MILITARY HANDBOOK

MIL-HDBK-17A, PART II
(Proposed Revision)

Superseding
MIL-HDBK-17, PART II
14 August 1961

PLASTICS FOR AEROSPACE VEHICLES

PART II TRANSPARENT GLAZING MATERIALS
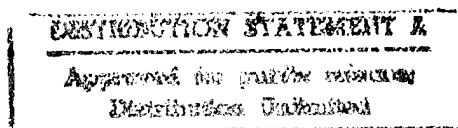
Richard S. Hassard

Goodyear Aerospace Corporation
Litchfield Park, Arizona

GERA-1863
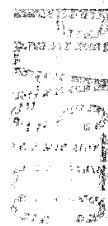
CONTRACT F33615-71-C-1465

PROJECT 7381

JANUARY 1973

AIR FORCE MATERIALS LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

When Government drawings, specifications, or other data are used for any purpose
other than in connection with a definitely related Government procurement operation,
the United States Government thereby incurs no responsibility nor any obligation
whatsoever; and the fact that the government may have formulated, furnished, or in
any way supplied the said drawings, specifications, or other data, is not to be regarded
by implication or otherwise as in any manner licensing the holder or any other person
or corporation, or conveying any rights or permission to manufacture, use, or sell
any patented invention that may in any way be related thereto.

Copies of this report should not be returned unless return is required by security
considerations, contractual obligations, or notice on a specific document.

Every effort has been made to reflect the latest information on all transparent mate-
rials which may possibly have applications for aircraft use. It is the intent to review
this handbook periodically to ensure its completeness and accuracy. Users of this docu-
ment are encouraged to report any errors discovered or recommendations for changes
or inclusions to Research and Technology Division (MAAE), Air Force Materials
Laboratory, Wright-Patterson Air Force Base, Ohio 45433.

DEPARTMENT OF DEFENSE
WASHINGTON, D.C. 20025

Preparing Activity
Air Force
Project No. 7381

PLASTICS FOR AEROSPACE VEHICLES

PART II TRANSPARENT GLAZING MATERIALS

Richard S. Hassard

FOREWORD

This is a revised edition of Part II of MIL-HDBK-17 "Transparent Glazing Materials." The compilation and editing of data were performed by Goodyear Aerospace Corporation, Litchfield Park, Arizona, under contract number F33615-71-C-1465.

The work was done for the United States Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio. The Air Force Project Engineer is Mr. R. E. Wittman, AFML/LAE.

Acknowledgment is given to the numerous sources of data, which include the authors of the previous revision, material producers, the airframe and missile industry, reports on Government-sponsored research, the open literature, and certain information extracted from internal publications by permission of the originators.

Some of the materials compared in this report were commercially produced and were not developed or manufactured to meet Government specifications, or to necessarily meet all the operational parameters presented. Any inability of a material to equal or surpass the selected properties of another material presented in this handbook is no reflection on any of the commercial items discussed herein, or on any manufacturer.

Goodyear Aerospace Corporation has assigned GERA-1863 as a secondary number to this report.

R. S. Hassard is the Project Engineer for Goodyear Aerospace Corporation. This report was submitted by the author on 19 January 1973.

This technical report has been reviewed and is approved.

Albert Olevitch

ALBERT OLEVITCH, Chief
Materials Engineering Branch
Systems Support Division
AFML

ABSTRACT

The information in this handbook includes and augments
the contents of the previous revision by expanding the data
to embrace the more recent material innovations and design
complexities. The format treats the facets of transparent
enclosure design in a sequence which starts with material
properties and logically progresses to the ultimate compos-
ites complete with edge attachments. Explanations are
interspersed which provide an understanding of various, and
possibly unfamiliar, technical disciplines which have become
more apparent as the sophistication of aircraft design and
mission increases.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF TABLES

CHAPTER 1 - GENERAL

1.1 PURPOSE AND SCOPE

1.1.1 INTRODUCTION

This handbook has been prepared for the Air Force to provide information for the selection of transparent glazing materials and the factors to be considered in their installation and use in military aircraft.

In the last decade, aircraft glazing configurations have become increasingly complex, to the extent of not only performing as structural members but also as protective coverings in a wide variety of situations. Structural loading in the flight profiles of high-performance aircraft involves not only differentials between cockpit pressurization and outer ram air loading, but also transient thermal conditions that tax the lower extremities of material strength spectrums.

Adding the protective features usually increases the transparency thickness and weight beyond that required for structural integrity. If a special coating is required, an additional transparent coating or sheet is often necessary to protect the active coating from damage. In situations where differences of thermal expansion coefficients are critical between two rigid materials, a separating elastic interlayer is added as a further complexity. With one exception, any of the additional protective features will act negatively toward light transmission and optical integrity.

The design engineer has to carefully evaluate the structural and protective requirements of the aircraft transparency, keeping in mind that the final design must meet certain optical requirements which can be very critical in areas used for landing or gun-sighting operations and less critical in general viewing areas.

1.1.2 SCOPE

This handbook contains information on materials currently being used or considered for aircraft glazing. The format of the document provides for continuous revisions which can be

accomplished by adding to or removing information from under the various topical headings. Because of the many materials now available and the more complex design parameters, the data are organized in the progression the engineer would probably follow to finalize the transparent enclosure design.

The data on the mechanical, thermal, optical, and other properties of transparent plastics and glass have been selected from a number of specifications and reports. Sufficient test data were not available on all materials for establishing design allowables. Therefore, some material property data are only representative values and should be considered as such. Because most configurations are complex, the designer should prepare test specimens of the final design configuration and conduct confirmation tests of all critical design factors.

The format essentially starts with materials and sources available for transparent enclosures and includes both glazing and supplementary materials for the design and manufacture of composite constructions. Design considerations follow which concern allowable strength values and a discussion of some of the more critical properties that influence design. The majority of the technical data is presented in Chapter 4, which treats each type of monolithic transparent sheet as a separate entity and is grouped in two parts, with military specified materials divided from those which are being considered for aircraft use.

Supplementary materials follow, headed by discussions of transparent interlayer and coating properties. The opaque cloth laminates and adhesives used in edge attachments are the final material properties needed for all-plastic configurations.

Glass data becomes a separate topic because of the great difference in properties from those of plastic. Thermal and chemical tempering are mentioned in the process of explaining monolithic properties. The inherent brittleness of glass and its relatively low tensile strength usually relegate it to a sandwich construction with a flexible interlayer. A few designs have incorporated glass-plastic configurations.

Edge attachment designs have become more and more complex as the demands on enclosure requirements have increased. Because most edge attachments are developed for a particular

aircraft, it becomes impractical to specify a certain design for a given set of parameters. Discussions ensue on problematical areas and are supplemented with sketches of edge attachments which have been used or proposed as a guide.

The final chapter explains environmental factors which, for the most part, are transient but can cause concern or actual physical damage if they are not compensated for in the design of the transparency.

Where available, applicable references will be found in the Bibliography; they are listed in the sequence in which they are mentioned or apply. Some of the references are considered valuable background material and are included in the bibliography, although their content may not be specifically referenced in the text.

1.1.2.1 PROPRIETARY PRODUCTS

The mention of any trade name or proprietary product in this handbook does not constitute an endorsement by a Government agency, nor does it indicate that the products will necessarily meet Government specifications.

1.2 APPLICABLE SPECIFICATIONS AND STANDARDS

The requirements for glazing materials are generally presented in military service specifications. In this handbook, the plastics glazing materials are identified by their military specification numbers wherever possible. These and other related specifications are listed in the following tabulation. The user should be certain he has the current revision. The noted revisions in this tabulation were current at the time of its issuance:

Federal Specifications

L-P-391C (1) -	Plastic Sheets, Rods, and Tubing, Rigid Case, Methacrylate
L-P 516A -	Plastic Sheet and Plastic Rod, Thermosetting, Cast
P-P-560 -	Polish, Plastic
DD-G-451C -	Glass, Plate, Figured (Float, Flat for Glazing, Corrugated, Mirrors, and Other Uses)

Federal Specifications (cont)

TT-I-735A –   Isopropyl Alcohol

TT-N-95B –   Naphtha; Aliphatic

Federal Standards

Federal Test Method Standard No. 175A – Adhesives: Methods of Testing

Federal Test Method Standard No. 406   – Plastics: Methods of Testing

Military Specifications

MIL-A-8576B (2) –   Cement; Acrylic Base (for Acrylic Plastic)

MIL-A-46108A –   Armor, Transparent, Laminated Glass-Faced Plastic Composite

MIL-C-675A (3) –   Coating of Glass Optical Elements (Anti-Reflection)

MIL-C-6799E (2) –   Coatings, Sprayable, Strippable, Protective, Water Emulsion

MIL-C-7439D –   Coating System, Elastomeric, Rain Erosion Resistant

MIL-C-27315A –   Coating Systems, Elastomeric, Thermally Reflective and Rain Erosion Resistant

MIL-D-16791E (3) –   Detergents, General Purpose (Liquid, Nonionic)

MIL-G-1366E –   Glass, Window, Aerial Photographic

MIL-G-5485C –   Glass, Laminated, Flat, Bullet Resistant

MIL-G-25667B (1) –   Glass, Monolithic, Aircraft Glazing

MIL-G-25871A (1) –   Glass, Laminated, Aircraft Glazing

MIL-P-5425C (4) –   Plastic; Acrylic Sheet, Heat Resistant

MIL-P-5952 (1) –   Plastic Areas, Transparent, Aircraft, Optical Inspection of

MIL-P-8184B (1) –   Plastic: Acrylic Sheet, Modified

MIL-P-8257B (1) –   Plastic, Sheet, Thermosetting, Transparent

MIL-P-9071A –   Plasticizer Content for Transparent Laminated Glazing Materials, Determination of

MIL-P-25374A (1) –   Plastic Sheet, Acrylic, Modified, Laminated

MIL-P-25690A (3) –   Plastic, Sheets and Parts, Modified Acrylic Base Monolithic, Crack Propagation Resistant

MIL-P-83310 –   Plastic Sheet, Polycarbonate, Transparent

Military Specifications (cont)

MIL-R-9300B –   Resin, Epoxy, Low Pressure, Laminating

MIL-R-25506A (ASG)–Resin, Silicone, Low Pressure, Laminating

MIL-T-5842A (1) –   Transparent Areas, Anti-Icing, Defrosting, and Defogging
                       Systems, General Specification for

MIL-V-22272B(AS) – Visors, Protective, Helmet

MIL-W-80C –   Window, Observation, Acrylic Base, Antielectrostatic, Transparent

MIL-W-6882D –   Water Repellant Kits, Window, and Windshield, Glass and Plastic

Military Handbooks

MIL HDBK 80-1 –   Handbook of Instructions for Airplane Designs

MIL HDBK-141 –   Military Standardization Handbook, Optical Design

MIL-HDBK-691A –   Military Standardization Handbook Adhesives

MIL-HDBK-700(MR) – Military Standardization Handbook Plastics

MIL-HDBK-722 –   Military Handbook, Glass

MIL-HDBK-725 –   Military Handbook, Adhesives

Military Standards

MIL-STD-810B(4) –   Environmental Test Methods

MIL-STD-850B –   Aircrew Station Vision Requirements for Military Aircraft

Technical Orders

1-1A-12 –   Fabrication, Maintenance, and Repair of Transparent Plastics.

1.3 DEFINITIONS

The following are definitions of words and terms as they are used in this handbook. They do
not necessarily constitute complete definitions, but are presented to prevent confusion with
any other meanings that the terms may have:

Acrylic – Plastic based on resins made by the polymerization of acrylic monomers, such as methyl methacrylate.

Adhesive – A substance capable of holding materials together by surface attachment.

Airframe – See enclosure frame.

AM – Amplitude modulated; refers to a type of electronic receiving equipment which is more susceptible to static interference than other types.

Angular (optical) deviation – The change in direction of a ray of light caused by incidence with a reflector or refractor. It is the angle from a vector having the direction of the incident ray to a vector in the direction of the same ray on emergence.

Annealing – A controlled heating and cooling process used to reduce internal stresses caused by previous forming or machining processes performed on glass or plastic sheet materials.

Arc – A continuous high-current discharge between points of relatively low potential. The arc sustains itself by heating and ionizing its air path until the potential difference is removed or reduced.

Biaxial Stretching – (see Stretching)

Birefringent – Double refracting property of a transparent material which splits a ray of incident light into two components which travel at different velocities.

Bus-Bar – An electrical conductor used to transmit power to the edge of a thin conductive film.

Canopy – The transparent portion of an enclosure, exclusive of the windshield. See Enclosure and Windshield.

Catalyst – A small amount of a substance that markedly speeds up the cure of a resin without affecting the chemical properties of the primary reactants.

Cement – See Adhesive.   See also Monomeric Cement and Solvent Cement.

Chemical Tempering – An ion exchange process used on glass sheet which hardens the outer surfaces and places the material between into a tensile mode. Also referred to as chemical strengthening.

CIP – Cast-in-place; a term used to identify a type of interlayer material which is poured between the transparent face sheets of a fabricated part and cured as a component part of the assembly.

Conductivity – The reciprocal of resistivity (electrical)
– Time-rate of heat transfer through a unit volume at a unit difference in temperature.

Copolymer – A compound consisting of two combined polymers

Corona – An electrical field emission surrounding a conducting body; characterized by ionization of the air and often a visible glow.

Corner Reflector – A trihedral reflector composed of mutually intersecting conducting surfaces normally used as a highly efficient radar target.

Crack Propagation Resistance – A measure of the work, other than that resulting in permanent deformation, which is absorbed per unit nominal area of crack extension, determined at the time when a creeping natural crack leaps forward. This property is sometimes called "shatter resistance" or "toughness." In this handbook it is expressed as K-value. See K-value, Shatter Resistance, Toughness.

Crazing – Fine cracks which may extend in a network over or under the surface or through a plastic. These cracks gradually enlarge with continued application of load.

Creep – The change in deformation of a material with time under load, following the instantaneous elastic or rapid deformation.

DBS – Di-Butyl Sebacate (abbreviation), plasticizer for polyvinyl butyral.

Dew Point – The temperature of a surface at which condensation of water vapor in the air takes place above freezing temperatures.

Diathermanous – Highly transparent to infrared radiation.

Diffusivity – The quantity of heat energy which can pass through a defined surface area of a sheet material, under a temperature gradient condition per unit of time.

Distortion – A rapid change in angular deviation over a small area which optically destroys the portion of a true image projected through it.

EC Coating – Electrically conductive coating.

Edge Attachment – The means of fastening the side edges of the glazing to the enclosure side beams. Also includes expansion joints and any other connection between the glazing and the enclosure frame. See Enclosure Frame, Expansion Joint.

Emissivity – The heat energy radiated per unit of time from a surface to its adjacent environment which is at a different temperature.

EV – Electron volt; a unit of electrostatic energy, not a measure of potential difference.

Electrochromic – A crystalline material property which allows changes of color when electrically excited. See Lattice Imperfection.

Enclosure – The complete movable assembly, including canopy, edge attachments, frames, fairings, side beams, seals, etc.

Enclosure Frame – The entire structure immediately surrounding the canopy including side beams, transverse frames, and other reinforcements, but not including such items as aft fairings.

ETA – Ethylene terpolymer adhesive (abbreviation)

ETP – Ethylene terpolymer (abbreviation)

Expansion Joints – Points of contact between the glazing material and enclosure frame designed to accommodate thermal expansion of the glazing material. Expansion joints are not load bearing as are edge attachments, but may be used to help support the glazing material. See Edge Attachment, Enclosure Frame.

Fill Direction – The direction of the threads of woven cloth which are parallel to the width of the roll.

Frost Point – The temperature of a surface below the freezing point at which water vapor changes directly to the solid state without going through a liquid phase.

Hoop – The peripheral edge attachment of a canopy.

Hydrophylic Compound – A material which has an affinity for moisture.

Hysteresis – Concerns the inability of a material to return to its original linear dimensions after exposure to a defined temperature cycle.

Impregnate – See Laminate.

Interlayer – A transparent flexible material used as a thermally compensating layer and adhesive between face sheets which expand or contract at different rates.

IR – Infrared spectrum (abbreviation).

Isothermal – Does not change temperature during the imposition of other variables.

K-Value – A measure of the toughness or crack propagation resistance of a glazing material. See Crack Propagation Resistance.

Laminar Shear Strength – The shear strength parallel to the laminar plane of a composite; also, in stretched acrylic, the shear strength parallel to the principal surfaces.

Laminar Tensile Strength – Flatwise tensile strength perpendicular to the laminar planes.

Laminate – A product made by bonding together two or more materials. The type of layup differs for different materials or applications.

The transparent laminates used as glazing materials consist of two or more sheets of transparent plastic or glass bonded with or without an adhesive.

The reinforced laminates used for edge attachments consist of one or more layers of reinforcing materials such as glass cloth or synthetic fabric cloth impregnated with a laminating resin. When the resin is cured, the resulting laminate has better properties than either component material. In some instances the laminating resin, if cured in contact with the glazing material, may act as an adhesive between the glazing material and the reinforced laminate. Reinforced laminates are sometimes referred to as impregnates.

Laminated Glass – A sandwich consisting of two or more layers of glass with a plastic interlayer between the layers of glass.

Lattice Imperfection – A molecular imperfection in a crystalline structure which allows it to change its optical properties upon application of external excitation.

Masking – The process of protecting a highly polished plastic surface, usually accomplished by the application of heavy kraft paper to the surface with a pressure-sensitive adhesive that is not harmful to the plastic or by the application of a strippable coating.

Modulus of Rupture – The fictitious tensile or compressive stress, s, in the extreme fiber of a beam computed by the flexure equation $S = Mc/I$, where M is the bending moment that causes rupture, c is the distance from the neutral axis to extreme fiber, and I is the moment of inertia of the cross-sectional area about the neutral axis.

Monolithic – One-ply of "as-cast" sheet, plastic or glass.

Monomer – A relatively simple compound that can react to form a polymer.

Monomeric Cement – Monomer used as an adhesive; it polymerizes (thickens and hardens) under the influence of heat, light, and/or catalyst in the joint.

Multiaxial Stretching – See Stretching.

Notch Sensitivity – The ratio of the unnotched and the notched strengths of a material.

Perturbations – Disturbances.

Photochromic – A crystalline material property which changes color when exposed to certain light frequencies. See Lattice Imperfection.

Physical Tempering – See Thermal Tempering.

Plastic (noun) – A material that contains as an essential ingredient an organic substance of high molecular weight, is solid in its finished state and, at some stage in its manufacture or in its processing into finished articles, can be shaped by flow.

Plastic (adjective) – Indicates that the noun modified is made of, consists of, or pertains to a plastic.

Plasticizer – A chemical agent added to plastic compositions to make them more flexible and more readily moldable.

Polarizer – An optical device or film whose crystalline or molecular orientation tends to allow transmission of light in parallel planes and attenuate all other components of random light.

Polyblend – A compound consisting of two or more polymers.

Polycarbonates – A family of polymers of which only the "bisphenol A" type is considered for structural aircraft glazing.

Polyesters – See Unsaturated Polyesters.

Polymer – A high molecular weight organic compound whose composition can usually be represented by a chain of repeating structural units.

1-11

Polymerization – The process of chemically linking or curing monomeric materials into a polymer.

PVB – Polyvinyl butyral (abbreviation).

RCS – Radar cross-section (abbreviation); the display of a returned radar signal from reflective surfaces which is considered a cross-section of the target.

RH – Relative humidity (abbreviation).

Rail – The horizontal edge attachment of a canopy.

Ram Air Loading – The pressures on the forward surfaces of an aircraft which are derived from the compressive forces of the aircraft against the air mass through which it is flying.

RTV Rubber – A type of flexible silicone rubber which is room temperature vulcanizing.

Rubber – Any of a number of elastomeric compounds. Some are used in polyblends to improve impact resistance.

Sag Forming – A process used for forming glass sheet by reheating it to a sufficient degree of flexibility for bending over a mold shape.

Shatter Resistance – See Crack Propagation Resistance, K-Value, Toughness

Solvent – Any liquid that attacks and dissolves certain solids with which it comes in contact. Used in this handbook to designate solvents which attack acrylic and other transparent plastics, e. g. , acetone, benzene, carbon tetra- chloride, fire extinguisher and deicing fluids, lacquer thinners, aviation and ethyl gasolines, and certain glass cleaning compounds.

Solvent Cement – A solvent or mixture of solvents, sometimes including monomer, that softens a plastic so that two or more pieces may be bonded.

Spark – A high-energy thermal emission of short duration of which lightning is the most severe case, and an electrostatic discharge spark between small bodies of opposite charge is the milder case.

1-12

Star Fracture – A minute radial craze usually originating from an inclusion, bubble or other microscopic defect. Can be detected by a bright pinpoint reflection in oblique light.

Strain Point – That temperature at which the internal stress in a glass is substantially relieved in about four hours. Also, that temperature at which glass has a viscosity of $10^{14.5}$ poises.

Streamering – An electrical field emission characterized by forklike glows in the presence of a high potential difference.

Stretching – Stretching a heated plastic sheet either in two perpendicular directions or in all directions in the plane of the sheet to improve the physical properties by orientation of the molecules. For purposes of this handbook, no differentiation is made between the methods of obtaining these improvements in physical properties by stretching.

Surface Resistivity – A nondimensional number in ohms/square which is used to classify the thickness of metallic coatings with relation to their electrical resistances.

Target Acquisition Signature – The shape and intensity of a returned radar signal which identifies an aircraft.

Temper – A condition in which glass surfaces have acquired a skin effect which is abrasive resistant and has placed the core of the sheet into tension.

Thermal Tempering – A process of heating glass to near its softening point and rapidly cooling it under rigorous control to achieve its tempered characteristics. Thermally tempered glass can range from "annealed" to "full," with semi-tempered glass being approximately midway between the two.

Thermoplastic (adjective) – Capable of being repeatedly softened by increase of temperature and hardened by decrease of temperature. Thermoplastic applies to those materials whose change upon heating is substantially physical.

Thermoplastic (noun) – A plastic that is thermoplastic in behavior.

Thermoset (noun) – A plastic that, when cured by application of heat or chemical means, changes into a substantially unfusible and insoluble product.

Thermosetting (adjective) – Capable of being changed into a substantially unfusible or insoluble product when cured by application of heat or by chemical means.

"Tin Float" or "Float" Glass – A process in which the glass is floated on molten metal at a sufficient temperature to heat polish while the opposite side is flame polished.

Toughness – See Crack Propagation Resistance, K-Value, Shatter Resistance.

Ultraviolet-Absorbing Plastic – A transparent plastic sheet in which the spectral transmittance at any wavelength in the 290–330 millimicron wavelength band does not exceed 5 percent when measured on a specimen 0.250 inch thick.

Uniaxial Stretching – A process used in the manufacture of certain films which also makes them birefringent by virtue of the molecular orientation.

Unsaturated Polyesters – Compounds containing linear condensation products made from unsaturated dibasic acids, polyhydric alcohols, and a reactive monomer, usually styrene. Under the influence of heat and catalyst and, in some cases, an accelerator, the linear unsaturated polyester chains are cross-linked by the reactive monomer into thermoset solids.

UV – Ultraviolet spectrum (abbreviation).

V-50 – Designation of a ballistic test used on armor to determine its effectiveness.

Warm Forming – A process of forming stretched acrylic by forming at less than its deformation temperature in order to prevent relaxation to its original unstretched dimensions and properties.

Warp Direction – The direction of the threads of woven cloth which are perpendicular to the width of the roll.

Windshield – The areas used for forward vision in taking off, flying, and landing; usually made of laminated glass.

CHAPTER 2 – MATERIALS AND SOURCES

2.1 GENERAL

Glazing materials in aircraft are used in windows, windshields, canopies, and other locations. The plastics materials available in commercial quantities for aircraft glazing are presented in Table 2.1-I. Materials which are not as yet specified for military use are included because their interesting properties contribute to a more complete knowledge in the field of transparencies. More advanced information may be obtained from the suppliers as the material development progresses.

In the field of polymer chemistry, the design engineer has to be aware of more than the generic code of the material in which he is interested. A few of the transparent plastic materials which have not been defined by a military specification retain their original resin code names, although several variations exist as polymers, copolymers, or polyblends with distinctly different properties.

Often a chemical supplier will develop a basic resin and provide data from cast laboratory samples after assigning a code designation of "XY-19" as an example. Processors evaluate the properties of the resin and convert it for a particular use by adding one or two other polymers in certain mix ratios in which the basic resin is usually the largest constituent. Although a new product is developed, it may now be trademarked "Magix XY-19," and another processor may have a "Crystal XY-19." For design purposes, the data from processors who are able to provide sheets of the required size and properties are preferable. The basic resin data can sometimes be misleading because it does not actually represent the end product. In final analysis, the processor's data should be used as a guide and confirmed by tests of the critical properties by the designer, once the probable materials are chosen.

TABLE 2.1-I – TRANSPARENT MATERIALS SOURCES

Type	Specification	Trade name	Manufacturer code*
Acrylics:			
Heat-resistant cast poly (methyl methacrylate)	MIL-P-5425	EVR-Kleer, Type II	A
		Polycast Acrylic 101	A
		Plexiglas II UVA	B
		Swedlow 320	C
		Swedcast 301	C
Modified acrylic	MIL-P-8184	Plexiglas 55	B
		Swedlow 350	C
Stretched modified acrylic	MIL-P-25690	Ultra-Glas	D
		(Designate by MIL-SPEC)	E
		Douglas-Glass	F
		Sierracin 1000	G
		Acrivue Acrylic Transparencies	C
Laminated modified acrylic	MIL-P-25374	LOF Laminated Plexiglas 55	H
		PPG Laminated Plexiglas 55	I
		Sierracin Corp. Laminated P55	G
Polyesters:			
Cast polyester	MIL-P-8257	Sierracin 611	G
	(Commercial) Consult supplier	Sierracin 900 I	G
	L-P-516a** Class G-3	Homalite 911	J
Polycarbonates:			
Extruded polycarbonates	MIL-P-83310**	LEXAN SL-2000-111***	K
		MERLON M50U***	L
Glass	MIL-G-5485 (Laminated, bullet resistant)	(Designate by MIL-SPEC)	H
		(Designate by MIL-SPEC)	I
	MIL-G-25871** (Laminated)	(Designate by MIL-SPEC)	H
		(Designate by MIL-SPEC)	I
	MIL-G-25667** (Monolithic)	(Designate by MIL-SPEC)	M
		(Designate by MIL-SPEC)	H
		(Designate by MIL-SPEC)	I
Interlayer material			
Sheet form			
Polyvinyl butyral base	(Refer to MIL-P-9071) Consult supplier	Saflex DS or DB for Acrylics PT or WS for Glass	N
Ethylene terpolymer base	(Commercial) Consult supplier	ETA	N
Liquid form (cast-in-place)			
Acrylic base	(Commercial) Consult supplier	Swedlow SS-6084	C
Polyester base	(Commercial) Consult supplier		E
Silicone base	(Commercial) Consult supplier	F-4X	E
	(Commercial) Consult supplier	Sierracin S-100	G

TABLE 2.1-I – TRANSPARENT MATERIALS SOURCES (CONT)

Type	Specification	Trade name	Manufacturer code*
	(Commercial) Consult supplier	Swedlow SS-5272Y (HT)	C
		F-3X-40	E
Polyurethane base	(Commercial) Consult supplier	F-5X-1	E
	(Commercial) Consult supplier	CIP 97	I
Coatings			
Vacuum deposition processors	(Commercial) Consult supplier		C
			O
			E
			P
			G
			Q
Films			
Polarizing film	(Commercial) Consult supplier		R

*Manufacturer Code:

A – Polycast Technology Corporation
69 Southfield Avenue
Stamford, Connecticut 06902

B – Rohm and Haas Company
Independence Mall West
Philadelphia, Pennsylvania 19105

C – Swedlow Incorporated
12122 Western Avenue
Garden Grove, California 92642

D – Dyna-crylic Corporation
25663 West Avenue Stanford
Valencia, California 91355

E – Goodyear Aerospace Corporation
Arizona Division
Litchfield Park, Arizona 85340

F – McDonnell Douglas Astronautics Company
3000 Ocean Park Boulevard
Santa Monica, California 90406

G – The Sierracin Corporation
12780 San Fernando Road
Sylmar, California 91342

H – Libbey-Owens-Ford Glass Company
608 Madison Avenue
Toledo, Ohio 43604

I – PPG Industries, Inc.
Aircraft and Specialty Products
Suite 777, SNB Building
Huntsville, Alabama 35801

J – The Homalite Corporation
11-13 Brookside Drive
Wilmington, Delaware 19804

K – General Electric Company
Plastics Department
1 Plastics Avenue
Pittsfield, Massachusetts 01201

L – Rowland Products, Incorporated
34 Fairview Lane
Kensington, Connecticut 06037

M – Corning Glass Works
Corning, New York 14830

N – Monsanto Company
Polymers and Petrochemicals Company
St. Louis, Missouri 63166

O – American Optical Corporation
Southbridge, Massachusetts 01550

P – Optical Coating Laboratory, Incorporated
2789 Giffen Avenue
Santa Rosa, California 95403

Q – Liberty Mirror Division
Libbey-Owens-Ford Company
851 Third Avenue
Brackenridge, Pennsylvania 15014

R – Polaroid Corporation
Cambridge, Massachusetts 02139

Notes:

**No qualified products list available at the time of publication.

***These materials must be press polished from MIL-P-46144A (MR) Type II Grade A (natural) sheet in order to meet the optical requirements of MIL-P-83310.

Although some of the materials have not been manufactured recently, they are retained on this list until the military specification becomes inactive.

2.2 DESCRIPTION OF RIGID PLASTIC MATERIALS

2.2.1 GENERAL

No one material is able to satisfy all the requirements of all designs. The property spectrum of transparent materials ranges from glass to rubber, the latter being an inter-layer material and also proposed for windows in inflated orbital laboratories. Structurally, however, glass is treated separately from plastics, and plastics are divided into two broad categories of "thermoset" and "thermoplastic" materials.

Rigid thermoplastic materials can be heated into a consistency of sheet rubber, formed, and cooled into shapes with deep draws and double curvatures. Some thermoplastics can also be stretched in the rubbery state and cooled into a stretched sheet with different properties than the parent blank. The stretched sheet can then be warm-formed into simple curvatures with the new properties retained. Thermoplastic materials are often used as primary load bearing structures.

Thermoset materials have forming characteristics limited to shallow shapes or forms of single curvature. A few of the thermoset materials have been available in a partially cured state which allowed for better formability prior to a final heat cure. Being more notch-sensitive than the thermoplastic materials and tending toward the properties of glass, these materials are relegated toward secondary members of transparent laminates. Their greater resistance to abrasion and chemical attack are their most desirable properties.

Glass has traditionally been used for flat windshield panels as the most durable and optically acceptable material for critical sighting areas on aircraft. The glass can be twin ground to parallel optical surfaces, although the industry is turning toward "tin-float" glass as a less expensive method of obtaining near-prime optical quality. Monolithic glass has been used structurally in some instances, but normally is laminated to another sheet of glass with a flexible interlayer. The latter offers better reliability and a degree of shatter protection.

Sag forming of glass to large, single-curvature radii can be performed by the glass manufacturers. After forming, the part can be tempered by either thermal or chemical means, although some warpage can be expected, depending upon the size of the part.

Strengthened glass, by either thermal or chemical means, is synonymous with tempering. The processes harden the surfaces of the glass into an ideal compressive mode and place the core into tension. Any cutting or grinding has to precede these processes, because a break in the compressive surface causes a stress unbalance which can be expected to result in a complete failure of the part or sheet. Tempering of the glass increases its tensile strength property approximately 3-1/2 times that of annealed glass, and because the tensile property is the most critical failure mode, the advantage of tempering is great.

2.2.2 MILITARY SPECIFICATION THERMOPLASTICS

2.2.2.1 MIL-P-5425, HEAT RESISTANT CAST POLYMETHYL METHACRYLATE SHEET

The material is unplasticized, ultraviolet-absorbing polymethyl methacrylate and is the predecessor of the modified and stretched methacrylates. It now is used mostly in specialized applications, one being the requirement of certain color pigments or dyes not compatible with the modified acrylics. The supplier should be checked if the application requires colored transparent materials.

Stretching of acrylics was first accomplished with this material, but again, was superseded by the introduction of the modified acrylics and has not become included as a militarily specified material in the stretched condition. Thin sheets of the acrylic are used as protective coverings for transparent coatings in various types of composites to be discussed subsequently. Commercial versions of military aircraft sometimes use this material under the trade names shown in Table 2.1-I.

2.2.2.2 MIL-P-8184, MODIFIED ACRYLIC SHEET

This material has slightly higher heat resistance than the MIL-P-5425 material, and better crazing and solvent resistance. Its usage as a cast material has been largely replaced by the stretched modification specified in MIL-P-25690. Commercial versions of military aircraft

sometimes use the cast material under the trade names shown in Table 2.1-I. The material is primarily produced for military use.

2.2.2.3 MIL-P-25690, STRETCHED, MODIFIED ACRYLIC SHEET

This specification covers the stretched version of the MIL-P-8184 material. When stretched multiaxially and parallel to the surface within a range of 60 to 80 percent, the material acquires an increased resistance to crazing, higher impact strength, and improved crack propagation resistance without detrimental effect on other properties except for abrasion resistance and laminar tensile and shear strengths, which decrease.

Properties are optimized during the stretch processing by controlling temperature, rate of stretching, and rate of cooling. Stretched flat sheets can then be formed at temperatures lower than the stretching temperatures by the process otherwise known as "warm forming." The forming temperature is low enough to prevent a negligible loss in orientation, but high enough so that residual stresses are not critical. Shapes are limited in complexity because of the stiffness of the sheet at these "warm forming" temperatures.

2.2.2.4 MIL-P-83310, PLASTIC SHEET, POLYCARBONATE, TRANSPARENT

Advantages of this material over the others are inherent in the structural properties more than in the surface conditions. Its impact resistance is excellent, and its heat deflection point is over 60 deg F higher than that of the MIL-P-8184 material. Surfaces are sensitive to solvent attack and have a low abrasion resistance to the extent that coatings have been developed for surface protection. It is almost mandatory that all material be dried before forming to prevent bubbling. Most forming has to be done inside an oven, which is a divergence from the processing of materials that require lower forming temperatures.

2.2.3 MILITARY SPECIFICATION THERMOSETS

2.2.3.1 MIL-P-8257, PLASTIC SHEET, THERMOSETTING, TRANSPARENT

Because of notch sensitivity, these materials are normally not used monolithically as glazings. Their abrasion and chemical resistance surfaces are, however, a distinct asset

which allows for their use as external protection for a more surface-sensitive thermoplastic load-bearing member. The temperature restrictions of the polyesters are relatively low when considering today's higher-performance aircraft requirements. The material has found a use, because of its hard surface, as a substrate for coatings which will be discussed later in this handbook. Formability of the thermosets, as mentioned previously, is restrictive.

2.2.4 FEDERAL SPECIFICATION THERMOSETS

2.2.4.1 L-P-516a, PLASTIC SHEET AND PLASTIC ROD, THERMOSETTING, CAST

Formerly, this material was under class G-3 of MIL-P-77C. It is now under class G-3 of this specification, which concerns a general-usage material with a heat deflection temperature minimum of 149 F, and an emphasis on dielectric properties. The material has been used successfully as a substrate for coatings. It is capable of continuous service at 176 deg F and intermittent service at 302 deg F without a load. Its surface hardness and ability to withstand these temperatures have made it useful as a substrate for heated anti-icing and anti-fogging panels. It has a high impact strength, being of the carbonate family.

2.2.5 MILITARY SPECIFICATION GLASS

2.2.5.1 MIL-G-25667, GLASS, MONOLITHIC, AIRCRAFT GLAZING

The current revision of this specification embraces five different types of glass as follows:

Type I Ready-cut, commercial float or polished plate glass

Type II Ready-cut, color clear polished plate glass

Type III Ready-cut, heat-absorbing polished plate glass

Type IV Ready-cut, low expansion borosilicate and sodium aluminum borosilicate polished plate glass

Type V Ready-cut, polished plate glass, chemically strengthened; Type V is subdivided into Class A flat, Class B curved.

(Types I through IV may be annealed and tempered (thermally).) Although the types of glasses have not changed considerably over the years, sciences of chemical strengthening and tin-floating have been added to the suppliers' processing abilities to improve the mechanical and optical properties of the existing glasses. Surface crystallization is another process known to increase strength, but the process is apparently not available at this time for producing the optical quality in the sizes and classes of material normally used.

Sources of glasses are shown in Table 2.1-I.

2.2.6 COMMERCIAL TRANSPARENT SHEET PLASTICS

2.2.6.1 ACRYLONITRILE BUTADIENE STYRENE (ABS), MODIFIED

The modified material is clear and has high energy impact resistance. Light transmission is less than aircraft glazing can tolerate in the current formulations, and the strengths are less than those of the MIL-P-83310 material.

2.2.6.2 POLYMETHYLPENTENE

Polymethylpentene is a highly transparent thermoplastic capable of withstanding temperatures continuously up to 320 F. It is not considered a structural material and is not recommended for sunlight exposure without a protective additive or coating.

2.2.6.3 POLYSULFONES

These are a family of thermoplastic materials which exhibit outstanding mechanical properties throughout a range of -300 to +500 deg F. The sheet is formed at very high temperatures after it has been thoroughly dried. The forming temperatures may cause some tint discoloration in the plastic. The surface of the finished part will be harder than any of the plastic materials discussed in section 2.2.2. The ability of these materials to sustain high temperatures will also make them adaptable to stronger adhesive systems which require high temperature cures. Currently, work is being accomplished to improve optical properties and reduce ultraviolet (UV) sensitivity. The materials at this point are undergoing further development.

2.2.6.4   POLYTEREPHTHALATE

The material is not a structural material, but has an advantage of impact resistance and clarity which makes it attractive for nonstructural applications such as instrument covers. Its heat distortion temperature is below that of MIL-P-8184 material.

2.2.6.5   POLYURETHANE

Both thermoplastic and thermoset forms of the material are available. The thermoplastic form has a superior toughness, impact strength, chemical resistance, and hydrolytic stability. The characteristic yellow tint is sometimes found objectionable except for certain specialized applications.

The thermoset version is crystal-clear, and displays good weatherability. Although the impact resistance is not as good as that of the thermoplastic version, the clear material does appear to exceed the requirements of MIL-P-8257.

2.2.6.6   OTHER MATERIALS

Industry is constantly developing new materials by purifying some resins to a transparent product, modifying others to optimize certain groups of properties, and developing new ones to meet the increasing demands placed upon them by military and commercial aircraft designs. Not all of these materials have been listed at this time, either because of commercial unavailability, or because their development is under a security classification which prohibits their disclosure in this handbook of unlimited distribution.

The majority of the transparent materials are organic, but advances in crystalography are now producing inorganic window materials of somewhat limited size, although large enough for practical application in specialized high-temperature and aerospace applications. The latter are essentially large slabs of crystal.

2.3 DESCRIPTION OF FLEXIBLE INTERLAYER MATERIALS

2.3.1 GENERAL

Historically, flexible interlayers were used in both glass and plastic transparent laminates to offer some degree of reliability and shatter resistance. In addition, certain panels of glass utilized electrical heating elements or conductive coatings (NESA)[a] and (Electrapane)[b] which required an interlayer to also be a thermally compensating medium between the glass face sheets.

The advent of stretched acrylic reduced the structural need for sandwich configurations, but the need for anti-fogging and anti-icing electrical coatings remained. An electrical coating for plastic was developed which could be applied to a thin transparent sheet and subsequently be adhered to the thicker load-bearing member with an interlayer. The requirement for interlayer not only remained, but service conditions for high-performance aircraft required that interlayers be capable of compensating for greater temperature ranges than the original polyvinyl butyral could withstand.

2.3.2 SHEET INTERLAYERS

2.3.2.1 POLYVINYL BUTYRAL BASE

The most widely used interlayer material for laminating plastics glazing materials, as well as for glass laminates, has been polyvinyl butyral (PVB). In plastics laminates the plasticizer content of the interlayer is usually 37.5 parts dibutyl sebacate; the plasticizer content of this material is determined in accordance with MIL-P-9071. In glass laminates the plasticizer content of the interlayer is usually 20 parts of triethylene glycol di-2-ethyl butyrate (3GH). Plasticized polyvinyl butyral interlayer material is manufactured in sheets of 0.015 to 0.025 inch thick. Several layers of the material are used to build up the thickness required for the laminate, usually about one-third of the total thickness of the laminate. The tensile strength drops from approximately 9000 PSI at -75 deg F to 500 PSI at +150 deg F.

---

[a] TM, Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania.
[b] Libbey-Owens-Ford Glass Co., Toledo, Ohio.

2.3.2.2   ETHYLENE TERPOLYMER BASE

A more recent material which can also be classified as a sheet adhesive has been developed. It was primarily developed for use with polycarbonate face sheets, but has shown adaptability to glass-polycarbonate laminates. The tensile strength versus temperature curve of the interlayer is similar to the PVB curve above room temperature.

2.3.3 CASTABLE INTERLAYERS

2.3.3.1   POLYESTER BASE

One of the first cast-in-place (CIP) materials was primarily formulated for the lamination of as-cast and stretched acrylic sheets of MIL-P-8184 and MIL-P-25690 materials. Modifications were developed to accommodate compatibility with certain coatings. Tensile strength drops from approximately 10,000 PSI at -75 deg F to 500 PSI at +160 deg F.

2.3.3.2   SILICONE BASE

Although these materials are of a lower strength, they are capable of maintaining a tensile range of between 500 and 560 PSI, which is reached at approximately 180 deg F and remains level throughout +260 deg F.

2.3.3.3   POLYURETHANE BASE

Polyurethanes are noted for their tenacity to most substrates. As an interlayer, it has a higher tensile strength in the lower temperature range than any of the other materials. It is approximately twice the strength of PVB at -75 deg F. It approaches the tensile strength of the silicone base materials at 500 PSI at approximately +240 deg F.

2.4   EDGE ATTACHMENT MATERIALS

2.4.1   GENERAL

The components of an edge attachment usually consist of one or more layers of a reinforcing material and an impregnating resin and/or an adhesive, depending on the edge attachment

design and the fabrication techniques. The materials used for these components are described in general terms in the following sections. Specific materials properties are not detailed because such variables as the type of weave in woven fabrics, and the type of reinforcement and the conditions of curing in impregnating resins and adhesives are so diverse as to make the listing of values for all materials impractical. Information about a specific material may be inferred from the properties data for combinations of materials as given in section 7.1, if the specific material is included in one of the combinations. More complete information on current materials may be obtained from materials suppliers.

2.4.2 REINFORCING MATERIALS

The materials used for reinforcement of edge attachments have usually been of a woven structure, but they have varied widely in composition, including stainless wire mesh screen; unidirectional, square weave and satin weave glass fabric; Nylon,[a] Dacron,[b] and Nomex[c] (a high-temperature nylon fabric). Glass fabrics of various weaves are used for edge attachments, but can cause considerable difficulty in maintaining a bond because of the very low coefficient of thermal expansion and high modulus of elasticity of glass as compared to a plastic substrate to which it is being bonded. The synthetic fabrics are generally better for plastic glazing edge attachments because of their near coefficient-of-expansion match. Temperature limitations of the fabric, however, will dictate its use.

2.4.3 IMPREGNATING RESINS

Acrylic, modified acrylic, polyester, and epoxy resins are the most commonly used impregnating resins. They have mechanical, chemical, and thermal properties very similar to those of the plastics glazing materials. The acrylics usually exhibit the best tensile strength and resistance to weathering, but have low bearing strength at elevated temperatures. Epoxy resins have the best bearing strength and superior heat resistance, but the resistance to weathering is not equal to that of the acrylics. The polyesters are weaker, mechanically, than the acrylics and epoxies, especially in interlaminar shear strength when used in laminates.

[a, b, c] TM, E.I. Dupont de Nemours, Inc., Wilmington, Delaware.

2.5 ADHESIVES

2.5.1 GENERAL

Adhesives are elusive materials when it seems necessary to identify them and compare properties. Because the substrates to be adhered are varied as well as their environmental ranges, classification becomes almost impossible. The use of primers, mechanical surface treatments, and varying cures removes adhesives from the materials category and places them into the processing procedures.

Military handbooks MIL-HDBK-691A and -725 provide a very detailed insight to the adhesive problem. Currently, only two adhesives are specified for transparent plastics, and both are for acrylic materials as specified in MIL-A-8576B(2). Ceramic adhesives are available which have been used satisfactorily to bond a titanium edge attachment directly to glass, but are not specified.

Because the adhesives problem is complex, it is suggested that several of the many adhesive suppliers be contacted for recommendations toward a solution. Full environmental information and materials to be bonded will be required by the suppliers.

2.6 COATINGS

2.6.1 GENERAL

Coating materials and processes are, for the most part, proprietary and vary from processor to processor for any particular type. Some coatings are complex in that they consist of several layers of different materials. The result of the total processing is usually referred to as a singular coating by its use (i. e., anti-reflective coating, anti-fogging coating, etc.). The sources of most coatings are from the processors rather than from the material suppliers.

2.6.2 ABRASION RESISTANT COATINGS

These are of two types as far as processing is concerned. The most prevalent type, which is fluid, can be flow-coated or dipped and then cured to the required hardness. Although the coatings are hard and transparent, they vary in their ability to protect the substrate from

solvents. Some coatings are better than others in retaining their integrity after extended weathering or humidity exposure. A vacuum deposition process is currently being evaluated (the second type) which should provide better uniformity of coating, and possibly, better adhesion.

Abrasion resistant coatings are used as a direct protection of monolithic materials with relatively soft surfaces or as protection for other fragile coatings. They cannot be used to protect anti-reflective coatings without reducing the latter's effectiveness.

2.6.3 ANTI-FOGGING, ANTI-ICING COATINGS

The basic principle of anti-fogging and anti-icing coatings is the same. The difference lies in the amount of power required and the surface of the transparency to which it is to be delivered. In some cases, an anti-icing coating may also serve to prevent fogging on the inside surface.

The transparent coatings are electrically resistive, thin metallic or metallic-oxide films which convert electrical energy to heat at an approximate flux of 1 watt per square inch for inside anti-fogging applications, and 3 to 5 watts per square inch for anti-icing requirements. The power is applied through bus-bars at opposite edges of the coating and is controlled by strategically placed heat sensors. The limitation on a coating's capability is primarily the temperature its adjoining interlayer is capable of sustaining.

Application of the films on plates requires vacuum deposition techniques which depend upon the substrate, the film to be deposited, the required resistance, and the curvature of the part. Usually, the film is applied to a thin sheet of high modulus material which is subsequently laminated with a flexible interlayer to the load-bearing member of the composite. Intermediate processing complexities limit sources to organizations with proprietary processes as shown in Table 2.1-I. Vacuum deposition processing is not used for stannous oxide coatings on glass.

For lighter-weight glazings, the anti-fogging coating can sometimes (depending on the substrate) be deposited on the load-bearing member and then protected with an abrasion resistant coating or sandwiched between load-bearing members in a dual load path.

2.6.4 RADAR REFLECTIVE COATINGS

Radar reflective coatings were the offspring of anti-fogging coatings, and the sources are the same as those which vacuum deposit metallic films. The purpose of the radar reflective coatings is to minimize the "corner reflector" type of return the cockpit presents in an impinging radar beam. This is accomplished by coating the transparent enclosure over the cockpit with an optically transparent metallic film which will reflect radar radiation in a lesser concentration.

2.6.5 RADIATION PROTECTIVE COATINGS

These coatings are similar to the radar reflective coatings, but are needed for pilot protection in situations where electronic detection systems are in the vicinity of the cockpit and fringe radiation can become a problem. These coatings are more critical as far as coverage is concerned than the previous coatings. Sources of manufacture are the same as those of the radar reflective coatings.

2.6.6 SOLAR PROTECTIVE COATINGS

Solar protection is not solely provided by coatings. The metallic coatings previously mentioned offer some protection, and in instances where they are used, optical restrictions would make it impractical to add more protection to those particular panels. Eyebrow windows or other overhead lights are sometimes tinted in the base material. Blue, green, and grey tints have been used, but have disadvantages during flight in overcast conditions or during night operations. Plastic sheet processors can obtain these tinted materials, although it should again be noted that MIL-P-8184 sheets are not, for all practical purposes, tinted. MIL-P-5425 and MIL-P-83310 materials can be tinted by the sheet suppliers.

Other protections from solar radiation are in the form of bandpass filters, photochromic materials, and electrochemical devices. Bandpass filters are composites of alternating layers of transparent substrates and coatings of different indices of refraction. The substrate material is usually glass of a very thin cross section. Their designed combination of high tolerance thicknesses allow high transmission of the visible spectrum and rejection of the infrared (IR) band.

Photochromic (light-sensitive) materials as glass additives are known, but are not available for extensive use in aircraft glazing at the time of this publication. These materials darken upon exposure to sunlight, and are currently used in ophthalmic prescriptions which are also sun glasses.

Electrochemical devices require auxiliary equipment for the energizing of an electrochromic material which becomes activated to the extent of changing to a color. Coatings of various ionic crystalline materials, such as certain alkaline halides, are colorless in their unexcited state, but develop color centers when excited as a result of created lattice imperfections. These imperfections theoretically change the absorption band of the crystal to accept a predominant color. The massive effect of an activated crystalline coating is one of an over-all coloration which appears as a tinted transparency. This approach is of interest because a pilot can possibly control the color density for his own comfort, irrespective of solar intensity.

2.6.7 ANTI-REFLECTIVE COATINGS

The bandpass filter concept, mentioned as a means of solar protection, was primarily designed as an anti-reflective coating. It would transmit the visible portion of the light spectrum and suppress not only the IR band but also the UV band. Its being of a precision type of multilayer construction, its use would be limited to lenses and small windows for optical instruments or cameras.

Obviously, the bandpass filter approach is very efficient and very specialized. Optical design for a filter which will transmit most light frequencies at near equal efficiencies resolves itself into multilaminar constructions which are not practical or economically feasible for large aircraft transparencies. Anti-reflective coatings for large panels are, however, needed for less sophisticated purposes.

Cockpits with large areas of glazing, especially helicopters, are particularly susceptible to sunlight reflection over long distances. This could be a compromising factor in tactical situations. Instrument reflections can become fatiguing to the eyesight as well as visually disruptive during night flying operations. For these reasons, an anti-reflective coating is

desirable which will grossly reduce reflections without any required frequency discrimination within the visible spectrum.

Coatings such as these are available for application on glass substrates and are used for instrument cover glasses and other limited applications. The coating most commonly used is vacuum-deposited magnesium fluoride, which cannot be applied to plastic materials that are unable to accept the high deposition temperatures. Development has established anti-reflective coating systems for plastic materials which are now being evaluated.

2.6.8   ANTI-STATIC COATINGS

Plastic materials have an affinity for collecting static charges from almost any frictional impingement, whether it be from a cleaning operation or a flight through a snowstorm. In-flight charging can result in radio interference should charges become of sufficient magnitude to discharge to adjacent areas or points. The net result from any charging source is one of dust and dirt attraction, which not only obstructs visibility, but can cause damage to the glazing through improper cleaning.

Frictional impingement implies a charge transfer from the impinging particle to the plastic surface. Experimentation has shown that islands of charges build up on a glazing surface when it is rubbed with a clean piece of flannel cloth. These charges can become sufficiently concentrated to cause a discharge over an infinitesimal neutral zone to islands of opposing charge. Flushing with tap water removes all the charges.

Application of an anti-static coating accomplishes a similar function as the flushing. Instead, the coating, which is usually hydrophylic, allows the many charges to transfer to one another and neutralize to either a zero charge or a negligible evenly distributed net charge (usually negative). A recharge from impingement is distributed on the coating, and the net charge remains small. Most surface-applied anti-static agents depend upon a relative humidity of above 25 percent for most efficient operation. Unfortunately, this type of coating is not too durable and requires re-application. A hard transparent conductive salt or metallic coating would serve the same purpose.

A second type of anti-static compound is used as an additive in the original casting or extrusion of the sheet transparent stock. None is currently used in the military specified material, and their effects on the now-acceptable physical and optical properties are not known.

Sources of anti-static compounds are numerous and may be found in Reference 1.

2.6.9 STATIC DISCHARGE COATINGS

Static discharge coatings are similar to anti-static coatings except that a grounding provision is included, and the coating is usually a vacuum-deposited metallic oxide on glass. Conductive coatings for field applications have been developed, but are restrictive in their use because of short lifetime expectancy.

2.6.10 RAIN REPELLANT COATING

Rain removal is accomplished by both active and passive means. The purpose is to provide rain clearance for all approach, landing, and takeoff speeds through excessive rain intensities. The active means are through the use of windshield wipers, hot air jet system, and in-flight applied liquid repellants. The passive means is through a coating that is essentially an anti-wetting agent. The agent forces water to ball up into droplets which are blown off.

2.6.11 SHEET POLARIZERS

Although not coatings, these materials are well-known and should be mentioned as an auxiliary light control. The polarizing systems are anti-reflective in a different sense than are the anti-reflective coatings. The latter increase light transmission by reducing the surface reflections in the aircraft glazing. Sheet polarizers suppress those light sources which mostly generate their state of polarizations by reflections from surfaces (i.e., bodies of water, road beds). The sheet polarizers will accept light only in parallel planes; therefore, if the planar axis of the polarizing material is oriented 90 deg to that of the plane of the reflecting surface, the majority of the reflection is suppressed, and only the remaining random (scattered) light is admitted.

Sets of two parallel polarizer assemblies, with one fixed and one hand-rotated part, have been considered for controlling, variably, the light transmission through passenger windows in aircraft. The material is generally available in flat sheet form, protected by transparent face sheets, and the whole may be readily formed into plates of simple curvatures. The source is listed in Table 2.1-1.

CHAPTER 3 – DESIGN CONSIDERATIONS

3.1 GENERAL

Three design considerations that are important for good utilization of plastics glazing
materials are discussed in this chapter: design allowable strength values, the notch
sensitivity and crazing susceptibility of transparent plastics, and the environmental and
other factors affecting the structural properties of transparent plastics.

3.2 DESIGN ALLOWABLE STRENGTH VALUES

Specifications for plastics generally do not specify minimum guaranteed values of the usual
mechanical properties. The tremendous number of individual tests that would be required to
establish reliable statistical minimum values for plastics makes the "typical property"
approach the only logical one to follow. The data on structural properties presented in
this handbook represent typical test values. Low values in data tabulations often represent a
sporadic defect in the incremental test area of the material or possibly in the test specimen
preparation through an unnoticed stress riser caused by machining. The conservative
approach of using low values to determine design allowables is not considered practical for
the purposes of this handbook. The amount of reduction of typical test values for use in
design is dependent on the material and the application and is left to the discretion of the
engineer.

3.3 CRITICAL PROPERTIES OF TRANSPARENT PLASTICS

3.3.1 GENERAL

Two phenomena exhibited by transparent plastics that should receive special attention for
good design are notch sensitivity and crazing. The as-cast or as-extruded thermoplastics
are sensitive in varying degrees to stress crazing and are moderately notch sensitive. The
thermosets (i.e., polyesters) are highly resistant to crazing, but they are exceedingly notch
sensitive,and consequently are almost invariably used in laminated form. Stretched acrylic
plastics possess greater resistance to notch effects than do unstretched thermoplastics,

and also have considerably greater resistance to crazing. Polycarbonates exhibit a toughness greater than the other materials but are extremely susceptible to crazing.[a]

The critical properties of notch sensitivity and crazing are the two limiting factors which first identify degradation of material under operational or testing conditions. Factors affecting structural properties are discussed in section 3.4.

3.3.2 NOTCH SENSITIVITY

Unstretched plastics glazing materials are very sensitive to stress concentrations and have little resistance to crack propagation, so that once a crack has started, little extra energy is needed to cause complete failure. Internal stresses and common service damage such as scratches, nicks, and star fractures can reduce tensile and flexural strengths appreciably. The amount of strength reduction varies widely with the type, size, shape, direction, and spacing of the defects. Because this damage can occur in random fashion, no precise evaluation of strength reductions can be presented.

Shallow, smooth-bottomed scratches and nicks have little effect on plastics materials, but deeper scratches or nicks, especially those with sudden discontinuities of surface; and cracks, even those of microscopic nature, may reduce the strength of the plastics materials considerably. Star fractures can reduce the tensile and flexural strengths of unstretched acrylics by 50 percent and or polyester materials by 80 percent. The polyesters are especially susceptible to star fractures. The stretched acrylics are practically immune to star fractures and possess good crack propagation resistance. Polycarbonates are reasonably resistive to notch sensitivity until exposed over a long period of time to ultraviolet radiation.

Some measure of the notch sensitivity of a glazing material may be determined by flexural and impact tests with controlled notches on the tension side of the specimens (see sections 4.3.3.2 and 4.3.5.2). The strength of notched specimens is usually constant over a wide temperature range, but the notch sensitivity, being a ratio of the unnotched and notched strengths, increases with decreasing temperature because the unnotched strength tends to increase with decreasing temperature.

---

[a]Refer to Section 11, Environmental Factors.

Stretched MIL-P-8184 material, which is now specified as MIL-P-25690, exhibits a

sensitivity to the bonding of other materials to it, which is more pronounced than the notch

sensitivity of the material. See section 3.5.2, which concerns interlayer bonding.

3.3.3 CRAZING

All of the transparent plastics materials currently available are susceptible to crazing,

though in widely varying degrees. Crazing has been defined as fine cracks which may

extend in a network over or under the surface or through a plastic. These fine cracks

are often difficult to discern, because they are approximately perpendicular to the surface,

very narrow in width, and usually not over 0.001 inch in depth. They can be seen by re-

flection from their surfaces and appear as bright lines when the specimen is viewed at

varying angles to the incident light.

Crazing results from a variety of causes, the more prominent of which are: (1) residual

stresses caused by uneven stretching and cooling involved in forming; (2) contact with

solvents and solvent vapors in the manufacture, operation, and servicing of aircraft,

including the adhesives used in making joints;[a] and (3) stresses induced in the material by

machining, buffing, polishing, mounting, and other fabricating operations. When the craze

cracks are in a random pattern, the crazing can usually be ascribed to the action of solvent-

vapors and is referred to as solvent crazing. When the cracks are approximately parallel,

the crazing is usually due to the application of mechanical stresses and is referred to as

stress crazing. These two types are not mutually exclusive, so that the effect may be

produced by the simultaneous action of stress and solvent, referred to as stress-solvent

crazing. Internal stress is, in fact, essential to solvent crazing. In stress crazing and

stress-solvent crazing, the craze cracks appear perpendicular to the applied stress.

Tensile and flexural stresses cause crazing, whereas purely compressive stresses do not

produce crazing. Crazing is not a reversible property of the acrylic plastics, although

visible crazing may disappear. Experiments have shown that craze cracks produced by

flexural stresses became invisible to the naked eye upon heating the specimens at 212 deg F;

after cooling and on restressing, crazing was rapid; and the original crazing pattern re-

appeared (References 2 and 3).

[a]Refer to Section 11, paragraph 11.7.

Crazing reduces the luminous transmittance of the transparent plastics materials and interferes with vision, especially when the aircraft is flying into the sun. It also affects the structural properties of the plastics. Crazing cracks 0.006 inch deep resulted in a 30-percent loss in tensile strength of MIL-P-5425 material in one investigation. The extreme stress concentration at the bases of the fissures results in propagation of the crazing with time under load. Small changes in the depths of the cracks are accompanied by large decreases in the impact strength. In extreme cases, crazing can reduce tensile, flexural, and impact strengths to virtually zero. In comparison to the thermoplastic materials, MIL-P-8257 material is highly craze-resistant.

The acrylic materials can be sensitive to interlayer plasticizers under certain circumstances. Polyvinyl butyral interlayer material contains a sizeable amount of dibutyl sebacate as a plasticizer which acts as a solvent for acrylic plastics. Because the threshold crazing stress for stress-solvent crazing is much lower than for stress-crazing, acrylic plastic laminates are much less craze-resistant than are the equivalent solid sheeting.

Monomer present in acrylic plastic sheets prior to forming also is a solvent and produces crazing. It has therefore become the practice of some manufacturers to anneal the finished sheets to remove this monomer and to relieve residual casting stresses. To date, stretching of acrylic plastics represents the most effective preventive measure against crazing.

Long-time cantilever loading of test specimens, with and without various solvents applied to the tensile surface, has been used to estimate the threshold crazing stress under various conditions (see Figure 4.3-20, p. 4-29). A more realistic test of craze resistance is the longer-term weathering under load test described in Figure 11.3-8, p. 11-14.

3.4 CONDITIONS AFFECTING STRUCTURAL PROPERTIES OF MONOLITHIC MATERIALS

The physical properties of plastics glazing materials are greatly influenced by temperature, rate of loading, duration of loading, environment, and other factors. This behavior is not unique to plastics, but it is much more pronounced than in metals.

3.4.1 PROCESSING

Historically, sheets of the MIL-P-8184 material were laminated with a polyvinyl interlayer and stored in a dehumidified room at +120 deg F. Without this procedure, bubbling could be expected during the forming cycle which was, at least, detrimental to optical quality. With the advent of more hygroscopic rigid materials, such as the polycarbonates, extended drying cycles at +265 deg F are recommended to prevent bubbling during the processing. Bubbles in the rigid material, can, of course, affect structural properties in a localized area. Also important, however, is that the drying cycle itself affects the over-all properties of the sheet by creating a tendency toward embrittlement and notch sensitivity. Extended high-temperature processing has also shown evidence of microscopic "seed" bubbles which are postulated as being caused by the outgassing of included impurities and are possible sources of notch defects.

3.4.2 TEMPERATURE EFFECT

In general, throughout the range of service temperatures, increasing temperature is accompanied by decreasing physical properties, except for elongation, and in thermoplastics, the impact strength. As the temperature is increased, these materials change from a relatively brittle material at subzero temperatures to a semiflexible sheet at operational temperatures, with higher ductility. At the subzero temperatures, tensile breaks are characterized by a brittle type of failure. At temperatures above zero, ductile failures become the rule, with the yield points occurring at less strain as temperature increases, and elongations to rupture occurring at much higher strains. The strains at ultimate can become academic in high-temperature tensile testing, as with polycarbonates, because the elongations far exceed any practical limit. Thermosetting materials are not as sensitive to increases in temperature and do not drop in tensile value as much.

Under most flight conditions, there will be a temperature gradient across a monolithic material which represents the difference between cockpit temperature and skin temperature. As a result of this gradient, the cold side of the sheet carries a greater part of the load than the hot side. This unusual distribution of stress tends to produce crazing in the thermoplastic

materials and failure in the thermosetting materials at much lower tensile stresses than would normally be expected. If an interlayer is involved in a laminate design, caution in interlayer selection should be observed because the plasticizer used in some of the interlayers may attack the surface of the face sheet under the higher stress and induce crazing (see Figures 4.3-66, -67, and -68 for the effects of temperature on the dimensional and form stability of stretched plastics glazing materials).

3.4.3 RATE OF LOADING EFFECT

In testing monolithic plastic materials, some attention should be given to the rate of loading, because the effect is not the same for all plastics. The apparent tensile strength tends to increase at the yield point as the rate of crosshead separation increases. The rate of tensile strength increase varies from one material to another.

The low rate of loading of 0.20 to 0.25 inch per minute is adequate for obtaining a minimum tensile strength. Loading from approximate 0.25 inch to 5.0 inches per minute tends to present a characteristic curve of toughness as exemplified by the area beneath the tensile stress-strain curve at rupture, especially with the more ductile materials such as polycarbonate. High rates of loading between 5.0 and 20.0 inches per minute exhibit failures at less and less strain with an increase in rate which approaches the transient condition of bird impact. The latter results indicate edge attachment designs which will allow for compensating movement.

The comparable differences of modulus of elasticity between materials with increasing crosshead rate is shown in Figure 3.4-1.

3.4.4 DURATION OF LOADING EFFECT

Most structural materials are subject to creep deformation and creep rupture effects; that is, they will suffer gradually increasing permanent deformation and eventual failure from a constant load that is only a fraction of the normal static strength. Plastics materials exhibit this effect to a marked degree, particularly at elevated temperatures. The creep-rupture strength of a thermoplastic at 1000 hours' duration of stress may be only 50 percent of the
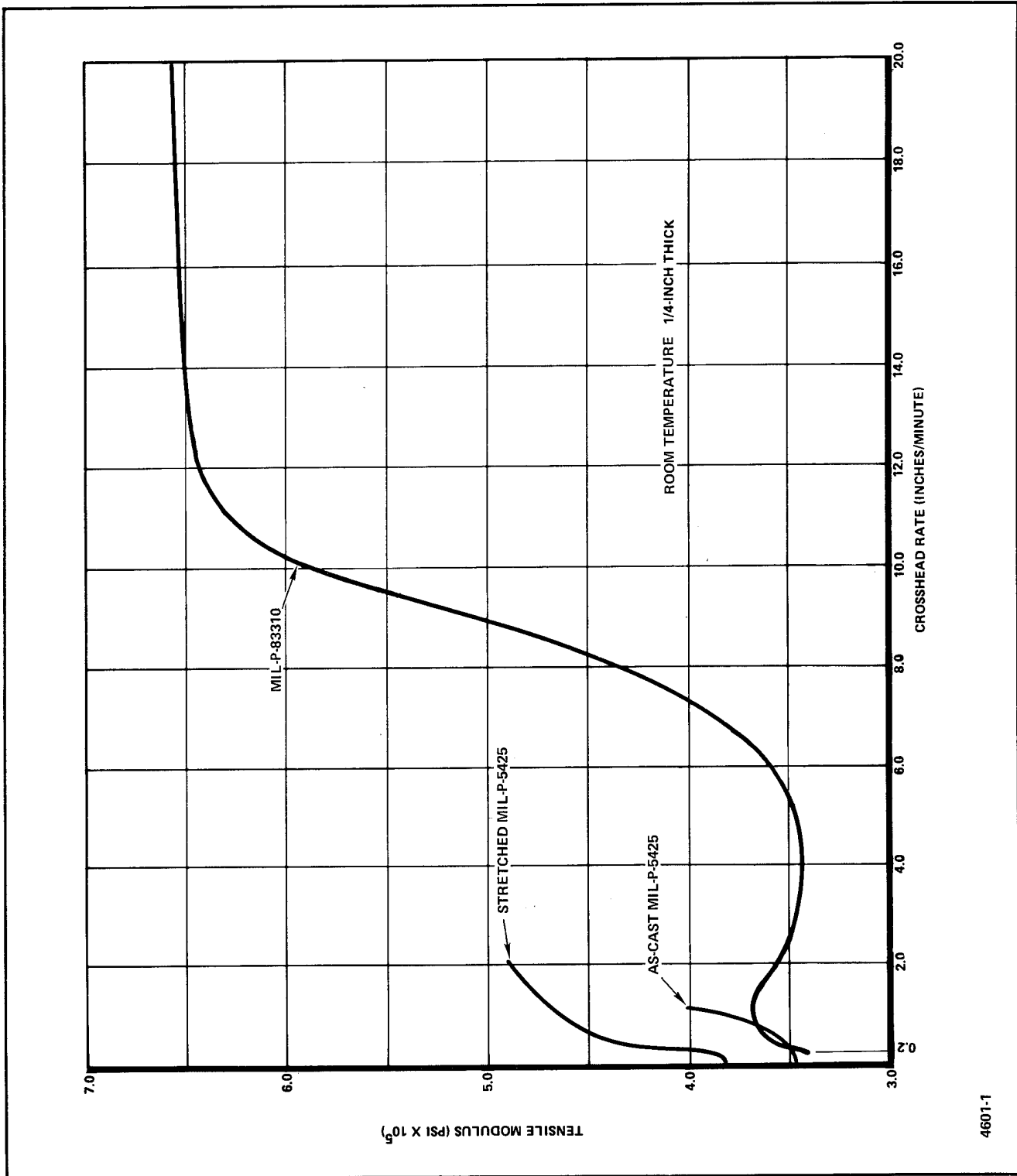
Figure 3.4-1 - Tensile Modulus versus Crosshead Rate

strength found in the usual static tests. Some materials are more sensitive than others upon exposure to the combination of stress and high temperature, and over a period of time exhibit surface crazing. If the period of time before crazing occurs is less than 1000 hours, then the allowable strength for that temperature exposure has to be reduced.

Generally, the creep deformation or crazing becomes objectionable before the danger of creep rupture develops, particularly with acrylic pastics, so that the creep deformation characteristics of a plastics material are important in design. However, because the maximum deformation of MIL-P-8257 material is only slightly more than four percent, the possibility of creep rupture is great where deformation of this extent might be encountered.

Considerable test work has been done to determine creep rates and creep-rupture times of several materials under various conditions of temperature and stress. It has been found that the creep rupture times of all materials are reduced, sometimes drastically, if the tests are conducted outdoors.

Very little is known about the effects of creep under intermittent loading (see Figure 4.3-33).

3.5 ACCESSORY COATINGS AND LAMINATIONS

In addition to the load-bearing monolithic glazing, designs often require that the visual area perform other functions which enhance the over-all performance of the aircraft. Because any one coating or lamination becomes a component part of the glazing assembly, each one is also an interacting mechanical and chemical complex with the primary transparency. Certain critical design considerations are necessary to combine these features into a glazing of maximum effectiveness.

3.5.1 COEFFICIENT OF EXPANSION

As far as the primary transparent structure is concerned, the edge attachment can be designed to mechanically compensate for any gross change in the expansion or contraction of the complete enclosure. Coatings and laminates, however, are adhered to the surface of the transparency in one way or another and are subject to direct shear forces caused by differentials in their thermal coefficients of expansion. If the differential between the

accessory layer and the primary glazing is too great, an intermediate elastic material is necessary which is compatible with both materials and capable of compensating for the shear movement. It cannot be overemphasized that the hardest problem of a complex laminate design is that of compensating for coefficients of expansion over the wide temperature range experienced by high-performance aircraft.

3.5.2 INTERLAYER CONSIDERATIONS

Glass and plastic materials have an obvious difference in coefficients of expansion which requires compensation with an interlayer material as a most extreme case. The selection of an interlayer material requires an analysis of face sheet movement (i.e., glass and plastic) that can be expected throughout its operational temperature range. Thermal gradient conditions can make the problem more severe. The interlayer invariably moves to compensate for the movement differential between the face sheets caused by the thermal expansion and gradient mismatch.

The movement has to occur reversibly, without rupture or delamination of the interlayer surface bonds. Since lamination of the face sheets and interlayer undergoes a processing thermal history of some sort, a built-in shear stress can be expected.

The weaker bond strength at the interfaces is primarily one of the flatwise tensile component of the shear force. The flatwise tensile strength is further compromised by the compatibility of the bonding medium with the rigid substrate. Compatibility can be complex within itself in that both face sheets have to remain adhered throughout the force range generated by the composite, and not attack either of the materials chemically.

Elongation of the interlayer (and possibly rupture) can be compensated for by adjusting its thickness. Interlayer materials do not bond equally well to all substrates and can be expected to have different operational temperature ranges. Thermoplastic and thermosetting face sheets of material also often require flexible interlayers.

3.5.3 THERMAL CONDUCTIVITY

The theoretical determination of temperatures within a complex laminate requires the use of the coefficient of thermal conductivity for all of the involved plastic materials. These temperatures are used to determine the degree of expansion or contraction that can be expected in conjunction with coefficient of expansion curves (temperature versus expansion).

In anti-fogging and anti-icing coatings which are electrically heated, the thermal conductivity becomes very important. The thicknesses of the material and the required surface temperature dictate the required resistivity of the electrical coating through calculations involving the coefficient of thermal conductivity. The resistivity, in turn, is used to determine the power requirement to be supplied by the ship's electrical system.

3.5.4 ABRASION RESISTANCE

Abrasion of plastic materials has always been a problem, but has become increasingly critical because of part replacement rates necessary to maintain optically acceptable enclosures installed on the aircraft. Part of this is caused by more intensive dust environments (i.e., helicopter field operations), and is partly caused by the fact that newer and structurally tougher polycarbonate materials exhibit a weak surface resistance to abrasion.

Two alternatives are possible. One is the lamination of a more highly abrasive resistant thin sheet material to the exposed face, and the other is the application of an abrasion resistant coating. As previously mentioned, thermoset sheet materials offer more abrasion resistance than the thermoplastic materials, have some formability, and have been used for this purpose. Glass would be the best for abrasion resistance, although weight and formability become limiting factors. The sheet protection philosophy usually requires a flexible interlayer, because of the difference in coefficients of expansion previously mentioned, which acts as a transparent bonding material compatible with both sheet materials. One other technique which has been used experimentally with thermoplastic materials is that of heat-fusing a sheet of MIL-P-5425 material to a MIL-P-83310 substrate. The abrasion protection would then be as good as that of the cast MIL-P-5425 material.

Fusion bonding, however, reduces the normal impact resistance of the polycarbonate to that of the acrylic face sheet, and should not be used in acrylic-polycarbonate applications which are highly prone to impact energies.

3-10

Should weight, form, or other considerations prevent the use of thin sheet cladding, the option of hard coatings is available. One type of material may be used as a dip or as a flow-coating for the part with a subsequent heat cure. Another method is that of vacuum deposition of a glassy inorganic type of material which is experimental at the time of this publication.

Again, coating materials have to be chemically compatible with the substrate or be linked adhesively to the substrate through an intermediate priming agent.

3.5.5 FILM COATING CONSIDERATIONS

Activated coatings require auxiliary equipment and interfaces which have to be coordinated with the aircraft designer. Passive coatings which have any permanence have to be applied by a processor. Radar reflective coatings do not require grounding for their reflective function, and consequently do not need the bus-bars required for anti-icing and anti-fogging currents. A grounding point may be required to prevent an electrostatic accumulation in the coating if radio or compass interference is experienced. Radiation protective coatings should be grounded to the airframe to prevent the coating from re-radiating as an antenna. The coating should offer complete shielding in this case rather than the panel approach used in electrically heated coatings. Anti-reflective coatings of the bandpass type are used only for small specialized glazings. Single-coat anti-reflective systems should be shown on a drawing as applied on both sides of the glazings for greatest efficiency and the angle of incidence specified for reflection suppression. Anti-reflective coatings lose their effectiveness with a protective overcoat; therefore, the outer reflective coating must be abrasion and weather resistant. The best coatings usually require a high-temperature application or cure, and although compatible with glass, the high temperatures may not be compatible with some plastics. The advice of the processor should be sought for the best solution.

3.5.6 OPTICAL RELIABILITY

In the previous paragraphs, various types of materials, devices and possible problem solutions have been mentioned to the point it may appear that inclusion of most of them in one

design will provide the optimum transparent enclosure. Unfortunately, this is not true and is one facet of design most often neglected.

First, the shape of the enclosure is usually dictated by the frame which is designed by the aerodynamicist. The primary window structure material and thickness may be on the control drawing of the glazing designer with noted indications of protective coatings or laminates to be added. The callout of an optical specification usually completes the case with the location of the pilot's eye position on the drawing. The optical integrity of the design is usually not known until a prototype is measured. Calculative optical techniques should be used as much as possible to establish imagery deviations from the "pilot's eye position" to determine practical zones of optical tolerances prior to prototype fabrication.

3.6 SHAPE

The previous paragraph mentioned shape from the standpoint of the aerodynanamist. Often, especially in high-performance aircraft, the glazing shape has to conform to the fuselage streamlining. Airframe designers should note, however, two problems of the glazing fabricators. Tight tolerance contours and unusual shapes will undoubtedly be mold formed. The process of mold-forming thermoplastic materials often causes a condition of "mark-off" in which any mold discontinuity, hot spot, or foreign particle surface contamination will appear in the glazing as optical distortions. Pressure shapes of less tolerance and the best optical properties can be formed with compressed air or vacuum without mold contact. Conical, cylindrical, or spherical segments should be used for large shapes which will enclose a pressurized cockpit.

CHAPTER 4 – PROPERTIES OF MONOLITHIC PLASTIC MATERIALS

4.1 GENERAL

4.1.1 CHOICE OF MATERIAL

Choosing a plastic for a monolithic glazing is not overly difficult. Of the materials now specified for aircraft use, only a few choices are available after an initial screening of forming properties. The shape of the transparency can be the primary factor. Any design that requires a deep draw and double curvature or curvature reversal will require a thermoplastic material such as the acrylic (MIL-P-5425), modified acrylic (MIL-P-8184), or polycarbonate (MIL-P-83310). Stretched acrylic (MIL-P-25690) is marginal because of its lower forming temperature range, which restricts its thermoplastic properties.

Flat panels and shapes of single curvature or very shallow draws can be formed from allyl copolymer G-3 (L-P-516), polyester (MIL-P-8257), and in more specific cases, glass (MIL-G-25667). These are the more notch-sensitive, brittle materials. With the exception of glass, these are known as thermosetting materials and in complex designs are relegated as a secondary member-coating substrate or abrasion protection. Monolithically, these materials can be used in low-velocity, unpressurized aircraft, although the toughness of the thermoplastic materials is usually preferred. The thermoset materials have the distinct advantage of good abrasion and stress-solvent crazing resistance.

Materials as yet unspecified have been developed which are delivered to the processor in a semicured thermoplastic state. Further cure converts the sheet properties to those of a thermoset material. This approach provides the forming advantages of a thermoplastic material and a final part with thermoset properties.

Other monolithic materials are constantly being developed which also fall into the previous categories. The newer materials extend operational temperature ranges, formability, properties, and resistance to abrasion and impact.

Short-time tensile tests usually form the basis for comparing the strength properties of plastics materials. Flexural strength is a related quantity because flexural failures in these materials are in most instances the result of tensile fracture. Tensile properties have usually been evaluated over a wide range of temperature, but since flexural strength is not often used as a design criterion, it has not been evaluated at all temperature conditions. Nevertheless, it is known to vary in much the same manner as the tensile strength.

The allowable tensile stress for long-time loading of thermoplastic materials is taken as the threshold crazing stress and is determined for each application. In these materials crazing constitutes the start of creep-rupture. To preclude premature crazing in flexure, the allowable flexural stress for long-time loading is usually assumed equal to the threshold crazing stress in tension.

The polyester materials are very craze resistant, but their creep-rupture strength is low, especially at elevated temperatures. The threshold crazing stress of MIL-P-5425 material at temperatures above 160 F is higher than the creep-rupture strength of MIL-P-8257 materials, thus offsetting the noncrazing properties of the latter.

For analysis, the long-time applied loading is taken as the sum of residual stresses, clamping and thermal stresses, and stresses caused by steady external loads. It is standard practice to consider tensile strain at failure of plastics as the total deformation at failure, including the elastic deformation.

4.2 COMPARATIVE PROPERTIES

Because specimen conditioning and test methods may vary to some degree between testing agencies, it is presumptuous to superimpose most data from one source onto the data of another. As a consequence, this section is devoted primarily to the presentation of comparative data as supplied from single testing sources, unless otherwise noted. Stretched MIL-P-5425 data are included as background information because it is not often used in the stretched form.

4.2.1 TENSILE PROPERTIES

Short-time tensile properties of plastics glazing materials are graphed in this section along with creep-rupture curves at various temperatures. Figure 4.2-1 shows the relative stress-strain curves of various thermoplastic materials with the MIL-P-8257 thermoset material. Figure 4.2-2 compares the ultimate tensile strengths versus temperature of the stretched and unstretched acrylics compared with that of polycarbonate. Specimens were 1/8-in. thick and tested in accordance with ASTM D638. Figures 4.2-3, 4.2-4, and 4.2-5 are curves which represent the decrease in rupture strength over a period of time for various materials under three separate temperature conditions. The higher stresses sustained by the stretched acrylic materials are an obvious advantage when compared to the as-cast acrylic forms and the low stresses displayed by the polyester data. Figure 4.2-6 displays the effect of weathering on the tensile-rupture behavior of several materials.

4.2.2 CRACK PROPAGATION RESISTANT PROPERTIES

This property was originally defined for stretched acrylic material to determine the ability of the material to resist the propagation of crack of controlled size (Reference 4). Temperature has its effect as shown in Figure 4.2-7.

4.2.3 FLEXURAL FATIGUE

Figure 4.2-8 demonstrates the slightly better flexural fatigue characteristic of the unmodified acrylic, stretched and unstretched, over the modified acrylic.

4.2.4 COEFFICIENT OF LINEAR THERMAL EXPANSION

Figure 4.2-9 compares the coefficient of linear thermal expansion of a group of transparent plastic materials.

4.2.5 IMPACT STRENGTH VERSUS SCRATCH DEPTH

Figure 4.2.10 shows the effect of scratches on the strength of various materials. Although not all the available materials are represented, the effect is of great importance because it demonstrates the necessity of scratch prevention.

A MIL-P-4257
B MIL-P-8184
C MIL-P-5425
D MIL-P-5425
STRETCHED 100 PERCENT
E MIL-P-83310*

*DRIED 18 HR AT +265 DEG F BEFORE TESTING
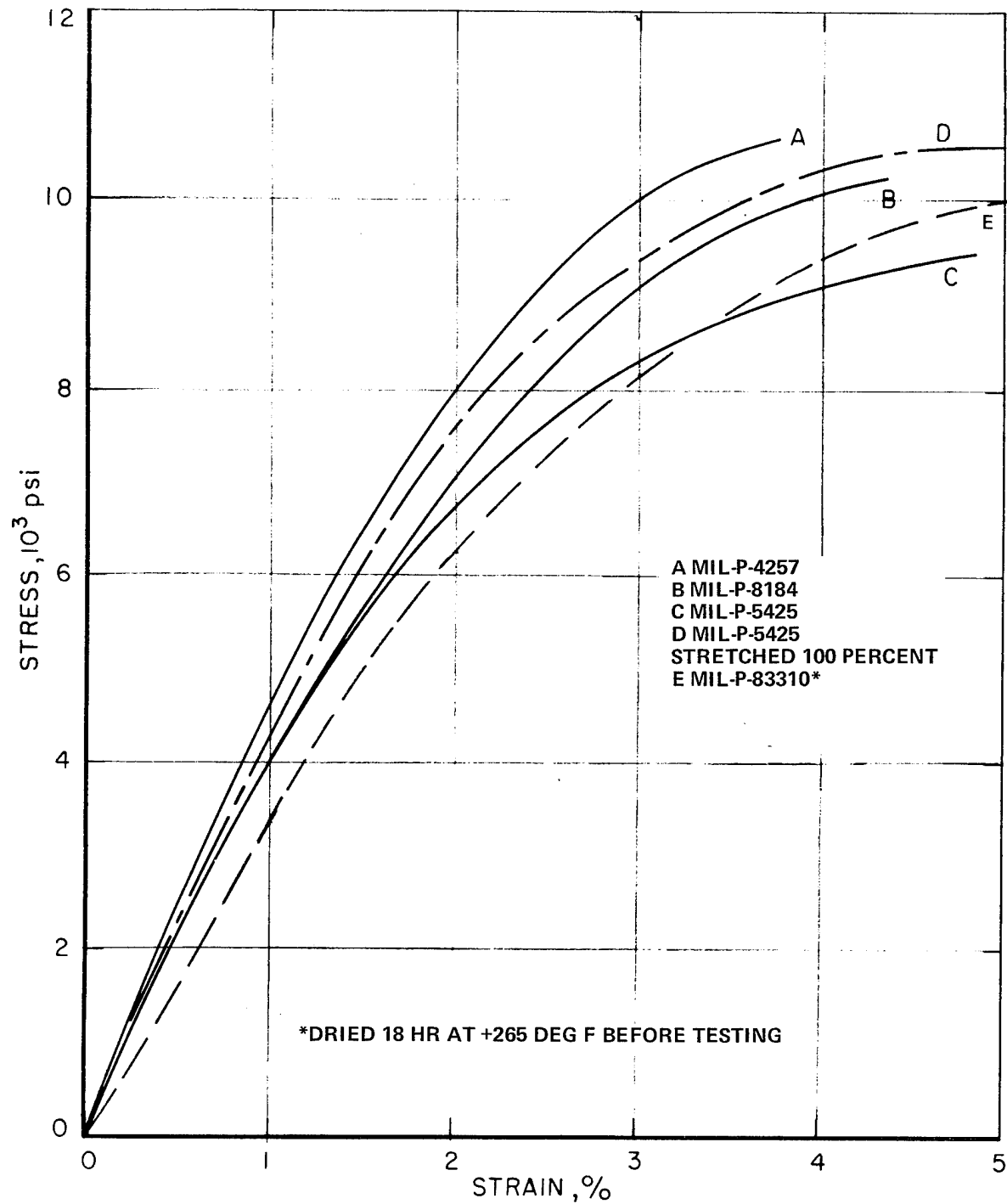
Figure 4.2-1 – Tensile Stress-Strain Curves for Some Transparent Glazing Materials
at Room Temperature – Crosshead Rate 0.05 In./Minute

NOTE: DATA SUPPLIED BY MCDONNELL-DOUGLAS.
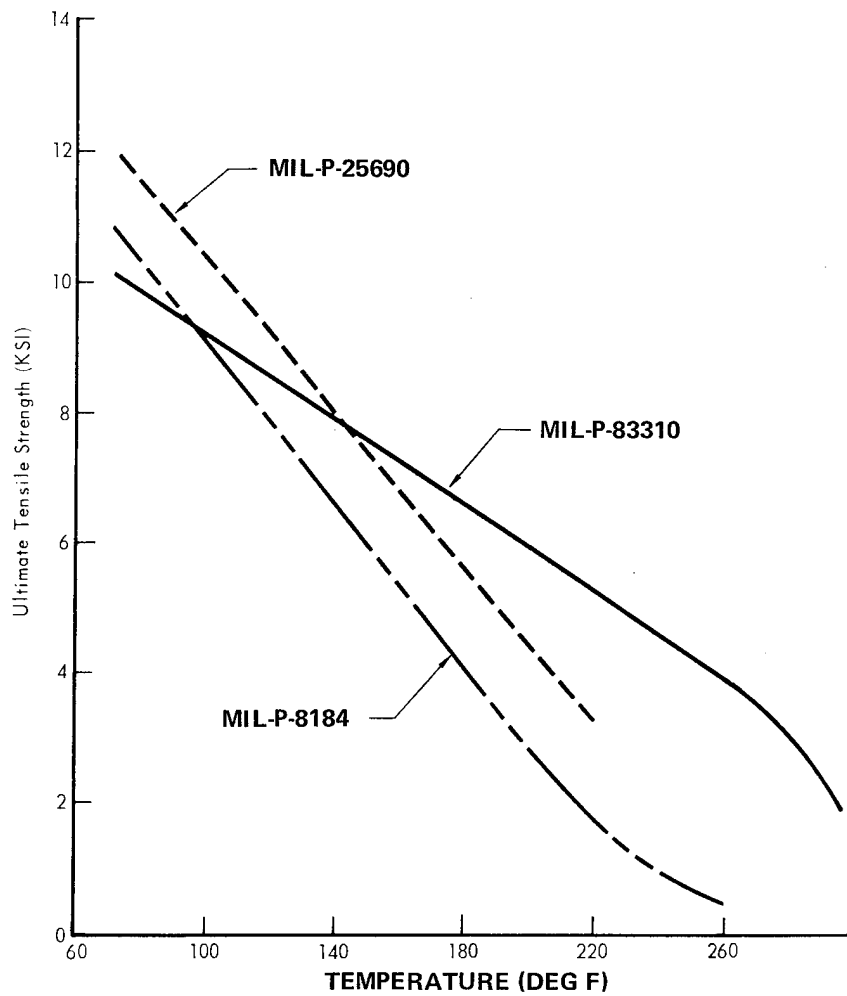
Figure 4. 2-2 – Tensile Strength versus Constant Temperature for Various Plastic
Materials – ASTM D638, 1/8-In. Thick
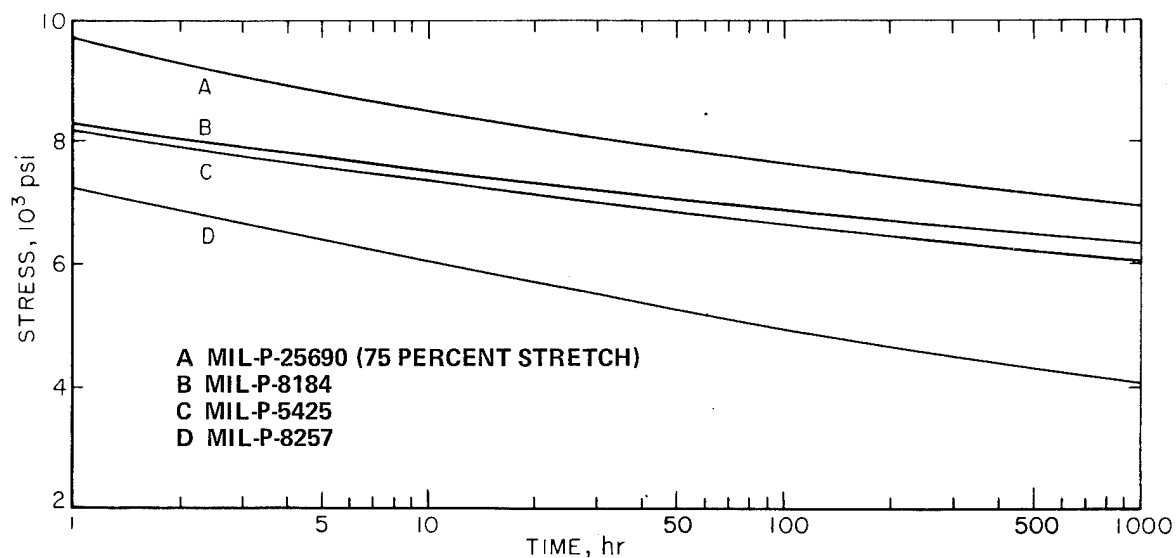
Figure 4. 2-3 – Effect of Duration of Loading on the Tensile Rupture Behavior of
Plastics Glazing Materials at 80 Deg F
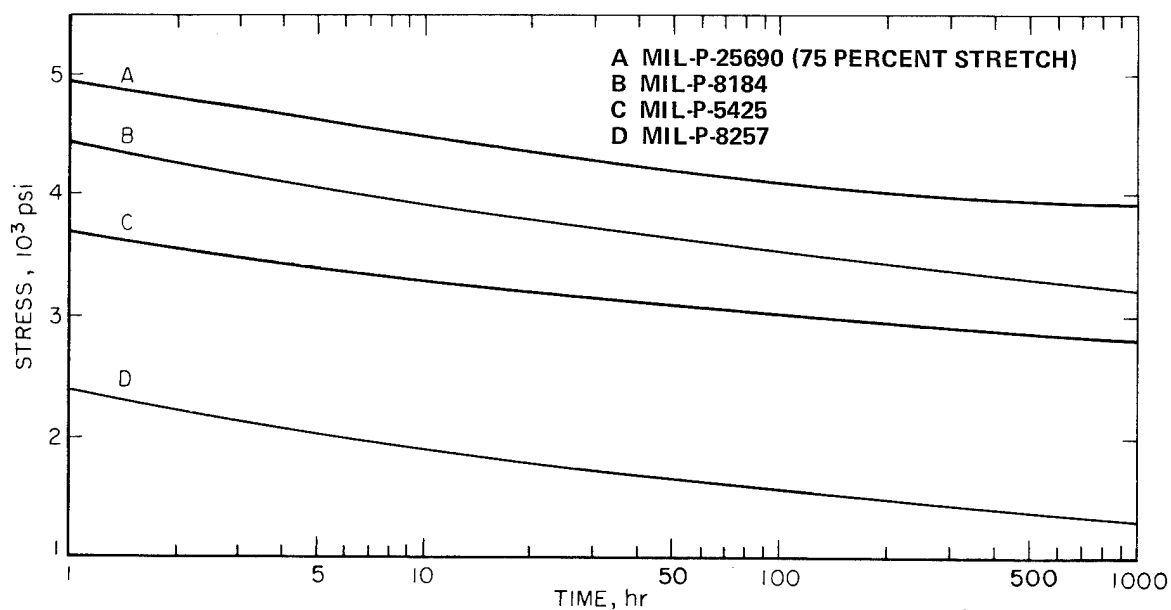
Figure 4. 2-4 – Effect of Duration of Loading on the Tensile Rupture Behavior of
Plastics Glazing Materials at 160 Deg F
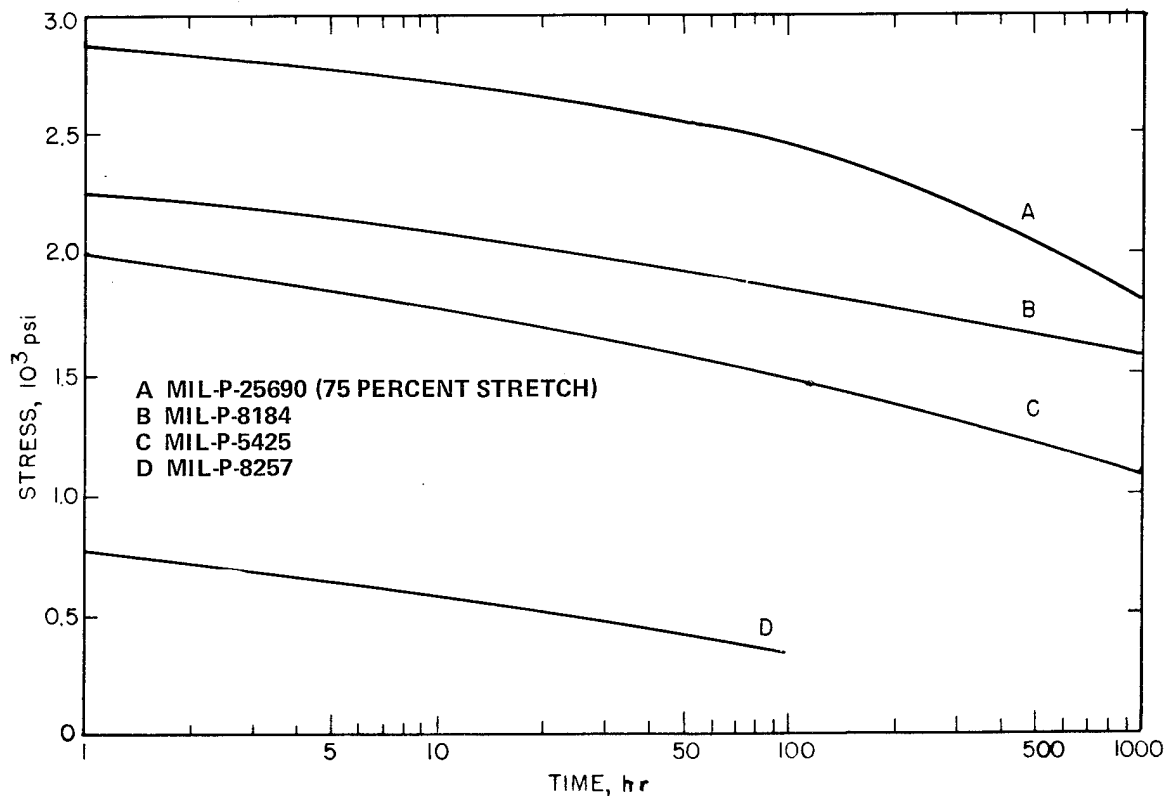
Figure 4.2-5 – Effect of Duration of Loading on the Tensile Rupture Behavior of
Plastics Glazing Materials at 200 Deg F

4.2.6 LUMINOUS TRANSMITTANCE AND HAZE OF STRETCHED AND UNSTRETCHED MATERIALS

Table 4.2-I tabulates and compares changes of luminous transmittance and haze as a result
of calibrated abrasion with Taber equipment.

