistant Applications, -40° to +80°F					
Tensile Strength, psi	540	560	950	1200	1050
300° Modulus, psi	410	370	850		
Ultimate Elongation, %	420	420	320	260	150
Compression Set, %	45	45	40	40	40
Tear Resistance, lb/in.	80	80	100	200	150
Volume Swell in toluene, 1 month at 80°F, %	+70	+70	+70	+70	+70
Dielectric Constant			6.8 - 7.3		
Volume Resistivity, ohm-cm			0.2 - 5 x 10 ⁻³		

PROPERTIES - SI

Properties	Hardness, Durometer A				
	40	50	60	70	80
Oil Resistant Application, -40° to +100°C					
Tensile Strength, MPa	3.72	3.86	6.55	8.27	7.24
300° Modulus, MPa	2.83	2.55	5.86		
Ultimate Elongation, %	420	420	320	260	150
Compression Set, 22 hr at 70°C, %	45	45	40	40	40
Specific Gravity			1.33 - 1.38		
Tear Resistance, N/m	14,010	14,010	17,513	35,025	26,269
Volume Swell in ASTM No. 3 Oil, %	+7	+7	+7	+7	+7
Low Temperature Stiffness, E = 68.95 MPa, °C	-51	-51	-51	-51	-51
Aromatic Hydrocarbon Resistant Applications, -40° to +27°C					
Tensile Strength, MPa	3.72	3.86	6.55	8.27	7.24
300° Modulus, MPa	2.83	2.55	5.86		
Ultimate Elongation, %	420	420	320	260	150
Compression Set, %	45	45	40	40	40
Tear Resistance, N/m	14,010	14,010	17,513	35,025	26,269
Volume Swell in toluene, 1 month at 27°C, %	+70	+70	+70	+70	+70
Dielectric Constant			6.8 - 7.3		
Volume Resistivity, ohm-cm			0.2 - 5 x 10 ⁻³		

MIL-HDBK-149B

DATA SHEET NC. 22

ASTM DESIGNATION

PROPYLENE OXIDE - ALLYL GLYCIDYL ETHER

GPO

General: This is a sulfur-vulcanizable copolymer of propylene oxide and about 5% allyl glycidyl ether. In resilience, flex life, and low temperature flexibility, it is similar to natural rubber but has lower tensile strength. It has excellent resistance to heat and ozone and some oil resistance. Fabrication, including metal adhesion, can be performed using conventional rubber processes.

Notable Resistance Properties: High temperature and ozone. Some oil resistance.

Notable Mechanical Properties: Good resilience and good flex resistance. In some applications the flex is superior to natural rubber.

Useful Temperature Range: -67° to +400°F (-55° to +200°C).

Applications: Motor mounting and other mounting applications requiring high temperature resistance. Other mechanical parts requiring resilience, high temperature resistance and excellent ozone resistance.

Unsuitable: For exposure to solvents, oils, or temperature over 400°F (200°C).

NOTE

Where only occasional contact with oil (vapors or splashing) is experienced, propylene oxide rubber can be used.

MIL-HDBK-149E

GPO

DATA SHEET NO. 22

(Continued)

PROPERTIES

Polymer Specific Gravity	1.01
Color	White to Light Amber
Does Polymer Stain?	No

TYPICAL COMPOUND PROPERTIES

Tensile, psi	1800-2500
(MPa)	(12.41-16.55)
Elongation, %	500-800
Hardness, Durometer A	50-65
Dry Heat Resistance after 10 days at 257°F (125°C)	
Tensile Change, %	-15
Elongation Change, %	-35
Hardness Change, Durometer A Points	-6 to -10
Compression Set, ASTM D395, Method B,	
As molded, after 70 hr at 300°F (150°C), %	75
Post-cured for 16 hr at 300°F (150°C) in air,	
after 70 hr at 300°F (150°C), %	55
Volume Change in:	
Water, 70 hr at 212°F (100°C), %	+5
ASTM Oil No. 1,	
70 hr at 212°F (100°C), %	+10
70 hr at 300°F (150°C), %	+20
ASTM Oil No. 3,	
70 hr at 212°F (100°C), %	+75
70 hr at 300°F (150°C), %	+125
ASTM Ref. Fuel B,	
70 hr at 73°F (23°C), %	+140
Bashore Resilience, %	48
Ozone Resistance	
ASTM D1149 (0.50 ppm) hours to first crack	2500
Low Temperature Stiffness,	
ASTM D1053, T _{10,000} , °F (°C)	-72 (-58)

MIL-HDBK-149P

DATA SHEET NO. 23

ASTM DESIGNATION

PYRIDINE-BUTADIENE RUBBER

PBR

General: This rubber is used in cements which permit adhesion of rubber to metal or other rigid substances.

