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Expandable Structures for Construction of Astronaut Transfer Tunnel

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Prepared for COMMANDER SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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EXPANDABLE STRUCTURES FOR CONSTRUCTION OF ASTRONAUT TRANSFER TUNNEL

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ABSTRACT

This study investigates the feasibility of using the expandable concept for construction of a transfer tunnel from Gemini B to the Manned Orbiting Laboratory. Current and advanced technology of expandable and/or inflatable structures and data to support its application are presented. The effect of space environment on materials of construction, in addition to various design configurations, properties of reinforcement, elastomers, and fabrication methods are also presented.

The study indicates that current technology of expandables is sufficiently advanced such that the construction of an expandable tunnel can be realized if materials, fabrication methods, and design are properly chosen. A self-erectable double-wall composite consisting of a preformed foam interlayer capable of expanding (elastic recovery concept) is considered the best design approach.

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I. INTRODUCTION

A. PURPOSE AND SCOPE OF REPORT

This report was prepared by the Solid Mechanics Department of the Applied Mechanics Division, Aerospace Corporation, in response to a request from the Gemini B - MOL Program Office to determine the feasibility and application of expandable structures for construction of the transfer tunnel. The use of expandable structure has been proposed as an alternative to the heat shield hatch concept.(1)

The purpose of this report is to (1) furnish information on the current state-of-the-art of inflatable and/or expandable structures, (2) show application of current technology for the construction of the space tunnel, (3) investigate materials, composites, design, and fabrication processes, and (4) list the problem areas in connection with the construction of the transfer tunnel. Only those design concepts which are applicable to the astronaut transfer tunnel are discussed.

B. CURRENT DEVELOPMENT EFFORT

Current and advanced technology and development efforts in space erectables indicate a strong possibility of deploying a tunnel which will be capable of withstanding internal pressure, in space, for extended periods without appreciable loss in pressure.(2) Considerable research and development effort is currently being expended by the Air Force and NASA on expandable structures for space and ballistic reentry systems. Development of more resistant materials to meet space environmental conditions is vigorously being pursued. Fabrication techniques and processes for construction of transfer tunnels are considered adequate and may not require extensive development. Current technology on expandables indicates that a reliable, high performance, inflatable structure can be constructed if materials, design and fabrication techniques are properly chosen.

C. SOURCES OF INFORMATION

Information contained in this report was extracted from various sources on current and advanced technology on expandable structures. Technical information is also the result of Aerospace Corporation effort during the past two years on advanced systems research and planning studies on expandables in which the author has participated in the various systems and application studies of expandable structures.

Technical information was also extracted from reports published by other government agencies and laboratories as well as certain private contractors. These include: Air Force/Research and Technology Division, Aeropropulsion Laboratory, Materials Laboratory; Air Force/Space Systems Division; Goodyear Aircraft Corporation, Aerospace Division; Narmco Research and Development, a Division of Whittaker Corporation; and Battelle Memorial Institute, Radiation Effects Information Center.

II. CURRENT TECHNOLOGY FOR CONSTRUCTION OF EXPANDABLE STRUCTURES

A. TYPE OF CONSTRUCTION

Several types of expandable structures have already been designed for reentry and space applications.(3, 4, 5) These make use of pressure stabilized, foam rigidized, and self-rigidizable concepts. The specific design chosen for expandable structures is largely dependent on the system application and design requirements. A comprehensive survey on the various inflatable, expandable, and rigidizable structures is reported in a recent aerospace conference on expandable structures.(6, 7)

The composite wall of an inflatable structure can be fabricated from either organic or metallic fabric, the selection being dependent on the environmental conditions. The composite wall of the expandable structure may be fabricated by multi-ply laminations, woven seamless tubing, integrally woven core strands or cloth, or by the toroidal filament-winding method. Description and evaluation of these methods for various applications follows.

1. INFLATABLE STRUCTURES - PRESSURE STABILIZED

a. Airmat

The development of Airmat, a sandwich structure consisting of woven cloth faces and a core of vertical threads normal to the faces, offers shape control not otherwise possible with inflated materials. The space between the double wall can also contain a preformed flexible foam to provide insulation and micrometeorite energy absorption. This composite structure has been applicable to transonic, supersonic, and reentry regimes for ballistics and paragliders.(8, 9, 10) The flexible material also has a direct application to cylindrical or toroidal configurations for space application (Figure 1A).

Considerable theoretical and experimental work on expandable structures made from organic and metallic fabric has been reported. Studies have been made in four major categories:

(1) Methods of analysis of expandable fabrics and Airmat structures,
(2) Experimental determination of the usually-orthotropic stress/strain characteristics of fabrics and Airmat in various biaxial stress conditions,
(3) Technology and fabrication (weaving of Airmat, spot-welding techniques, coating procedures, etc.), and
(4) Structural response to external loadings at various pressures, including correlation of test data and theoretical results.

A number of other structural components, consisting of circular cylinders and Airmat beams and plates, have been tested under various loadings and pressure conditions.

Double wall Airmat type construction is directly applicable to the astronaut transfer tunnel. Fabrication processes, seam joining, foaming reinforcement, and field repair techniques have been developed. Elastomeric materials are available for space environmental conditions for low orbit and limited time for various mission requirements.

b. Flexible Impregnated Cloth-High Temperature Use

A flexible metallic filament-woven structure with a predictable strength, porosity, and folding endurance over a temperature range to about 1500° F, in combination with a flexible radiative coating, has been developed.(11) Low leakage rate and high strength make this type of structure applicable to expandable structures, contoured lifting surfaces, and rigidizable aerospace structures. An internal bladder, however, would be required for pressure maintenance.

2. FOAM-RIGIDIZED

a. Expandable Self-Rigidizing Honeycomb

This concept utilizes a flexible woven-fabric honeycomb or corrugated type core pre-impregnated with polyacrylic, polyurethane, or any epoxy plasticized resin.(12) The structure is initially flexible and can be rigidized after inflation. Loss of plasticizer or release of catalysts within the wall structure will cause rigidization. This method is considered to be in a development phase and is not recommended for current applications. A sketch of this design is shown in Figure 1B.

b. Predistributed Micro-encapsulation Foam

Encapsulated resin and catalyst formulations have been developed which produce foam by thermal activation or gas catalysts at a prescribed time. The dry powder encapsulants can be predistributed within a sandwich structure in the packaged condition prior to launch. Foaming in space can be initiated after the structure is inflated by either of the methods described above.(9) Other rigidization processes using dry powder have been developed by which foaming can be initiated either by thermal activation, ultra violet radiation, or gas catalysts.

3. ELASTIC RECOVERY

a. Composite Multi-Ply

An elastic recovery concept which sandwiches a compressible core between two or more flexible facings has been developed and evaluated for space expandable structures.(13) The materials used for this construction can be folded and compressed into an extremely small container and, upon release, the stored potential energy of the core will expand and rigidize the structure. This concept has all of the design features required of a good bumper-type meteoroid shield. The outer skin may be composed of a shield of aluminized mylar and act as a bumper as well. The foam will permit the shock wave to spread, as well as absorb some of the energy; the fabric will act as the major energy absorber.

The composite multi-ply configuration (Figure 1D) appears to have many advantages over the various wall configurations that may be adaptable for tunnel construction. It offers thermal as well as micrometeorite protection, and it contains a structural wall and also an outer and inner bladder type seal. An inner anti-scuff liner to protect the astronaut suit during maneuvers has also been considered.

A tunnel could be fabricated by applying Dacron fabric over a mandrel form, using a composite materials approach, built up layer by layer. The composite wall shown in Figure 1D is about 1-1/8 inches thick. For packaging, the total thickness would be compressed to 3/16 to 1/4 inch by exhausting air from the open cell polyurethane foam by vacuum.

Packaging densities for the wall construction shown in Figure 1D may range from 20 to 25 pounds per cubic foot, based on past packaging tests. The weight of the structural wall composite for either the toroidal or cylindrical tunnel is estimated to be about 65 pounds; this results in a packaging volume requirement of 2-1/2 to 3 cubic feet. The packaging volume allowance given by the envelope dimensions of the Gemini/MOL system, for example, indicates 3.1 cubic feet of volume available. Thus, the packaging requirement is consistent with the volume available.(2)

b. Filament-Wound Toroid

Analytical studies to optimize filamentary pressure vessels have been performed in which the matrix is considered to be compliant, the tension in the filament being the dominant load-carrying stress in the structure.(14) A filament-wound toroidal type of pressure vessel has been constructed and tested. Analytical techniques can be effectively used to obtain the necessary design criteria for construction of a toroidal filament-wound tunnel.

B. PROBLEM AREAS

No significant problems are expected in the area of fabrication for construction of Airmat, filament winding, foam-rigidized, or composite multi-ply structures. Joining, seaming and attachment of the tunnel ends to the hatch will, however, require further development. Final checkout of the compressed and packaged inflatable structure can be performed with pyrotechnics for abort. Explosive techniques can also be used to jettison the tunnel at the point of attachments.

The effect of aerodynamic heating during launch on the materials used for construction of the inflatable structure should be considered. A high temperature phenolic fairing laminate combined with high temperature insulation is recommended as a thermal protective system for the packaged expandable tunnel.