4.2.7 SINGULAR VALUE PROPERTIES

Table 4.2-II contains the properties of each material which are usually represented by
single values rather than curves of values. More often than not, these values were obtained
at room temperature. Where several values have been reported, a range is presented.
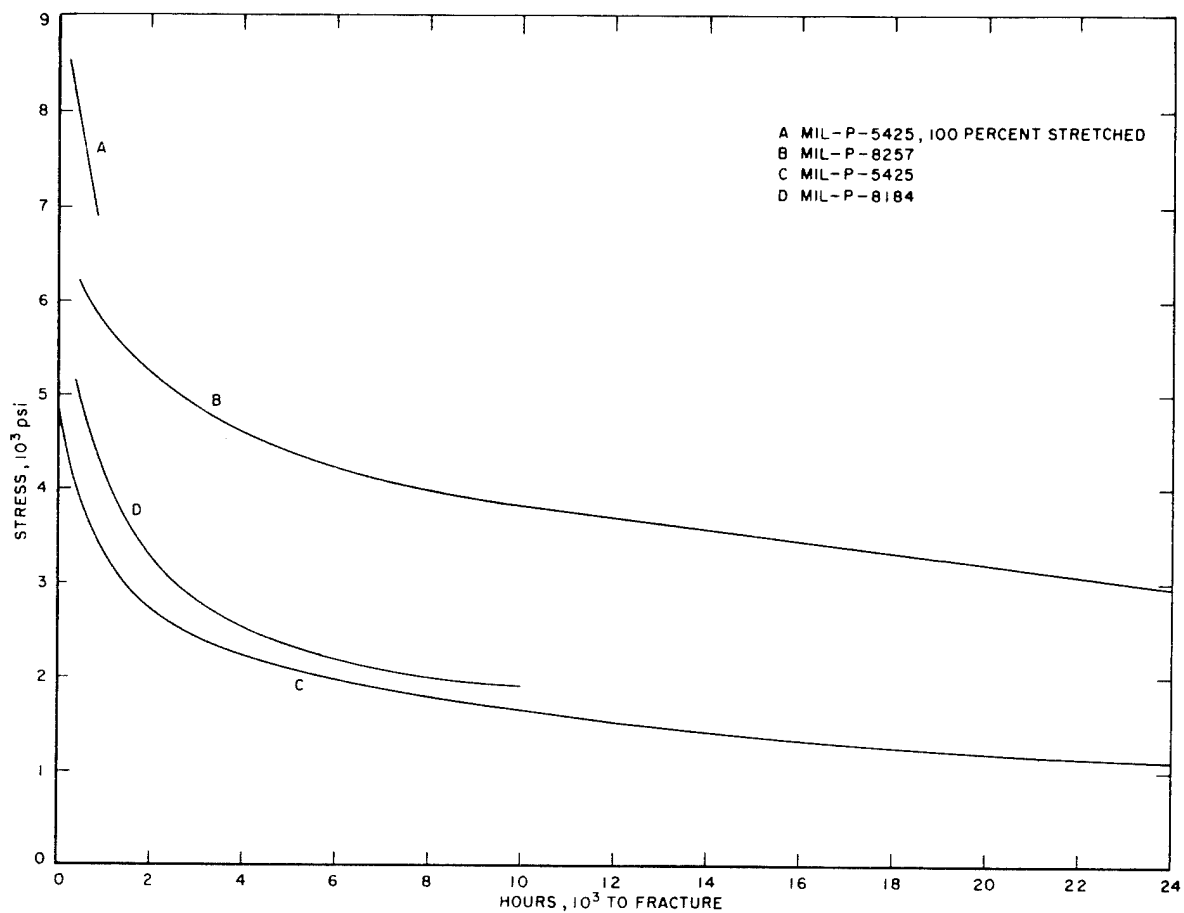
Figure 4.2-6 – Effect of Duration of Loading During Exposure Outdoors on Tensile Rupture
Behavior of Several Plastics Glazing Materials

4-8
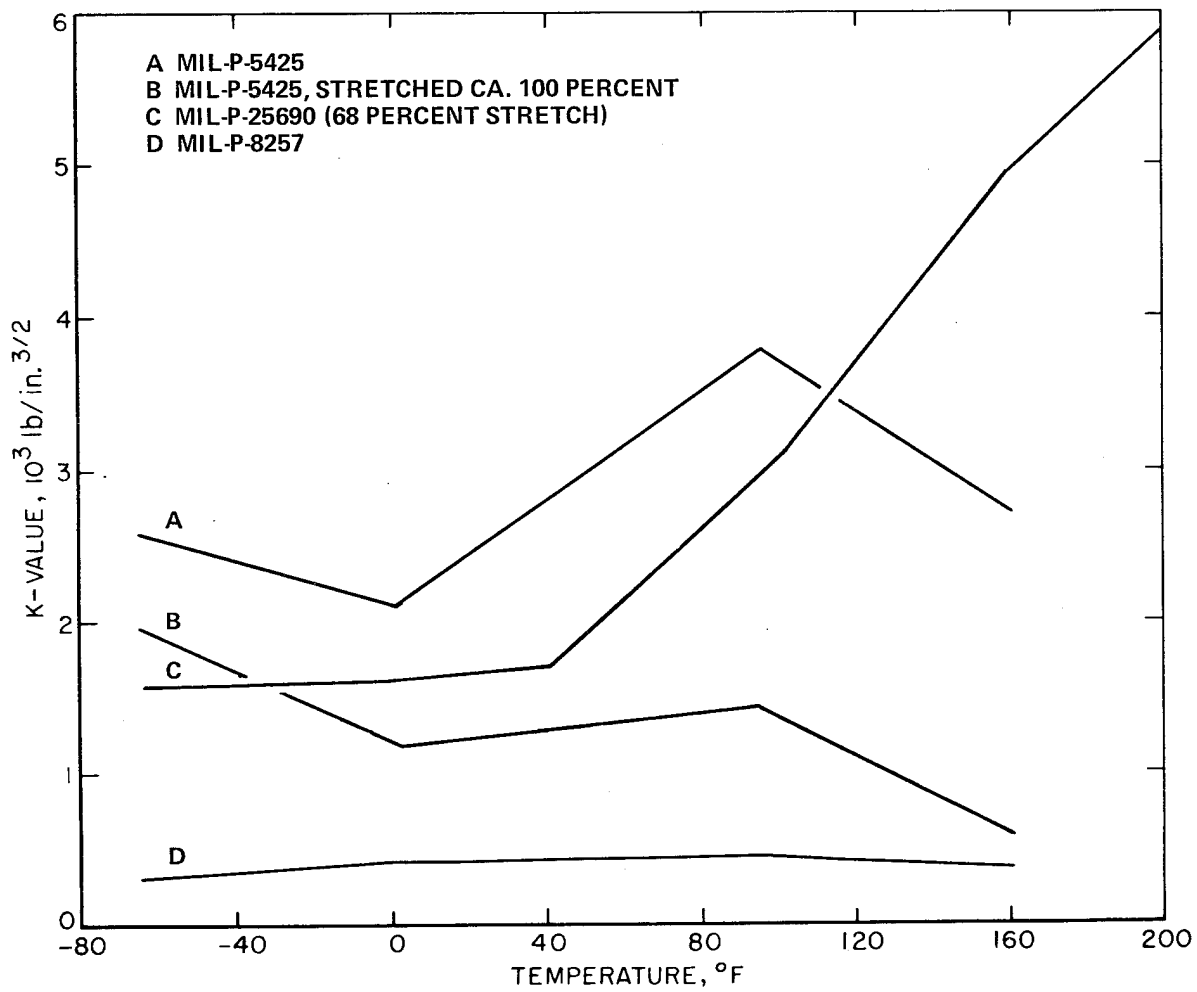
Figure 4.2-7 – Effect of Temperature on the K-Value of Glazing Materials
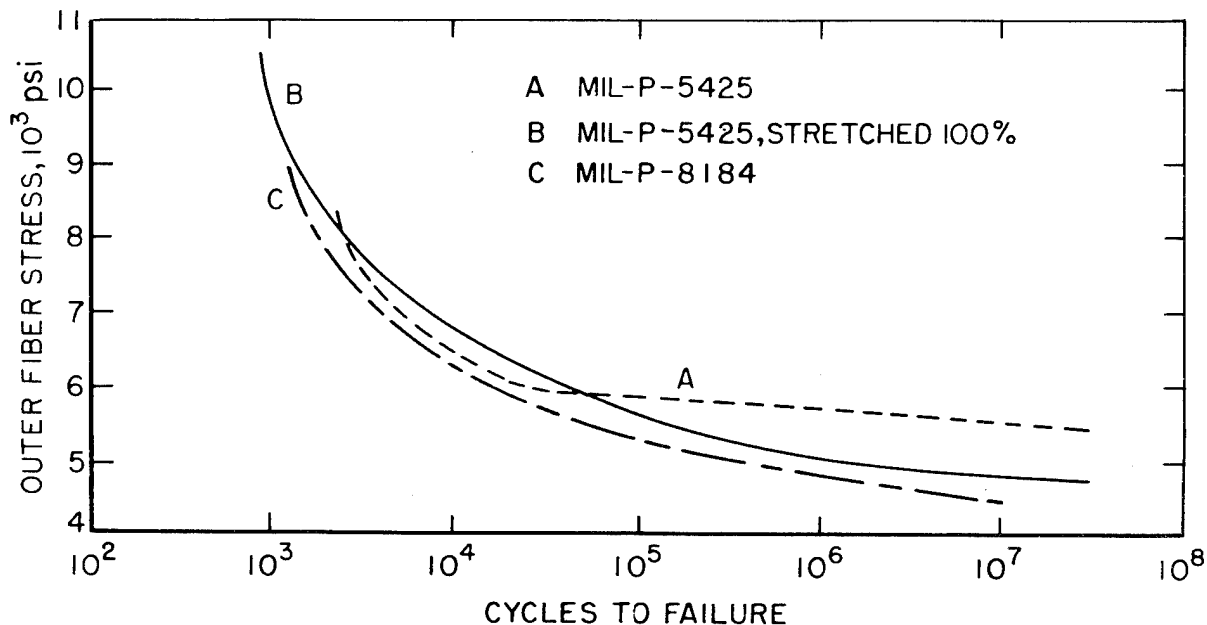
Figure 4.2-8 – Flexural Fatigue Curves for 0.250-Inch-Thick Plastics Glazing
Materials at Room Temperature

The ASTM and FTMS 406 methods utilized for obtaining the data are listed for reference
with the units used. Variations within the test method may have influenced the data;
therefore, the reader should use discretion in making direct comparisons and should treat
the values as being typical.

4.3   PROPERTIES OF MATERIALS SPECIFIED FOR AIRCRAFT USE

4.3.1   L-P-516a, CLASS G-3

4.3.1.1   GENERAL

This material is commercially recognized as CR-39[a] in the monomeric state which meets
this specification. Copolymers of the CR-39 monomer, glycol bisallyl carbonate, have
been developed, but are not covered by this specification. The material is a polyester and
has the properties of a thermoset sheet. The general characteristics are summarized as

[a]TM, Pittsburgh Plate Glass Company, Pittsburgh, Pennsylvania 15222
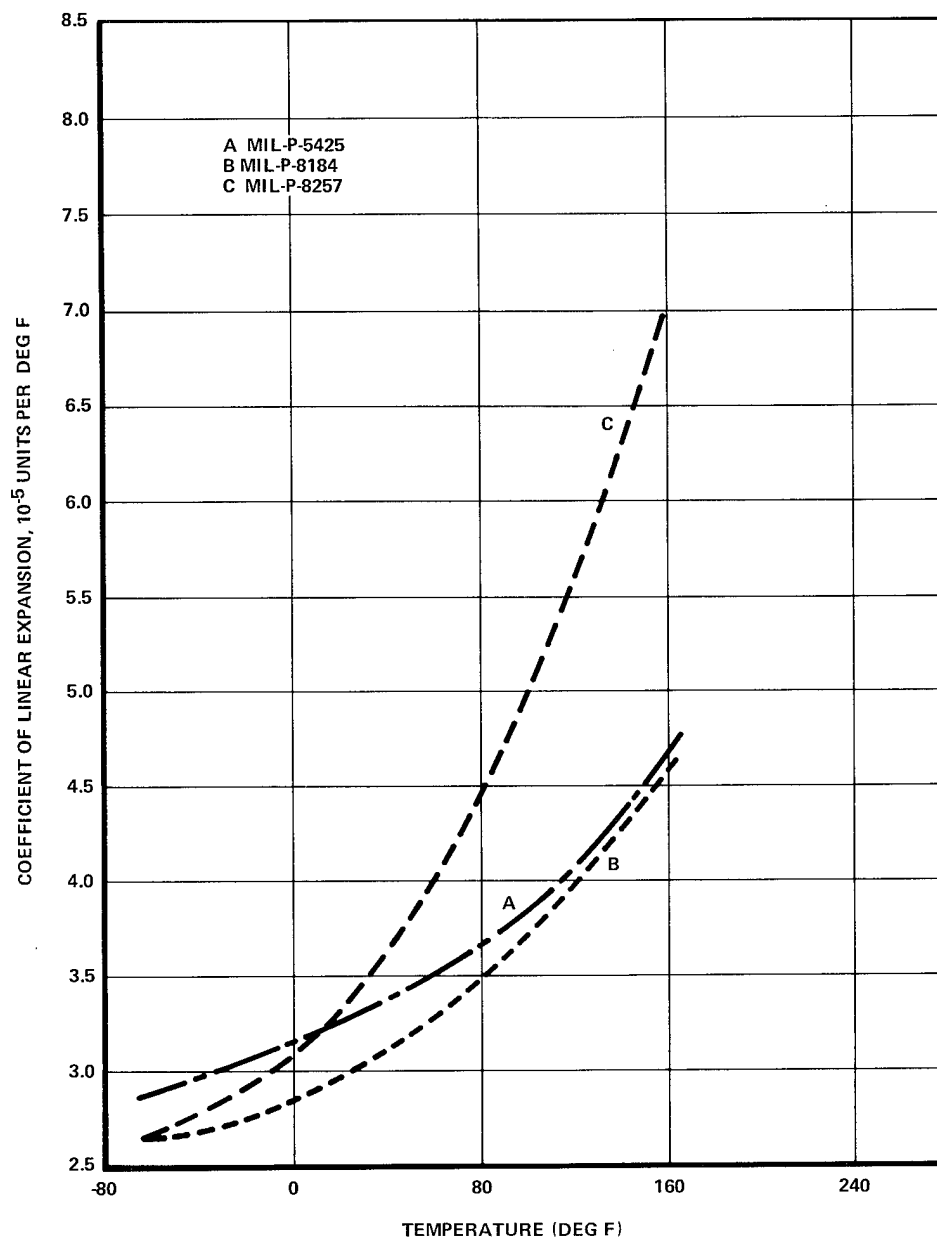
Figure 4.2-9 – Effect of Temperature on the Coefficient of Linear Thermal Expansion of
Several Plastics Glazing Materials

4-11
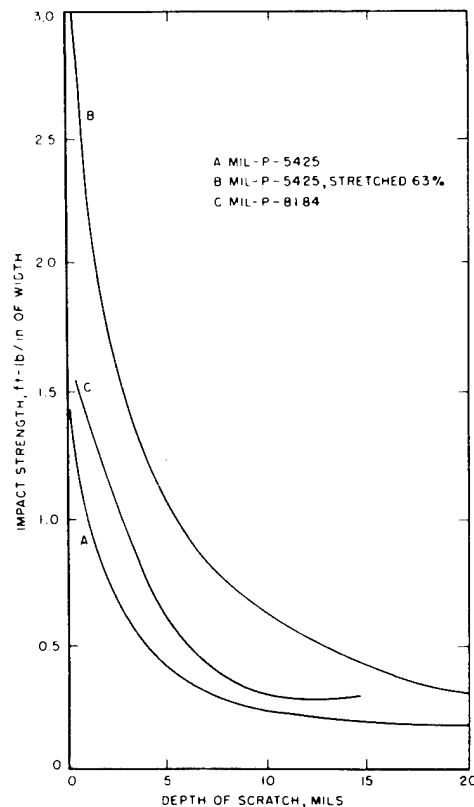
Figure 4.2-10 – Effect of Depth of ARTC Needle Scratch on Izod Impact Strength of Plastics Glazing Materials at Room Temperature

being excellent, optically and electrically, but physically brittle and restrained to a mean operational temperature of approximately +200 F. It has been used successfully as a face sheet for abrasion protection of thermoplastic substrates and as a substrate for protective coatings.

4.3.1.2 PROPERTIES

Typical properties may be found in the singular properties chart of Table 4.2-II.

Table 4.3-I reports values obtained from testing a representative piece of sheet stock. Figure 4.3-1 displays the differences in abrasion resistance as defined by haze measurements performed after controlled abrasion by ASTM Test Method D-1044.

TABLE 4.2-I – LUMINOUS TRANSMITTANCE AND HAZE OF GLAZING MATERIALS
BEFORE AND AFTER ABRASION WITH TABER ABRASER*

Material	Taber abraser		
	Revolutions (number)	Luminous transmittance (percent)	Haze (percent)
MIL-P-5425, as cast	0	92	1
	25	. . . .	15
	250	88**	23**
Stretched*** (percent)			
50	25	. . . .	25
100	25	. . . .	38
150**	250	87	32
160**	250	84	43
MIL-P-8184, as cast	0	91	1
	25	. . . .	18
	250	88**	22**
MIL-P-25690 stretched*** (percent)			
45	250	88	25
50	25	. . . .	31
75**	25	. . . .	43
80**	250	88	27
MIL-P-8257**	0	87	1
	150	85	17

*The luminous transmittance and haze before and after abrasion were determined in
accordance with method 3021 in Federal Specification L-P-406, unless otherwise
noted. This method is replaced by method 3022: see**.
**Test method 3022 in Federal Specification L-P-406.
***The values for luminous transmittance and haze of the stretched materials are
approximately the same as those for unstretched materials.

4-13

TABLE 4.2-II – SINGULAR VALUE PROPERTIES REFERENCE CHART

Property	ASTM method	FTMS 406 method	Units	MIL-P-5425	Stretched MIL-P-5425	Percent stretch	MIL-P-8184	MIL-P-25690	Percent stretch	MIL-P-83310	MIL-P-8257	L-P-516 (G-3)	Remarks
Type	-	-	-	Acrylic	S/acrylic		M/acrylic*	S/M/acrylic*		Polycarbonate	Polyester	Allyl carbonate	*S = stretched; M = modified
Poisson's ratio	-	-	-	0.35			0.35						
Tensile strength	D-638	1011	PSI × 10^3	9.8-10.5	10.0	100	10.5-11.0	11.5-11.9	55-75	9.0-11.5		5.0-6.0	0.2 in./min head travel
Ultimate elongation	D-638	1011	Percent	4.9-6.4	35.0	100	6.7	42	55-75	75 percent min			
Tensile modulus	D-638	1011	PSI × 10^5	4.5-4.6	4.3	100	4.5-4.7	4.5-4.9	55-75	3.0-3.5		4.2	
Compressive strength	D-695	1021	PSI × 10^3	18.0			19.0			12.5		22.8-24.7	
Compressive modulus	D-695	1021	PSI × 10^5	4.5			4.5					2.3	
Flexural strength	D-790	1031	PSI × 10^5	16.0	16.2	100	16.0	16.0-17.5	55-75	10.3-13.5		8-10	
Flexural modulus	D-790	1031	PSI × 10^5	4.5	4.6	100	4.5	5.0	55-75	3.2-3.5		2.5-3.3	
Shear strength	D-732	1041	PSI × 10^3	9.0-10.0			9.5-9.7	1.5-3.0					
Izod impact, notched	D-256	1071	Ft-lb/in.n	0.3-0.99			0.31-0.45			12-18*	0.20-0.43	0.3-0.4	*1/8-in. thick
Izod impact, unnotched	-	-	Ft-lb/in.w	1.5-3.0			1.41-4.55				1.18-2.52	2.0-3.0	
Rockwell hardness (M)	D-785	1081	-	92	96-98	50-100	93-96	92-97		78	103	95	
Coefficient of thermal expansion	D-696	2031	In./in./deg F × 10^-5	4.1*			4.1*		55-75	3.47		10.7**	*Extrapolated **Per deg C, 25 deg C to 50 deg C
Specific gravity	D-792	5011	-	1.19	1.19		1.19	1.19		1.2		1.32	
Thermal conductivity	C-177	-	BTU/hr-ft²/deg F/in.	1.3-1.70			1.2-1.35	1.15		1.35	1.56	1.45-1.96	
Specific heat	-	2011	BTU/lb/deg F	0.35			0.35			0.28*	0.7	0.55*	*Cal/deg C/gram
Heat deflection Temperature at 264 PSI	D-648		Deg F	204-205			219	212		265-290			
Temperature at 66 PSI			Deg F	217-225			234	225		288-290			
Flammability	D-635	2021	In./min	1.1			0.5-0.7			Self-extinguishing			
Refractive index	D-542	3011	n_d	1.491	1.491	100	1.496	1.495	75	1.586	1.52	1.50-1.58	
Transmittance, luminous	D-1003	3022	Percent	91	91	100	91	91		88-91		90-92	
Haze	D-1003	3022	Percent	<1.0	<1.0	100	<1.0	<1.0		<1.0		1.0-2.0	
Dielectric constant ε at 60 CPS	D-150	4021	-	3.7			3.9			3.11-3.17		3.78	
ε at 10^6 CPS			-	2.5			2.1			2.96-3.00		3.55	
Power factor at room temperature at 60 CPS	D-150	4021	-	0.05			0.05			0.0009		0.0121	
at 10^3 CPS			-	0.04			0.04			0.0010		0.0565	
at 10^6 CPS			-	0.03			0.03			0.0100			
Volume resistivity	D-257	4031	Ohm-CM	500			530			400		568	
Dielectric strength	D-149		Volts/mil										
Water absorption	D-570	7031	Percent	0.2*			0.2*			0.15-0.18*		0.15**	*24 hr **168 hr

TABLE 4.3-I – PROPERTIES OF CR-39 FACE SHEET MATERIAL

Property	Characteristic
Specific gravity	1.32
Tensile strength	8600 PSI at 77 F (605 kg/cm^2 at 25 C)
Compressive strength	24,700 PSI at 77 F (1738 kg/cm^2 at 25 C)
Flexural strength	15,200 PSI at 77 F (1069 kg/cm^2 at 25 C)
Tensile modulus	420,000 PSI at 77 F (29,551 kg/cm^2 at 25 C)
Impact strength charpy test	0.35 ft-lb per inch of notch) (0.019 kg-m per centimeter of notch)
Impact strength, falling ball	45 ft (height for 1/2-lb ball to break 1/4-in.-thick panel) (13.7 m for 0.23-kg ball to break 6.4-mm panel)
Hardness (Rockwell)	95
Light transmission	92 percent
Haze	1 percent
Refractive index	1.58
Thermal conductivity	1.96 BTU/hr-deg F-ft^2/in. (349.9 cal/hr-deg C-cm^2/cm)
Specific heat	0.35 BTU/lb-deg F (350 cal/kg-deg C)
Thermal expansion	5.4 × 10^{-5} in./in.-deg F (9.72 × 10^{-5} mm/mm-deg C)
Heat distortion	160 deg F (164 PSI test) $\left[71.1 \text{ deg C } (11.5 \text{ kg/cm}^2)\right]$
Water absorption	0.15 percent (168 hr at 77 F) 0.15 percent (168 hr at 25 C)

Note: Data supplied by Goodyear Aerospace.
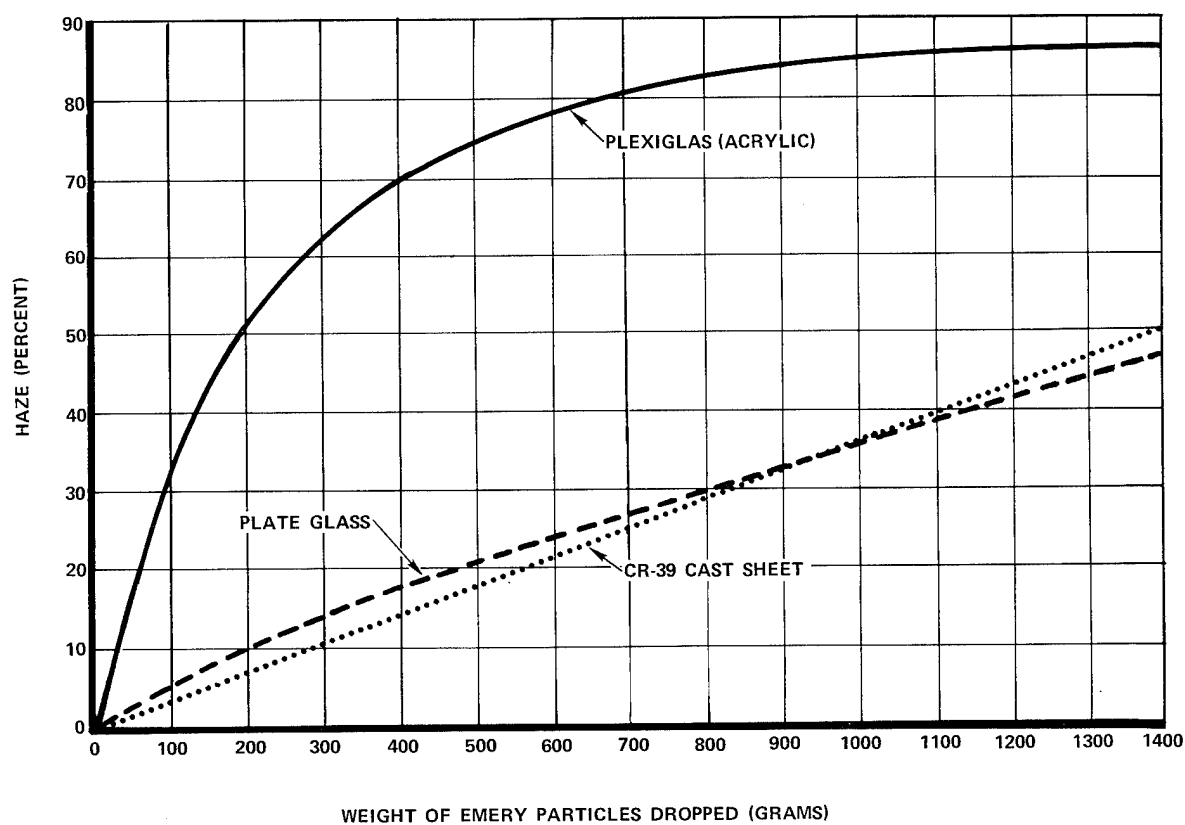
Figure 4.3-1 - Abrasion Resistance of CR-39 and Plate Glass

4.3.2 MIL-P-5425

4.3.2.1 GENERAL

The commercially trademarked materials which meet the MIL-P-5425 specification are listed in Table 2.1-I. This material was the forerunner of the modified acrylic. The historic discovery of the crack propagation resistant property of stretched acrylic was developed through the "bi" or multiaxial stretching of MIL-P-5425 sheets up to 100 percent of their original linear dimension. Data are included for stretched MIL-P-5425 material as a matter of background because it is seldom used and has never reached military specification status.

The cast material is utilized monolithically for low-speed aircraft, but has been largely replaced by MIL-P-8184 and MIL-P-25690 acrylics. With the advent of coatings and the need for a cladding material for polycarbonate (MIL-P-83310) surface protection, the MIL-P-5425 acrylic has found new usage.

4.3.2.2 PROPERTIES

The tensile stress-strain, stress rupture, crack propagation resistance versus temperature, flexural fatigue, coefficient of thermal expansion versus temperature curves, and the effect of scratch depth on Izod impact data are found in Figures 4.2-1 and 4.2-3 through 4.2-5 on pages 4-4 and 4-6 through 4-7 in the section on comparative properties (4.2). MIL-P-5425 curves not in the comparative data section 4.2 are in this section.

4.3.2.2.1 CROSSHEAD RATE EFFECTS

The tensile curves of Figures 4.3-2, 4.3-3, and 4.3-4 show the effects of different crosshead rates for two thicknesses of material at two temperatures and the effects on the tensile modulus of elasticity at room temperature.
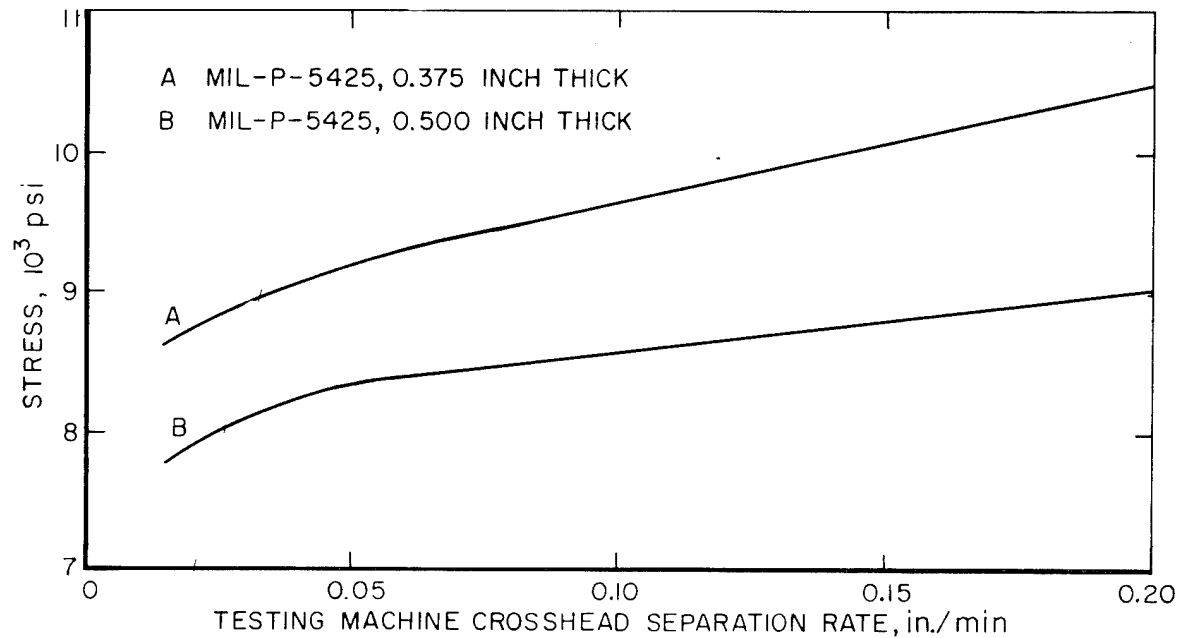
Figure 4.3-2 – Effect of Rate of Crosshead Separation on Tensile Strength of MIL-P-5425 Material at 77 Deg F
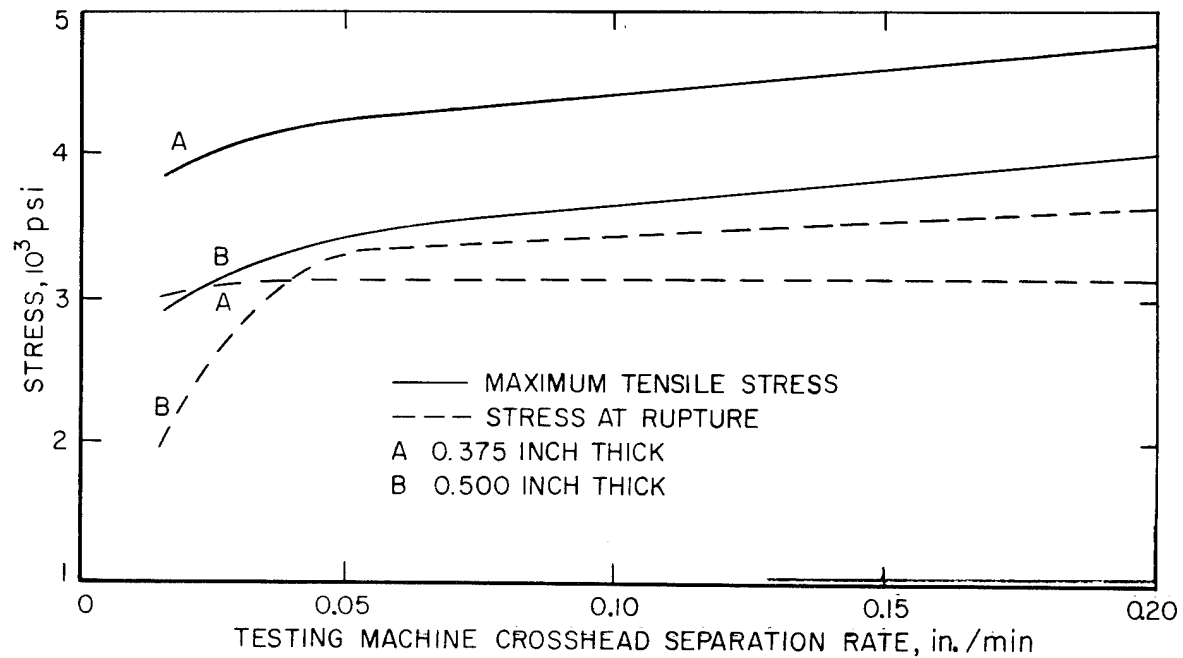
Figure 4.3-3 – Effect of Rate of Crosshead Separation on Tensile Strength of MIL-P-5425 Material at 160 Deg F

4-18
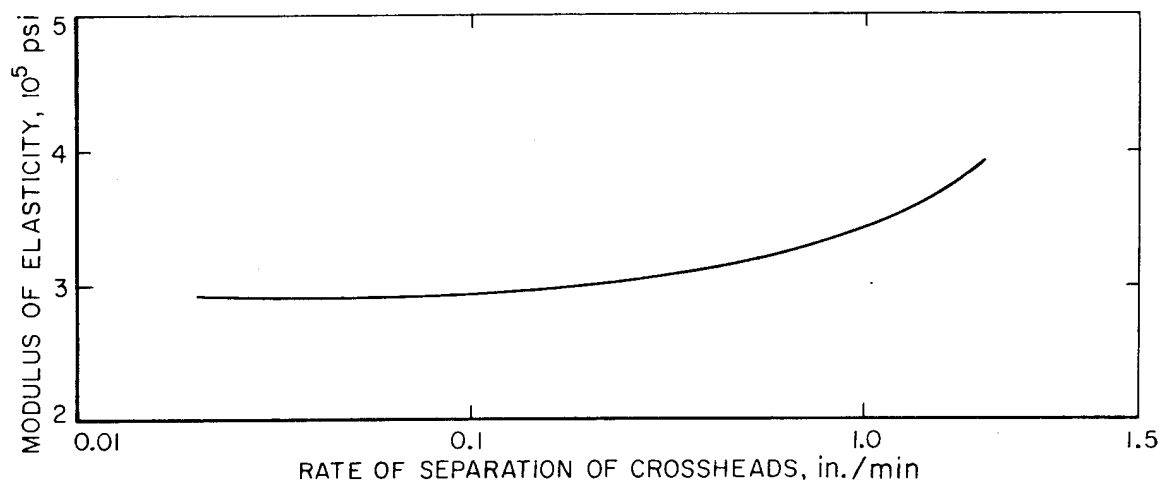
Figure 4.3-4 – Effect of Rate of Crosshead Separation on Tensile Modulus of Elasticity
(Short-Time Test) of MIL-P-5425 Material

4.3.2.2.2 TENSILE DATA

One thousand hour stress-creep curves are found in Figures 4.3-5 through 4.3-7 for three
temperatures. Creep-strain and modulus curves for various temperatures are found in
Figures 4.3-8 through 4.3-11. Short-time tensile data versus temperature follow in
Figure 4.3-12.

4.3.2.2.3 FLEXURAL DATA

Short-term temperature effects on flexural data appear in Figure 4.3-13. Creep data follow
for 1000-hour tests in Figure 4.3-14 and for 10,000 hours in Figures 4.3-15 and 4.3-16,
in which two material thicknesses are considered, both notched and unnotched. The 60-deg,
0.005-in.-deep notch was located on the tension side of the sample and is referred to as the
"Standard ARTC Needle Scratch." Rupture and crazing curves for material being weathered
under load are found in Figure 4.3-17.
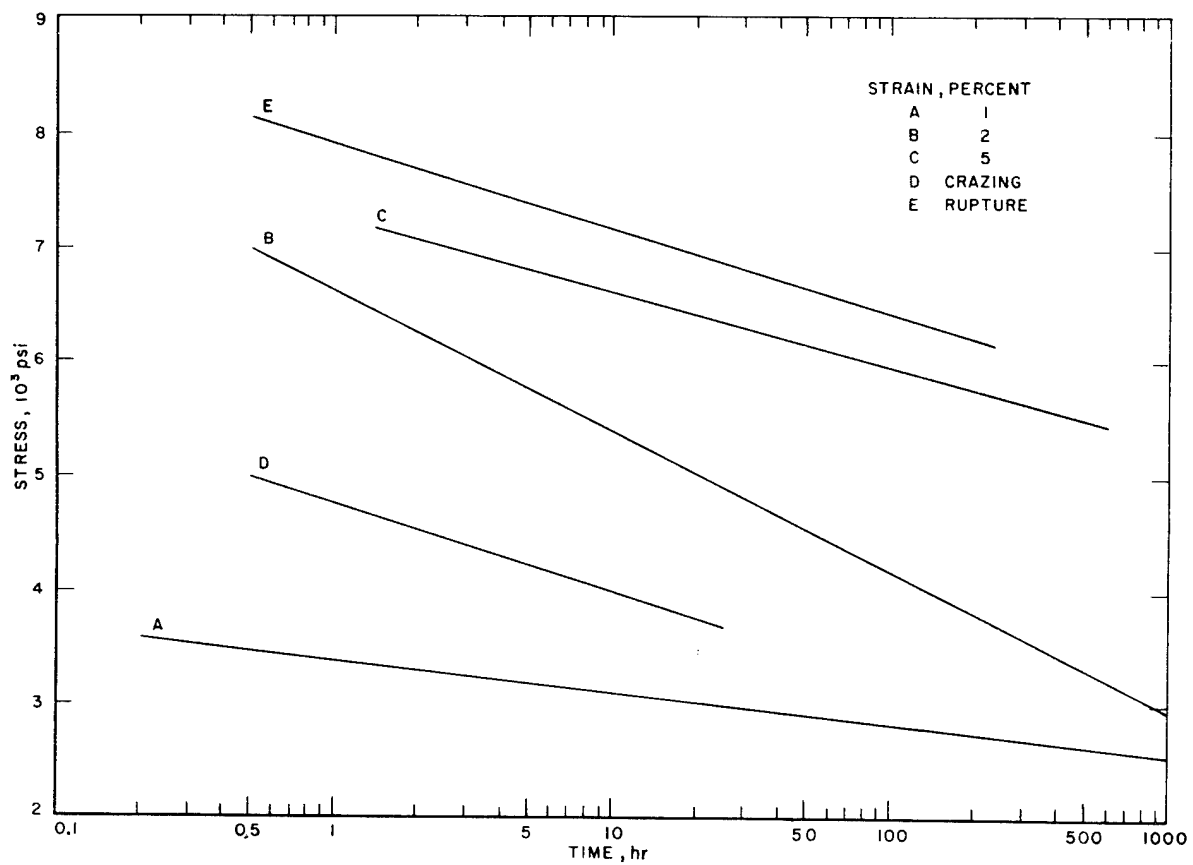
Figure 4.3-5 – Tensile Creep Data for MIL-P-5425 Material at 80 Deg F
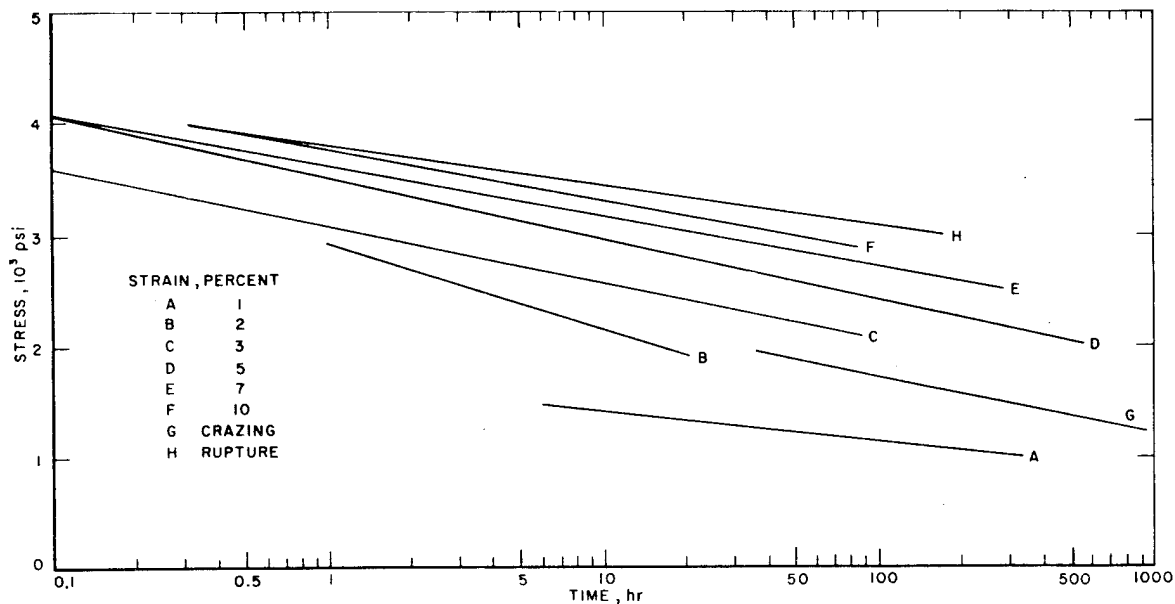
Figure 4.3-6 – Tensile Creep Data for MIL-P-5425 Material at 160 Deg F
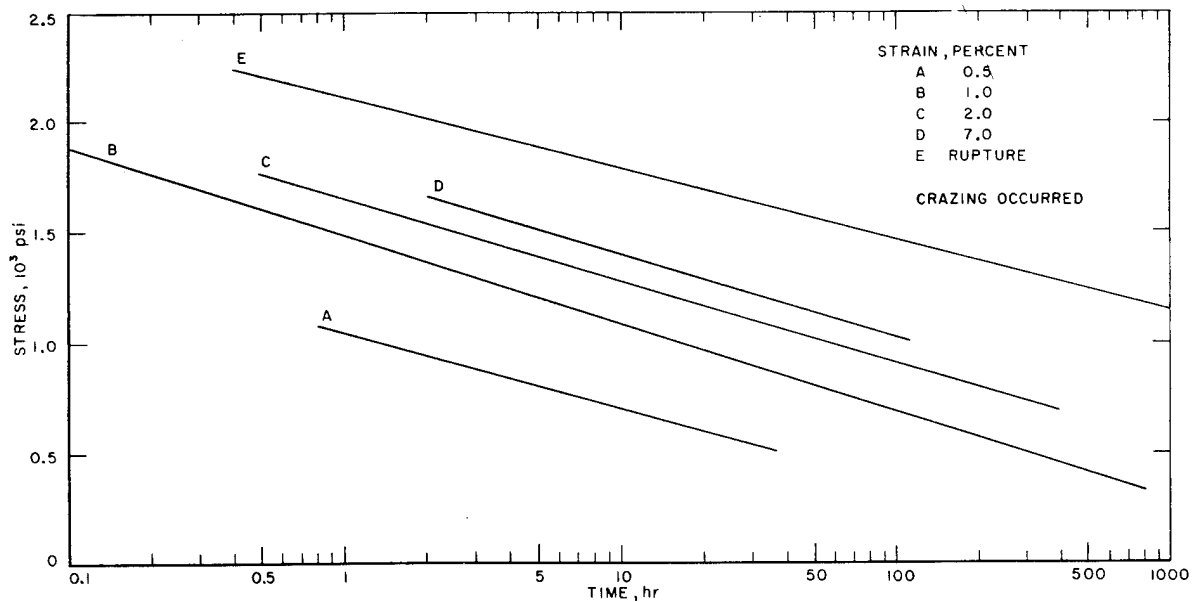
Figure 4.3-7 – Tensile Creep Data for MIL-P-5425 Material at 200 Deg F

4-21
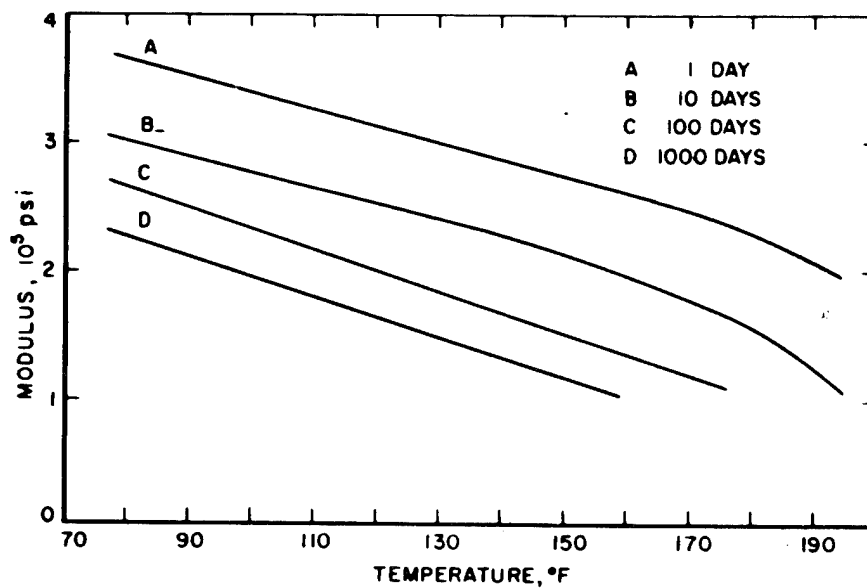
Figure 4. 3-8 – Effect of Temperature on Creep Modulus in Tension of MIL-P-5425
Material for Various Periods of Time
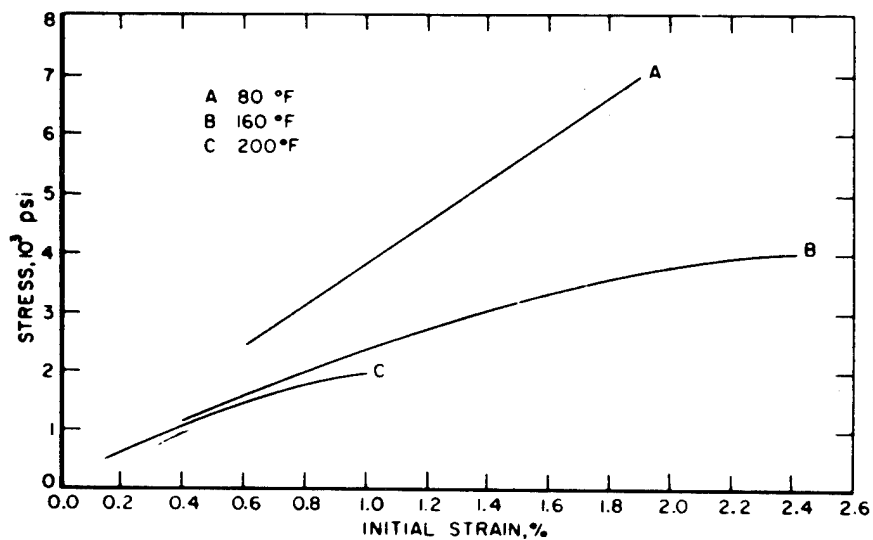
Figure 4. 3-9 – Effect of Stress on Initial Strain in Tensile Creep of MIL-P-5425
Material at Various Temperatures

4-22
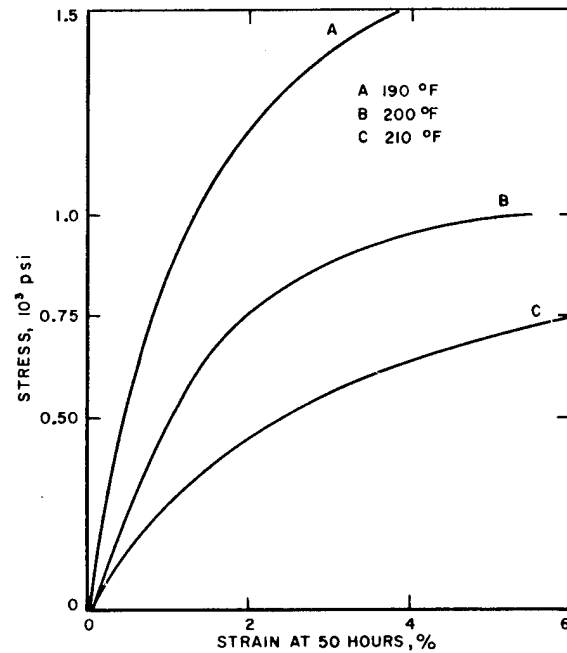
Figure 4. 3-10 – Creep Strain of 75-Percent Stretched MIL-P-5425 Material at Various
Temperatures at 50 Hours after Stress was Applied
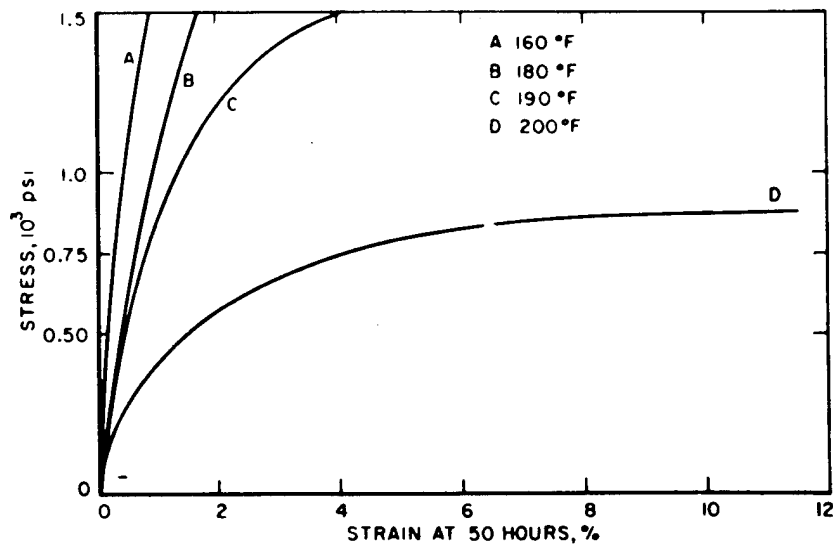
Figure 4. 3-11 – Creep Strain of MIL-P-5425 Material at Various Temperatures at
50 Hours after Stress was Applied

4-23
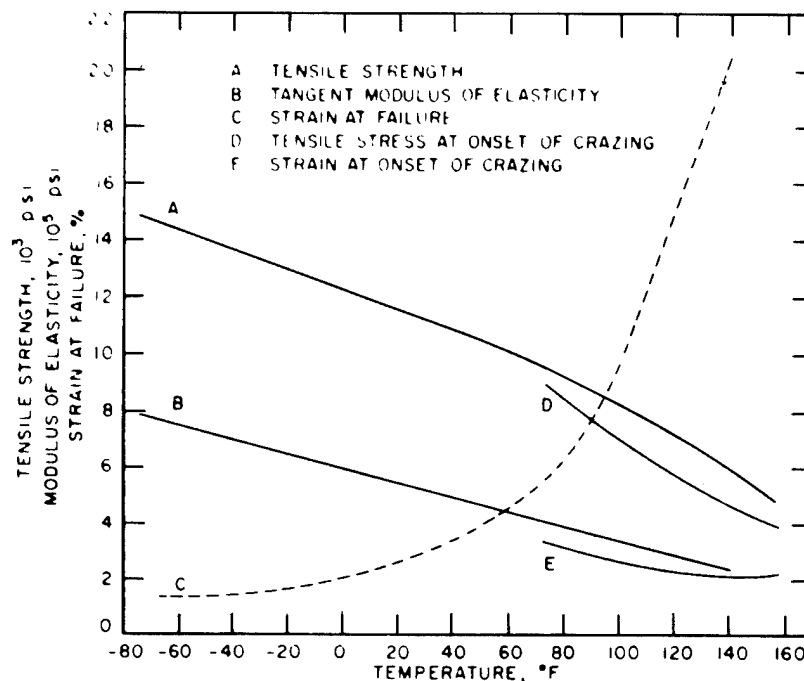
4601-23

Figure 4. 3-12 – Effect of Temperature on Tensile Properties (Short-Time Test) of
MIL-P-5425 Material
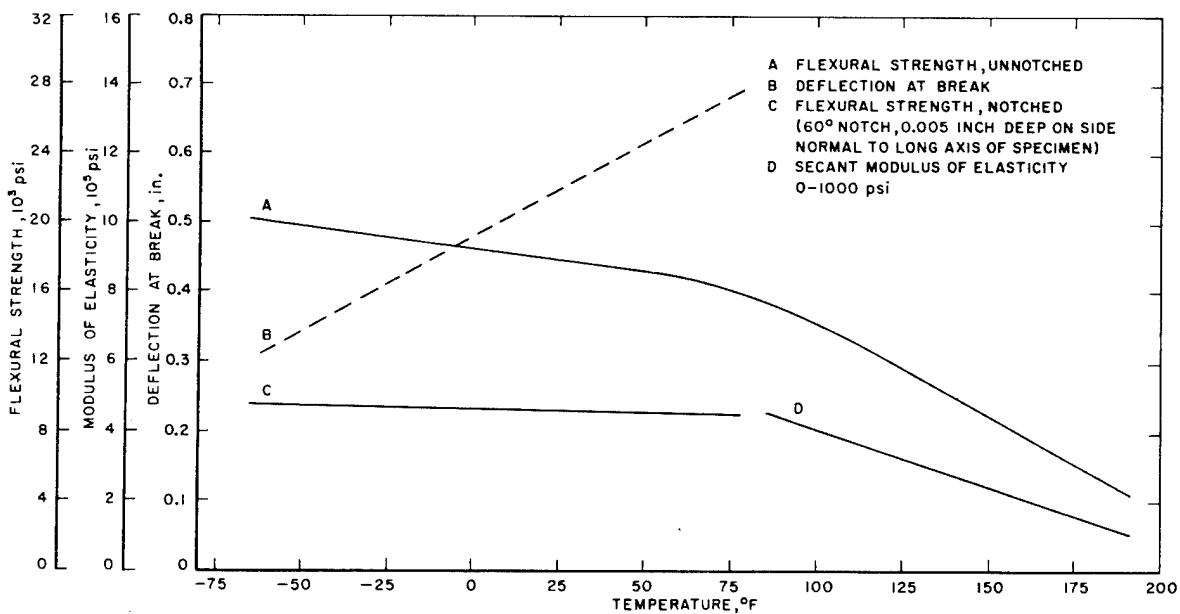
4601-24

Figure 4. 3-13 – Effect of Temperature on Flexural Properties (Short-Time Test)
of MIL-P-5425 Material

4-24
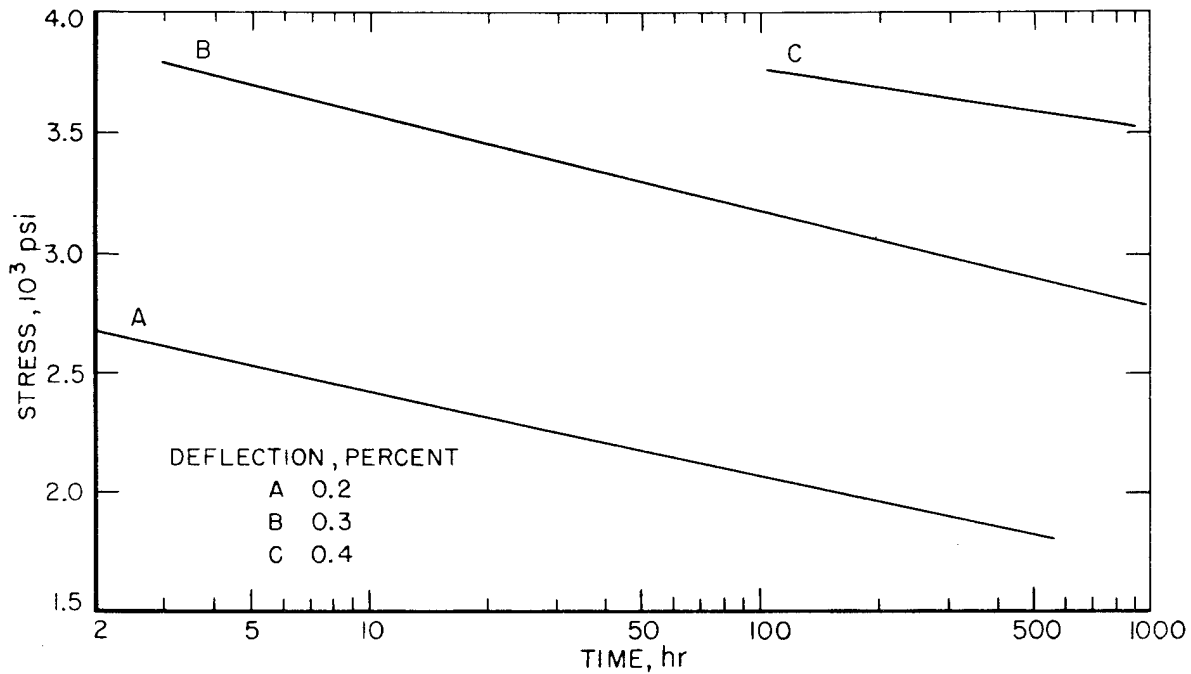
Figure 4.3-14 – Flexural Creep Data for MIL-P-5425 Material at Room Temperature
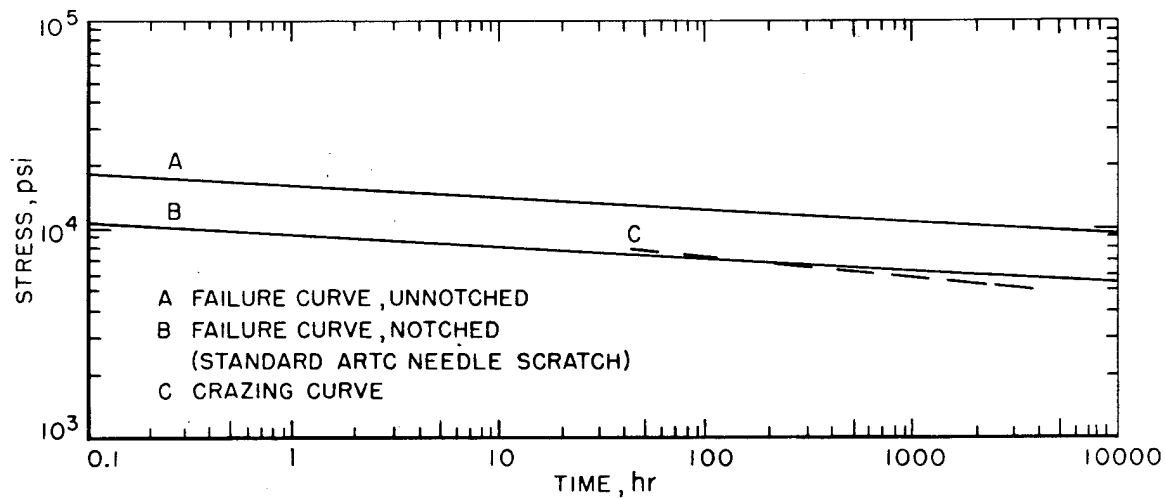
Figure 4.3-15 – Effect of Duration of Loading on Flexural Properties of 0.250-Inch-Thick
MIL-P-5425 Material at Room Temperature

4-25
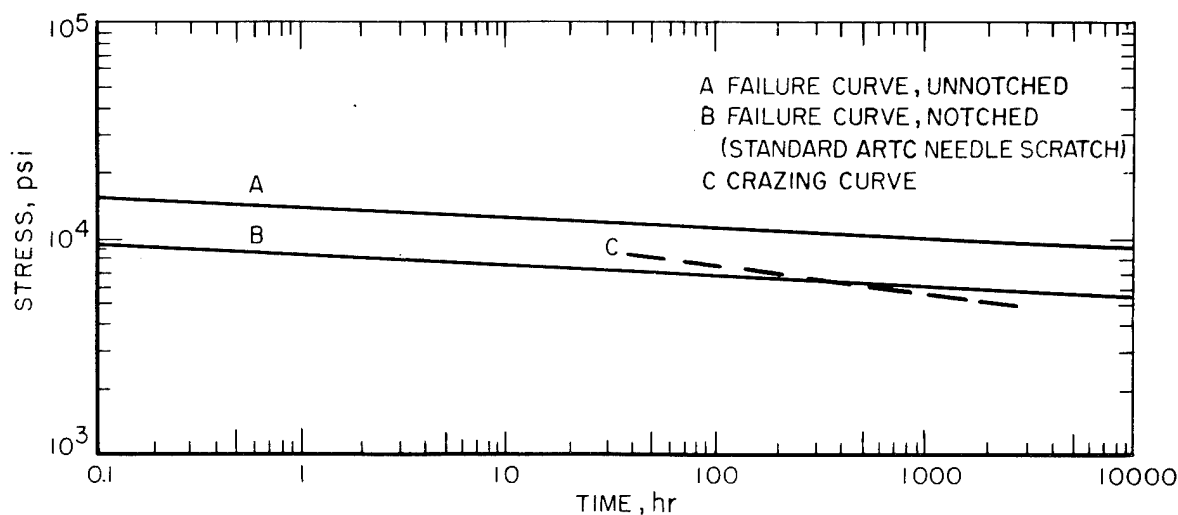
Figure 4.3-16 – Effect of Duration of Loading on Flexural Properties of 0.750-Inch-Thick
MIL-P-5425 Material at Room Temperature
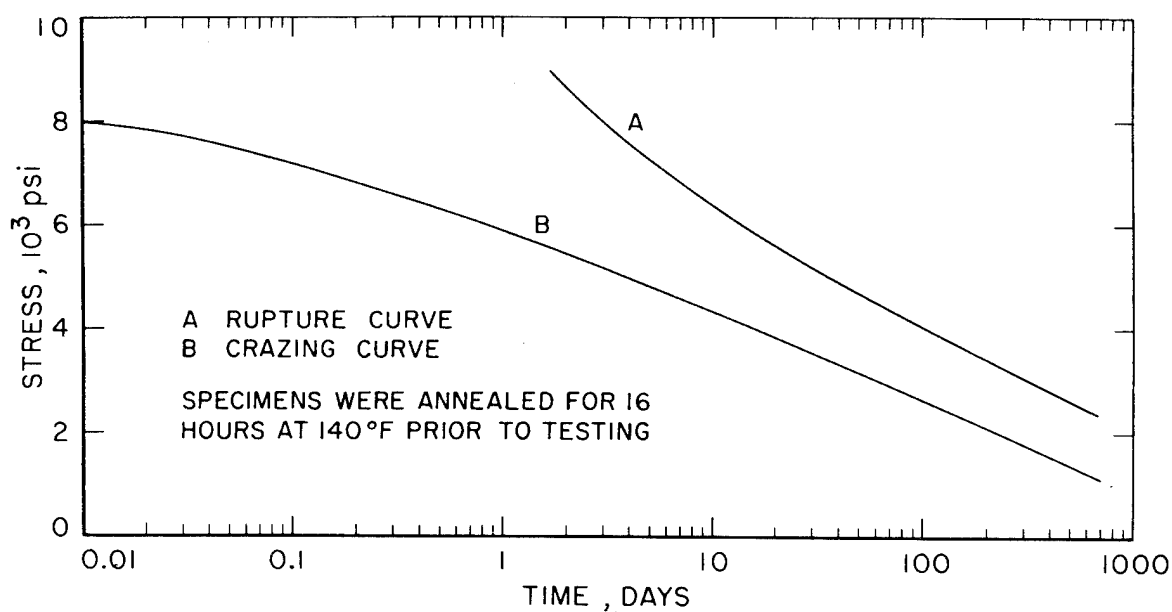
Figure 4.3-17 – Effect of Duration of Loading on Flexural Properties of 0.250-Inch-Thick
MIL-P-5425 Material Tested Outdoors

4.3.2.2.4   COMPRESSIVE-CREEP DATA

Compressive-creep data at room temperature are shown at various percentages of deformation in Figure 4.3-18.

4.3.2.2.5   RELATIVE HUMIDITY EFFECTS

Figure 4.3-19 demonstrates the linear change that can be expected from water absorption at various relative humidity levels.

4.3.2.2.6   EFFECTS OF STRETCHING ON TENSILE AND CRAZING DATA

Figures 4.3-20 and 4.3-21 show the dramatic effect that stretching has on raising the stress-solvent crazing threshold.   Stress-crazing (without solvent) points are shown for unstretched material as a reference.

4.3.2.2.7   TEMPERATURE EFFECTS ON STRETCHED MATERIAL

The effect of temperature with and without the presence of moisture is shown in Figures 4.3-22, curves A and B.   The first curve indicates an increase in crack propagation resistance when wet over that of dry material.   Unnotched Charpy impact data in Figure 4.3-23 compares the increase in impact resistance of 100-percent stretched material over that of as-cast material; and Figure 4.3-24 provides tensile data over an operational temperature range.

4.3.2.2.8   THE EFFECT OF ANNEALING

Annealing is normally performed to relieve localized stress risers through the application of heat.   The stretched material, however, loses some of its resistance to crack propagation as a result of annealing.   Figure 4.3-25 demonstrates the effect which may be attributable to thermal relaxation toward the unstretched condition.   Table 4.3-II, however, shows that a change of stretch processing by increasing the percentage of stretch can reverse this trend.
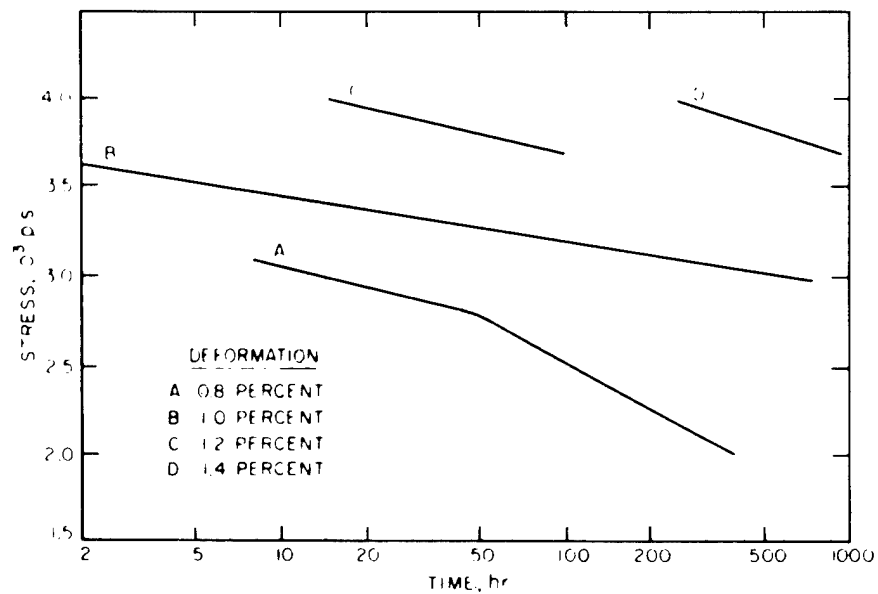
Figure 4.3-18 – Compressive Creep Data for MIL-P-5425 Material at Room Temperature
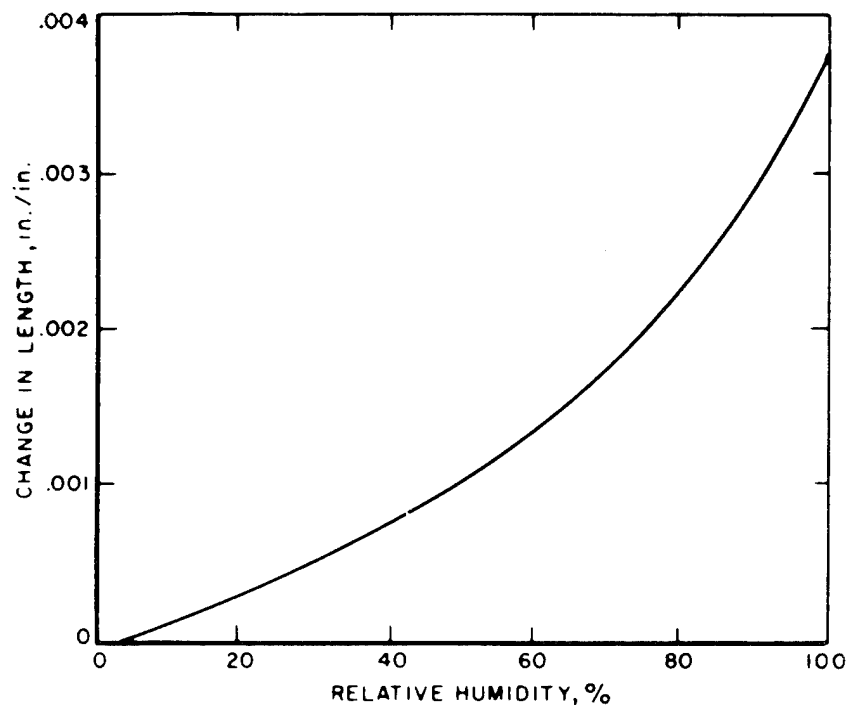
Figure 4.3-19 – Effect of Relative Humidity on the Change in the Length of MIL-P-5425
Material at Room Temperature

4-28
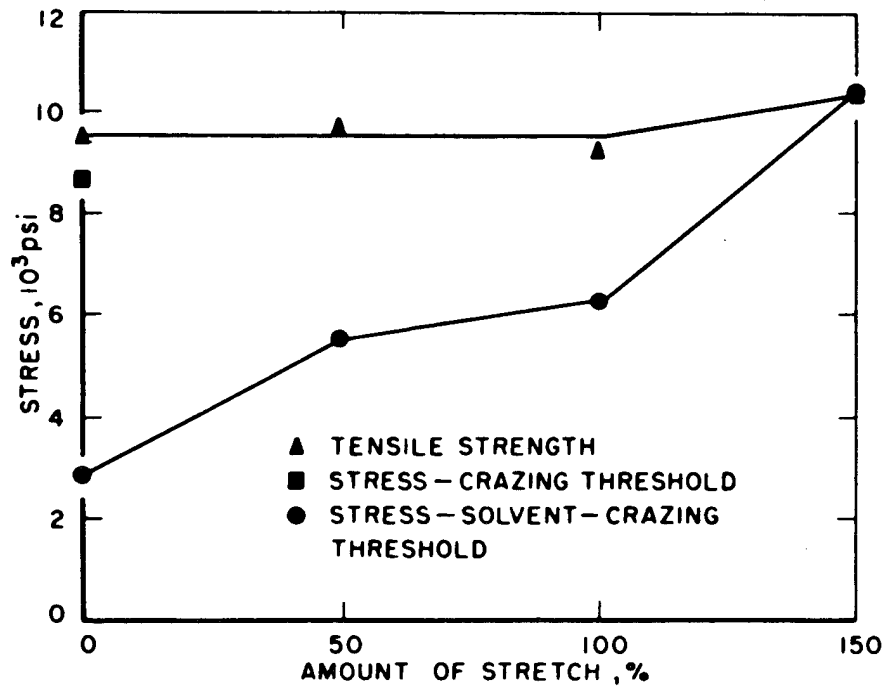
Figure 4. 3-20 – Effect of Stretching on Tensile Properties (Short–Time Test)
of MIL–P–5425 Material at 73 Deg F
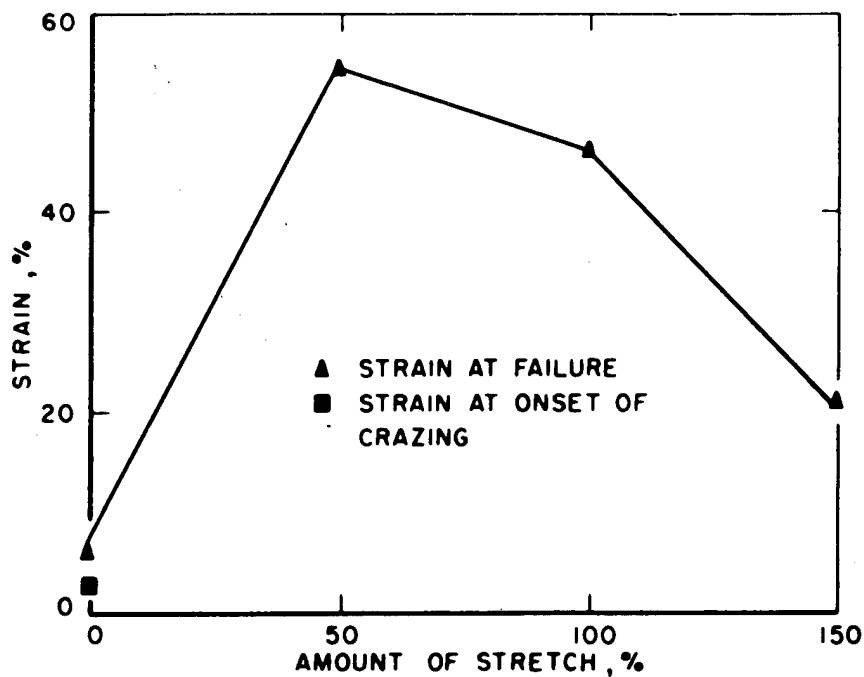
Figure 4. 3-21 – Effect of Stretching on Strain at Failure and Strain at Onset of
Crazing (Short–Time Test) of MIL–P–5425 Material at 73 Deg F

4-29
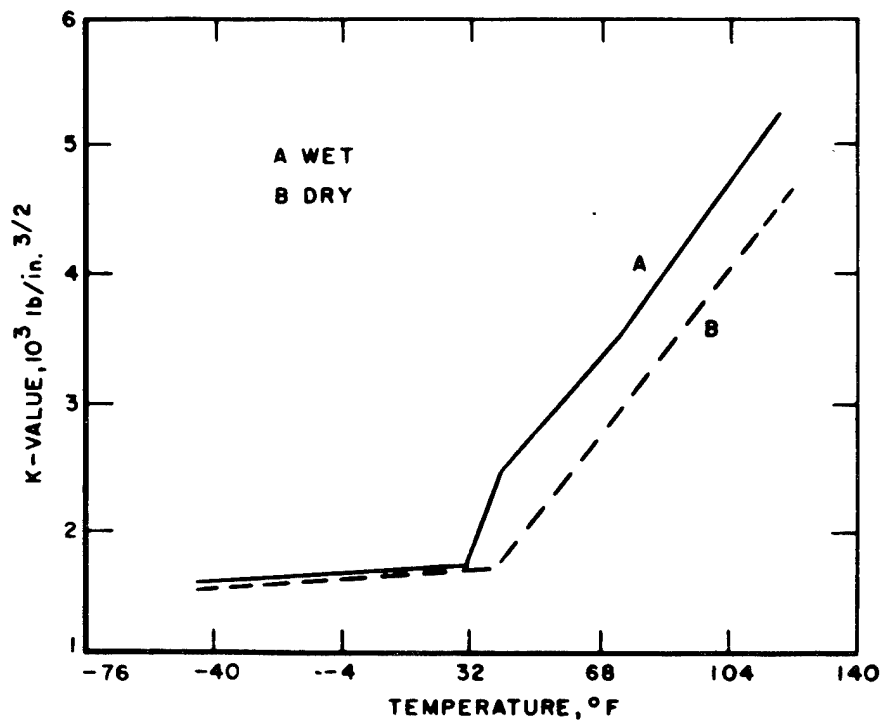
Figure 4. 3-22 – Effect of Temperature and Moisture on the K-Value of 76-Percent Stretched
MIL-P-5425 Material
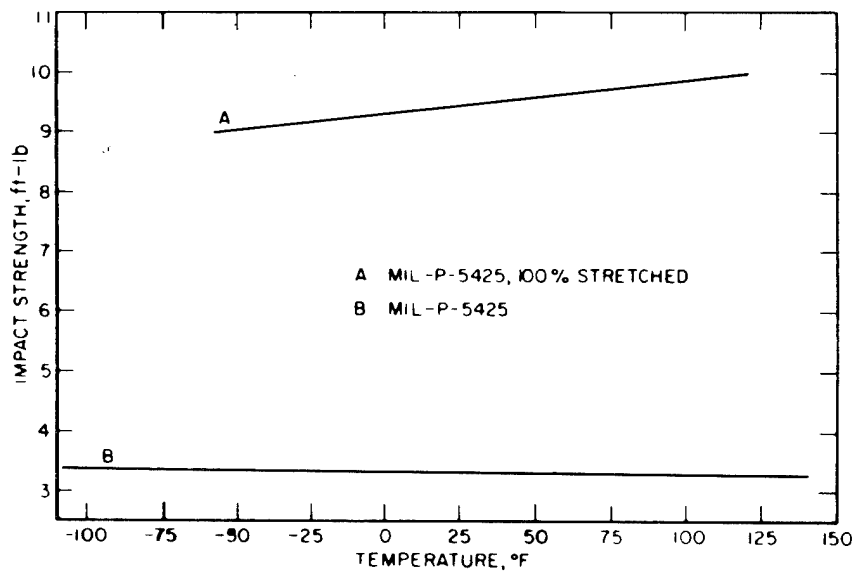
Figure 4. 3-23 – Effect of Temperature on Charpy Impact Strength of Unstretched and
Stretched MIL-P-5425 Material – Specimens 0. 5- by 0. 5-Inch Unnotched Bars
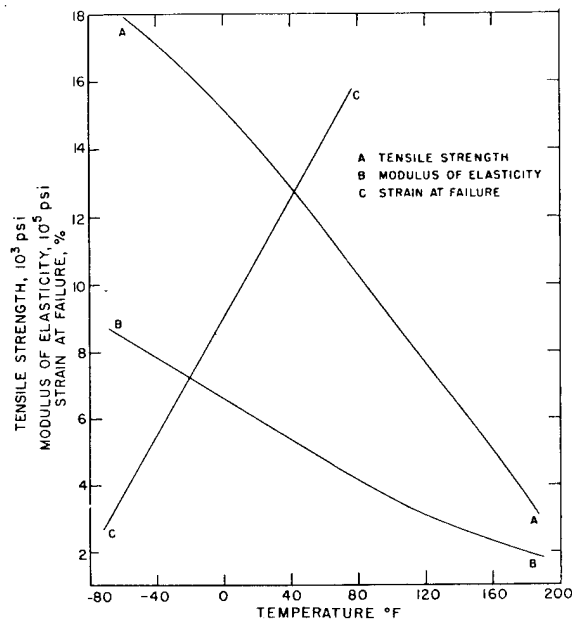
Figure 4.3-24 – Effect of Temperature on Tensile Properties (Short–Time Test) of 100–
Percent Stretched MIL-P-5425 Material – Specimens 0.125 Inch Thick
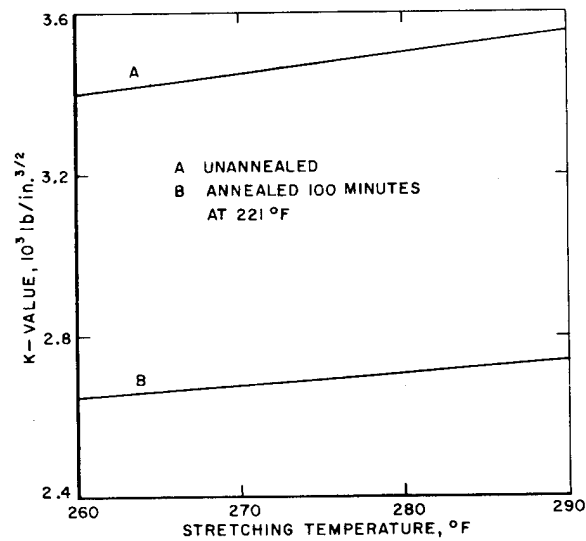
Figure 4.3-25 – Effect of Stretching Temperature and of Annealing on the K-Value of
73-Percent Stretched MIL-P-5425 Material

TABLE 4.3-II - EFFECT OF ANNEALING ON THE K-VALUE OF STRETCHED
MIL-P-5425 MATERIAL

Stretching temperature (deg F)	Degree of stretch (percent)	K-value	
		Unannealed (10^3 lb/in.$^{3/2}$)	Annealed (10^3 lb/in.$^{3/2}$)
260	73	3.44	2.58
270	73	3.38	2.85
290	73	3.58	2.68
390	100	3.23	3.50
310	100	3.39	3.22

4.3.3   MIL-P-8184

4.3.3.1   GENERAL

The MIL-P-8184 material was developed to support the higher temperatures required by aircraft designs at the time as well as to have the capability of a greater resistance to crazing than the MIL-P-5425 material.

4.3.3.2   PROPERTIES

Tensile stress-strain, ultimate strengths versus temperature, and creep-rupture curves are found in section 4.2, Figures 4.2-1 through 4.2-6. Flexural fatigue and coefficients of thermal expansion versus temperature are found in Figures 4.2-8 and 4.2-9 of the same section (4.2) with the information of Table 4.2-I, which concerns light transmittance and haze before and after controlled Taber abrasion.

4.3.3.2.1 TEMPERATURE EFFECTS ON TENSILE PROPERTIES

The stress-strain curves at various temperatures above room temperature are shown in Figure 4.3-26. Figure 4.3-27 is a cross plot which shows the effect of temperature on tensile strength, modulus of elasticity, and strain at failure. Tensile-creep data follow at three temperatures in Figures 4.3-28 through 4.3-32. Cyclic tensile creep-strain curves are in Figure 4.3-33.

4.3.3.2.2 FLEXURAL DATA

Both notched and unnotched specimens were tested. The notch was of the ARTC standard needle scratch 5 mils deep by 60 deg. Failure curves are shown for both. A third curve represents the crazing level of stress versus time in Figure 4.3-34. Figure 4.3-35 demonstrates the effect of craze depth on the flexural strength. Figure 4.3-36 contains the remaining flexural data and shows the loss in strength caused by notching.

4.3.3.2.3 THE EFFECT OF ANNEALING

As with the MIL-P-5425 material, annealing improves the resistance to crazing as shown in Table 4.3-III. The level at which crazing occurs is at a higher stress and percentage of strain than the unannealed material for both stress and stress-solvent crazing.

4.3.3.2.4 LUMINOUS TRANSMITTANCE

The luminous transmittance of MIL-P-8184 material is shown in Figure 4.3-37 over a wide frequency range which includes ultraviolet and part of the infrared spectra.