Applications: Adhesives.

MIL-HDBK-149B

DATA SHEET NO. 24

ASTM DESIGNATION

SILICONE RUBBER

PMQ, PVMQ, VMQ

General:	Silicone rubber is a heat-stable semi-organic rubber, which has only modest room temperature strength properties, but retains as high as 75% of these properties at 300°F (150°C). The basic structure is composed of long chains of alternate silicon and oxygen atoms to which heat-stable organic groups are attached to give elastomeric properties.
Notable Resistance Properties:	Resistance to strong alkalis, petroleum-base engine oil, ozone, weather, and sunlight.
Notable Mechanical Properties:	High and low temperature properties good, low compression set, excellent live steam resistance, high thermal conductivity, ideal for extrusion purposes, can be molded and calendered.
Useful Temperature Range:	See property tables.
Electrical Properties:	Excellent insulation for environmental extremes for long periods of time, high dielectric properties.
Applications:	Seals, shock mounts, hose insulating jackets, bellows, diaphragms.
Unsuitable:	For hydraulic fluid and aromatic fuel applications; generally poor performance. For strong acids, aromatic and chlorinated solvents. Too costly for applications where only moderate temperatures are experienced. See Fluorosilicone Rubber, FVMQ, Data Sheet No. 16, for fuel resistant silicone rubber.
Fillers and Reinforcing Agents:	Silica constitutes the most satisfactory filler (carbon black is of little use) and results in appreciable increase in tensile strength and elongation.

NOTES

Silicone components must be handled carefully as their room temperature strength is lower than that of other rubbers. While they stand up at high temperatures, they may tear while being installed at room temperature. For this reason special care must be taken in design of components to minimize pulling and stretching during installation. However, handling of high strength silicones is equivalent to other rubbers.

Parts which must withstand temperatures above 300°F (150°C) might require an oven-cure after vulcanizing. This weakens the room temperature properties. If circumstances permit, the curing should be done after installation. Some compounds do not need postcuring.

PMQ, PVMQ, VMQ

DATA SHEET NO. 24

(Continued)

NOTES (Continued)

For above 300°F (150°C) applications, special consideration must be given to venting the component and to allow adequate "breathing" space. Failure to observe this may cause reversion, that is, softening and deterioration of physical properties.

A few simple design guides should be followed: Metal inserts, which primarily aid attachment to adjacent components also help reinforce the rubber. Inserts of aluminum and steel, coated with silicone monomer, are better than adhesive bonding. Brass and bronze inserts should be avoided because they are difficult to bond.

High tensile, up to 1500 psi (10.34 MPa), and high tear, up to 250 lb/in. (43 782 N/m), compounds are available now. Continuous service temperatures for these compounds are limited to 400°F (200°C) and for intermittent to 500°F (260°C).

Estimated life of silicone rubber components as a function of temperature based on oven-aging is shown below.

Service Temperature, °F (°C)	Estimated Service Life, years
480 (250)	1/4
410 (210)	2
300 (150)	5
250 (120)	10

Methyl Silicone, MQ, has been replaced by Methyl Phenyl Silicone, PMQ, Methyl Phenyl Vinyl Silicone, PVMQ, and Methyl Vinyl Silicone, VMQ.

MIL-HDBK-149B

PMQ, PVMQ, VMQ

DATA SHEET NO. 24
(Continued)