C. FOLDABILITY AND DEPLOYMENT

Methods of folding various types of expandable structures have been developed and successfully deployed in space. Some of the developments include such structures as the Inflatoplane, Paraglider, the Ballute, Echo I and II, and the more recent ground tests of the expandable solar power collectors. Tests performed on the Inflatoplane(4) indicate that wrinkles have a limited effect on Airmat pressure strength, for example. Repeated folding had a negligible effect on pressure losses, whereas dead load resulted in permanent set and creep after approximately 300 hours at room temperature. A good example of folding techniques and successful deployment has been demonstrated for Echo I and Echo II. The composite wall structure of Echo I consisted of an aluminized mylar film; for Echo II, mylar film was sandwiched between two layers of aluminum foil. Both organic and metallic cloth materials are applicable as outer skins for double wall sandwich construction. Metallic impregnated cloth, however, will be more susceptible to the effect of wrinkling, folding and strength losses than organic type fabrics.

Take for example the elastic recovery concept for expandable structures(13) which can be folded and compressed into an extremely small container. Upon release, the stored potential energy of the compacted material is sufficient to expand and rigidize the structure. Advantages of this system are:

(1) High ratio of expanded volume to packaged volume, i.e., between 30:1 and 100:1.

(2) No auxiliary force required for expansion, such as gas pressurization, chemical reaction or mechanical devices.

(3) The method is adaptable for multiwall construction for meteorite and radiation protection.

(4) The structure is extremely light in weight.

(5) Construction is based on available state-of-the-art materials which are compatible with space environments.

(6) Fabrication is adaptable to standard manufacturing processes.

(7) The method offers reliable expansion incorporating fail-safe principles.

The weight of the structural composite wall for the elastic recovery concept described above would vary between 0.370 to 0.732 pounds per square foot (Table 1), i.e. if the composite is made of Dacron fabric and polyurethane foam. The deployment sequence which occurs (for the tunnel design) would be as follows: First, the stored energy of the compressed foam (micrometeoroid barrier compressed for packaging) may be used to automatically deploy the structure to its general shape. Second, a small amount of (purposely) entrapped air may be used to augment deployment by forcing full expansion to final shape of the structure at low pressure. Thus, either one or both methods can be used to effect automatic deployment of the structure. The only requirement in the deployment sequence would be the jettisoning of the cover plate, after which the structure would automatically deploy to final shape.

Recent developments utilize an expandable-foam rigidizable concept which was used for the construction of 44-foot diameter solar collectors in conjunction with the Reflector Orbital Experiment.(6, 9) In addition, an expandable self-rigidizable concept which is capable of a high packaging efficiency and positive pressure deployment has also been demonstrated.(12) The potential of a foldable, space deployable, filament-wound pressure chamber capable of withstanding internal pressures up to 1110 psi has also been demonstrated.(15)

In summary, it can be stated that with existing materials it is possible to design and fabricate a space chamber for astronaut transfer with a reasonably high degree of reliability. High packaging efficiencies are also obtainable; this, of course, will be dependent on the design and materials selected.

D. RIGIDIZATION

Several methods of rigidization have been investigated, some of which have been developed for various applications. These include: solvent release of plasticizer; hardening by resin/catalyst; thermal cure; ultra-violet cure; high energy radiation; foam in place (powder); foam in place (encapsulation); and strain hardening of metal foil.

Variable density of foam can be pre-determined by formulation. Rigidization can be controlled remotely, so that complete cure can be attained within two to four hours using solar energy and space vacuum.

If a high packaging density is required, a predistributed foam powder could be used within a sandwich structure. The foaming process of this formulation could be initiated by thermal activation or release of a gas catalyst or solvent. Where criticality of packing density is not important, the elastic recovery concept which utilizes a preformed foam as the sandwich material is preferred over foam-in-space reaction.

E. REINFORCEMENT MATERIALS

Materials which are most applicable for the astronaut inflatable tunnel are organic fibers, yarns, cloths, elastomers, and special coated cloths. Property comparisons of some filamentous materials are given in Table 2. Details on description of materials follows.

1. YARNS

The effect of temperature on the ultimate tensile strength and modulus of nylon, Dacron, and HT-1 fiber is given in Figures 2 and 3. Data shown in these curves indicate that Dacron 52 has the best all-around properties applicable for an inflatable tunnel. Dacron 52 exhibits a much higher strength-to-weight ratio than HT-1 for temperatures up to 350°F, as shown in Figure 4. The yarn breaking-tenacity and strength-to-density ratio versus temperature for various fibrous materials are plotted in Figure 5.(16)

2. UNCOATED FABRIC

Load-elongation curves for Dacron 52 cloth are given in Figure 6. A single ply of Dacron 52 has an ultimate breaking strength of 400 pounds per inch in the warp and 700 pounds per inch in the fill direction at 40 percent elongation. Yarn strength to fabric strength is also compared. Dacron is preferred over nylon because of its higher modulus and tensile strength. The strength properties of plain Dacron 52 cloth as a function of weight and thickness are plotted in Figure 7. Physical properties and specifications of Dacron cloths are given in Tables 3 and 4, respectively.

3. COATED CLOTHS

Important considerations for selection of a coated fabric for tunnel construction are: strength/volume ratio, strength/weight ratio, permeability, flexibility, and packaging characteristics. Other considerations include reinforcements and degree of shear stiffness required for two-ply cloth laminates. Weight and physical properties of Dacron/elastomer coated cloth are given in Tables 5 and 6. Tensile strengths for Dacron/Hypalon and Dacron/neoprene were found to be practically the same.

4. AIRMAT CLOTH

Both organic type (Dacron or nylon) and metallic cloth (stainless steel, Rene' 41, etc.) can be used for Airmat type construction. The selection of reinforcment materials is usually governed by the design requirements, environmental factors, ease of packaging and method of deployment.

Properties of Dacron cloth used for Airmat construction are given in Table 7. If the temperature requirement exceeds 500°F, metallic cloth coated with a silicone ceramic frit, CS105 for example, can be effectively used.(11)

Mechanical property data for stainless steel Airmat cloth are given in Table 8. These data show that the ultimate tensile strengths for the stainless steel and Dacron cloths are about the same at room temperature. Ultimate tensile strength and elongation for stainless steel wire and stranded yarn are given in Table 9. These results can be compared to the organic yarns shown in Figure 2. Single-ply Dacron cloth, coated or uncoated, is one-fourth the weight of an equivalent stainless steel cloth.(17) See Table 10.

F. FABRICATION PROCESSES

1. AIRMAT CONSTRUCTION

Since adequate information is available in literature on Airmat,(3, 10) only a brief description regarding its construction will be given. Airmat consists of two layers (face piles) of cloth impregnated with an elastomer or sealant to withstand pressurization and joined by drop threads extending between the upper and lower fabric surfaces (Figure 1A). When pressurized, the structure attains a predetermined shape as established by the lengths of the drop thread. With Airmat construction, sections can be formed in the shape of flat panels, contoured airfoils, or varying cross-sectional shapes.

a. Foamed Airmat

A semirigid wall structure can be constructed by filling the Airmat cavity with polyurethane foam under pressure. A foam density of 1.2 pounds per cubic foot is recommended for meteoric protection as well as a separator and stiffener for the double wall construction.

b. Foam-in-Space Airmat

The technique of foaming the sandwich structure in space is considered to be currently feasible. A predistributed resin formulation of encapsulated material (NCR Formulation) could be applied and foamed upon thermal activation.(9) Initiation of the reaction could be remotely controlled. This method is recommended if only a high packing density is required.

c. Problem Areas

Some problems in fabrication are anticipated for the construction of a cylindrical Airmat transfer tunnel, especially in the joining area. Either Dacron or stainless steel cloth can be woven and impregnated with special modified elastomers such as silicone, butyl, neoprene, and Hypalon sealants. Foaming remotely in space is considered to be under development. The method of attachment of the cylindrical section to the hatch of the Gemini and MOL is an area of most concern. With proper design and reinforcement, no serious problems are anticipated.

2. INTEGRALLY WOVEN SANDWICH CORE CONSTRUCTION

A new technique has been developed which integrally weaves the core to the outer skins. The structure can be made from Dacron, glass or steel filamentous materials. By adapting the weaving process, three-dimensional cloth preforms can be fabricated into symmetrical or irregular shapes. Details of fabrication of this type of sandwich construction are described by the manufacturer.(5) The most significant property of this type of construction is the web integrally woven to the facings. Peeling or delamination of the integrally woven skin from the core is rather difficult without causing core damage.

3. FOAM FLUTED CORE

The integrally woven fluted core can be inflated and filled with a low density foam similar to the process described for the Airmat construction. The sandwich construction can be prefoamed prior to launch or foamed in space. If a high packing density is required, foam-in-space techniques can be used. A predistributed foam resin can also be used in the foaming process. A preformed foam sandwich structure is recommended since relatively high packing densities can be obtained. A typical cross-section of the fluted core is shown in Figure 1B.

Seaming and attachment of the tube to the hatches of the space structures are considered critical problem areas. If longitudinal fluted cores are used, methods to increase hoop strength remain to be solved. Bonded joints and reinforcement will require further development.