4.3.4 MIL-P-25690

4.3.4.1 GENERAL

With the discovery of the crack propagation resistance property associated with stretched acrylic, MIL-P-8184 material was found to also be stretchable but to a lesser degree than MIL-P-5425. Because the MIL-P-8184 acrylic is partially cross-linked in its molecular structure, it cannot consistently attain the high percentages of stretch associated with the MIL-P-5425 material. Stretching within a 65- to 75-percent range, however, provided

4-33
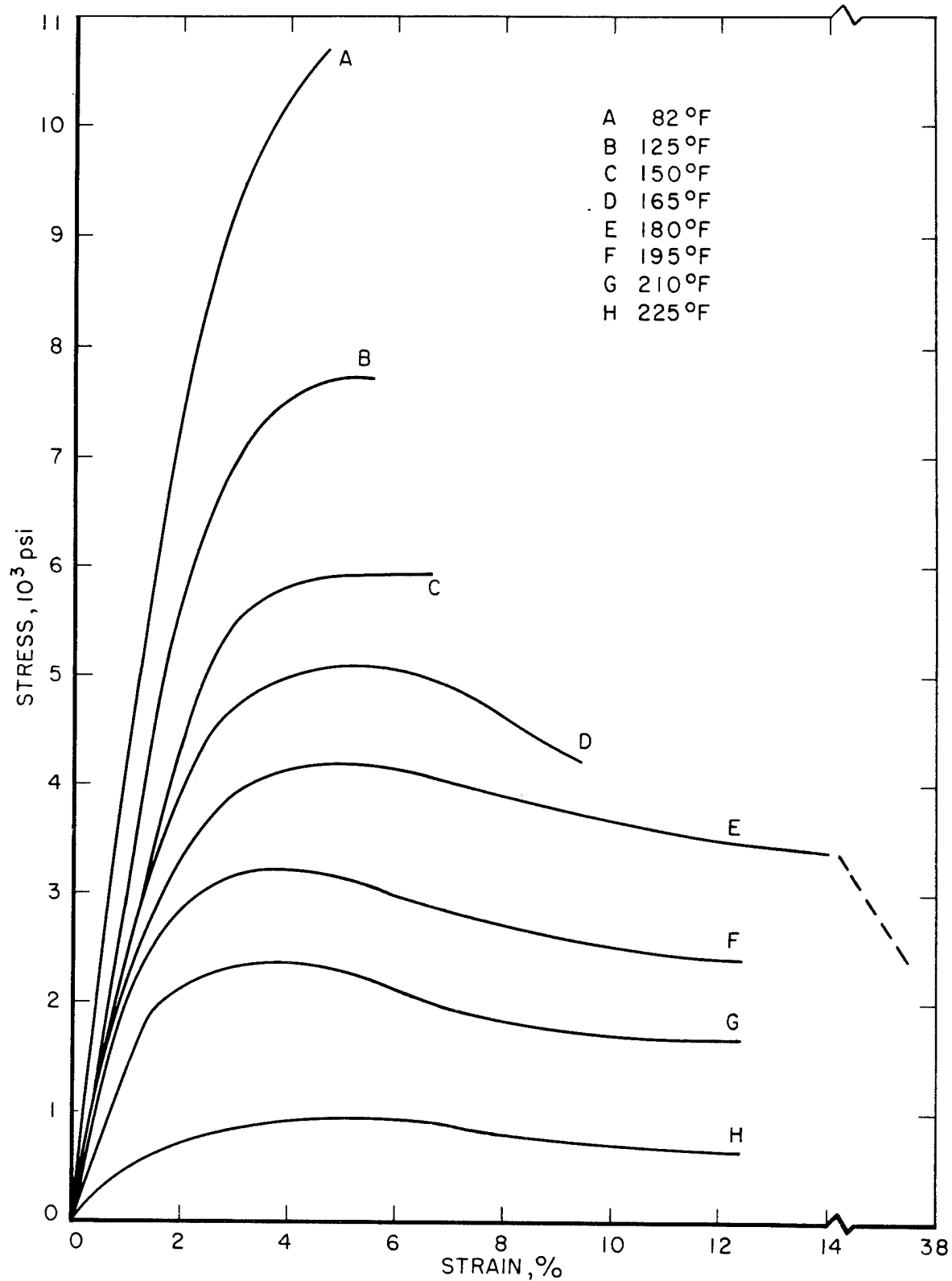
Figure 4. 3-26 – Tensile Stress-Strain Curves for MIL-P-8184 Material at Various
Temperatures

4-34
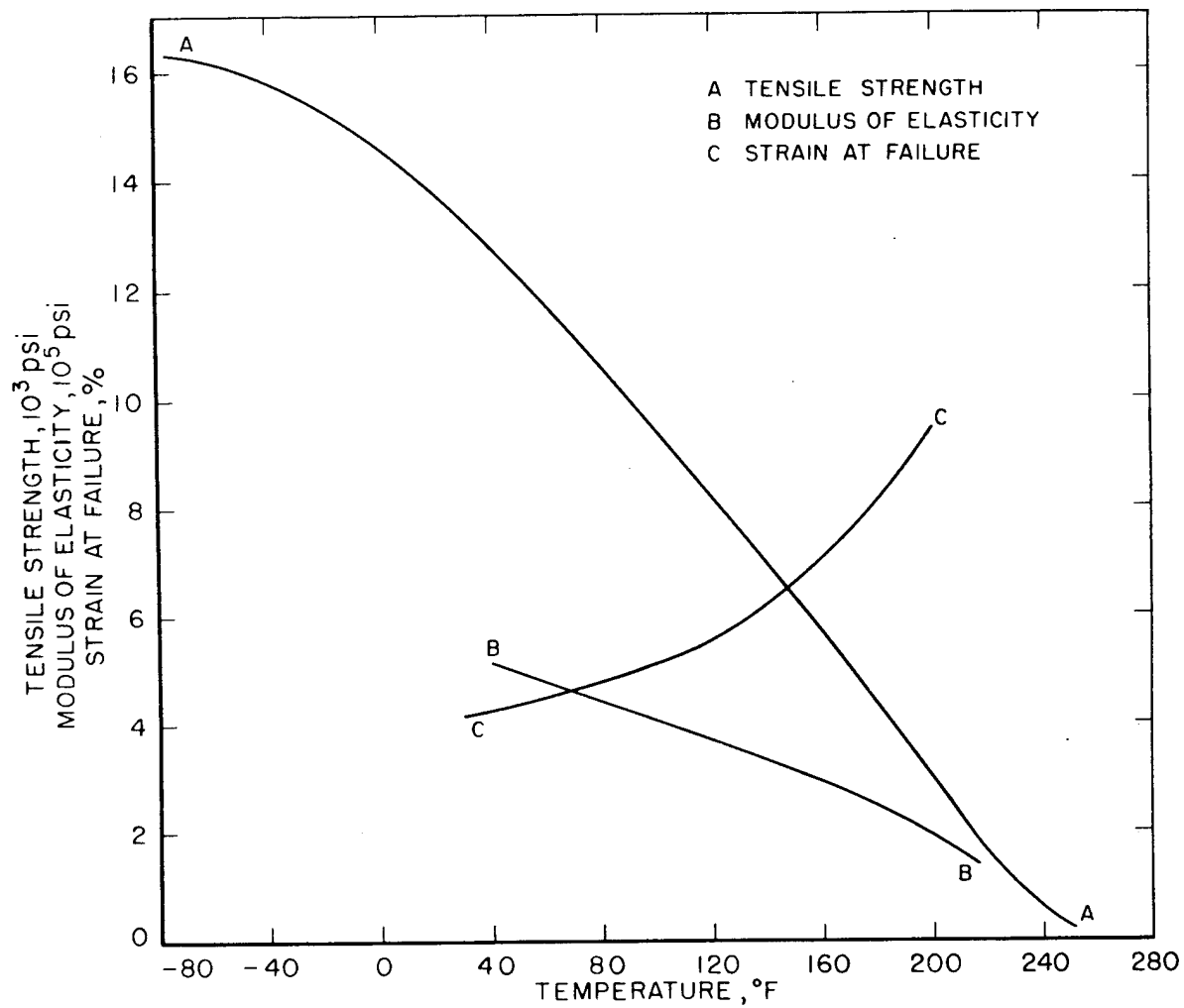
Figure 4.3-27 – Effect of Temperature on Tensile Properties (Short–Time Test) of
MIL–P–8184 Material

4-35
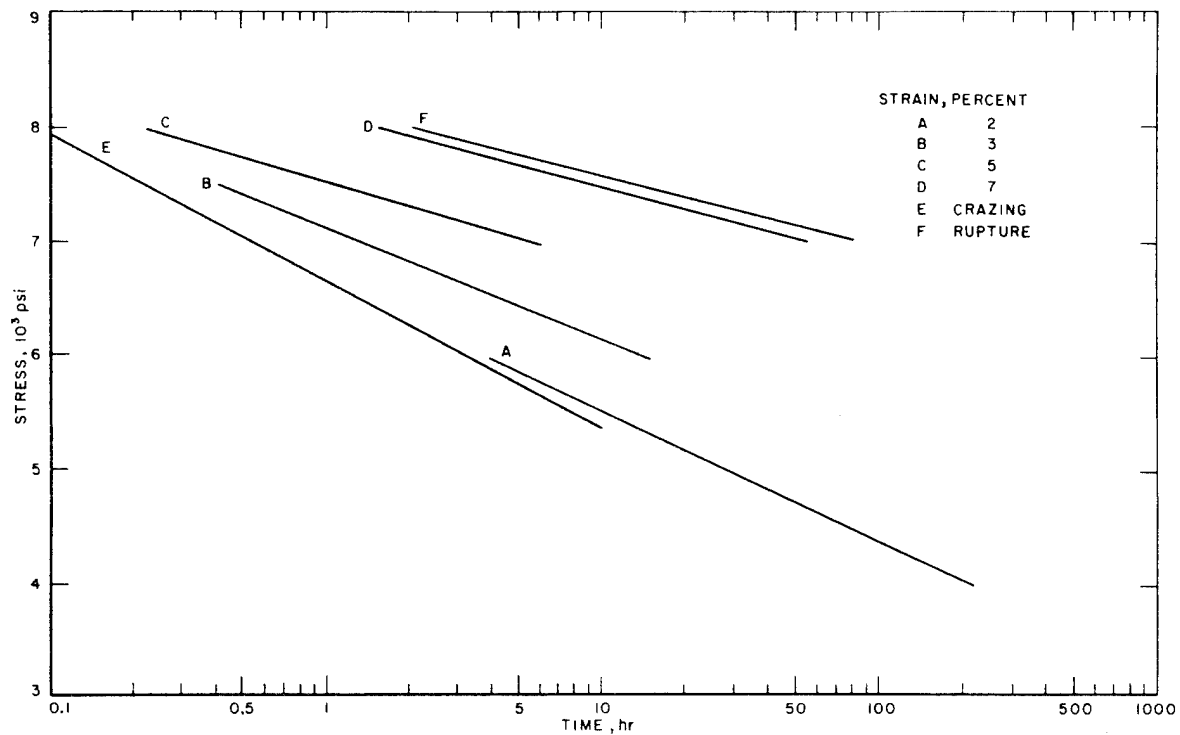
Figure 4. 3-28 – Tensile Creep Data for MIL-P-8184 Material at 80 Deg F
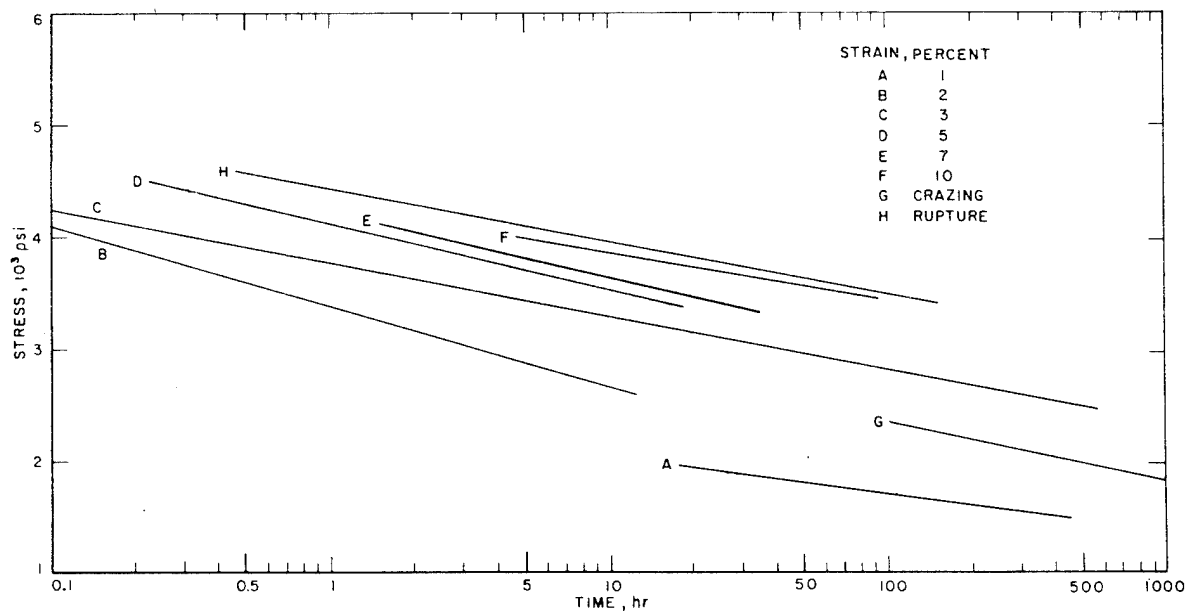
Figure 4. 3-29 – Tensile Creep Data for MIL-P-8184 Material at 160 Deg F

4-36
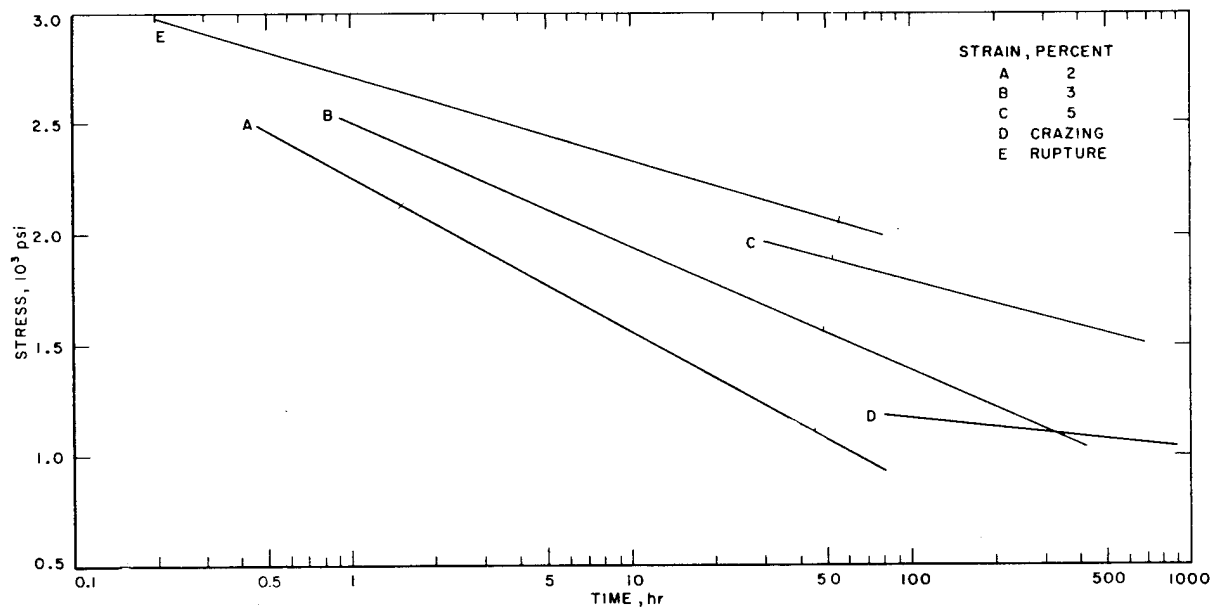
Figure 4. 3-30 – Tensile Creep Data for MIL-P-8184 Material at 200 Deg F
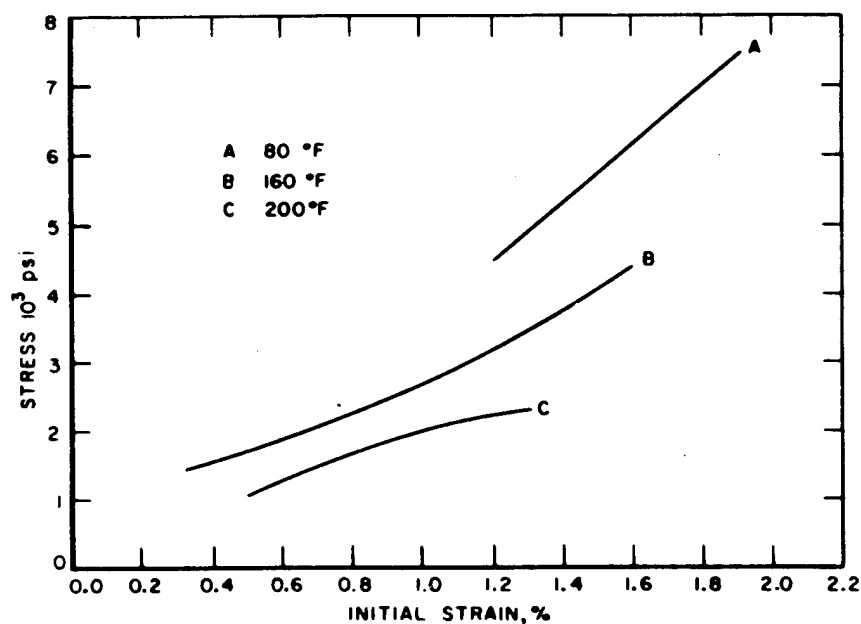
Figure 4. 3-31 – Effect of Stress on Initial Strain in Tensile Creep of MIL-P-8184
Material at Various Temperatures

4-37
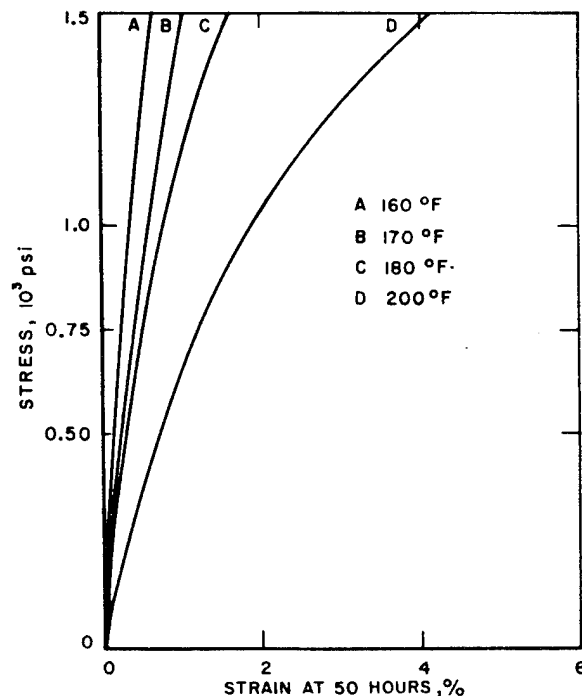
Figure 4.3-32 – Creep Strain of MIL-P-8184 Material at Various Temperatures
at 50 Hours after Stress Was Applied

superior crack propagation and craze resistance to that of the stretched MIL-P-5425 material. As a consequence, stretched MIL-P-5425 never held military specification status, and the stretched MIL-P-8184 became the specified MIL-P-25690 material.

Material which has been stretched gains the crack propagation resistant property, but loses laminar shear strength. This change is attributed to an internal realignment during stretching which tends to straighten out the molecular chains into a semiparallel orientation. In this process, the strengths in the chains also become oriented to be nearly parallel with the surface of the material, and the 90-deg components of the chain structures, which represent shear strength, become weakened. As a result, edge attachment designs for stretched material depend upon a bolt-through construction rather than a construction which depends upon adhered reinforcements to the surfaces.
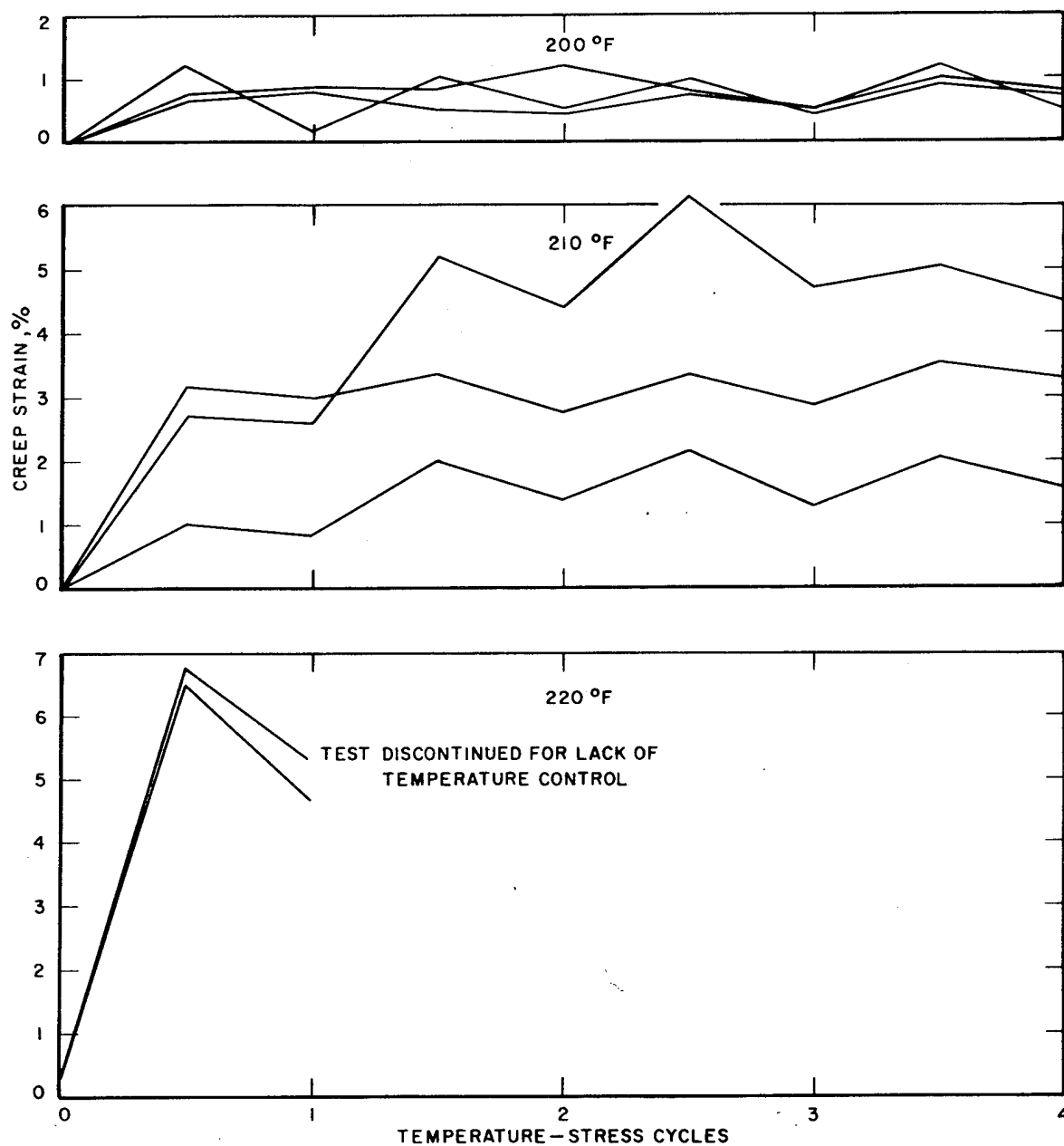
NOTES:
EACH CYCLE CONSISTED OF—
1. ONE HOUR AT TEST TEMPERATURE WITH NO LOAD.
2. ONE HOUR AT TEST TEMPERATURE WITH A STRESS OF 600 POUNDS PER SQUARE INCH.
3. ONE HOUR AT TEST TEMPERATURE WITH NO LOAD.
4. STEPS 2 AND 3 WERE REPEATED TWICE.
5. THE LOAD WAS REAPPLIED AND AFTER ONE HOUR THE MAXIMUM EXTENSION WAS DETERMINED.
6. THE SPECIMENS WERE UNLOADED AND COOLED TO ROOM TEMPERATURE. AFTER 16
   HOURS THE PERMANENT EXTENSION WAS MEASURED.

Figure 4.3-33 – Creep Strain of MIL-P-8184 Material Under Cyclic Stress-Temperature
Conditions

4-39
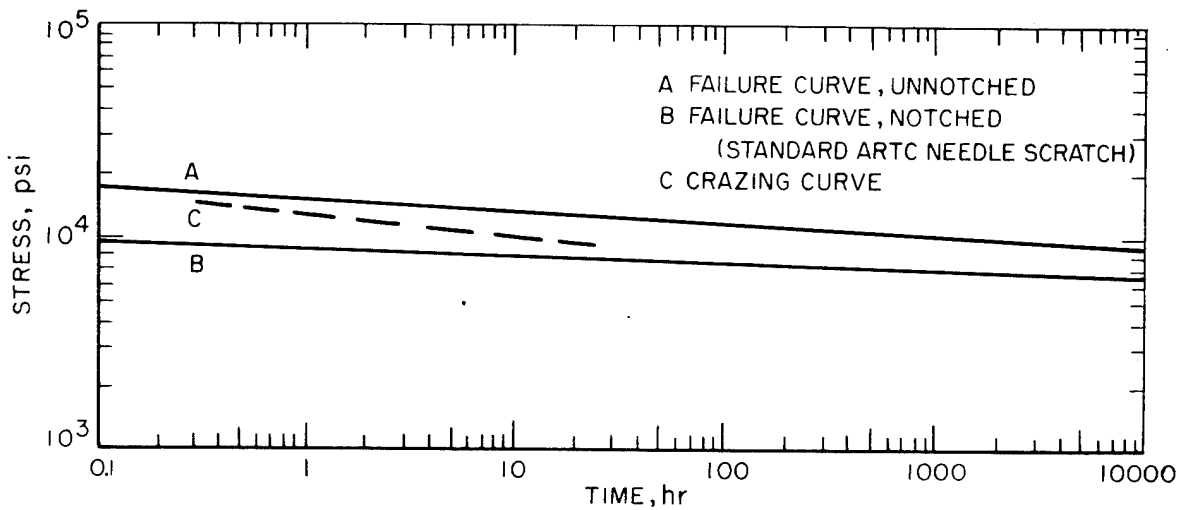
Figure 4. 3-34 – Effect of Duration of Loading on Flexural Properties of
0. 250-Inch-Thick MIL-P-8184 Material at Room Temperature
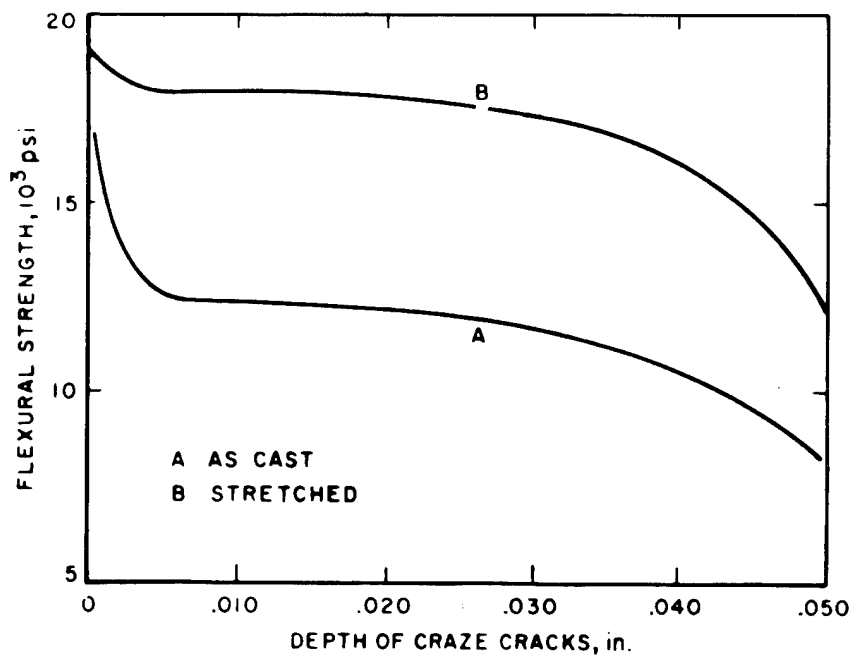
Figure 4. 3-35 – Effect on Depth of Craze Cracks on the Flexural Strength of
Crazed MIL-P-8184 Material

4-40
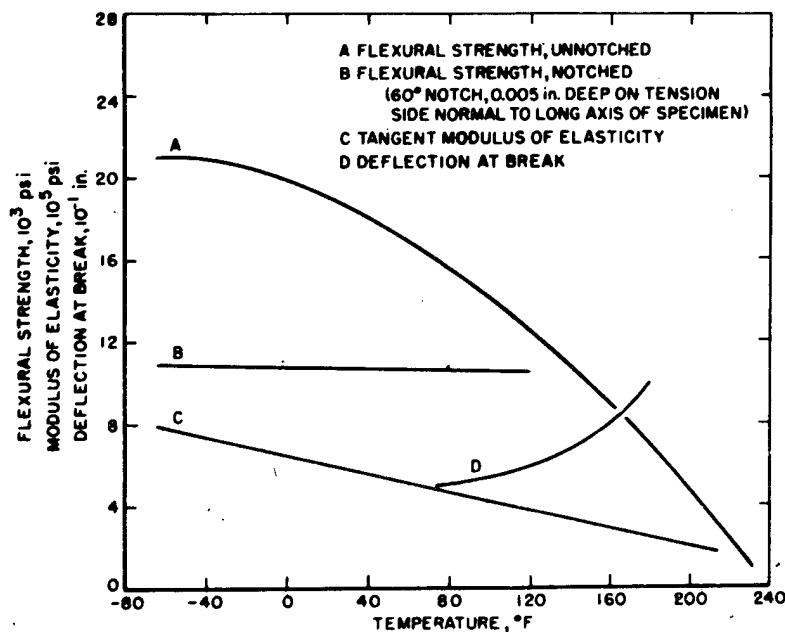
4601-47

Figure 4. 3-36 – Effect of Temperature on Flexural Properties (Short-Time Test)
of MIL-P-8184 Material

4. 3. 4. 2   PROPERTIES

Among the comparative properties of other materials, tensile-rupture cures at three
temperatures are in Figures 4. 2-3, 4. 2-4, and 4. 2-5 on pages 4-6, 4-6, and 4-7. K-value
versus temperature is found in Figure 4. 2-7 on page 4-9; and luminous transmittance after
Tabor abrasion in Table 4. 2-I on page 4-13.

4. 3. 4. 2. 1   TENSILE DATA

Stress-strain, tensile strength versus temperature, stress versus secant modulus curves,
tensile creep data, and acrylic creep data are found in Figures 4. 3-38 through 4. 3-52. The
modulus of rupture curve (Figure 4. 3-42) indicates +160 F to be the optimum operational
temperature.

TABLE 4.3-III - EFFECT OF HEAT TREATMENT ON THE CRAZING PROPERTIES OF MIL-P-8184 MATERIAL UNDER TENSILE LOAD AT 73.5 DEG F

	Stress (PSI $\times 10^3$)	Strain (percent)	Threshold stress for stress solvent crazing (PSI $\times 10^3$)
MIL-P-8184			
Unannealed	9.6	3.4	2.4
Annealed*	10.2	4.0	3.1
Heated**	9.8	4.0	2.7
Heated and annealed	10.0	4.0	3.2

Notes:
1. Test method 1011 of Federal Specification L-P-406, type 1 specimens. Testing speed was 0.05 inch per minute up to 10 percent strain at which point the speed was increased to 0.25 inch per minute. The relative humidity was 50 percent. Data are based on 3 to 8 specimens.
2. Threshold stress for stress-solvent crazing is the minimum stress required to cause crazing upon application of solvent. The solvent used in these tests was ethylene dichloride.

*Annealing: heated to 212 F for 6 hours, followed by slow cooling.
**Heating: heated to 365 F for 39 minutes, followed by rapid cooling in air.
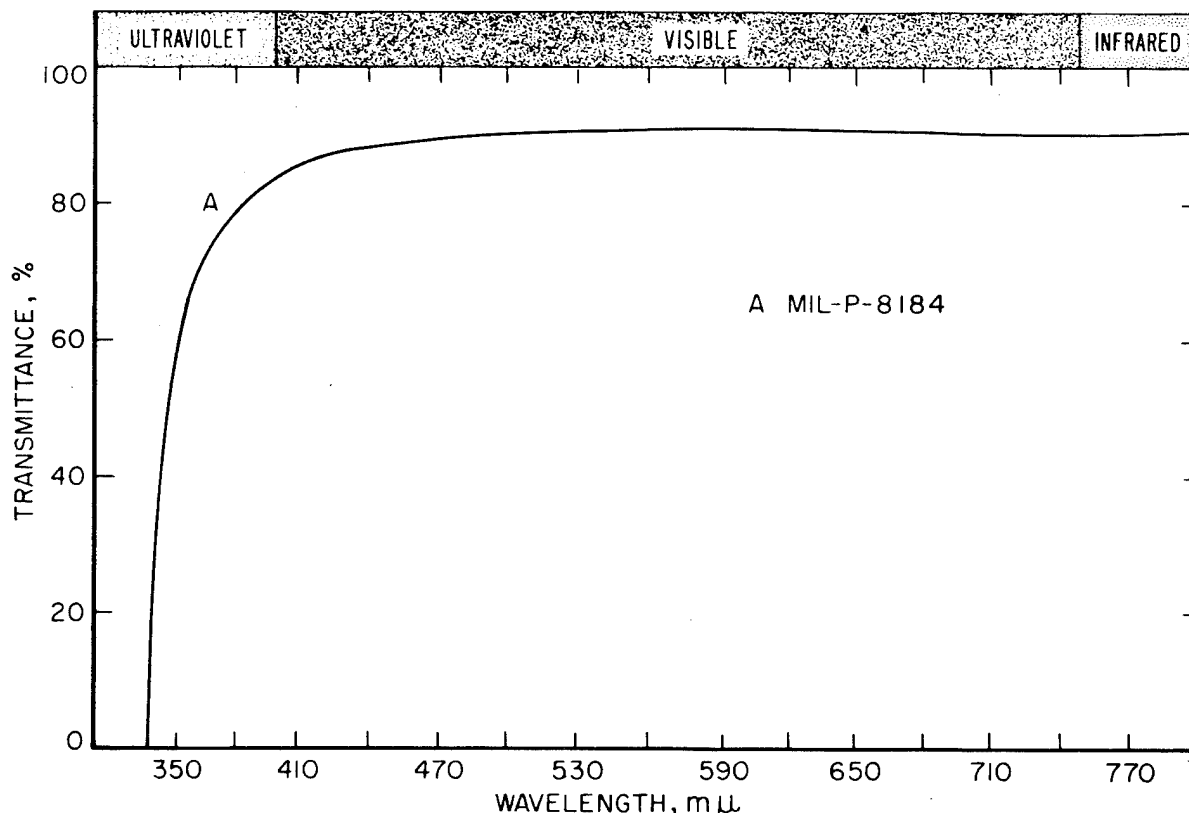
Figure 4.3-37 - Luminous Transmittance of MIL-P-8184 Material
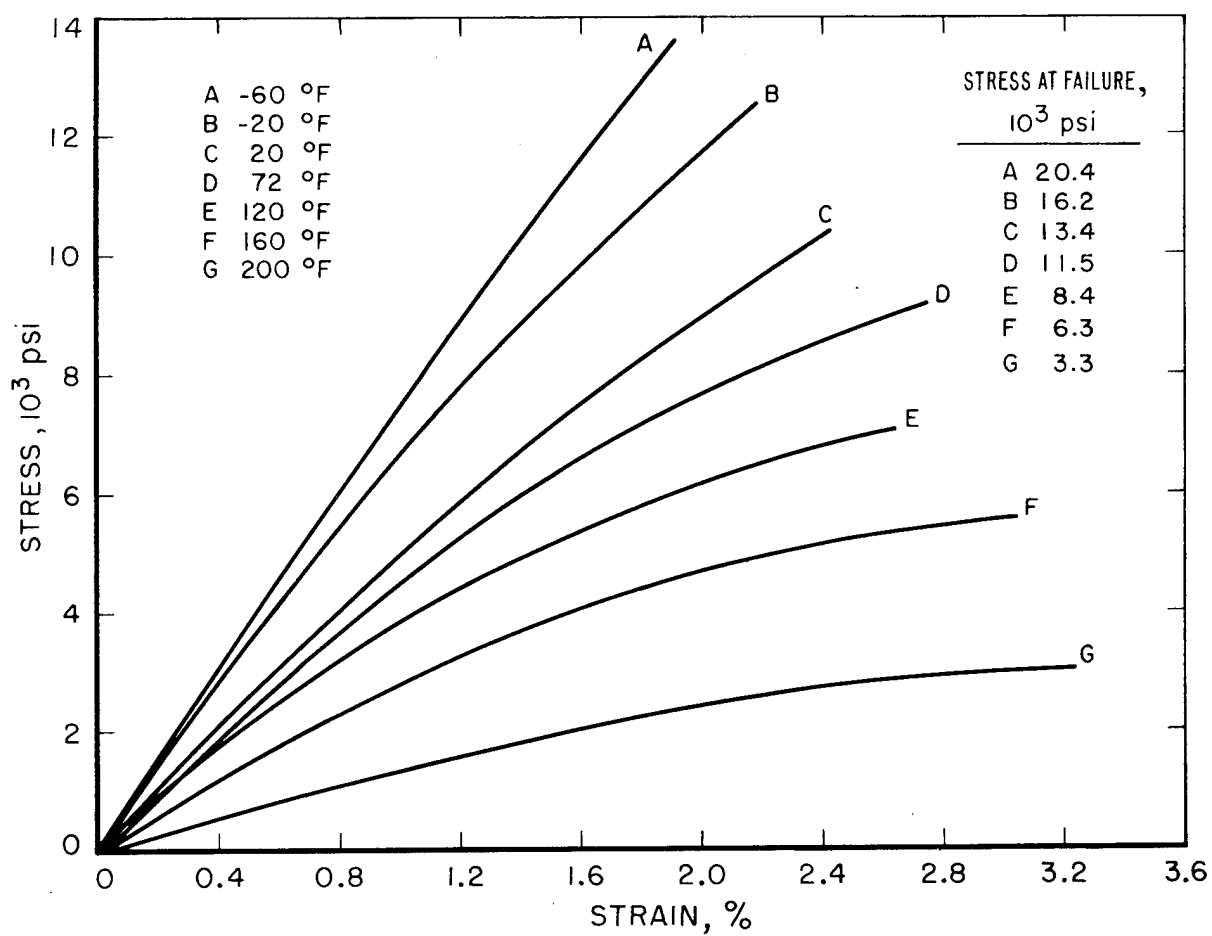
Figure 4.3-38 – Tensile Stress-Strain Curves for 0.350-Inch-Thick MIL-P-25690
Material at Various Temperatures

4-43
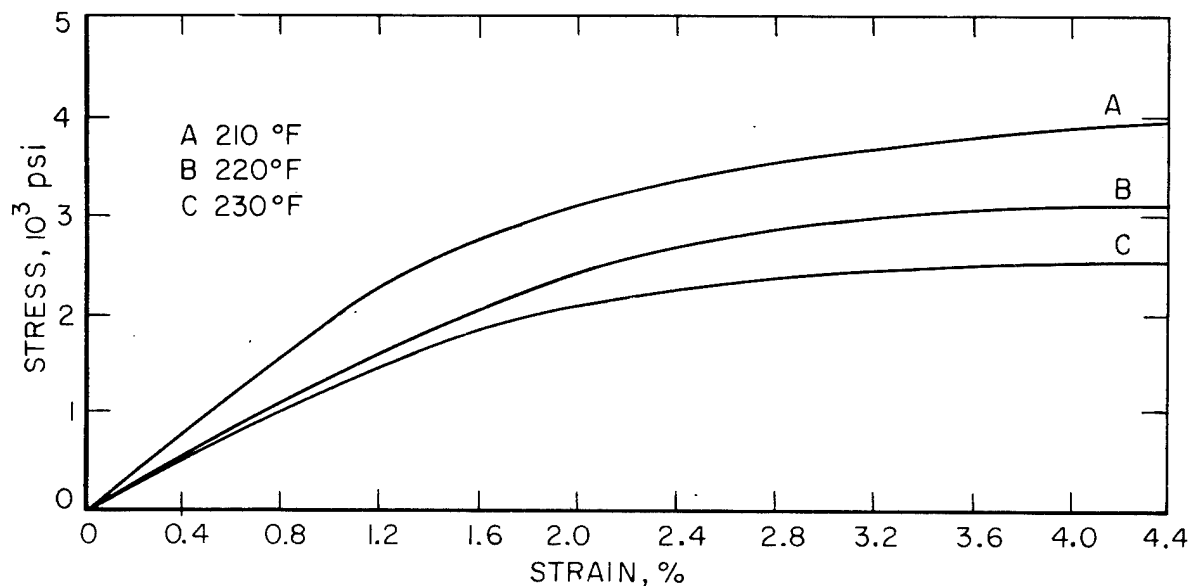
Figure 4. 3-39 – Tensile Stress-Strain Curves for 0. 350-Inch-Thick MIL-P-25690
Material at Elevated Temperatures, Tested at a Crosshead
Separation Rate of 0. 20 Inch per Minute

4. 3. 4. 2. 2   COMPRESSION DATA

Stress-strain, stress-modulus, and compressive strength versus temperature curves are found in Figures 4. 3-53 through 4. 3-55.

4. 3. 4. 2. 3   FLEXURAL DATA

Figure 4. 3-56 demonstrates the degradation of flexural properties which occur as a result of notching or reinforcing.   The symmetry refers to the thickness of the laminate bonded to the surface of the specimens.   The standard stress-deflection curve of the MIL-P-25690 material is also shown.
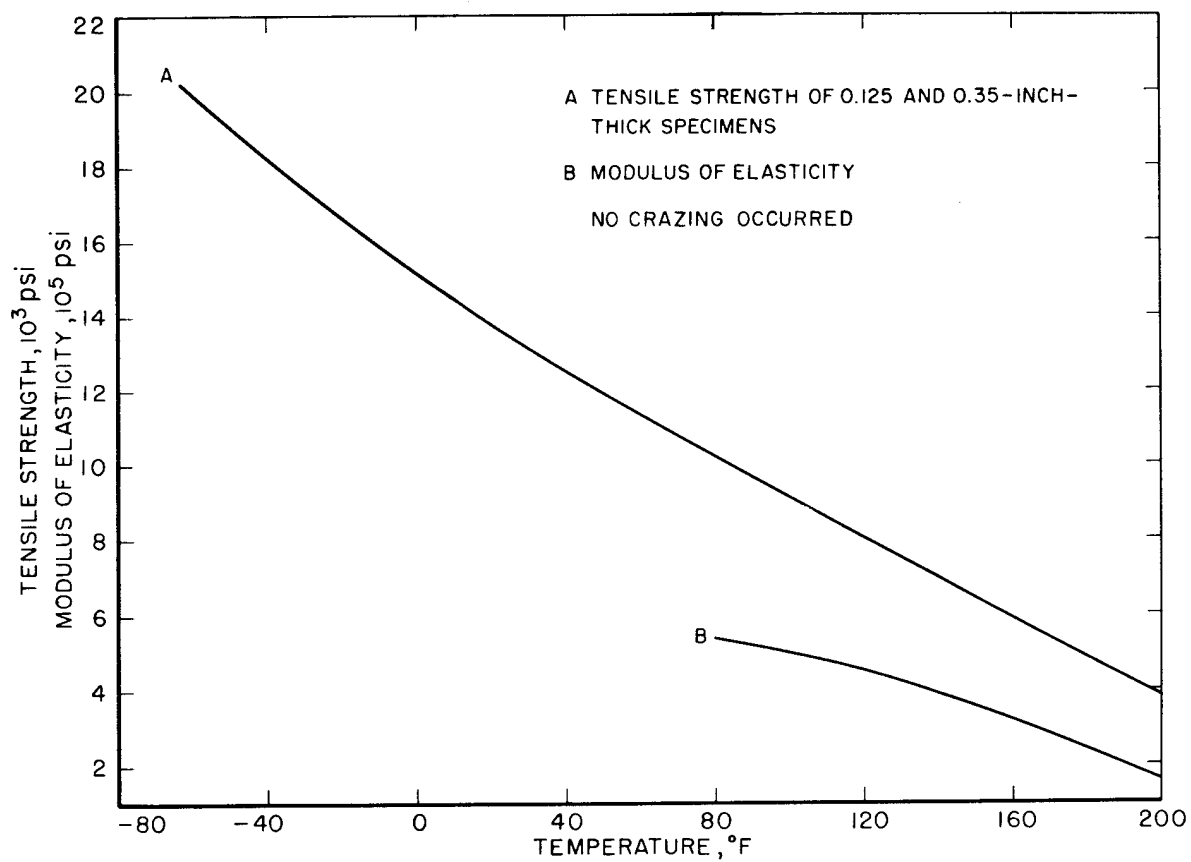
Figure 4.3-40 – Effect of Temperature on Tensile Properties (Short–Time Test) of
75–Percent Stretched MIL–P–25690 Material

4-45
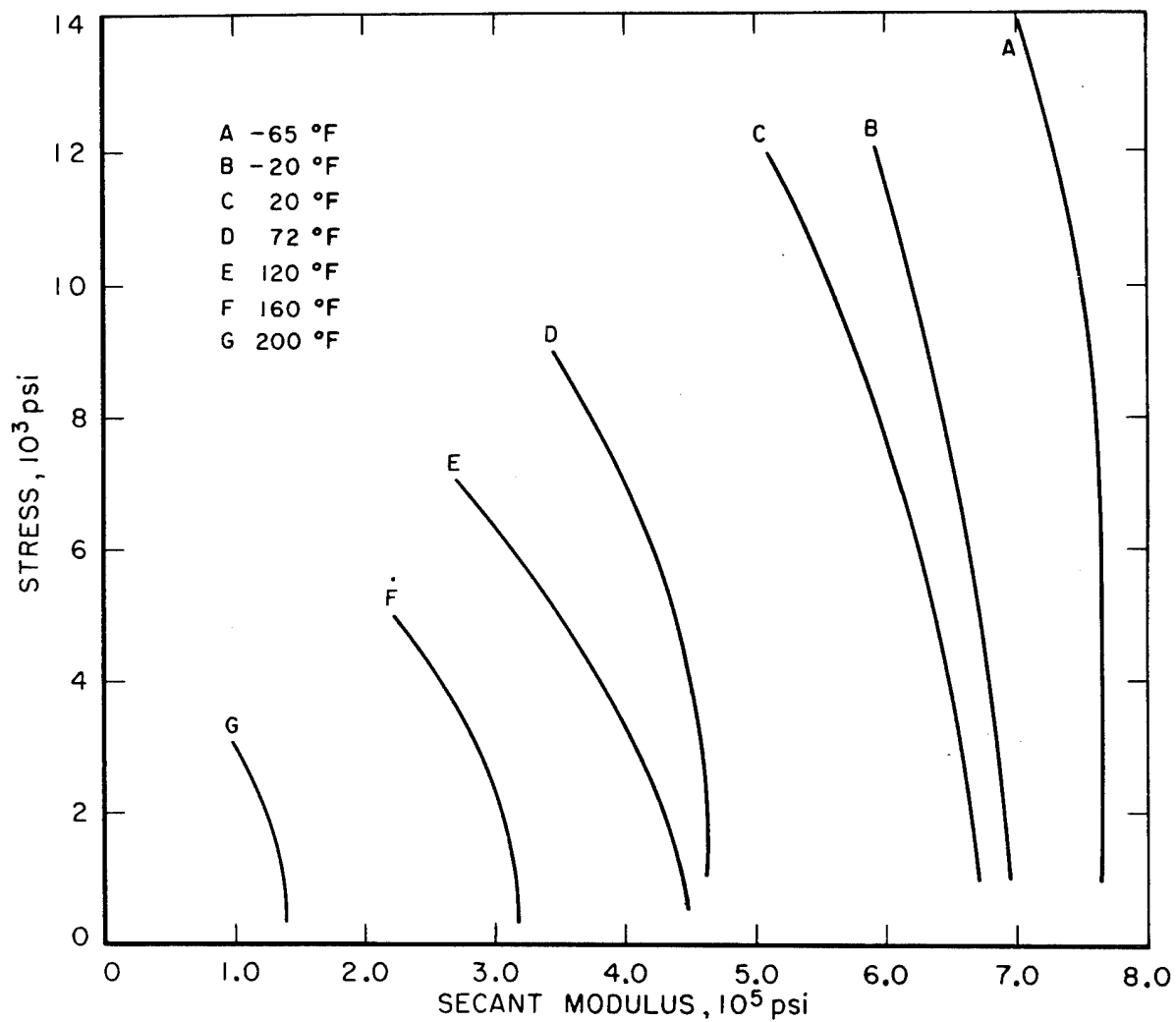
Figure 4.3-41 – Tensile Stress versus Secant Modulus for 0.350-Inch-Thick MIL-P-25690
Material at Various Temperatures

4-46

NOTE:
DATA CALCULATED FROM TENSILE STRESS—STRAIN AND ULTIMATE STRENGTH VERSUS TEMPERATURE CURVES.
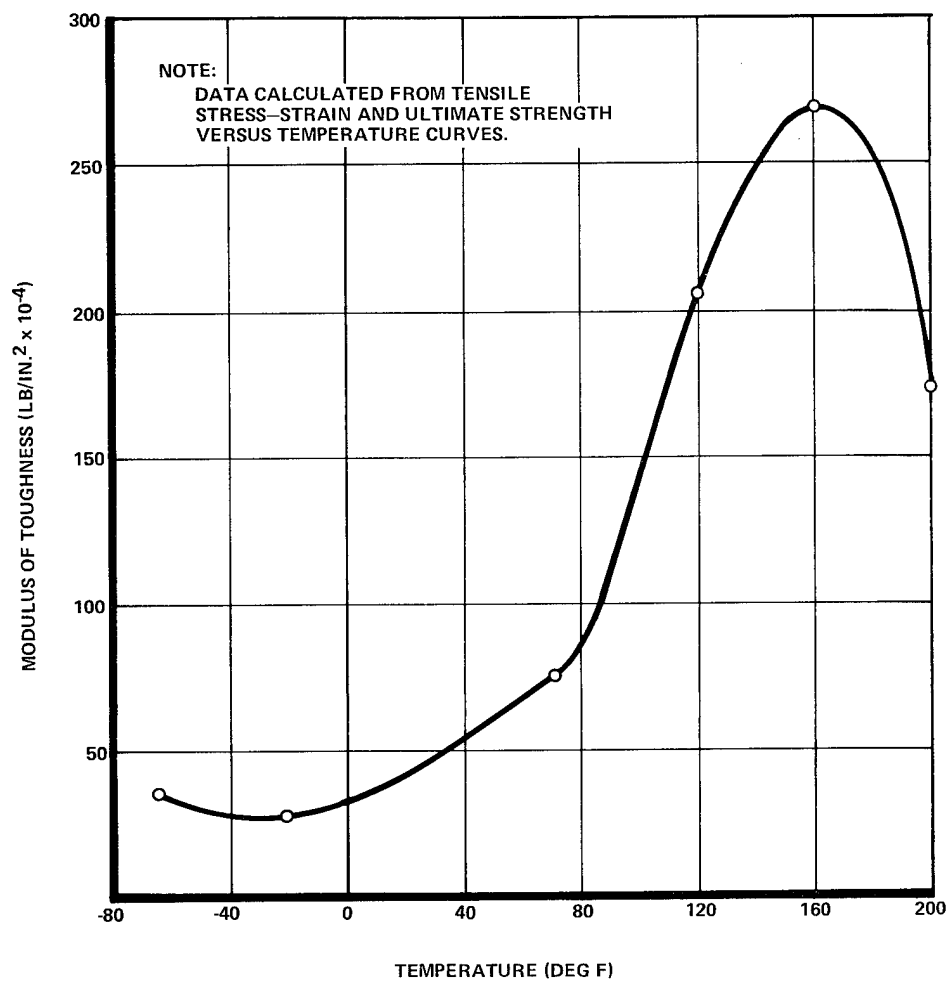
NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.

4601-53

Figure 4.3-42 - Modulus of Toughness versus Temperature for 0.350-Inch-Thick MIL-P-25690 Material

4-47
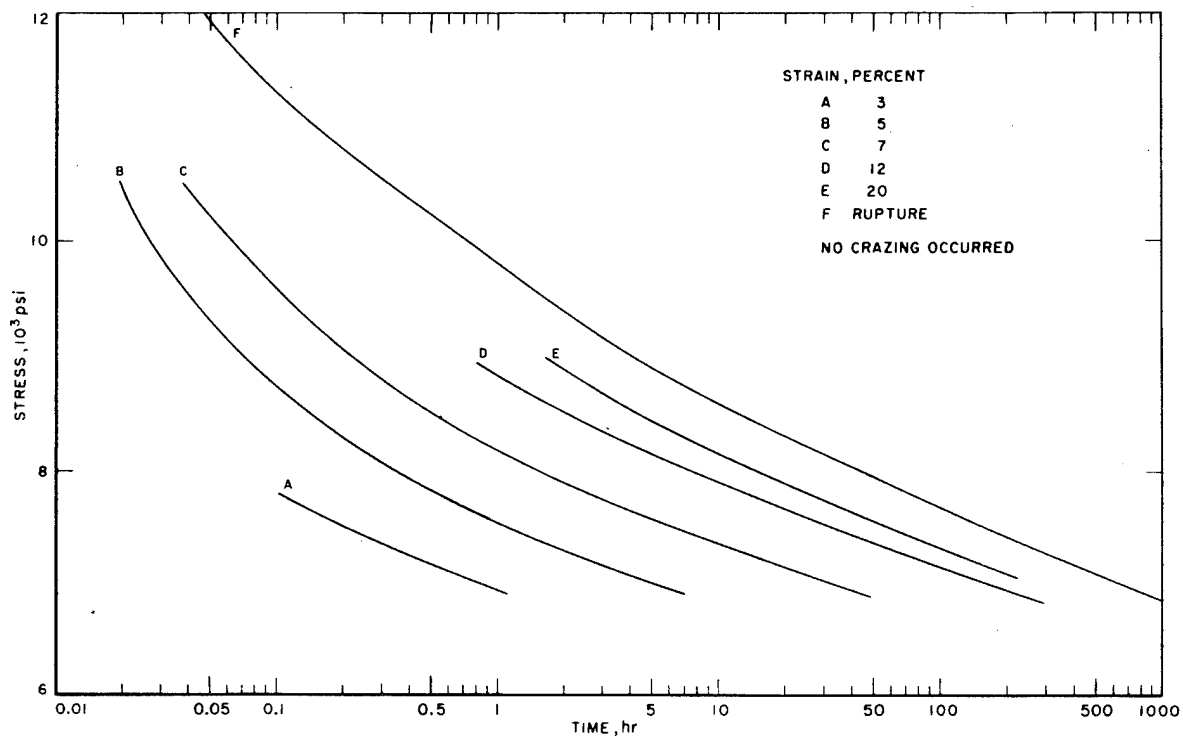
Figure 4.3-43 - Tensile Creep Data at 80 Deg F for 0.125-Inch-Thick
MIL-P-25690 Material Stretched 75 Percent
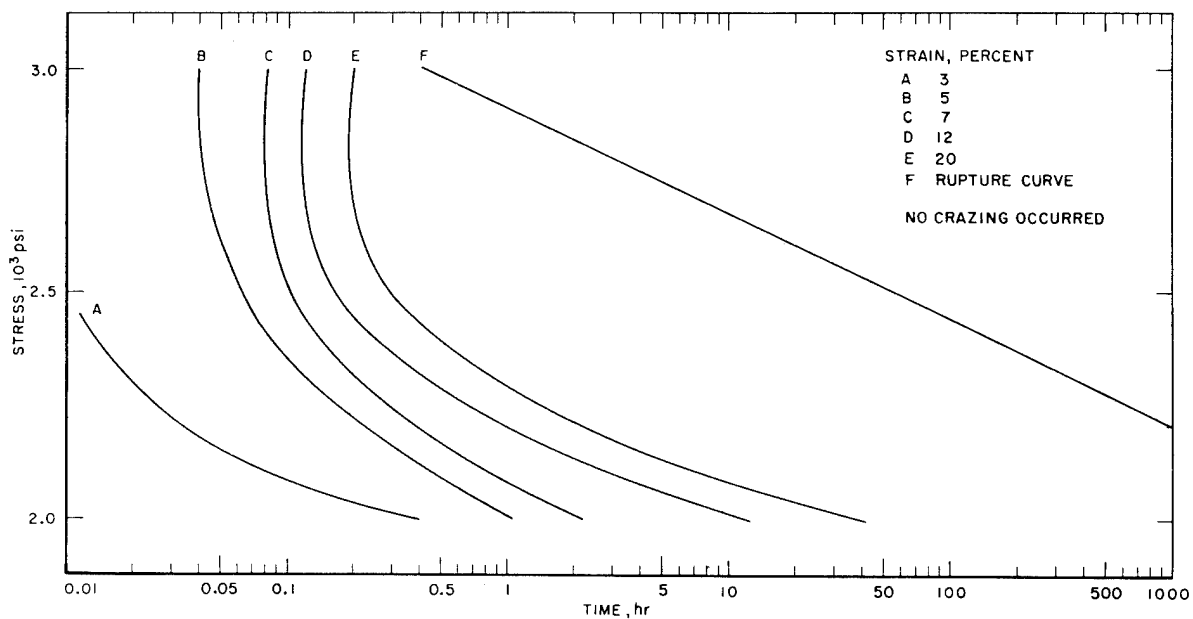
Figure 4.3-44 - Tensile Creep Data at 200 Deg F for 0.125-Inch-Thick
MIL-P-25690 Material Stretched 75 Percent
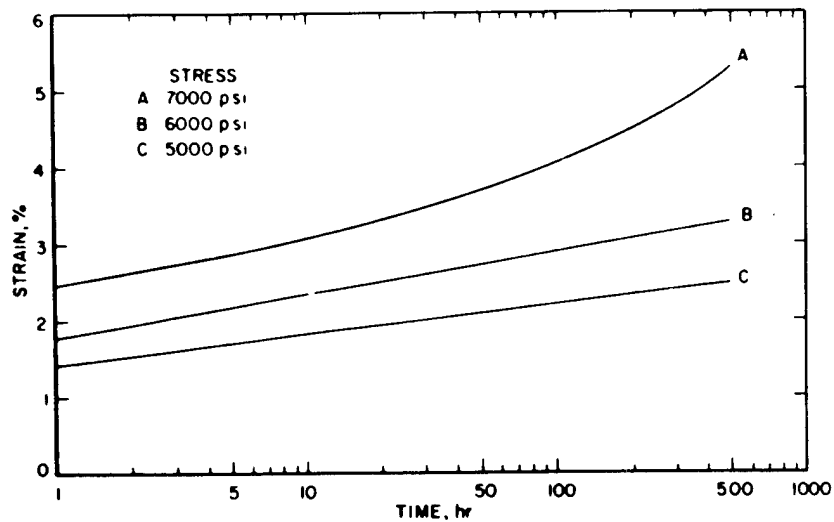
Figure 4.3-45 – Tensile Creep Data for 0.350-Inch-Thick MIL-P-25690
Material at Room Temperature
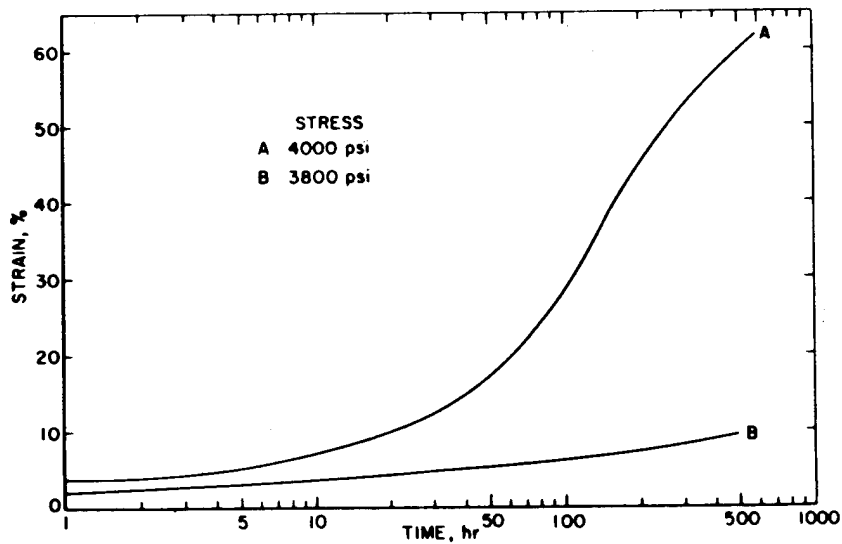
Figure 4.3-46 – Tensile Creep Data for 0.350-Inch-Thick MIL-P-25690
Material at 160 Deg F
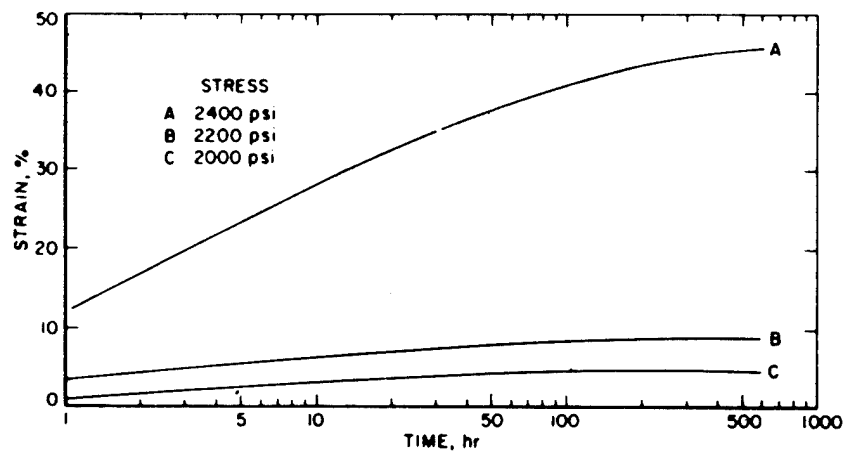
Figure 4.3-47 – Tensile Creep Data for 0.350-Inch-Thick MIL-P-25690
Material at 195 Deg F
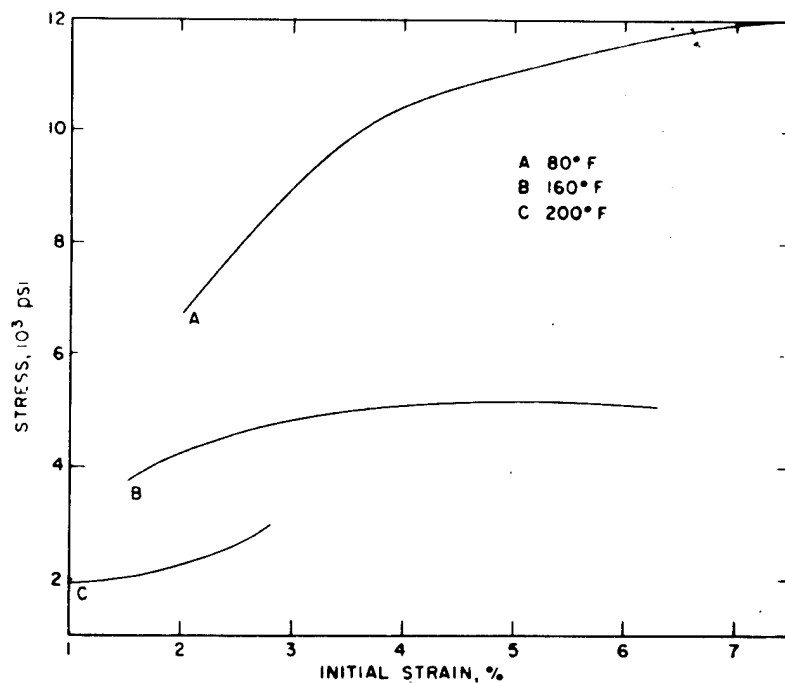
Figure 4.3-48 – Effect of Stress on Initial Strain in Tensile Creep of 75-Percent
MIL-P-25690 Material at Various Temperature
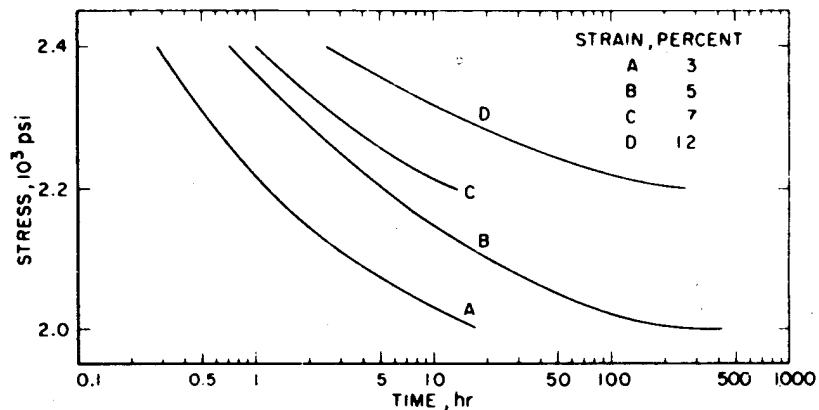
Figure 4. 3-49 – Tensile Creep Data for 0. 350-Inch-Thick MIL-P-25690
Material at 195 Deg F
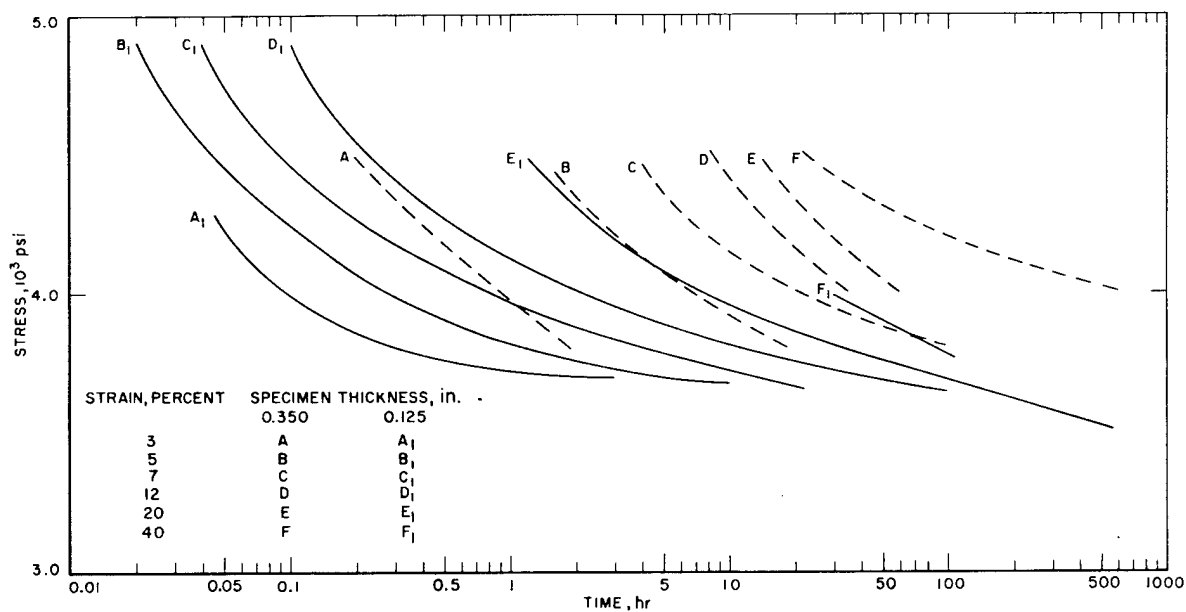
Figure 4. 3-50 – Tensile Creep Data for 75-Percent MIL-P-25690
Material at 160 Deg F

4-51

TEST CYCLE DESCRIPTION
1. SPECIMEN HEATED TO 160 DEG F SOAK TEMPERATURE.
2. LOAD APPLIED TO 2600 PSI.
3. MAINTAIN 2600 PSI FOR 18 MINUTES.
4. UNLOAD AND COOL TO ROOM TEMPERATURE.

TOTAL STRAIN UNDER LOAD

ACCUMULATIVE DEFORMATION

NOTE: DATA SUPPLIED BY NORTH AMERICAN ROCKWELL.

STRAIN (PERCENT)

TEST CYCLE NUMBER
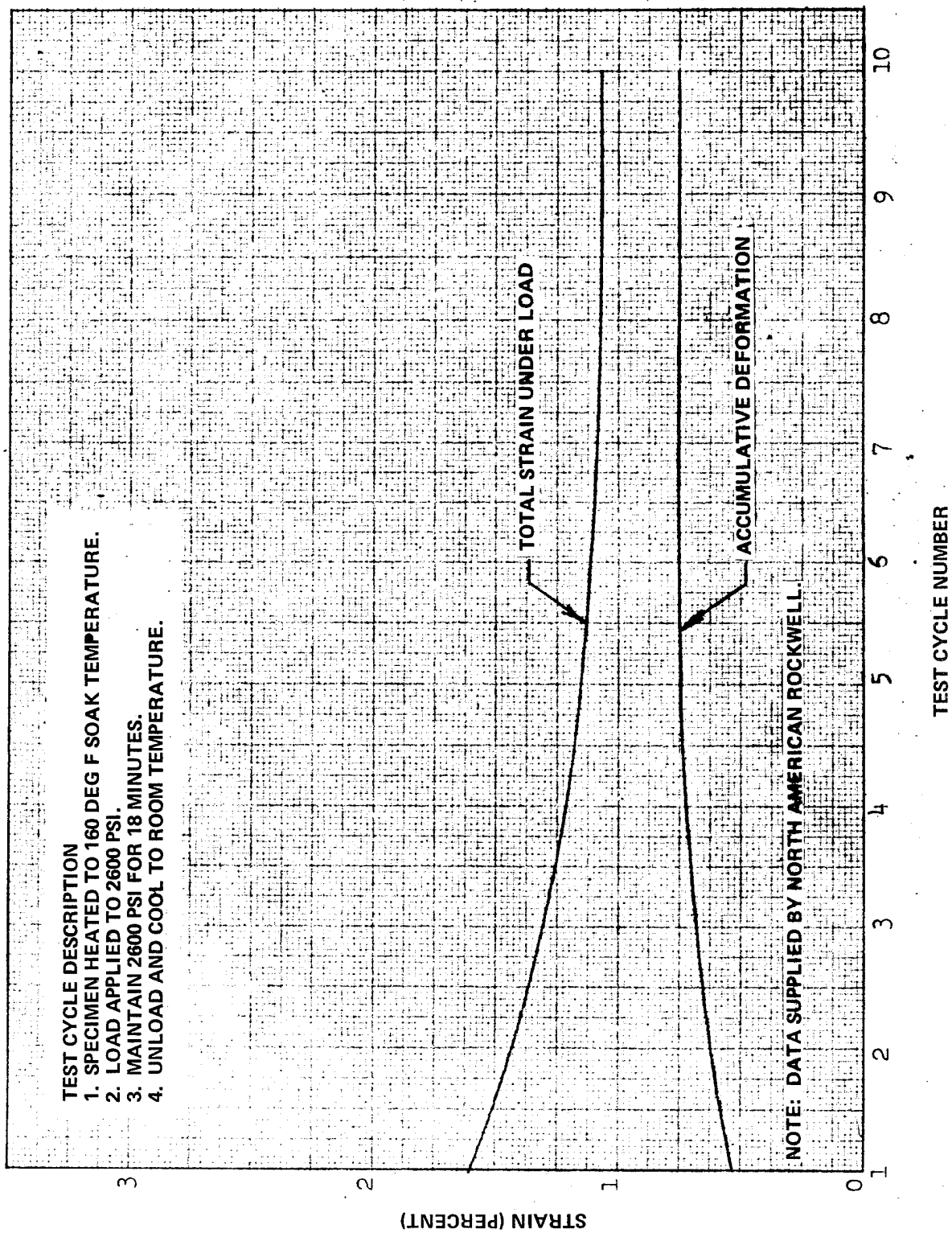
Figure 4.3-51 – Cyclic Creep Properties of MIL-P-25690 Material at 160 Deg F

4-52

TEST CYCLE DESCRIPTION
1. SPECIMEN HEATED TO 180 DEG F SOAK TEMPERATURE.
2. LOAD APPLIED TO 2600 PSI.
3. MAINTAIN 2600 PSI.
4. UNLOAD AND COOL TO ROOM TEMPERATURE

ACCUMULATIVE DEFORMATION

TOTAL STRAIN UNDER LOAD

NOTE: DATA SUPPLIED BY NORTH AMERICAN ROCKWELL.

TEST CYCLE NUMBER

STRAIN (PERCENT)
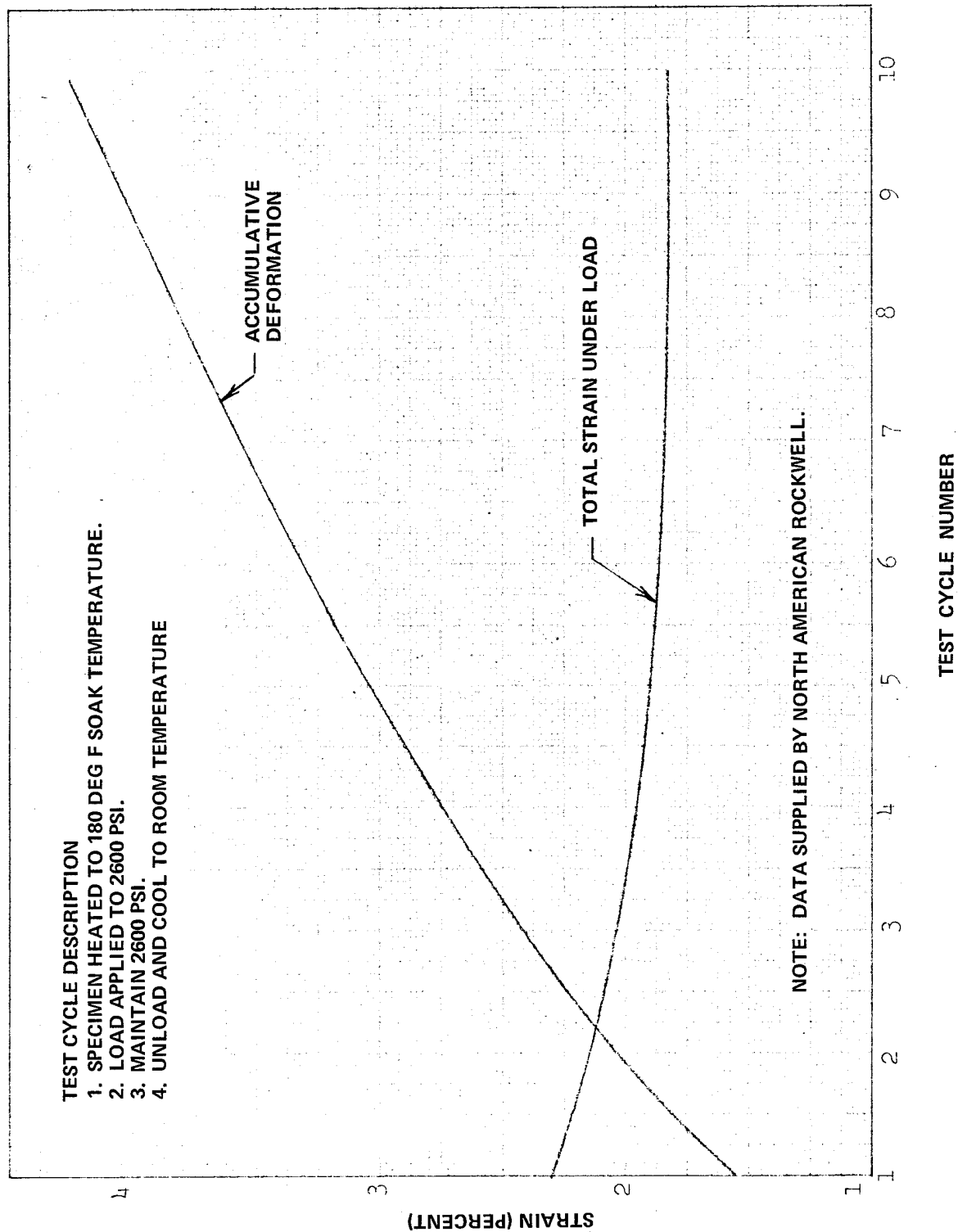
Figure 4.3-52 – Cyclic Creep Properties of MIL-P-25690 Material at 180 Deg F

4-53
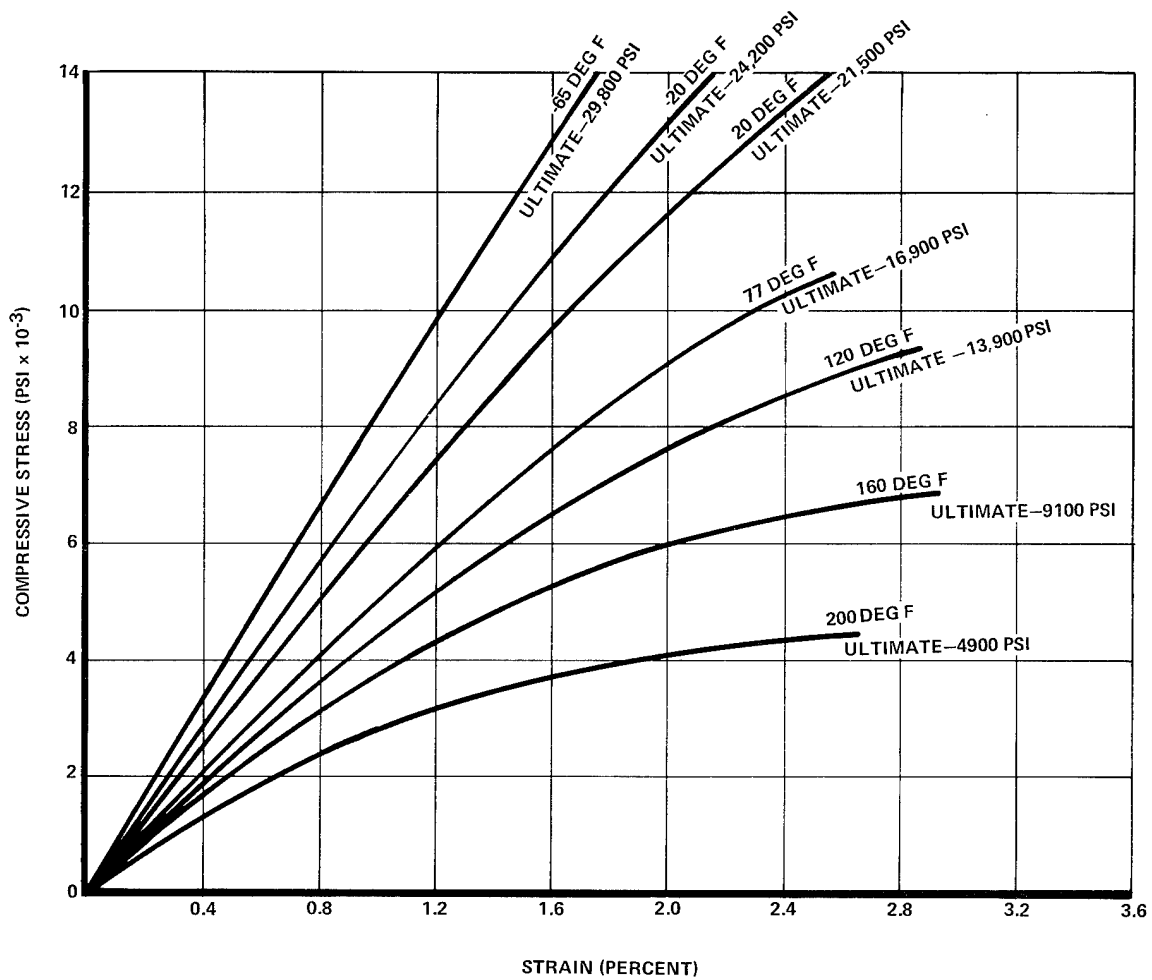
Figure 4.3-53 - Compressive Stress-Strain Data for 0.350-Inch-Thick MIL-P-25690 Material

4-54
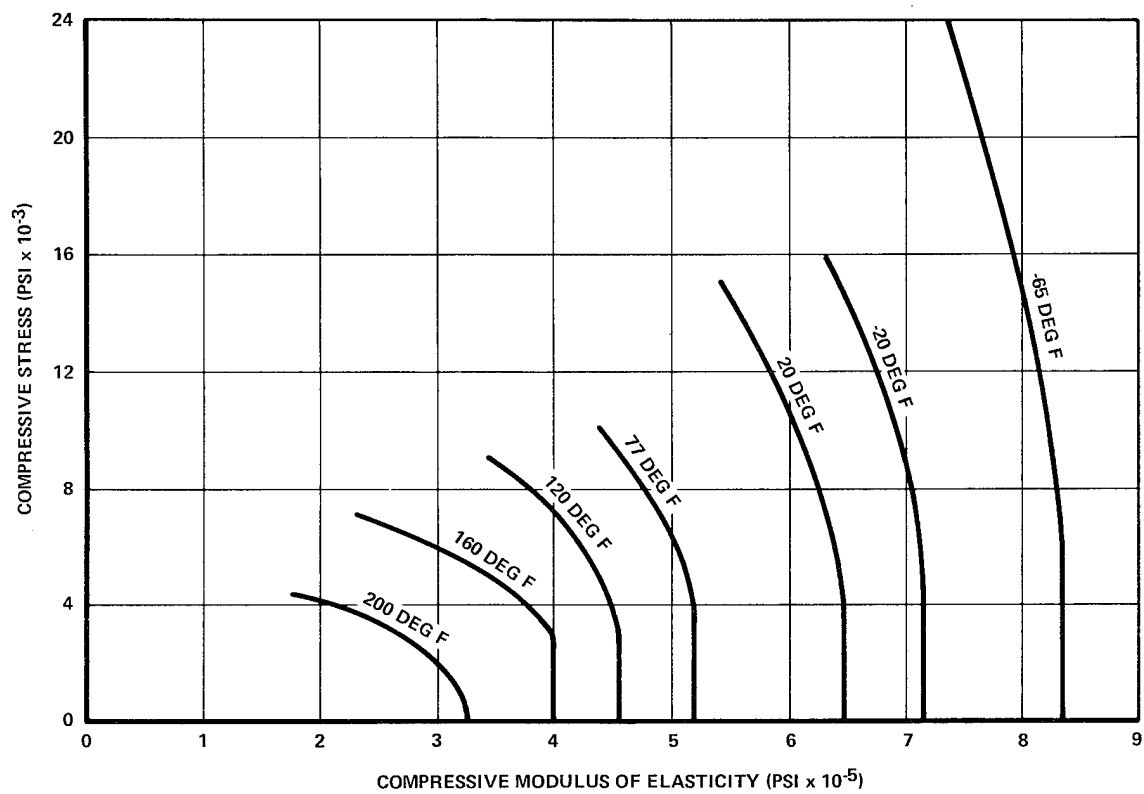
4601-65

Figure 4.3-54 - Compressive Stress versus Secant Modulus for 0.350-Inch-Thick MIL-P-25690 Material

4-55
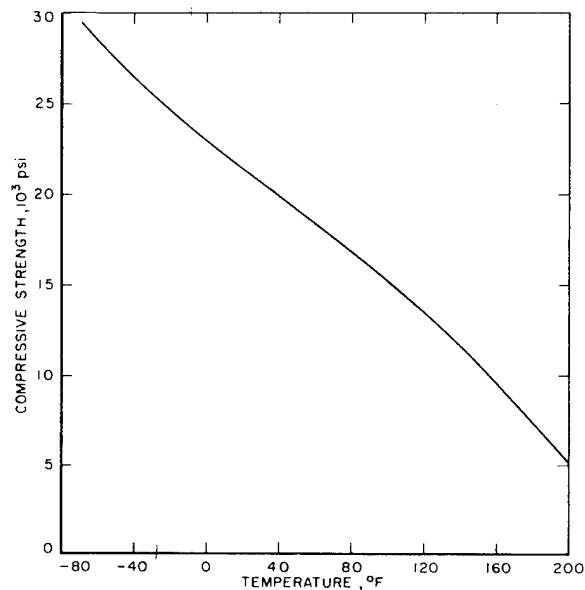
Figure 4.3-55 – Effect of Temperature on Compressive Strength of 0.350-Inch-Thick
MIL-P-25690 Material
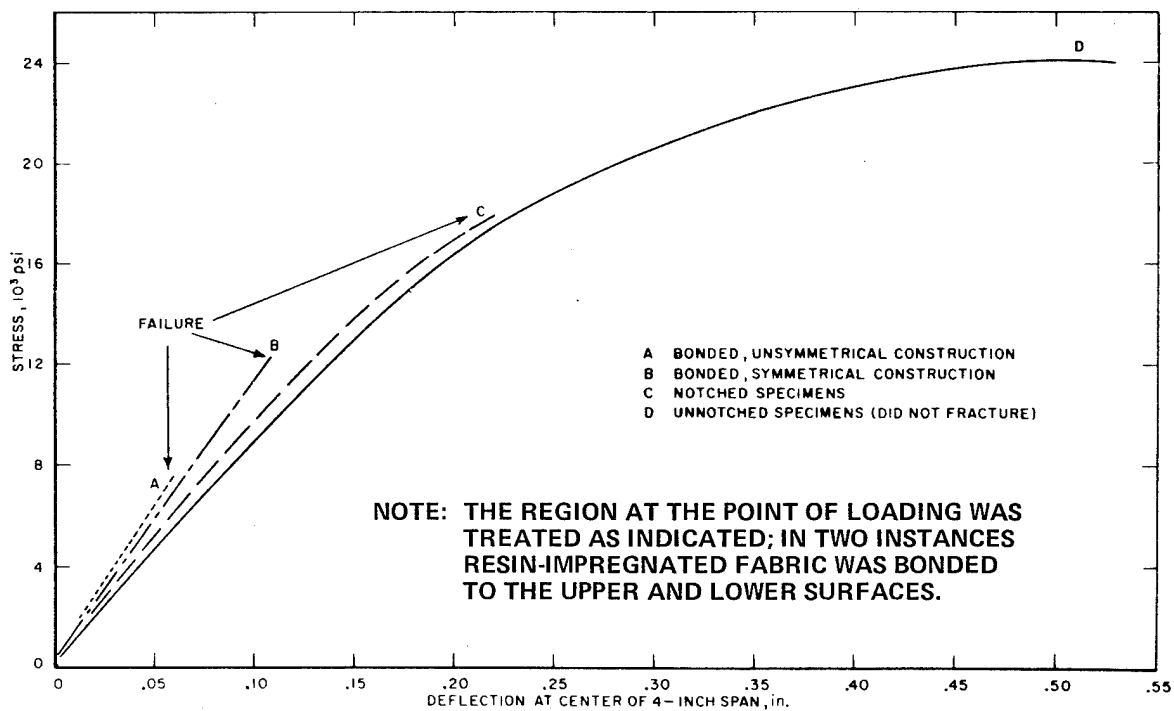
Figure 4.3-56 – Flexural Stress-Deflection Curves for MIL-P-25690
Material at 80 Deg F

4-56

4.3.4.2.4   BEARING STRENGTH

This test was performed in accordance with LP 406b, Method 1051, except that measurement
was based on four-percent hole elongation only, rather than the tangential method of the
October 1961 revision now in force (FTMS 406).   The test is a simulation of bolt hole
strength and is shown in Figure 4.3-57.   This information is of specific value for stretched
acrylic edge attachment designs which normally utilize a bolt-through fastening.

4.3.4.2.5   CRACK PROPAGATION RESISTANCE

This property is commonly known as the K-value and has the units $(lb/in.)^{1.5}$. The factor
was derived from an incremental ratio of dW/dA in $lb/in.^2$ The latter units better explain
the property in that it represents the amount of work necessary to propagate a crack of
defined area.   References 5 and 6 explain the derivation and development of the test.   The
property is dependent on the stretching process with temperature and rate of stretching being
the variables as shown in Figure 4.3-58.

Figure 4.3-59 partially demonstrates the effect of temperature on the property of crack
propagation resistance.   At the higher temperatures the material becomes more ductile and
is able to distribute the loads of stress risers from cracks more easily.   The data for
Figure 4.3-59, however, were obtained from samples which had been heated only long enough
to assure the sample was without a temperature gradient during the test.   Figure 4.3-60
shows that prolonged heating at 200 F and above tends to decrease the K-value.