PROPERTIES

Properties	Hardness, Durometer A				
	40	50	60	70	80
General Purpose Silicone Rubber, VMQ Service Temperature -75° to +500°F					
Tensile Strength, psi	1000	750-1000	700-1000	600-900	750-1100
Ultimate Elongation, %	500	300-400	200-300	125-300	90-300
Tear Resistance, lb/in.	50	50-80	50-100	50-100	50-125
Compression Set, 22 hr at 300°F, %	20-35	20-50	20-50	30-60	25-70
Volume Swell, ASTM No. 3 Oil, 70 hr at 300°F, %	50	50	50	50	50
Specific Gravity	1.14	1.2	1.2	1.25	1.3
Hardness Change, 70 hr at 450°F	+5	+5	+5	+5	+5
Brittle Temperature, °F	-90 to -120	-90 to -120	-90 to -120	-90 to -120	-90 to -120
Stiffening Point T_{10} , °F	-65	-65	-65	-65	-65
Dielectric Strength, v/mil	500-1000				
Dielectric Constant		3.1			
Volume Resistivity, ohm-cm		1.3×10^{12} to 4×10^{14}			
Water Absorption, %	1-6	1-6	1-6	1-6	1
Mold Shrinkage, %	25-45	25-45	25-45	25-45	25-45
Thermal Conductivity, BTU-in./ft ² ·h·°F	1.1-3	1.1-3	1.1-3	1.1-3	1.1-3
Linear Thermal Expansion $\times 10^{-6}$, in./in.-°F	3.2-7	3.2-7	3.2-7	3.2-7	3.2-7
Low Compression-Set Compound, VMQ Service Temperature -75° to +450°F					
Tensile Strength, psi	500-700	750-900	750-900	800-1000	900-1100
Ultimate Elongation, %	250-350	250	90-130	80-120	60-80
Tear Resistance, lb/in.		40-60	40-65	40-70	40-75
Compression Set, 22 hr at 300°F, %	5	10	10	13	16
Brittle Temperature, °F	-90 to -120	-90 to -120	-90 to -120	-90 to -120	-90 to -120
Hardness Change, 70 hr at 450°F, Durometer A	+5	+5	+5	+5	+5
Specific Gravity	1.10	1.2	1.25	1.25-1.35	1.35-1.45
Extreme Low Temperature Service Compound, PMQ, PVMQ Service Temperature -150° to +500°F					
Tensile Strength, psi	1000	750-1000	900	800	750
Ultimate Elongation, %	500	250-300	200	100	90
Tear Resistance, lb/in.	125	50-75	65	50	50
Compression Set, 22 hr at 300°F, %	20	55	20	70	80
Brittle Temperature, °F	-150	-150	-150	-150	-150
Low Temperature Stiffness, T_{10} , °F	-106	-106			
Hardness Change, 70 hr at 450°F, Durometer A	+5	+5 to +10	+5	+5 to +10	+5 to +10
Specific Gravity	1.14	1.16	1.25	1.35	1.40
Extreme High Temperature Compound, VMQ Service Temperature -75° to +600°F					
Tensile Strength, psi	500-700	800-900	800	900	
Ultimate Elongation, %	250-300	200-250	200	180	
Tear Resistance, lb/in.	50	50	40	75	
Compression Set, 22 hr at 300°F, %	50	10-40	20	5	
Brittle Temperature, °F	-90 to -120	-90	-90	-90	
Hardness Change, 70 hr at 450°F, Durometer A	+4	+10	+10	+3	
Specific Gravity	1.10	1.2	1.5	1.4	
High Strength Silicone, VMQ, PVMQ Service Temperature -105° to 500°F					
Hardness, Durometer A	30	50	60	70	80
Tensile Strength, psi	1100	1600	1400	1400	1200
Ultimate Elongation, %	900	700	600	500	300
Tear Resistance, lb/in.	170	200	200	175	125
Compression Set, 22 hr at 300°F, %	30	20-50	20-50	50	50
Hardness Change, 70 hr at 400°F, Durometer A	+2	+10	+6	+10	+10
Swell in ASTM No. 1 Oil, 70 hr at 300°F, %	+10	+10	+10	+10	+10
Specific Gravity	1.13	1.15-1.20	1.15-1.25	1.17-1.30	1.34

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PMQ, PVMQ, VMQ

DATA SHEET NO. 24
(Continued)