4. FILAMENT WOUND CONSTRUCTION

The construction of a cylindrical filament-wound pressure vessel for astronaut transfer is considered to be entirely feasible. Advanced technology of filament winding used for the development of the Minuteman and Polaris rocket motor chambers is applicable for the construction of the astronaut transfer tunnel. Packageable filament wound Dacron/polyurethane containers have been fabricated for operating pressures up to 560 psig. This type of structure is adaptable to space inflatable pressure stabilized structures. For this type of structure, a polyurethane foam sandwich would be required on the outer shell for material protection. Various sizes of inflatable filament-wound structures have been fabricated using glass and/or Dacron filament with epoxy and elastomer type resin binders. Properties of various filamentous materials are given in Table 2. Monolithic pressure vessels 3 feet in diameter by 24 feet long, and 7 feet in diameter by 13 feet long, with elliptical or hemispherical domes, have been constructed. The properties of the 2-foot diameter by 24-foot long Dacron/neoprene filament-wound structure are as follows:(2)

Operating pressure, psig	15
Design burst, psig	45
Material density, lb/ft^3	70
Foam density, lb/ft^3	1 to 1.2
Packaging factor (no foam)	3
Packaging factor (foam)	4
Packaging density, lb/ft^3	25
Percent of inflated	2

If a monolithic cylindrical pressure vessel with hemispherical domes is filament wound, it will be necessary to cut each dome and attach a segment of a filament-wound elbow to fit the hatches of the space vehicles. Joining of the curved section to the cylinder will require further development and is a problem area.

III. SPACE ENVIRONMENTAL EFFECTS ON ELASTOMERS

There is, at present, some concern regarding the resistance of elastomeric materials in space environment. Results of recent ground tests on elastomeric materials subjected to combined vacuum, ultra violet radiation, and temperature predict 10 percent degradation (weight loss) for periods up to one year. It is predicted that this degradation will not seriously affect the strength properties of the material.

The effect of a space environment on elastomers is discussed as follows:

(1) The effect of UV radiation on elastomeric materials can be overcome by vapor depositing a metallic coating on the surface.

(2) High energy radiation is considered more damaging than UV radiation. The effects of high energy radiation on materials such as plastics is not considered too severe in the lower fringes of the Van Allen belt, however, the extent of deterioration will be a function of exposure time. In some instances, the use of controlled high energy radiation is used to enhance the strength properties of organic polymers by radiation cross-linking.(19)

(3) High temperature effects should not be a serious problem since coatings are available for thermal control. Thermal balance may, however, be altered since the α/ϵ ratio will change with time due to the erosive effect of meteoric impact. A foam interlayer material will act as a thermal barrier in addition to protecting the structural skin from meteoric damage.

(4) The effect of vacuum is not considered to be too critical for the time period involved. Results indicate that the greatest loss of volatiles from elastomers occurs in the initial few hours when placed in a hard vacuum, after which time the losses are not too significant.

(5) Protection against micrometeorites can be accomplished by a low density foam, 1.2 pounds per cubic foot. The probability of no penetration through the tunnel wall for a one-year period can be expected to approach 0.995.(2)

To summarize, results of extensive development programs indicate that neoprene, butyl, polyurethane and silicone are the most promising elastomers for space applications. For extreme temperature range usage (-100°F to +250°F) silicone appears to be the best material; its permeability, however, is not considered favorable. Polyurethanes have best resistance to vacuum, UV, and high energy radiation. Both Dacron/neoprene and Dacron/Hycar exhibit the best resistance to permeability over other types of elastomers, with polyurethane showing a slightly higher permeability. Lower permeability values can be expected for lower temperatures.

A. ULTRAVIOLET RADIATION

Ultraviolet radiation will affect only those elastomeric parts of a space vehicle exposed to solar radiation. Elastomeric material can be protected by a thin metallic coating. Vapor-deposited aluminum, 4,000 Angstroms thick, for example, has been considered adequate to protect mylar film and other plastic material. Tests have been conducted on the coatings under combined vacuum and UV exposure of 75,000 joules/cm^2 (equivalent to 70 days of continuous exposure to solar UV). Results showed that only minimum degradation occurred and that an orbital life expectancy of one year can be expected for elastomeric materials.

B. VACUUM

An elastomer exposed to high vacuum quickly loses its volatile constituents. The rate will vary with the vapor pressure of the material and the temperature and time of exposure. The effects of high vacuum at elevated temperatures on physical and mechanical properties of various elastomers have been thoroughly investigated.(20, 21, 22) Results of tests indicate that the silicone elastomer experienced no loss in strength after exposure to 1.2×10^{-4} mm Hg at 450° F after 4.5 hours.

A 60-day test on polyurethane elastomers, foams and Dacron fabrics under hard vacuum conditions (10^{-6} torr) was conducted which resulted in a negligible weight loss of plasticizer boil-off. From the results of such tests, it has been concluded that a one-year lifetime for such materials under vacuum conditions is entirely feasible and realistic.(18) Degradation appears to be more severe with the combined effect of vacuum, temperature and UV radiation. Experiments have also proven that air aging at elevated temperature is more severe than high vacuum exposure, which indicates that oxygen under normal atmospheric conditions presents a more severe condition than the extreme vacuum.

The effect of vacuum environment on the mechanical properties of polymeric materials in combination with ultraviolet radiation is given in Table 11. Tests performed at 280°F at 5×10^{-6} mm Hg for 120 hours resulted in a weight loss between 5.7 and 7.8 percent for the neoprene, butyl, silicone and polyurethane elastomers.(23) The rate of weight loss was generally higher in the initial exposure period in which the strength reduction varied between 30 and 64 percent. The resistance of elastomers to vacuum and UV radiation can be considerably increased by the application of metallic coating facing the radiation source. A vapor-deposited aluminum or aluminum powder in polyurethane resin has proved to be effective in the coating for a Dacron/neoprene fabric. This material resulted in a weight loss of 2 percent and reduction in tensile strength of 1.1 percent after 770 hours at 60°F. It has been reported that the primary result of UV radiation in a vacuum is polymer cross-linking instead of polymer degradation or scission.(24) Because of this, it was considered that some polymers should be more resistant to UV radiation in a space environment than in the earth's atmosphere. Butyl rubber, Viton A and B, and LS-63 fluoro-silicone were found to be most resistant, whereas ordinary silicone elastomer is considered to be least resistant.

The effects of vacuum on temperature limits for various elastomers(20) are given in Table 12. The temperature required to produce 10 percent weight loss per year at 10^{-4} mm Hg indicates that silicone and Viton fluoro rubber are the most temperature resistant.

C. SPACE RADIATION

The effect of high energy radiation on elastomeric materials is considered far more damaging than UV radiation. The only polymeric materials that have been found to sustain exposure of 10^9 rads are asbestos-filled phenolic, polystyrene, furan-type resins and polyvinyl carbazole.(20, 25)

Generally, the tolerance of elastomeric materials to high energy radiation varies between 10^7 to 10^8 rads. For a composite structural wall (as shown in Figure 1D), the material that would be least sensitive to radiation damage would be polyurethane elastomer. The tolerance of this material (50 percent decrease in elongation) is 10^8 rads (Cobalt 60 source). The dose absorbed by passing through the lower fringes of the Van Allen belt (low energy electrons in keV range) would have to be calculated and related to the MOL orbit. However, estimates have already been made for solar flare radiation effects (high energy protons in the MeV range) indicating a materials tolerance for 100 to 1000 Class 3+ flare encounters. As a result, electrons in the lower fringes of the Van Allen belts are not expected to pose any problem. Of the elastomer materials, natural rubber and SBR are considered to be most resistant and have a life expectance of about 200 hours when exposed to radiation intensities in the order of 10^5 rad/hr. in vacuum.(2)

The stability of organic polymers can be related to molecular structure and degree of cross-linking.(19) A comparison of thermal and radiation stability of elastomers is presented in Table 13. Whereas silicone is most thermally resistant, it ranks fourth for radiation resistance. Polyurethane ranks fourth in temperature resistance and is regarded an excellent choice of material. In general, elastomers are not as resistant to radiation as the majority of plastics.(20, 26)

D. TEMPERATURE

The effect of extreme temperature cycling ($+250^{\circ}F$ to $-100^{\circ}F$) on elastomeric materials used for the transfer tunnel is not considered critical. Materials can be selected compatible with earth-orbital environment such that a fair degree of flexibility can be expected over the entire temperature range. Silicone elastomers, for example, are reasonably flexible at $-60^{\circ}F$ and become progressively rigid as temperature is decreased. A number of changes can take place in an elastomer as a result of exposure to low temperature. It is important to note that these changes are reversible. Returning the material composition from cryogenic to room temperature, or slightly elevated temperature, results in a restoration of its original properties. The effect of extremely high temperature exposure on the elastomer may, however, produce a permanent change in composition and properties of the material.(23)

No serious degradation of silicone material is expected for temperatures varying between $-100^{\circ}F$ to $250^{\circ}F$ as may be encountered for the transfer tunnel. High temperature gradients (that may occur due to attitude of the structure in space) will not greatly affect the composite wall structure. Silicone elastomer, for example, is fairly resistant to high temperature gradients such as would be encountered at the hot/cold junctions caused by the shadow-direct solar impingement effect.

For elastomeric materials, the tensile modulus increases with decreasing temperature and may increase in stiffness a hundred-fold over a narrow temperature range. The temperature at which abrupt changes occur in the slope of property versus time is defined as the transition point of a material. Around the transition temperature, the modulus of elasticity may increase by a factor of 400 to 1000 and the coefficient of expansion could decrease by a factor of 3 or more.(23) Since the elastomer composite materials can be reinforced with fibers, resistance to shatter or sudden bending or impact is considered to be good. The resistance to failure of the material at lower temperature will also be dependent on the rate of application of load. Stiffness of several elastomers over a broad temperature range is shown in Figure 8. Whereas silicone appears to have good low temperature flexibility down to -120°F, neoprene flexibility may become critical at temperatures varying from +40 to -20°F, depending on the chemical structure. Any material to be used in space environment for temperatures near or below the stiffening temperature should be analyzed in terms of predicted component temperature and strain rate in addition to verification by laboratory experiments. The selection of elastomers that will not crystallize or become brittle at low operating temperatures should also be taken into consideration.