Thickness of the material has an effect on K-values versus percent of stretch as shown in
Figure 4.3-61, wherein a considerable spread develops between thicknesses of 0.10 to
0.55 inch, with the thicker materials having the lower values.   The thicker materials
obviously have more mass, which makes them less resilient.   In the calculation for K, K is
inversely proportional to thickness and proportional to the failure load.
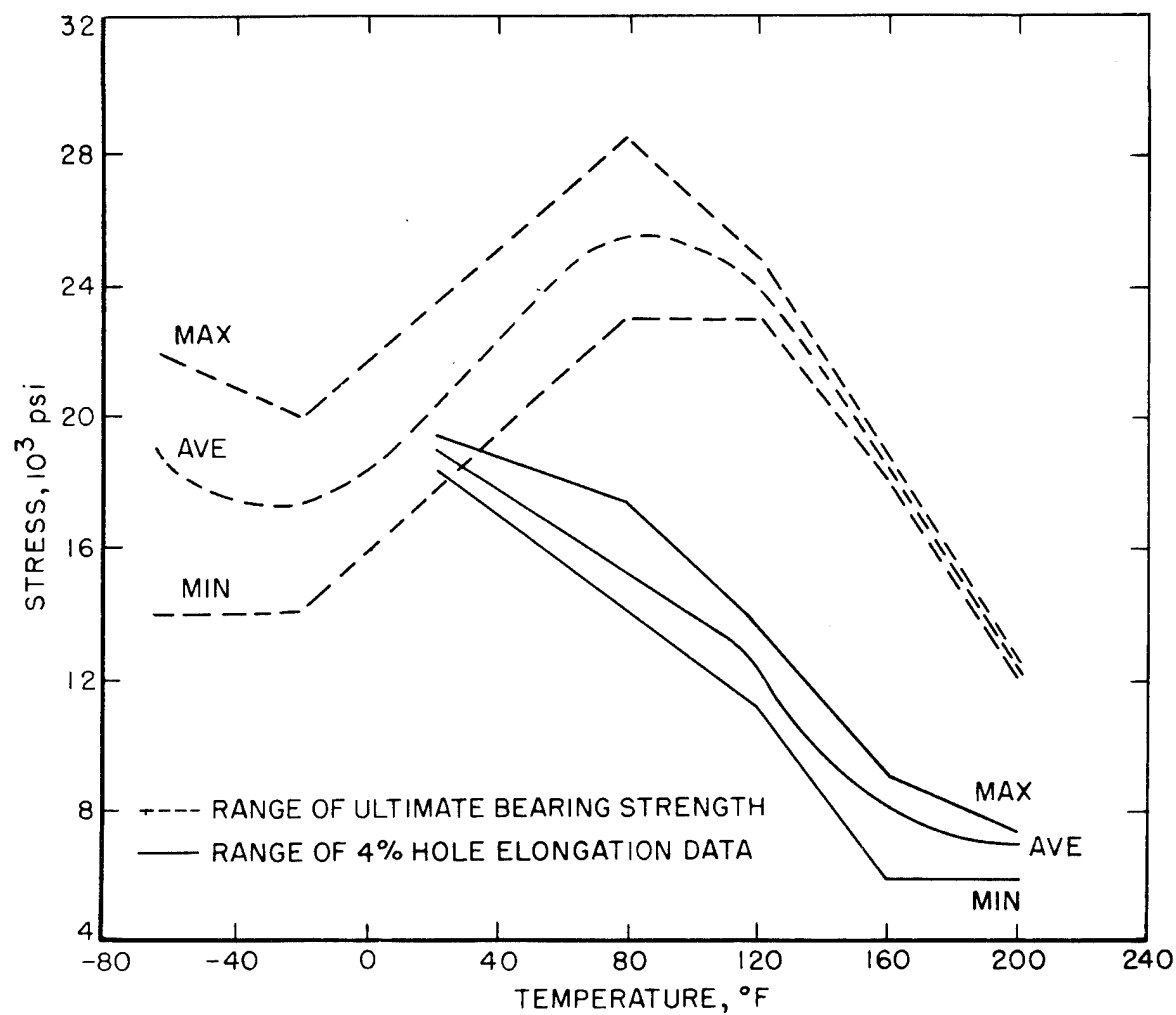
Figure 4. 3-57 – Effect of Temperature on the Bearing Strength and Hole Elongation of
0. 350-Inch-Thick MIL-P-25690 Material

4-58
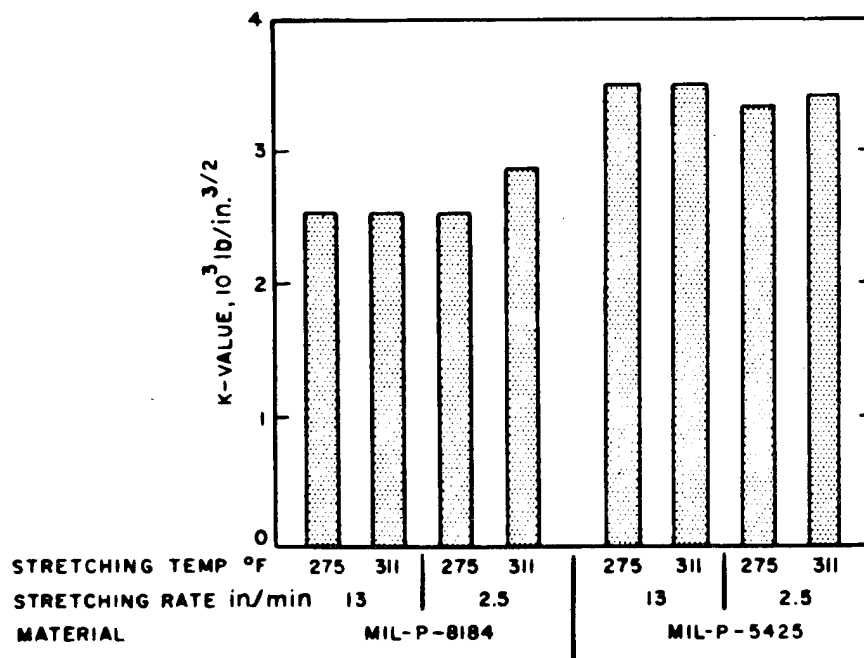
Figure 4.3-58 – Effect of Stretching Temperature and Stretching Rate on the K-Value of MIL-P-5425 and MIL-P-8184 Materials Tested at Room Temperature
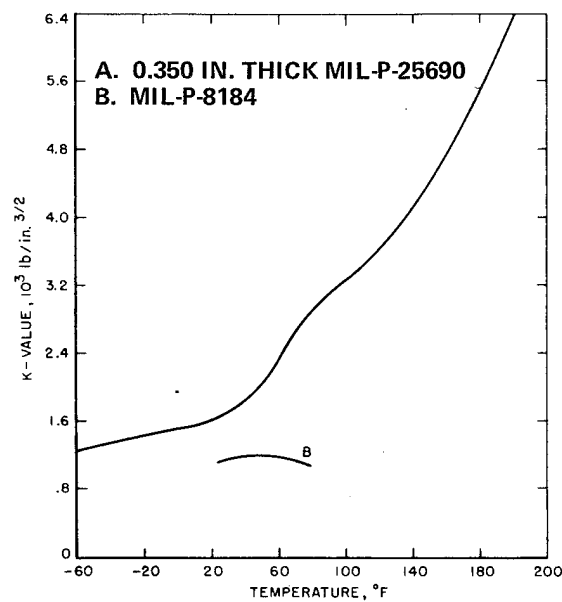
Figure 4.3-59 – Effect of Temperature on the K-Values of Acrylics

4-59
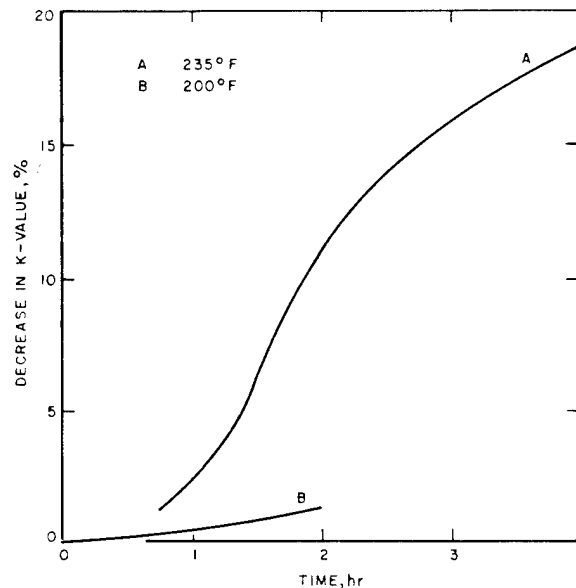
Figure 4.3-60 – Effect of Time and Temperature on the K-Value of MIL-P-25690 Material

The basic value of crack propagation resistance is also subject to reduction if prolonged processing is required at warm forming temperatures. Figure 4.3-62 demonstrates the reduction which can be expected from 0.900-inch-thick material, which undoubtedly requires longer subjection to heat to become formable. Figure 4.3-63 adds quantitative data in K reduction for a 0.900-inch sheet which had been stretched 64 percent and subsequently subjected to +225 deg F over a period of 48 hours. Curves of degradation are shown for other thicknesses of MIL-P-25690 material for various prolonged temperature environments in Figure 4.3-64.

4.3.4.2.6   THERMAL EXPANSION

The curve of thermal expansion versus temperature (see Figure 4.3-65) indicates that the percentage of stretch can decrease at temperatures of +200 F and above, based on the hysteresis of the curve, which shows a negative expansion (or contraction) beyond its original state at a given temperature.

4-60

NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.
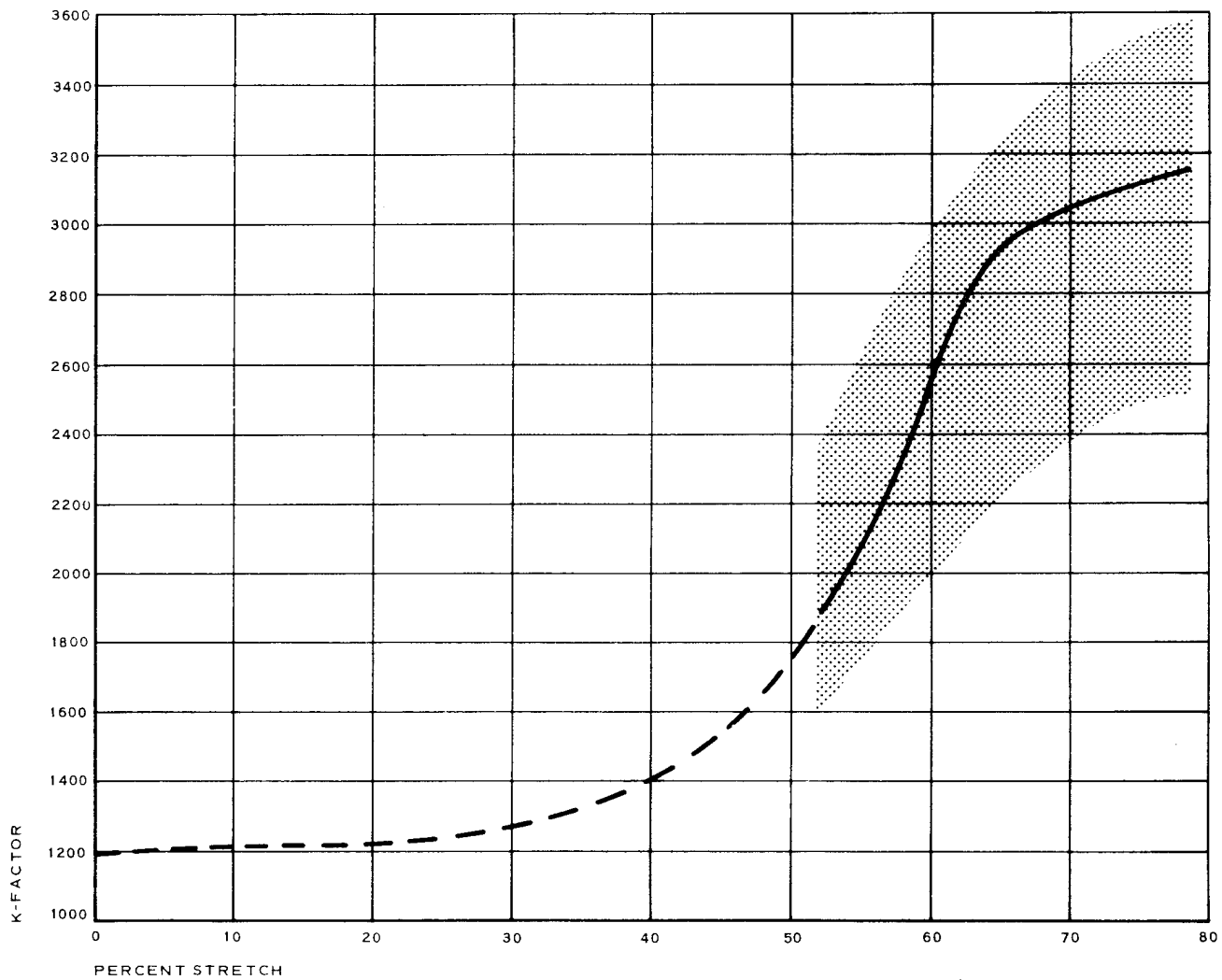
Figure 4. 3-61 – K-Factor Values for Material in Thickness Range from 0. 10 to 0. 55 In.
Tested at 75 Deg F

NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.
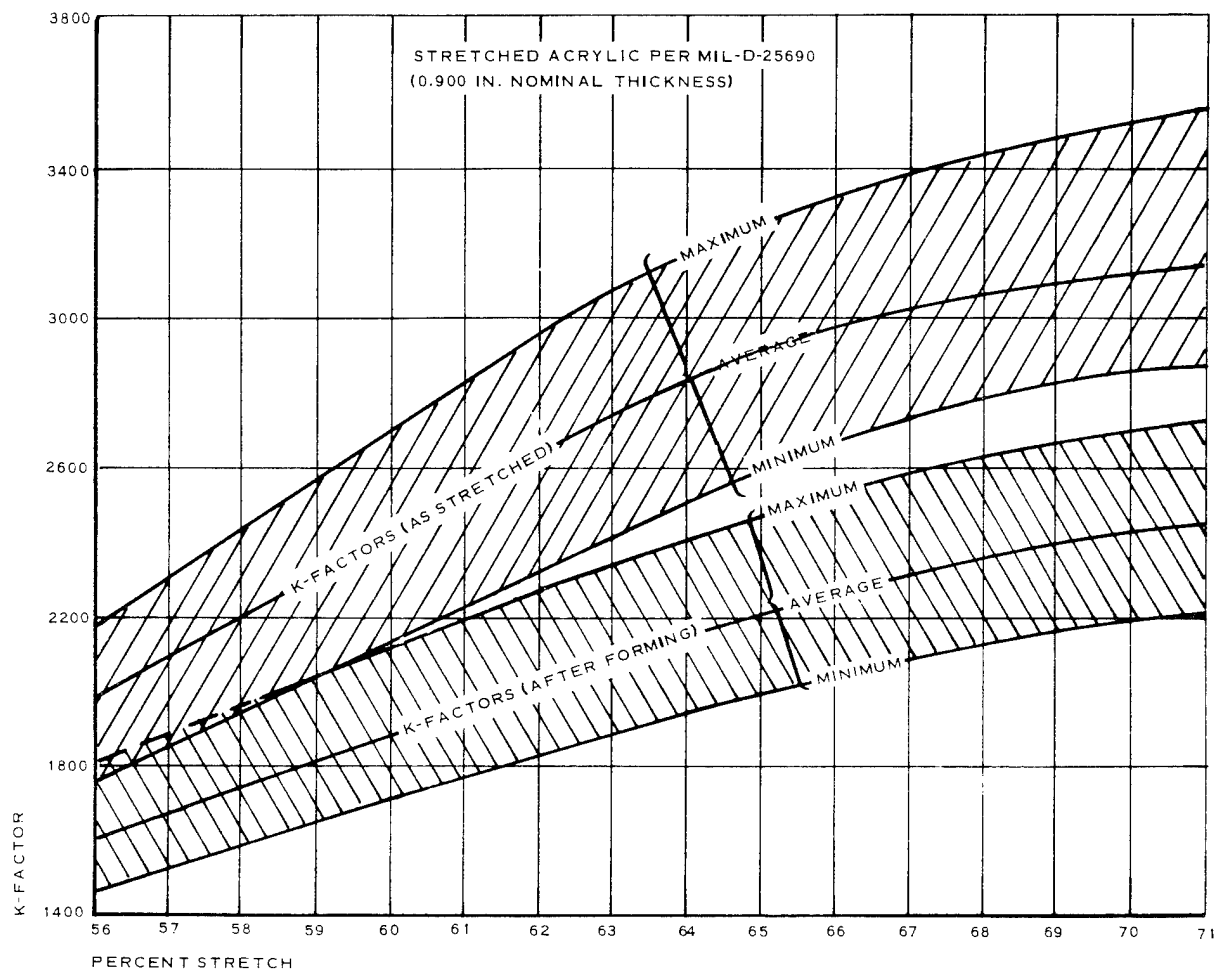
Figure 4.3-62 – K-Factors for As-Stretched and After-Forming Acrylic versus Percent Stretch

4-62

NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.
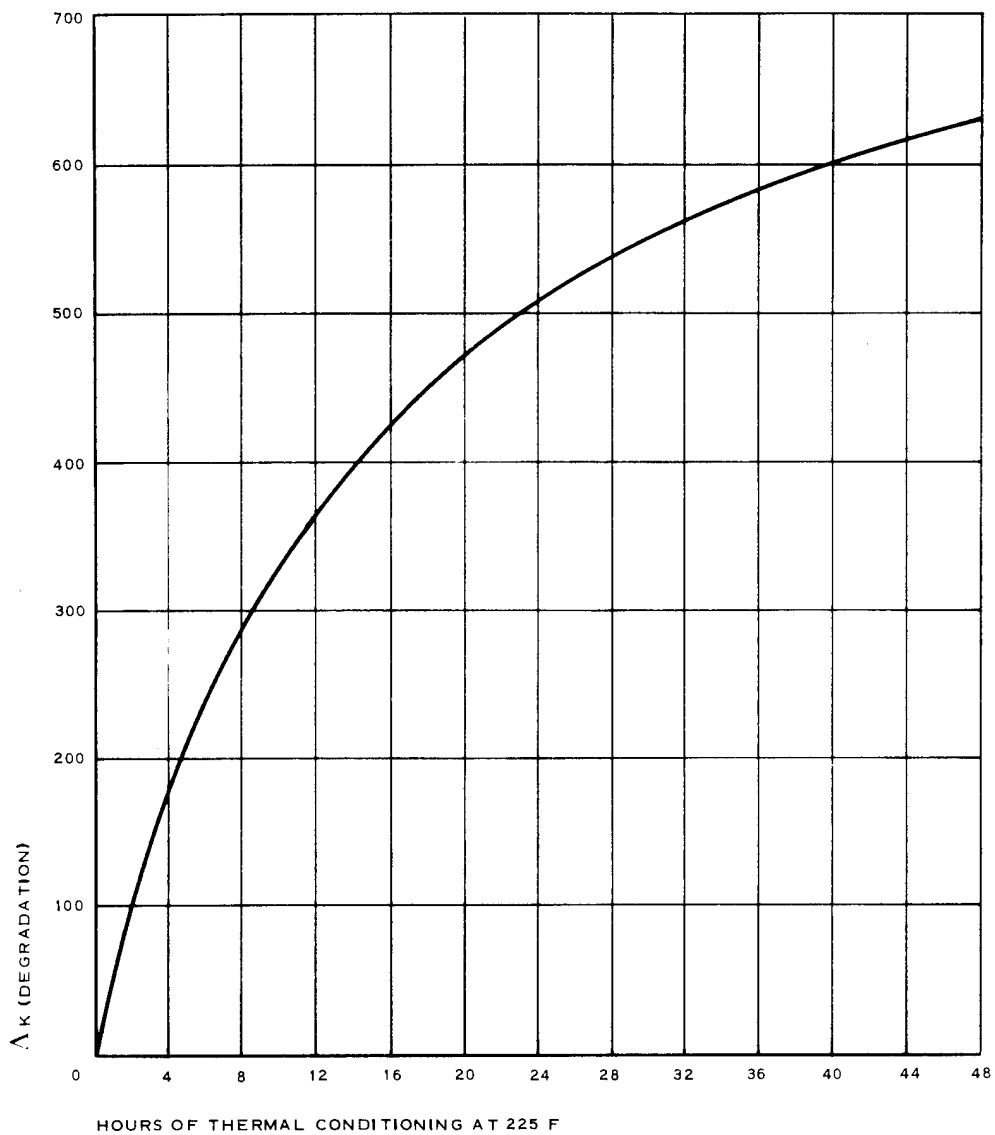
Figure 4.3-63 - K-Factor Degradation of 0.900-In.-Thick Acrylic Stretched at
64 Percent versus Thermal Conditioning at 225 Deg F

4-63
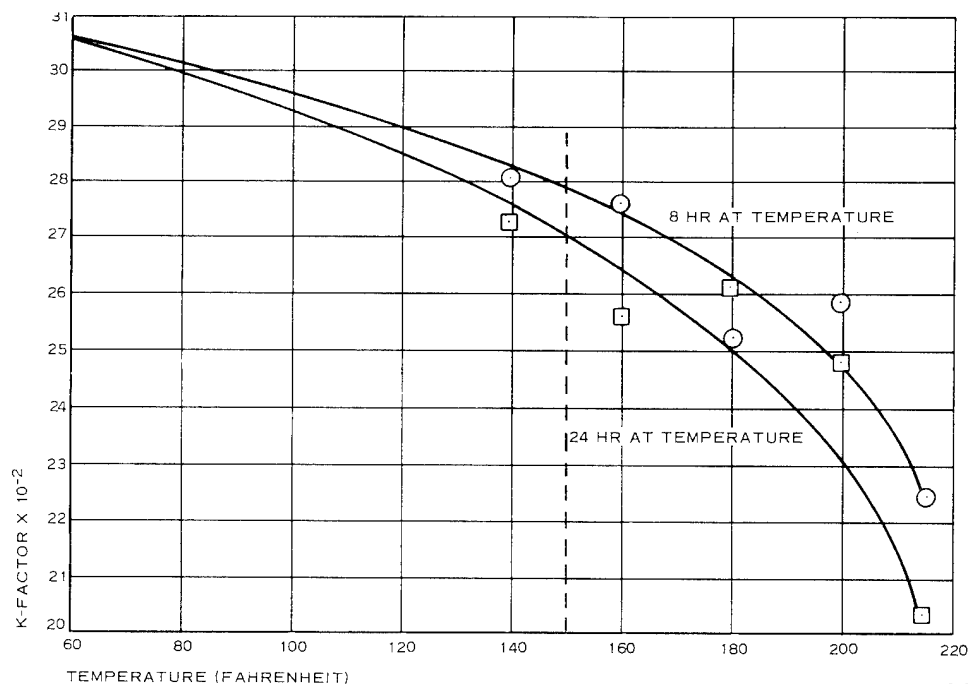
NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.

Figure 4. 3-64 – K-Factor Degradation of Stretched Acrylic (0. 060 to 0. 080 In. Thick)
at Various Temperatures

4. 3. 4. 2. 7   THERMAL RELAXATION

The reduction in percentage of stretch indicated in the previous paragraph is referred to as
thermal relaxation and is actually used as a test criterion to determine the extent to which
the original sheet was stretched.   Figures 4. 3-66 and 4. 3-67 show these effects for various
times and temperatures.   At +200 deg F, thermal relaxation seems to be marginal at being
stable, depending on the original percentage of stretch.   Little long-term relaxation can be
expected for material stretched 65 percent when subjected to +200 deg F, and more relaxation
can be expected of material stretched 70 percent under the same condition.   The +200 F seems
to be a marginal threshold temperature which can be sustained under operational conditions.
Temperatures above +200 F, but below +225 F, are in the warm-forming range.   Figure
4. 3-68 demonstrates the length of time required for normal relaxation at +225 F.   Consider-
ing that this temperature is a maximum within the warm-forming range, a short-term form-
ing cycle would have a slight dimensional effect on the final part.

4-64
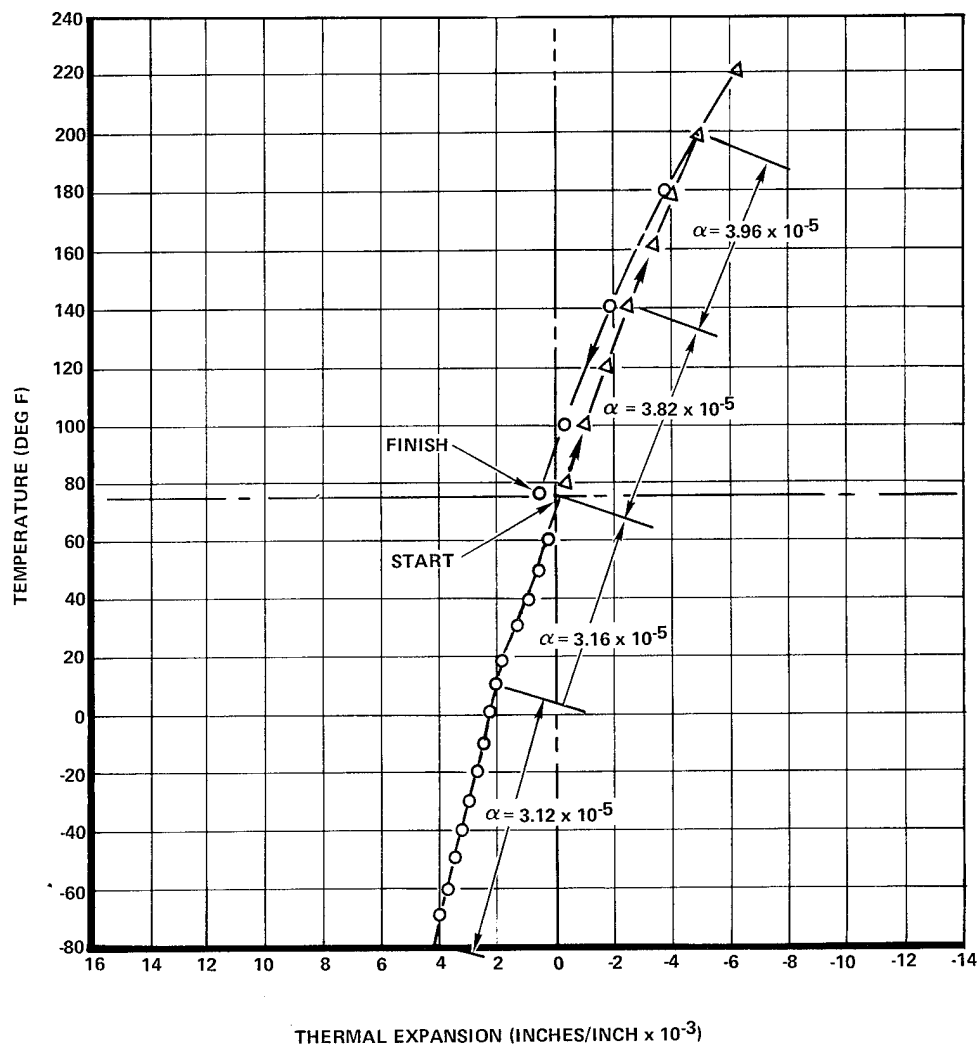
Figure 4.3-65 - Thermal Expansion versus Temperature for 0.250-Inch-Thick Stretched Acrylic

4-65
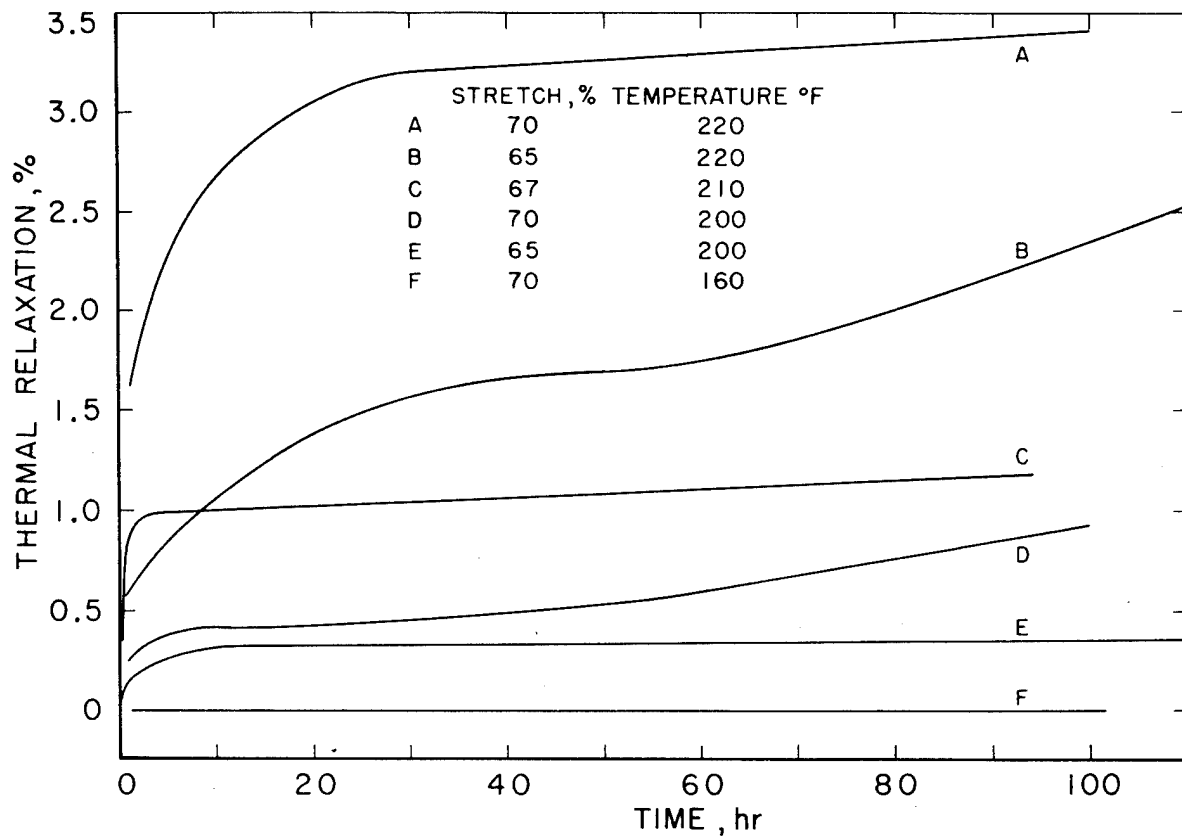
Figure 4. 3-66 – Effect of Duration of Exposure at Various Temperatures on the Thermal
Relaxation of 0. 350-Inch-Thick MIL-P-25690 Material
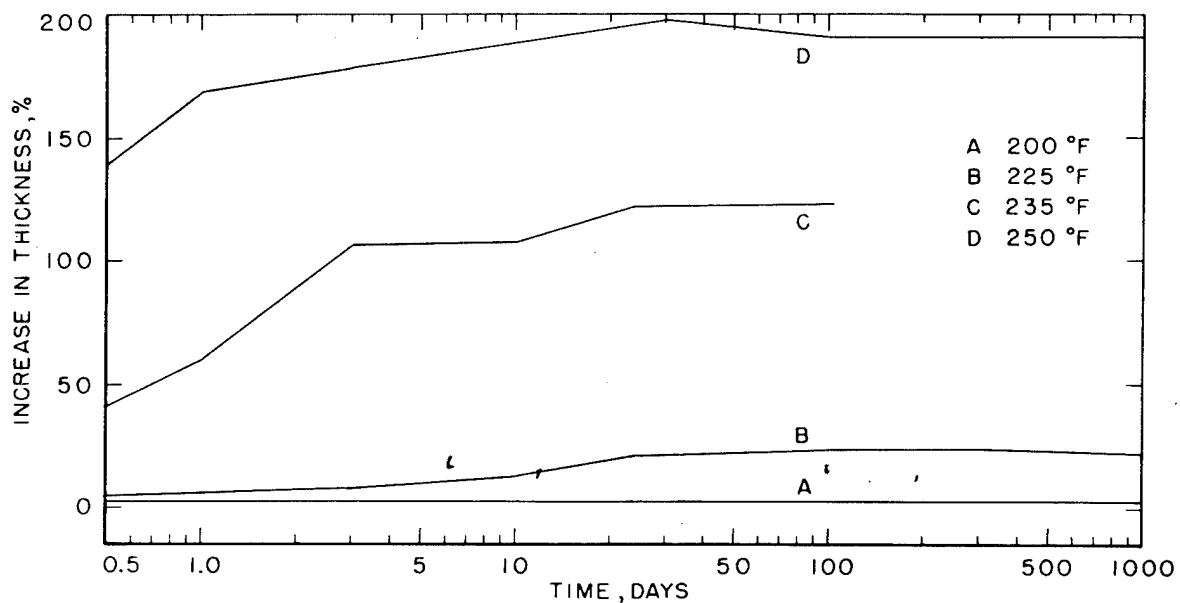
Figure 4. 3-67 – Effect of Duration of Exposure at Various Temperatures on the Increase in
Thickness due to Thermal Relaxation of 0. 125-Inch-Thick MIL-P-25690 Material
Stretched 75 Percent

4-66
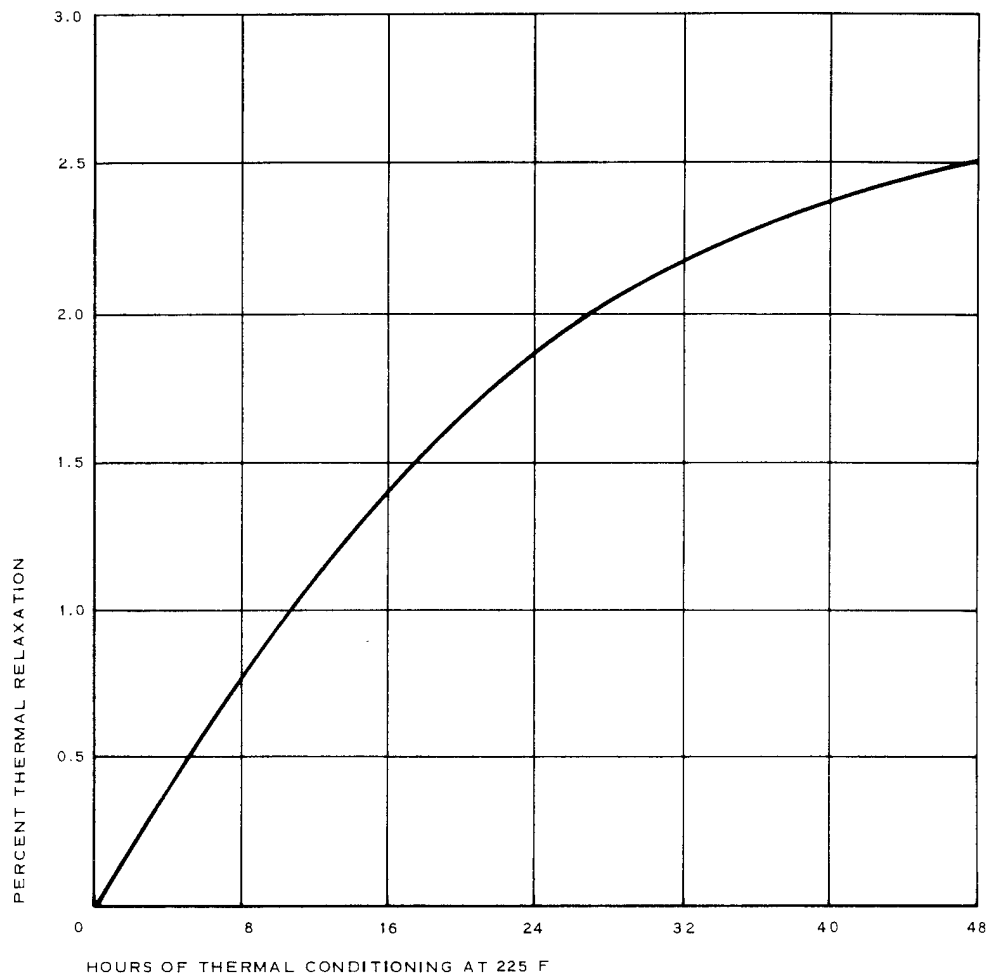
Figure 4. 3-68 – Thermal Relaxation as a Function of Time

4.3.5   MIL-P-83310

4.3.5.1   GENERAL

Polycarbonates for aircraft use are limited to the bisphenol "A" formulations which appear under the commercial designations of Lexan SL-2000-111[a] and Merlon M50U.[b] Because the forming temperature range for this thermoplastic is above +300 F, moisture absorption of the material can become a problem during part processing, as demonstrated in Figure 4.3-69.

The solution to this problem has been a predrying cycle at +260 ±5 deg F in accordance with the following schedule:

Thickness (Inch)	Drying Time (Hours)
0.125	4
0.250	18
0.375	29
0.500	46.5 .

Although some experimentation has taken place at this time in stretching polycarbonate, the data which follow concern unstretched material which has been "press polished" and in most cases annealed after machining according to the following schedule:

Thickness (Inch)	Annealing Time
0.125	45 minutes
0.250	1-1/2 hours
0.375	2-1/4 hours
0.500	3 hours .

---

[a]TM, General Electric Co., Pittsfield, Massachusetts.

[b]TM, Mobay Chemical Co., St. Louis, Missouri.

NOTE: DATA SUPPLIED BY MCDONNELL-DOUGLAS.
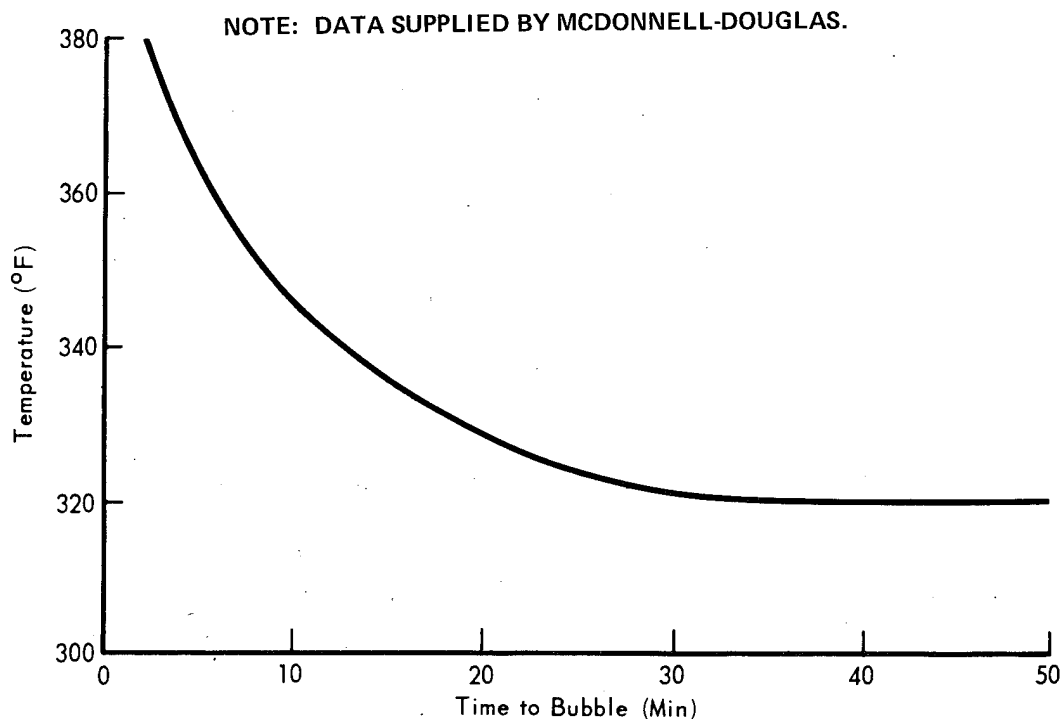
Figure 4.3-69 – Polycarbonate Time to Bubble versus Exposure Temperature
(Specimen Thickness 0.15 In.)

The press-polishing process is proprietary with firms who perform the service. In almost all aircraft applications the process is mandatory for good optical quality. The process further imposes temperatures above 300 F for some period of time, depending upon the material thickness. The result of the extensive thermal history, of which this is a part, is a noticeable degradation in several of the physical properties.

Although the material partially loses some of its properties through the combined processes of press-polishing, drying, forming, and annealing, it definitely retains its distinct advantage of having a higher deformation temperature under load than acrylics and is consequently a candidate for high-performance aircraft applications. Its toughness exceeds that of any of the other specified materials.

In a later chapter, abrasion resistant coatings are discussed. These are found to be necessary in most polycarbonate applications for surface protection. The data in this section concern only the basic material in a dried, polished, and annealed condition. Coating processes also add to the thermal history.

4.3.5.2 PROPERTIES

4.3.5.2.1 TENSILE DATA (CROSSHEAD RATE EFFECTS)

Crosshead rate effects are shown in Figures 4.3-70 and 4.3-71. The curves were charted during the tests through the use of an area compensating device in the testing machine. The portions of the curves beyond the yield points are therefore indicative of pattern relationships rather than quantitative data, which would account for a decrease in cross-sectional area of the test specimens. The near-constant 7500-PSI portion of the curves indicates that the load rate is constant and independent of crosshead rate. The failure patterns were predominantly ductile and dependent on crosshead rate (Reference 7).

The modulus curve of Figure 4.3-71 was of interest in that two different polycarbonate materials followed the same pattern. Two low points in the curves at 0.05 inch and 4.0 inches per minute appeared to be the best rates for testing on the basis of modulus. On the basis of toughness (area under the stress-strain curves), 2.0 inches per minute would be chosen.

4.3.5.2.2 TENSILE DATA (TEMPERATURE EFFECTS)

Figures 4.3-72, 4.3-73, and 4.3-74 show the effects of temperature on tensile properties. The stress-strain curves in Figure 4.3-72 were obtained from samples exposed to the extensive thermal history previously discussed for 1/4-inch material. The Figure 4.3-73 curve of tensile strength (based on the yield point) versus temperature was performed on samples which were exposed to normal test conditioning. At lower temperatures, the comparative yield strengths were close, but diverged at the higher temperatures, showing that the extensive thermal history has increased the tensile strengths toward that of a more brittle material. The modulus curves of Figure 4.3-74 represent the extensive thermally conditioned polycarbonate products of two manufacturers.
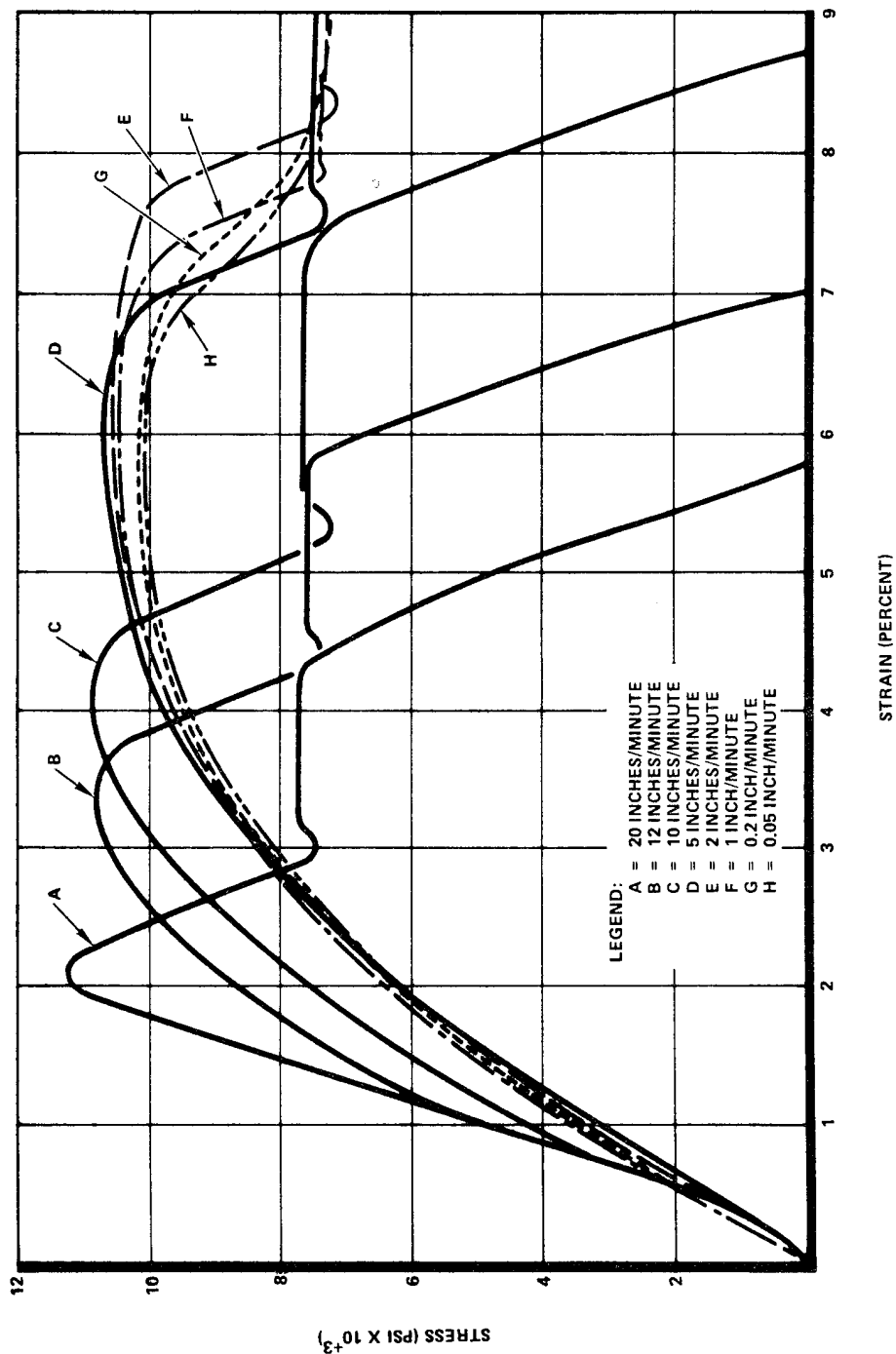
Figure 4.3-70 – Stress versus Strain for 1/4-Inch-Thick MIL-P-83310 Material at
Room Temperature after Thermal Conditioning

4-71
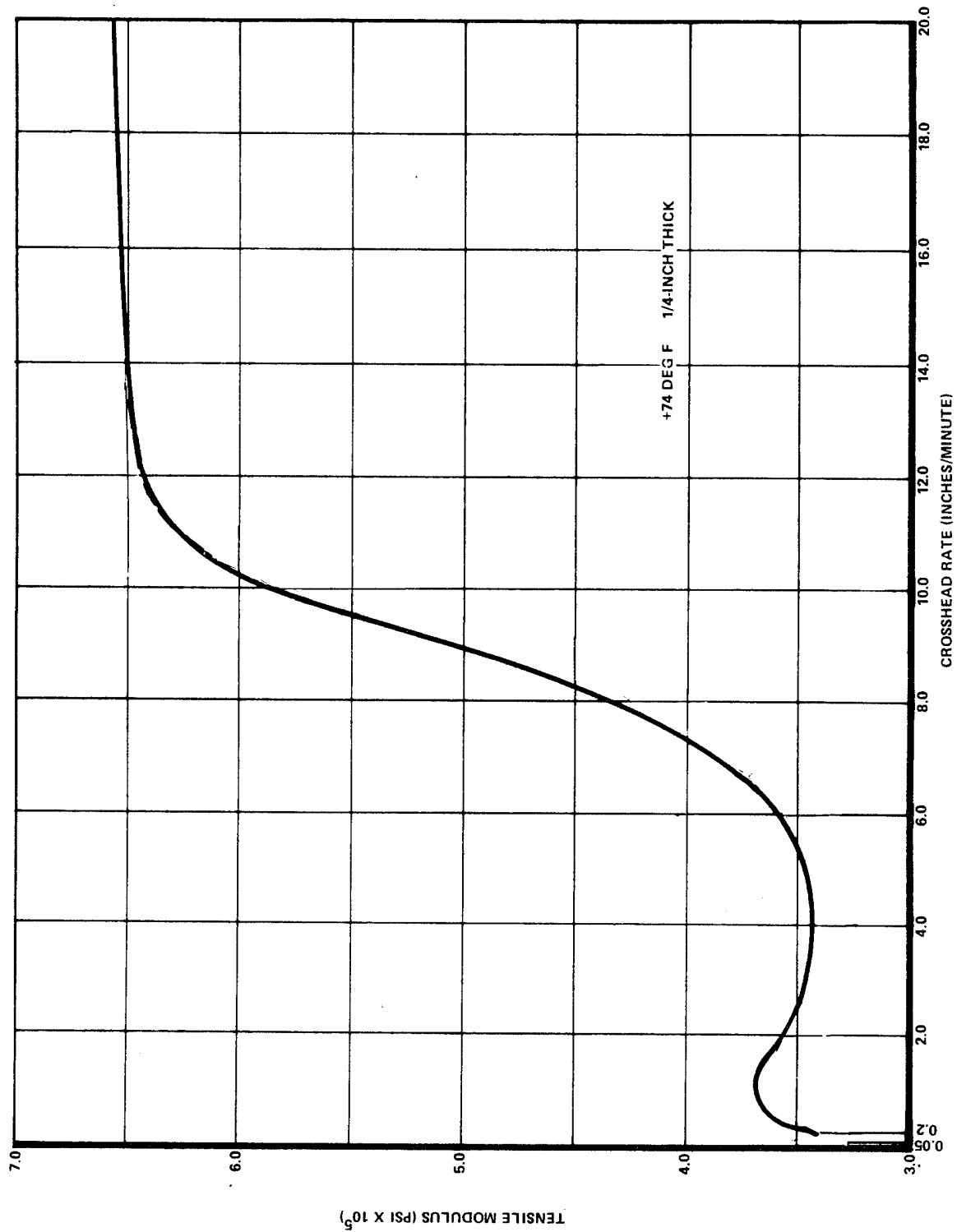
Figure 4. 3-71 – Tensile Modulus versus Crosshead Rate for MIL–P–83310 Material
after Thermal Conditioning
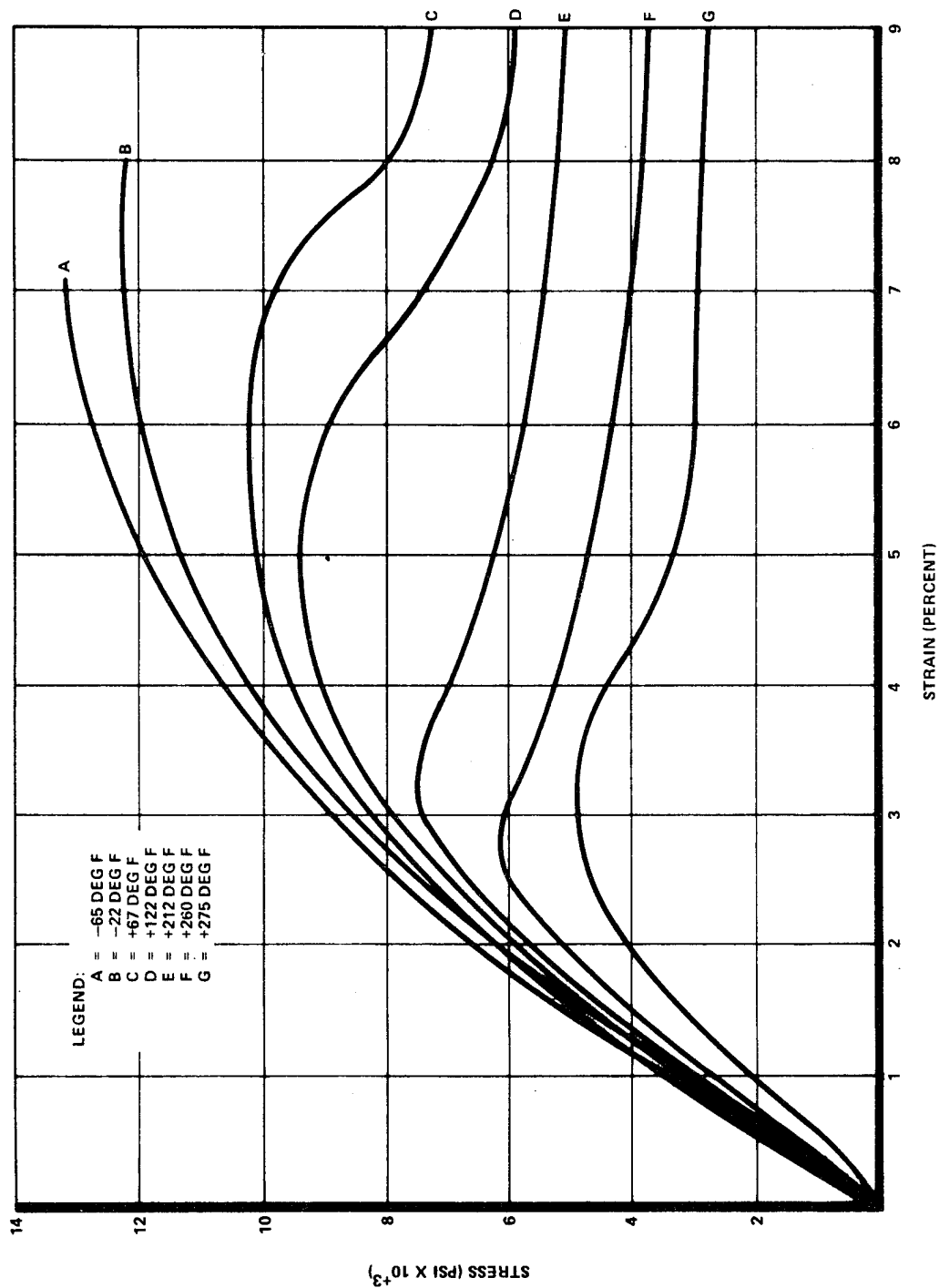
Figure 4.3-72 - Stress versus Strain (Tensile) for 1/4-Inch-Thick MIL-P-83310 Material - after Thermal Conditioning - Crosshead Rate 0.2 Inch/Minute

4-73

NOTE: DATA SUPPLIED BY NORTH AMERICAN ROCKWELL.
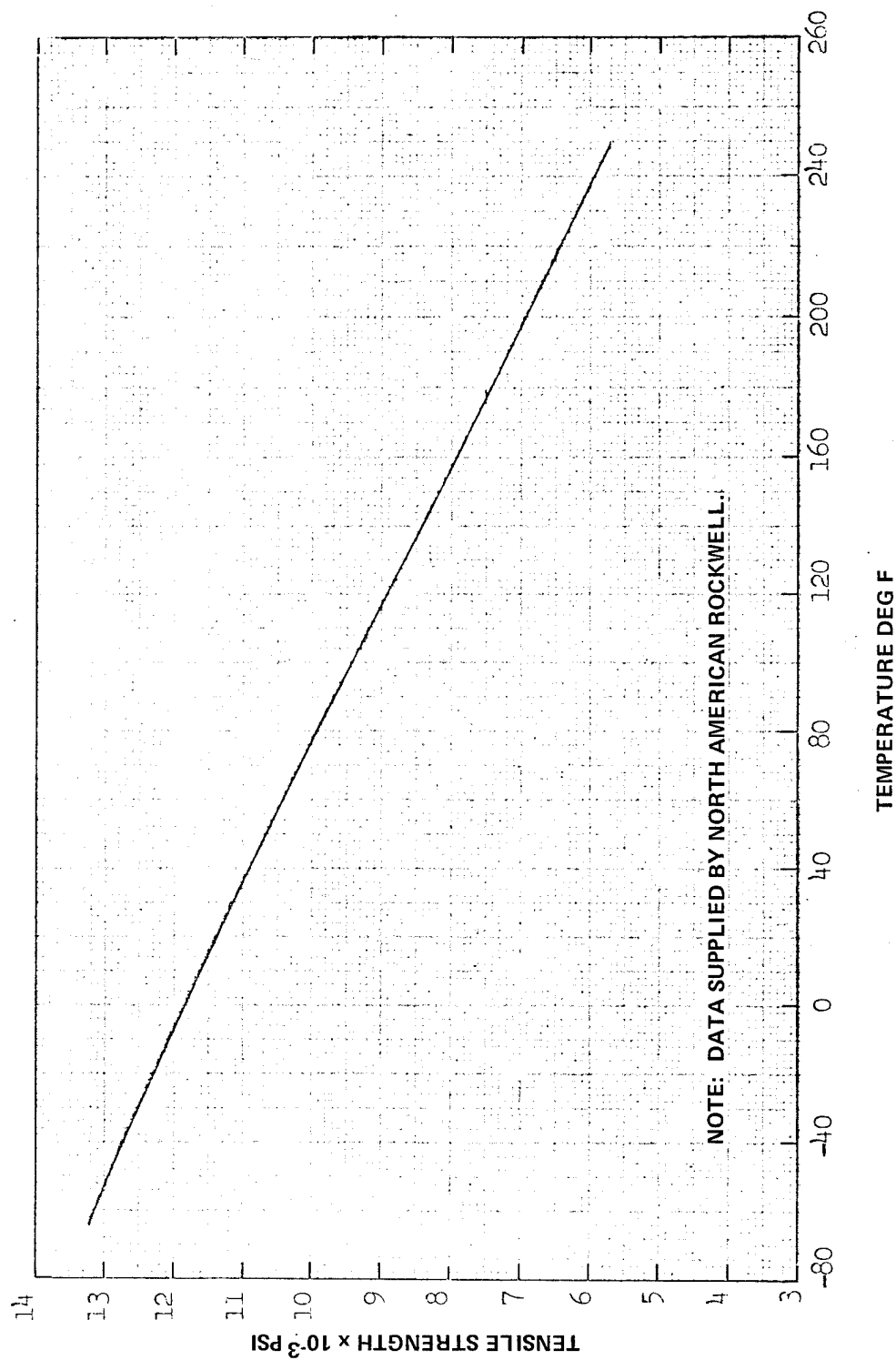
Figure 4.3-73 – Tensile Strength versus Temperature of MIL–P–83310 Material

4-74
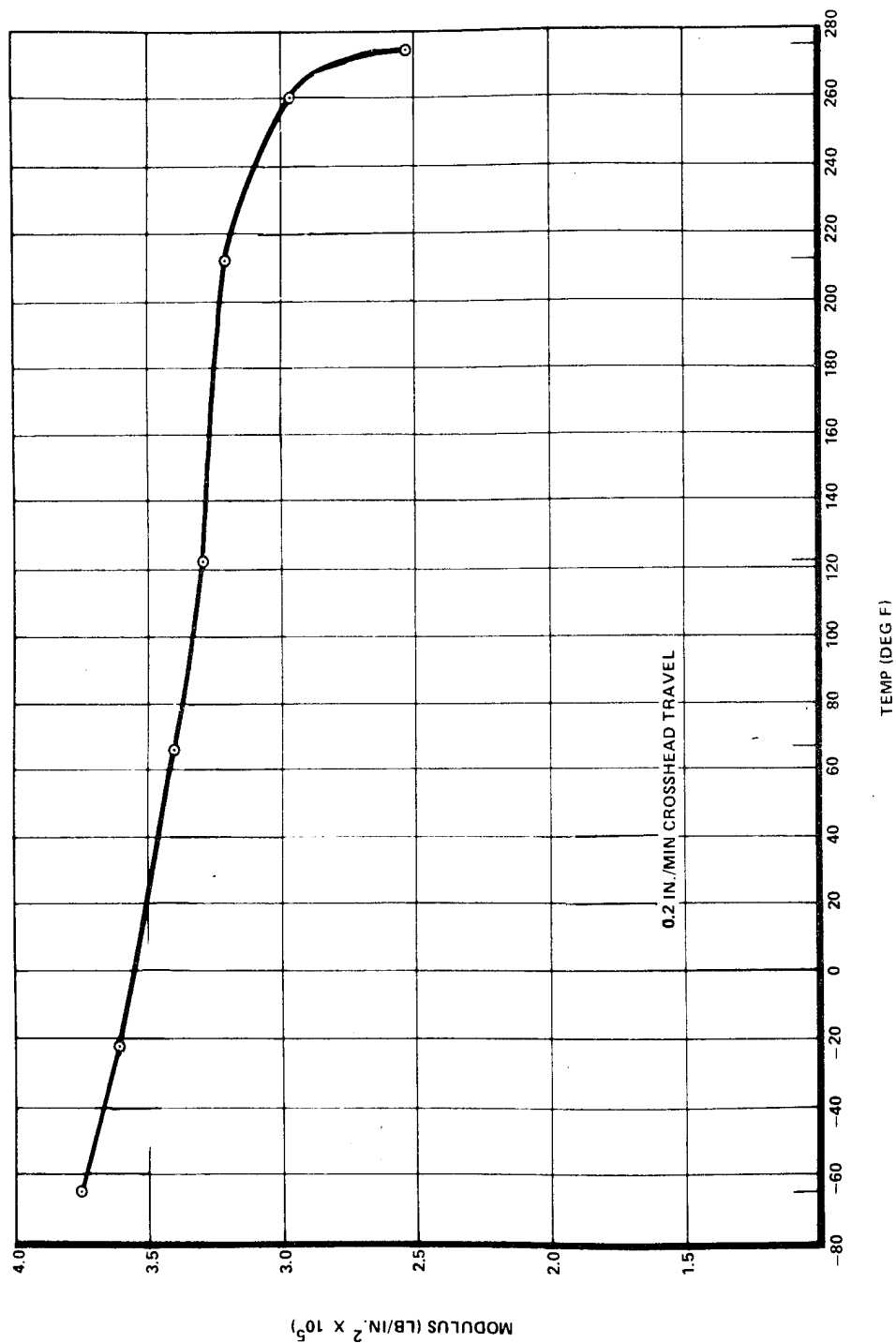
Figure 4.3-74 – Tensile Elastic Modulus versus Temperature for MIL-P-83310
Material after Thermal Conditioning

4.3.5.2.3   TENSILE DATA (CREEP EFFECTS)

Ranges of creep data at room temperature are shown in Figure 4.3-75 based on the extensive thermally conditioned samples from two suppliers. A total of four samples for each loáding were run. The Figure 4.3-76, 4.3-77, and 4.3-78 curves are cyclic creep data performed at three different temperature cycles at a 2600-PSI loading.

4.3.5.2.4   COMPRESSION DATA

Compression strength versus temperature data on material normally conditioned for testing are found in Figure 4.3-79.

4.3.5.2.5   FLEXURAL DATA

The curves of Figures 4.3-80 through 4.3-83 represent four thicknesses of material extensively conditioned thermally and tested at the crosshead rate prescribed by FTMS 406, Method 1031, Procedure B, which is the higher than normal testing speed, and at three temperatures. The data shown in Figure 4.3-84 give flexural strengths at five-percent strain and modulus throughout the operational temperature range. Figure 4.3-85 compares the effect of notching throughout the same temperature range on two competitive polycarbonate products.

4.3.5.2.6   BEARING DATA

Bearing strength versus temperature for normally conditioned polycarbonate is found in Figure 4.3-86. Room temperature data of material which was previously exposed to extensive thermal conditioning shows a higher bearing strength of between 8400 PSI and 8600 PSI for an edge distance ratio of 3.0.

4.3.5.2.7   SHEAR DATA

The shear data (see Figure 4.3-87) obtained perpendicular to the surface of 1/8-inch-thick specimens with a Johnson Shear tool. The material had been extensively preconditioned with the addition of six months' weathering on half of the samples. No appreciable difference was noted for this amount of weathering.
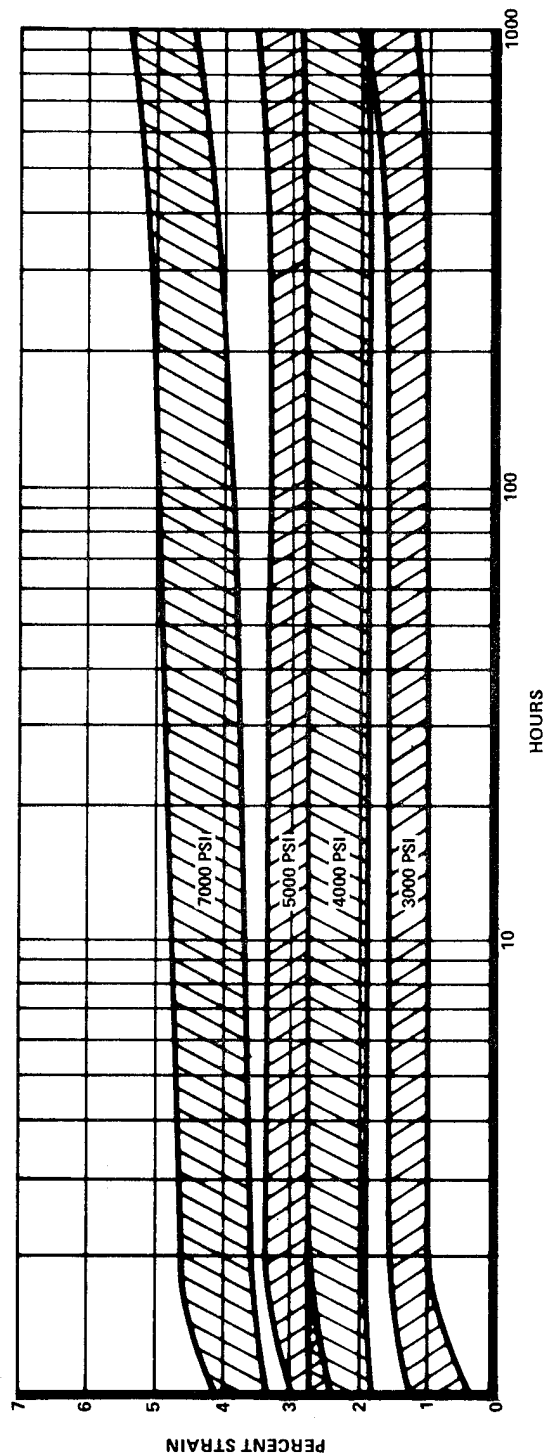
Figure 4. 3-75 – Typical Tensile Creep Curves of MIL-P-83310 Material at
Room Temperature after Thermal Conditioning

4-77
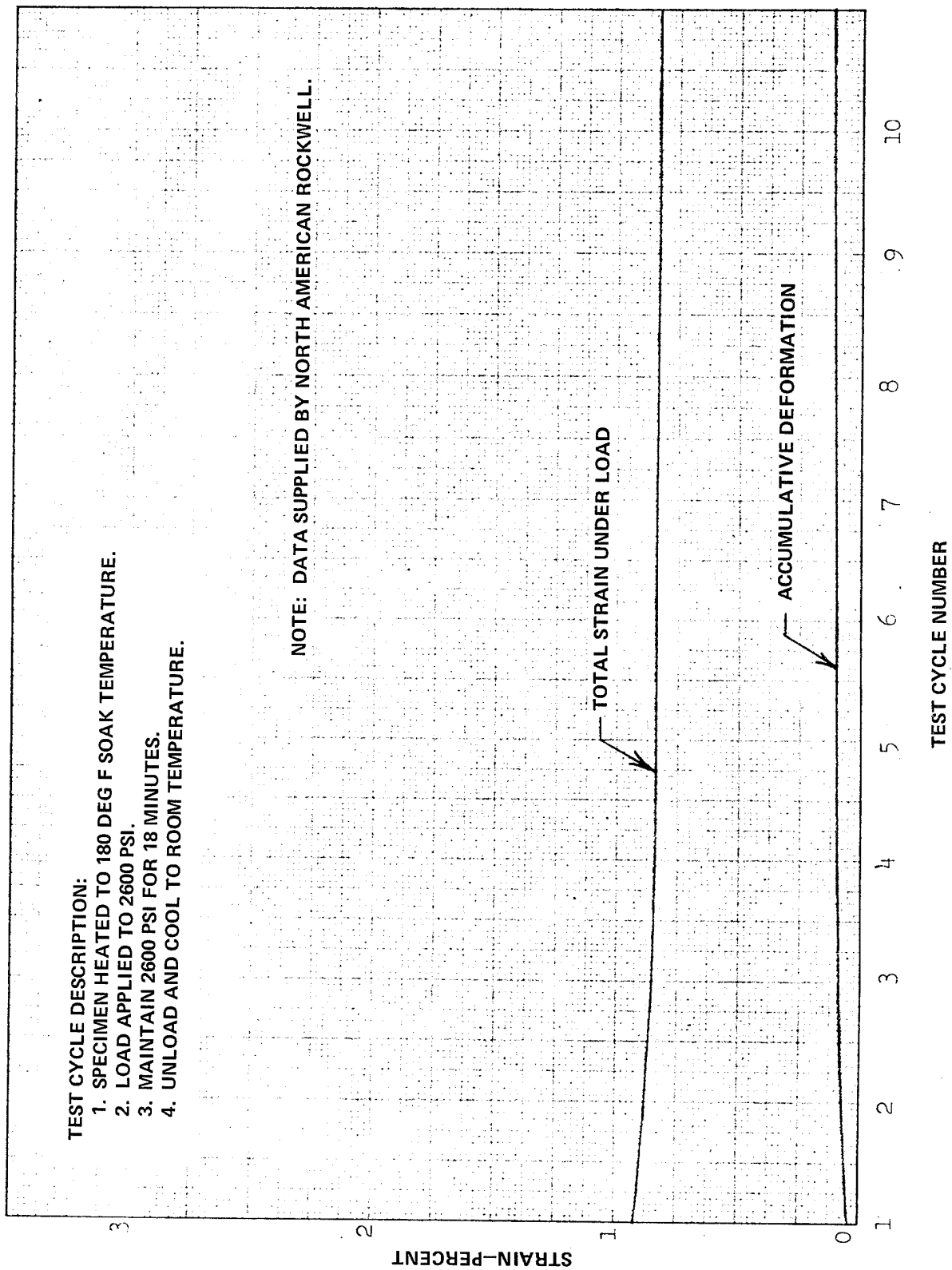
Figure 4.3-76 – Cyclic Creep Properties of MIL-P-83310 Material at 180 Deg F
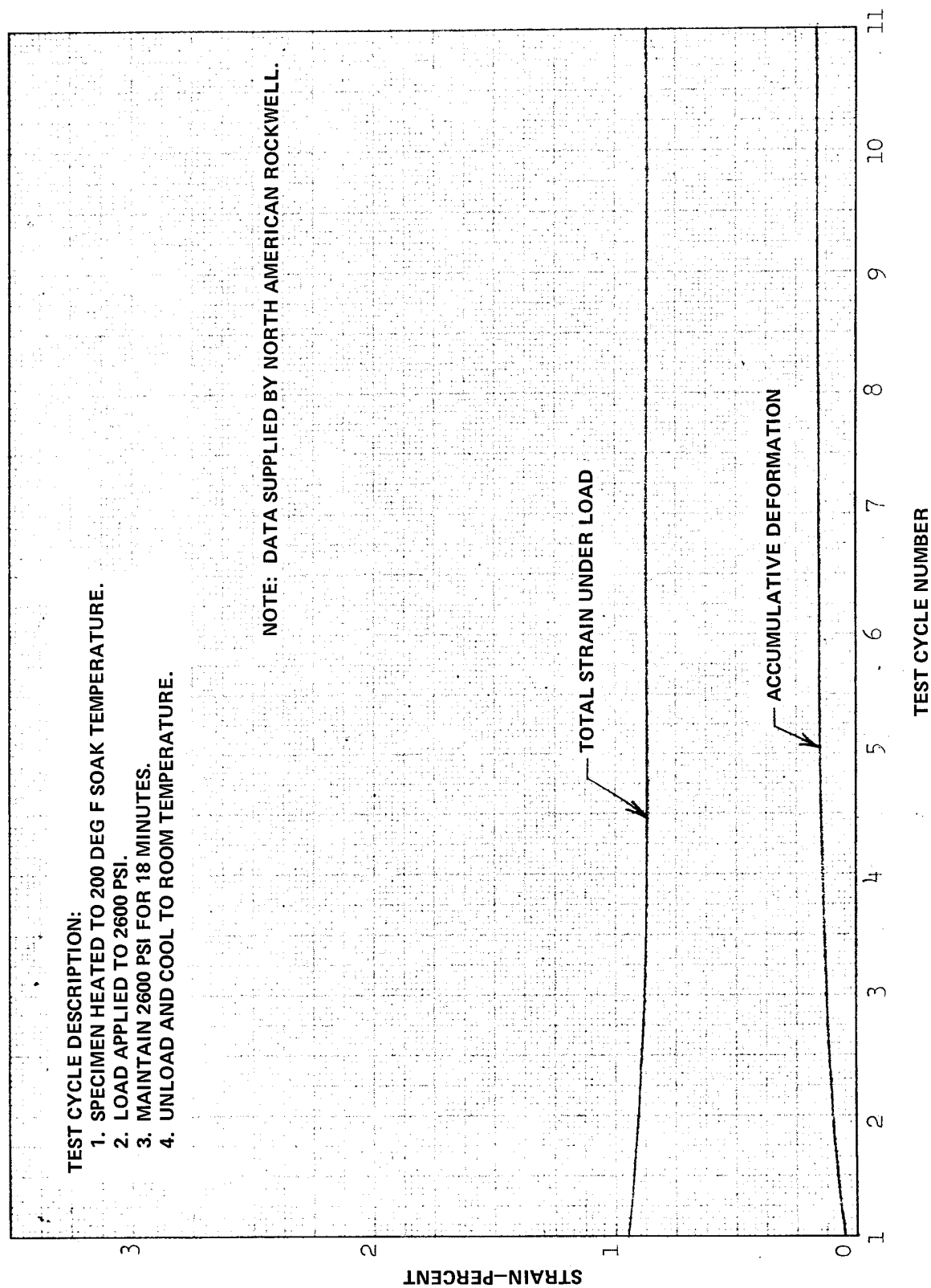
Figure 4.3-77 – Cyclic Creep Properties of MIL-P-83310 Material at 200 Deg F

TEST CYCLE DESCRIPTION:
1. SPECIMEN HEATED TO 220 DEG F SOAK TEMPERATURE.
2. LOAD TO 2600 PSI.
3. MAINTAIN 2600 PSI FOR 18 MINUTES.
4. UNLOAD AND COOL TO ROOM TEMPERATURE.

NOTE: DATA SUPPLIED BY NORTH AMERICAN ROCKWELL.

TOTAL STRAIN UNDER LOAD

ACCUMULATIVE DEFORMATION

TEST CYCLE NUMBER

STRAIN—PERCENT
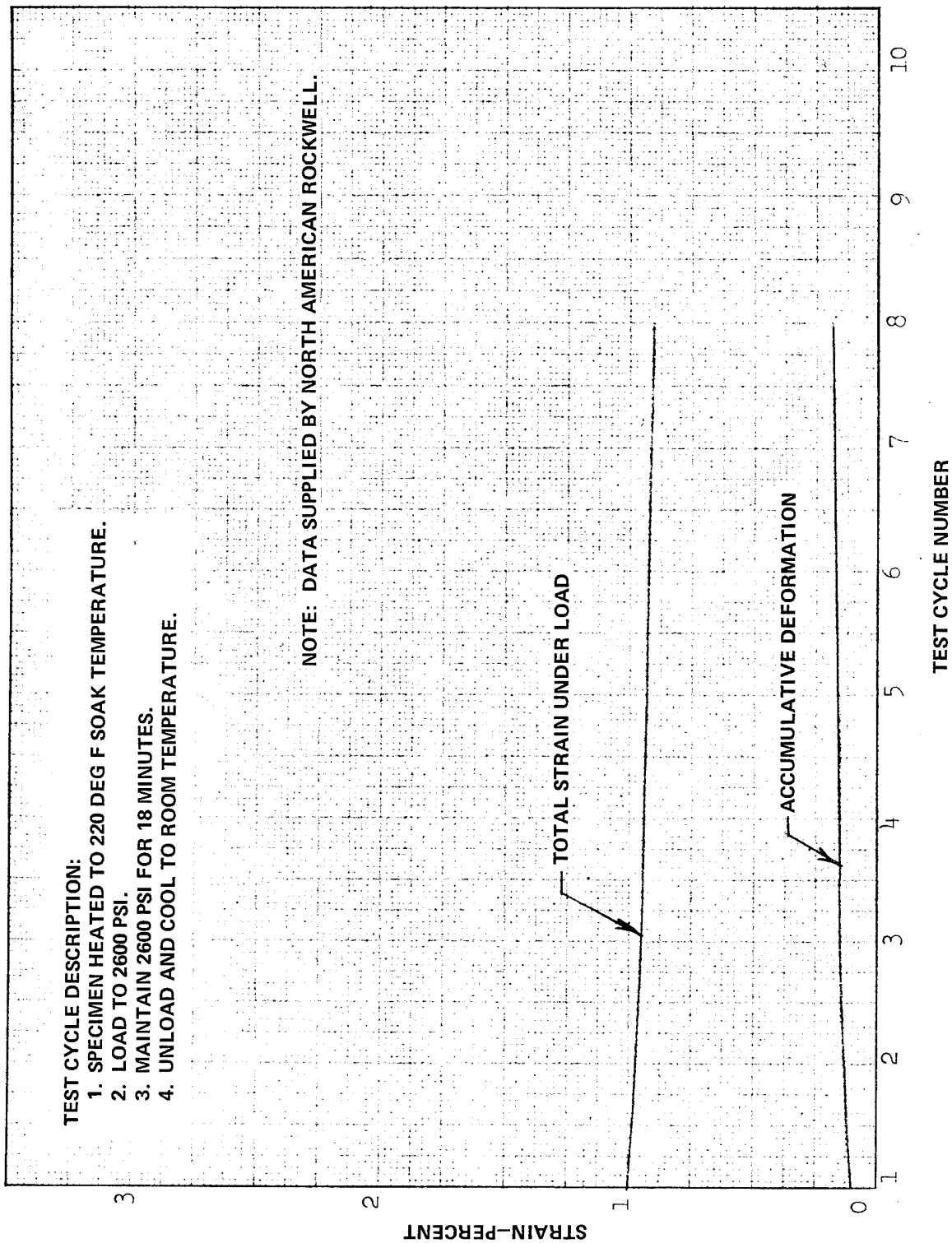
Figure 4. 3-78 – Cyclic Creep Properties of MIL-P-83310 Material at 220 Deg F

4-80
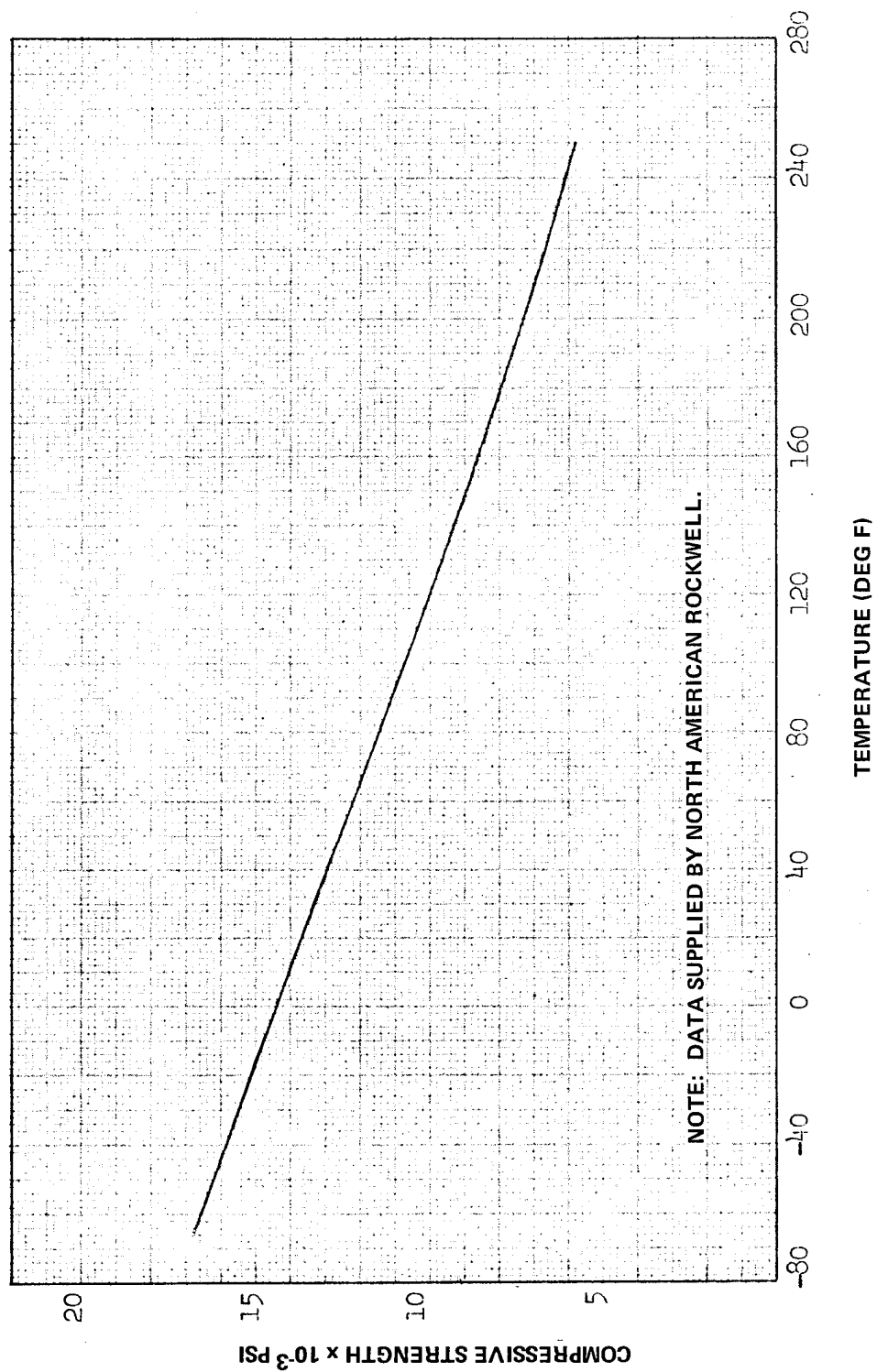
Figure 4.3-79 – Compressive Strength versus Temperature of MIL-P-83310 Material

4-81
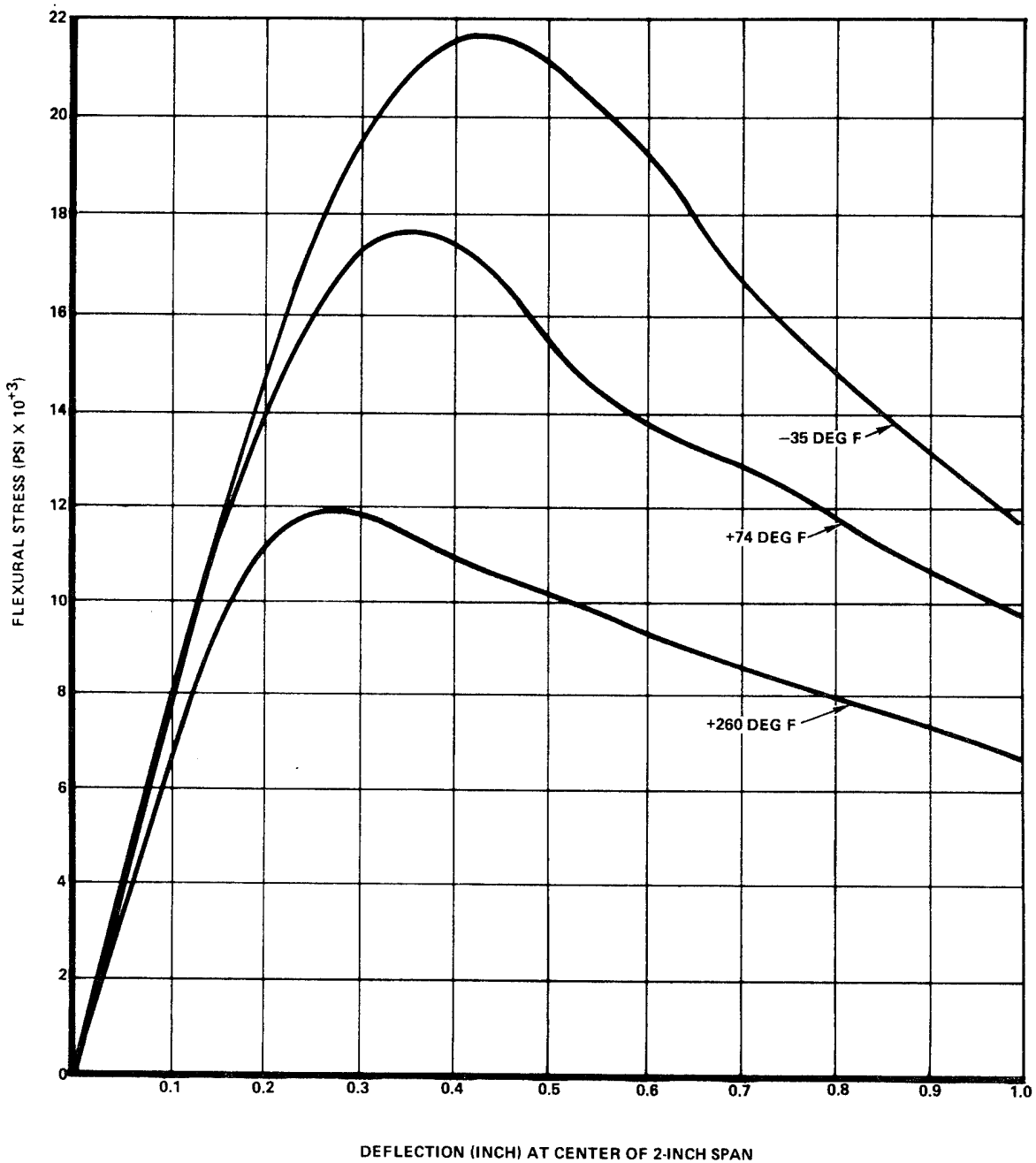
Figure 4.3-80 – Flexure; Unnotched; 1/8-Inch Thick MIL-P-83310 Material
after Thermal Conditioning
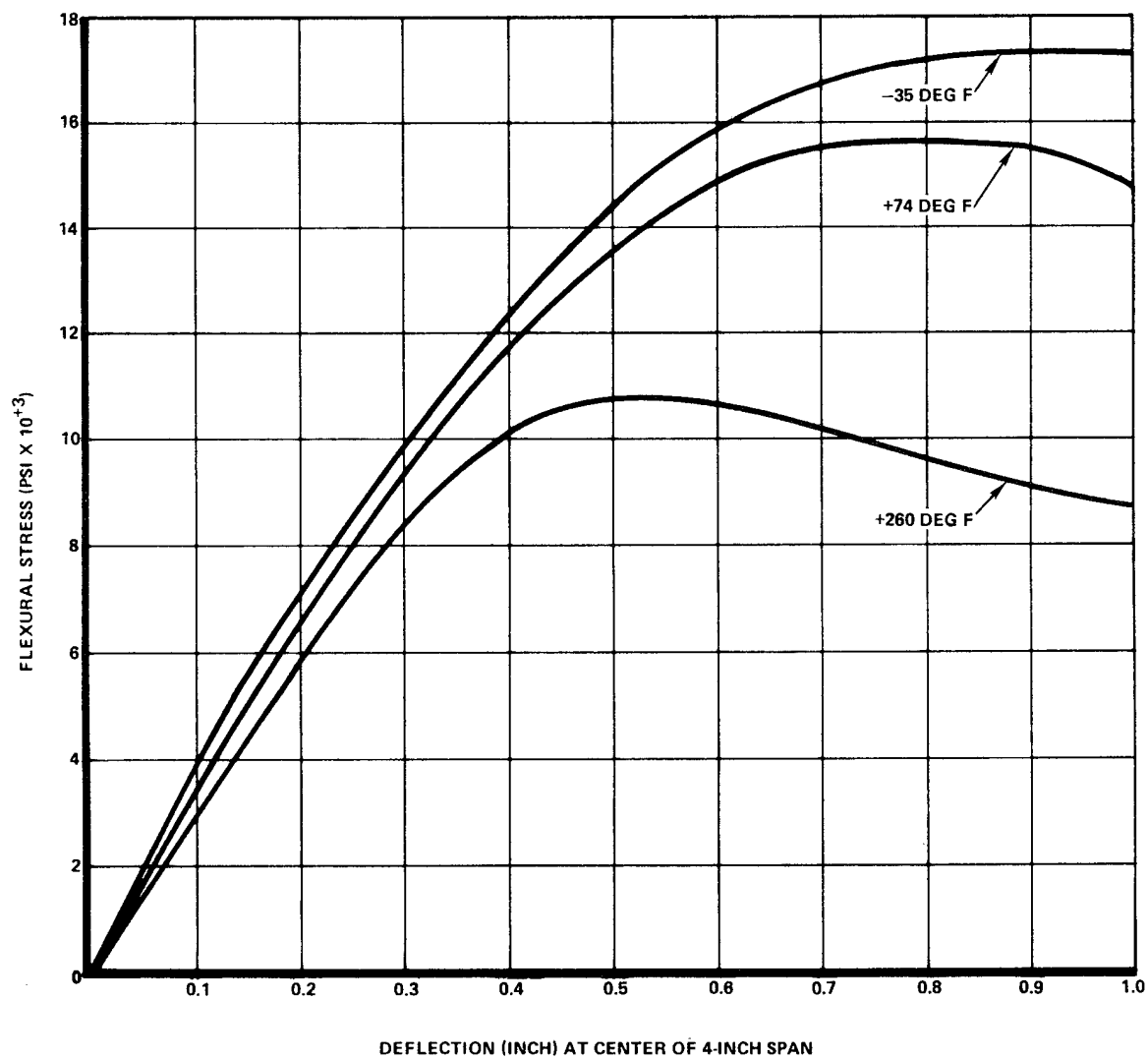
Figure 4.3-81 – Flexure; Unnotched; 1/4-Inch Thick MIL-P-83310 Material
after Thermal Conditioning
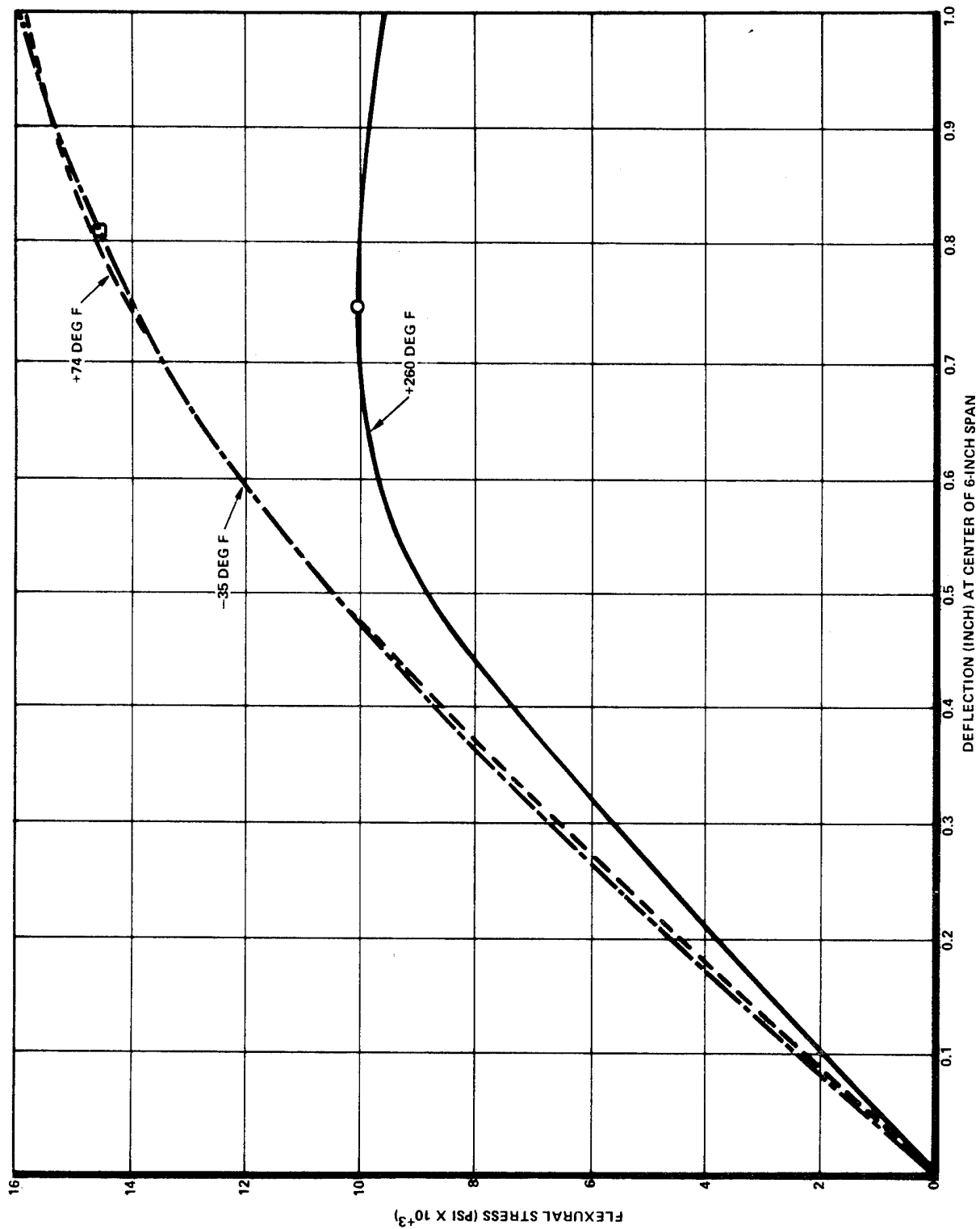
Figure 4.3-82 – Flexure; Unnotched; 3/8-Inch Thick MIL-P-83310 Material
after Thermal Conditioning