PROPERTIES - SI

Properties	Hardness, Durometer A				
	40	50	60	70	80
General Purpose Silicone Rubber, VMQ Service Temperature -10° to 260°C					
Tensile Strength, MPa	6.89	5.17-6.89	4.83-6.89	4.14-6.21	5.17-7.58
Ultimate Elongation, %	500	300-400	200-300	125-300	90-300
Tear Resistance, N/m	8,756	8,756-14,010	8,756-17,513	8,756-17,513	8,756-21,891
Compression Set, 22 hr at 150°C, %	20-35	20-50	20-50	30-60	25-70
Volume Swell, ASTM No. 3 Oil, 70 hr at 150°C, %		50			
Specific Gravity	1.14	1.2	1.2	1.25	1.3
Hardness Change, 70 hr at 200°C	+5	+5	+5	+5	+5
Brittle Temperature, °C	-68 to -85	-68 to -85	-68 to -85	-68 to -85	-68 to -85
Stiffening Point T_{10} , °C	-55	-55	-55	-55	-55
Dielectric Strength, v/mm	19 685-39 370				
Dielectric Constant		3.1			
Volume Resistivity, ohm-cm		1.3×10^{13} to 4×10^{14}			
Water Absorption, %	1-6	1-6	1-6	1-6	1
Mold Shrinkage, %	25-45	25-45	25-45	25-45	25-45
Thermal Conductivity, W/(m·K)	0.16-0.43	0.16-0.43	0.16-0.43	0.16-0.43	0.16-0.43
Linear Thermal Expansion $\times 10^{-4}$ (mm/mm)°C	5.76-12.6	5.76-12.6	5.76-12.6	5.76-12.6	5.76-12.6
Low Compression-Set Compound, VMQ Service Temperature -60° to 230°C					
Tensile Strength, MPa	3.45-4.83	5.17-6.21	5.17-6.21	5.52-6.89	6.21-7.58
Ultimate Elongation, %	250-350	250	90-130	80-120	60-80
Tear Resistance, N/m		7,005-10,508	7,005-11,383	7,005-12,259	7,005-13,135
Compression Set, 22 hr at 150°C, %	5	10	10	13	16
Brittle Temperature, °C	-68 to -84	-68	-68	-68	-68
Hardness Change, 70 hr at 200°C, Durometer A	+5	+5	+5	+5	+5
Specific Gravity	1.10	1.2	1.25	1.25-1.35	1.35-1.45
Extreme Low Temperature Service Compound, PMQ, PVMQ Service Temperature -100° to 260°C					
Tensile Strength, MPa	6.89	5.17-6.89	6.21	5.52	5.17
Ultimate Elongation, %	500	250-300	200	100	90
Tear Resistance, N/m	21,891	8,756-13,135	11,383	8,756	8,756
Compression Set, 22 hr at 150°C, %	20	55	20	70	80
Brittle Temperature, °C	-101	-101	-101	-101	-101
Low Temperature Stiffness, T_{10} , °C	-77	-77			
Hardness Change, 70 hr at 200°C, Durometer A	+5	+5 to +10	+5	+5 to +10	+5 to +10
Specific Gravity	1.14	1.16	1.25	1.35	1.40
Extreme High Temperature Compound, VMQ Service Temperature -60° to 315°C					
Tensile Strength, MPa	3.45-4.83	5.52-6.21	5.52	6.21	
Ultimate Elongation, %	250-300	200-250	200	180	
Tear Resistance, N/m	8,756	8,756	7,005	13,135	
Compression Set, 22 hr at 150°C, %	50	10-40	20	5	
Brittle Temperature, °C	-68 to -84	-68	-68	-68	
Hardness Change, 70 hr at 200°C, Durometer A	+4	+10	+10	+3	
Specific Gravity	1.10	1.2	1.5	1.4	
High Strength Silicone, VMQ, PVMQ Service Temperature -76° to 260°C					
Hardness, Durometer A	30	50	60	70	80
Tensile Strength, MPa	7.58	11.03	9.65	9.65	8.27
Ultimate Elongation, %	900	700	600	500	300
Tear Resistance, N/m	29,772	35,025	35,025	30,647	21,891
Compression Set, 22 hr at 150°C, %	30	30-50	20-50	50	50
Hardness Change, 70 hr at 200°C	+2	+10	+6	+10	+10
Swell in ASTM No. 1 Oil, 70 hr at 150°C, %	+10	+10	+10	+10	+10
Specific Gravity	1.13	1.15-1.20	1.15-1.25	1.17-1.30	1.34

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DATA SHEET NO. 25

ASTM DESIGNATION

STYRENE-BUTADIENE RUBBER (SBR)

SBR

General: SBR is a general purpose, nonoil resistant rubber which finds use in 80% of all man-made rubber products consumed in the United States. It is manufactured by copolymerization of butadiene and styrene, generally in a 3:1 ratio. "Hot" SBR is polymerized at 120°F (50°C); "Cold" SBR at 40°F (5°C). The latter has superior physical properties. Unreinforced SBR has poor tensile properties. Requires antioxidants for ozone and weather protection. SBR can be blended with most other synthetics and natural rubber.

Notable Resistance Properties: Resistant to weak acid, and strong and weak alkalis. Medium resistance to alcohol, esters and ketones.

Notable Mechanical Properties: High strength. Excellent abrasion resistance. Excellent low water-absorption characteristics.

Useful Temperature Range: -80° to +250°F (-60° to +120°C).

Applications: Tires, footwear, mechanical goods, hose, battery boxes, and belting.

Unsuitable: In presence of solvents and oils.

Fillers and Reinforcing Agents: Carbon black (best), fine silica, calcium silicate, clays (lower cost).

NOTES

Most applications now use cold SBR because of superior strength properties.

Black compounds have lower specific gravity and higher strength than mineral-filled, light colored compounds.

Oil-extended compounds have substantially the same strength as the base polymer and, because of easier processing capacity, result in lower product cost.

During the processing and aging, mineral-filled compounds are subject to surface embrittlement which results in cracking when the rubber part is subjected to bending. Surface embrittlement has been determined a function of the antioxidant employed in the compound, with some amine antioxidants being superior.