E. PERMEABILITY AND LEAKAGE

Permeability is not considered to be a serious problem, as one may expect, since leakage rates as low as 10^{-5} pounds of gas per ft^2-day have been experienced with various materials. Recent information on the effect of heat aging and hard vacuum exposure for Dacron with various elastomers is given in Table 14. Results of tests indicate that polyurethane, neoprene, butyl and silicone elastomers all have low permeability rates; butyl and neoprene elastomers being most impermeable. Dacron/neoprene permeability at 11 psig increased by a factor of 300 after heat aging at 150°F for 100 hours. After vacuum exposure for 2 months at 2×10^{-4} torr, the leakage rate was increased from 0.606×10^{-7} to 0.06×10^{-6} $cc/cm^2/sec/cm$. Gas permeability constants for several elastomers are compared in Table 15.

F. METEOROID PENETRATION

The effect of meteoroid penetration on various types of materials and composite structures has been extensively studied. An over-all survey of the theoretical and experimental work conducted in the area of hypervelocity impact by the Air Force, NASA, and others has been reviewed by Frost.(27) A composite double-wall construction consisting of a low density polyurethane foam (1.2 to 1.5 pounds per cubic foot) sandwiched between a coated Dacron fabric is considered a good design approach.

Hypervelocity impact tests were recently conducted at Armour Research on polyurethane as a micrometeorite barrier. It was concluded that polyurethane foam is 10 times as effective as single sheet aluminum on the basis of equal mass per unit area. At a projectile velocity of 20,000 fps, it was found that aluminum will suffer greater damage than an equivalent weight of fabric wall.(28, 29) A 1.2 pounds per cubic foot barrier is considered equivalent to an aluminum sheet 0.36 cm thick (0.96 gm/cm^2) with respect to penetration resistance. Considering the 0.36 cm thickness of aluminum, the corresponding critical particle mass for penetration is 6.5 x 10^{-3} gm. The penetrating particle flux corresponding to the critical mass is 2.3 x 10^{-8} particles/ft^2-day. The probability then of no penetrations through the tunnel wall for a one-year period may exceed 0.995.(2)

A summary of penetrated weight of several target specimens by pyrex projectiles of approximately equal velocities (20,000 ft/sec) is given in Table 16. The order of specimens lists the most resistant specimen first and subsequent specimens in a descending order of resistance. The total penetrated weight of the specimens seems to decrease as the bumper and spacer masses decrease to some finite value.

Hypervelocity particle impact tests conducted on a space shelter indicated that the double-wall construction offers >0.995 probability of no penetration on a 310-square foot area for 400 days.(18) For tunnel design, the outer surface could consist of organic, glass or metallic cloth. The bumper (metal or glass) acts to fragment the particle upon impact, whereas the foam spacer acts as an energy absorber and arrests the particles by vaporization.

The effect of meteoric impact on a fabric/elastomer skin under stress should also be considered. Catastrophic rupture could occur if the material is notch sensitive and has a low tear resistance.

IV. CONCLUSIONS

Results of this study indicate that the application of inflatable and/or expandable type structures for construction of an astronaut transfer tunnel is feasible. Materials and fabrication methods have been devised to meet the design requirements and space environment for a limited time period. Current technology is sufficiently advanced such that the construction of an expandable tunnel can be realized if materials, fabrication methods, and design are properly chosen. A self-erectable double-wall composite consisting of a preformed foam interlayer capable of expanding (elastic recovery concept) is considered the best design approach for immediate application. Future expandable systems for space application may utilize foam-in-place methods.

The effect of space environment on materials used for construction does not appear to be as critical as anticipated for the proposed orbiting altitude and time periods considered. Some degradation of elastomeric type materials is expected; however, the extent of deterioration will not seriously impair the strength property of materials proposed for tunnel construction. Life expectancy for the most resistant materials used for the tunnel is estimated between 6 and 12 months.

High packaging efficiency is obtainable for inflatable structures such that a composite two inches thick can be depressed to a reasonably small package. Weight of the composite wall structure may vary between 0.370 and 0.732 pounds per square foot excluding attachments.

Fabrication and deployment methods for the proposed tunnel do not impose any restrictions regarding size or geometry. Methods of repairing and sealing defects such as small pinholes or cracks to prevent leakage of internal pressure during inflation are readily available.

Table 1. Weight Comparison Estimates for Various Composite Structures.

(A) Airmat	lb/ft^2
Dacron/elastomer, 52 oz/yd^2, two-ply	0.164
Foam, polyurethane, 1.2 lb/ft^3	0.100
Bladder pressure seal	0.080
Thermal coating, 1 mil	0.001
Aluminum foil bumper, 1.8 mil	0.025
	0.370
Stainless steel cloth (100 x 100 x 0.0045) two-ply plus coating, foam and bladder	0.532
(B) Integrally Woven Structure	
Dacron/elastomer, 52 oz/yd^2	0.382
Foam, polyurethane, 1.2 lb/ft^3	0.100
Bladder pressure seal	0.080
Thermal coating, 1 mil	0.002
Aluminum bumper, 1.8 mil	0.025
	0.589
Fiberglass/elastomer plus coating, foam and bladder	0.732
(C) Filament Wound	
Dacron/elastomer plus coating, foam and bladder	0.289
Stainless steel/elastomer plus coating and bladder	0.407

Table 2. Properties of Some Filament Wound Pressure Vessel Materials (Reference 14).

Material	t_m Melting Point °F	ρ Density lb/in^3	E Modulus 10^6 in.	E/ρ 10^6 in.	F_{tu} Ult. Strength 10^3 psi	F_{tu}/ρ Sp. Strength 10^6 in.
Filament						
Nylon	450	0.041	0.7	17	134	3.0
HT-1	800-1000	0.050	2.7	50	100	2.0
Dacron	450	0.050	1.9	38	140	2.8
E Glass	1400	0.09	9	100	300	3.3
S-994	1400	0.09	10	110	400	3.3
Carbon Steel Wire	2700	0.29	29	100	640	2.2
Boron Filament	3400	0.09	55	610	500	5.5
Composites - 30 % Fiber - 20 % Matrix						
Dacron Polyurethane	400	0.05	1.5	30	112	2.2
E-Glass Epoxy	450	0.082	7.2	87	240	2.9
S-994 Glass-Epoxy	450	0.082	8.0	98	320	3.9
Steel Wire - Polyurethane	450	0.240	23	96	510	2.1
Boron-Epoxy	450	0.082	45	550	400	4.9

Table 3. Physical Properties for Nylon and Dacron Cloth (Reference 3).

Property	Nylon Code 3594	Dacron Code 9004
Weight, oz/yd^2	12.0	12.9
Tensile; lb/in., warp/fill	625/625	600/600
Weave	2 x 2 basket	plain
Yarn type	300	52
Yarn size, denier	1050	1100
Yarn ply, warp/fill	1/1	1/1
Yarn/inch, warp/fill	40/40	42/36

Table 4. Specification Properties of Finished Cloth (Reference 3).

Property	Specification		Wellington Sears	
	Type I	Type II	Type I	Type II
Weight, oz/yd^2	9 ± 0.5	12 ± 0.7	9.8	12.9
Tensile, lb/in.	(min)	(min)		
Warp	400	500	466	553
Fill	600	800	649	882
Elongation	(max)	(max)		
Warp	25	25	14.8	20.8
Fill	25	25	21.2	19.5
Count				
Warp	Not specified	Not specified	48	58
Fill	Not specified	Not specified	37	49

Table 5. Two-Ply Weight of Various Cloth-Elastomers (Reference 18).

Cloth-Elastomer	Fabric Weight, oz/yd^2	Fabric Thickness, inch
Nylon-Neoprene	43.5	0.0566
Nylon-Butyl	40.4	0.0570
Nylon-Hypalon	47.0	0.0599
Dacron-Neoprene	52.2	0.0560

Table 6. Physical Properties of Dacron-Elastomer Coated Cloth (Reference 18).

Tests	Dacron 52		Dacron Neoprene		Dacron-Hypalon	
	RT	160°F	RT	100°F	RT	160°F
Strip Tensile, lb/in.						
Warp	830		825	762	794	782
Fill	832		750	666	837	677
Permeability						
cc/m^2/24 hr atmos.	---	---	142	131	67	61
Weight, oz/yd^2	18.75		39.1		37.6	
Thickness, in.	0.030		0.047		0.047	
Density, lb/ft^3	52		69.4		72.8	

Table 7. Properties of Airmat (Dacron Cloth) (Reference 18).

Property		Property	
Material	Dacron	Yarn ply	1
Yarn type	51	Weave	Plain
Yarn size, denier	220	Yarns/in., warp/fill	112/50
Yarn filaments	50	Weight, oz/yd^2, face ply	5.0
Yarn twist, turns/in.	7	Pile or drop threads, yarns/in.^{2}	25
Ult. tensile strength, lb/in.		Burst strength, psi	50
Warp	200		
Fill	115		

Table 8. Mechanical Properties of Stainless Steel and Dacron Cloths (Reference 17).

Material	Direction	Strength lb/in.	Elongation Percent
Type 304 Stainless Steel 100 x 100 x 0.004 Monofilament Cloth	Warp	129	23.0
	Fill	167	10.9
Type 304 Stainless Steel 100 x 100 x 7(0.0016 in. diameter) Stranded Yarn Cloth	Warp	136	31.8
	Fill	163	17.2
Type 304 Stainless Steel 98 x 98 x 0.004 Airmat Faces (Basket Weave)	Warp	153	14.5
	Fill	160	16.3
N363A10 Dacron	Warp	170	20.0
	Fill	150	20.0

Table 9. Mechanical Properties of Metal Wire and Stranded Yarn (Reference 17).