4-84
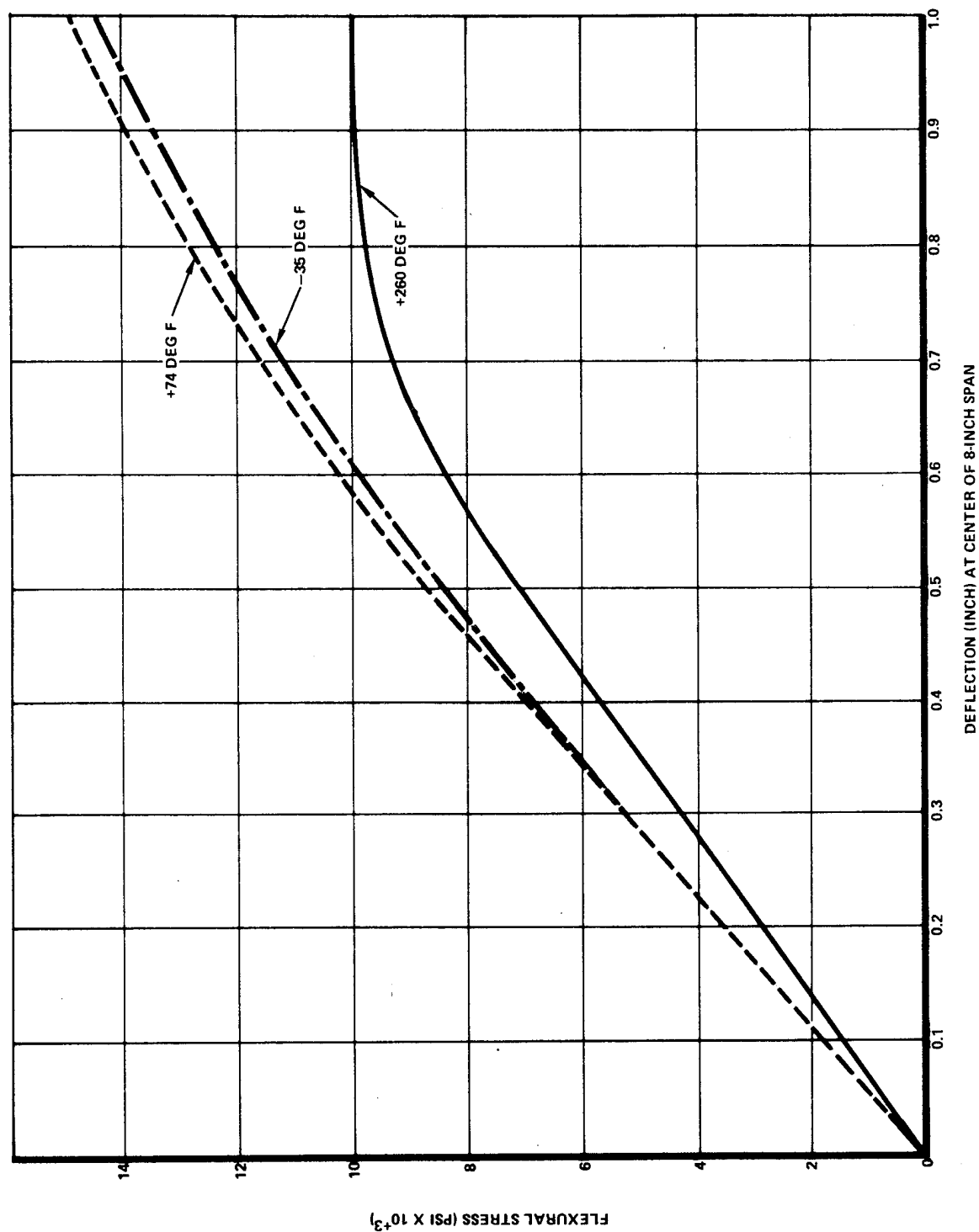
Figure 4.3-83 – Flexure; Unnotched; 1/2-Inch Thick MIL-P-83310 Material
after Thermal Conditioning

4-85
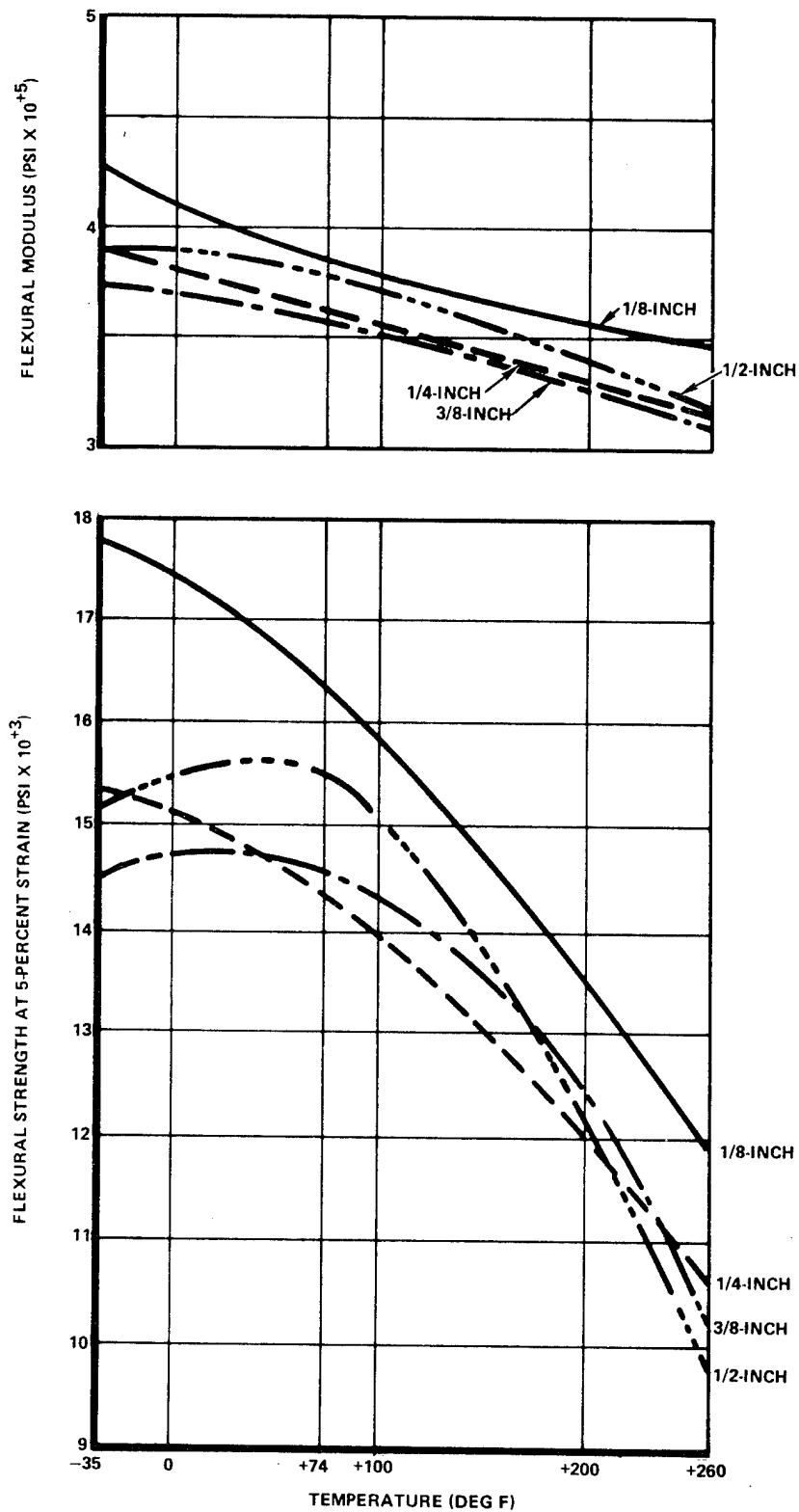
Figure 4.3-84 – Unnotched; Flexural Tests; Four Thicknesses; MIL–P–83310 Material after Thermal Conditioning

4-86
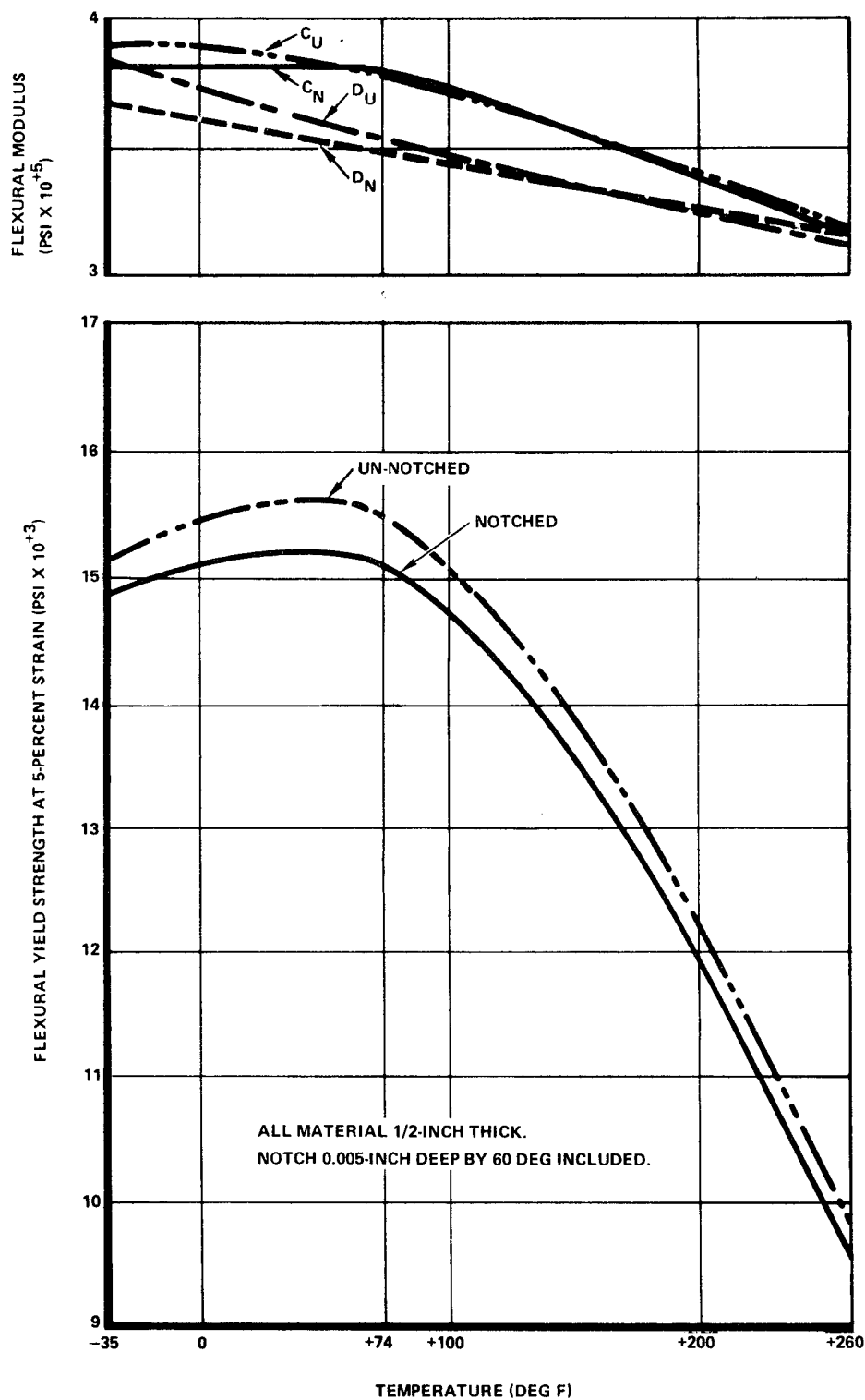
Figure 4.3-85 – Comparative Flexural Tests; Notched and Unnotched
MIL-P-83310 Material after Thermal Conditioning

4-87
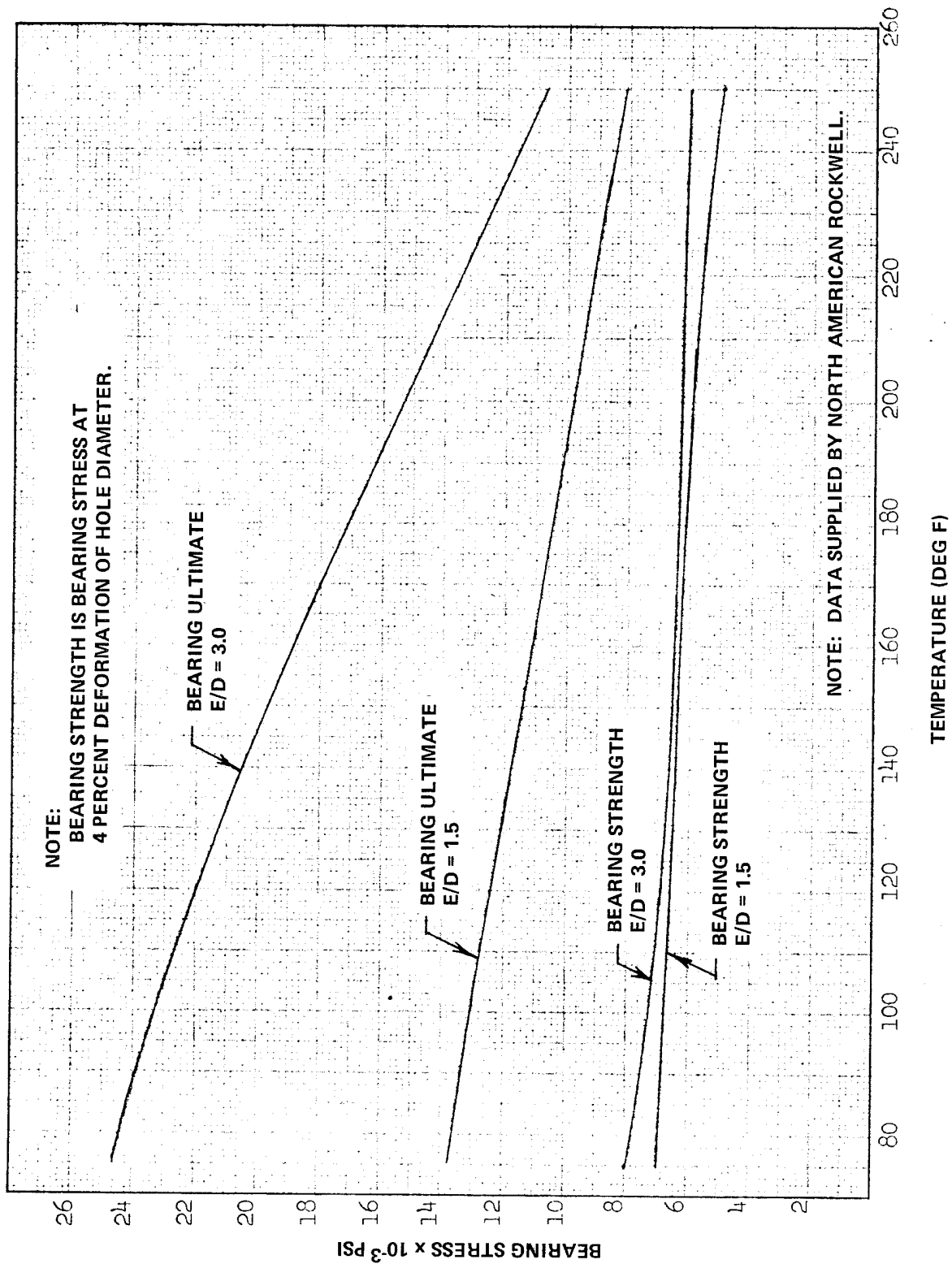
Figure 4.3-86 – Bearing Strength versus Temperature of MIL-P-83310 Material

4-88
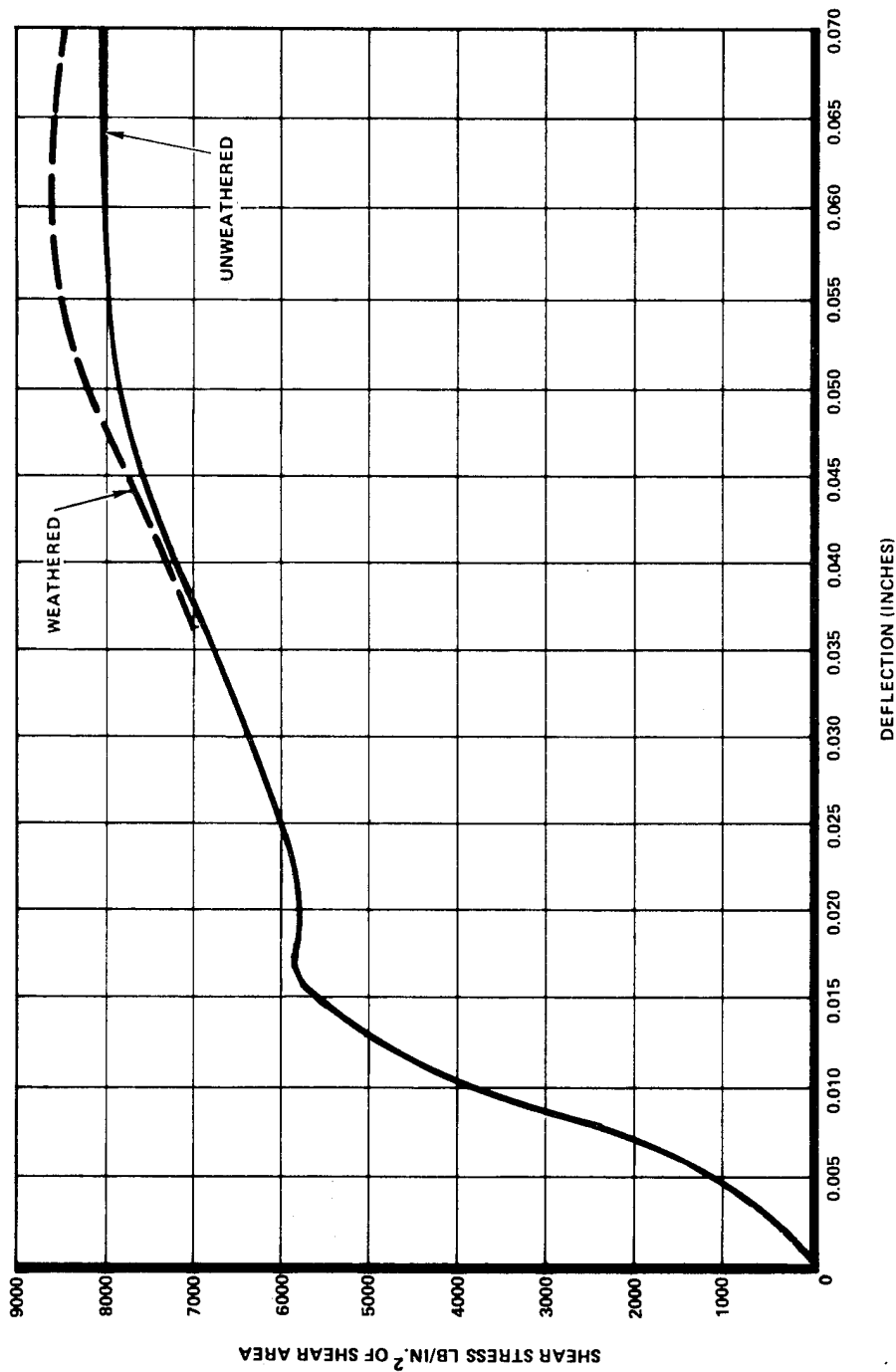
Figure 4. 3-87 – Double Shear; Typical Curves for 1/8-Inch-Thick (+74 Deg F)
MIL-P-83310 Material after Thermal Conditioning

4-89

4.3.5.2.8 IMPACT DATA

The notched Izod impact curves of Figure 4.3-88 and 4.3-89 are for extensively precon-
ditioned material of various thicknesses and at test temperatures. All samples were tested
edgewise. The relatively low energies required to fracture compared to the values of un-
conditioned material of approximately 17 ft-lb/in. of notch on 1/8-inch material are
attributed to degradation caused by the thermal preconditioning.

4.3.5.2.9 COEFFICIENT OF THERMAL EXPANSION

The thermal expansion versus temperature curve for normally conditioned material is found
in Figure 4.3-90.

4.3.5.2.10 LIGHT TRANSMISSION AND HAZE DATA

Light transmission and haze data are provided for materials from two manufacturers.
Samples had been extensively preconditioned. The "D" material is representative of un-
acceptable stock caused by inclusions, bubbles, and other foreign imperfections. Curves
are found as functions of thickness in Figure 4.3-91.

4.3.6 MIL-P-8257

4.3.6.1 GENERAL

Originally this thermosetting polyester was in competition with the acrylics, to some extent,
as a more abrasion resistant and chemically resistant monolithic material. The thermo-
plastic materials, however, eventually relegated the polyester as a notch-sensitive material
to a secondary role in glazings as a possible substrate for coatings.

4.3.6.2 PROPERTIES

The tensile stress-strain, stress rupture, crack propagation resistance versus temperature,
and coefficient of thermal expansion versus temperature curves are found in Figures 4.2-1,
4.2-3, 4.2-4, 4.2-5, and 4.2-6 on pages 4-4 and 4-6 through 4-8. Crack propagation
resistance, Figure 4.2-8; and coefficient of thermal expansion, Figure 4.2-10, are found on
pages 4-10 and 4-12. MIL-P-8257 curves not found in the comparative data section 4.2 are
in this section.
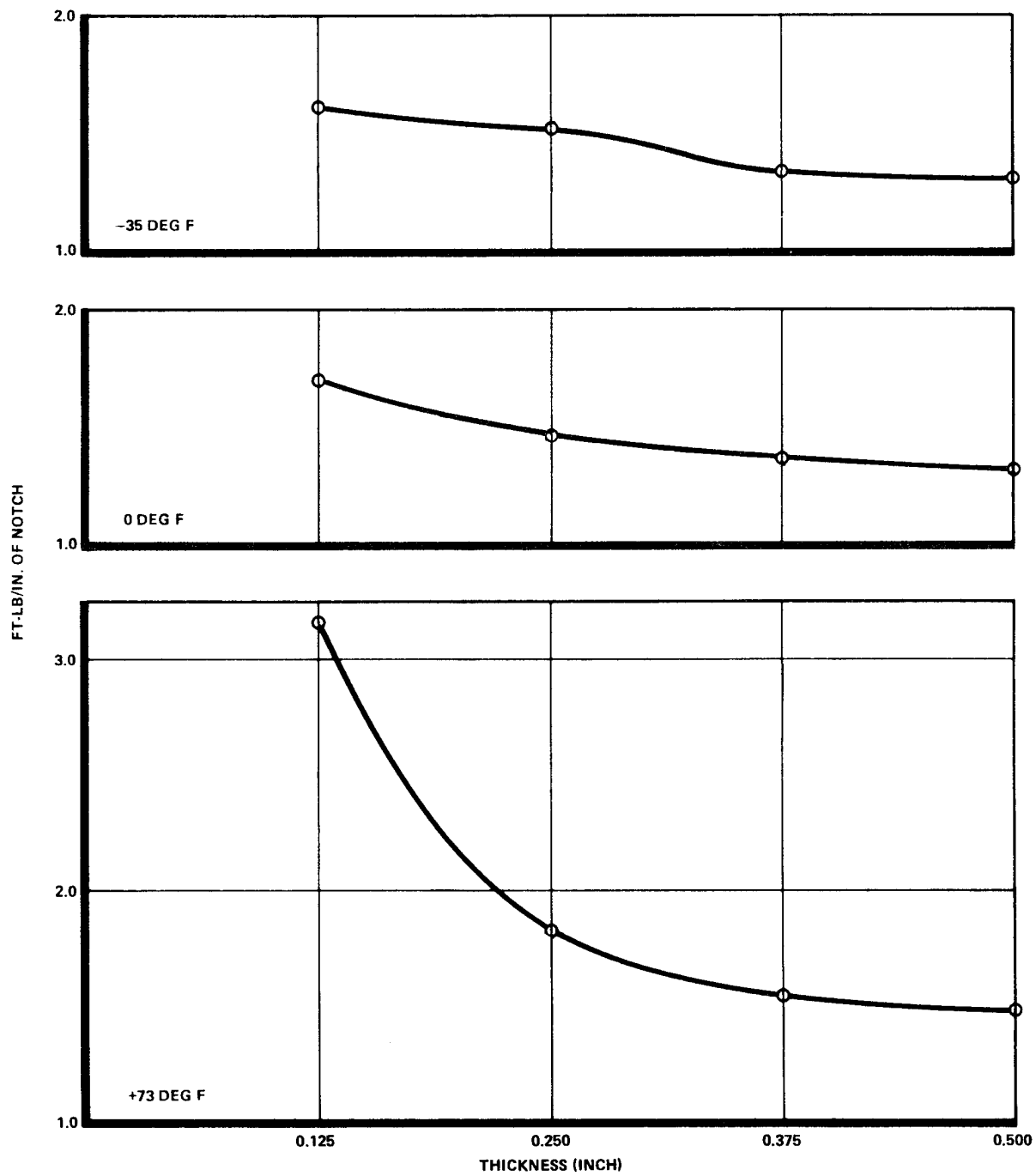
Figure 4.3-88 – Izod Impact Curves for MIL-P-83310 Material after Thermal Conditioning
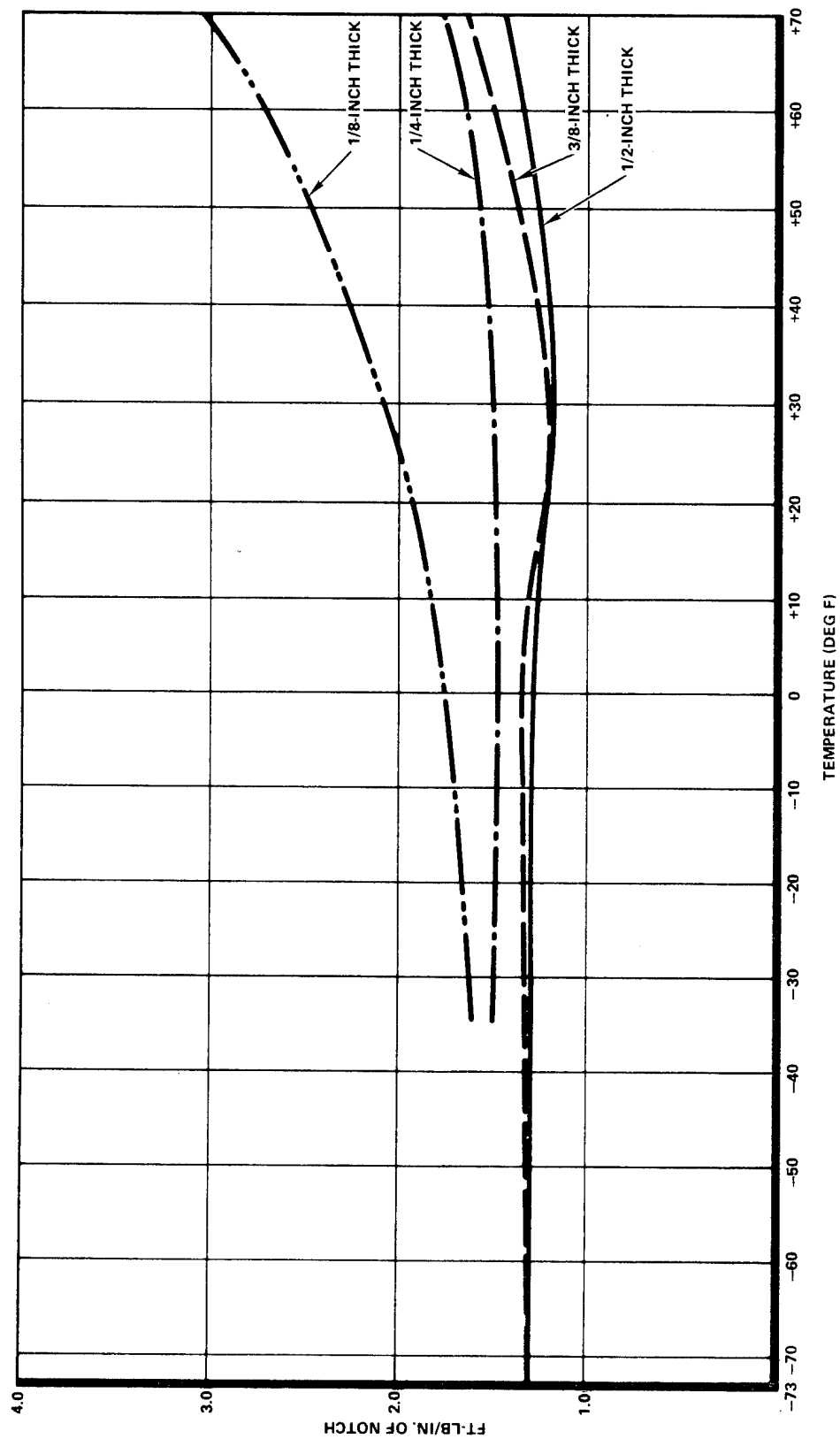
Figure 4.3-89 – Izod Impact Tests for MIL-P-83310 Material after Thermal Conditioning

THERMAL EXPANSION COEFFICIENT = $3.47 (10)^{-5}$
SPECIMEN LENGTH = 4.004 INCHES

TEST PERFORMED AND CALCULATED PER
FEDERAL TEST METHOD STD. N O. 406,
METHOD 2031

TEMPERATURE (F)

THERMAL EXPANSION (INCHES X 10^{-3})
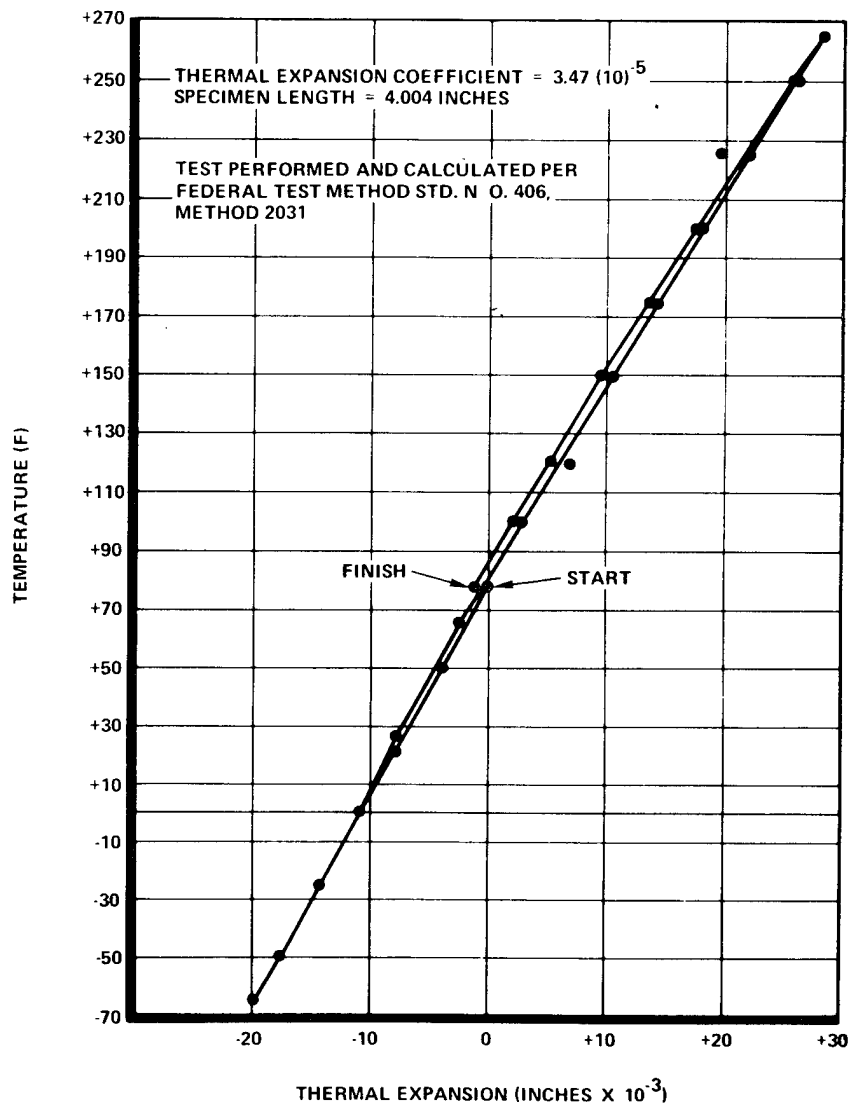
Figure 4. 3-90 – Thermal Expansion Data for Lexan Polycarbonate, Type 9030-111

4-93
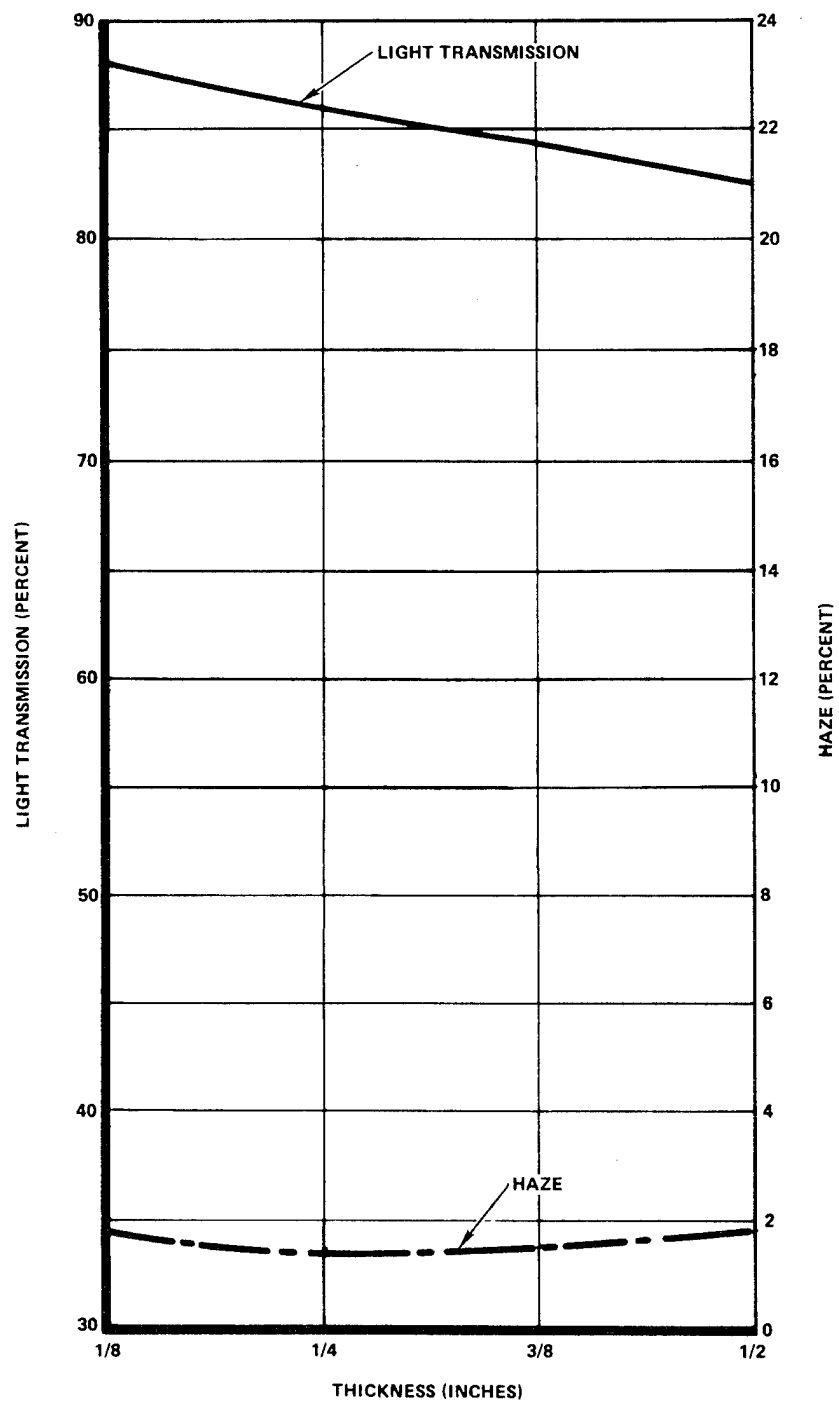
Figure 4.3-91 – Light Transmission and Haze before Weathering of MIL-P-83310 Material after Thermal Conditioning

4.3.6.2.1   TENSILE DATA

The effect of temperature on tensile properties is found in Figure 4.3-92.   The Figure
4.3-93 curve shows the effect of thickness.   Tensile creep data are shown in the Figure
4.3-94 through 4.3-98 curves.   The Figure 4.3-99 curve demonstrates the effects of cyclic
stress temperature conditions. Table 4.3-IV tabulates conditions for fracture in terms of
time during creep tests in which a thermal gradient was maintained.

4.3.6.2.2   FLEXURAL PROPERTIES

Flexural strength, curves, notched and unnotched, with the modulus, are found in Figure
4.3-100.   Flexural creep curves of notched and unnotched material are found in Figure
4.3-101.   Sheet thickness effect on notched and unnotched material are plotted against the
flexural strength and Izod impact strength in the Figure 4.3-102 and 4-3-103 curves.
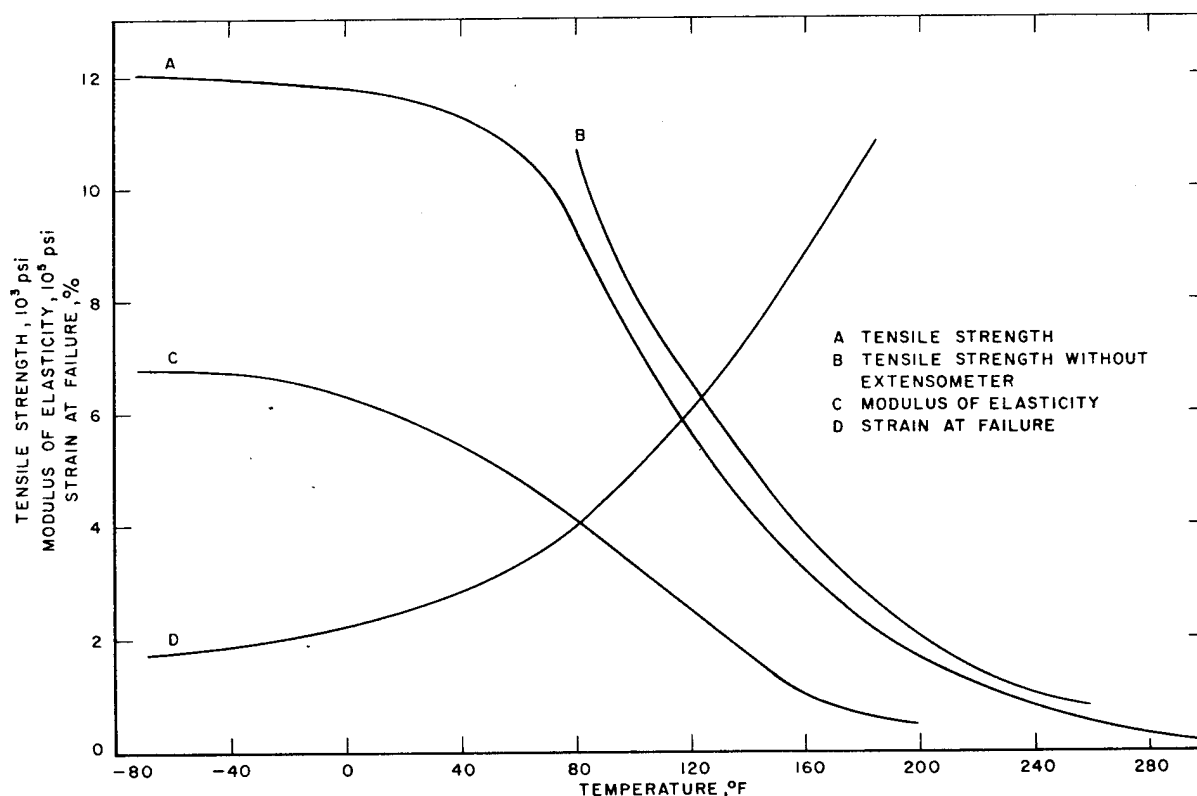
Figure 4.3-92 – Effect of Temperature on Tensile Properties (Short–Time Test)
of MIL–P–8257 Material

4-95
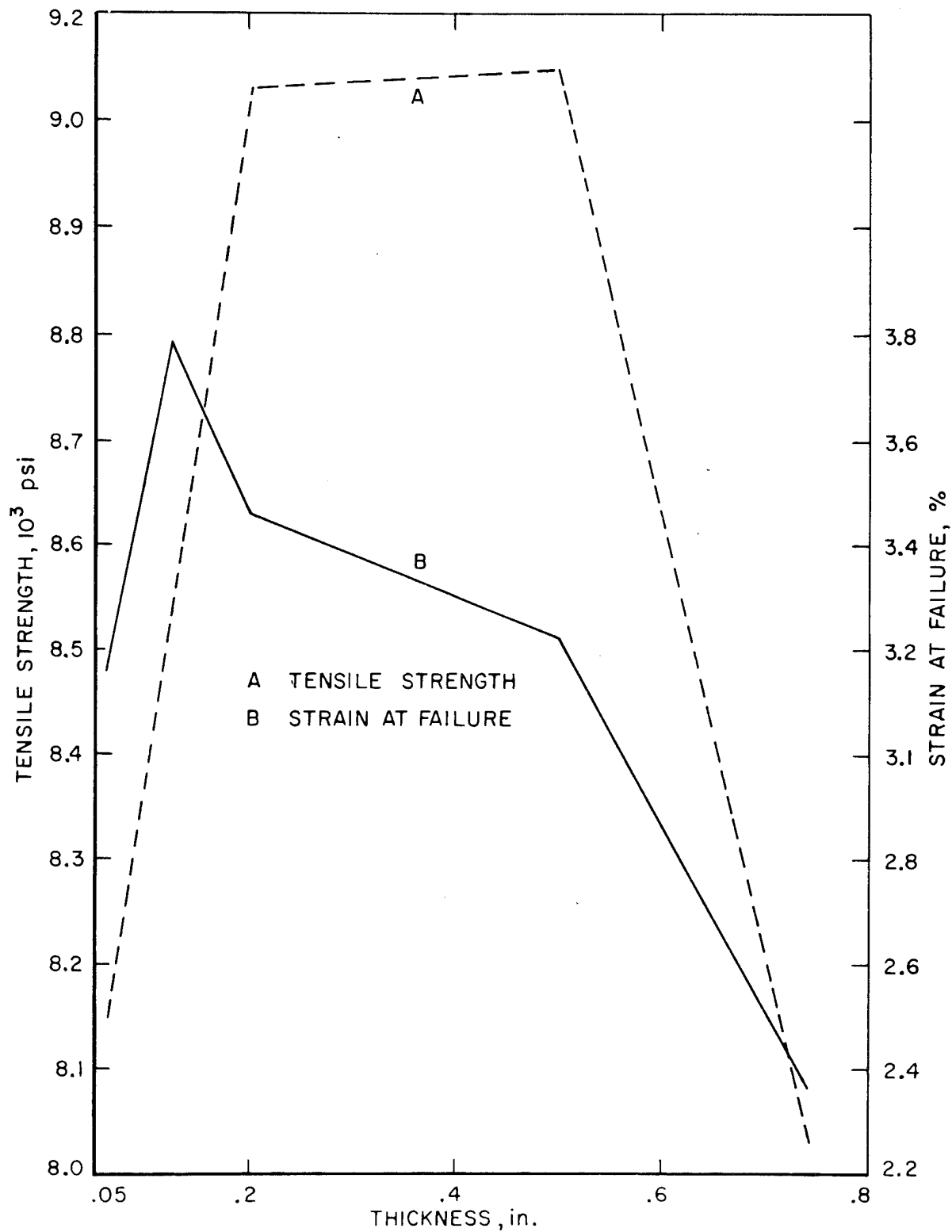
Figure 4.3-93 – Effect of Sheet Thickness on Tensile Strength and Strain at Failure of
MIL-P-8257 Material

4-96
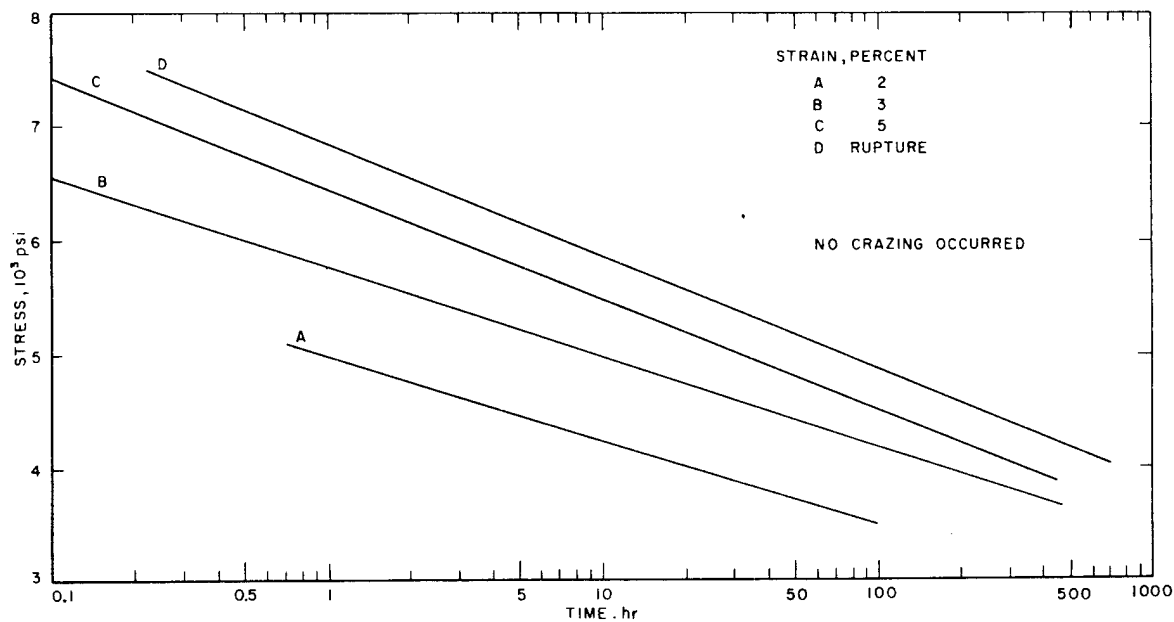
Figure 4.3-94 – Tensile Creep Data for MIL-P-8257 Material at 80 Deg F
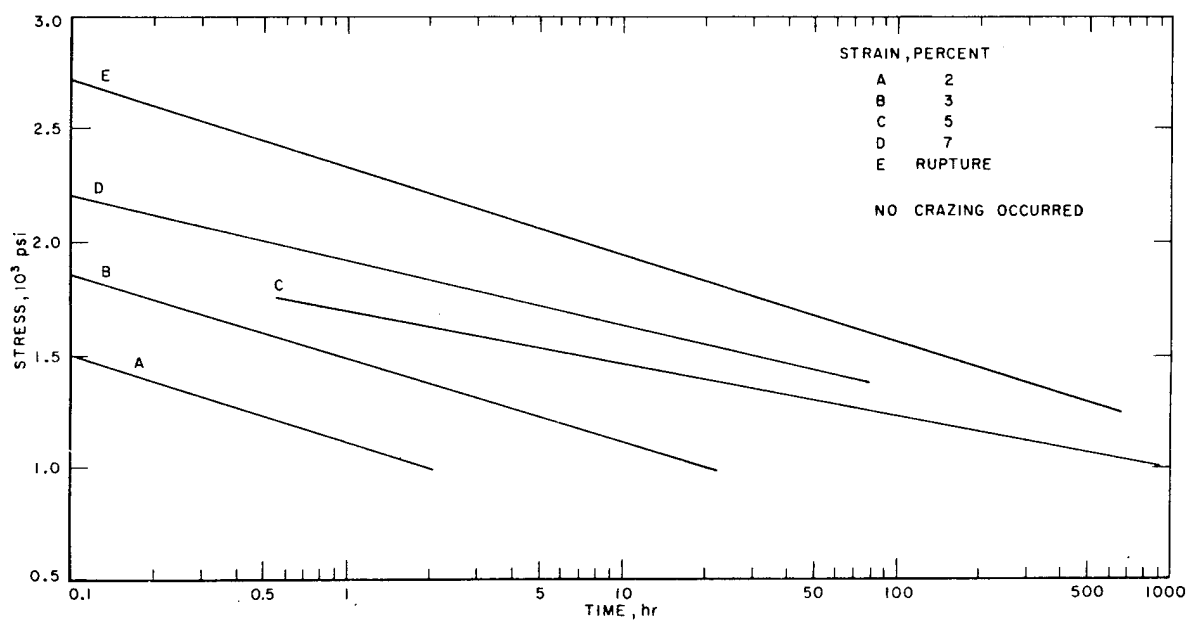
Figure 4.3-95 – Tensile Creep Data for MIL-P-8257 Material at 160 Deg F

4-97
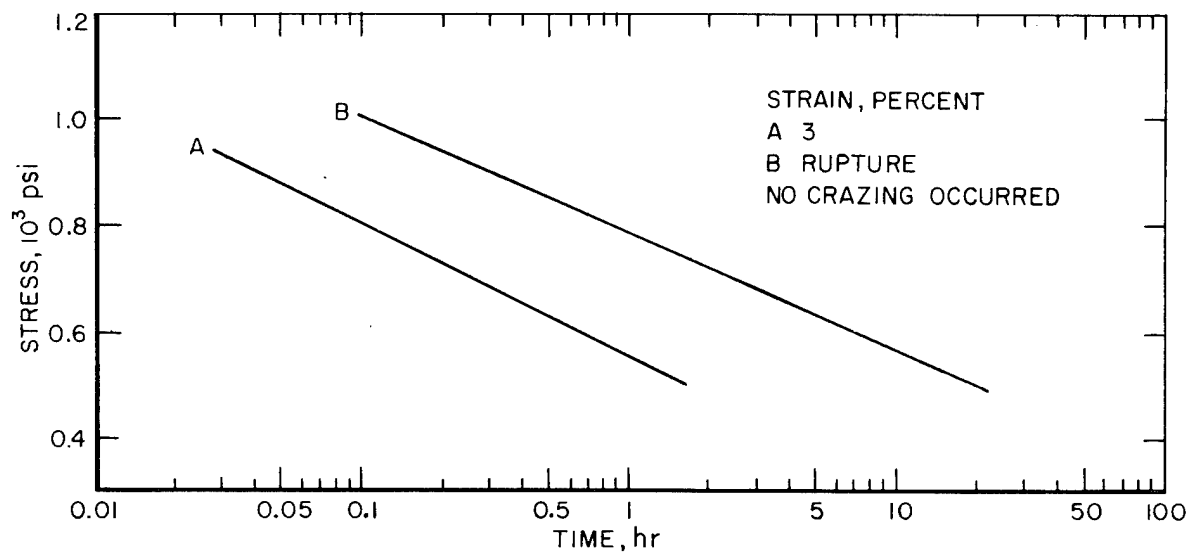
Figure 4.3-96 – Tensile Creep Data for MIL-P-8257 Material at 200 Deg F
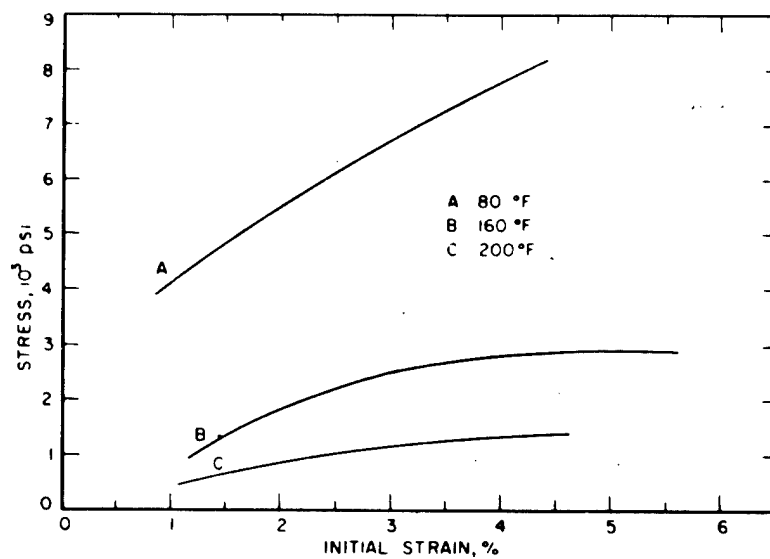
Figure 4.3-97 – Effect of Stress on Initial Strain in Tensile Creep of MIL-P-8257
Material at Various Temperatures

4-98
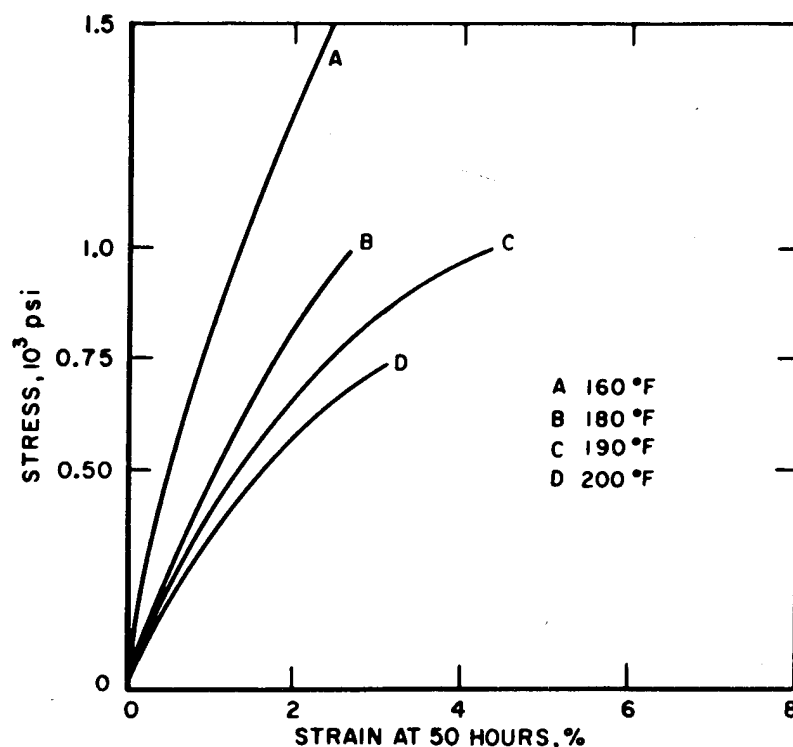
Figure 4.3-98 – Creep Strain of MIL-P-8257 Material at Various Temperatures at
50 Hours after Stress Was Applied

4.4 PROPERTIES OF MATERIALS CONSIDERED FOR AIRCRAFT USE

The nonspecification materials which follow are included in this handbook to afford the reader
an opportunity to become acquainted with other transparent materials, which may or may
not be structurally oriented, but have characteristics which could become useful in future
aircraft applications. The majority of the data are from resin suppliers rather than sheet
processors. As a consequence, materials are described with only a few of their more
interesting differentiating properties.

Although surface hardness cannot be equated directly to abrasion resistance, it does serve
as an indicator in the absence of abrasion data. Heat deflection temperature is a good
processing guide for comparing plastic materials. In situations where light transmission
and haze are currently unacceptable, one should consider that improved resin processing
may add another specified material to the availability list of the future.
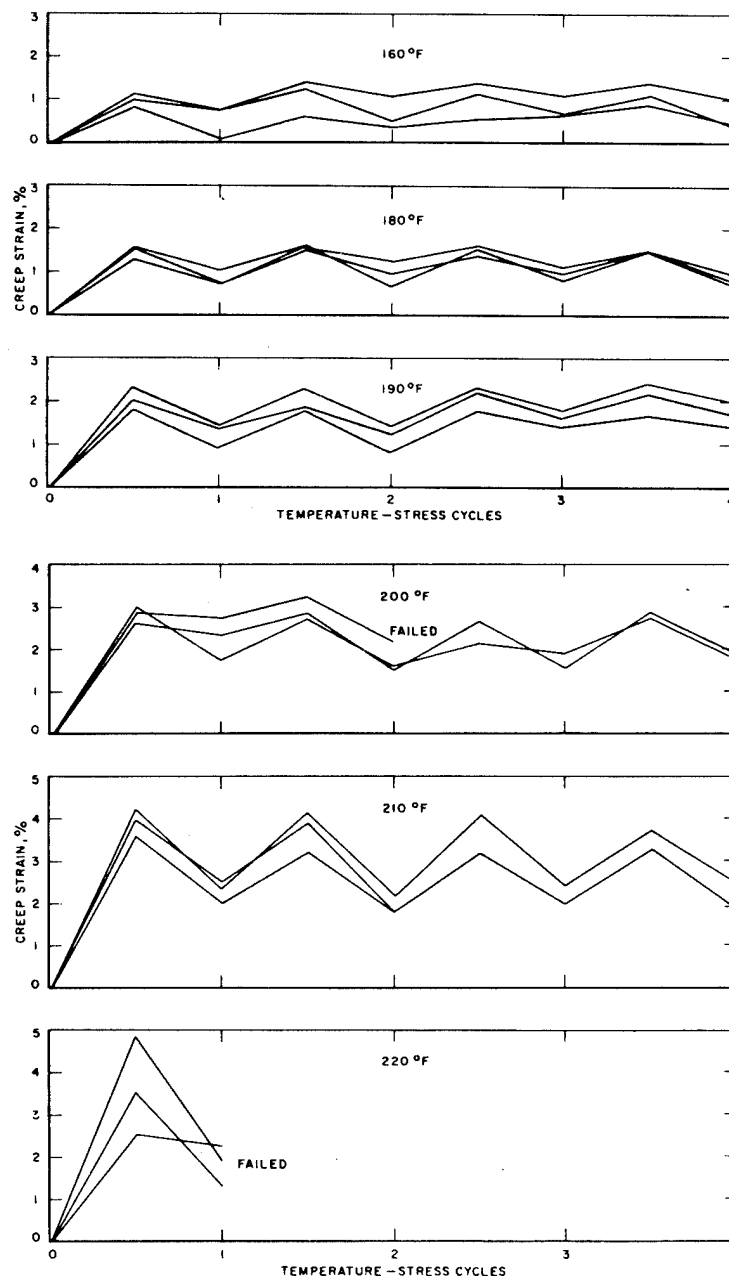
NOTES:
EACH CYCLE CONSISTED OF—
1. ONE HOUR AT TEST TEMPERATURE WITH NO LOAD.
2. ONE HOUR AT TEST TEMPERATURE WITH A STRESS OF 600 POUNDS PER SQUARE INCH.
3. ONE HOUR AT TEST TEMPERATURE WITH NO LOAD.
4. STEPS 2 AND 3 WERE REPEATED TWICE.
5. THE LOAD WAS REAPPLIED AND AFTER ONE HOUR THE MAXIMUM EXTENSION WAS DETERMINED.
6. THE SPECIMENS WERE UNLOADED AND COOLED TO ROOM TEMPERATURE. AFTER 16
   HOURS THE PERMANENT EXTENSION WAS MEASURED.

Figure 4.3-99 – Creep Strain of MIL-P-8257 Material under Cyclic Stress-Temperature
Conditions

4-100

TABLE 4.3-IV- CONDITIONS FOR FRACTURE OF MIL-P-8257 MATERIAL SUBJECTED TO TEMPERATURE GRADIENTS IN TENSILE CREEP TESTS

Temperature (deg F)	Stress (PSI)	Time (hr)	Strain at failure (percent)
180 ±10	1,500	9.8	5.0
	1,500	5.2	4.3
180 ±30	1,500	35.5	5.1
	1,500	35.7	2.2
	1,500	43.9	3.9
190 ±0	1,500	1.8	7.6
	1,500	1.8	7.5
190 ±40	1,500	8.1	4.0
200 ±0	1,500	0.25	
	1,500	0.75	
	1,000	9-20	5.6
	1,000	9-20	5.6
200 ±50	1,000	49.8	4.0
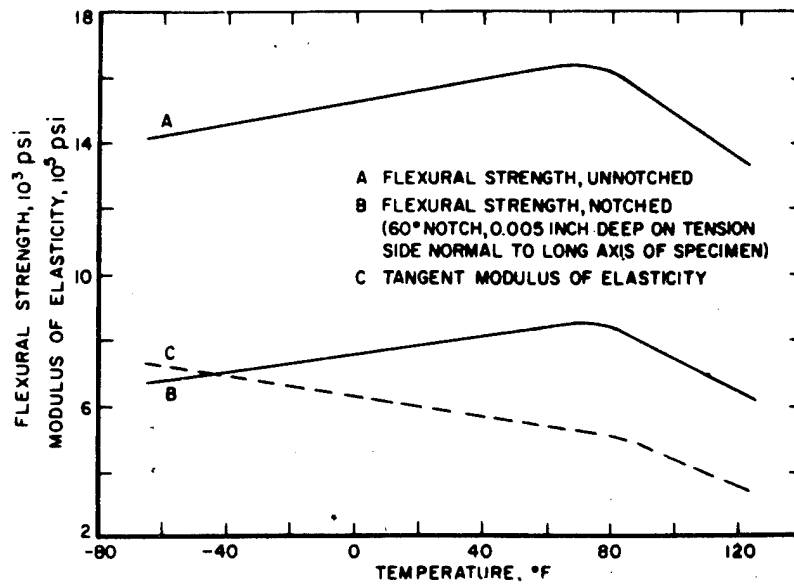
Figure 4. 3-100 – Effect of Temperature on Flexural Properties (Short–Time Test)
of MIL–P–8257 Material
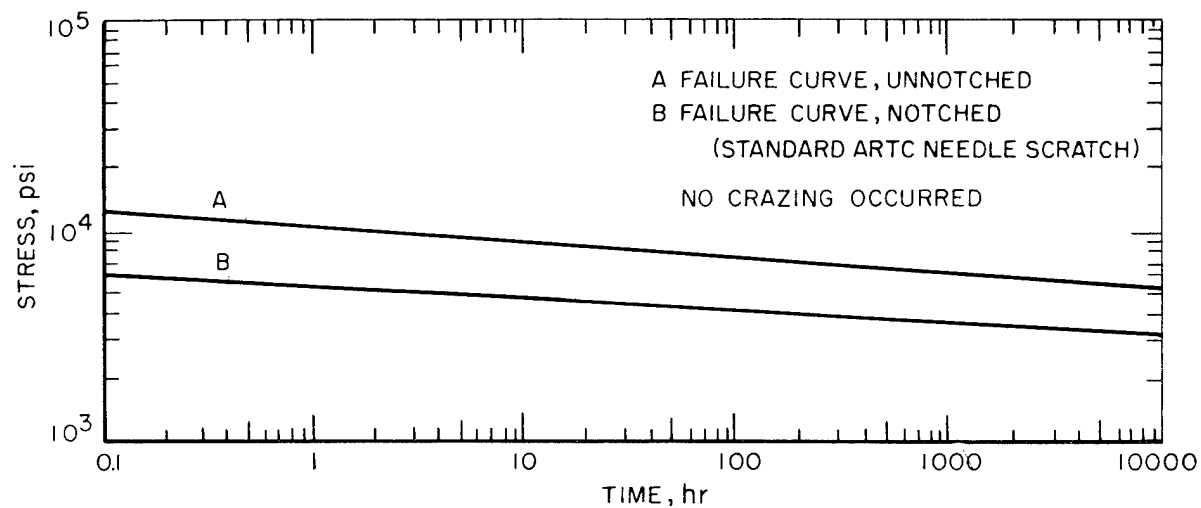
Figure 4. 3-101 – Effect of Duration of Loading on Flexural Properties of 0. 250-Inch Thick
MIL-P-8257 Material at Room Temperature
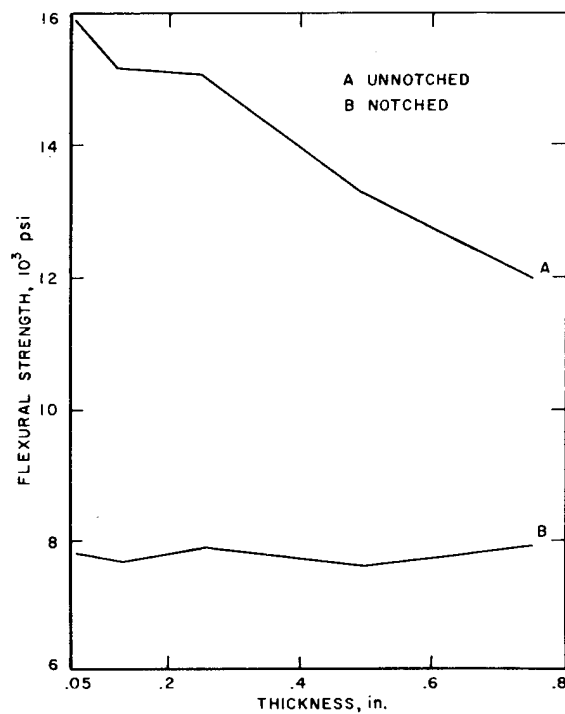
Figure 4.3-102 – Effect of Sheet Thickness on the Unnotched and Notched Flexural
Strengths of MIL-P-8257 Materials at Room Temperature
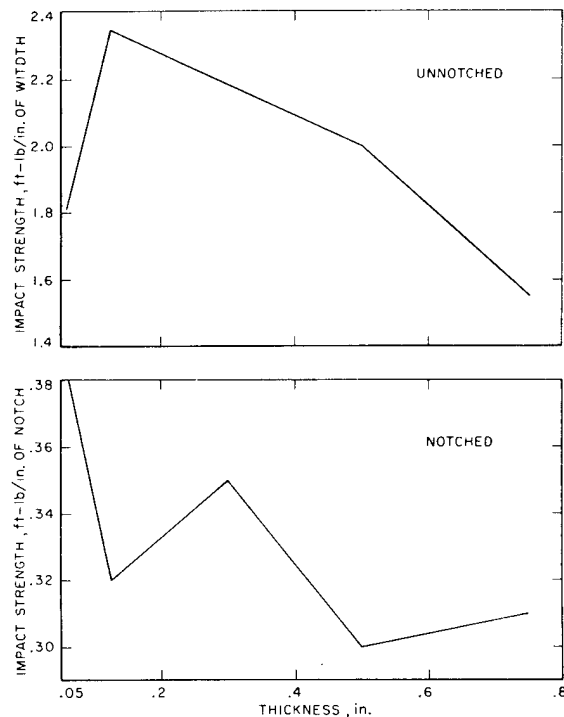
Figure 4.3-103 – Effect of Sheet Thickness on the Unnotched and Notched Izod Impact
Strength of MIL-P-8257 Material

4.4.1 POLYMETHYLPENTENE

Polymethylpentene has a water-white clarity almost equivalent to that of the unmodified acrylics and a very low specific gravity of 0.83. It evidently is very susceptible to UV degradation in its current form and would require a novel type of protection to serve as an aircraft material. Impact resistance is in the same range as the cast acrylics. Rockwell hardness falls between the "R" and "M" ranges. The material is thermoplastic and non-structural. Its operational high-temperature capability is between +250 F to +320 F. The material is commercially known by the trade name "TPX" and is manufactured by Imperial Chemical Industries, Ltd.

4.4.2 POLYSULFONES

4.4.2.1 GENERAL

Polysulfones are of two types, one being referred to as "polysulphone," and the other as "polyarylsulfone." The former is manufactured by Union Carbide Corporation under the trade name of "Bakelite" Polysulfone P-3500, and the latter by Minnesota Mining and Manufacturing Co. under the trade name ASTREL 300. Both are self-extinguishing and are true thermoplastic materials. From the deflection temperature data, it appears that these materials have inherent forming problems.

4.4.2.2 POLYSULFONE

Polysulfone is a high-temperature material with reasonable impact resistance and a heat deflection temperature of +345 F at 264 PSI outer fiber tension. The Rockwell hardness of M69 (R-120) is less than polycarbonates rating in the as-received condition. The low hardness figure makes the material suspect for external abrasion environments, but the temperature capability may provide a better substrate for conductive coatings which require high-temperature processing.

4.4.2.3 POLYARYLSULFONE

Polyarylsulfone variations offer different heat deflection temperatures which range between +420 F and 550 F at 264 PSI outer fiber stress. Under these conditions, part forming will have to be controlled remotely in equipment and tooling capable of withstanding these temperatures, and higher. The Rockwell hardness of M110 indicates better surface properties than any of the thermoplastic materials now available. The notched Izod test data of two to four ft-lb/in. of notch, with other exceptional mechanical properties, tentatively classify the material as being structurally adaptable to high-performance aircraft applications.

4.4.3 POLYTEREPHTHALATE

Polyterephthalate properties have been surpassed by other specified materials for aircraft enclosure use. The transparency is characterized by a slight amber tint and a heat deflection temperature of +154 F with a 264 PSI outer fiber stress. It is less notch-sensitive than the cast acrylics and more resistant to chemical attack. The Rockwell hardness of M62 (R-108) is not exceptional, but the abrasion resistance is claimed to be better than the acrylics. The plastic is highly thermoformable and offers possibilities as a secondary non-structural material. Eastman Chemical Products, Inc. manufactures the basic resin under the trade name of "Tenite" 7DR0.

4.4.4 POLYURETHANES

4.4.4.1 GENERAL

Polyurethanes at one time were identified as being physically unstable after prolonged exposure to moisture. The property of hydrolytic stability became one of the principal governing factors in choosing, from the vast family of urethanes, compounds capable of withstanding military environments.

One test for hydrolytic stability was devised primarily for materials used in military equipment by Rock Island Arsenal, Illinois. It consisted of suspending sample material over distilled water maintained at 158 deg F for 30 days. The criterion was that the material has to retain 70 percent of its original tensile strength after this exposure.

Two chemically different materials have been developed, one of which is thermoplastic and the other thermosetting in their forming properties. Both materials were cast into sheets.

4.4.4.2 POLYURETHANE; THERMOPLASTIC

This material has a characteristic yellow tint which rates a Gardner 6 color for 0.4-inch-thick material. The yellow tint is inherent in the compound and not caused by impurities. The deformation temperature is +170 F at 264 PSI. The material was developed primarily for transparent armor applications and is manufactured by Goodyear Aerospace Corporation under the trade name of GLASHIELD 574-2-a. The material passed the hydrolytic stability test successfully. The Shore "D" hardness measures at 78-80. Light transmission of 0.4-inch-thick material is 80 percent, haze 0.9 percent.

4.4.4.3 POLYURETHANE; THERMOSETTING

By color and by physical properties, the thermosetting material is completely different. The surface is harder as measured by the Shore "D" scale at 84. The material is colorless and has withstood the test for hydrolytic stability. Its Izod impact strength is low, measuring at an average of approximately 0.5 ft-lb/in. of notch. This material is apparently similar to other thermosetting materials in its general properties. It has been found to be effective as a spall shield on the inner surface of transparent armor. The deformation temperature is +170 F at 264 PSI. The material has been manufactured by Goodyear Aerospace Corporation under the trade name of GLASHIELD 575a-1.

4.4.5 MODIFIED ABS (ACRYLONITRILE-BUTADIENE-STYRENE)

ABS materials have been noted for their impact strength. The modified ABS is the transparent version of the material in which a methacrylate polymerization component has become a part of the resin system. The material is of a yellow tint and has a heat deflection temperature of 165 F at 264 PSI outer fiber stress. Its Izod impact value of 5.3 ft-lb/in. of notch is attractive. A Rockwell hardness of 100R and a low tensile strength apparently limits its use to nonstructural applications. The modified ABS (MABS or MBS) is manufactured by the Marbon Division of Borg-Warner Corporation under trade name of Clear Cycolac Grade CIT.

4.4.6   MODIFIED ACRYLIC (RUBBER)

Commonly referred to as "rubber modified acrylic," the modifying rubber of 2-ethylhexyl acrylate-styrene is grafted to methyl methacrylate. The Izod impact strength is greater than that of the cast acrylics, being in the range of 0.8 to 1.5 ft-lb/in. of notch. The heat deflection temperature range of 158 to 167 F at 264 PSI is about the same as that of MABS. The material is clear and water-white. Its tensile strength is slightly lower than that of MABS, and its flexural strength slightly higher. Both of the latter properties are less than the values of other military specified transparent thermoplastics.

CHAPTER 5 – PROPERTIES OF INTERLAYER MATERIALS

5.1 GENERAL

Interlayer materials are unique in that they must serve as a transparent flexible rubber sheet, as an energy–absorbing medium, and as an adhesive. Choices of materials are currently limited to polyvinyl butyral, ethylene terpolymer, polyester, polyurethane, and silicone bases. Because polyvinyl butyral is the earlier interlayer material, it has become the standard by which the other materials are compared.

5.2 POLYVINYL BUTYRAL BASE

The properties of polyvinyl butyral (PVB) interlayer sheet material vary, depending on the type and amount of plasticizer used. For glass laminates about 20 parts of triethylene glycol di–2–ethyl butyrate plasticizer (3GH) are used per hundred parts of resin. Some physical and thermal properties for this particular composition are given in Table 5.2-I and Figures 5.2-1 and 5.2-2.

TABLE 5.2-I – PROPERTIES OF POLYVINYL BUTYRAL PLASTICIZED WITH 21 PARTS OF TRIETHYLENE GLYCOL DI–2–ETHYL BUTYRATE

Specific heat		Thermal conductivity	
Temperature (deg F)	BTU/lb/ deg F	Temperature (deg F)	BTU-in. /ft^2 hr deg F
-89	0.23	-85	1.29
0	0.285	48	1.54
60	0.36	52.5	1.47
120	0.45	53	1.48
Index of refraction		145	1.49
1.496 at -35 deg F		Density	67.8-68.1 lb/ft^2
1.488 at 129 deg F			
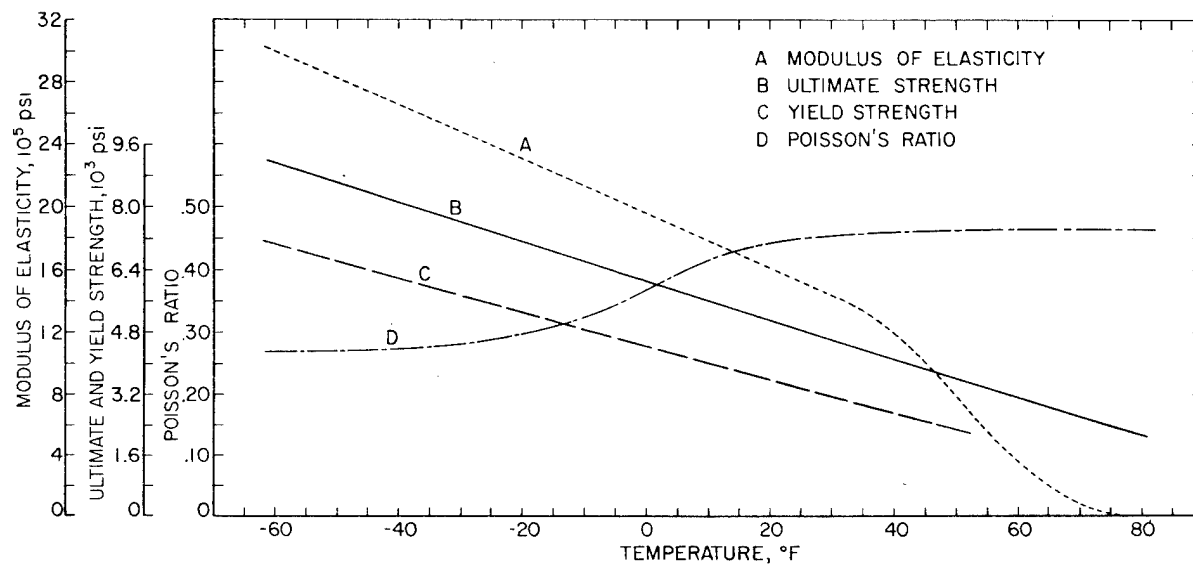
Figure 5.2-1 – Effects of Temperature on Tensile Properties of Polyvinyl Butyral Plasticized
with 21 Parts of Triethylene Glycol Di-2-Ethyl Butyrate (3 GH)
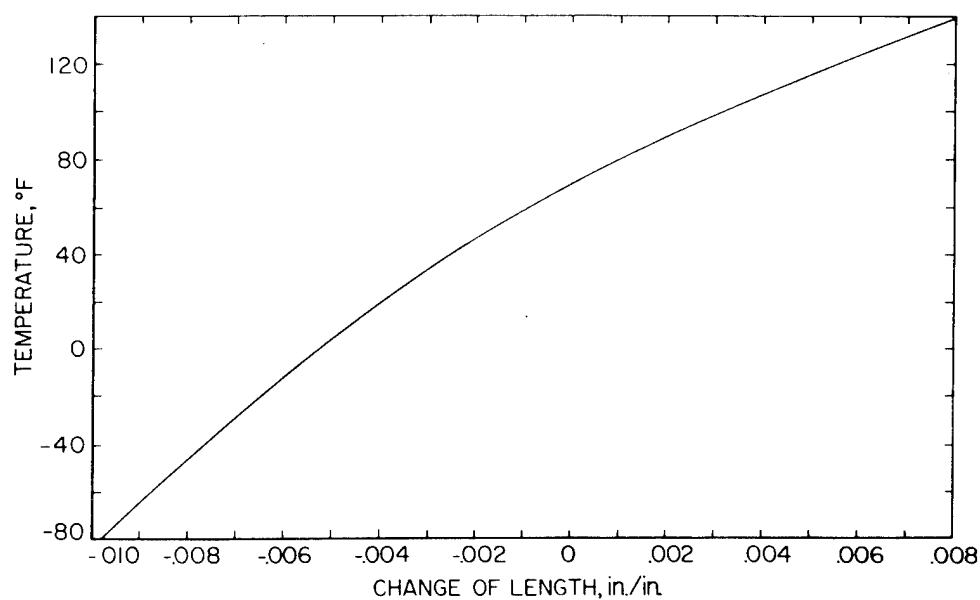
Figure 5.2-2 – Effect of Temperature on Coefficient of Linear Thermal Expansion
of Polyvinyl Butyral Plasticized with 21 Parts of Triethylene Glycol
Di-2-Ethyl Butyrate (3 GH)

5-2

For plastic laminates, the plasticizer content was changed to about 37.5 parts of dibutyl sebacate. The additional plasticizer helped in making a better expansion and contraction match with the plastic face sheets by making the material more flexible.

Bartoe and Robinson (Reference 8) indicate that above 32 deg F the interlayer responds as a highly extensible material, but below 32 deg F performs like a rigid substance. Mattimoe reports in Reference 9) that the light transmittance for an 0.075-inch-thick material is 87.6 percent and haze is 0.93 percent.

Bubbles develop in the interlayer when a laminate with a polyvinyl butyral interlayer is exposed to elevated temperatures for extended periods of time. Figure 5.2-3 shows the time to produce bubbles in the interlayer at various temperatures. Folk and Iler (Reference 10) found that the moisture content of the interlayer is an important factor in bubbling at high temperatures. Interlayers conditioned in an atmosphere with a relative humidity of 15 percent were exposed at 300 deg F for 45 minutes and at 350 deg F for 30 minutes without producing bubbles. Chen and his coworkers (Reference 11) report that by careful preparation, the upper temperature limit for polyvinyl butyral has been extended to 325 F.
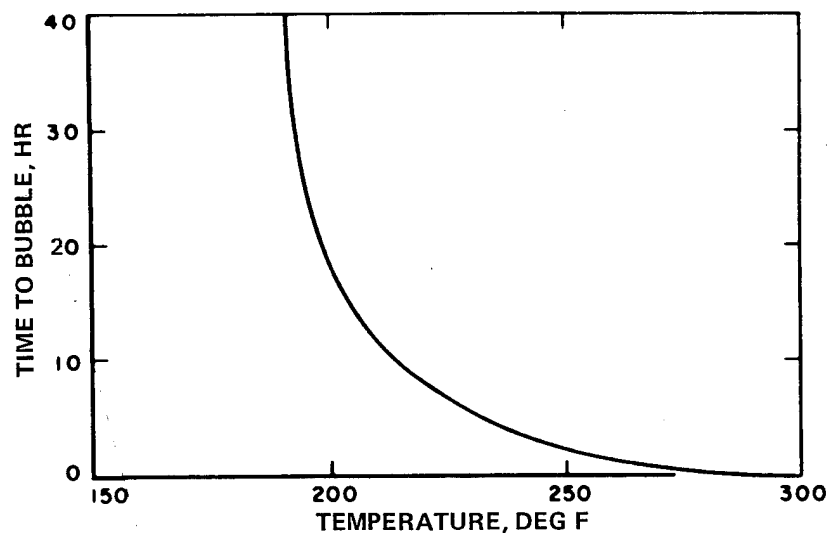
Figure 5.2-3 – Effect of Temperature on Time to Produce Bubbling of Polyvinyl Butyral Interlayer

5-3

5.3   ETHYLENE TERPOLYMER BASE

With the advent of polycarbonate as a tougher structural material and its probable inclusion in composite aircraft transparencies with glass, the ethylene terpolymer (ETP) was developed as an optimum adhesive interlayer sheet for a glass-polycarbonate laminate.

Figure 5.3-1 compares the tensile strength of the terpolymer with PVB over a broad temperature range. The curves are relatively close above +40 deg F. Below this temperature, the ETP material constrained itself to a smooth curve, but the PVB exhibits a curve reversal which reappears in the modulus of toughness (see Figure 5.3-2), tear strength (see Figure 5.3-3), and tensile impact (see Figure 5.3-4) curves. The tensile elongation, impact, and product curves are in Figures 5.3-4, 5.3-5, and 5.3-6.

5.4   POLYESTER BASE

The polyester type of interlayer was one of the first cast-in-place (CIP) interlayers developed. The curves of Figures 5.4-1 and 5.4-2 which were reproduced from original information reflect an extension in the temperature range beyond that of the polyvinyl butyral capability in terms of elongation. The material, however, has been replaced for the most part by the polyurethane based interlayers.

5.5   SILICONE BASE

As transparent silicone resins were developed, they became obvious candidates for interlayer materials because of their higher temperature capability. The low tensile strengths of the silicones are characteristic and are shown in Figure 5.5-1 with respect to temperature and compared to polyvinyl butyral. Figures 5.5-2 through 5.5-5 show the variation of shear stress versus strain for a temperature range of -65 F through +250 F.