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SBR

DATA SHEET NO. 25
(Continued)

PROPERTIES

Properties	Hardness, Durometer A		
	60 Black Reinforcement	70 Oil Extended	80 Light Colored Reinforcement
Tensile Strength, psi	2900-3800	2850-3550	1400-1550
Ultimate Elongation, %	400-800	400-750	50-450
300% Modulus, psi	1775-2000	450-1600	850-1400 100% Mod. 1.37-1.63
Specific Gravity	1.13		
Tensile Strength at 212°F, psi	1000-1460		
Ultimate Elongation at 212°F, %	210-300		
Static Modulus of Elasticity at 20% Deformation, psi	800-1000		
Dynamic Modulus of Elasticity at 20% Deformation, psi	1425-1580		
Yerzley Resilience, %	60-67	41-45	
Tensile Strength RT, aged at 212°F, 8 days, psi	2100-2485		
Ultimate Elongation RT, aged at 212°F, 8 days, %	195-230		
Compression Set, 22 hr at 158°F, %	15-30	5-15	20-40
Compression Set, 22 hr at 212°F, %	34-47		
Brittle Temperature, °F	-73		
Low Temperature Stiffness T ₅ , °F	-50 to -60		
Swell in ASTM No. 3 Oil, 2 days at 212°F, %	150		
Water absorption 7 days at 212°F, %	18		
Tear Resistance at RT, lb/in.	200-260		245-300
Tear Resistance at 212°F, lb/in.	80-110		
Dynamic Fatigue Life* Cycle x 10 ³	3,000	1,000,000 to 3,000,000	
Coefficient of Thermal Expansion in./in.-°F		4 x 10 ⁻⁴	
Thermal Conductivity BTU-in./ft ² -h-°F		1.68 10 ¹⁴	
Volume Resistivity, ohm-cm		500-600	
Dielectric Strength, v/mil		3-7	
Dielectric Constant			

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SER

DATA SHEET NO. 25

(Continued)

PROPERTIES - SI

Properties	Hardness, Durometer A		
	60 Black Reinforcement	70 Oil Extended	80 Light Colored Reinforcement
Tensile Strength, MPa	19.99-26.20	19.65-24.48	9.65-10.69
Ultimate Elongation, %	400-800	400-750	50-450
300% Modulus, MPa	12.24-13.79	3.10-11.03	5.86-9.65 100% Mod. 1.37-1.63
Specific Gravity	1.13		
Tensile Strength at 100°C, MPa	6.89-10.07		
Ultimate Elongation at 100°C, %	210-300		
Static Modulus of Elasticity at 20% Deformation, MPa	5.52-6.89		
Dynamic Modulus of Elasticity at 20% Deformation, MPa	9.83-10.89		
Yerzley Resilience, %	60-67	41-45	
Tensile Strength RT, aged at 100°C, 8 days, MPa	14.48-17.13		
Ultimate Elongation RT, aged at 100°C, 8 days, %	195-230		
Compression Set, 22 hr at 70°C, %	15-30	5-15	20-40
Compression Set, 22 hr at 100°C, %	34-47		
Brittle Temperature, °C	-58		
Low Temperature Stiffness T ₅ , °C	-46 to -51		
Swell in ASTM No. 3 Oil, 2 days at 100°C, %	150		
Water absorption 7 days at 100°C, %	18		
Tear Resistance RT, N/m	35,020-45,533		42,906-542,538
Tear Resistance at 100°C, N/m	14,010-19,264		
Dynamic Fatigue Life* Cycle x 10 ³	3,000	1,000,000 to 3,000,000	
Coefficient of Thermal Expansion mm/mm°C		7.2 x 10 ⁻⁴	
Thermal Conductivity, w/m·K		0.24	
Volume Resistivity, ohm-cm		10 ¹⁴	
Dielectric Strength, v/mm		19,685- 23,622	
Dielectric Constant		3-7	

FOOTNOTE:

*Cycles to appearance of flex-cracks visible by pocket magnifier. Bending radius equals 4X thickness.

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DATA SHEET NO. 26

ASTM DESIGNATION.

STYRENE-ICSPRENE

SIR

General: These "rubber" materials are not usually vulcanized, but are used in the unvulcanized state, frequently in pressure sensitive adhesives.

Notable
Resistance
Properties: Water.

Notable
Mechanical
Properties: Good low temperature resistance, good flexibility and good compression set at temperatures of 80°F (26°C) or less.

Useful
Temperature
Range: -67° to +160°F (-55° to +70°C).

Applications: Hot melt adhesives, pressure sensitive adhesives, plastic modification.

Unsuitable: For temperatures above 160°F (70°C).

PROPERTIES

Hardness, Durometer A	35
Tensile	800 to 2400 psi (5.5 to 16.5 MPa)
Ultimate Elongation	150 to 250%
Low Temperature Flexibility	-67°F (-55°C)

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APPENDIX D

TRADE NAME INDEX

Listed below are the TRADE NAMES of polymers and compounds mentioned in this Handbook. For further Trade Name references, the latest issue of "RUBBICANA", published by Rubber & Plastic News, and the Rubber Red Book (available from Rubber Red Book, 6285 Barfield Road, Atlanta, GA 30328), should be consulted.