Material	Ult. Tensile Strength, psi	E x 10^6 psi	Ult. Elongation, %
Type 304 Stainless Steel Airmat Wire 0.0045 in. diameter	115,330	(warp) 4.4 (fill) 10/5	33.8
Type 304 Stainless Steel Stranded Yarn 7 x 0.0016	130,640	---------	45.6

Table 10. Weight Comparison (lb/ft^2) of Coated and Uncoated Steel and Dacron Cloth Material (Reference 17).

Material	Uncoated	Coated	Elastomer Weight	
			Total	per ply
Single Ply				
Standard Cloth (SS)	0.134	0.218	0.083	0.083
Stranded Cloth (SS)	0.122	0.222	0.100	0.100
Dacron	0.283	0.049	0.021	0.021
3-inch Airmat (SS)	0.328	0.516	0.188	0.094
Two-ply (SS)				
Stranded Cloth	0.270	0.425	0.155	0.078
3-inch Airmat	0.598	0.926	0.082	

SS = stainless steel

Table 11. Effects of Combined Vacuum and Ultraviolet Radiation on Polymer Materials (Reference 23).

Material	Loss in Weight, %	Loss in Ultimate Tensile Strength, %
Neoprene	7.8	30
Butyl	6.6	57
Silicone	5.6	67
Urethane	5.7	64
Aluminized Dacron/Neoprene	1.94	1.1

Table 12. Effect of Vacuum and Temperature Limits for Various Elastomers (Reference 20).

Elastomer	Temperature Required for 10% Weight Loss per Year at 10^{-4} mm Hg
Vitonfluoro rubber	490 °F
Silicone	400 °F
Buna-N	300-450 °F
Butyl	250 °F
Neoprene	200 °F

Table 13. Comparison of Thermal and Radiation Stability of Elastomers (References 20, 25).

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

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

Table 14. Environmental Effect on Strength and Permeability of Elastomer-Coated Fabrics (Reference 30)

Material Condition	Dacron Polyurethane	Percent Change	Dacron Neoprene	Percent Change	Dacron Hycar	Percent Change	Nylon Neoprene	Percent Change
As received (Control)								
Thickness, inches	0.023	----	0.016	----	0.047	----	0.052	----
Break Strength, lb								
Warp	347	----	435	----	432	----	821	----
Fill	316	----	328	----	333	----	670	----
Tear Strength, lb								
Warp	4.7	----	9.0	----	28.6	----	65.4	----
Fill	5.3	----	10.1	----	87.2	----	88.1	----
Permeability; air, 11 psig (cc/cm^2/sec/cm)	0.03×10^{-7}	----	0.006×10^{-7}	----	0.06×10^{-7}	----	0.373×10^{-7}	----
Heated Aged 100 Hr at 158°F								
Break Strength, lb								
Warp	393	+5	465	+7	459	+6	345	+3
Fill	328	+4	335	+2	387	+16	708	+6
Tear Strength, lb								
Warp	4.7	0	0.1	+1	28.9	+1	76.9	+18
Fill	5.4	+2	9.8	-3	73	-16	81.9	-7
Permeability; air, 11 psig (cc/cm^2/sec/cm)	0.03×10^{-6}	----	0.02×10^{-7}	----	0.042×10^{-7}	----	0.58×10^{-7}	----
Weight Change, Percent	-0.5	----	-0.9	----	-0.6	----	0	----
Hard Vacuum Exposure (2 Mo at 2×10^{-4} Torr)								
Break Strength, lb								
Warp	263	-30	168	-61	432	0	657	-2
Fill	201	-36	137	-68	272	-18	691	+3
Tear Strength, lb								
Warp	4.5	-4	10.2	+13	20.8	-27	74.9	+15
Fill	6.1	-15	10.3	+2	46.3	-47	85.5	-3
Permeability; air, 11 psig (cc/cm^2/sec/cm)	----	----	0.06×10^{-6}	----	0.09×10^{-7}	----	----	----
Weight Change, Percent	----	----	-0.9	----	-6	----	----	----

Table 15. Gas Permeability Constants for Various Elastomers at Room Temperature*

	$\times 10^7 \frac{cm^2}{sec\ atm}$						
High Polymer	N_2	O_2	Air	H_2	CO_2	He	CH_4
Natural rubber	2	2	1	3	3	3	2
SBR	0.5	1	0.7	3	9	2	2
Butyl	0.08	0.05	0.1	0.4	0.2	0.9	---
Hypalon	---	---	0.7	---	---	---	---
Neoprene	0.1	0.3	0.1	1	2	0.6	0.2
Buna N**	0.02	0.07	0.1	0.2	0.4	0.1	0.04
Thiokol FA	---	0.02	---	0.3	---	---	---
Silicone	70	---	10 - 70	---	200	100	---
Poly FBA	---	---	2	---	---	---	---
Urethane	0.04	0.1	0.05	---	---	---	---
Viton	---	---	0.007	---	---	---	---
Polyethylene	0.09	0.3	---	0.8	---	0.6	---
Teflon	0.02	0.8	---	2	---	60	---

Water Vapor Permeability Constants $\times 10^8$ measured in gm/hr/cm^2/cm

Natural rubber	7
SBR	10
Neoprene	3
Polysulfide	0.2

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

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

Source: SWRT. Also References 23 and 25.

Table 16. Penetrated Weight of Target Specimens (Reference 28).

Bumper Wall		Spacer		Penetrated Weight, lb/ft^2		
Material	Weight, lb/ft^2	Material	Weight, lb/ft^3	Total	Outer Wall	Foam
None	---	PU foam	1.2	0.20	----	0.20
1 mil Mylar	0.01	PU foam	1.2	0.21	0.01	0.20
Fiberglass-silicone	0.17	PU foam	1.2	0.33	0.17	0.16
Rene 41 - CS105	0.16	PU foam	1.2	0.36	0.16	0.20
Aluminum 2024T3	0.17	PU foam	1.2	0.37	0.17	0.20
Dacron-Neoprene	0.17	PU foam	1.2	0.39	0.42	0.78
Dacron-Butyl	0.42	Flexible PU	6.0	1.20	0.42	0.78