5.6   POLYURETHANE BASE

The transparent urethanes are the most recent of interlayer materials. These are characterized by the higher tensile strengths with respect to temperature as demonstrated in Figure 5.6-1 and by a natural tenacity to most materials with which they come into contact. Figures 5.6-2 and 5.6-3 present tensile stress-strain and temperature information on a typical urethane based material.
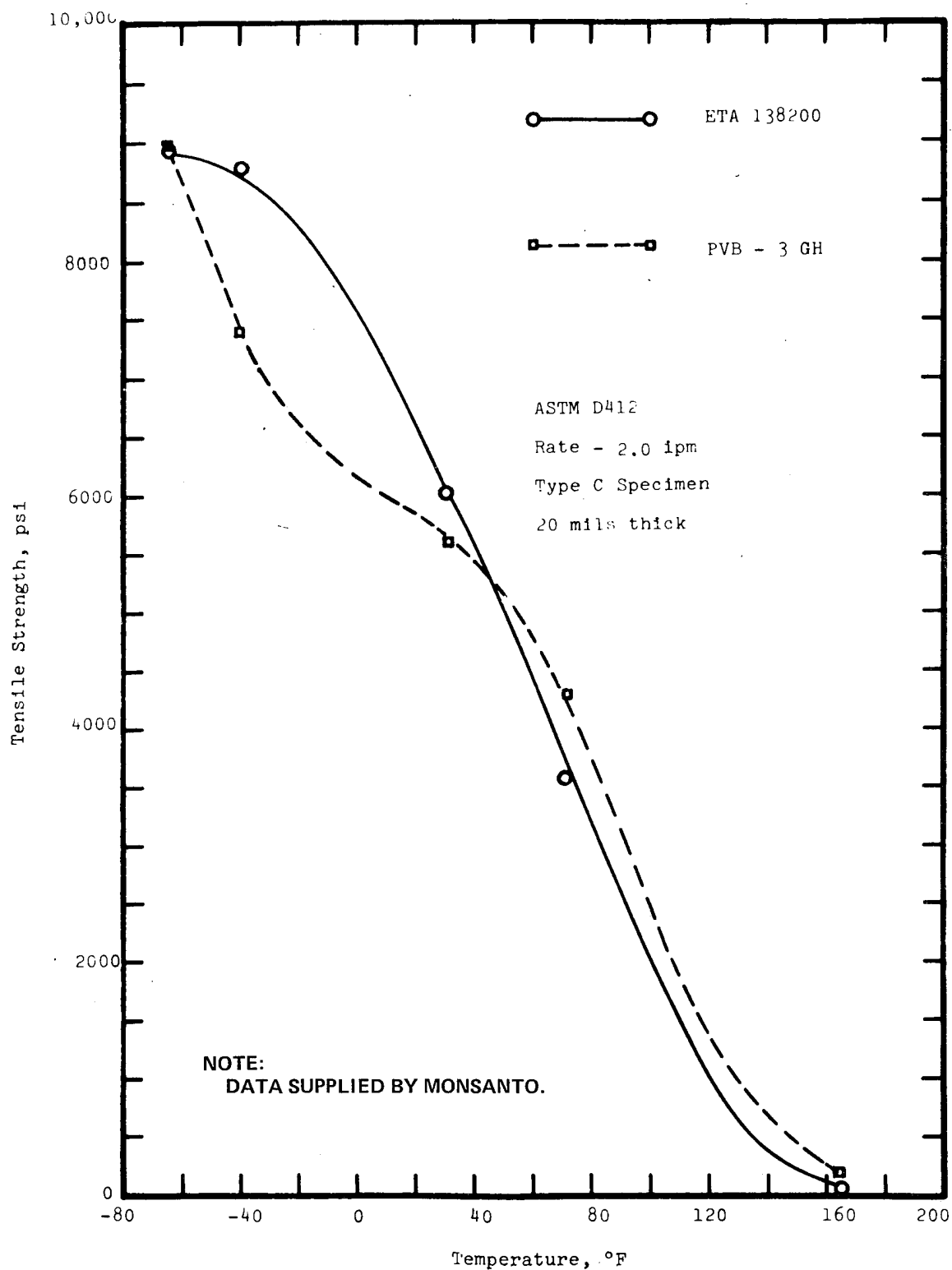
Figure 5.3-1 – Tensile Strength Characteristics of ETA and PVB as a Function of Temperature

5-5
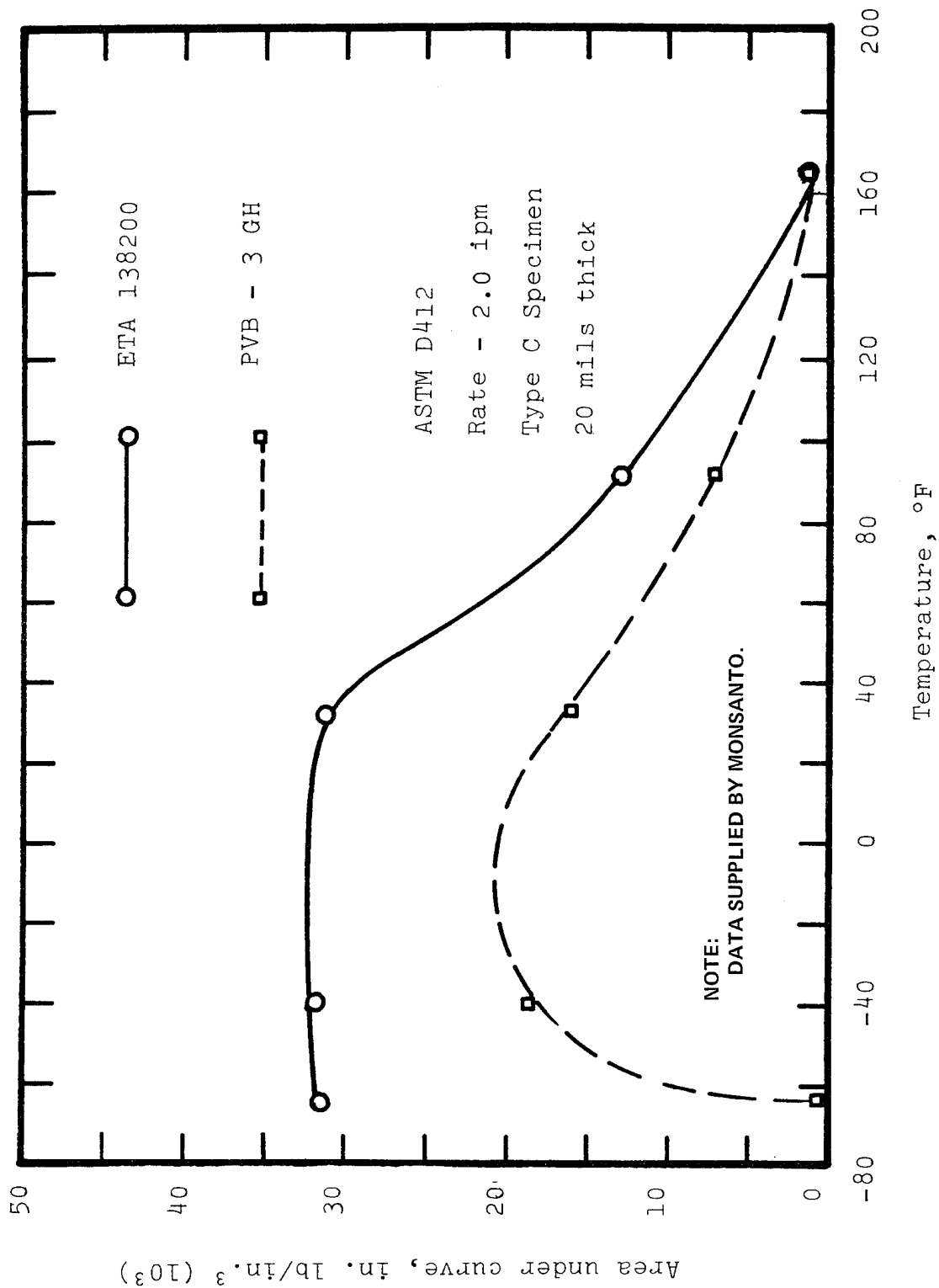
Figure 5.3-2 – Area Under the Stress–Strain Curve for ETA and PVB as a Function of Temperature

5–6
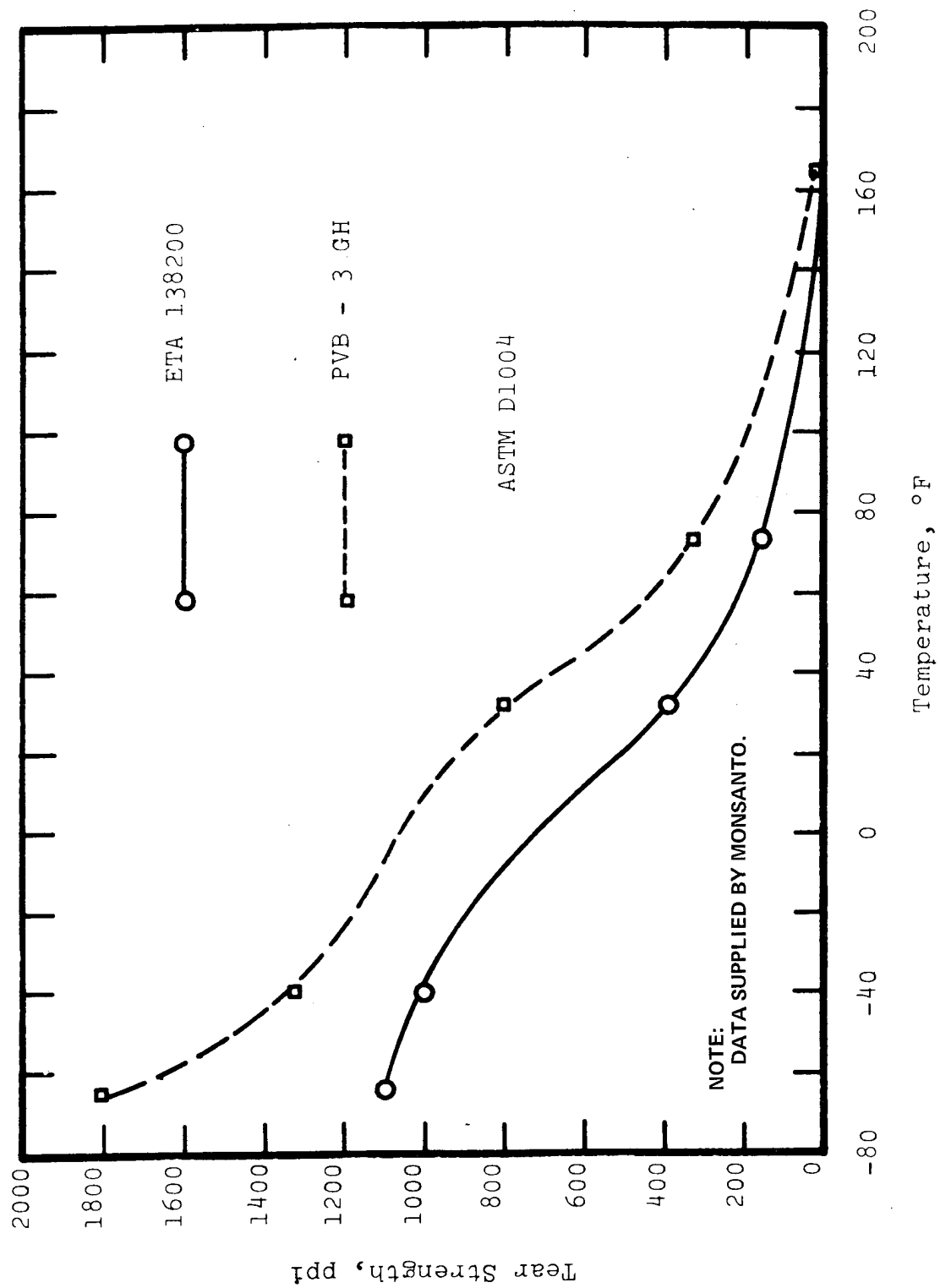
Figure 5.3-3 – Tear Strength Characteristics of ETA and PVB as a Function of Temperature
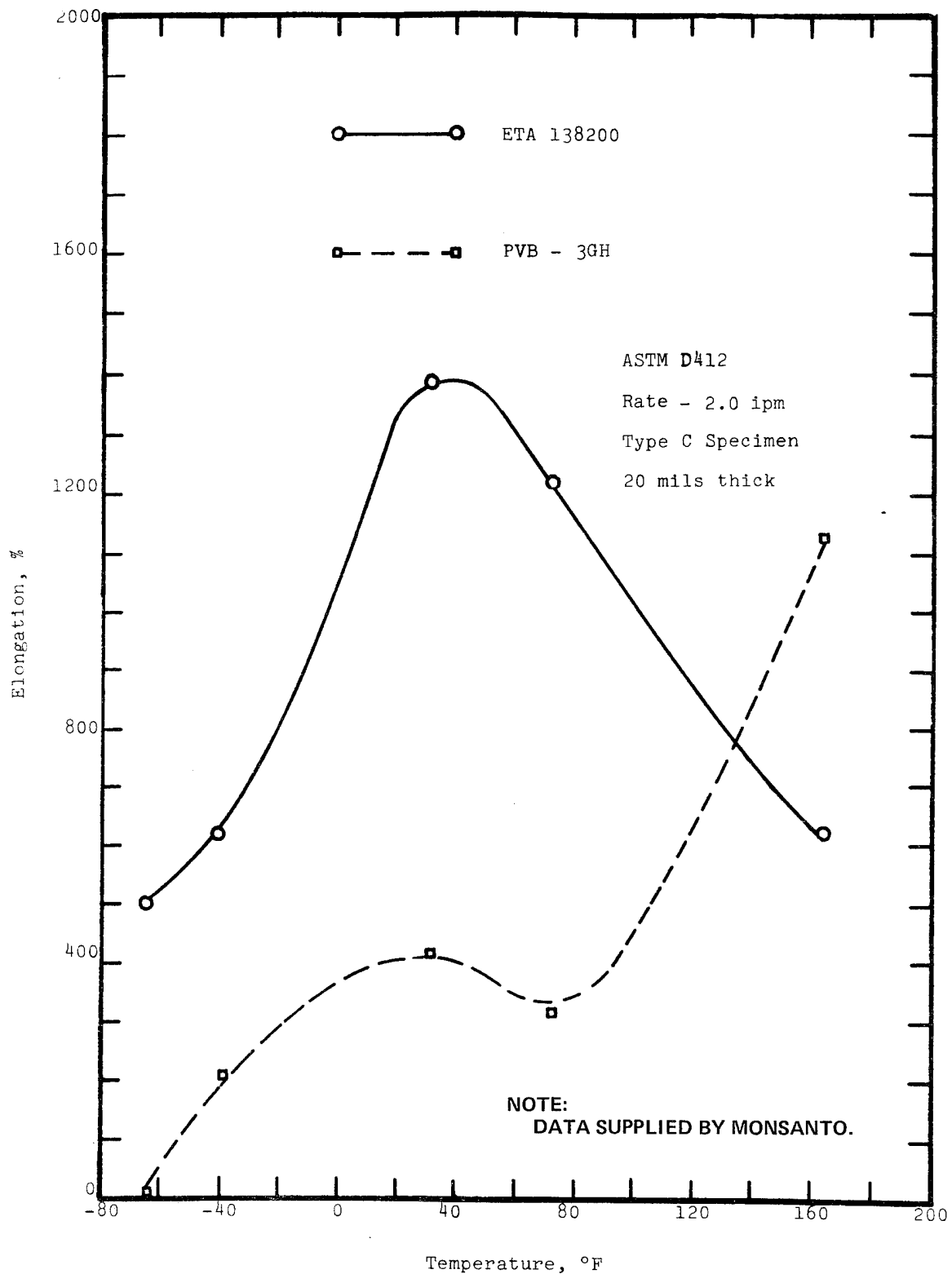
Figure 5.3-4 – Tensile Elongation Characteristics of ETA and PVB as a Function of Temperature

5-8
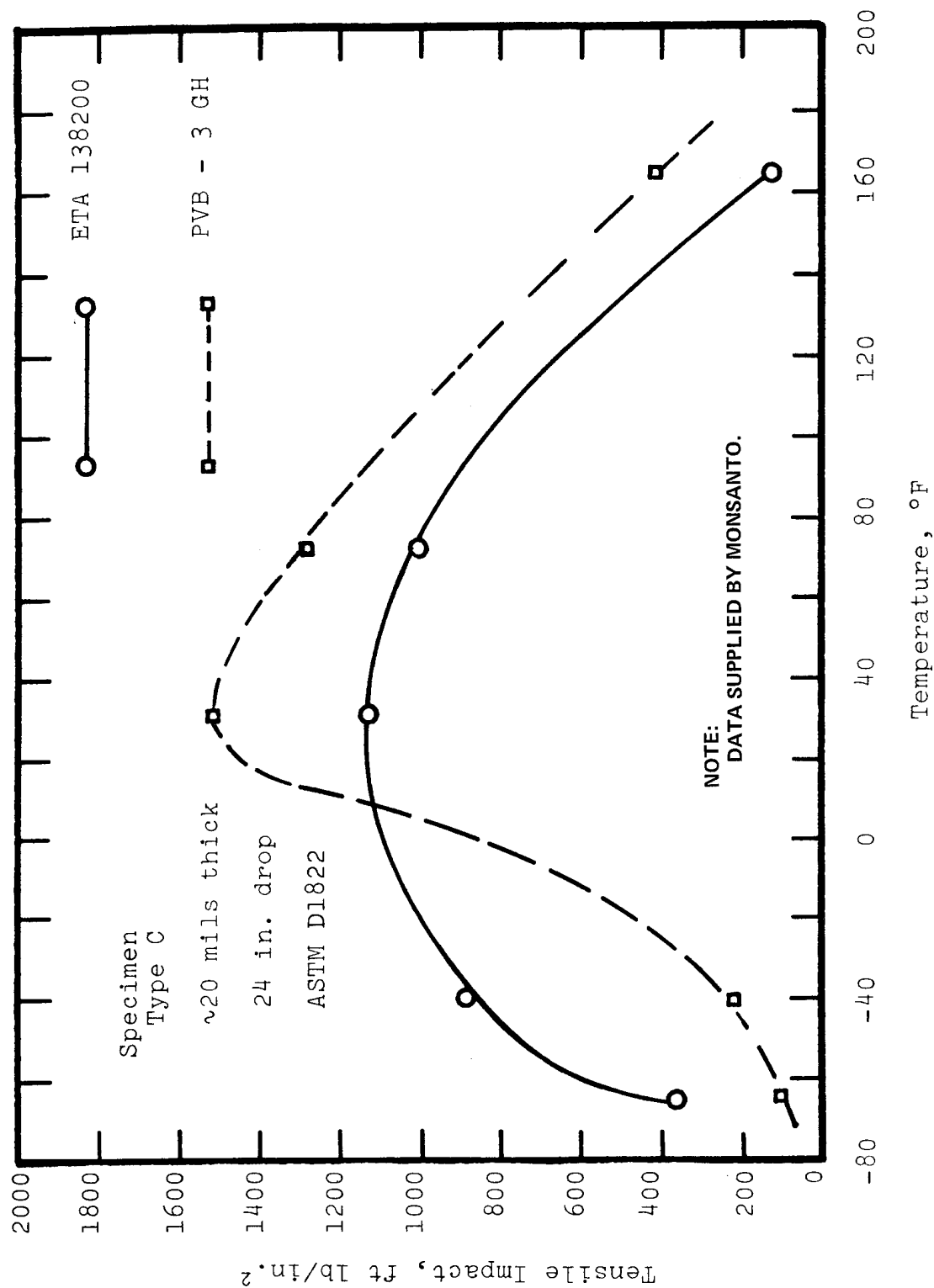
Figure 5.3-5 – Tensile Impact Characteristics of ETA and PVB as a Function
of Temperature

5-9
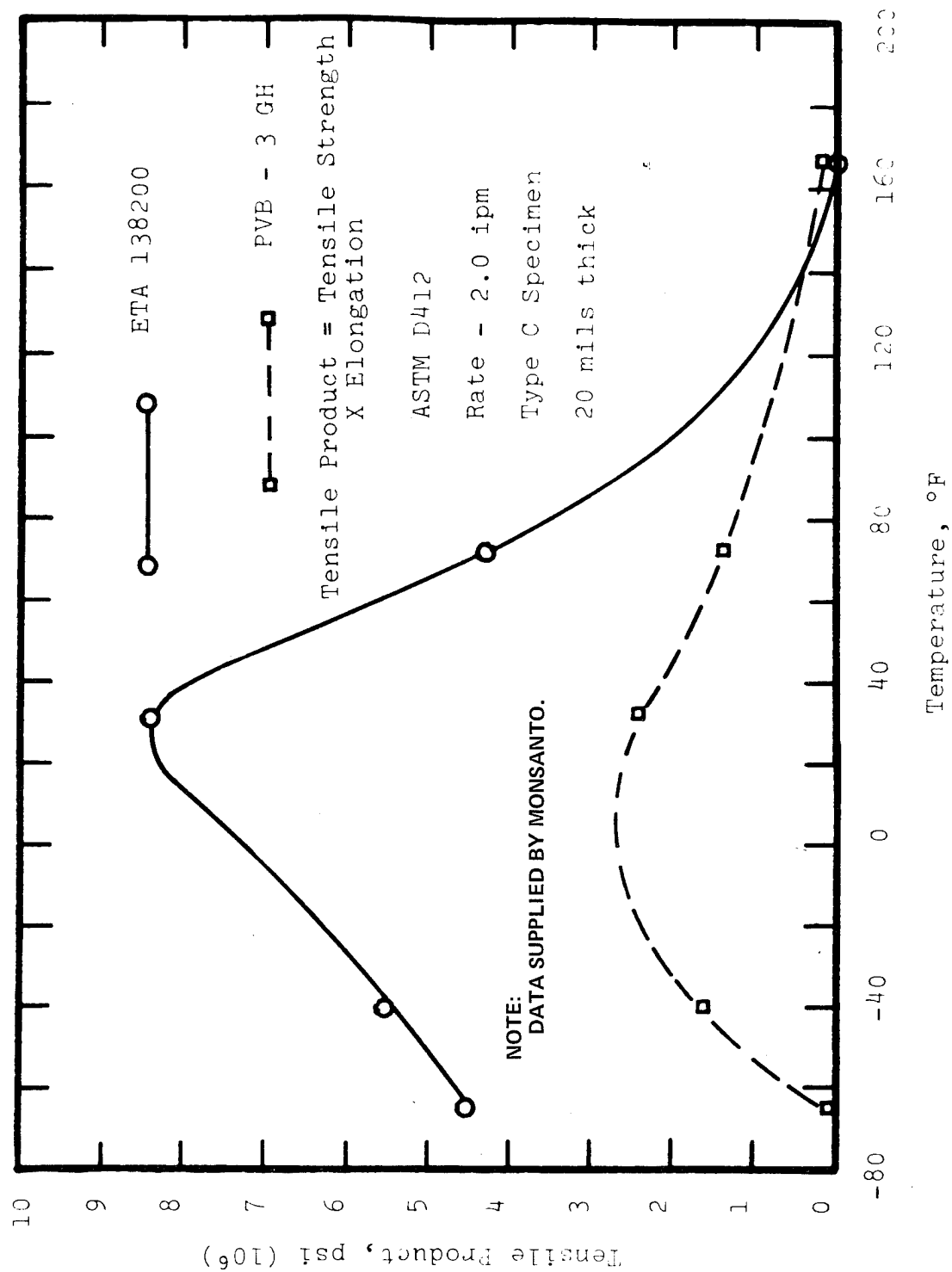
Figure 5.3-6 – Tensile Product Characteristics of ETA and PVB as a Function of Temperature

5-10
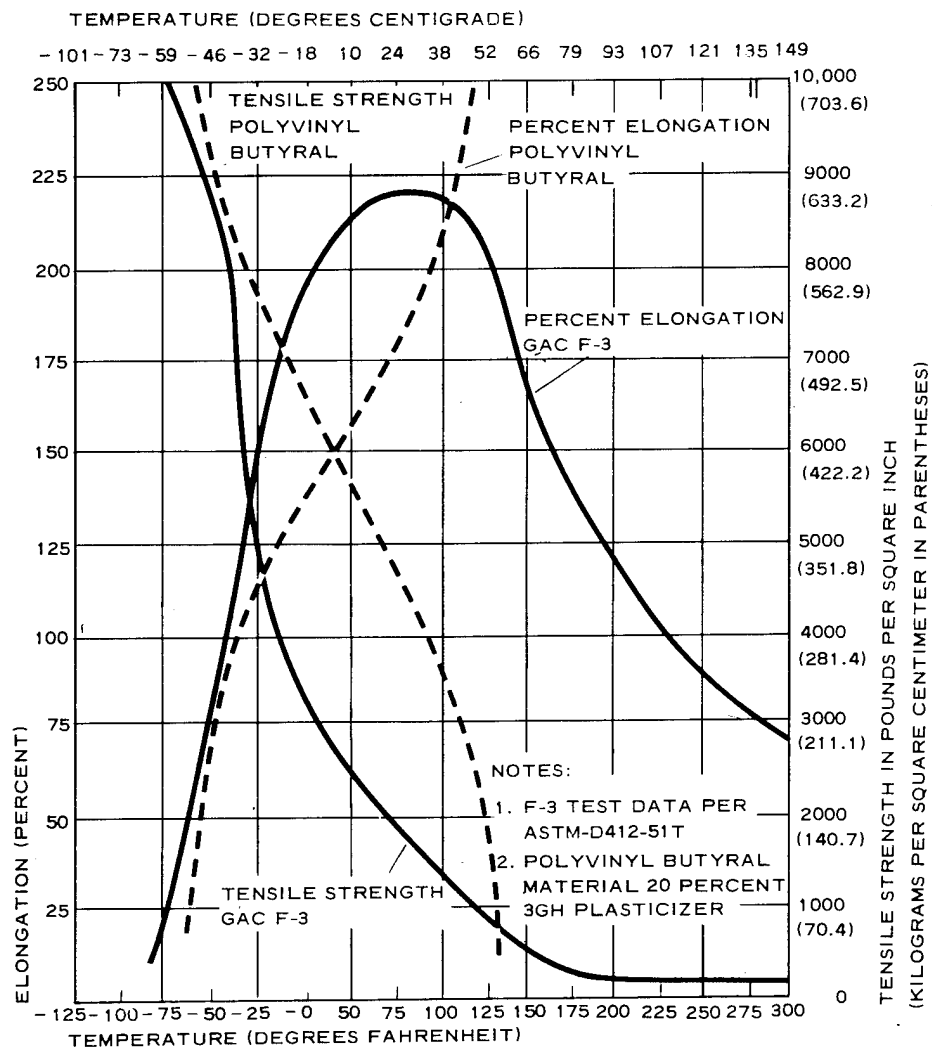
Figure 5.4-1 – Tensile Strength and Elongation of F-3 and PVB Interlayer
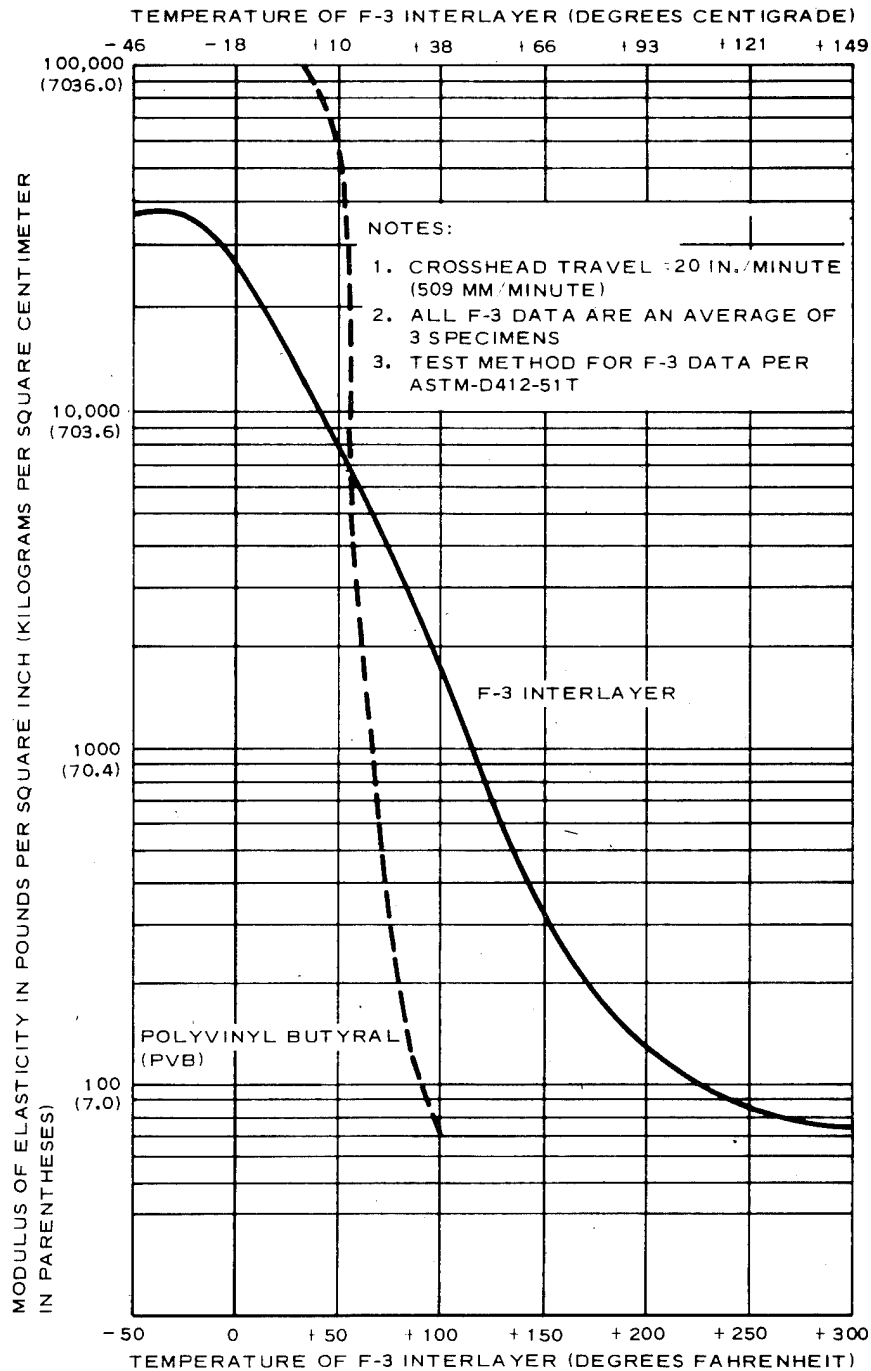
NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.

Figure 5.4-2 – Tensile Modulus of F-3 and PVB Interlayers

5-12
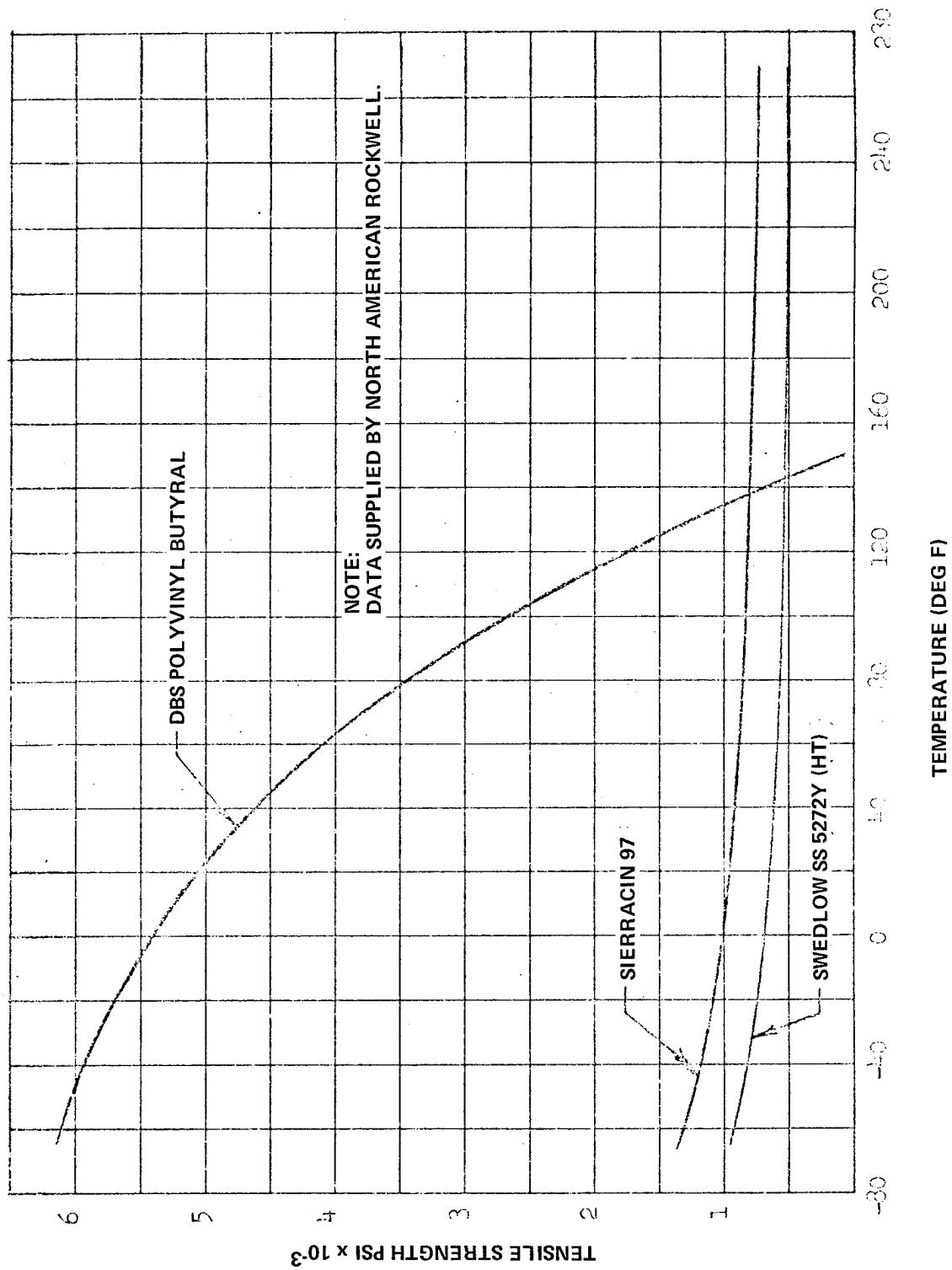
Figure 5.5-1 – Tensile Strength of Silicone and PVB Interlayers versus Temperature
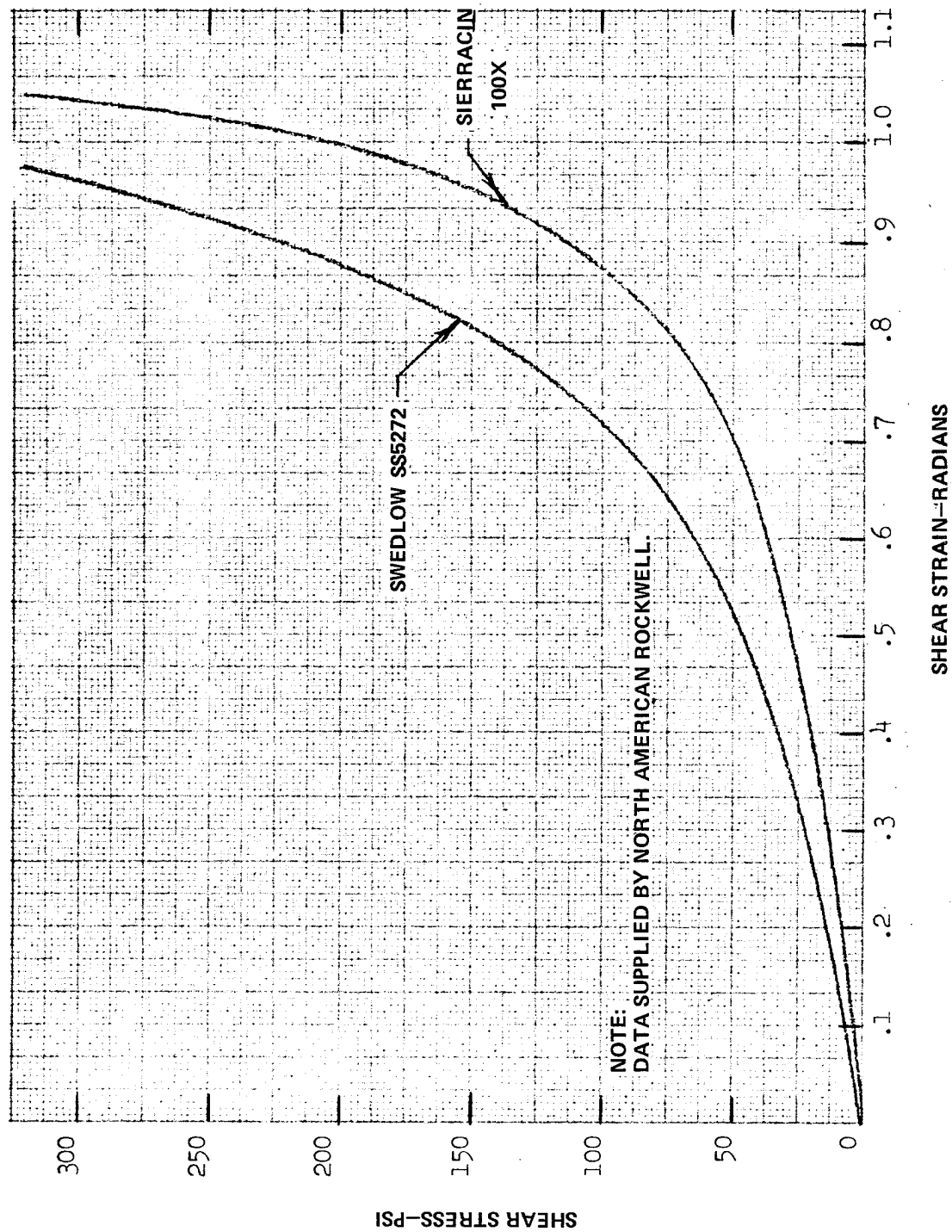
Figure 5.5-2 – Shear Stress versus Strain at -65 Deg F, Silicone Interlayers
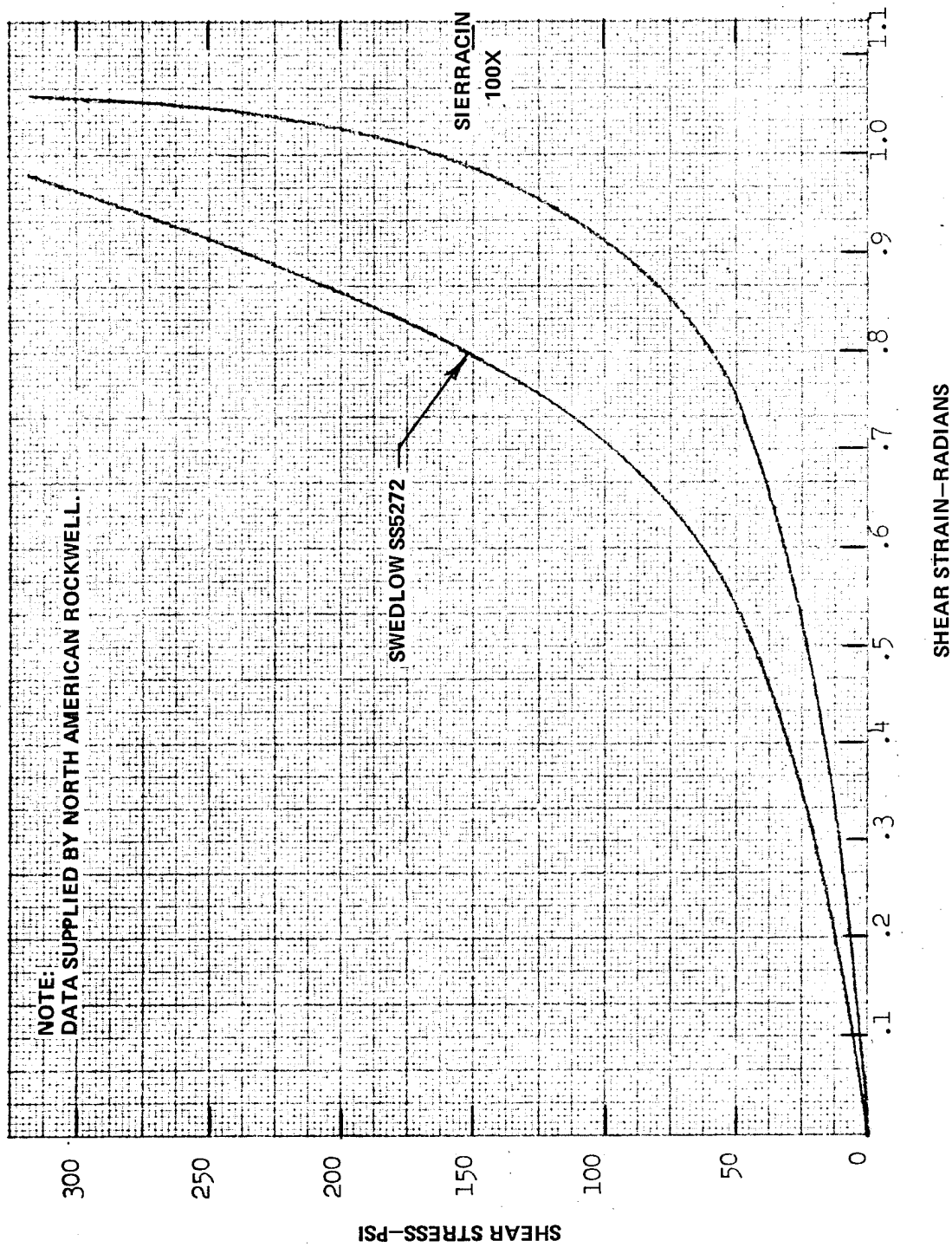
Figure 5.5-3 – Shear Stress versus Strain at Room Temperature, Silicone Interlayers

5-15
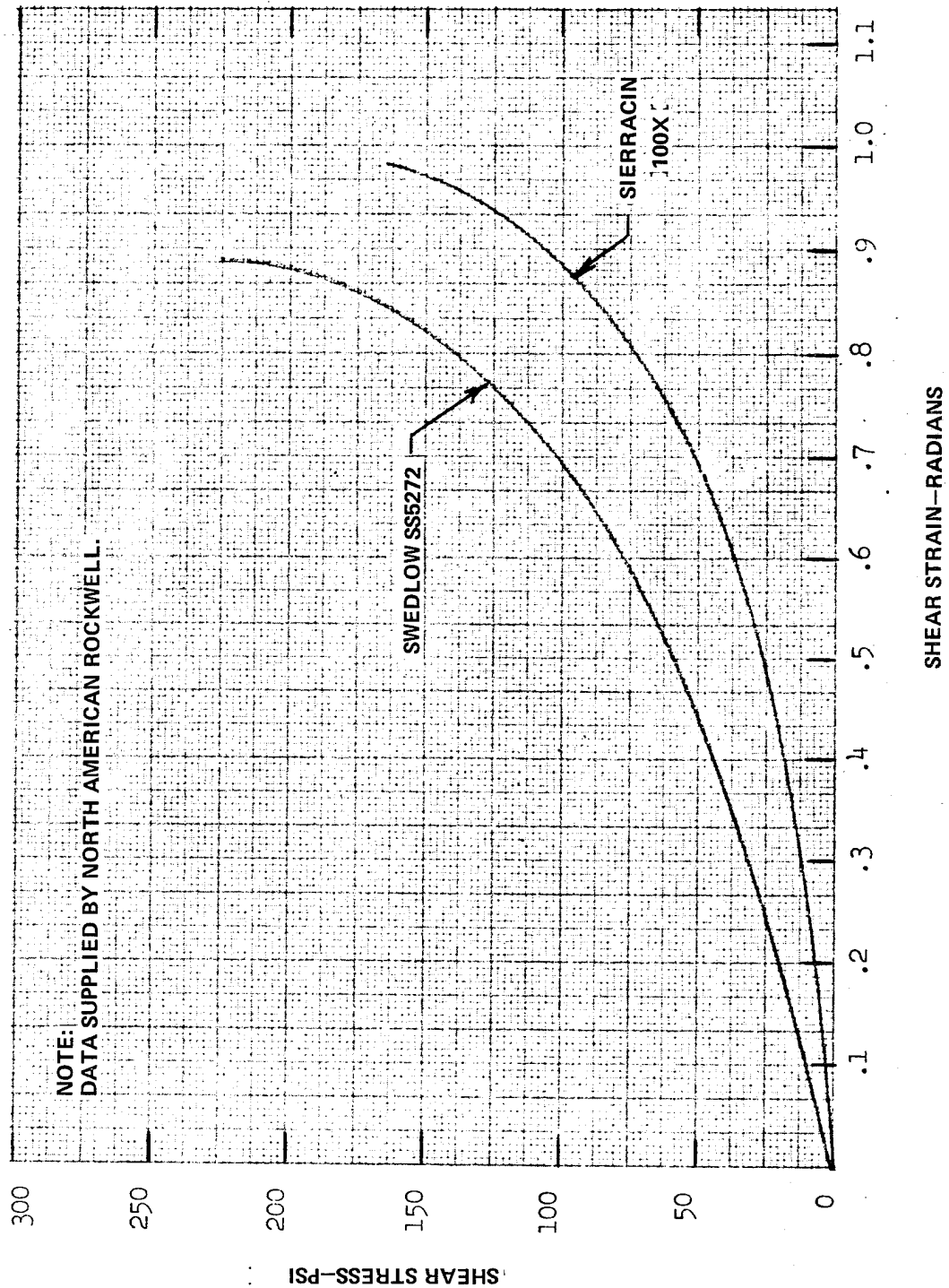
Figure 5.5-4 – Shear Stress versus Strain at 160 Deg F, Silicone Interlayers
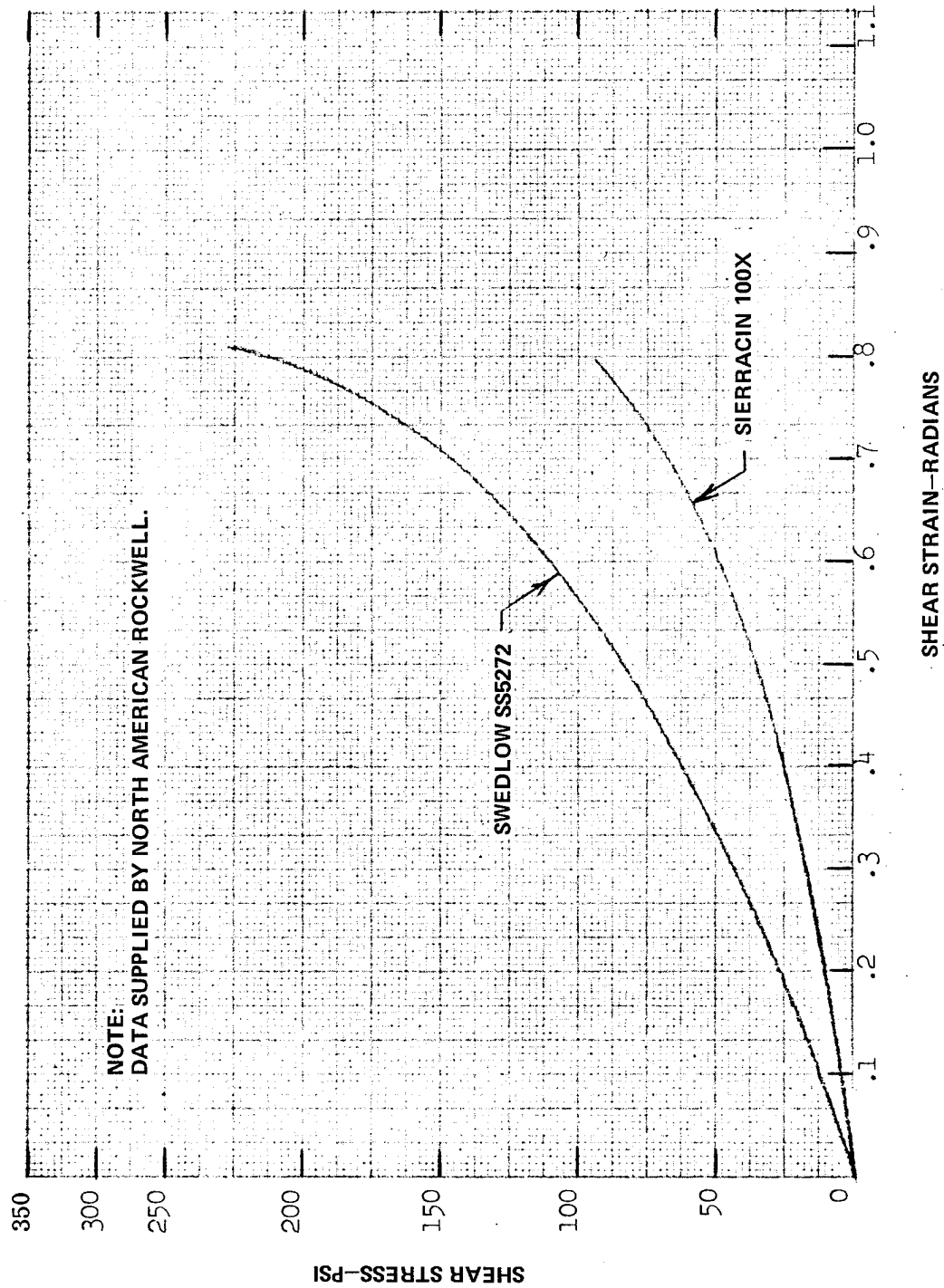
Figure 5.5-5 - Shear Stress versus Strain at 250 Deg F, Silicone Interlayers
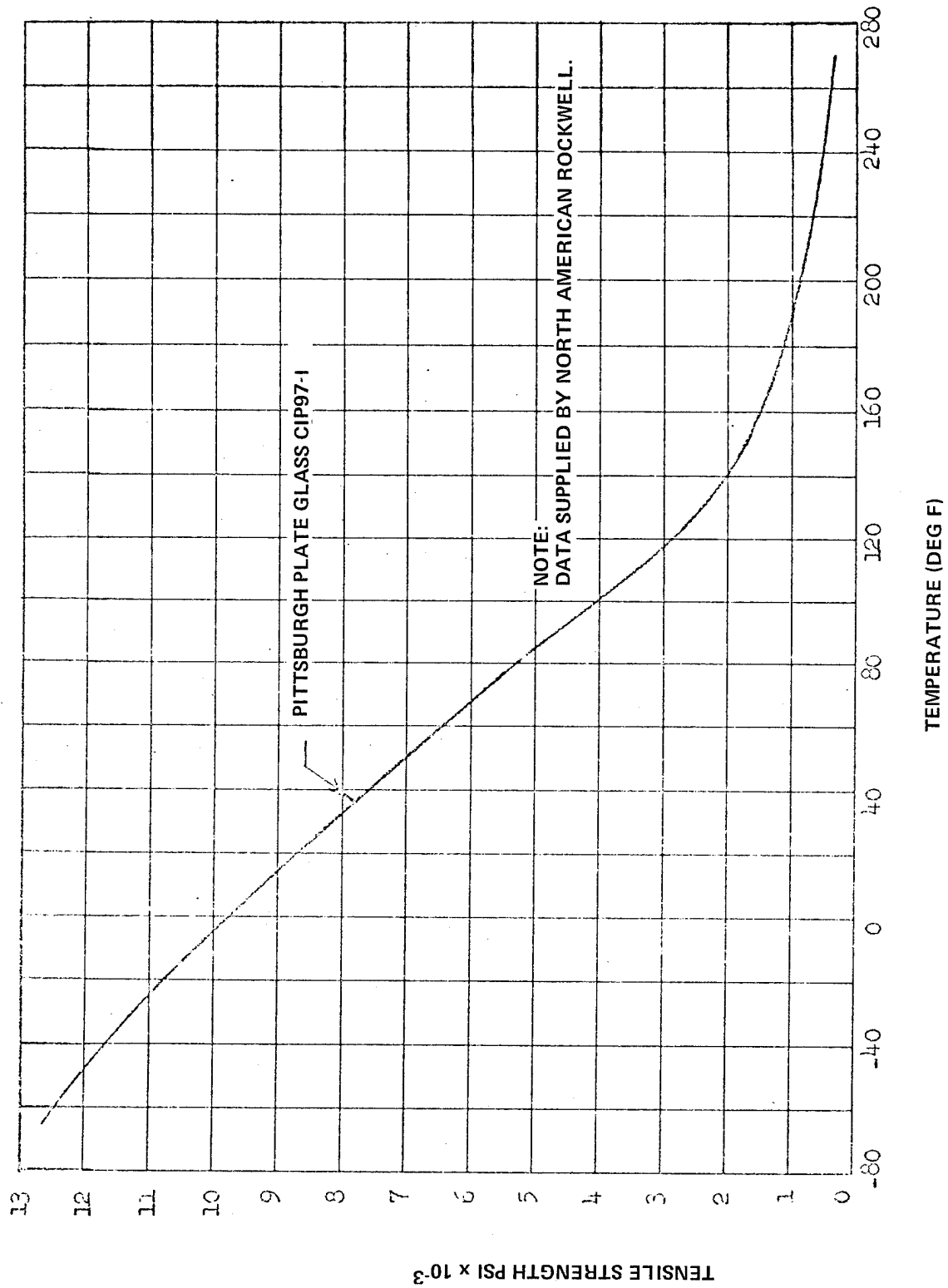
Figure 5.6-1 – Tensile Strength of Polyurethane Interlayer versus Temperature

NOTE: DATA SUPPLIED BY GOODYEAR AEROSPACE.
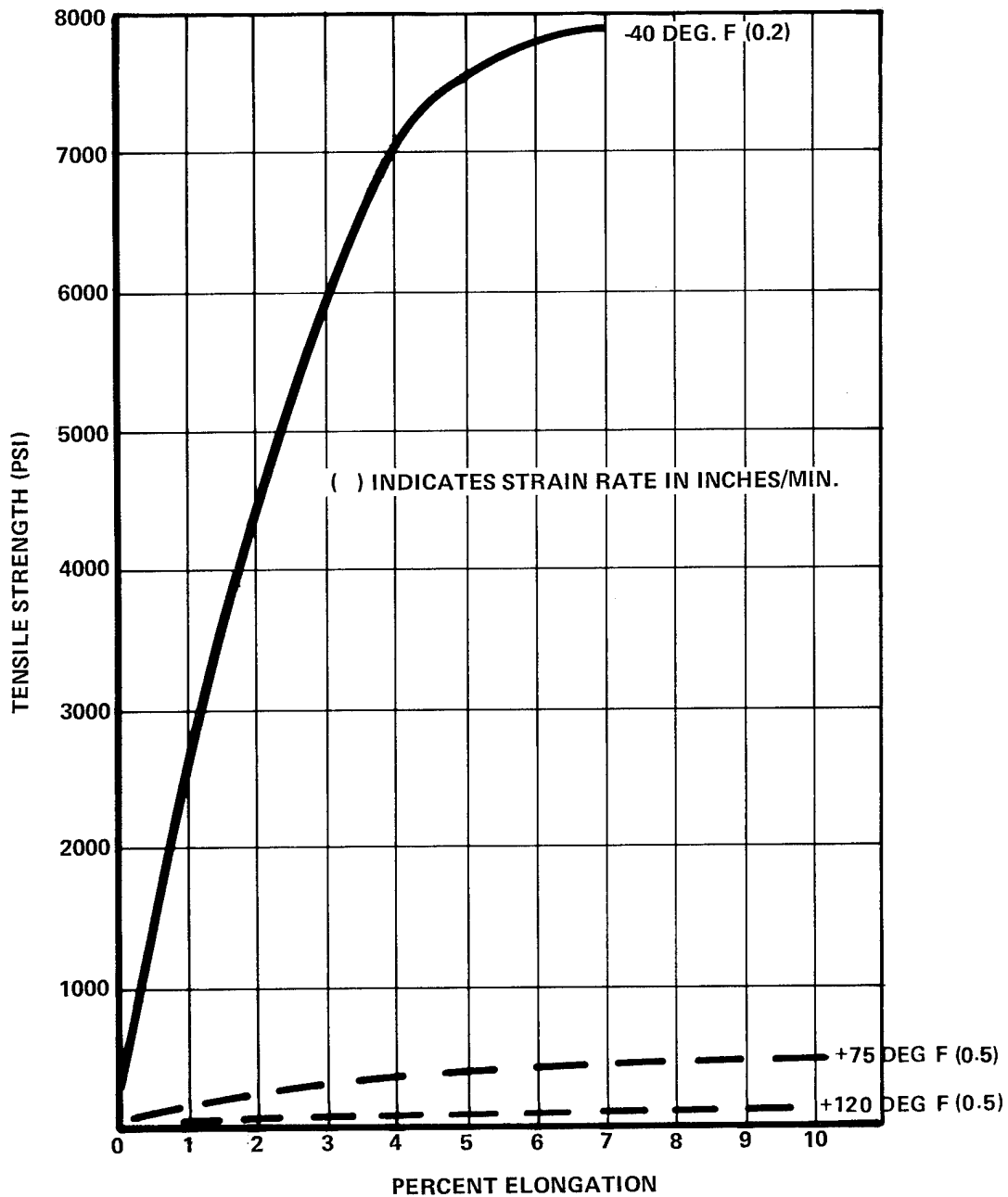
Figure 5.6-2 – Tensile Strength of F-3X-40 Polyurethane Interlayer versus
Strain at Various Temperatures

5-19
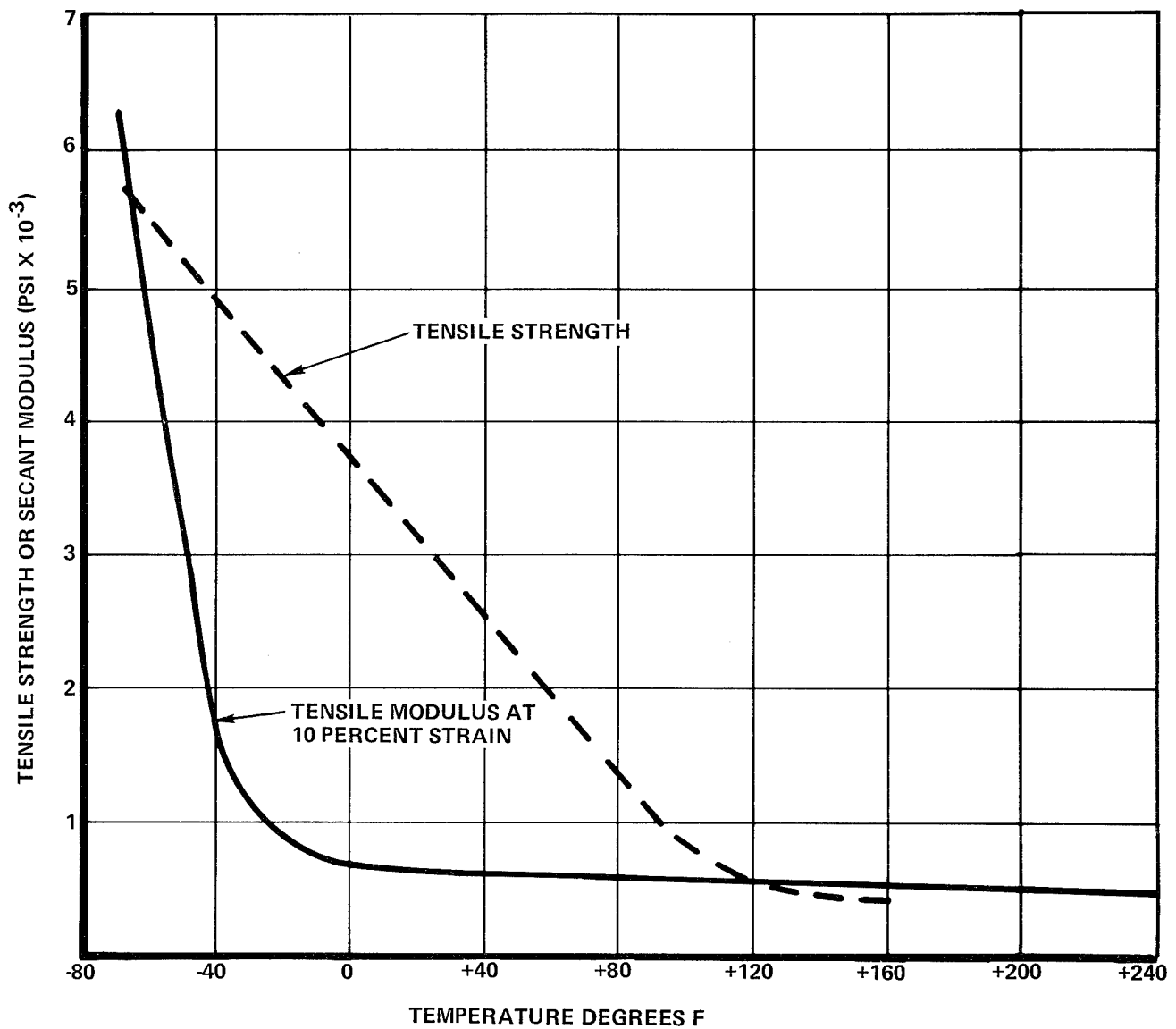
Figure 5.6-3 – Tensile Properties of F5X-1 Polyurethane
Interlayer versus Temperature

5-20

5.7 COMPARABLE INTERLAYER PROPERTIES

Various room temperature properties of interlayer materials are tabulated in Table 5.7-I.
The curves of Figures 5.7-1, 5.7-2, and 5.7-3 compare both silicone and urethane based
materials through a temperature range of -65 F through +270 F and provide elongation,
thermal conductivity, and specific heat information. Figures 5.7-4 and 5.7-5 provide the
shear strengths of two types of silicone interlayers on various substrates.

TABLE 5.7-I – MECHANICAL AND PHYSICAL PROPERTY DATA OF INTERLAYER MATERIALS

Property	Polyvinyl butyral	SS 5272 Y(HT) (Swedlow)	CIP 97I (PPG)	CIP 97 (Sierracin)
Specific gravity	1.08	1.02	1.146	1.05
Index of refraction	1.483	1.409	1.529	1.43
Light transmission (percent)	87	89	88	89
Thermal conductivity (BTU/hr/ft^2/deg F/in.)	1.5	0.98	0.99	0.89
Specific heat (Cal/cm/deg F)	0.35	0.31	0.37	0.37
Coefficient of expansion of	5×10^{-5}	21.2×10^{-5}		
Tensile strength PSI $\times 10^{-3}$ at room temperature	4.0	0.57	5.7	0.99
Ultimate elongation (percent at room temperature)	200	400	550	225

Notes: 1. The Swedlow and Sierracin interlayers are silicone base.
2. The Pittsburgh Plate Glass (PPG) interlayer is polyurethane base.
3. Data supplied by North American Rockwell.
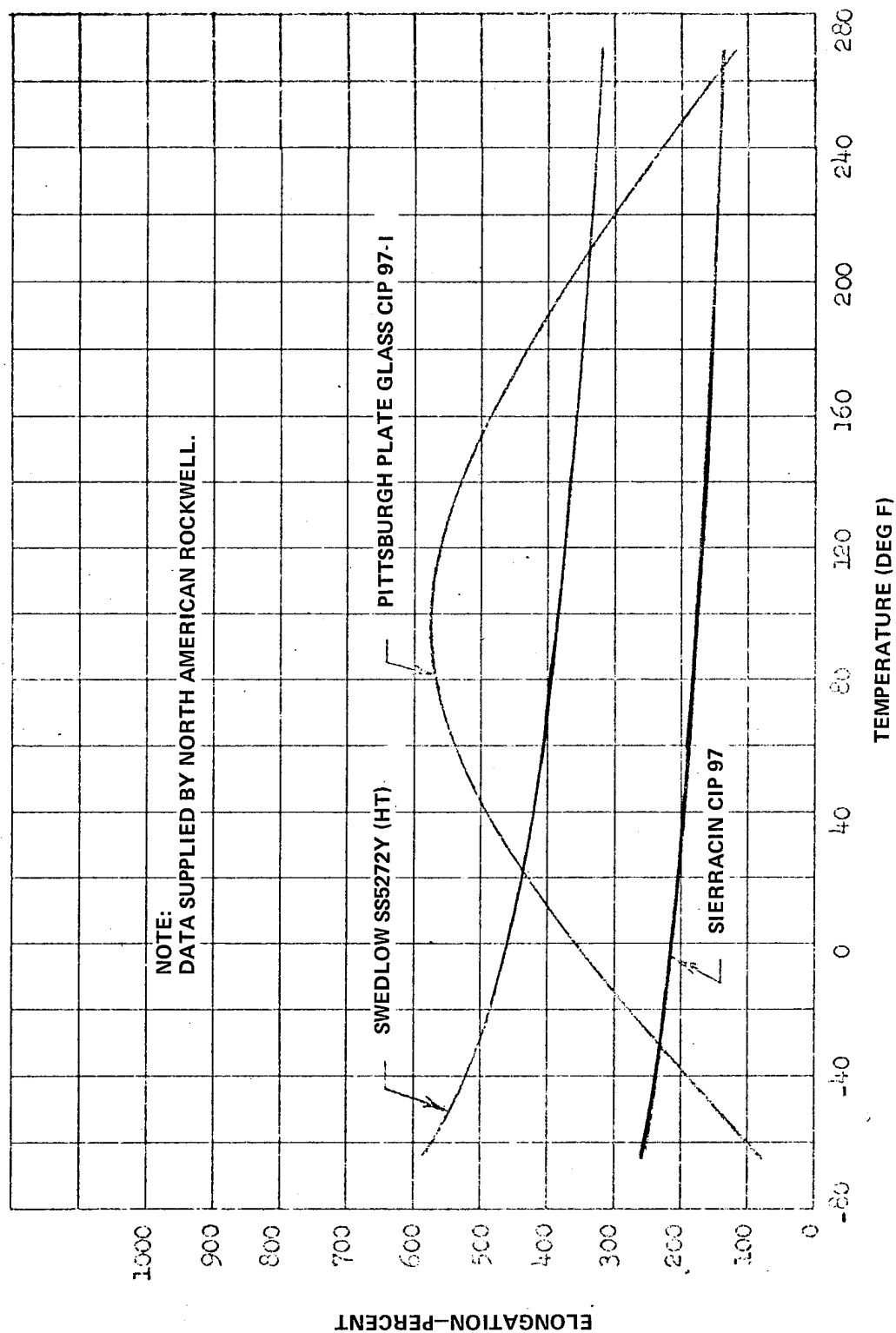
Figure 5. 7-1 – Elongation versus Temperature of Interlayer Materials
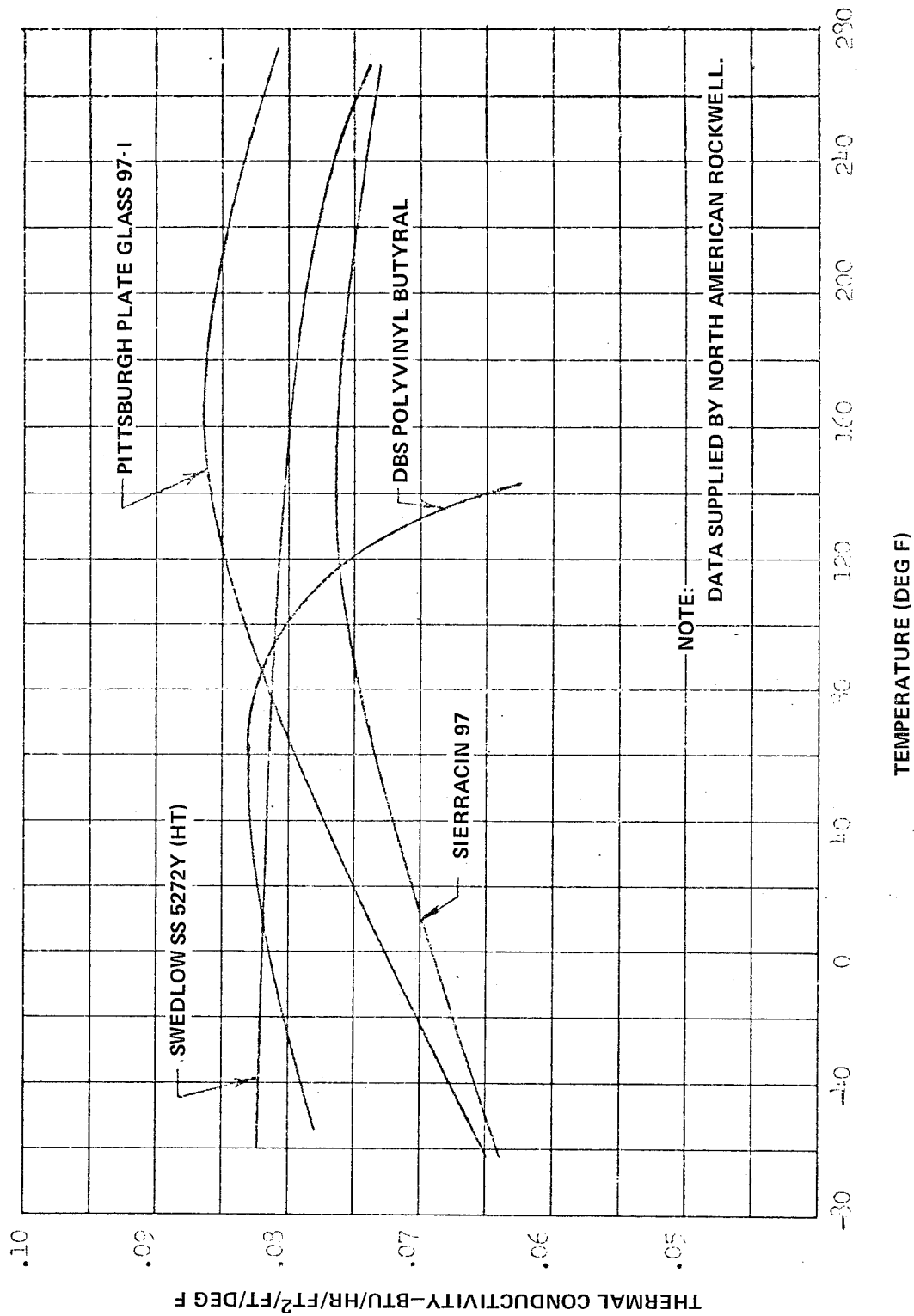
Figure 5. 7-2 – Thermal Conductivity versus Temperature of Interlayer Materials

5-24
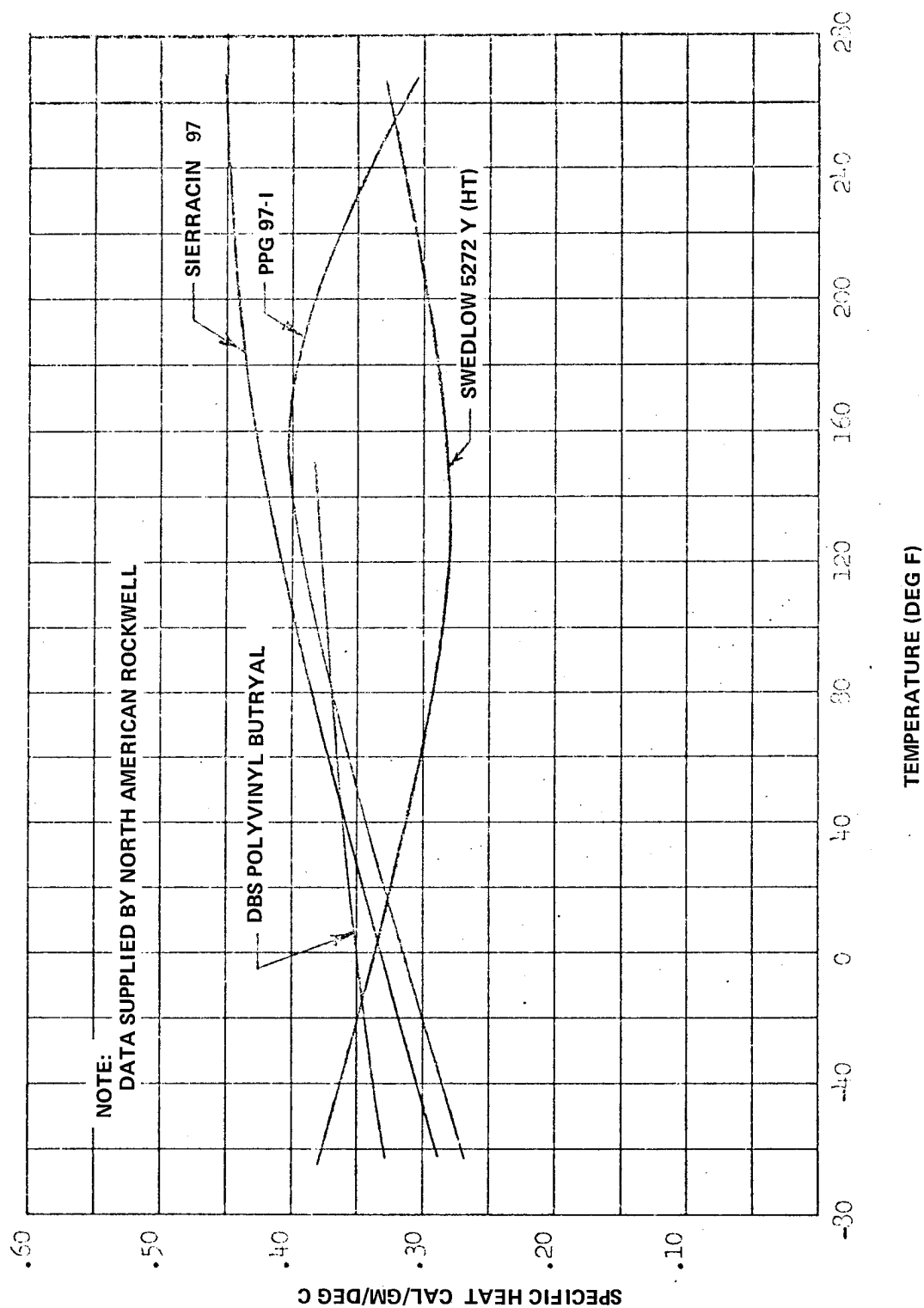
Figure 5. 7-3 - Specific Heat versus Temperature of Interlayer Materials
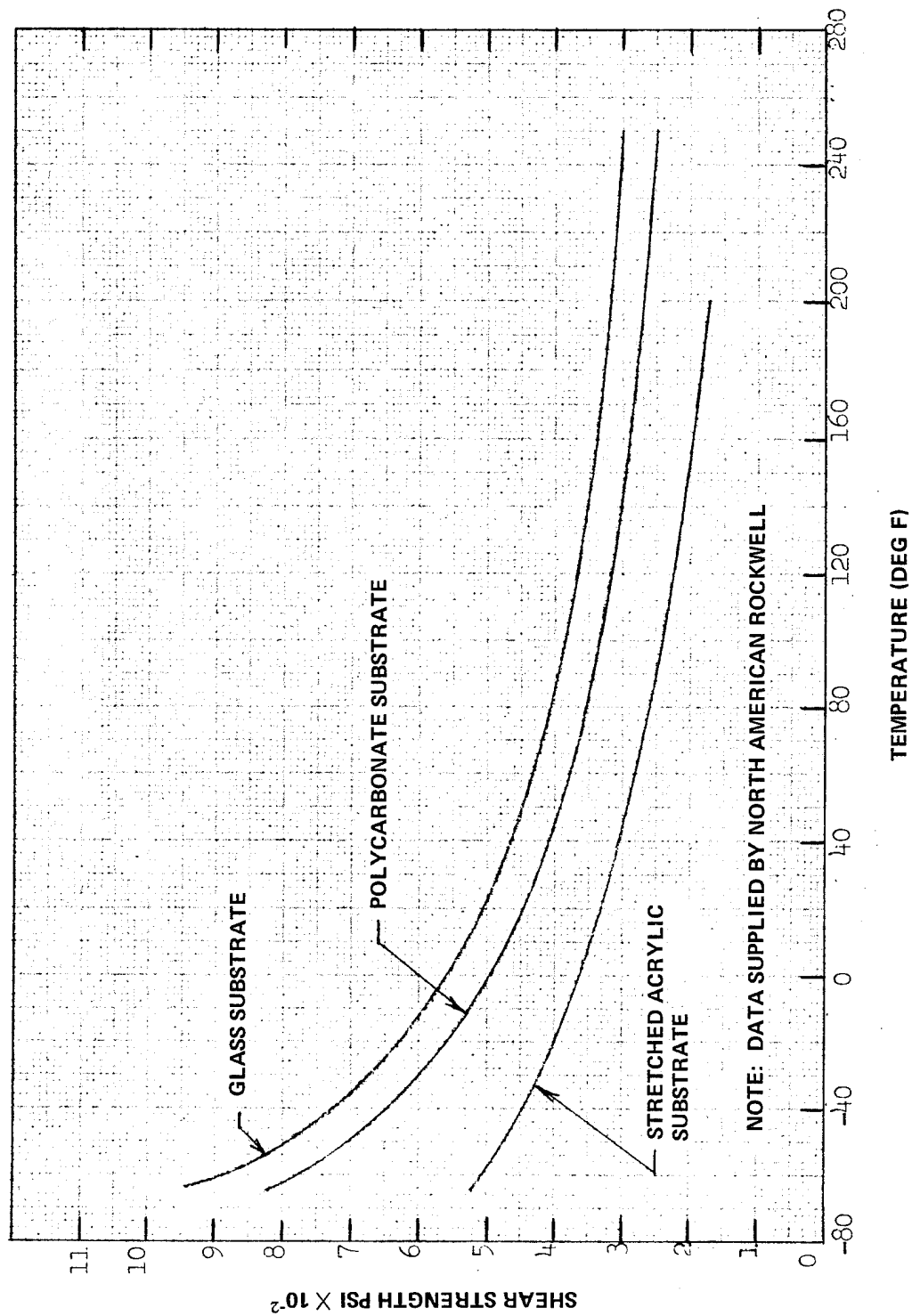
Figure 5.7-4 - Shear Strength versus Temperature, Swedlow SS5272 Silicone Interlayer
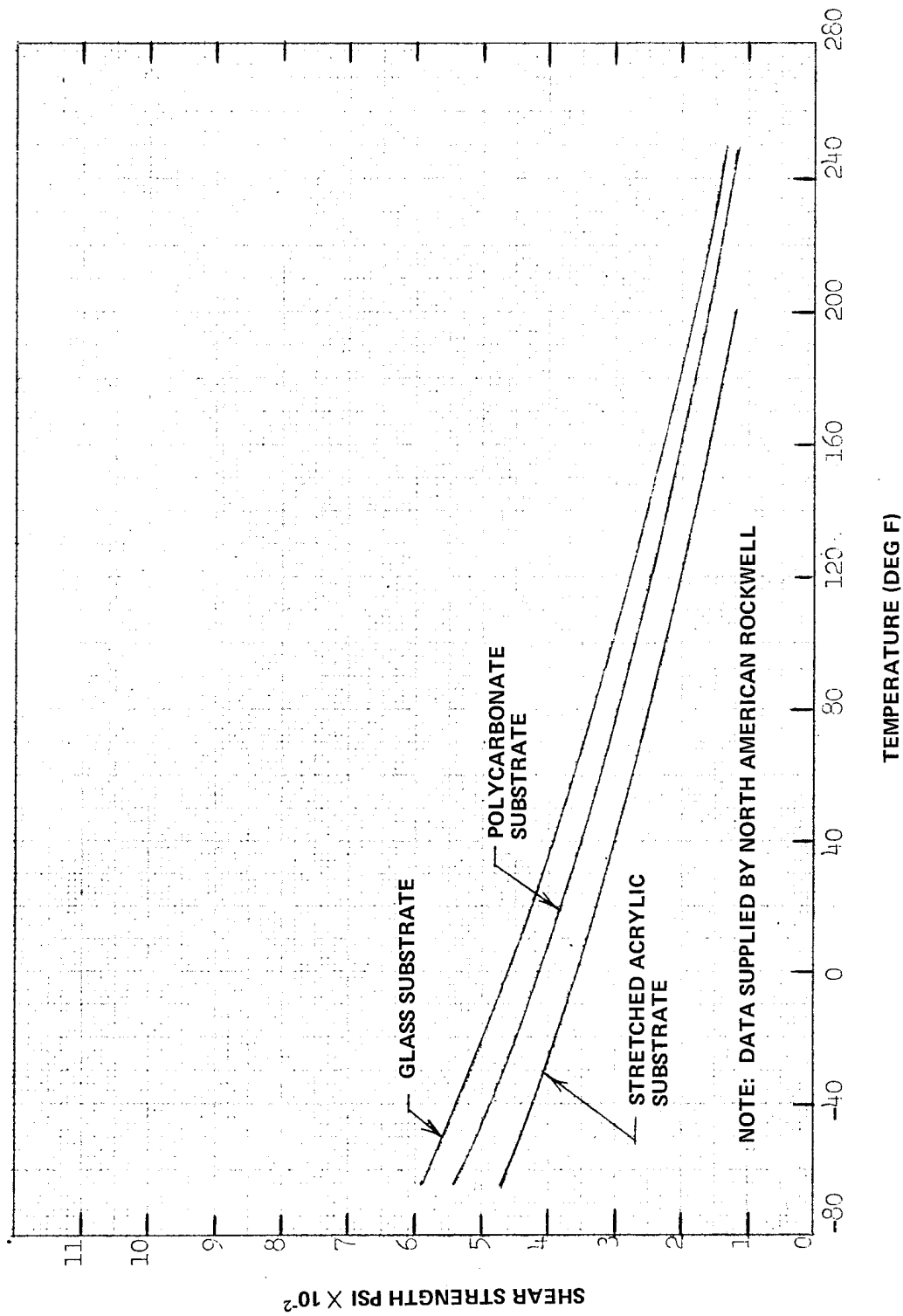
Figure 5. 7-5 – Shear Strength versus Temperature, Sierracin 100X Silicone Interlayer

CHAPTER 6 - COATINGS

6.1 GENERAL

Coatings, rather than being classified by physical or chemical properties, are identified according to usage. Coating application for the most part is proprietary and performed by processors. The designer, however, does have to be aware of some of the complexities and be able to provide the processor with the essential information he needs. The most complex coatings will be discussed first, because other types have been derived from them.

6.2 ANTI-ICING AND ANTI-FOGGING COATINGS

6.2.1 CHOICE OF SYSTEMS

Ice and fog can be prevented with hot air or chemical devices. Table 6.2-I evaluates hot air and conductive coating systems. This section, however, pertains primarily to electrically conductive coatings which are used as an integral part of glazing. Anti-icing coatings are located near the outboard surface of the glazing and are designed to keep the surface at a few degrees above freezing (usually +35 deg F). Anti-fogging coatings are sometimes located near the inboard surface, but more recent structural laminate designs locate the coated surface closer to the center of the over-all thickness. The coating is designed to keep the temperature of the exposed inner surface above the dew point. At temperatures below freezing, the frost point is below the dew point, in which case the inner surface temperature would have to be above the frost point. In many cases, the anti-icing coating may also serve as an anti-fogging protection. If not, it would become impractical to use two conductive coatings because of the severe decrease in light transmission which would occur. In such a case, both electrically conductive and hot air systems may be in order (see Figures 10.7-6 and 10.7-7 on pages 10-39 and 10-40).

6.2.2 INBOARD COATINGS

In designs where only an anti-fogging coating is necessary, the coating would primarily be heating the inboard surface. To accomplish this, the conductive coating is either applied to

6-1

TABLE 6.2-I – TRANSPARENT AREA ANTI-ICING SYSTEMS

Type	Description	Advantages	Disadvantages	Weight/cost
Electrical conductive coatings	Coating is constructed within the transparent laminates. Power is applied from outside producing internal heat. MIL–T–5842 applies.	Efficient – heat is applied at the surface required.	Visibility is reduced through the sighting areas. Windshield damage by overheat can be a problem.	Lowest weight/ Highest cost
Air jet	Engine bleed air is applied to the external face of windshield.	Visibility is not affected. Can be designed for rain removal as well.	Windshield damage by overheat can be a problem.	Highest weight/ Lowest cost

Defog–defrost systems

Type	Description	Advantages	Disadvantages	Weight/cost
Electrical conductive coatings	Coating is constructed in the transparency. MIL–T–5842 applies.	Efficient – heat is applied at the surface.	Visibility is reduced through the sighting areas. Overheat can cause transparency damage.	Lowest weight/ Highest cost
Air jet	Tempered bleed air is applied through nozzles to internal face of sight-ing areas.	Visibility is not affected.	Overheat can damage transparency. Affects temperature control of cabin adversely.	Highest weight/ Lowest cost

a thin transparent face sheet with a relatively hard surface (i. e., polyester) and laminated, with an interlayer adhering the coating and the substrate to the thicker structural member of the glazing or applied directly to the unexposed face of the inside ply of a structural laminate. Although most of the coating thermal energy will be moving toward the cold outboard side, a quantity will be penetrating and heating the surface of the inboard face sheet. External fogging occurs when a transparency which is coldsoaked, usually by flying at altitude, rapidly descends into warmer and/or moister air, causing condensation on the outside surface. In this case, the outside surface temperature must be maintained above that anticipated dew point. Naturally, this is automatically provided by anti-icing coating, if present.

Anti-fogging, defogging, and defrosting amount to suppressing the dew point at the inner surface by raising the surface temperature above the point at which vapor condensation would normally occur. The designer has to determine approximately where this point is under the worst operational condition. The dew point by definition involves constant pressure and no change in moisture content of the air. Because cockpit conditions may vary with altitude and moisture content, including crew breath moisture, the controlling temperature has to be specified slightly higher than the theoretical point derived from the worst static condition. If a parked aircraft requires de-icing prior to taxiing, an auxiliary external heat source may be required to assure rapid removal.

6.2.3 OUTBOARD COATINGS

Anti-icing is accomplished by maintaining the outer surface of the glazing at +35 deg F. Conductive coatings are preferably used as ice preventives rather than "de-icers," which would require more power to overcome the heat of fusion of the ice under a condition of rapid accumulation. The MIL-T-5842A Heating requirement is shown in Figure 6.2-1. For higher performance aircraft, a more rigorous analysis than that contained in MIL-T-5842A may be required.

6.2.4 REQUIRED DATA

Both types of coatings require heat transfer calculations which need other information that the designer or thermodynamicist has to supply. The thicknesses of each layer of the
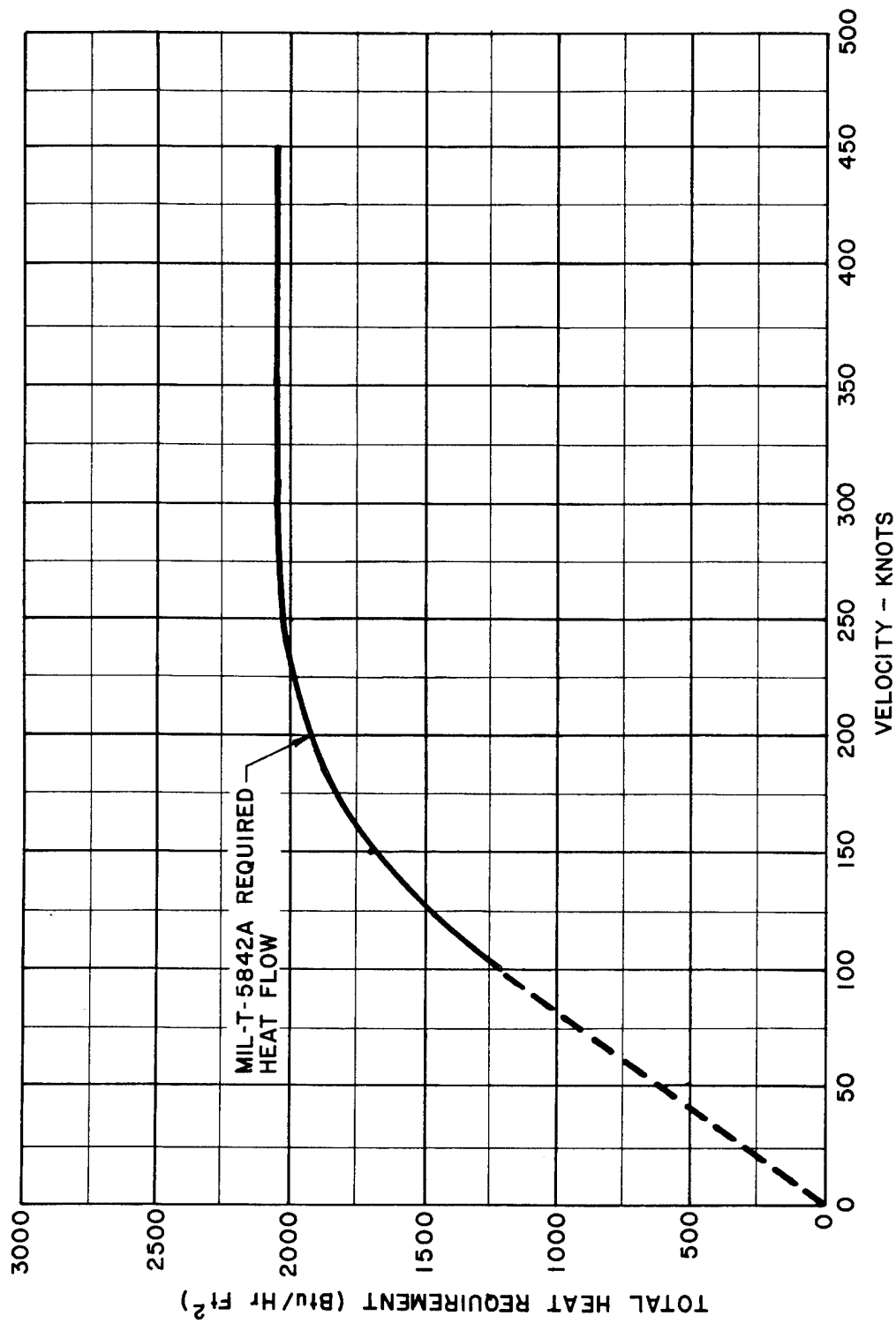
6-3

Figure 6.2-1 – Velocity versus Maximum Heat Requirement (Exterior Surface Temperature 35 Deg F)

6-4

transparent laminate with their coefficients of thermal conductivity are required. The most severe outer surface temperature to be expected is to be determined, which takes into account the temperature, density and humidity of the outside air, true speed of the aircraft, and shape of the glazing. The heat transfer coefficients at the surfaces will also be necessary. Once these data are accumulated, heat flow calculations can be performed which are translatable into electrical power per unit area. Through Ohm's law, the resistance of the electrically conductive coating can be determined in terms of "ohms per square." These calculations are well-defined in Reference 86. Examples of calculated gradients are shown in Figures 6.2-2, 6.2-3, 6.2-4, and 6.2-5.

6.2.5 RESISTIVITY MEASUREMENTS

Electrically conductive coatings use two terms of resistance which should be understood. The coatings may be one of several materials, depending upon the service required and the substrate. If any one of the coatings is considered as a four-sided geometric area, two of the opposite sides will be edged with bus-bars of highly conductive material which terminate in leads for attaching to the glazing heating control as shown in Figure 6.2-6. Unpowered, the resistivity across these leads is known as the bus-to-bus resistance and is measured directly in ohms.