TRADE NAME	ASTM D1418 DESIGNATION	DATA SHEET NUMBER	POLYMER OR COPOLYMER	MANUFACTURER (See D-6 for full name)
Acrylon EA-5	ANM	19	95% Ethyl Acrylate 5% Acrylonitrile	Borden Chemical
Acrylon BA-12	ANM	19	88% Butyl Acrylate 12% Acrylonitrile	Borden Chemical
Adriprene	EU	20	Polyether Urethane	DuPont
Ameripol CB	BR	4	Butadiene	Goodrich Chemical
Ameripol SBR	SBR	25	Styrene Butadiene	Goodrich Chemical
Ameripol SN	IR	17	Polyisoprene	Goodrich Chemical
AMSYN Latexes	SBR	25	Styrene Butadiene	American Synthetic
ARCON	AU	20	Polyester Urethane	Allied Resin
ASRC	SBR	25	Styrene Butadiene	American Synthetic
Bayprene	CR	9	Chloroprene	Mobay
Baysilone	MC	24	Methyl Silicone	Mobay
Betathane	EU	20	Polyether Urethane	Essex Chemical
Blensil	MC	24	Methyl Silicone	General Electric
Bromo Butyl X2	BIIR	3	Bromo Butyl	Polysar
Bucar	IIR	5	Butyl	Cities Service
Eudene	BR	4	Butadiene	Goodyear
Butachlor-A	CR	9	Chloroprene	A. Schulman
Butyl	IIR	5	Butyl	Exxon
Butyl	IIR	5	Butyl	Polysar
Castall	EU	20	Polyether Urethane	Polymer-West
Catapol	EU	20	Polyester Urethane	Arnco
Chemigum	NBR	1	Acrylonitrile Butadiene	Goodyear
Chemigum XSL		20	Polyurethane	Goodyear
Chlorobutyl	CIIR	7	Chloro Butyl	Exxon
CIS-4	BR	4	Butadiene	Phillips
Cisdene	BR	4	Butadiene	American Synthetic
Conothane	AU	20	Polyester Urethane	Conap
Conothane	EU	20	Polyether Urethane	Conap
Copo SBR	SBR	25	Styrene Butadiene	Copolymer Rubber
CPE Elastomer	CM	8	Chloropolyethylene	Down Chemical
Craco-thane	EU	20	Polyether Urethane	J. M. Cranz
Cyanacryl	ACM	19	Polyacrylate	American Cyanamid
Cyanaprene	AU	20	Polyester Urethane	American Cyanamid

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TRADE NAME	ASTM D1418 DESIGNATION	DATA		POLYMER OR COPOLYMER	MANUFACTURER (See D-6 for full name)
		SHEET	NUMBER		
Cyanaprene	EU	20		Polyether Urethane	American Cyanamid
Cytor	EU	20		Polyether Urethane	American Cyanamid
Diene	BR	4		Butadiene	Firestone
Duragen	BR	4		Butadiene	General Tire
Dutral CO	EPM	12		Ethylene Propylene	Montedison USA
Dutral-TER	EPDM	13		Ethylene Propylene	
				Diene Modified	Montedison USA
Elaprim	ACM	19		Polyacrylate	Montedison USA
Elaprim-S	NBR	1		Acrylonitrile	
				Butadiene	Montedison USA
Elastothane	EU	20		Polyether Urethane	Thiokol
Electrisil		24		Silicone	General Electric
Epcar 306	EPM	12		Ethylene Propylene	Goodrich Chemical
Epcar EPDM	EPDM	13		Ethylene Propylene	
				Diene Modified	Goodrich Chemical
Epsyn	EPDM	13		Ethylene Propylene	
				Diene Modified	Copolymer Rubber
Epsyn	EPM	12		Ethylene Propylene	Copolymer Rubber
Esthane	EU	20		Polyether Urethane	Goodrich Chemical
Fastcast	EU	20		Polyether Urethane	Arnco
Fluorel	FKM	14		Fluorocarbon	3M
FR-N	NBR	1		Acrylonitrile	
				Butadiene	Firestone
FR-S	SBR	25		Styrene Butadiene	Firestone
Gensil		24		Silicone	General Electric
Genthane S	AU, EU	20		Urethane	General Tire
Gentro	SBR	25		Styrene Butadiene	General Tire
Gentro-Jet	SBR	25		Styrene Butadiene	General Tire
Herchlor-C	ECO	11		Epichlorohydrin	
				Copolymer	Hercules
Herchlor-H	CO	11		Epichlorohydrin	
				Homopolymer	Hercules
HW-B10	SBR	25		Styrene Butadiene	Hanford
HYCAR 1001	NBR	1		Acrylonitrile (40)	
				Butadiene (60)	Goodrich Chemical
HYCAR 1002	NBR	1		Acrylonitrile (33)	
				Butadiene (67)	Goodrich Chemical
HYCAR 1042	NBR	1		Acrylonitrile	
				Butadiene	Goodrich Chemical
HYCAR 1072	XNBR	6		Carboxylic	
				Acrylonitrile	
				Butadiene	Goodrich Chemical
HYCAR 2001	SBR	25		Styrene Butadiene	Goodrich Chemical
HYCAR 2121X26	ANM	19		Ethyl Acrylate (95)	
				Acrylonitrile (5)	Goodrich Chemical
HYCAR 2121x27	ANM	19		Butyl Acrylate (90)	
				Acrylonitrile (10)	Goodrich Chemical
HYCAR 2202	BIIR	3		Bromo Butyl	Goodrich Chemical