PU = Polyurethane
Projectile density = 2.12 gm/cm^3

Mass = 4.54 mg

Velocity = ~ 20,000 fps

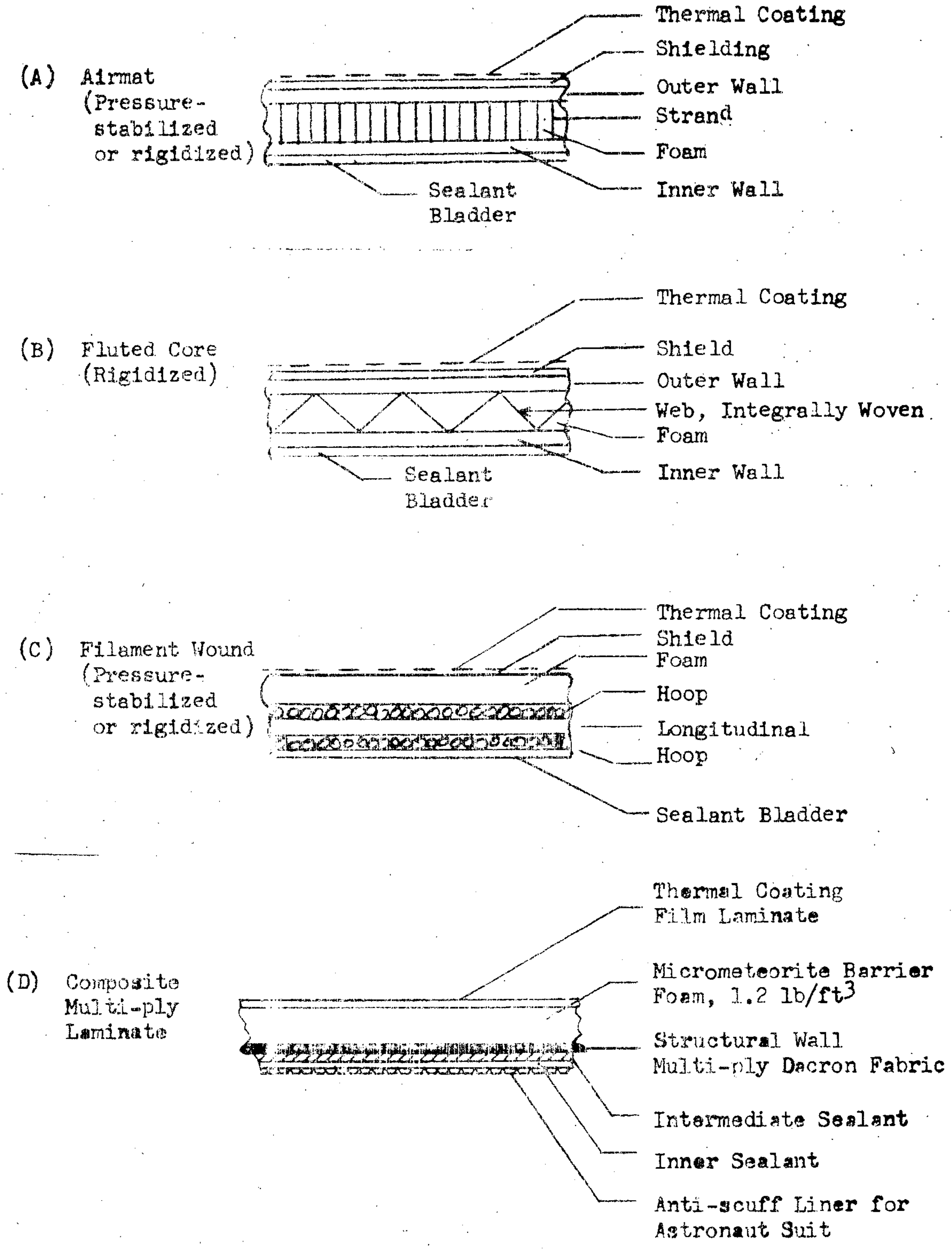


Figure 1. Composite Wall Configurations

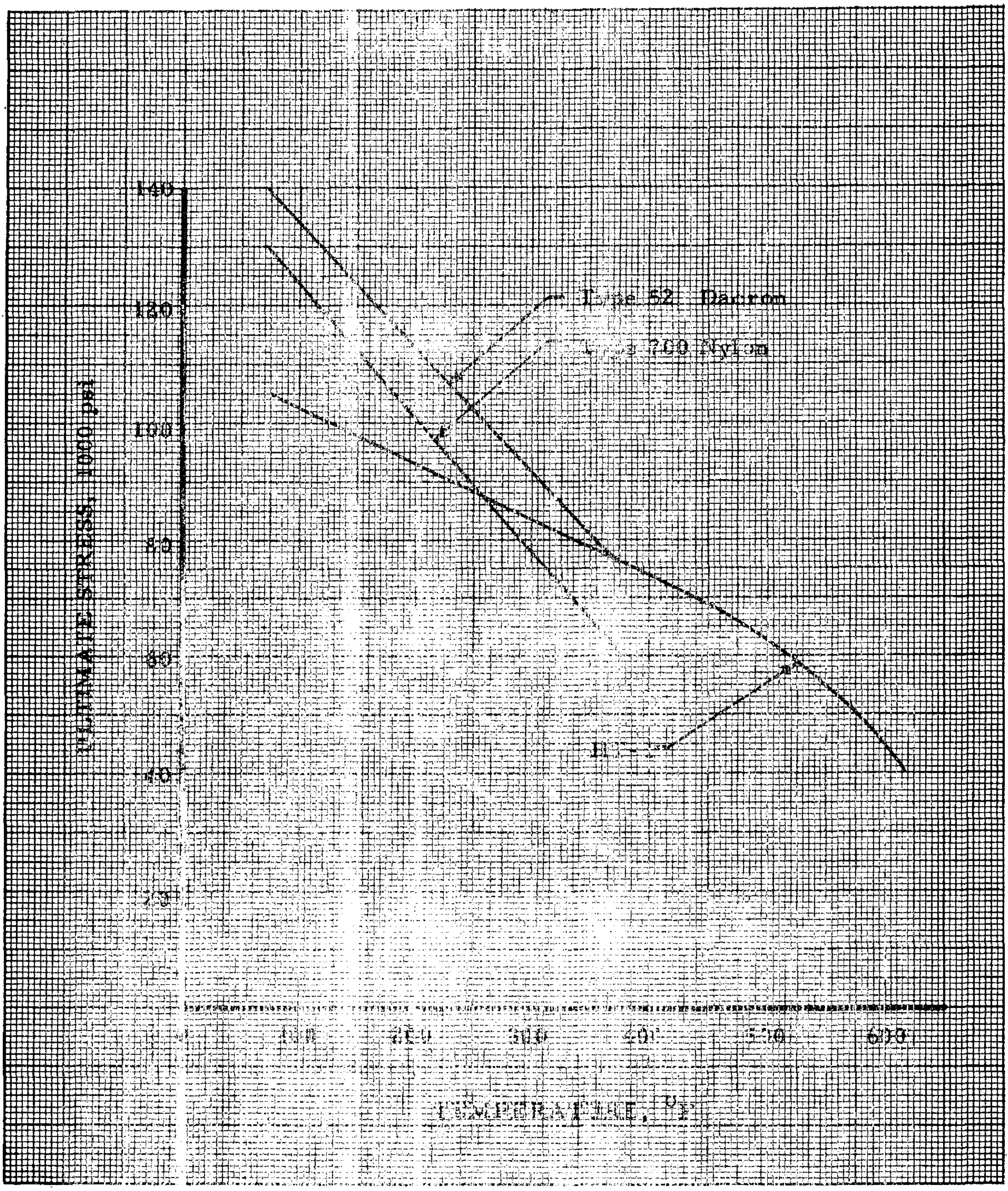


Figure [illegible] Yarn Ultimate Stress Versus Temperature (Reference 3).

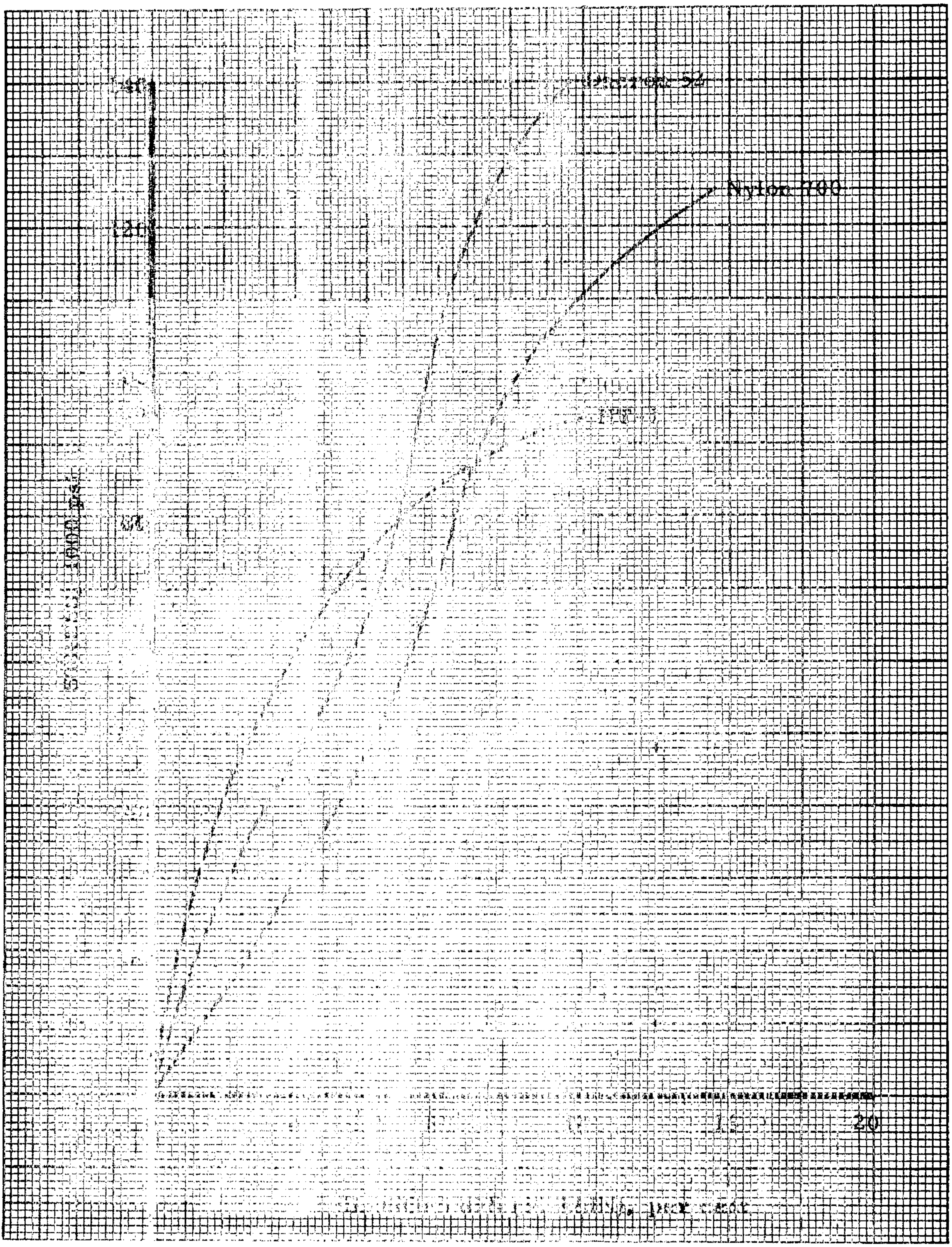


Figure [illegible] [illegible] Stress-Strain Curves at
[illegible] Temperature (Reference 5).