The second unit, ohms per square, or sheet resistivity, is used by the processor because it involves the thickness of the coating which is to be applied. Figure 6.2-7 shows how a section of coating is defined by its physical dimensions and the direction of the current flow. Ohms per square is a nondimensional measurement and does not refer to square inches or square feet. At a given thickness, t, the resistance between faces, x and y, is directly proportional to D and inversely proportional to W. When D and W are equal, and t remains the same, the resistance between faces x and y will be the same for any value of W equal to D. Varying t, then, is the means of varying resistance. In coating processes, therefore, coating thicknesses can be checked with square witness samples which contain bus-bars at two opposite edges and undergo coating on the bare substrate between them. In this case, a bus-to-bus reading is directly convertible to ohms per square as a check on suitable coating deposition.
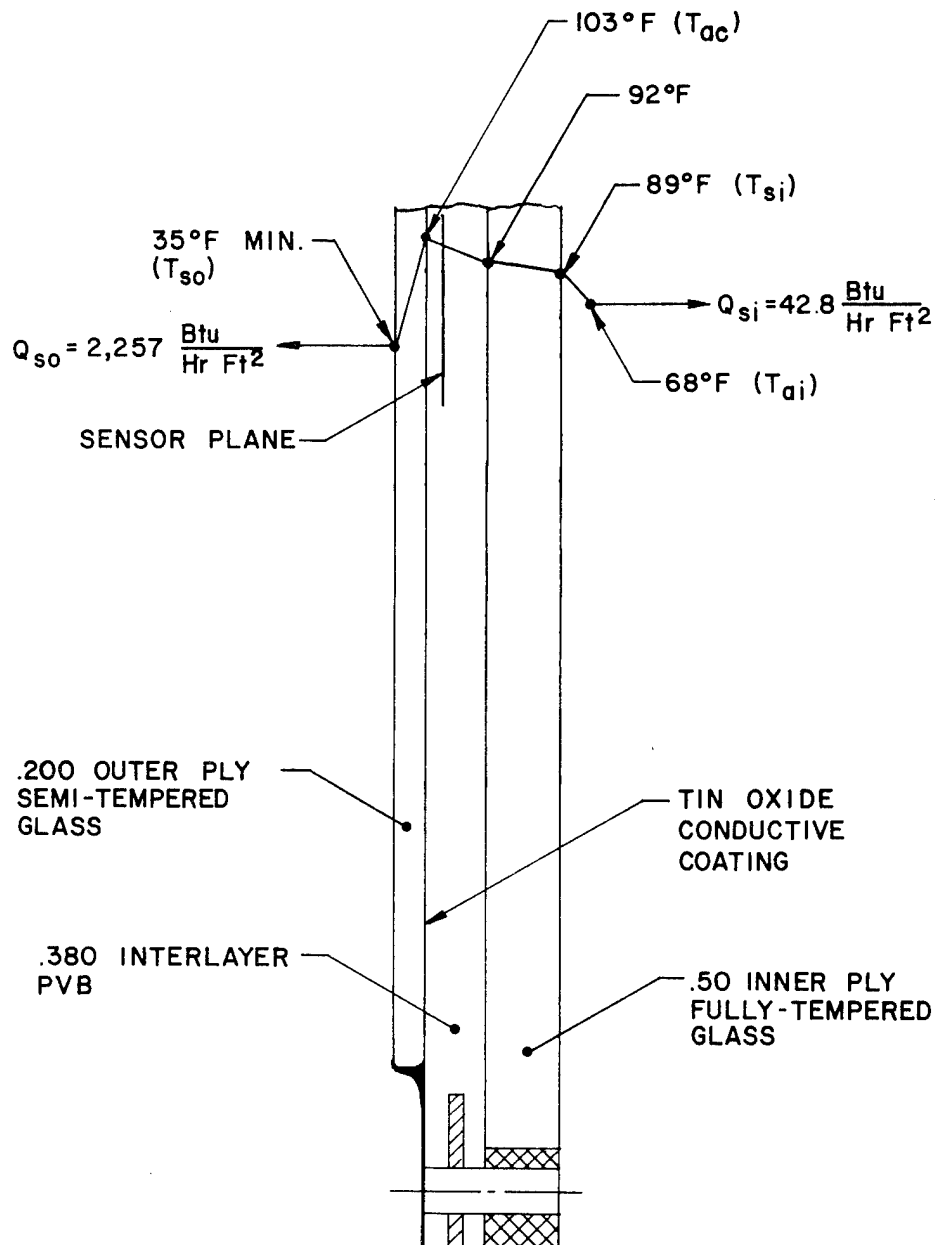
6-5

103°F (T_{ac})

92°F

89°F (T_{si})

35°F MIN.
(T_{so})

$Q_{so} = 2,257 \dfrac{Btu}{Hr\ Ft^2}$

$Q_{si} = 42.8 \dfrac{Btu}{Hr\ Ft^2}$

68°F (T_{ai})

SENSOR PLANE

.200 OUTER PLY
SEMI-TEMPERED
GLASS

TIN OXIDE
CONDUCTIVE
COATING

.380 INTERLAYER
PVB

.50 INNER PLY
FULLY-TEMPERED
GLASS

NOTE: ILLUSTRATION AND DATA SUPPLIED BY SIERRACIN CORPORATION; ALSO FROM REPORT BY P. A. MILLER.

Figure 6.2-2 – 707 Windshield Cross-Section and Approximate Temperature Profile
at Full Power Delivery
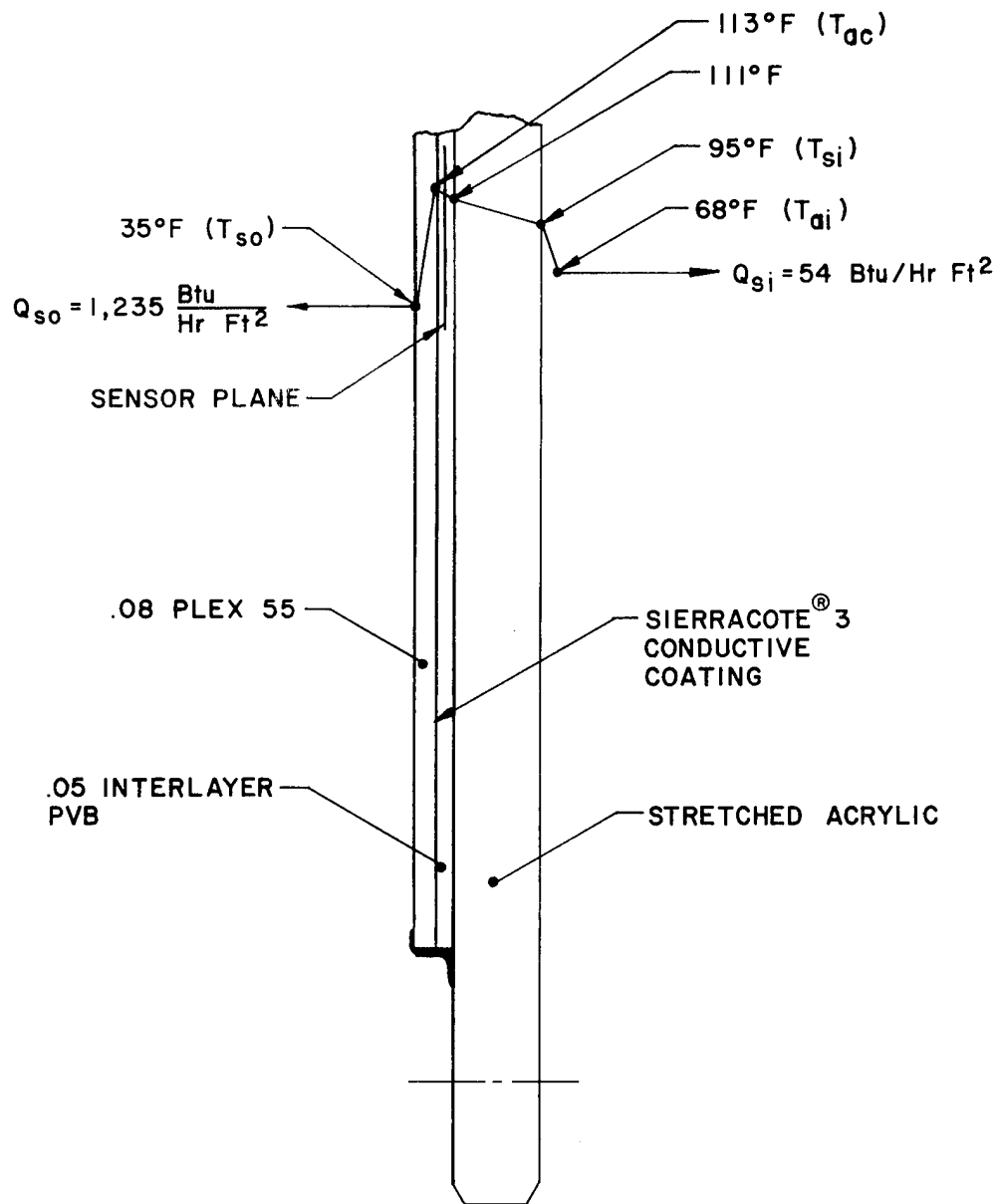
6-6

113°F (T_{ac})

111°F

95°F (T_{si})

68°F (T_{ai})

Q_{si} = 54 Btu/Hr Ft^2

35°F (T_{so})

Q_{so} = 1,235 $\dfrac{Btu}{Hr\ Ft^2}$

SENSOR PLANE

.08 PLEX 55

SIERRACOTE® 3
CONDUCTIVE
COATING

.05 INTERLAYER
PVB

STRETCHED ACRYLIC

NOTE: ILLUSTRATION AND DATA SUPPLIED BY SIERRACIN CORPORATION; ALSO FROM REPORT BY P. A. MILLER.

Figure 6. 2-3 – Cessna 421 Windshield Cross-Section and Approximate Temperature Profile
at Full Power Delivery
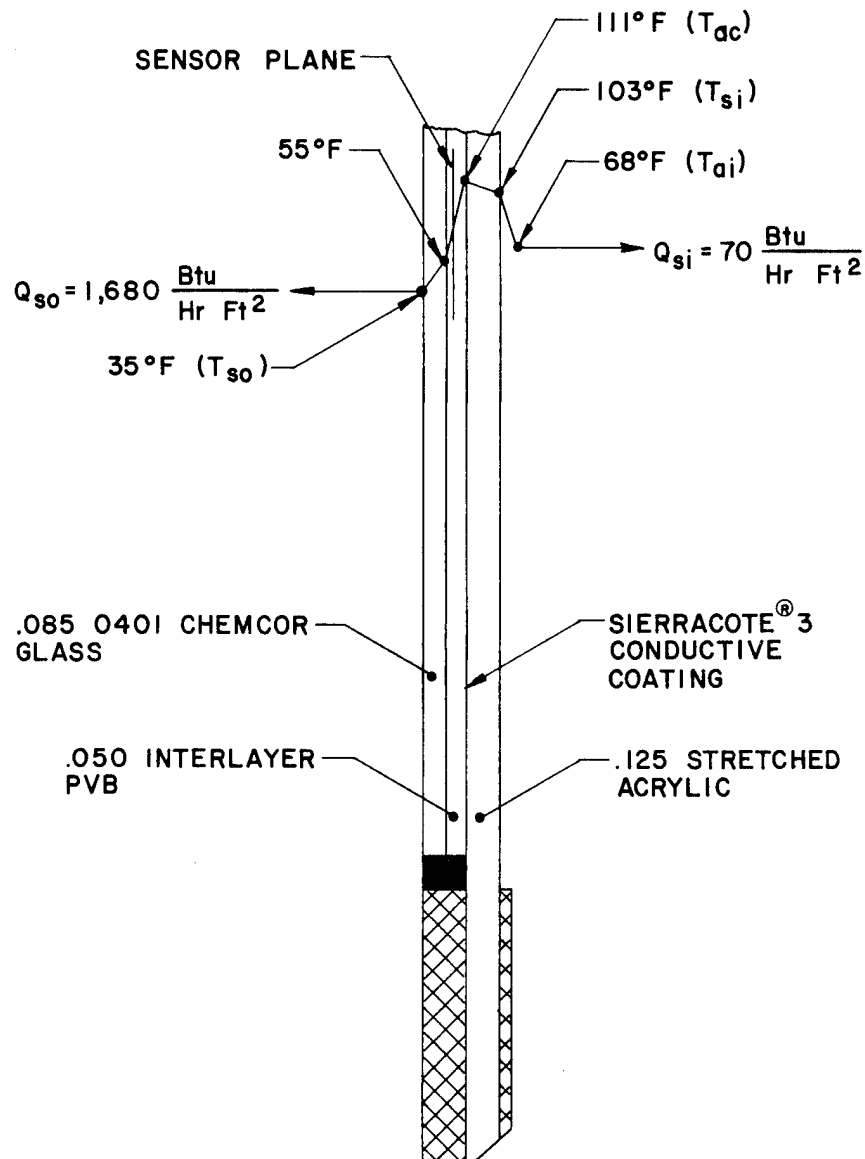
6-7

SENSOR PLANE

111°F (T_{ac})

103°F (T_{si})

55°F

68°F (T_{ai})

$Q_{si} = 70 \dfrac{Btu}{Hr\ Ft^2}$

$Q_{so} = 1,680 \dfrac{Btu}{Hr\ Ft^2}$

35°F (T_{so})

.085 0401 CHEMCOR GLASS

SIERRACOTE® 3 CONDUCTIVE COATING

.050 INTERLAYER PVB

.125 STRETCHED ACRYLIC

NOTE: ILLUSTRATION AND DATA SUPPLIED BY SIERRACIN CORPORATION; ALSO FROM REPORT BY P. A. MILLER.

Figure 6.2-4 – CH-47A Chinook Composite Windshield Cross-Section and Temperature Profile at Full Power Delivery
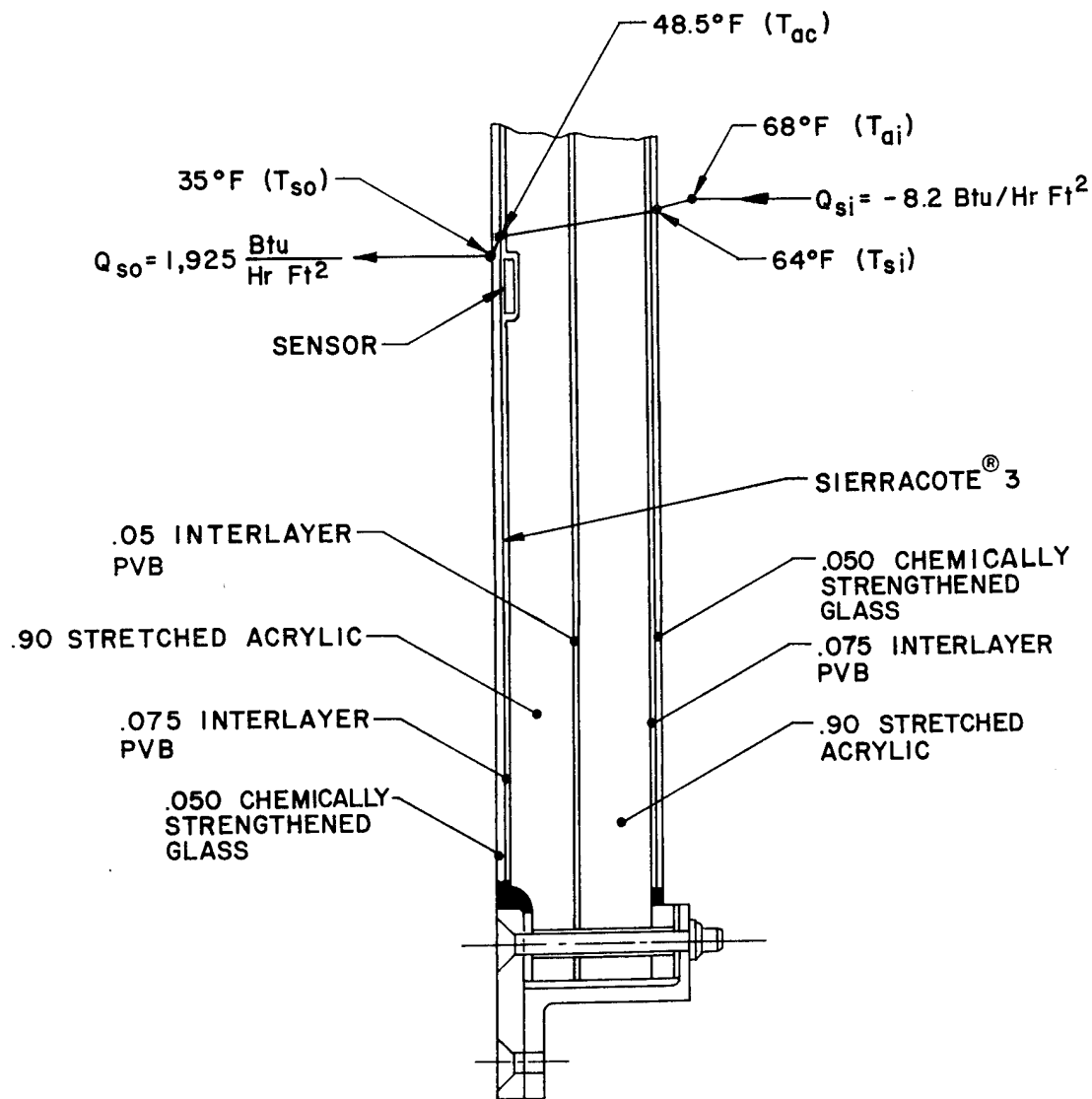
6-8

$48.5°F \ (T_{ac})$

$68°F \ (T_{ai})$

$35°F \ (T_{so})$

$Q_{si} = -8.2 \ Btu/Hr \ Ft^2$

$Q_{so} = 1,925 \dfrac{Btu}{Hr \ Ft^2}$

$64°F \ (T_{si})$

SENSOR

SIERRACOTE® 3

.05 INTERLAYER PVB

.050 CHEMICALLY STRENGTHENED GLASS

.90 STRETCHED ACRYLIC

.075 INTERLAYER PVB

.075 INTERLAYER PVB

.90 STRETCHED ACRYLIC

.050 CHEMICALLY STRENGTHENED GLASS

NOTE: ILLUSTRATION AND DATA SUPPLIED BY SIERRACIN CORPORATION; ALSO FROM REPORT BY P. A. MILLER.

Figure 6.2-5 – 747 Windshield Cross-Section and Temperature Profile at
Full Power Delivery

6-9

NOTE: ILLUSTRATION AND DATA SUPPLIED BY SIERRACIN CORPORATION; ALSO FROM REPORT BY P. A. MILLER.
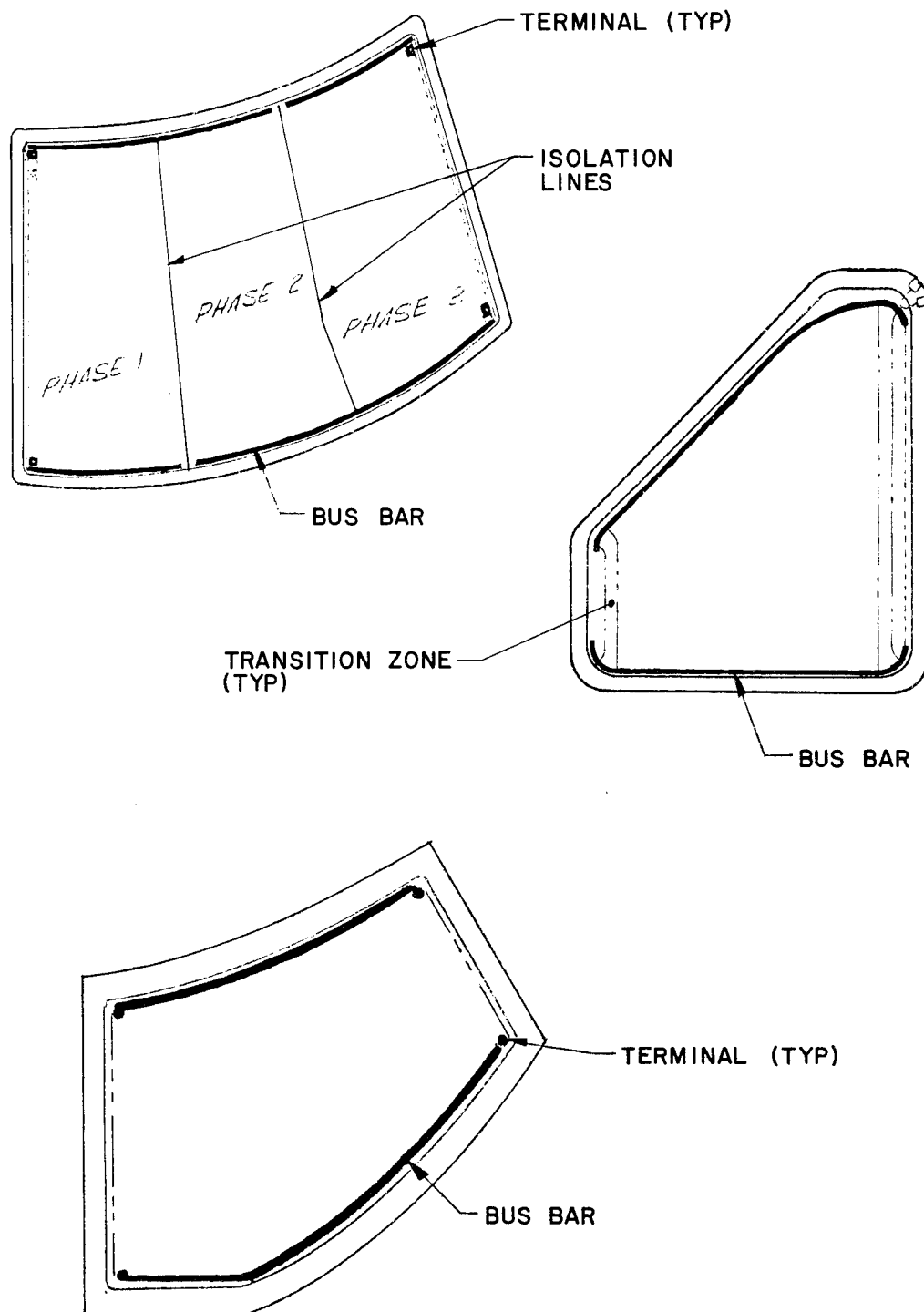
Figure 6.2-6 – Flat Pattern of Typical Electrically Heated Panels
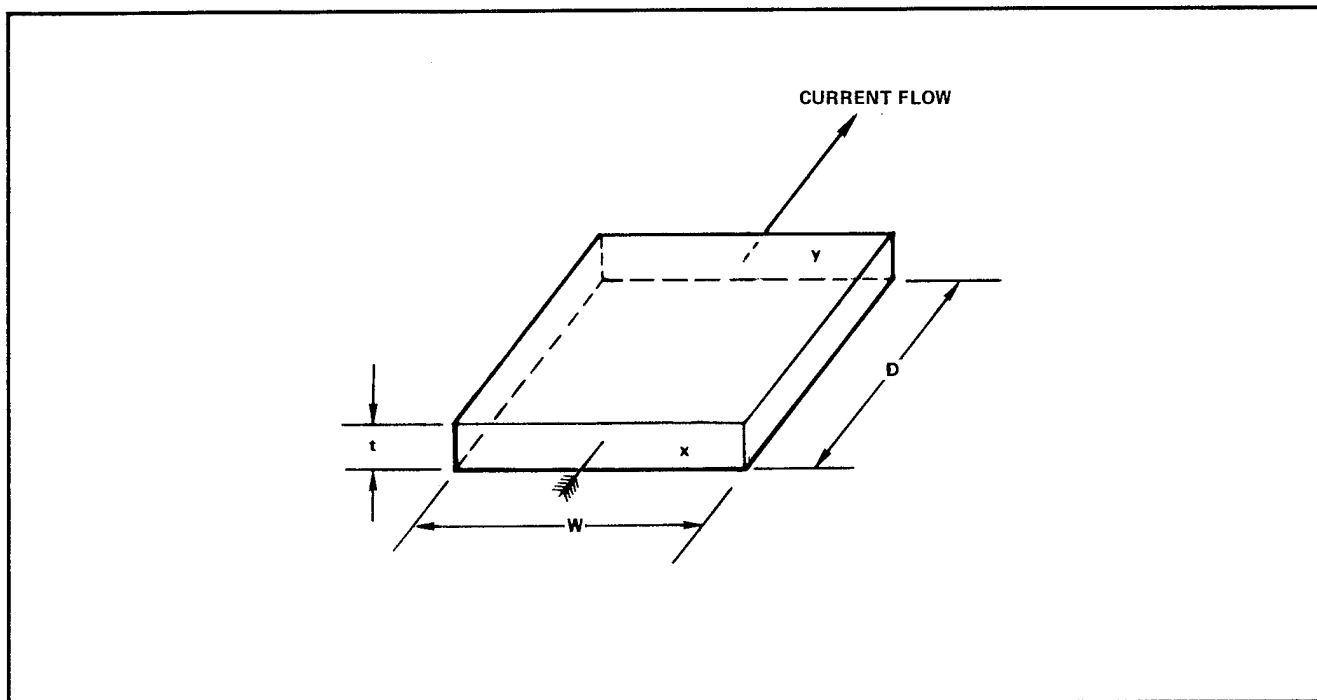
Figure 6.2-7 — Dimensional Model of a Film Increment in Ohms per Square

6.2.6   LIMITING FACTORS

Often the interlayer material will be the limiting factor, because it is next to the heated coating surface. Allowable maximum coating temperature in contact with polyvinyl butyral has been limited to 130 F, and for contact with silicone-interlayer, +250 F. For plastic substrates, anti-fogging coatings require approximately 1 watt/in.^{2} and anti-icing coatings up to 5 watts/in.^{2} The coatings for plastic substrates are usually gold and can be uniformly coated on simple curved surfaces.

Glass substrates have historically relied on tin oxide coatings which feature higher resistivity and the advantage of higher light transmittance but require pyrolytic application at approximately +1100 deg F, which degrades chemically tempered glass and cannot be used on plastic. An alloyed indium oxide has now been developed which can be applied to tempered glass at +500 deg F without destroying basic properties. Coated glass panels are usually fabricated as flat panes.

6.2.7   CONTROLS AND EQUIPMENT

All heated coating systems require a power source, a controller, and a sensor. If the power source is multiphased, then the conductive panels should be designed to nearly equally load all phases as indicated in Figure 6.2-6. For each differently shaped heated panel, a separate temperature sensor should be included. The sensors are small, but will require a position in the least noticeable part of the visual area. Two general types of sensors are available. One can be inserted or cast in the flexible inner layer material, and the other can be surface mounted. One sensor is needed to signal a demand for power from the controller. Others are sometimes used either as a temperature limit sensor or as a redundant fail-safe unit. The sensor is a low-voltage device which operates a controller that supplies power on an "on-off" or proportioning basis. Controllers are commercially obtainable and are specifically designed for this purpose. The aircraft power source usage has to be coordinated with the electrical designer by designating the expected load requirements.

6.2.8   PANEL LAYOUT

Again referring to Figure 6.2-6, the bus bars are laid out a short distance from the edge of the optical area, and the panels separated for a phased system have "isolation lines." Figure 6.2-8 details a typical layout. These gaps are internal and serve as insulators between electrically conductive components. Figure 6.2-9 dimensions the bus-bar separation, depending upon the power requirement and the E/S ratio of voltage over bus-bar spacing in inches with respect to the coating surface resistivity.

6.3   RADAR REFLECTIVE COATING

6.3.1   PURPOSE

The metallic coatings used for anti-icing and anti-fogging were found to also be radar-reflective. Considering a glazing in which radar reflection is the only requirement, the design criteria would be based on different parameters. The purpose of the coating is to prevent a radar search beam from being concentrated by the cockpit cavity and returned as an easily identified target. Such a return can be likened optically to a glint or flash from
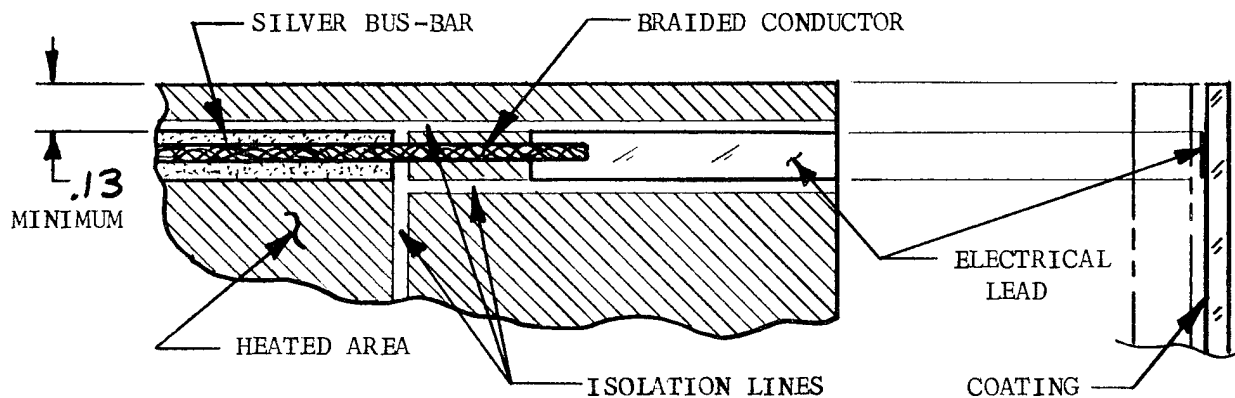
Note that bus-bars and leads are entirely enclosed in panels of laminated construction.

NOTE: FROM SIERRACOTE 3 ENGINEERING HANDBOOK (TECHNICAL BULLETIN 506).

Figure 6.2-8 – Typical Bus-Bar and Electrical Lead Installation

a distant sunlit chromed radiator grill which attracts one's eyesight to identify an approaching automobile. To suppress cockpit reflection, the transparent enclosure can be equipped with a transparent metallic coating which will blend the cockpit covering in with the general reflectivity of the fuselage and reduce its target acquisition signature or radar cross-section.

6.3.2   TERMS

Because radar has now become a complexity in transparency design, electrical terms should be explained for the mechanical designer to correlate to electromagnetic criteria. The decibel is sometimes a confusing unit to those who are used to working with parameters which are directly measurable as volts, amperes, ohms, and watts. Historically, the decibel was developed as a measurement for sound levels in telephone work and was defined as the smallest increase in sound power discernible to the human ear. This definition

6-13
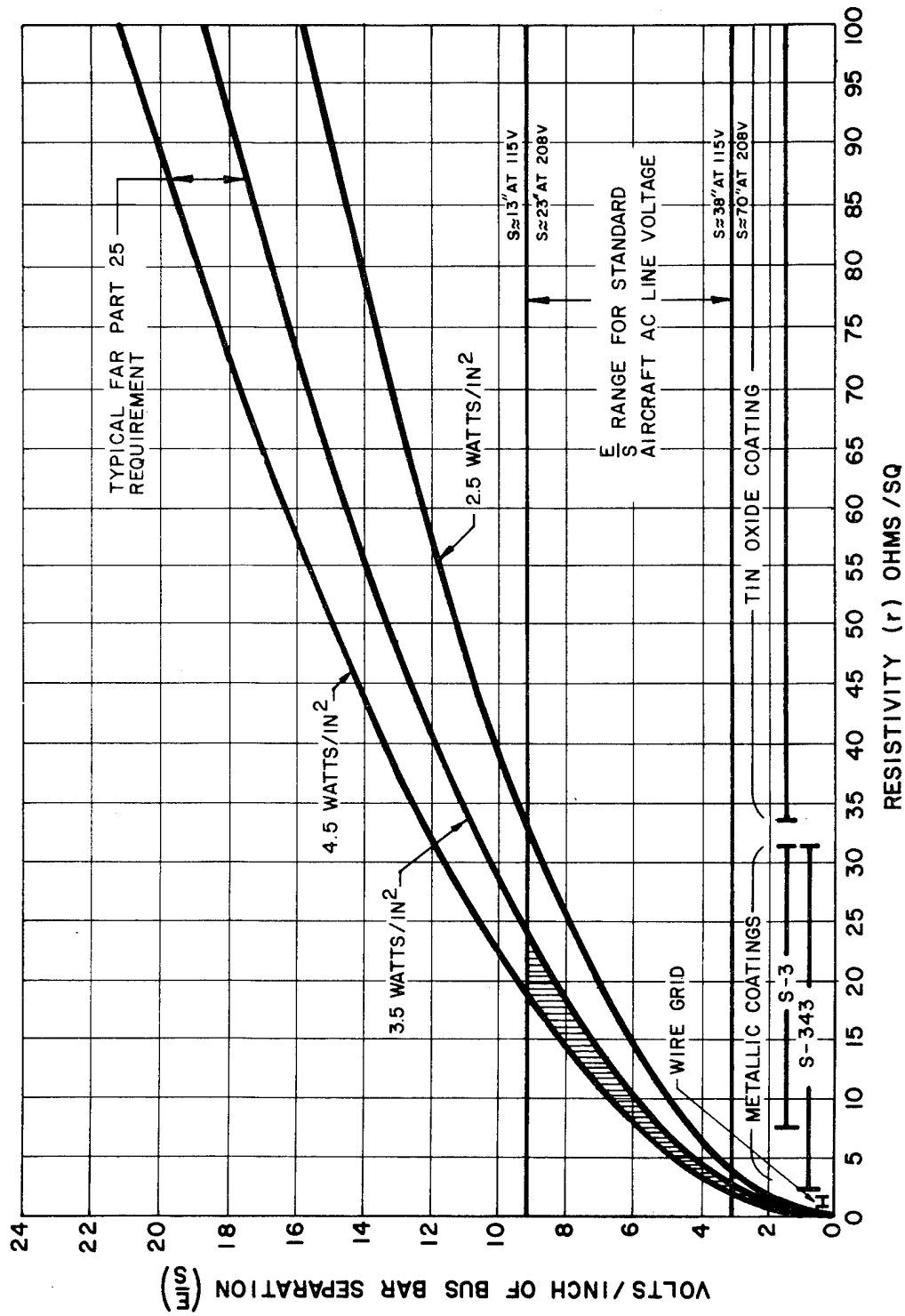
Figure 6.2-9 – Resistivity Characteristics and Effects of Various Conductive Coatings

denotes a change from some level already there. One understandable reason for this type of unit is that in telephone work there is most always a background level of noise, which is acoustical power and is discernible. Any sound of lesser power will be obliterated by the noise. Any sound of greater power will be noticed by its rising above the noise level. Rather than measure sound from zero, which is meaningless in a noisy background, as well as unobtainable, a reference level of power is chosen, P_R, and the decibel is defined as $10 \log_{10} \dfrac{P}{P_R}$, which implies that the human ear discerns power changes on a logarithmic curve. The decibel, being a nondimensional power ratio, was found to be a convenient unit for the microwave measurement of power losses through radomes. In radome testing, the power transmitted is compared with the power received. If a theoretically perfect radome were placed between a transmitter and receiver, no attenuation would occur; and the power sent would equal the power received, or P would equal P_R and the decibel would equal 0 or 100 percent transmission, in which P is the transmitted reference signal and P_R the received signal. If the received signal is attenuated by the insertion of a practical radome, which always has some loss through power reflection or absorption, P_R becomes less and the ratio increases. Because the ratio increase denotes a power loss in decibels, a negative sign is applied, and the measurement is often referred to as "db down" (from 0 db or less than 100 percent transmission).

In this case, db down can be associated directly with electromagnetic transmission by slide rule log scales or transmission versus db tables. Three db down is referred to as the "half-power point" and represents a 50-percent power loss, and 20 db down represents a 99-percent power loss. Anything below that is in the realm of noise from local radiation (static, neon signs, ignition noise, etc.).

6.3.3   ELECTRICAL THICKNESS THEORY

Because search radar may be of almost any frequency which can be directed as an electromagnetic wave front, the radar reflective coating should be able to defeat a broad band of frequencies. Broadband design usually implies testing at a representative number of frequencies between 3000 and 20,000 MHz. In this particular case, however, the coating

will serve as a mirror whose design thickness will vary inversely with the wavelength of the impinging radiation.

It is not considered necessary to test at all wavelengths in the S- through K-band frequency spectrum. A metallic coating which is sufficiently thick to repel any particular radiation accomplishes two principal actions. The majority of the signal is reflected. The remaining portion is penetrating or is being absorbed and reflected within the confines of the glazing. The penetrating portion is the radiation most affected by frequency. The coating plus the glazing is reacting as an inefficient radome with an extremely high dielectric constant. Ignoring interface reflections and absorbtions, and considering the electrical thickness of a thin wall radome, the following relationship may clarify the situation:

The electrical thickness
$$d_e = \frac{d \left(k - \sin^2 \theta \right)^{1/2}}{\lambda_o} \quad ,$$

where d is the thickness of the coating; k is the dielectric constant of some high value; and θ is the angle of incidence, which can be assumed as 0 for this explanation. Under these circumstances, $d(k)^{1/2}$ for a particular coating could be a constant, C; therefore, the electrical thickness is inversely proportional to the wavelength in free space. For an S-band frequency, assume a wavelength of four inches, and for X-band a wavelength of one inch. The electrical thickness of the same coating for the S-band frequency would be one-fourth of that for the X-band frequency.

The electrical thickness is defined as the thickness of the medium which will most efficiently transmit radiation of a certain wavelength. The lower the value of d_e, the better the transmission; conversely, the higher the value, the more attenuation. Therefore, if a particular coating under test satisfactorily attenuates an S-band signal, the attenuation of the penetrating X-band signal can be expected to be greater.

The over-all effect would be that an S-band frequency coating thickness will be slightly more efficient in protecting against any higher frequencies, because most of the signal is reflected upon impingement. For theoretical and testing purposes, θ is considered at 0 deg. Actually, θ is usually more than 0 deg, which further reduces the penetrating flux of the radiation.

6-16

6.3.4   COATING THICKNESS CRITERIA

The previous discussion indicates two test methods which involve direct radiation measurements. The work of Lt. M. J. Mann (Reference 13) was based on finding a coating thickness which reflected 90 percent of the impinging energy. The conclusions of requiring coating thicknesses of 10 ohms per square or less also impaired the light transmission characteristics of the coatings on 1/4-inch-thick glass substrates.

The second test method of checking for one-way transmission would more closely approach the actual situation in that concern is realistically toward the portion of the signal that enters the cockpit which is further attenuated upon its return path out of the cockpit. Actual data are currently of a classified nature, but indicate thinner coatings will suffice.

Once coating thickness criteria are established in terms of radiation defeat, a means of easily checking coating thickness is required. Bus-to-bus resistance is the easier measurement, but the incorporation of bus bars on each unit is an unnecessary expense if other means of control can be established. One-way radiation tests are easily performed, but obtaining repeatability on contoured surfaces is difficult. Production control of small flat witness samples with bus-bars which are coated with the part seems to be the more economic method, except that coating deterioration cannot be checked easily in the field. Bus-bars are not necessary for the coating to perform its function, although the coating should have grounding points to avoid an electrostatic charge accumulation.

6.3.5   RADIATION PROTECTIVE COATINGS

In situations where the pilot or crew are exposed to spurious radiations from its own externally mounted aircraft-electronic countermeasures radar, the same type of coating may be utilized, except that the coating can possibly be designed for a specific frequency. Being within the close proximity of the radiation source, the coating should provide coverage as completely as possible because any discontinuity will allow radiation penetration at nearly full power.

6.4 SOLAR PROTECTIVE COATING

6.4.1 SOLAR RADIATION

In most attack-type aircraft enclosure designs, the pilot is in a position of continuous exposure to solar radiation, which eventually causes discomfort and fatigue. Under certain conditions, the entry of infrared (IR) radiation into the cockpit also tends to cause excessive heat and adds to the cooling load of the cockpit conditioning system. Figure 6.4-1 shows the full transmittance spectrum through 0.375-inch-thick MIL-P-25690 material. Figures 6.4-2 and 6.4-3 demonstrate the effects of altitude and zenith angle on penetration of the same material.

6.4.2 IR ATTENUATING MATERIALS

The metallic coatings previously discussed have some IR attenuating properties by virtue of gross reflection. Figure 6.4-4 shows two vastly different laminates with the 9 ohm per square coating being the heavier and suppressing the IR portion of the curve more than the
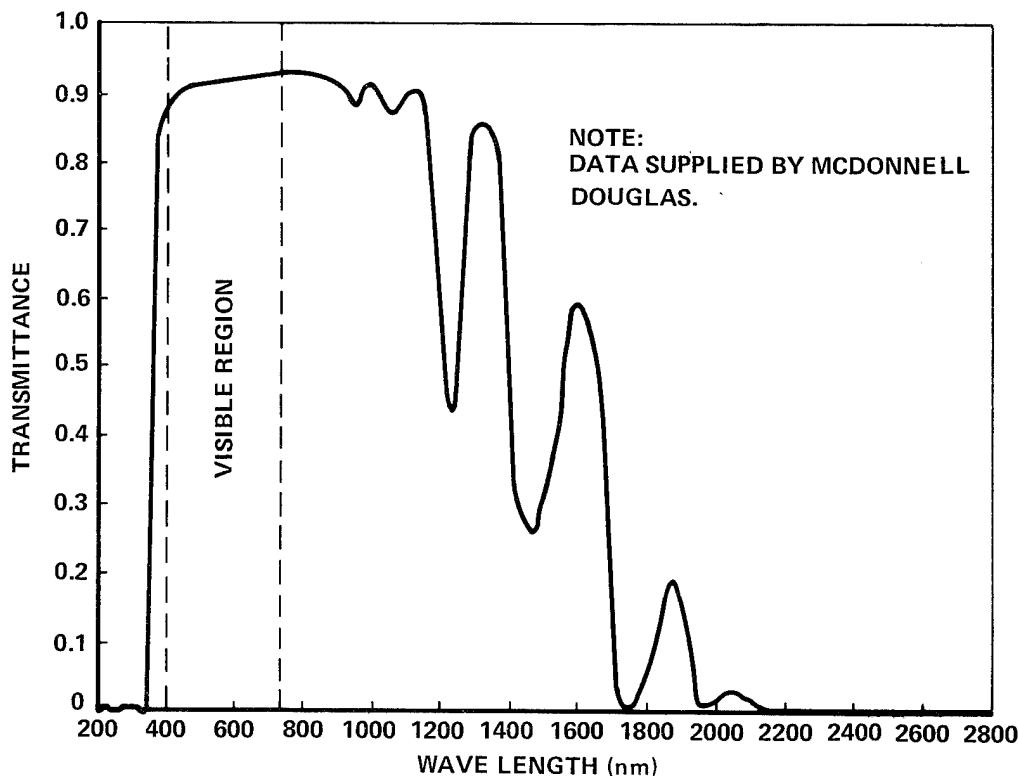
Figure 6.4-1 - Spectral Transmittance of 0.375-Inch-Thick
MIL-P-25690 Material

6-18
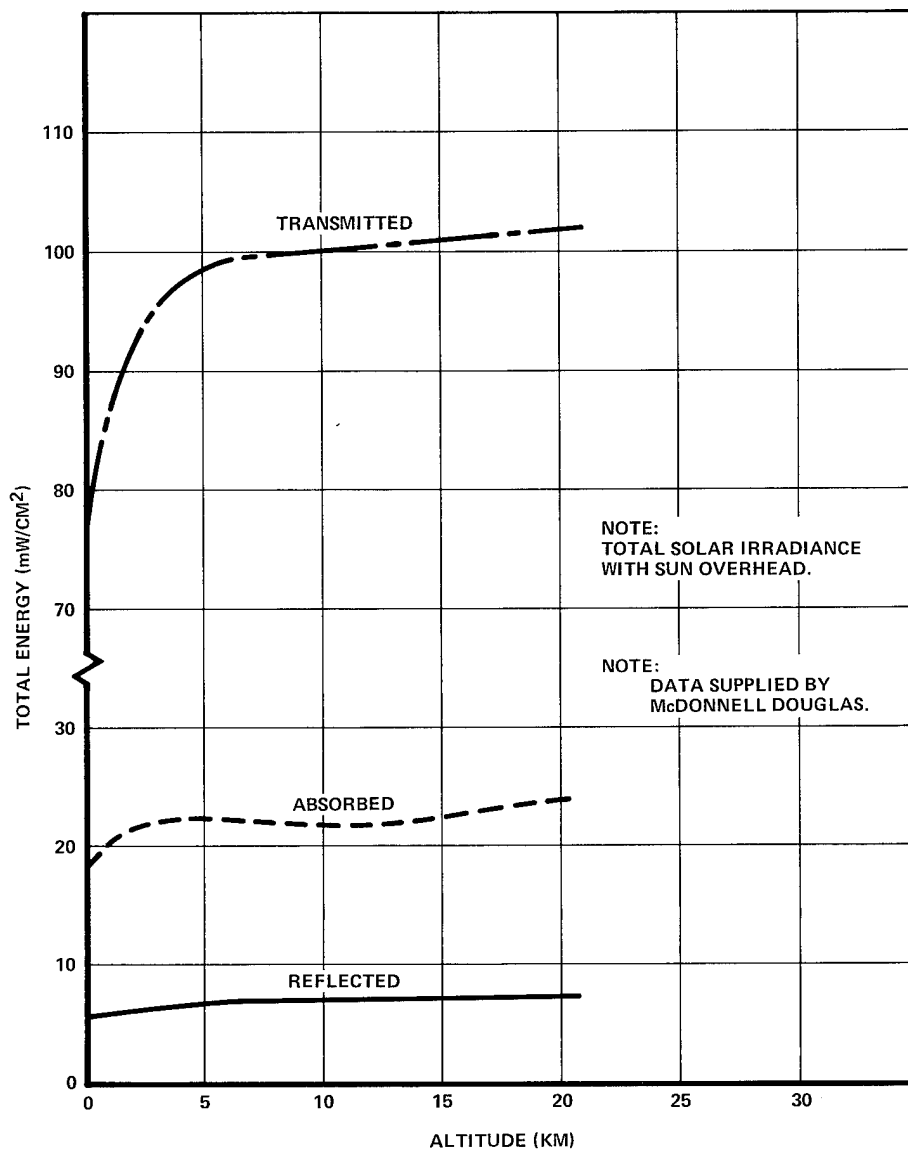
Figure 6.4-2 - Total Solar Energy Reflected, Transmitted, and Absorbed by 0.375-Inch-Thick
MIL-P-25690 Material as a Function of Altitude

6-19
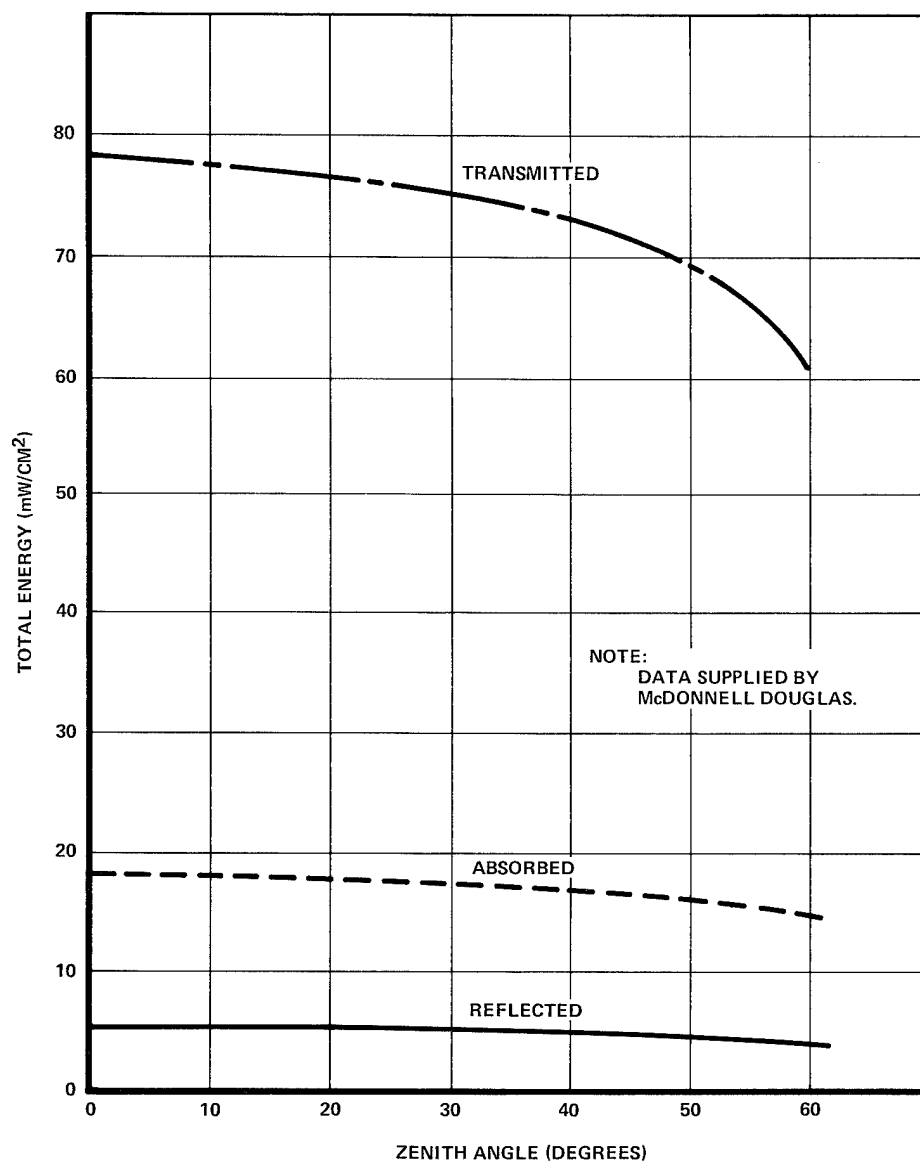
Figure 6.4-3 - Total Solar Energy Transmitted, Reflected, and Absorbed at Sea Level by
0.375-Inch-Thick MIL-P-25690 Material as a Function of Zenith Angle

6-20
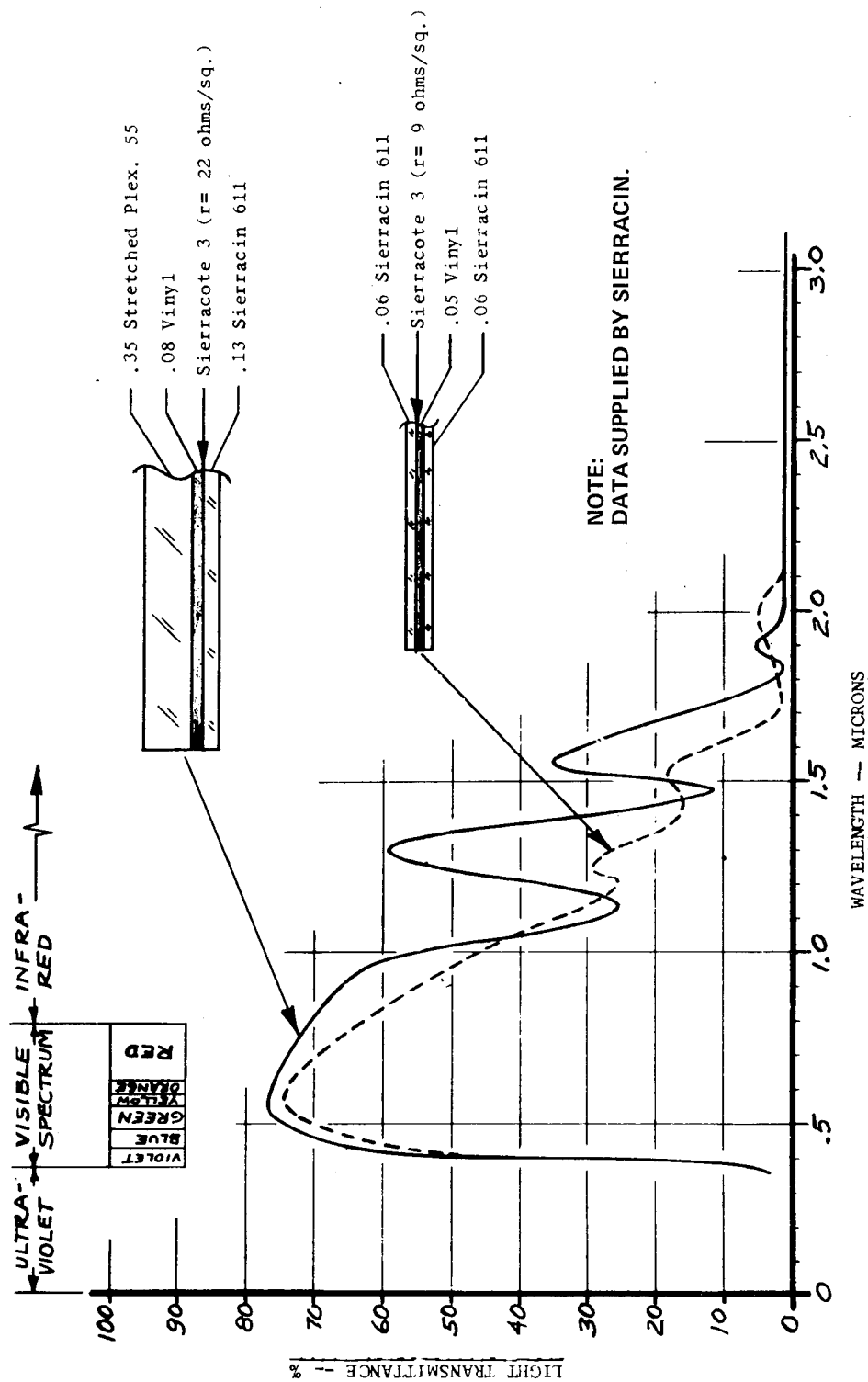
Figure 6.4-4 – Light Transmittance versus Wavelength for Two Sierracoted Panels

22 ohm per square material, irrespective of the thickness variation in the transparency face sheet materials. Figure 6.4-5 demonstrates the IR reflective properties of various laminates versus their electrical sheet resistivity. In this case, the electrical sheet resistivity is only a measure of coating thickness. The curves show that a relatively heavy coating of less than 15 ohms per square would be required for the most effective IR reflectivity.

Color tinting of glazing is of interest, although the associated loss of light transmission under conditions of overcast has to be considered. The primary function of tinting is to reduce glare. Since the far IR spectrum represents thermal energy rather than visible color, a tint alone, which is really a diluted color, cannot be expected to be efficient in preventing IR from entering the cockpit. Figure 6.4-6 demonstrates the interaction of primary colorants in the visible spectrum. Blue or green tints are at the opposite end of the spectrum from the reds and tend to partially filter out all the light frequencies except the physiologically "cool" colors to the eyesight. The combination of primary colors into a neutral grey tends to absorb all colors more or less equally, and visual color discrimination of objects outside the aircraft can be more easily retained.

Other methods of IR attenuation have been developed which are somewhat limited in their application because of available sizes and costs. Anti-reflective laminates of coatings and thin sheets of glass are designed for optical instrument windows for maximum light transmission in the visible range. The principle of the designs also suppresses the IR and UV spectrums.

Tinting of a dynamic sort is possible with photochromic materials which darken in the presence of light. The current state-of-the-art is well advanced, but its application to aircraft has raised questions concerning the speed of tint acquisition and recovery, and the material aging properties. Sunglasses which are photochromic and react primarily to the UV spectrum become inefficient when worn in cockpits covered with transparent materials containing UV absorbers.
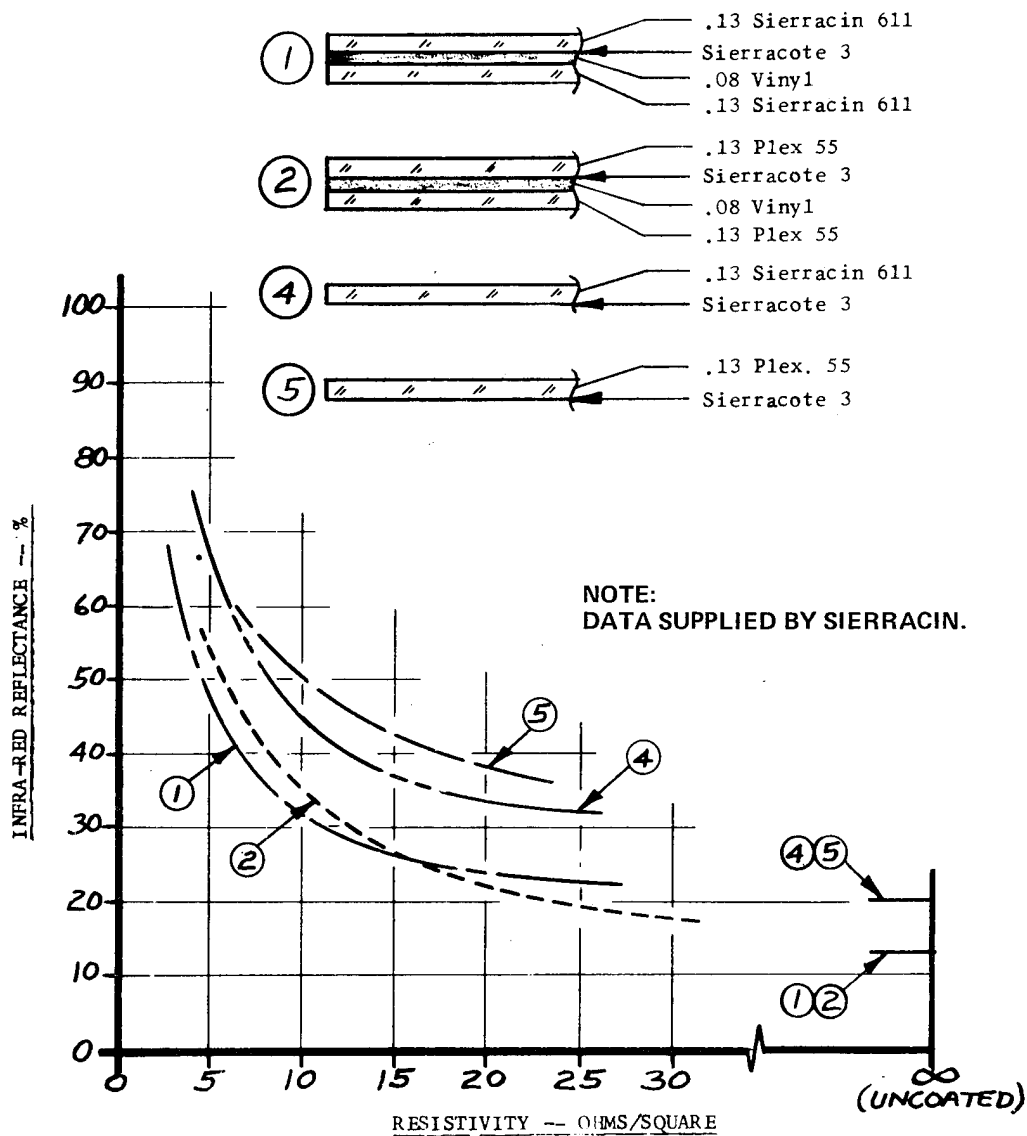
Figure 6.4-5 - Infrared Reflectance versus Resistivity for Several Types of Sierracoted Panels

6-23
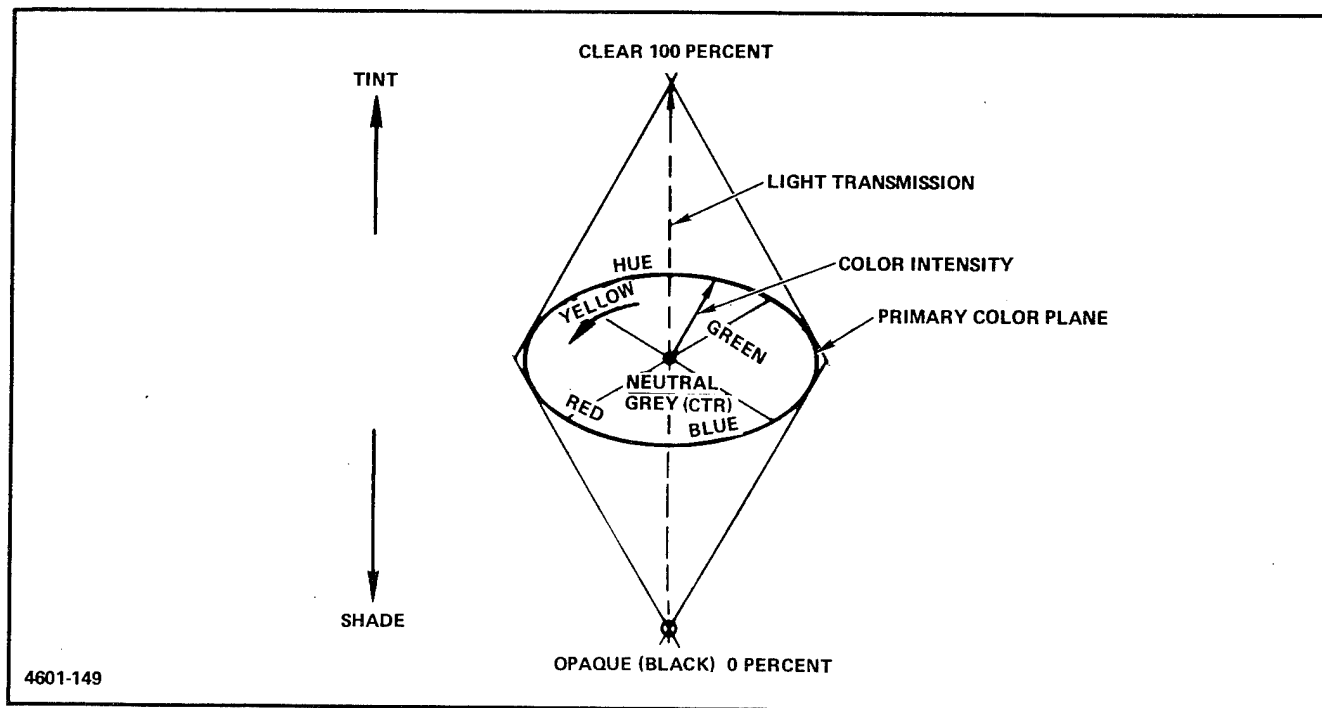
Figure 6.4-6 – Interaction of Primary Colorants in Visible Spectrum

Electrochromic materials have been investigated as a means of selectively shading a glazing by electrically exciting a coating of crystalline structure. The complexity and need for auxiliary equipment would seem to be impractical for a normal tinting requirement, but possibly could be of use as a protection against a nuclear flash if the shade were of sufficient density.

Polaroid[a] devices are another means of reducing the transmission of light, but are used more specifically for reducing the reflected portions of that light. These devices are discussed subsequently as an anti-reflective measure.

It should be added that more recent developments include the use of proprietary dye absorbers, to attenuate specifically the solar near-infrared radiations, especially in aircraft window panel polarizing elements as depicted in Figure 6.4-7, and the introduction of a special purpose element which eliminates the distracting colors due to the photoelastic effect in stressed outer window panels as viewed against polarized skylight in these systems.

[a]TM, Polaroid Corporation, Cambridge, Massachusetts.

6-24

**OPEN
(AXIS PARALLEL)**

**INTERMEDIATE
(AXIS CROSSED)**

**CLOSED
(AXIS PERPENDICULAR)**

LOCK TABS

ROTATING POLARIZED PANE
(0.132 IN. ACRYLIC)

WINDOW
REVEAL
PANEL

GEAR TO
ROTATING
POLARIZED
PANE

FIXED POLARIZED PANE
(0.132 IN. ACRYLIC)
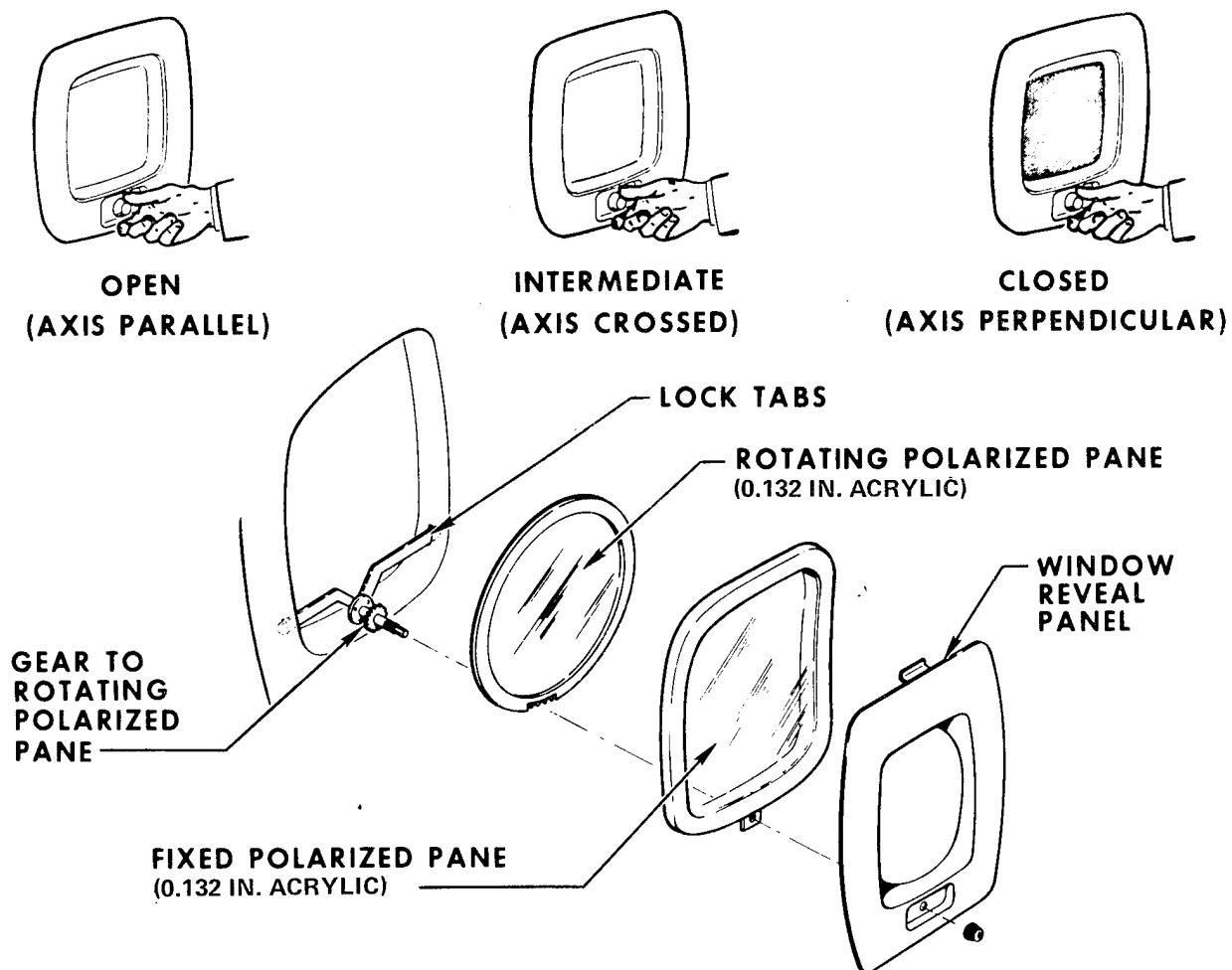
NOTE:
DATA SUPPLIED BY LOCKHEED.

Figure 6.4-7 – Window Light Control Unit

6.5   ABRASION PROTECTION

Coating for abrasion protection is a complex requirement. As an external protection for
monolithic material, such as polycarbonate, it has to withstand abnormal abrasion of dust
and dirt, water erosion in flight, the heat of solar radiation on the ground, the attack of
inappropriate solvents used to clean it, and long-term weathering. Adequate protection
against these variables is measured by the coating's ability to retain its optical integrity
as well as by its adhesive properties over a period of time.

An abrasion protection for the inboard surface is not as subject to the gross abrasive and
weathering forces of an external coating, but it does have to protect against unexpected
sources of damage such as helmet scratches and cleaning procedures which in themselves
can be abrasive. In designs requiring abrasive protection of another coating, an example
being the previously discussed metallic films, the overcoat must be chemically and
mechanically compatible with the undercoat.

The designer should be aware of the available coatings and their limitations. Of the many
coatings tested up to the date of this publication, two have evolved which are better than
others, although new coatings and modifications can be expected. The basic Glass Resins
(Trademark) of Owens-Illinois, Inc. and the Abcite (Trademark) resins of E.I. DuPont de
Nemours, Inc. have been modified by various licensees into material which is primarily
compatible with polycarbonate, although they have also been used on the acrylics. These
resins appear under the different nomenclatures of the processors for designated uses.
The processors should be contacted for recommended formulations for a particular applica-
tion.

Coatings have the advantage of being the lightest in weight of any protective measure, but
their inherent thinness makes them susceptible to imperfections in porosity, hardness, and
adhesion which are difficult to detect on the finished part. Tape tests, abrasion tests, and
chemical compatibility tests have been performed on a number of formulations with varying
degrees of comparable data obtained, including test data after weathering. Currently, the
design criteria are generally based on adhesion tests which utilize a specified contact-type

6-26

of adhesive tape rolled on the surface to be tested and removed under a controlled loading. Other than this "go-no go" test for coating removal, the finished part is checked optically by the method specified by the designer (discussed in Chapter 11), and for light transmission and haze (Method 3022 of FTMS 406). No attempt is usually made to discriminate, optically, between readings of the substrate with and without a coating, because the gross measurement of the complete glazing is the acceptance criterion.

6.6   ANTI-STATIC COATINGS

Understanding the mechanism of static charge accumulation may indicate better ways of preventing it. Previous experimentation has shown that electrostatic charges accumulate on many localized areas of an aircraft enclosure. Both positive and negative surface charges appear which are separated by thin neutral bands. Continued impingement of charged particles, such as dust, can build up these areas in charge until sufficient potential promotes a discharge across the neutral bands to an adjoining island of opposite charge by ionizing the air and making it conductive. These discharges, in addition to the ones caused by continuing particle contact or proximity with the surface, cause electrostatic interference to AM antenna-oriented equipment.

The proposed use of a conductive coating on the outer surface, which is grounded to the fuselage, would overcome the problem, if the coating did not shield any antennas mounted internally in the cockpit area. To date, however, none of the available conductive coatings can withstand the abrasive conditions encountered by high-performance aircraft for an extended period of time, and these are the aircraft most affected.

A temporary solution has evolved which is not completely satisfactory but is currently the only one available. Rather than conductive coatings, dielectric coatings are used which have polar mobility. Considering a plastic cockpit enclosure, the transparent material has a semipolar mobility of its own. Rubbing one surface of the glazing with a flannel cloth will produce charge areas on both sides and along the surfaces of the enclosure which will have both positive and negative polarities. These will remain indefinitely until a humid atmosphere, a water film, or some other agent neutralizes them.

Pure water in itself is an insulator with a dielectric constant of 80 at a frequency of 10^8 Hertz, which indicates that conduction is not the primary mode of charge removal. Being liquid and consisting of dielectric particles, each molecule can be considered as having a positive and negative charge in equilibrium. If the water molecule contacts a charged area and collects a finite number of electrons, it becomes negatively charged. If it loses electrons to the charged area, it becomes positively charged. If oppositely charged molecules of water meet, the charge transfer stabilizes to the predominant net charge. Because water is fluid and has mobility, the process repeats itself until the water film stabilizes to a neutral position or holds a slight charge.

Hydrophylic compounds have been developed as anti-static agents which when applied act as holding agents for the retention of a water structure that reacts as previously discussed. Another type of compound is silicone oil, which does not have as high a dielectric constant as pure water, but is an insulator, and acts similarly except that it is more viscous and is applied as an oil to the surfaces without an additional retaining compound.

The ultimate solution would appear to be a vacuum-deposited transparent semiconductor, of sufficient hardness, applied to the external surface of the glazing.

6.7 ANTI-REFLECTIVE COATINGS

The bandpass filter-type of assembly was previously mentioned as an IR suppressor (section 6.4.2) and as a specialized type of window (section 2.6.7). This type of assembly consists of mounted thin, coated glass sheets in a laminar stack. As many as 15 sheets of glass, coated on both sides, can provide approximately 80-percent transmission of the 450 to 600 millimicron wavelength range in the visible spectrum (see Reference 100).

For a general aircraft application, however, concern is for a coating on an existing thickness of transparency. Rather than being used to increase light transmission into an optical device, the coating is being used to decrease outer reflection of sunlight from the cockpit

covering. Such reflections can compromise a low-altitude flight mission by early visual recognition of the approaching aircraft by insurgent troops.

The principle of reducing reflection requires that a coating with a refractive index less than that of the substrate be applied in a thickness of which

$$d = \frac{\lambda}{4n_c} \quad ,$$

where

    d = coating thickness

    λ = wavelength of incident light at 0 deg

    n_c = refractive index of the coating.

The wavelength in this case would probably be at the point of maximum relative luminosity, or 0.55 micron. Coating both sides of the substrate is normally required to obtain the maximum reduction in reflection by this type of system.

A typical reflection curve for a precision coated substrate, HEA,[a] is shown in Figure 6.7-1. In this figure, the angle of incidence has an effect on the efficiency of the material. In recognizing that the film thickness has to be applied with precision, and that incident light may be penetrating at an angle different from that calculated into an ideal 1/4-wavelength thickness, a change in reflectance has to be expected. Design of an anti-reflective coating therefore requires that the angles of incident and reflected light of importance be specified so that a nominal film thickness may be calculated to compensate for them. This would include a reflectance angle at which visual target acquisition could be expected. Since the aircraft movement is constantly changing the angles of incidence with respect to the sun and the observer, the coatings cannot be expected to be completely effective.

Materials used for coating are usually applied with vacuum deposition techniques which vaporize halide salts onto glass substrates. Advances have been made in which anti-reflective materials can now be applied to plastic substrates. The durability of the coating, however, is dependent upon the heat of application and the substrate as much as upon the coating

---

[a] TM, Optical Coating Laboratory, Inc., Santa Rosa, California.

NOTE: DATA SUPPLIED BY OPTICAL COATING LABORATORIES.
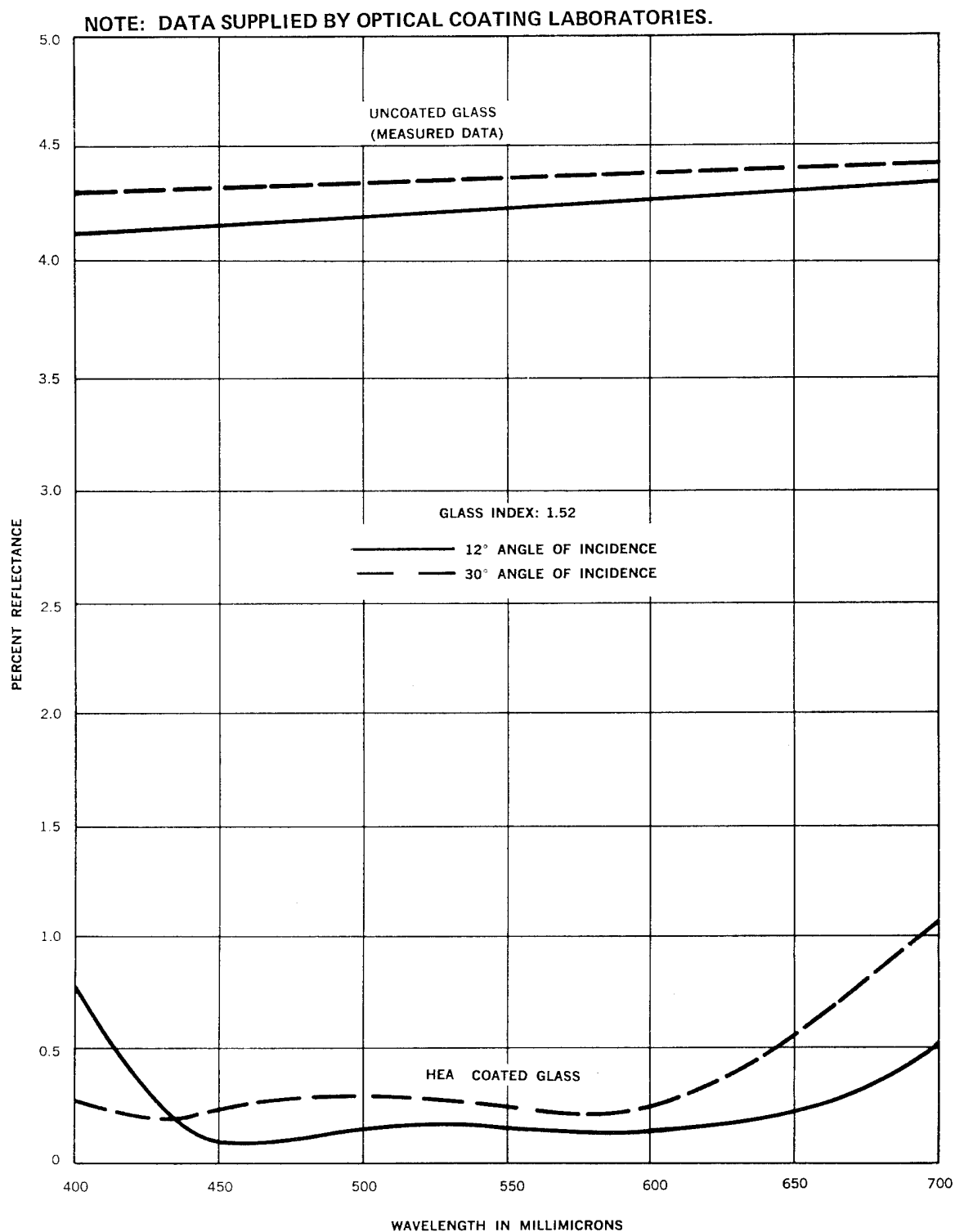
Figure 6.7-1 – HEA for Use Over an Angular Range from 0 to 30 Deg –
Measured Performance

6-30

material itself. The hardness and the adhesion of the coating must survive the service environment of the aircraft without any other protection.

The depositions used are normally conductive, and can be grounded to prevent an electrostatic charge from being generated (refer to section 6.6).

More detailed design information may be found in MIL-HDBK-141.

6.8 ANTI-REFLECTIVE FILMS

Anti-reflective films such as Polaroid[a] can be used singly to mask out planar reflections from most relatively flat or shiny surfaces such as lakes, snow-covered areas, road beds, or rocks. The films are relatively soft and have to be protected by lamination within hard face sheets. Laminating procedures require moderate temperature processing to avoid film damage. If simple curvatures are desired, the face sheets would probably have to be performed.

In principle, the film is initially clear and birefringent through its thickness. Its manufacture reorients the molecular structure of the material while heat softened so that most of the polymer chains tend to align themselves in one direction by being uniaxially stretched. The result is two gross indices of refraction in the two coplanar directions, 90 degrees to each other. Although the material is massively homogeneous, there is a microstructured difference in optical density through the chain centers of the molecules for polarized light, once it is stained with a linear absorber, as compared to the sides, where the bonds connect with adjoining molecules. Most of the incoming light whose planar direction is oriented parallel to the bond connectors between the chains will effectively pass while the light having perpendicular orientation will be absorved by the higher density centers. Any other orientation of the light will be crossing the striations of denser material at varying angles and will be absorbed in varying degrees by it.

The theory can be likened to a mechanical model consisting of a lightly clamped telephone book with soft covers, and a knife. The edge of the book would represent the surface of a single polarizing sheet, and the knife a planar component of light. In attempting to cut parallel

---

[a]TM, Polaroid Corporation, Cambridge, Massachusetts.

to the pages, the knife passes through without difficulty. Cutting across the pages at any other orientation meets with much more resistance. While, for light waves, the reverse situation occurs in actual practice, the model of description serves our purposes of illustration.

One film, therefore, having its absorbing axis parallel to the reflection plane, will absorb the planar glare being reflected. If two films are in series to a nonpolarized light source, and are oriented parallel to each other, the light coming through the first sheet is polarized into parallel planes and passes through the second sheet with the same orientation. Turning the second sheet to any other orientation, however, would be similar to rotating the telephone book edge, but holding the knife in the same position. The effect is called cross-polarization, and very little light penetrates when the two sheets are oriented 90 degrees from one another. Figure 6.4-7 demonstrates a practical use for passenger aircraft windows.

6.9   RAIN REPELLANTS

Rain-repellant materials are usually an auxiliary means of increasing the effectiveness of other rain removal systems. The removal system has to provide rain clearance for all approach, landing, and takeoff speeds of a particular aircraft under the conditions of Table 6.4-I. Various rain-repellant systems are tabulated in Table 6.4-II.

Two types of materials have been used as coatings. One is temporary and applied in-flight as a liquid jet of a silicone titanate copolymer. The ground-applied type is less temporary, depending upon the material used and the application process. Two principles have been acclaimed, with the latter apparently being more successful. Wetting agents allow the water droplets to collapse into a thin film which promotes better visibility than would occur with rivulets caused by tenacious drop movement. The most recent development is that of a more permanent "balling" agent which reacts oppositely. The droplets react as though on wax. The smaller contact area of a sphere allows them to fall or be blown off as fast as they strike.

6-32

TABLE 6.4-I – RAIN INTENSITIES AND VISIBILITY

Rain classification	Rain intensity (in./hr)	Rain intensity (mm/hr)	Droplet diameter (microns)	Water content (mg/m^3)	Visibility Nautical miles	Visibility Statute miles
Clear		0.00		0.00		
Fog		Trace	10	6.00		
Mist	0.002	0.05	100	55.5		
Drizzle	0.01	0.25	200	92.6		
Light rain	0.04	1.00	450	138.9	7.5	8.62
Moderate rain	0.16	4.00	1000	277.8	2.7	3.11
Heavy rain	0.59	15.0	1500	833.3	0.93	1.07
Excessive rain	1.6	40.0	2100	1851.9	0.49	0.56
Cloudburst	4.0 to 50.0	100 to 1000	3000	4,000 35,000	0.25	0.29

TABLE 6.4-II – RAIN REMOVAL AND REPELLANT SYSTEMS

Type	Description	Advantages	Disadvantages	Weight/cost
Rain removal systems				
Windshield wipers	Electro-mechanical. MIL-W-7233 applies.	Effective in moderate to heavy rain. Good at low speeds. Good reliability.	Scratch plastic, drag penalty. Good only to heavy rain intensity.	Low weight/ Low cost
Jet blast	Tempered bleed air-blown over windshield. WADC TR 58-444 is an acceptable design guide.	Effective in heavy rain. Good for anti-icing. Good at high aircraft speeds.	Engine penalty. Small area of coverage.	High weight/ High initial cost
Rain repellants				
In-flight applied	Liquid dispensed on windshield that repels water. MIL-R-83055 applies. MIL-R-83056 applies.	Effective in excessive rain - excellent at high air-craft speeds. Use only when necessary.	Maintenance on re-fills. Dispensing system necessary. Not very effective in light rain or at low speeds.	Low weight/ Low cost
Ground applied	Applied to wind-shield on ground by hand.	Can be used as quick-fix on any aircraft. Effective in excessive rain. Excellent at high aircraft speeds.	Low effective life. Maintenance problems. Not very effective in light rain at low speeds.	Very low weight/ Very low cost

6-34

CHAPTER 7 - EDGE ATTACHMENT MATERIALS

7.1 GENERAL

The components of an edge attachment usually consist of one or more layers of a reinforc-
ing material and an impregnating resin and/or an adhesive, depending on the edge attach-
ment design and the fabrication techniques. The materials used for these components
are described in general terms in the following sections. Specific materials properties
are not detailed because such variables as the type of weave in woven fabrics, and the type
of reinforcement and the conditions of curing in impregnating resins and adhesives are so
diverse as to make the listing of values for all materials impractical.

Information concerning several laminates utilizing epoxy resin systems are shown in
Figures 7.1-1 through 7.1-4. Further information concerning fiberglass-epoxy combina-
tions can be found in Chapter 4 of Part I of MIL-Handbook 17, entitled "Reinforced Plastics."
More diversified information can be obtained on current materials from laminators.

7.2 REINFORCING MATERIALS

The materials used for reinforcement of edge attachments have usually been of a woven
structure, but they have varied widely in composition, including stainless wire mesh
screen; unidirectional, square weave, and satin weave glass fabric; and nylon, Nomex,
Dacron, and Orlon synthetic fabrics. Glass fabrics of various weaves are still used for
edge attachments, but as indicated in section 2.4, they cause considerable difficulty in
application because of the very low coefficient of thermal expansion and the high modulus
of elasticity of glass. The current trend is to synthetic fabrics.