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TRADE NAME	ASTM D1418 DESIGNATION	DATA SHEET NUMBER	POLYMER OR COPOLYMER	MANUFACTURER (See D-6 for full name)
HYCAR 26 xx, 40 xx	ACM	19	Polyacrylate	Goodrich Chemical
HYCAR NBR	NBR	1	Acrylonitrile	
			Butadiene	Goodrich Chemical
Hydrin-100	CO	11	Epichlorohydrin	
			Homopolymer	Goodrich Chemical
Hydrin-200	ECO	11	Epichlorohydrin	
			Copolymer	Goodrich Chemical
Hypalon	CSM	10	Chlorosulfonated	
			Polyethylene	DuPont
Indpol	EU	20	Polyether Urethane	E. L. Puskas
K		24	Silicone	Union Carbide
Kalrez	FFKM	15	Perfluorocarbon	DuPont
Kel-F Elastomer	CFM	14	Fluorocarbon	3M
KEL-F 3700	CFM	14	Fluorocarbon	3M
Krylene	SBR	25	Styrene Butadiene	Polysar
Krymix	SBR	25	Styrene Butadiene	Polysar
Krynac	NBR	1	Acrylonitrile	
			Butadiene	Polysar
Krynac 211, 221	XNBR	6	Carboxylic	
			Acrylonitrile	
			Butadiene	Polysar
Krynac 833	NIR	2	Acrylonitrile	
			Isoprene	Polysar
Krynac 1000	XNBR	6	Carboxylic	
			Acrylonitrile	
			Butadiene	Polysar
Krynol	SBR	25	Styrene Butadiene	Polysar
Millathane	EU	20	Polyether Urethane	Tech-Sales
Multrathane	AU	20	Polyester Urethane	Mobay
Natsyn	IR	17	Polyisoprene	Goodyear
Naugatex	SBR	25	Styrene Butadiene	Uniroyal
Necprene	CR	9	Chloroprene	Denka
Neoprene	CR	9	Chloroprene	DuPont
Neoprene	CR	9	Chloroprene	Petro-Tex
Nordel	EPDM	13	Ethylene Propylene	
			Diene Modified	DuPont
Nysyn	NBR	1	Acrylonitrile	
			Butadiene	Copolymer Rubber
Paracril	NBR	1	Acrylonitrile	
			Butadiene	Uniroyal
Paracril Ozo	---	--	Acrylonitrile	
			Butadiene and	
			Polyvinyl Chloride	
			Copolymer	Uniroyal
Parel	GPO	22	Propylene Oxide-	
			Allyl Glycidyl	
			Ether Copolymer	Hercules
Penetrex	EU	20	Polyether Urethane	Arnco