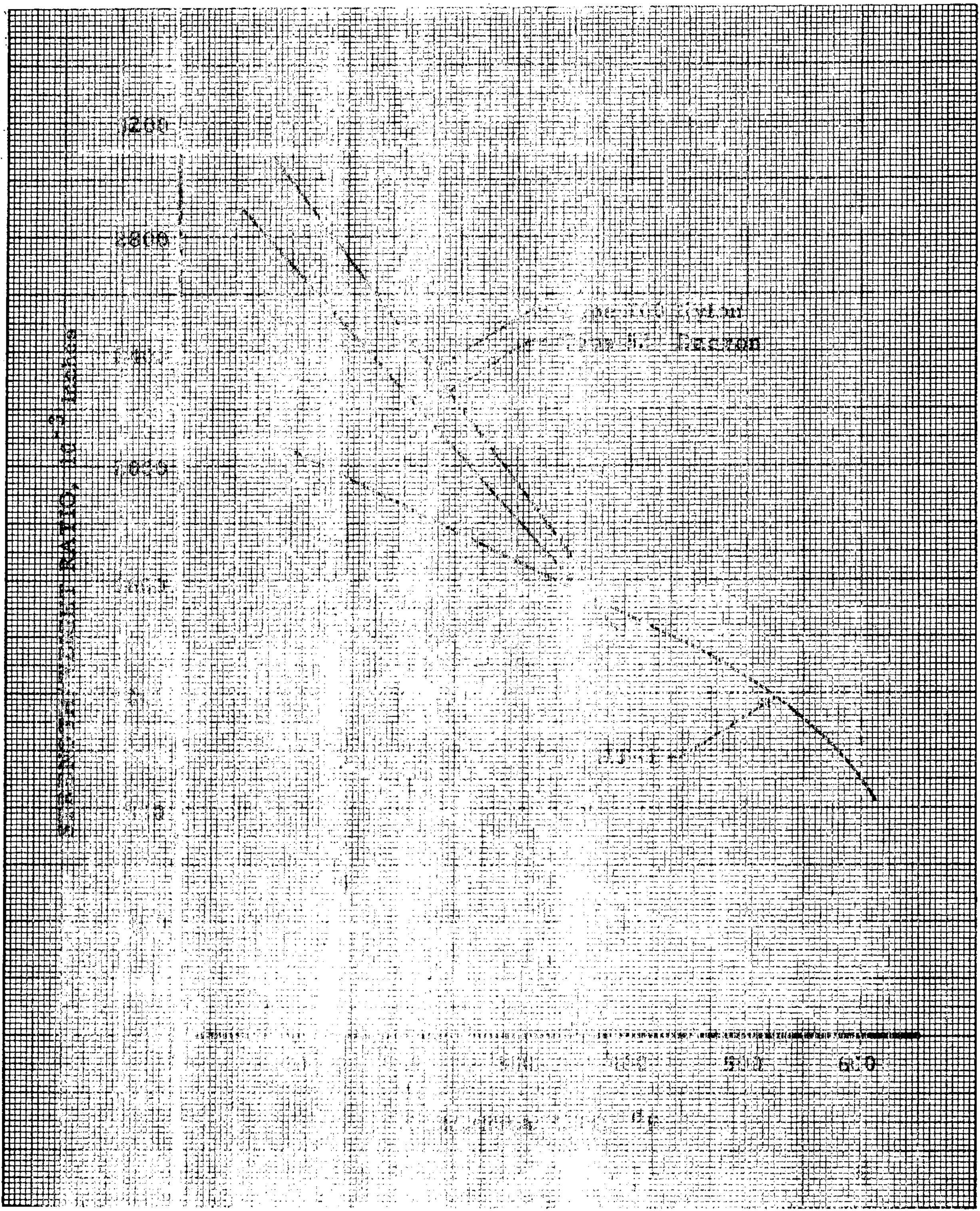


Figure [illegible] [illegible] Weight Ratio Versus
Temperature (Reference 3).

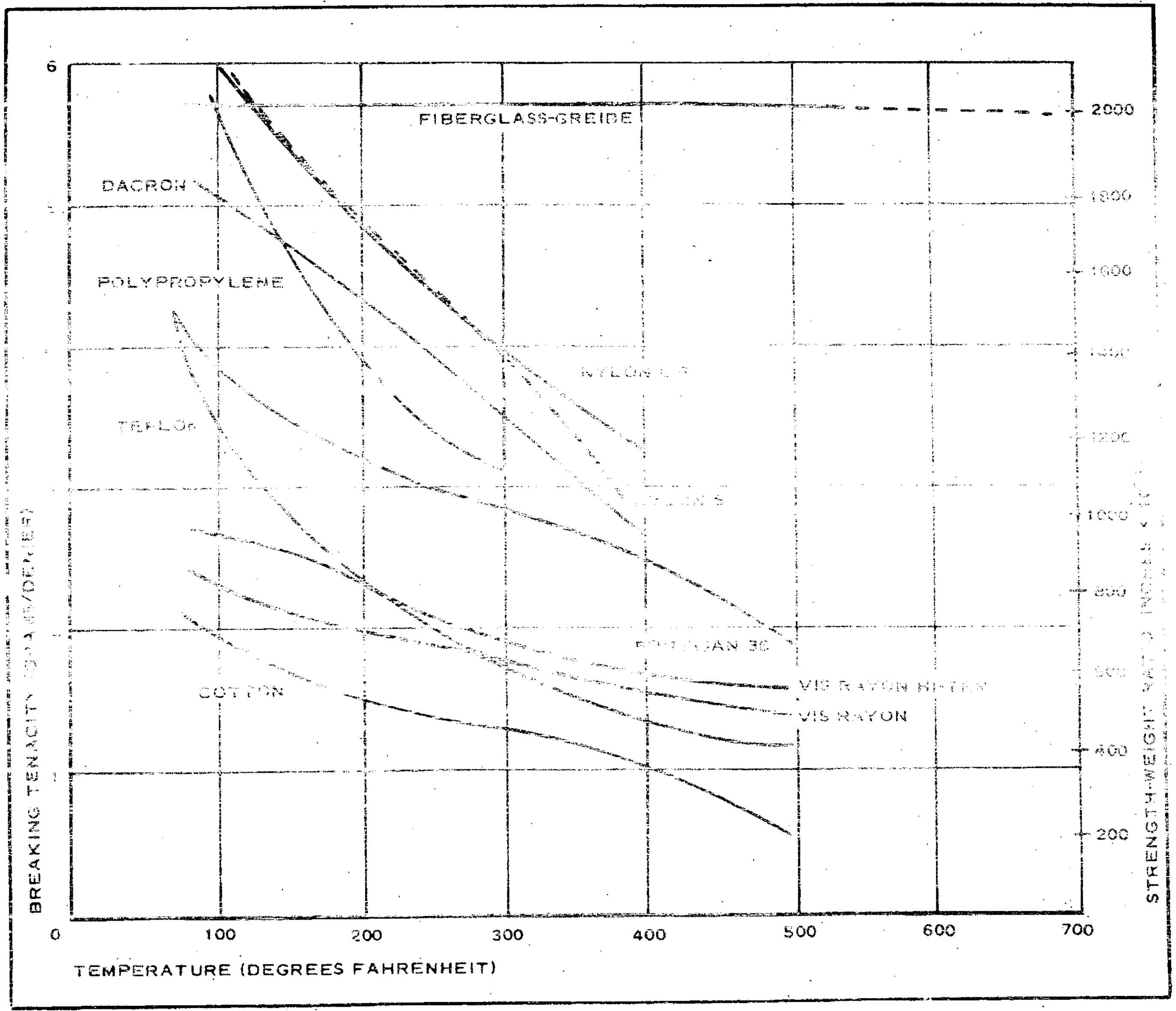
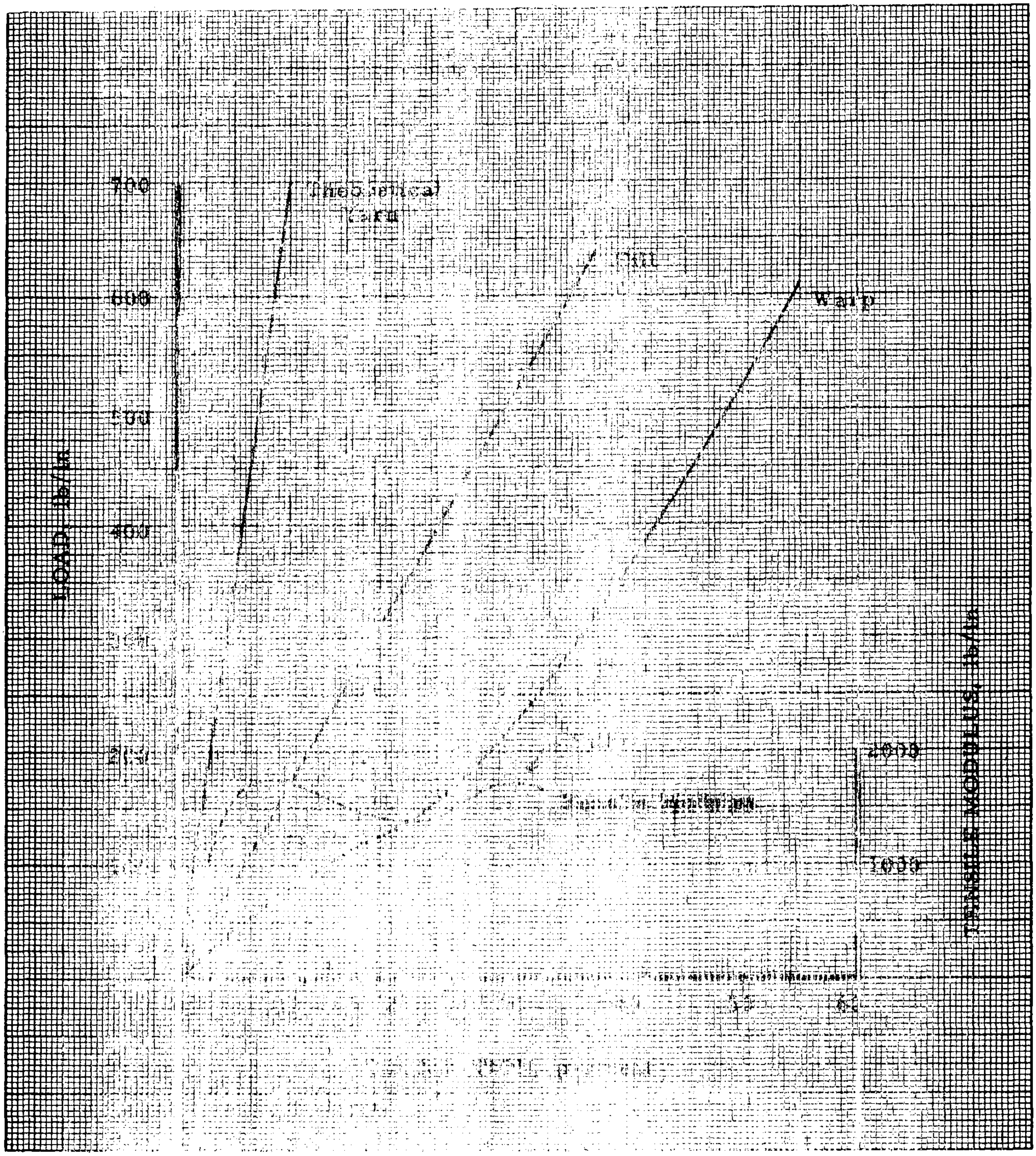


Figure 5. Yarn Breaking-Tenacity and Strength/Weight Ratio Versus Temperature (Reference 16).