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TRADE NAME	ASTM D1418 DESIGNATION	DATA SHEET		POLYMER OR COPOLYMER	MANUFACTURER (See D-6 for full name)
		NUMBER			
Perbunan-N	NBR	1	Acrylonitrile		
			Butadiene		Mobay
Perchlor-C	ECO	11	Epichlorohydrin		
			Copolymer		Hercules
Fermatire	EU	20	Polyether Urethane		Arnco
Philprene	SBR	25	Styrene Butadiene		Phillips
Plioflex	SBR	25	Styrene Butadiene		Goodyear
PNF	FZ	18	Phosphonitrilic		Firestone
Polyglycol Adipates	AU	20	Polyester Urethane		Molex
Polyphosphazene	FZ	18	Phosphonitrilic		Firestone
Polysar Bromo Butyl	BIIR	3	Bromo Butyl		Polysar
Polysar Butyl	IIR	5	Butyl		Polysar
Polysar SS	SBR	25	Styrene Butadiene		Polysar
Quickcast	EU	20	Polyether Urethane		Arnco
Reyno-foam	EU	20	Polyether Urethane		Hoover Universal
Rhodia RS		24	Silicone		Rhone-Poulenc
Royalene EPDM	EPDM	13	Ethylene Propylene		
			Diene Modified		Uniroyal
Royalene	EPM	12	Ethylene Propylene		Uniroyal
RTV Castall		24	Silicone		Polymer-West
Rucoflex	AU	20	Polyester Urethane		Hooker
SBR	SBR	25	Styrene Butadiene		ARCC/Polymers
SE		24	Silicone		General Electric
Silastic		24	Silicone		Dow Corning
Silastic					
Fluorosilicone	FVMQ	16	Fluorosilicone		Dow Corning
Solprene	SBR	25	Styrene Butadiene		Phillips
SWS		24	Silicone		SWS Silicones
Synpol	SBR	25	Styrene Butadiene		Texas-US Chemical
Synpol E-BF	BR	4	Butadiene		Texas-US Chemical
Taktene	BR	4	Butadiene		Polysar
Thiokol	ECT	21	Polysulfide		Thiokol
TransPip	IR	17	Polyisoprene		Polysar
Vamac	ACM	19	Polyacrylate		DuPont
Vibrithane	AU	20	Polyester Urethane		Uniroyal
Vistalon, 404, 702	EPM	12	Ethylene Propylene		Exxon
Vistalon 25xx, 37xx, 46xx, 56xx, 65xx	EPDM	13	Ethylene Propylene		
			Diene Modified		Exxon
Viton	FKM	14	Fluorocarbon		DuPont
Vyram	ACM	19	Polyacrylate		Monsanto

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APPENDIX D

MANUFACTURERS' NAMES

TRADE NAME INDEX CODE	MANUFACTURER'S FULL NAME
Allied Resin	ALLIED RESIN CORP.
American Cyanamid	AMERICAN CYANAMID CO. Polymer and Chemicals Dept.
American Synthetic	AMERICAN SYNTHETIC RUBBER CORP.
Arnco	ARNCO
Arco/Polymers	ARCO/POLYMERS, INC.
A. Schulman	A. SCHULMAN, INC.
Borden	BORDEN CHEMICAL CO.
Cities Service	CITIES SERVICE CO.
Conap	CONAP INC.
Copolymer Rubber	COPOLYMER RUBBER & CHEMICAL CORP.
Denka	DENKA CHEMICAL CORP.
Dow Chemical	LOW CHEMICAL CO.
Down Corning	DOW CORNING CORP.
DuPont	E. I. du PONT de NEMOURS CO., INC.
E. L. Puskas	Elastomer Chemicals Dept. E.L. PUSKAS CO.
Essex Chemical	ESSEX CHEMICAL CORP.
Exxon	EXXON CHEMICAL COMPANY U.S.A.
Firestone	FIRESTONE SYNTHETIC RUBBER & LATEX CO. FIRESTONE TIRE & RUBBER CO. Phosphazene Rubber Marketing GENERAL ELECTRIC, Silicone Products Dept. GENERAL TIRE & RUBBER CO. Chemical/Plastics Div. B. F. GOODRICH CHEMICAL CO. GOODYEAR TIRE & RUBBER CO. Chemical Div. HANFORD EXPERIMENTAL MATERIAL HERCULES INCORPORATED Process Chemical Div. HOCKER CHEMICALS & PLASTICS CORP. HOCVER UNIVERSAL CHEMICAL SPECIALTIES DIVISION J. M. CFANZ & CO., INC. MOBAY CHEMICAL CORP. MONSANTO CHEMICAL CO.
General Electric	
General Tire	
Goodrich	
Goodyear	
Hanford	
Hercules	
Hooker	
Hocver	
J. M. Cranz	
Mobay	
Monsanto	

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TRADE NAME INDEX CCDE	MANUFACTURER'S FULL NAME
Montedison	MONTEDISON U.S.A., INC.
Petra-Tex	PETRA-TEX CHEMICAL
Phillips	PHILLIPS CHEMICAL CO.
	Petrochemical and Supply Div.
Polymer-West	POLYMER-WEST INC.
Polysar	POLYSAR CORPORATION LTD.
Reichold Chemicals	REICHOLD CHEMICALS, INC.
Rhone-Poulenc	RHONE-POULENC INC.
SWS Silicones	SWS SILICONES CORP.
Tech-Sales	TECH-SALES & ENGINEERING CO., INC.
Texas-US Chemical	TEXAS-US CHEMICAL CORP.
Thiokol	THIOKOL CORP.
3M	3M COMPANY,
	Commercial Chemicals
Union Carbide	UNION CARBIDE CORP.
	Silicones Div.
Uniroyal	UNIROYAL CHEMICAL, Div. of Uniroyal, Inc.

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