700
Theoretical
Yarn
Fill
600
Warp
500
LOAD, lb/in
400
2000
Tensile Modulus
1000
TENSILE MODULUS, lb/in

[illegible]

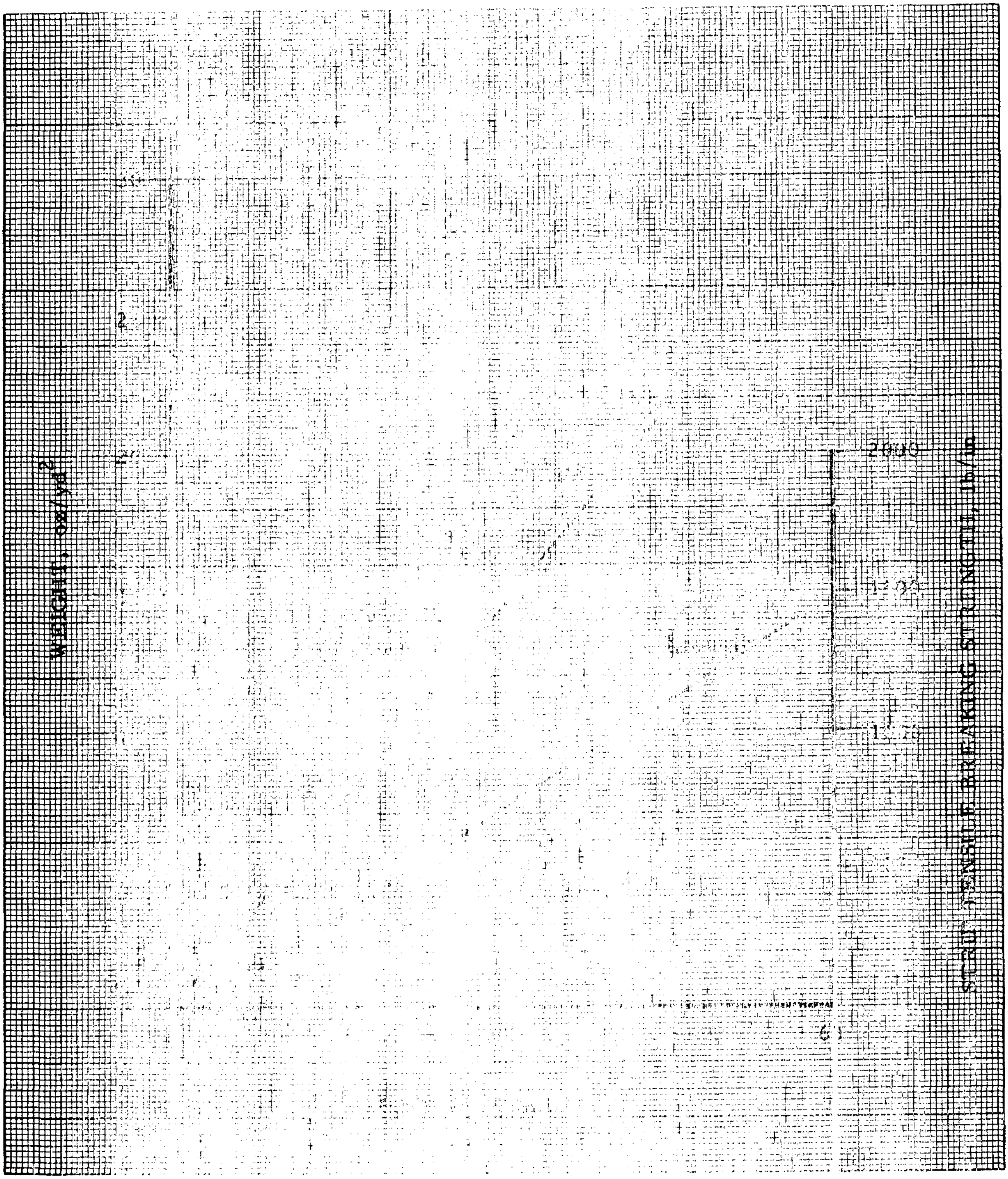


Fig. [illegible] Strength,
[illegible]

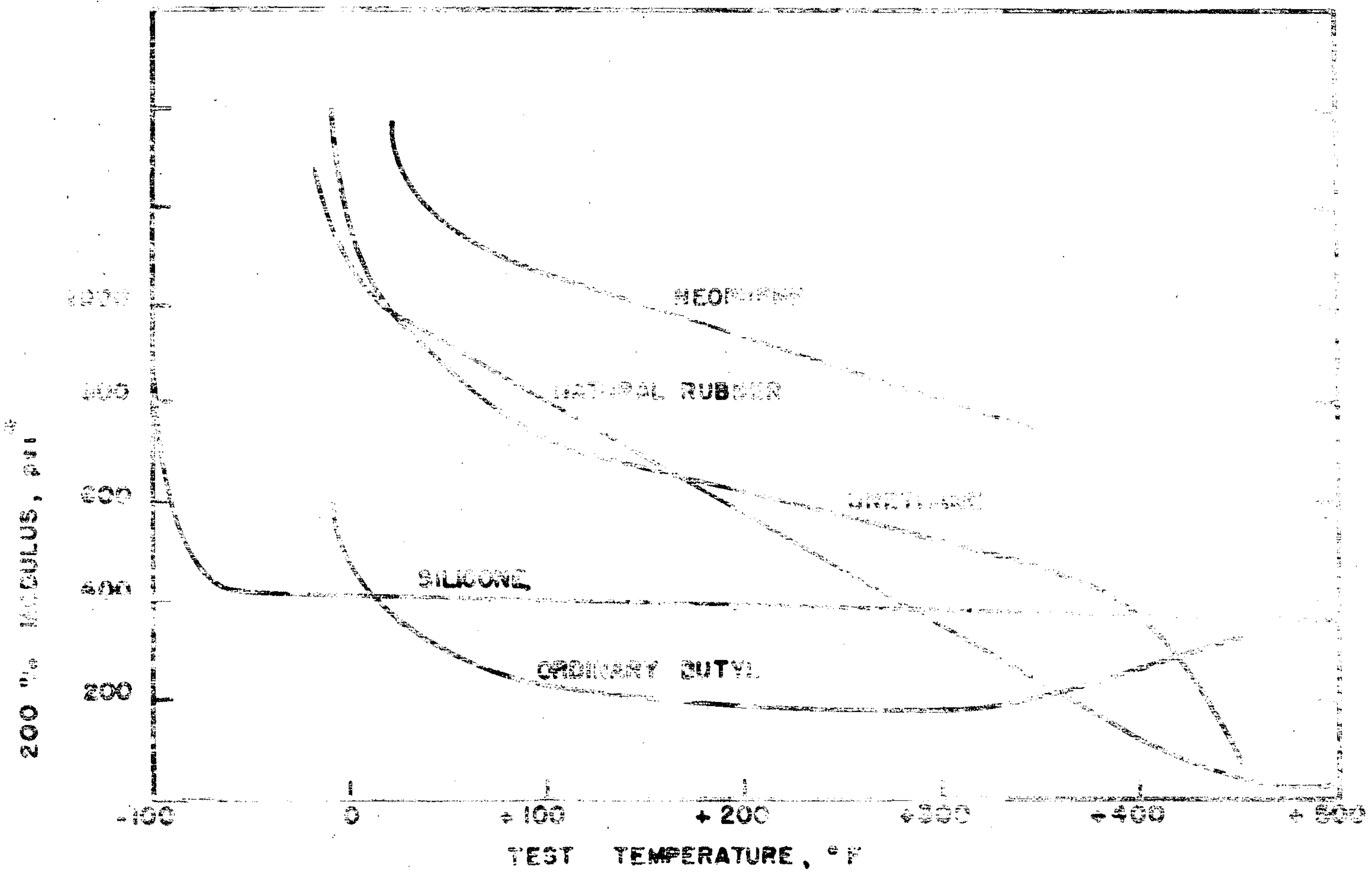


Figure 9. Stiffness of Various Elastomers Over a Broad Temperature Range (Reference 26).

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*Tensile stress at indicated elongation (200%)

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