The great variety of nylon, Dacron, and Orlon fabrics available precludes a comprehensive
evaluation in this section. Nylon, a polyamide, is available with a number of modifications
of the basic chemical structure; these modifications are intended to enhance one or
another property, usually at the expense of one or more of the remaining properties. A
surface treatment is also available for nylon; it improves the bond shear strength in

7-1
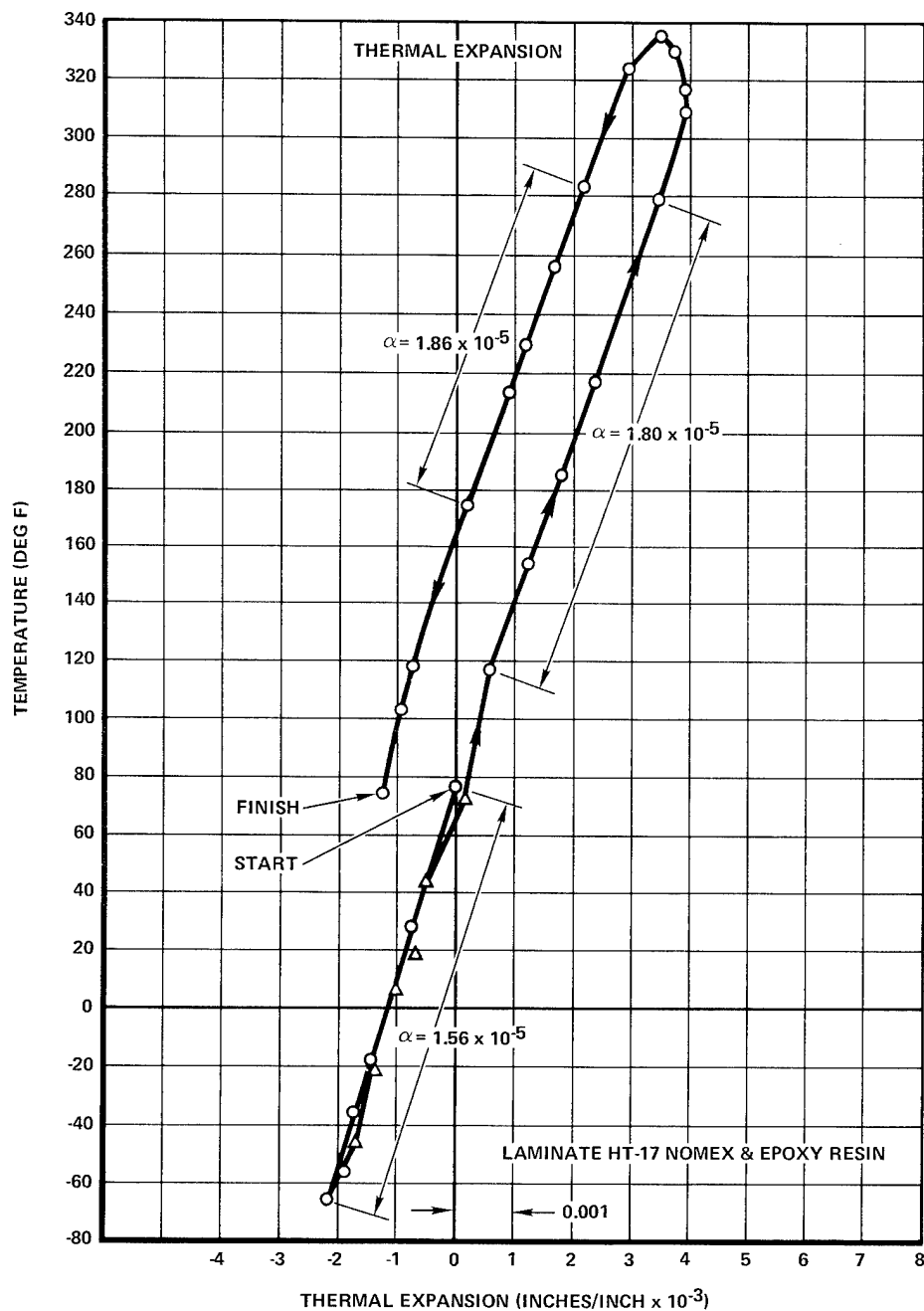
Figure 7.1-1 - Thermal Expansion versus Temperature—HT-17 Nomex-Epoxy Laminate
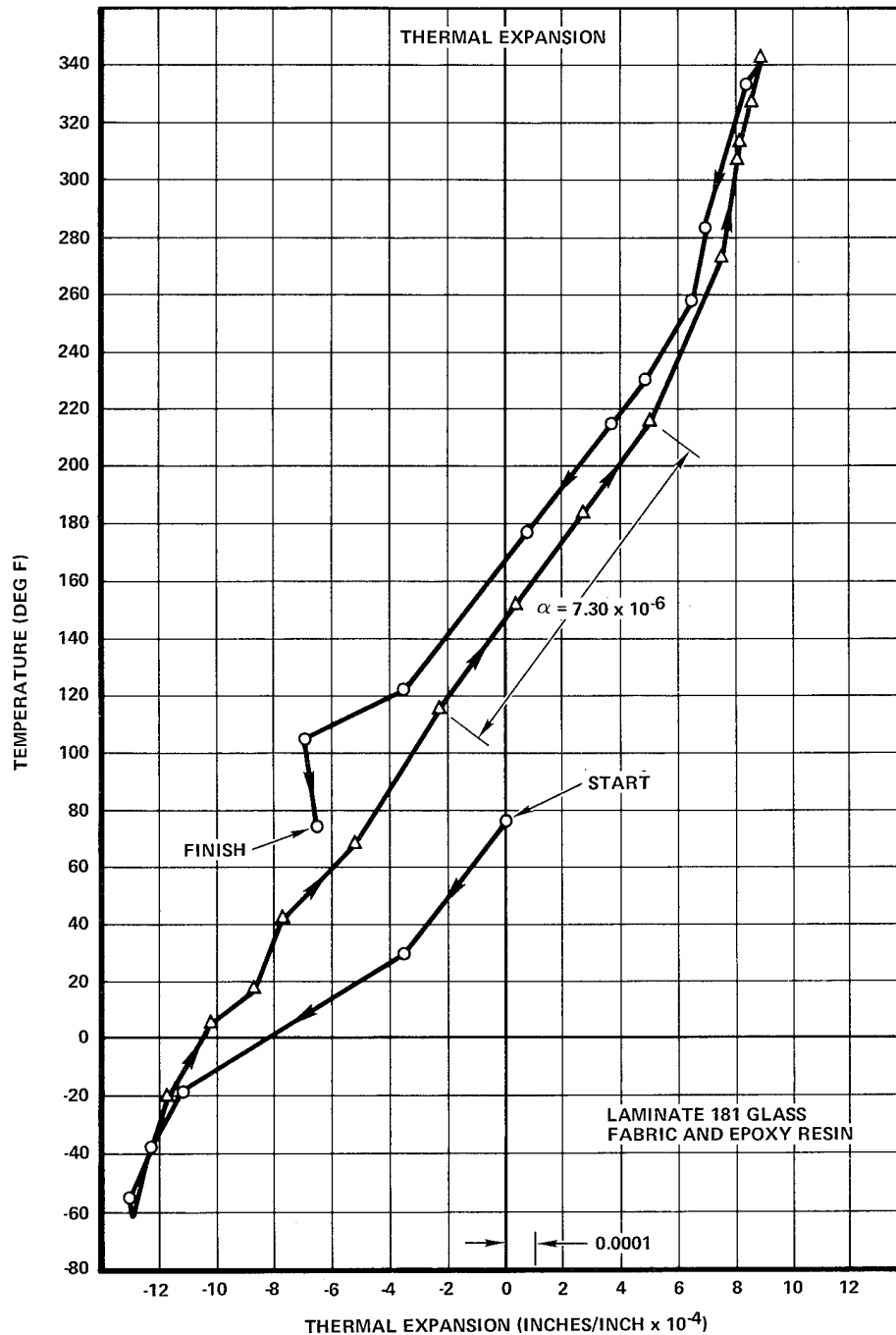
Figure 7.1-2 – Thermal Expansion versus Temperature—181 Fiberglas-Epoxy Laminate

7-3
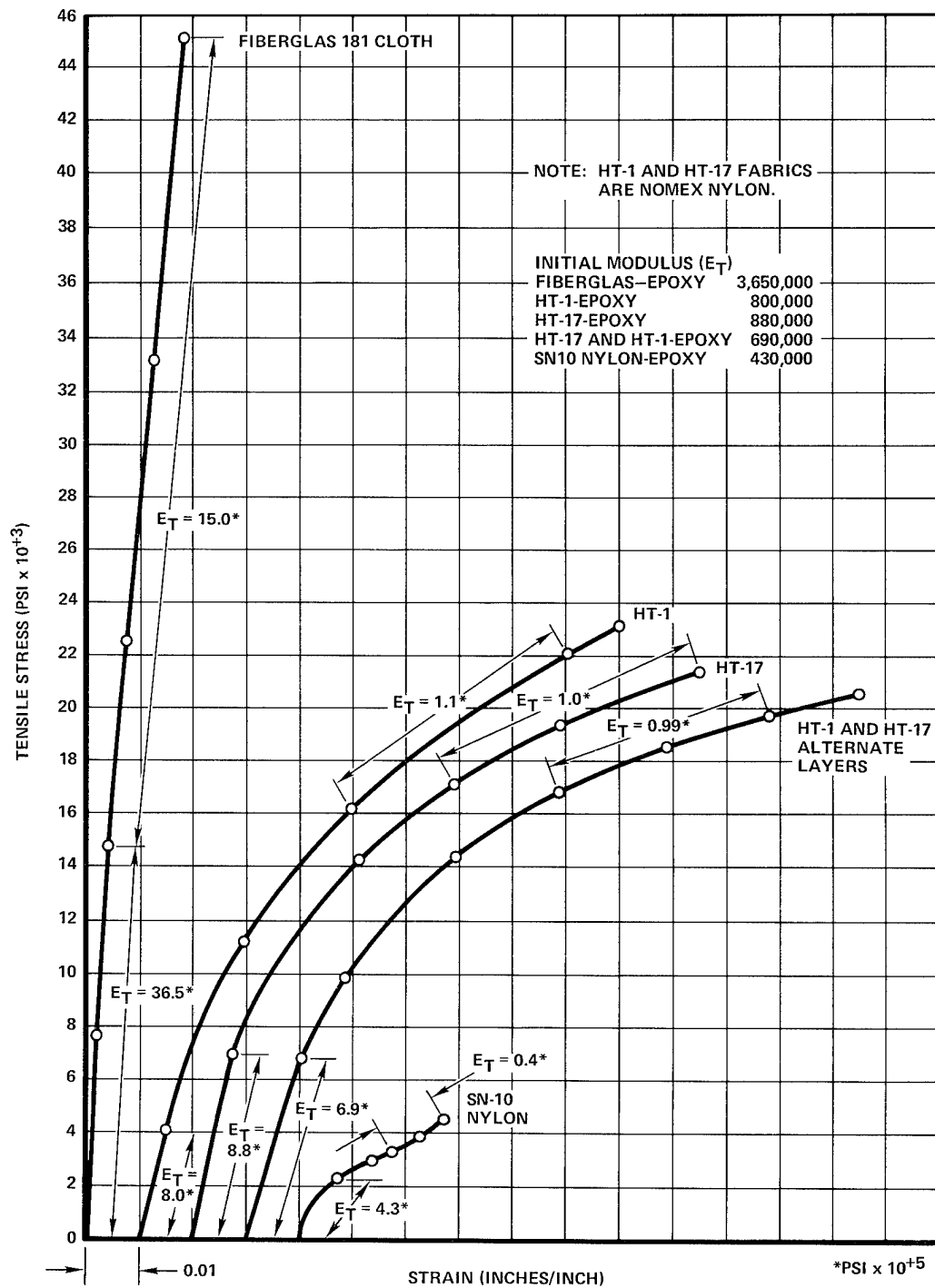
Figure 7.1-3 – Tensile Stress-Strain at Room Temperature for Various
Epoxy-Impregnated Edge Reinforcements

7-4
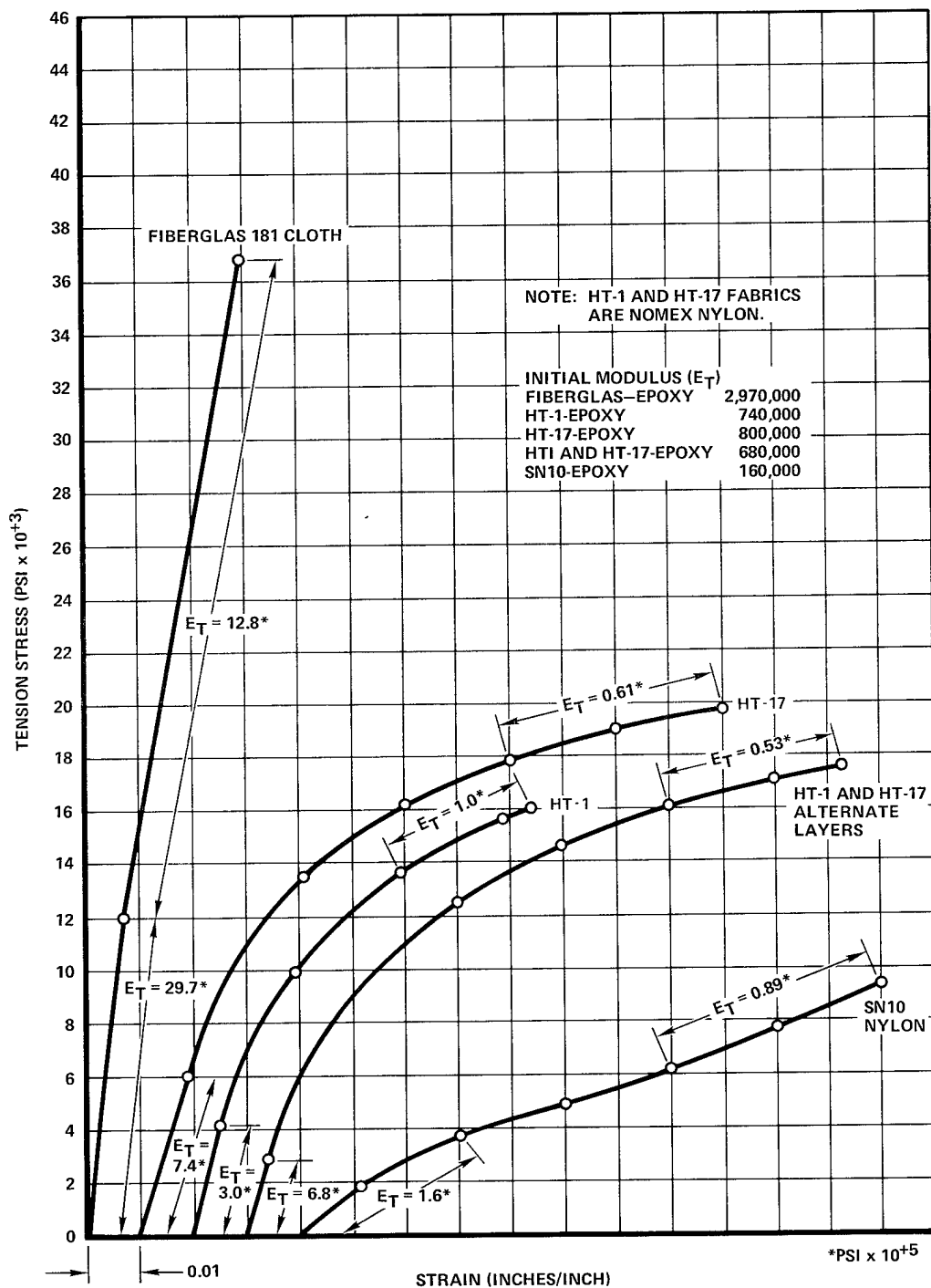
Figure 7.1-4 - Tensile Stress-Strain at 185 Deg F for Various Epoxy-Impregnated Edge Reinforcements

7-5

laminates but reduces the tensile strength. All these materials are available in a variety of weights and weaves, and the physical properties of a synthetic fabric are affected by changes in physical structure as well as by changes in chemical structure. This characteristic is exemplified in Table 7.2-I. The fabric in which the threads are twisted has a considerably lower tensile strength; the twist is added to improve the mechanical bonding between the resin and the fabric in laminates. A higher bond shear strength is the result.

TABLE 7.2-I - PHYSICAL PROPERTIES OF SYNTHETIC FABRICS WITH AND WITHOUT TWISTS IN THE THREADS

	Nylon A2953	Nylon A2951/3
Denier and plies	840/1	840/1
Twist, turns per inch	0	3-1/4
Thread count	22 × 21	27 × 22
Thickness per ply, inches	0.012	0.017
Tensile strength, PSI, warp	26,000	18,000
Tensile strength, PSI, fill	23,000	15,000
Bond shear strength, PSI	1,600	2,400

Another type of nylon which is receiving more attention is trademarked Nomex. The fibers are synthesized from a different nylon polymer which provides the high-temperature characteristic of decomposing at +700 F (it does not melt). Its structural temperature limitations are somewhat lower, but within the operational range of current plastic transparencies.

Nylon is used extensively for flexible, loop-type edge attachments as well as for laminated edge attachments. Dacron has been used principally in laminates, but is finding increasing use in loop-type attachments. The coefficient of thermal expansion for nylon is closer to

that of acrylic glazing materials than is the coefficient for Dacron, but both are appreciably better than most of the previously used materials. The low modulus of elasticity of the synthetic fabrics helps reduce strains in canopies resulting from unavoidable differences in thermal expansion and/or manufacturing misfits. Further, it has been shown that the reinforcing materials with low moduli of elasticity exhibit appreciably better fatigue strength than do the high modulus materials such as glass.

Orlon,[a] for a time, was not available in weaves for aircraft use, but is again an important edge attachment material. Being an acrylic fiber, its lamination with an acrylic resin makes an ideal material for transparent acrylic edge attachments. The match of coefficients of thermal expansions and ease of manufacture are its major design assets.

Dacron, a polyester, has a slightly higher tensile strength than nylon, but the strength is dependent to a considerable extent on the weight and weave of the fabrics. The bearing strength of nylon is considered poor in comparison with that of Dacron. The creep behavior of nylon is also poorer than that of Dacron. The creep of Dacron at 250 deg F is about the same as that of nylon at room temperature. Dacron is reported to show good resistance to creep up to 300 deg F. Because the synthetic fabrics are thermoplastic, like the acrylic glazing materials, their physical properties are temperature sensitive, and creep at elevated temperature is an important factor to be considered, especially with loop-type edge attachments where creep of the fabric may generate peel-type failures in the bond between the glazing and the edge attachment.

Dacron weathers well. Colored nylon weathers better than white nylon. The surface treatment for nylon discussed earlier improves the weathering characteristics of nylon. However, while nylon has failed in accelerated weathering tests, no failures have been reported in outdoor weathering tests, and nylon fabric loops have given three years' service without failure.

Glass cloth, for very high-performance applications, becomes ideal for designs requiring glass or ceramic types of glazing, again from the standpoint of a thermal coefficient of expansion match. In some cases, the fabric type of reinforcement has been eliminated in favor of metallic combs which are bonded directly to the glazing (Reference 14).

[a]TM, E.I. Dupont de Nemours Co., Wilmington, Delaware.

7.3   IMPREGNATING RESINS

Acrylic, modified acrylic, polyester, and epoxy resins are the most commonly used impregnating resins. They have mechanical, chemical, and thermal properties very similar to those of the plastics glazing materials. The acrylics usually exhibit the best tensile strength and resistance to weathering, but have low bearing strength at elevated temperatures. Epoxy resins have the best bearing strength and superior heat resistance, but the resistance to weathering is not equal to that of the acrylics. The polyesters are weaker, mechanically, than the acrylics and epoxies, especially in interlaminar shear strength when used in laminates.

In using glass cloth for high-temperature applications, silicone resins have come into use, being the more available and obvious materials for a compatible laminate. The tenacity of certain of the polyurethane family resins to glass and their reasonably high-temperature capabilities and elastomeric properties may offer new edge attachment material combinations.

CHAPTER 8 - ADHESIVES

8.1 GENERAL

The adhesives used for bonding edge attachments to plastics glazing materials include the commonly used impregnating resins and numerous commercial formulations that frequently consist of modified phenolics, polyesters, or synthetic rubbers. The properties, advantages, and disadvantages of the various commercial formulations are too numerous to discuss.

Acrylic resins are generally used when the glazing material is MIL-P-5425 material; they are not very successful with MIL-P-8184 material because of its resistance to the softening action of solvents. Epoxies in particular, but also polyesters, have good adhesion to MIL-P-8184 material.

Polyurethane adhesives have found applications as bonding agents for polycarbonate substrates and their edge attachments as well as for glass. Silicones, as adhesives, have generally lower tensile strengths than other bonding media, but do have the high-temperature attributes which make them more useful than other materials in the higher thermal range. Certain RTV silicone rubbers have been found to have excellent adherence to polycarbonate substrates. Blends of two or more adhesive systems have been developed for better performance than any of the component systems.

8.2 SELECTION AND APPLICATION

MIL-HDBK-691, "Adhesives," provides a detailed treatise on the general selection and application of adhesives. Aircraft design, however, has its special conditions which cannot be satisfied by all the normal procedures.

Although a manufacturer has recommended a special-purpose adhesive, the engineer should be aware of a few of the application problems which appear. Polycarbonate bonding represents one of the more outstanding examples. Polycarbonate's susceptibility to solvent attack has indicated that the adhesive system should have a low solvent and high "solids"

content. A particular adhesive of this type was found to have better adhesion if primers were used on the adherend surfaces. High viscosity and short pot life made coating in an even film difficult. The cure of the adhesive required a room temperature set of several hours, followed by an oven cure of a longer period under controlled clamping pressure. Controlled pressure was required because this particular adhesive exhibited a lessening in viscosity during cure which reacted to overpressuring by flowing out and leaving a "starved" bond.

These processing operations represent a considerable number of variables which should stimulate the engineer to evaluate a commercial adhesive through a comprehensive series of tests which represent conditions of preparation, processing, and service loading of the adhesive and substrates through a broad temperature range.

CHAPTER 9 - GLASS

9.1 GENERAL

In the past, monolithic glass has seldom been used for aircraft glazing. Now its use is
required in applications where aerodynamic heating is too severe to permit the use of
laminated glass with the presently available plastic inner layers. Monolithic glass will
probably be used as the outer panel of multiple glazed units, with air spaces separating
the panels. The properties of monolithic glass are also of interest because the properties
of glass laminates are greatly dependent upon the individual components rather than the
laminate as a whole.

Glass windshields are ordinarily used where resistance to abrasives, resistance to elevated
temperatures, and requirements for de-icing by means of fluids are of paramount importance.

Glass at ordinary temperatures is a brittle material; it does not exhibit the property of
plastic flow and consequently has no yield point. It obeys Hooke's law until rupture;
therefore, there is no permanent deformation before fracture. At high temperatures above
the strain point, viscous flow becomes perceptible. Even at temperatures slightly below
the strain point, glass will creep under load. The temperature at which glass starts to flow
is the limit for its use as a structural material.

Annealing essentially relieves most processing stress concentrations which could result in
a failure at less than the expected strength of glass.

Tempering by thermal means, which is accomplished by rapidly chilling the glass from
an elevated temperature, will increase both the strength and resistance to thermal shock.
The process is more effective on glasses with moderate to high thermal expansion than it is
on glasses of very low thermal expansions. There is also some difficulty in fully tempering
glass thermally which is less than 1/4-inch thick.

Tempering by chemical means is also referred to as "chemical strengthening" and has a similar effect on glass except that the surface compressive stress is much higher. Strengthening is obtained by an ion exchange in the subsurface of the glass as it is treated in a bath of a molten alkaline salt. Further explanations of the processing may be found in MIL-HDBK-722(MR), "Glass," and in Reference 15.

Because the tempering processes leave the glass with high compressive stresses in the surface, all cutting, grinding, or shaping must be done before the glass is tempered. The strength of fully tempered glass may be 2-1/2 to 3-1/2 times that of annealed glass (Reference 16).

When tempered glass breaks, it shatters into small, almost cubical particles. Generally, the higher the degree of temper, the smaller the fracture particle. Vision through fractured fully tempered glass is obscured, while vision through fractured semi-tempered glass may still be possible.

Because glass is a brittle material, it is difficult to test directly in tension. Almost all strength measurements on glass, other than fibers, are made by determining the modulus of rupture in bending.

Glass is much stronger under compressive loads than under tensile loads and is always considered to break in tension, with the fracture originating at the surface. Many factors affect the strength of glass. Abrading or scratching the surface of the glass will greatly reduce the strength, as will moisture and high humidity. Aging may cause some reduction in the strength of tempered glass (Reference 17). The strength of glass varies with the rate of loading: the faster the rate of loading, the higher the strength (Reference 18). Glass may break under sustained loads that are a fraction of the average modulus of rupture determined under rapid rates of loading (Reference 19). The size of the specimen will influence the strength; generally, the larger the specimen, the lower the unit strength (Reference 20).

Temperature also affects the strength of glass. For annealed glasses it is generally concluded that the strength is greater at low temperatures than at room temperatures. Above room temperature, tests have shown that the strength of glasses with low coefficients of expansion increases slightly with increasing temperature until near the strain point. The strength of glasses with high coefficients of expansion shows a slight drop in strength with increasing temperature until a minimum between 400 deg F and 700 deg F is reached, followed by a small increase in strength until the strain point is approached (Reference 21).

Elevated temperature acting over a period of time will remove the stress from tempered glass and consequently weaken the glass so that the strength becomes more closely that of annealed glass. The temperature at which the stress that is due to tempering starts to be relieved varies with the type of glass, but is lower than the strain point of the type. Tempered glass that has all of its stress removed may still be slightly stronger than annealed glass (Reference 21).

The spread of values for the breaking stresses obtained from testing a large group of glass specimens is much greater than from a corresponding group of metal specimens, so that the actual breaking stress for any individual specimen cannot be predicted with accuracy.

The strength of glass is greatly decreased by flaws such as scratches, bruises, and edge chips. Great care should therefore be taken during installation of glass to avoid damage to the surface or edges. Dry cloths that may contain abrasive dusts should not be used to clean glass.

Basic information on glass technology may be found in MIL-HDBK-722 (MR).

9.2   MECHANICAL PROPERTIES

A number of properties of glasses are reported in the following section, and numerical values are given. Many of these values have been taken from a variety of sources in the literature, and it is not always possible to identify exactly the composition of the glass that has been tested. However, a number of results that are reported are from previous tests made at the National Bureau of Standards (NBS) on six types of glass. The names and some properties of these glasses are listed in Table 9.2-I.

TABLE 9.2-I - COEFFICIENT OF EXPANSION, STRAIN POINT, SPECIFIC GRAVITY, AND AMOUNT OF TEMPER

Glass	Symbol used to report	Coefficient of expansion* (10^{-7} per deg C)	Strain point* (deg C)	Strain point* (deg F)	Specific gravity*	Semi-tempered (PSI)	Full tempered** (PSI)
Soda lime, Libbey-Owens-Ford, regular plate	LOF	92.0	517	963	2.51	3,830	7,450
Borosilicate, Pittsburgh Plate Glass Co. 3235	PPG 3235	62.0	493	920		3,890	7,450
Borosilicate, Corning Glass Works 7740 (Pyrex Brand)	CGW 7740	32.0	515	959	2.23	2,380	
Aluminosilicate, Corning Glass Works, 1723	CGW 1723	42.0	672	1,242	2.63	4,690	7,970
96 Percent Silica, Corning Glass Works 7900 (Vycor)	CGW 7900	8.0	820	1,508	2.18	1,340	
Fused Silica, Corning Glass Works 7940	CGW 7940	5.6	990	1,814	2.20		

*Data taken from the manuals of the glass producers.
**Average values obtained from at least 100 specimens measured at NBS. Measurement taken at a point midway between the two surfaces of the plate.

9.2.1 MODULUS OF RUPTURE

The strength of flat glass is generally determined in bending and reported as modulus of rupture. The modulus is affected not only by the various strengthening treatments, but also by abrasion, which reduces the modulus drastically. Because aircraft windshields are highly susceptible to abrasion, tests are often performed on material which has been sandblasted in a controlled manner. The effects of processing and abrasion on the modulus of rupture are listed in Table 9.2-II.

TABLE 9.2-II – EFFECTS OF PROCESSING AND ABRASION ON MODULUS OF RUPTURE

Glass	*	Size (inches)	Abraded	Rate of load (PSI/min)	Modulus of rupture (PSI)	ν (percent)
Soda	A	10 × 1-1/2 × 1/4	Yes	10,000	6,900	8.4
	A	10 × 1-1/2 × 1/4	No	10,000	11,320	21.2
Lime	S	10 × 1-1/2 × 1/4	Yes	10,000	13,410	5.6
	S	10 × 1-1/2 × 1/4	No	10,000	21,070	12.7
Silica	T	10 × 1-1/2 × 1/4	Yes	10,000	21,990	3.1
	T	10 × 1-1/2 × 1/4	No	10,000	29,600	9.5
B	CT	10 × 1-1/2 × 1/4	Yes	10,000	40,430	5.2
	CT	10 × 1-1/2 × 1/4	Yes	60,000	41,410	8.7
	CT	10 × 1-1/2 × 1/4	No	60,000	55,700	3.7
A	CT	10 × 1-1/2 × 1/4	Yes	10,000	41,160	7.2
	CT	10 × 1-1/2 × 1/4	Yes	60,000	39,540	4.3
	CT	10 × 1-1/2 × 1/4	No	60,000	55,980	5.2
B	CT	6 × 1 × 0.1	Yes	60,000	36,170	10.2
	CT	6 × 1 × 0.1	No	60,000	52,170	3.5
A	CT	6 × 1 × 0.1	Yes	60,000	38,190	9.2
	CT	6 × 1 × 0.1	No	60,000	53,930	7.5

*A – Annealed glass.
S – Semitempered glass.
T – Tempered (thermal) glass.
CT – Chemically tempered glass.
ν – Coefficient of variation.

Tong marks in tempered glass (the place where the tongs held the glass during the tempering process) also may seriously reduce the strength of tempered glass. If tong marks are not located properly with respect to the loading conditions, the effective strength may be reduced as much as 50 percent under the worst conditions (Reference 22).

9.2.2 EFFECT OF MOISTURE

Table 9.2-III shows the difference in strength between rods (approximately 1/4-inch thick) when tested wet and when thoroughly dried by a vacuum treatment (Reference 23). No data are available on the effect of moisture on the strength of flat glass, but it is expected that flat glass would show similar difference in strength when tested under the same conditions.

TABLE 9.2-III – STRENGTH OF GLASS RODS TESTED WET AND AFTER BAKING IN A VACUUM*

Glass	Average strength vacuum (PSI)	Average strength wet (PSI)
Soda lime	24,700	12,100
Borosilicate	44,300	17,700
Fused silica	27,900	16,700

*Data from Baker and Preston (Reference 23).

9.2.3 EFFECT OF THE RATE OF LOADING

The effect of the rate of loading on the strength of annealed regular plate glass is shown in Figure 9.2-1 (Reference 18). The strength of tempered glass is similarly affected by the rate of loading but the average strengths are, of course, higher.

9.2.4 EFFECT OF SIZE

There is considerable evidence to show that within the range of thickness and sizes that are of interest in aircraft glazing, the thinner specimens and the smaller specimens will have a slightly higher modulus of rupture (Reference 24). However, there are no data available that seem to be in a form useful for design purposes.
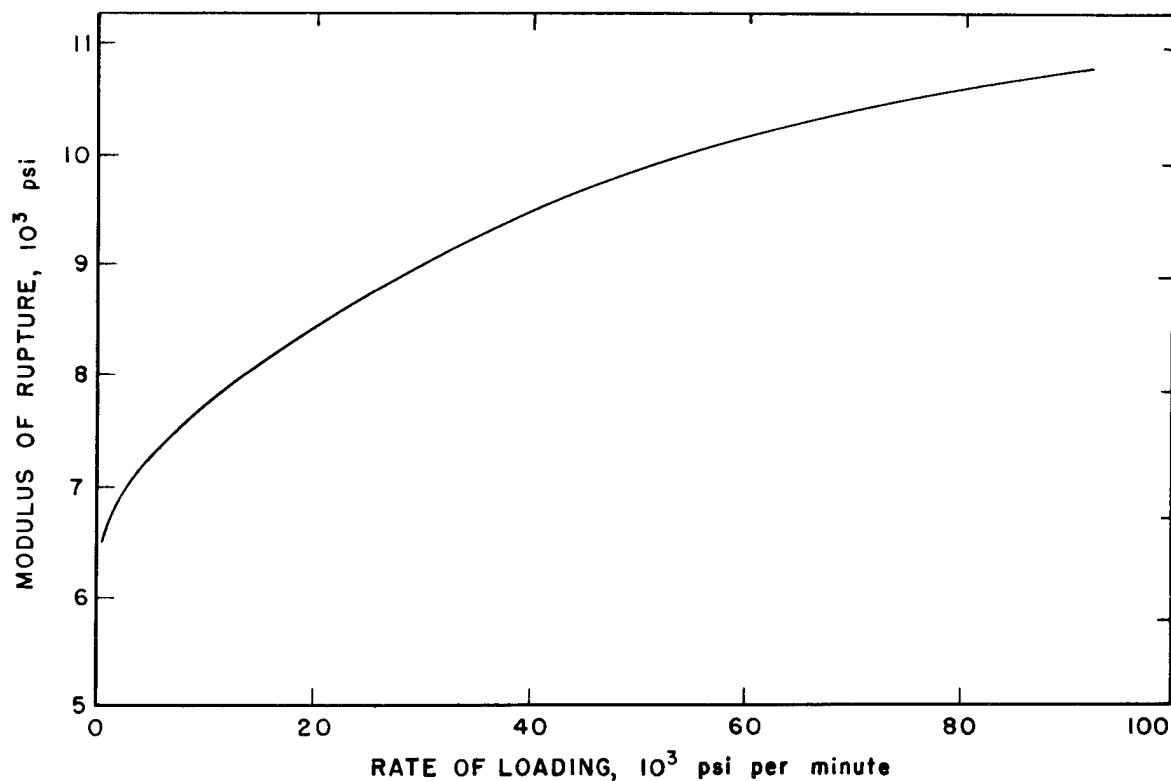
Figure 9. 2-1 – The Effect of the Rate of Loading on the Breaking Strength of
Annealed Plate Glass

9.2.5   EFFECT OF TEMPERATURE

Figures 9. 2-2 through 9. 2-7 show the effect of temperature on the modulus of rupture of
LOF, PPG 3235, CGW 7740, CGW 1723, CGW 7900, and CGW 7940 glasses.   The values
were obtained on 10-inch $\times$ 1-1/2-inch $\times$ 1/4-inch specimens supported to an 8-inch span
and loaded with two knife edges with a 2-inch separation and a rate of loading of 10, 000
pounds per square inch per minute.   The specimens had abraded surfaces, so the values
presented are useful for noting the effect of temperature but will be different from un-
abraded glass or glass with more or less severely abraded surfaces.
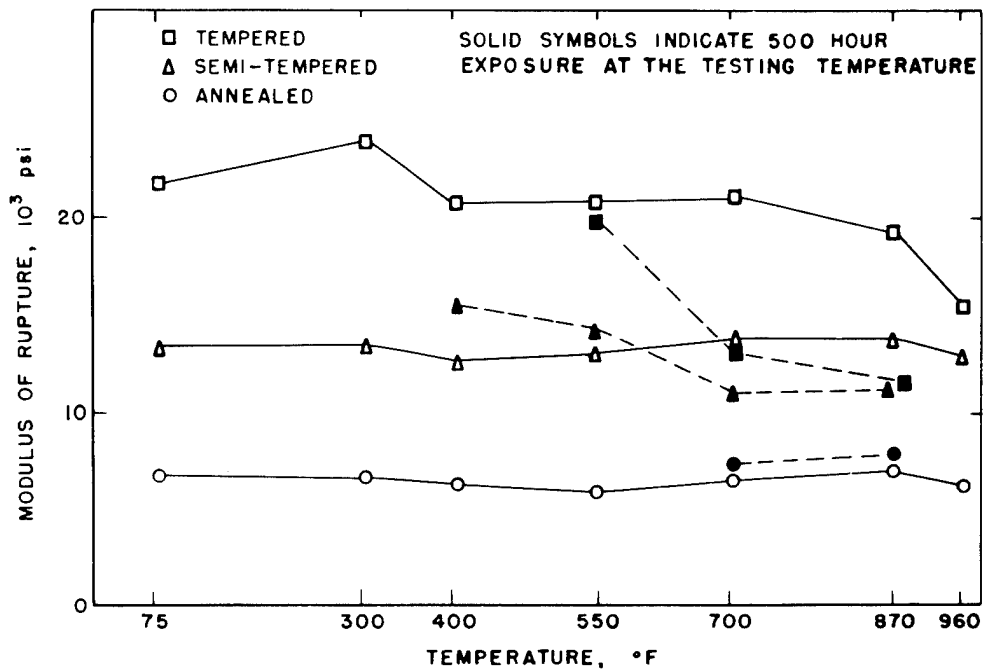
Figure 9.2-2 – Average Values for the Modulus of Rupture at Different Temperatures.
Glass: LOF, Sandblasted
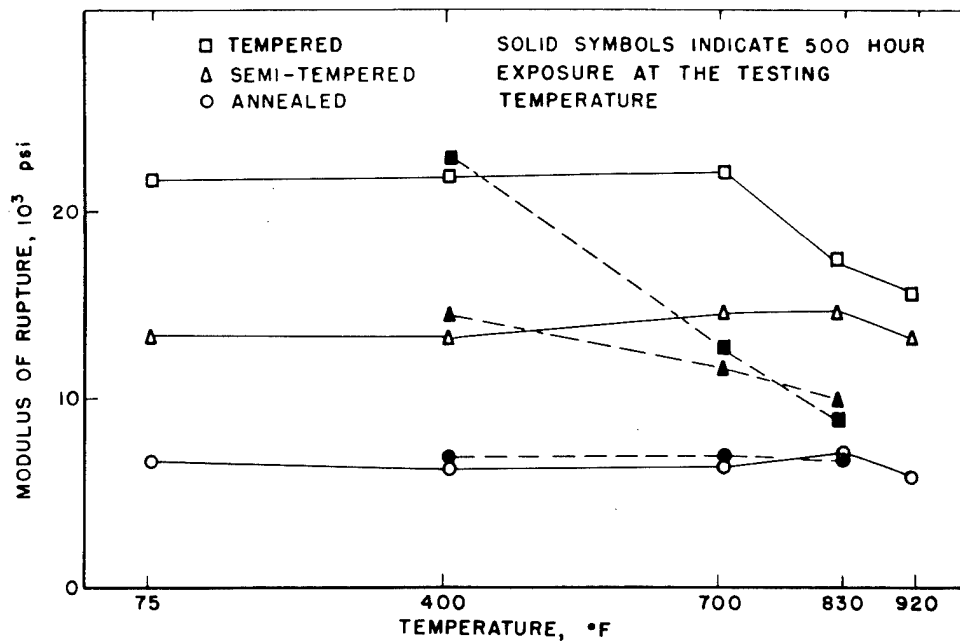
Figure 9.2-3 – Average Values for the Modulus of Rupture at Different Temperatures.
Glass: PPG 3235, Sandblasted.

9-8
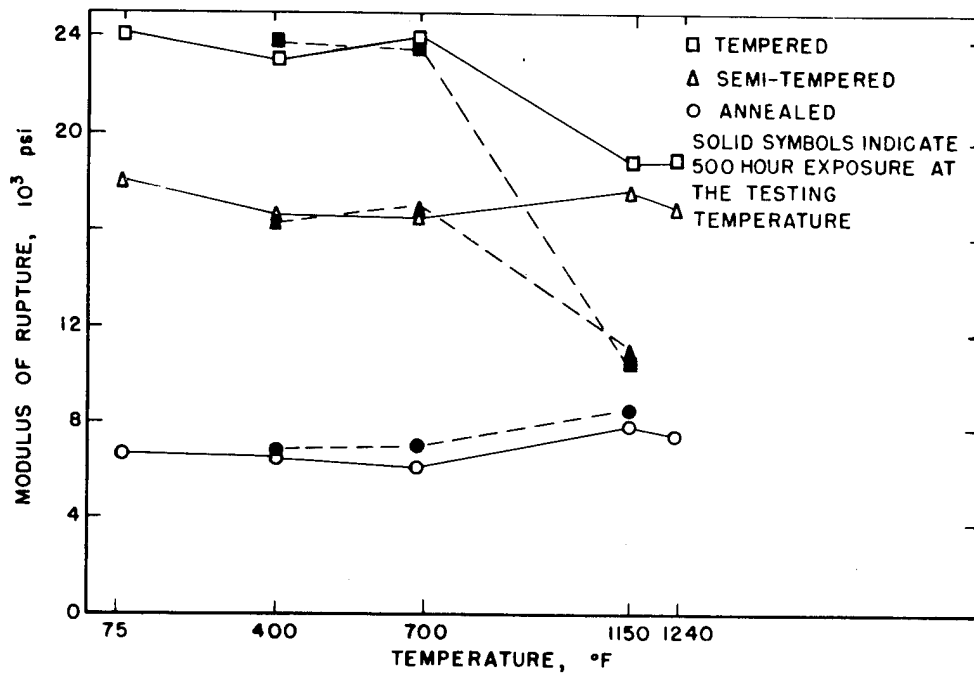
Figure 9.2-4 – Average Values of the Modulus of Rupture at Different Temperatures.
Glass: CGW 1723, Sandblasted
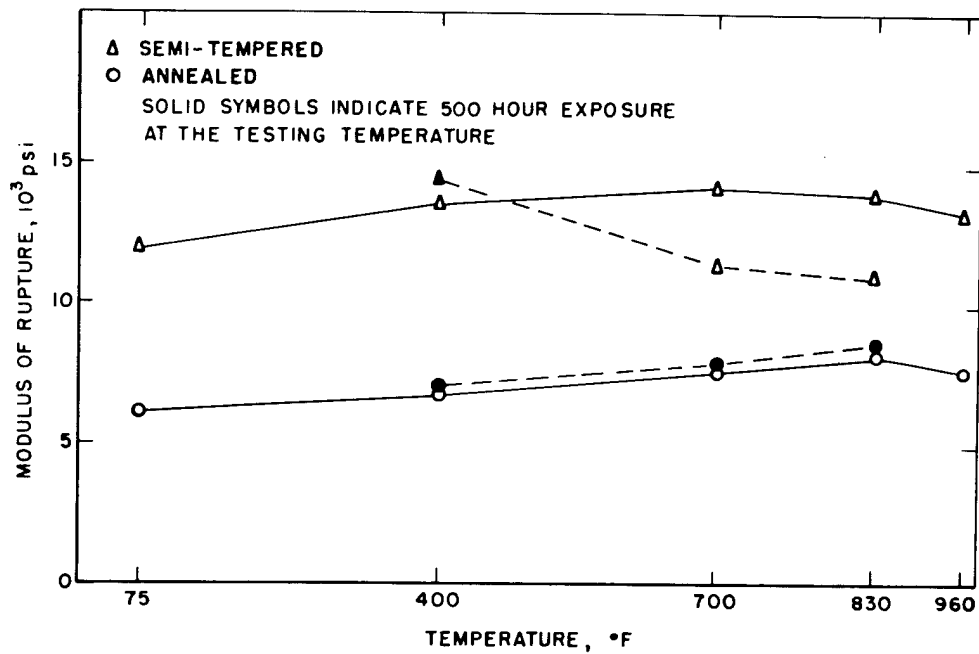
Figure 9.2-5 – Average Values of the Modulus of Rupture at Different Temperatures.
Glass: CGW 7740, Sandblasted
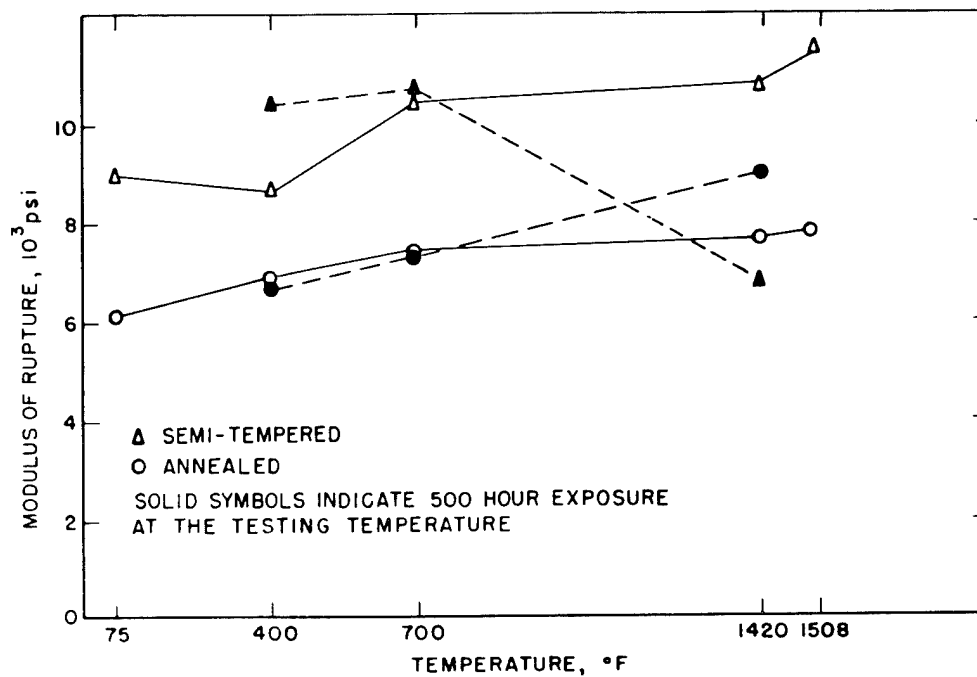
Figure 9.2-6 – Average Values of the Modulus of Rupture at Different Temperatures.
Glass: CGW 7900, Sandblasted
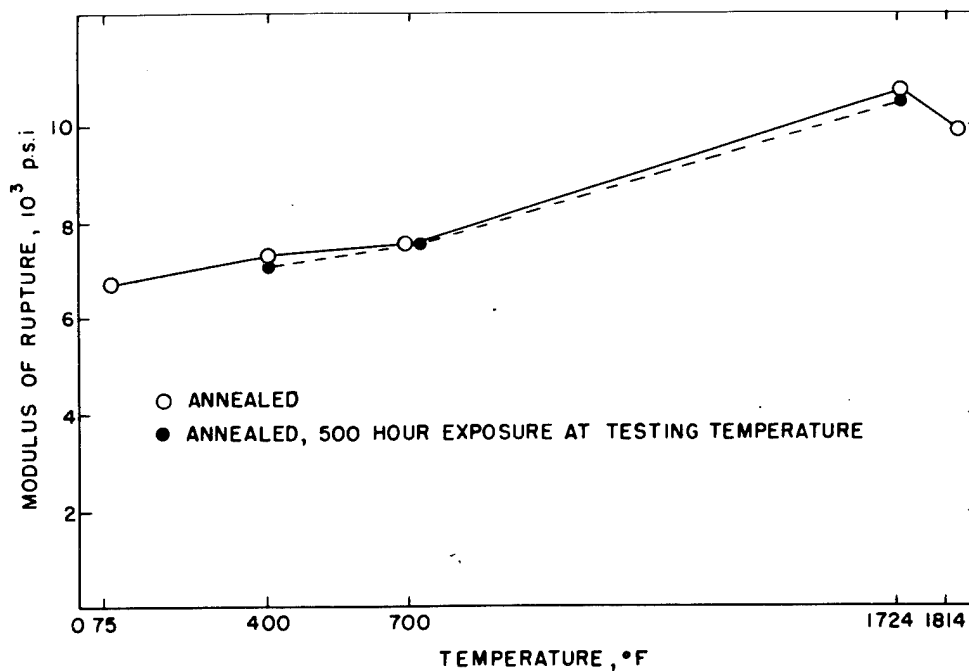
Figure 9.2-7 – Average Values of the Modulus of Rupture at Different Temperatures.
Glass: CGW 7940, Sandblasted

For annealed glass, the three glasses with the highest coefficient of expansion (42.0×10^{-7} per deg C and above), LOF, PPG 3235, and CGW 1723, first showed a slight decrease in strength followed by an increase in strength when heated above room temperature. A maximum strength is reached slightly below the strain point, followed by a decrease in strength at the strain point. The three glasses with low coefficients of expansion (32.0×10^{-7} per deg C and lower), CGW 7740, CGW 7900, and CGW 7940, all showed increases in strength as temperature increased to a temperature slightly below the strain point. Glasses CGW 7740 and CGW 7940 showed a small decrease in strength at the strain point. CGW 7900 did not show the slight decrease in strength at the strain point. Heating annealed glass for long periods (500 hours) does not adversely affect the strength (Reference 21) below the strain point and in some cases appears to increase the strength.

Figure 9.2-8 shows two annealed glasses of different silica contents. The high silica content of borosilicate shows a strength increase with temperature up to its strain point. The lesser content shows a decrease followed by an increase in strength.

The effect on Young's modulus is shown in Figure 9.2-9. Again, the silica content has its effect, with modulus increasing as temperature increases for the pure and near-pure silica. All other combinations decline in modulus except for one borosilicate (A), which does show some increase and evidently has more silica content than that of (B).

Semitempered and tempered glasses when exposed to elevated temperatures for a period of time lose their locked-in stress and consequently become weaker. Figures 9.2-2 through 9.2-7 show the change in modulus of rupture that occurs when specimens were heated for 1 hour and 500 hours at temperatures slightly below and above their strain points. The higher the temperature, the faster the loss in stress. The temperature at which the stress loss starts is dependent upon the composition of the glass. Tempered regular plate glass can be used continuously up to 500 deg F and for short intervals up to 700 deg F without appreciable loss of strength. The following list shows the loss of strain of regular plate glass (soda lime) at different temperatures (Reference 25).
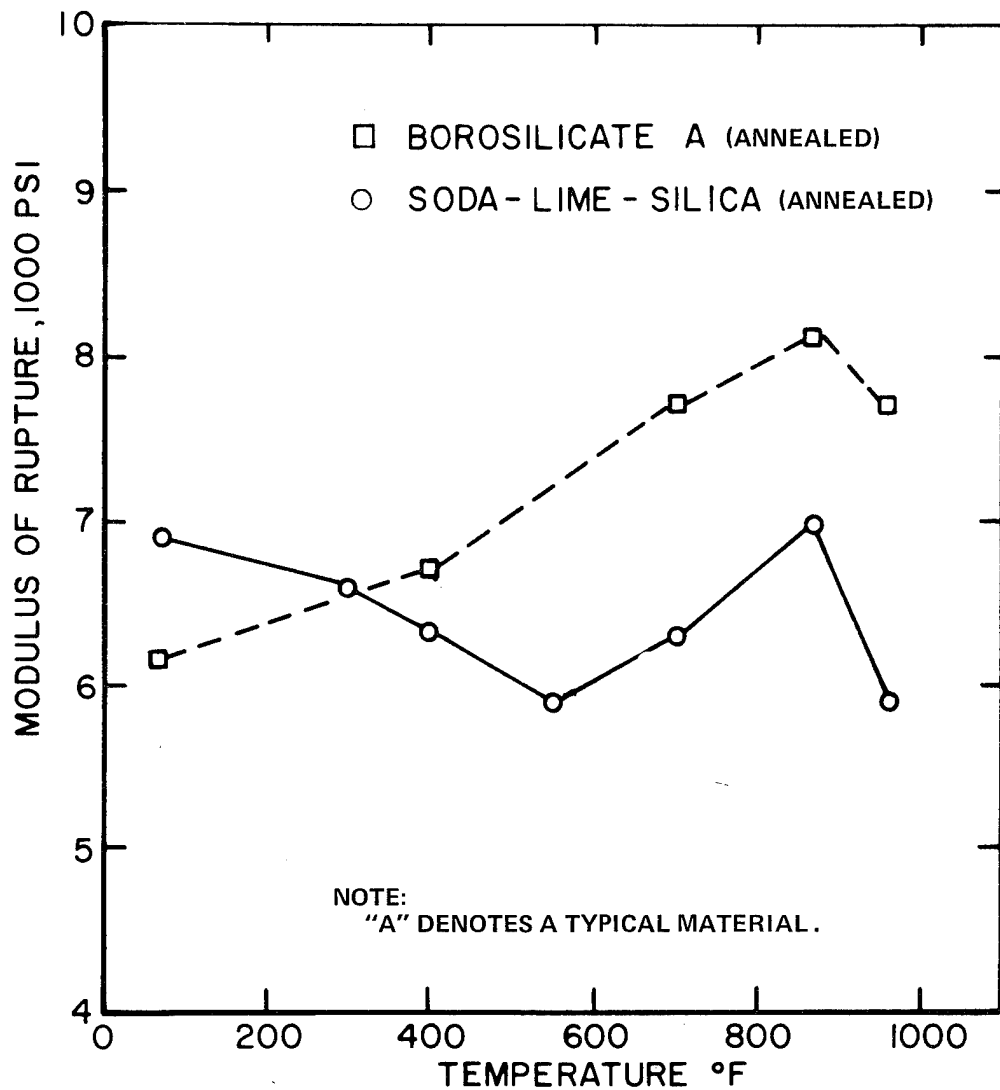
Figure 9. 2-8 – Effect of Temperature on Modulus of Rupture for Two Types of
Annealed Glasses

9-12
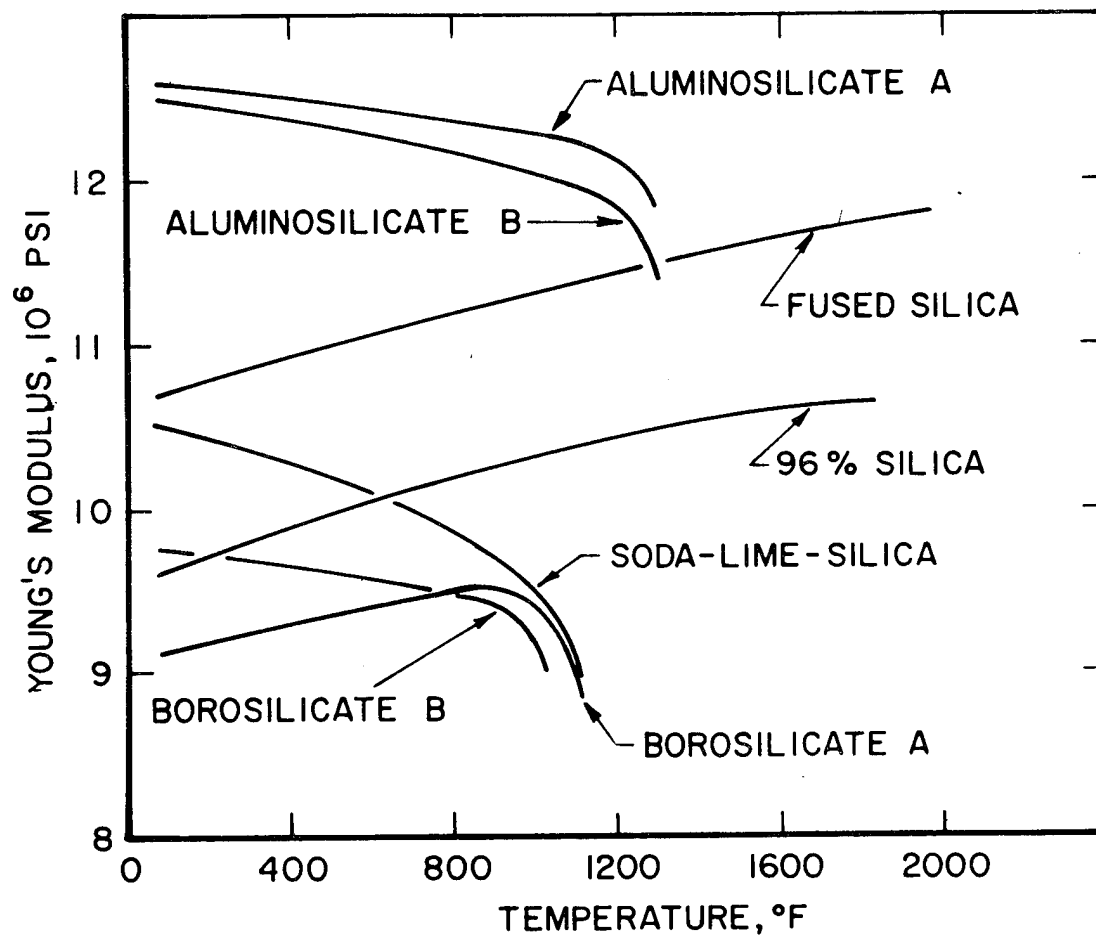
Figure 9.2-9 – Effect of Temperature on Young's Modulus for Several Types of Glasses

At 800 deg F approximately one-half of the temper is removed in 10 hours

At 700 deg F approximately one-half of the temper is removed in 100 hours

At 600 deg F approximately one-half of the temper is removed in 10,000 hours

At 500 deg F approximately one-fourth of the temper is removed in 10,000 hours

At 400 deg F temper removal is insignificant.

The previous times of temper removal should be used only as a rough guide, because the measurements used to obtain the data are subject to considerable error, and other observers have obtained results different from those given.

Figure 9.2-10 represents strength loss of chemically tempered material over various periods of time. Apparently loss of temper occurs in varying degrees at any continuous exposure beyond +300 deg F.

9.2.6 STATIC FATIGUE (SUSTAINED LOADING)

Annealed glass shows that when subjected to sustained loading (1,000 hours) it may fracture under stresses as low as 40 percent of the average short time breaking stress (Reference 19). Tempered glass will sustain stresses up to 70 percent of its short time breaking stress for prolonged periods (500 hours) without failure (Reference 21). For both annealed and tempered glass, the greater the applied stress the shorter the time the glass will be able to sustain the stress.

Figure 9.2-11 shows the effect of sustained loading on annealed sheet glass at room temperature (Reference 19).

The stress-rupture and creep results shown in Figures 9.2-12 through 9.2-17 were obtained on 10-inch $\times$ 1-1/2-inch $\times$ 1/4-inch sandblasted LOF specimens. The specimens were supported on an 8-inch span and loaded with dead weight through two knife edges 2 inches apart. Creep was measured as deflection in the center of the span.

Figures 9.2-12, 9.2-13, and 9.2-14 show the effect of sustained loads on regular plate (LOF) glass in the annealed, semitempered, and tempered conditions at different temperatures (Reference 21).
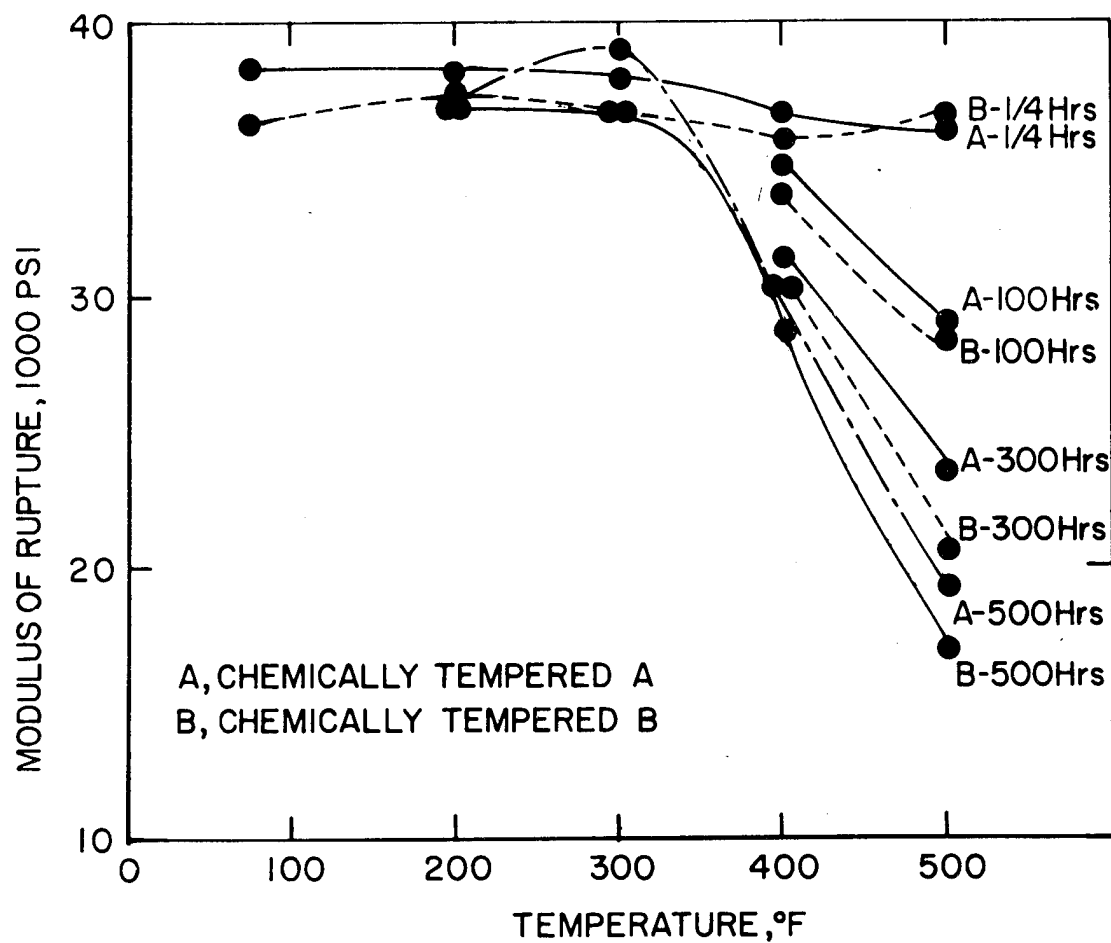
NOTE:
"A" AND "B" DENOTE MATERIALS OF DIFFERENT MANUFACTURERS.

Figure 9. 2-10 – Change in Modulus of Rupture of Chemically Tempered Material
after Thermal Aging

9–15
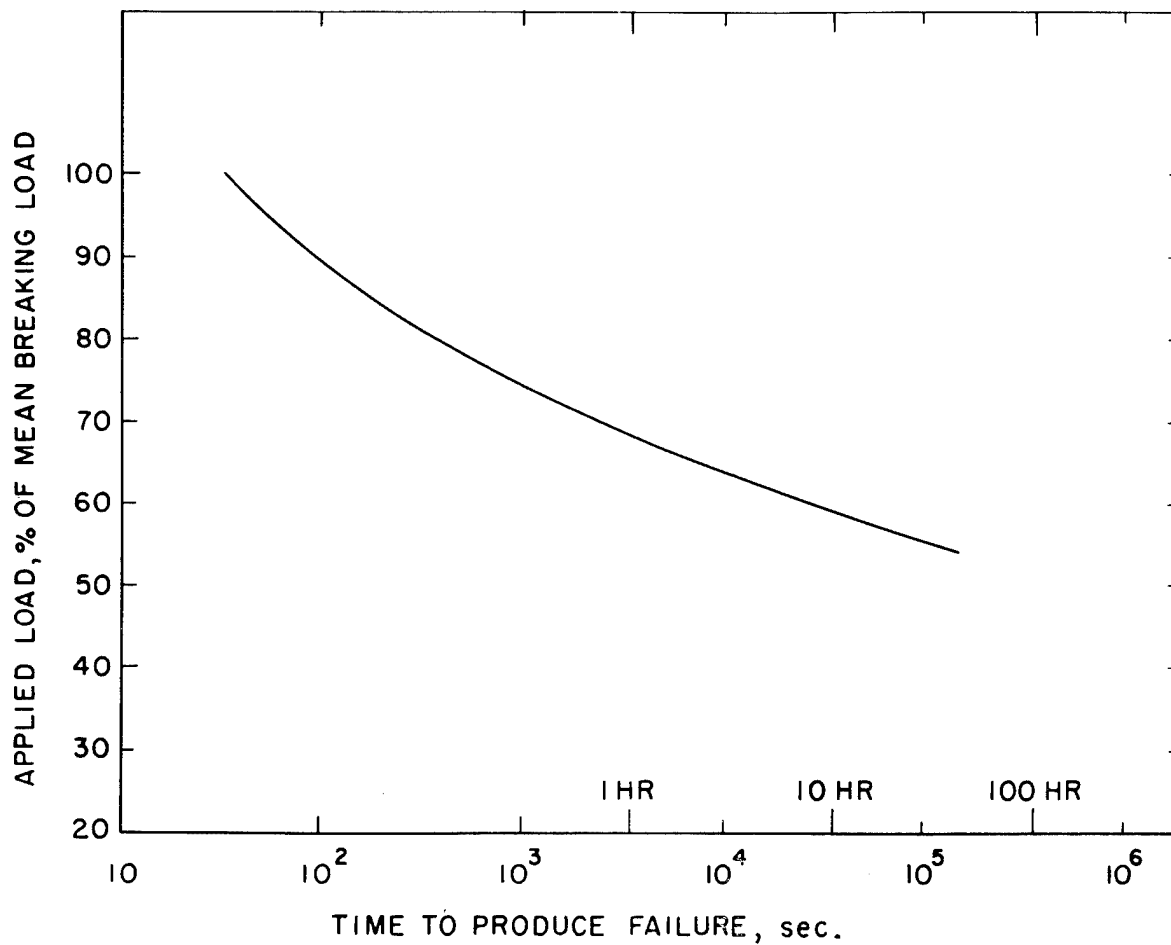
Figure 9.2-11 - The Effect of Sustained Loading on the Breaking Strength of
Annealed Sheet Glass

9-16
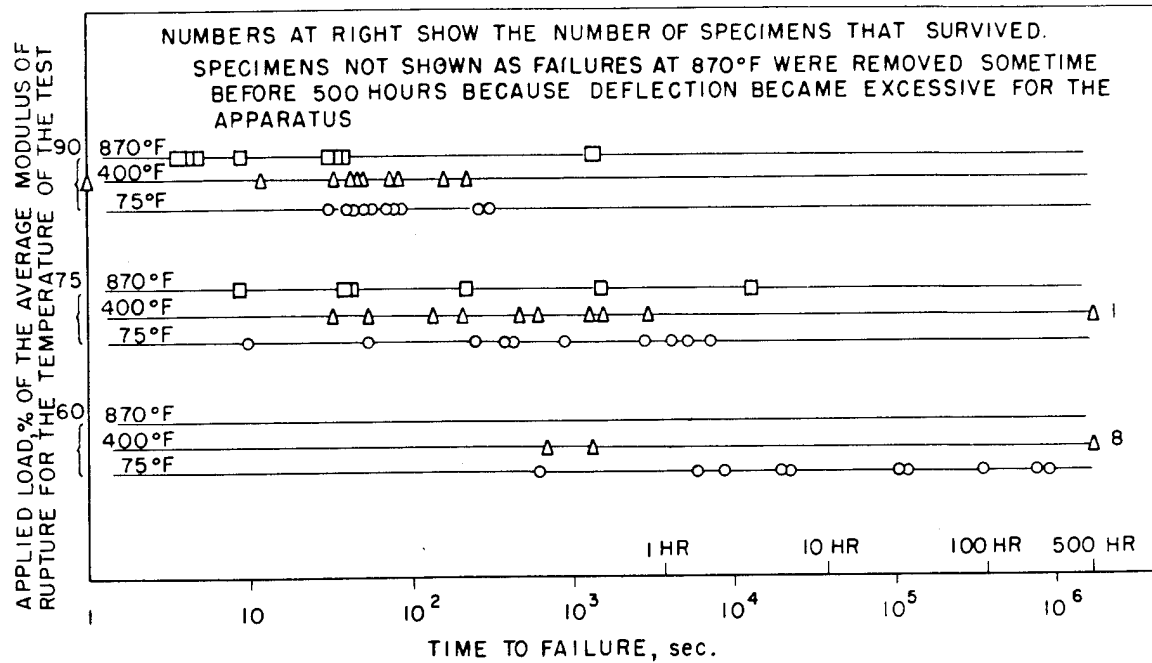
Figure 9. 2-12 – Time to Failure for Annealed LOF Specimens under Sustained Load
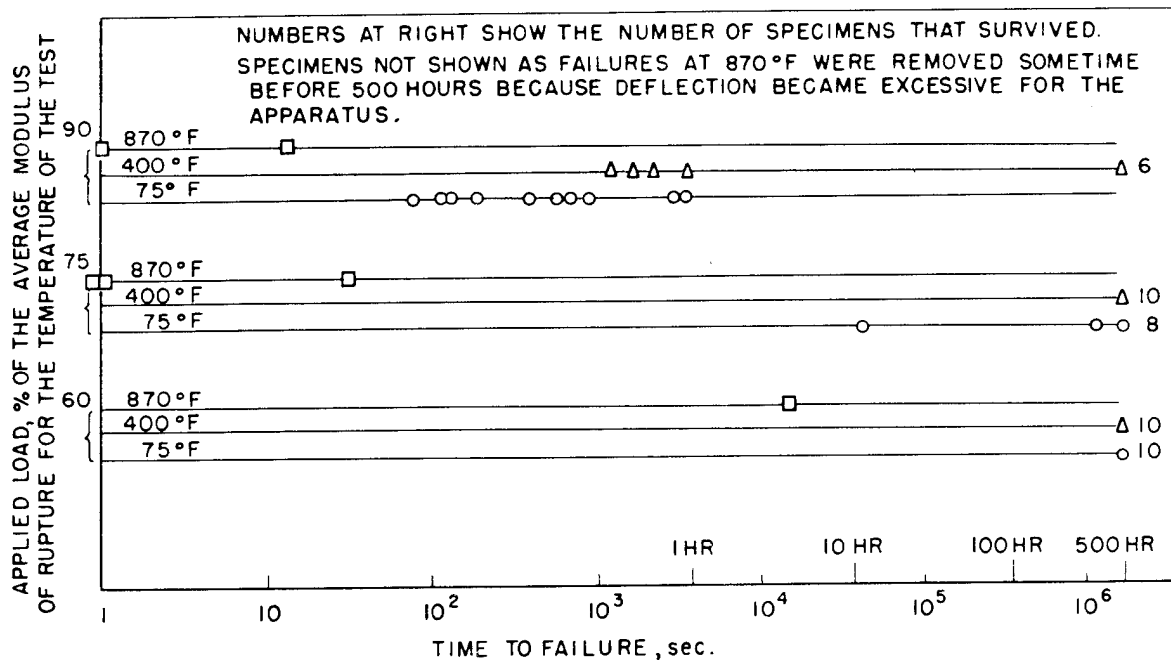
Figure 9. 2-13 – Time to Failure for Semitempered LOF Specimens under Sustained Load

9-17
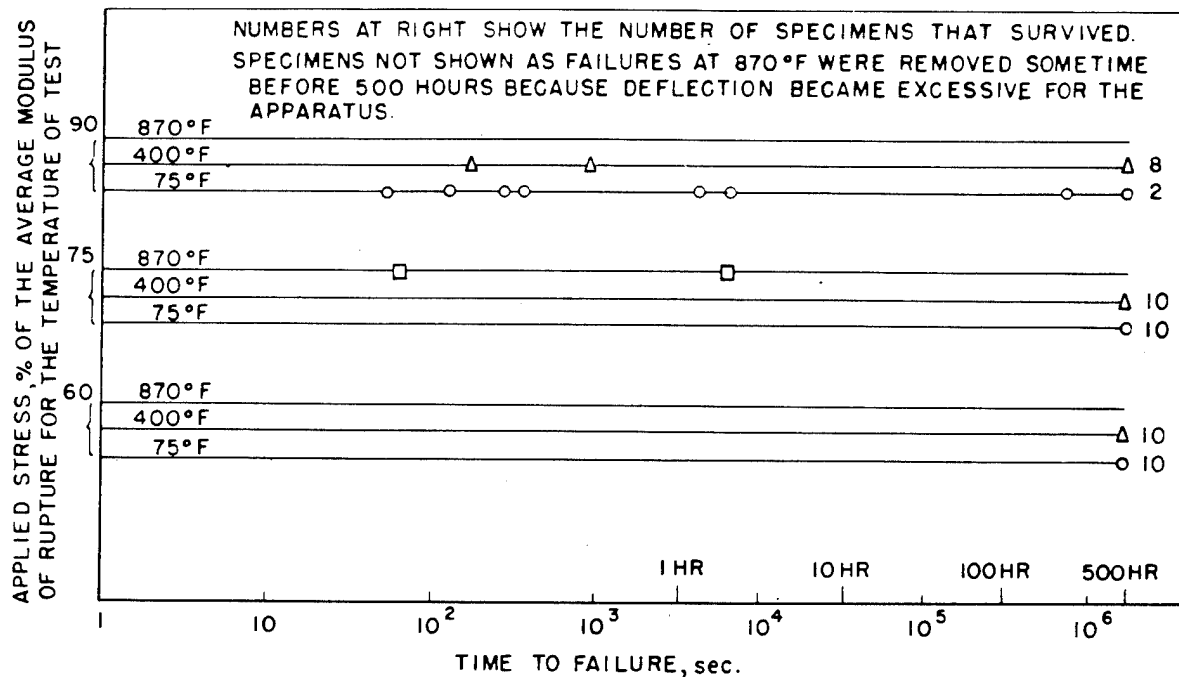
Figure 9.2-14 – Time to Failure for Tempered LOF Specimens under Sustained Load
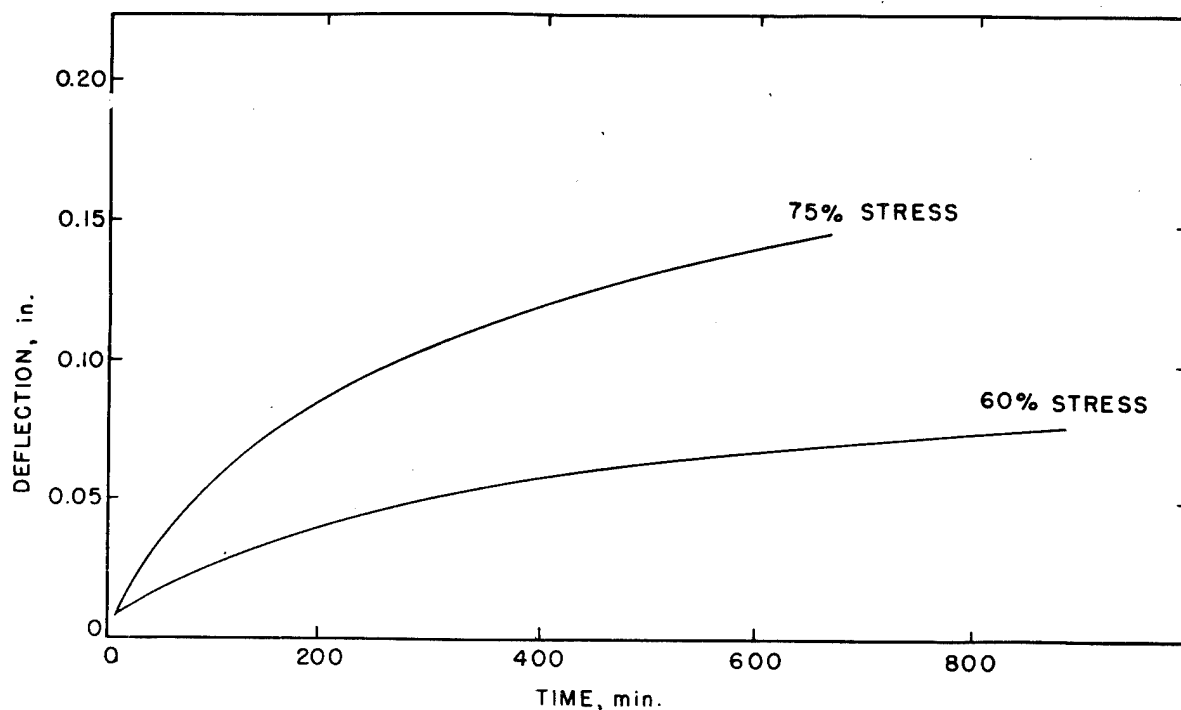
Figure 9.2-15 – Deflection-Time Curves for Annealed LOF Specimens under Sustained Load at 870 Deg F
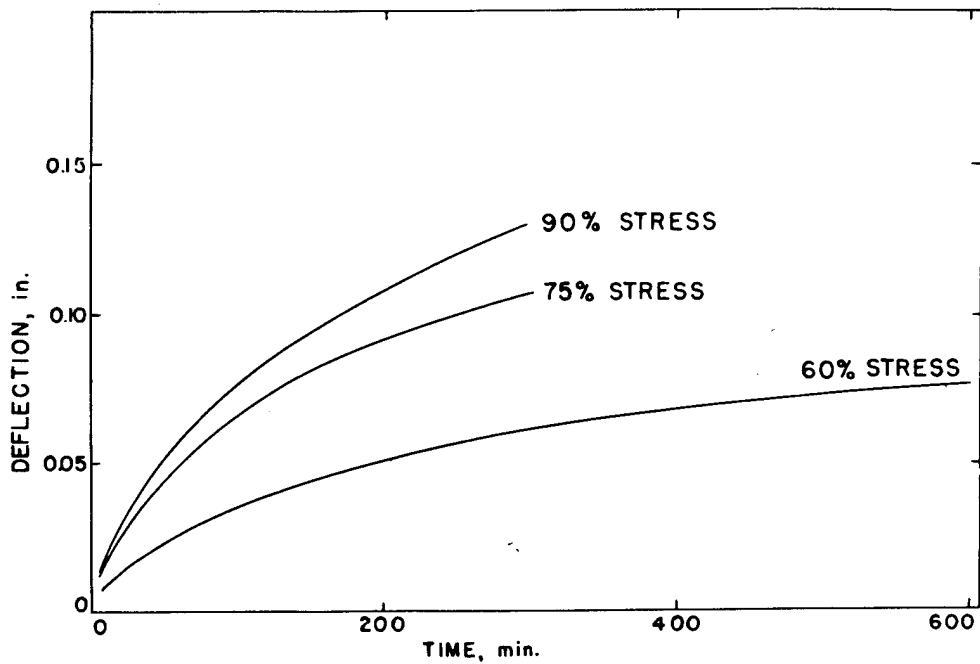
Figure 9.2-16 – Deflection–Time Curves for Semitempered LOF Specimens under
Sustained Load at 870 Deg F
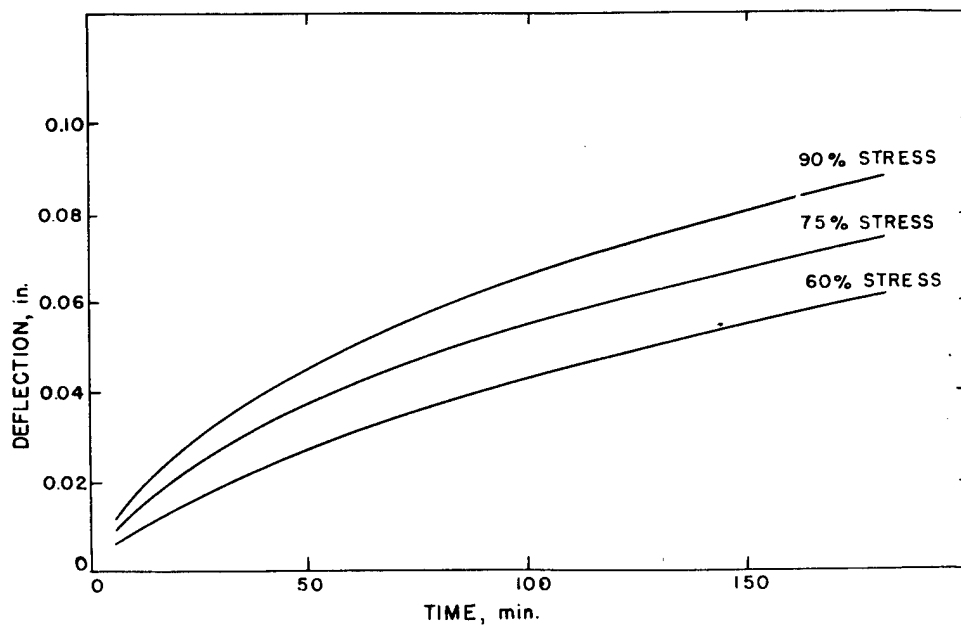
Figure 9.2-17 – Deflection–Time Curves for Tempered LOF Specimens under
Sustained Load at 870 Deg F

9-19

Creep occurs at elevated temperatures when stress is applied to the glass. An increase in temperature, stress, or both will increase the creep rate. Because of the difficulties involved in testing glass plates or laths in tension, creep is frequently determined as deflection. Figures 9.2-15, 9.2-16, and 9.2-17 show the rates of deflection of regular plate glass (LOF) in the annealed, semitempered, and tempered conditions at 870 deg F and under different stress levels (Reference 21).

9.2.7 POISSON'S RATIO

Poisson's Ratio for various glasses at room temperature is as follows:

Soda-lime	0.22
Aluminosilicate	0.26
Fused silica	0.17
96-percent silica	0.18
Chemically tempered glass	0.22

9.2.8 MODULUS OF ELASTICITY

The modulus of elasticity of most glasses lies between 9 million and 11 million pounds per square inch; however, glasses of some compositions may depart significantly from these values.

Figure 9.2-18 shows the variation of the modulus of elasticity with temperature for several glasses in the annealed condition (Reference 21). In this case the glasses were held at the testing temperature until constant value for modulus of elasticity was obtained. For LOF, PPG 3235, and CGW 1723, the modulus of elasticity decreases as the temperature increases. For CGW 7900 and CGW 7940, the modulus of elasticity increases with temperature. The modulus of elasticity of CGW 7740 first increases and then decreases as the temperature is increased.

Table 9.2-IV gives the modulus of elasticity results for several glasses (Reference 21). The modulus of elasticity values reported were determined at room temperature after the glass was heated at the reported temperature for 500 hours.
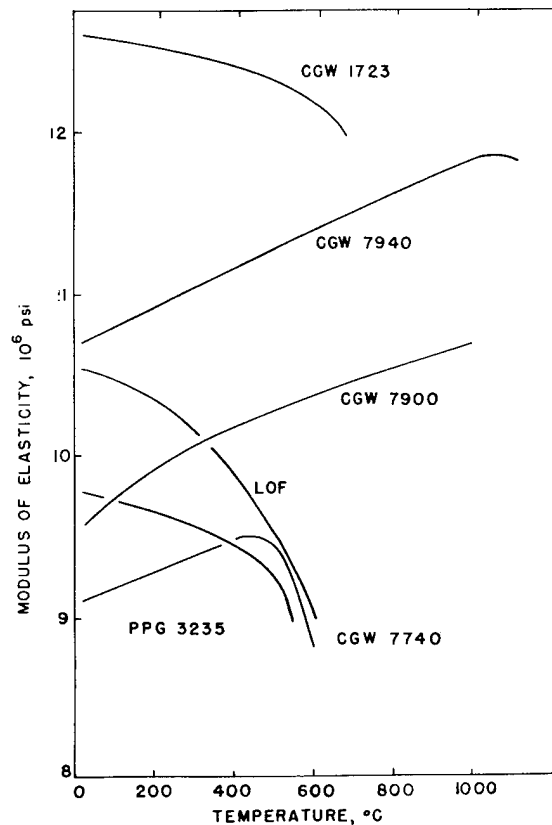
Figure 9.2-18 – Variation of the Modulus of Elasticity with Temperature for Several Glasses

Figures 9.2-19 and 9.2-20 demonstrate the effects of heating (run no. 1) at a rate of 180 deg F/min between readings (10-minute temperature threshold for measurements) followed by cooling at 175 deg F/hour to room temperature and then a repeated heat cycle (run no. 2). There is a general increase in modulus of the thermally tempered material, and no increase for the chemically tempered material.

9.2.9   HARDNESS

The most common hardness tests used on glass are:

1. Scratch hardness tests

2. Grinding or abrasion hardness tests

3. Penetration hardness tests.

9-21

TABLE 9.2-IV - MODULUS OF ELASTICITY AFTER HEATING FOR 500 HOURS AT
SEVERAL TEMPERATURES—MEASUREMENT MADE AT ROOM
TEMPERATURE

Glass	Condition of temper*	Modulus of elasticity in 10^6 PSI Temperatures in degrees Fahrenheit								
		75	400	550	700	830	870	1,150	1,420	1,725
LOF, regular, plate	A	10.50	–	–	10.61	–	10.77	–	–	–
	S	10.34	10.36	10.48	10.61	–	10.82	–	–	–
	T	10.16	–	10.34	10.46	–	10.73	–	–	–
PPG 3235	A	9.97	10.06	–	10.28	10.28	–	–	–	–
	S	9.80	9.87	–	10.21	10.42	–	–	–	–
	T	9.77	9.86	–	10.20	10.47	–	–	–	–
CGW 1723	A	12.56	12.55	–	12.78	–	–	12.60	–	–
	S	11.89	11.90	–	11.98	–	–	12.60	–	–
	T	11.81	11.80	–	11.93	–	–	12.57	–	–
CGW 7740	A	9.14	8.95	–	9.21	–	9.33	–	–	–
	S	9.00	9.04	–	9.29	–	9.69	–	–	–
CGW 7900	A	9.33	9.59	–	9.56	–	–	–	9.55	–
	S	9.51	9.51	–	9.54	–	–	–	9.30	–
CGW 7940	A	10.46	10.40	–	10.47	–	–	–	–	10.53

*A – Annealed. S – Semitempered. T – Tempered.
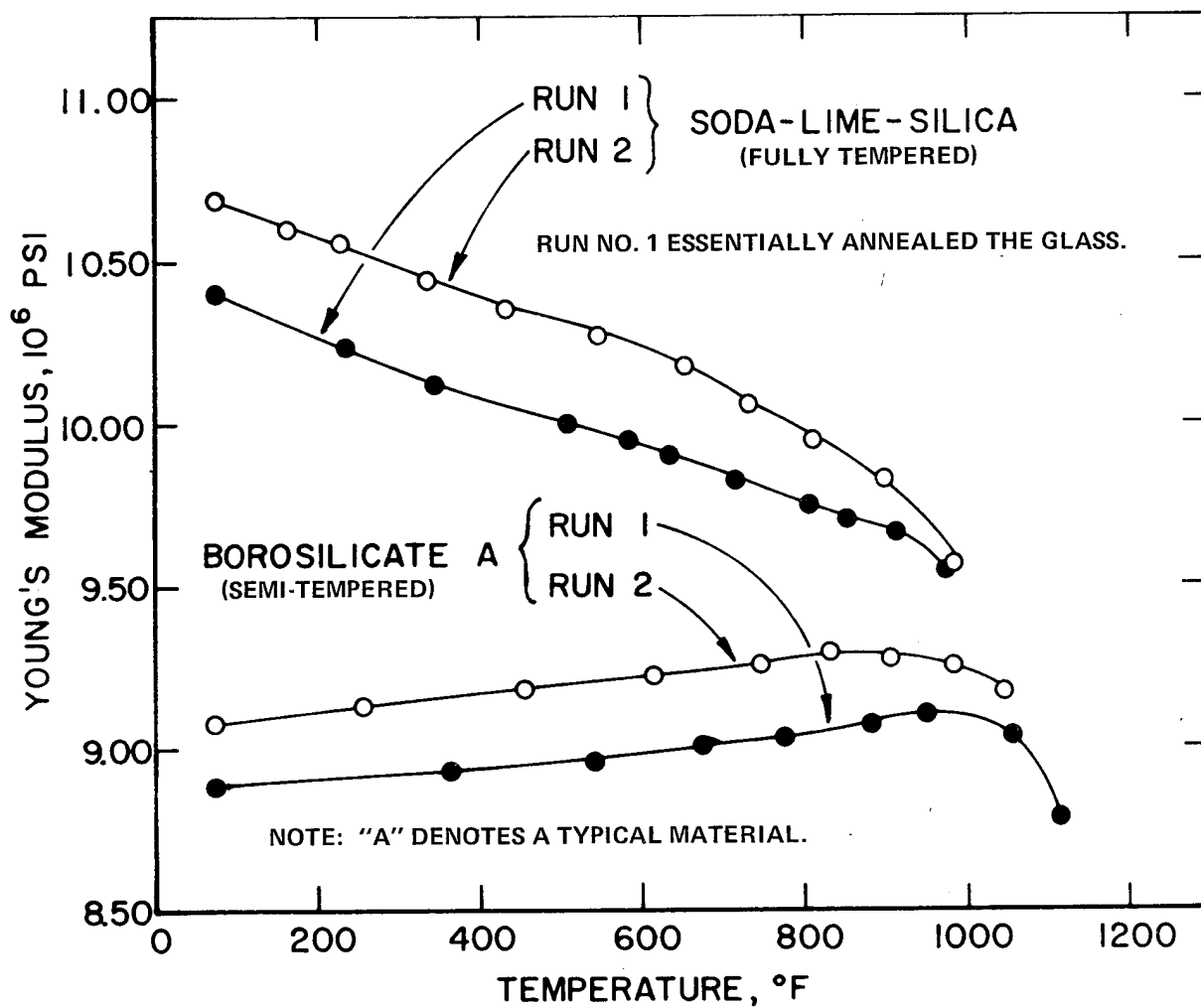
Figure 9.2-19 – Effect of Temperature on Young's Modulus for Thermally
Tempered Material
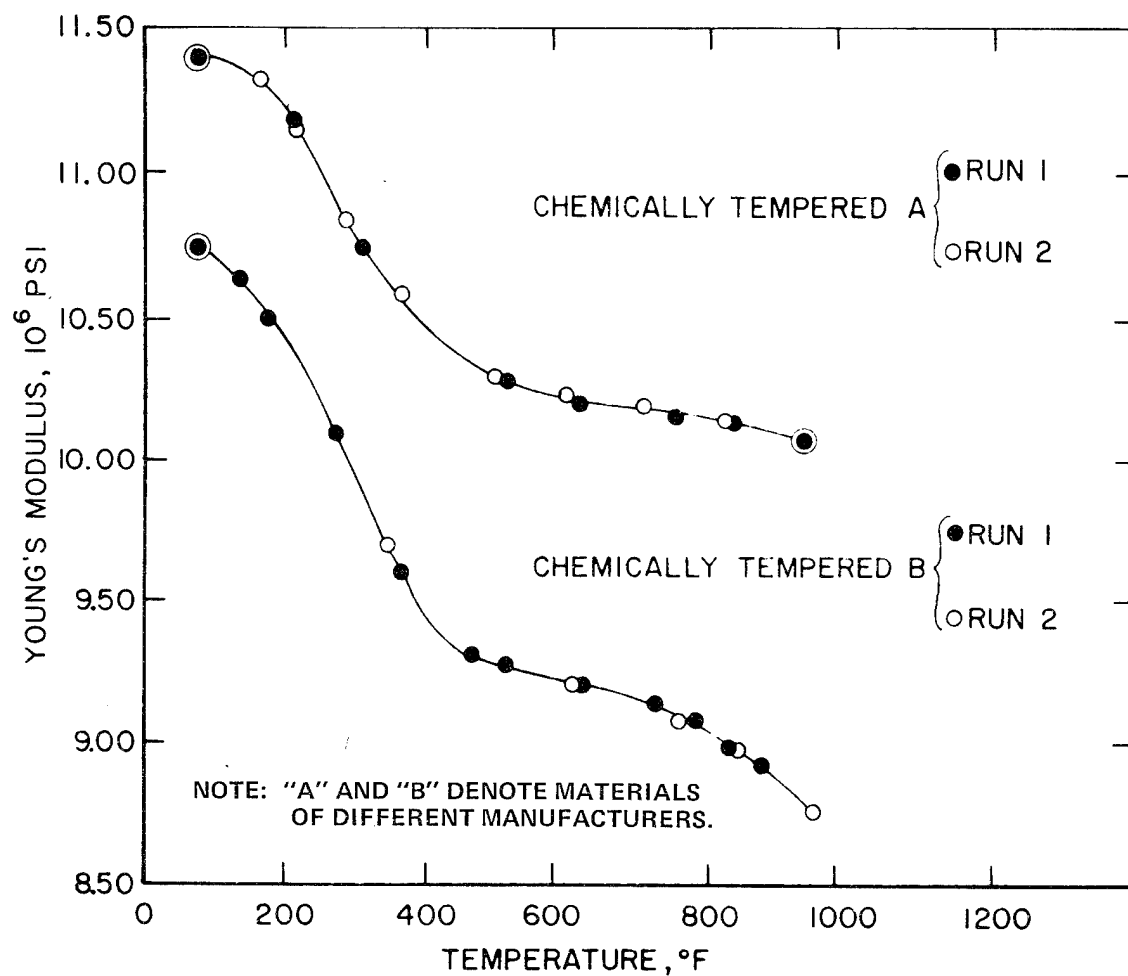
Figure 9. 2-20 – Effect of Temperature on Young's Modulus for Chemically
Tempered Material

9-24

The correlation between the hardness values obtained from the different tests is not good, and the order of hardness for a group of glasses may differ materially when determined by different methods.

Scratch hardness test results are generally rated on Mohr's scale of hardness. On this scale, glasses range between 4-1/2 and 6. The values obtained from grinding and abrasive hardness tests are compared to a soda lime plate glass (Reference 26). The penetration hardness tests give different values, depending on the test used. Table 9.2-V gives some typical hardness values for glass (Reference 27).

TABLE 9.2-V - MECHANICAL HARDNESS OF GLASSES*

Type of glass	Grinding silicon carbide no. 220 grit	Rouge polish	Impact abrasion	Indentation hardness, kg per sq mm			
				Diamond pyramid		Knoop	
				DPH_{50} **	Correct ***	KHN_{50} ****	Correct ***
Silica		2.55	3.60	780-800	710-720	640-680	545-575
96-percent silica			3.53			590	500
Soda-lime plate	1.00*****		1.00*****-1.07	580	540	575	490
Borosilicate	1.52	1.56	3.10	630	580	550	470
Aluminosilicate	1.36		2.03	640	586	650	550

*Data from Shand (Reference 26).
**DPH_{50}, diamond pyramid hardness under 50 g. load.
***Correct, length of impression corrected for resolution limit of microscope.
****KHN_{50}, Knoop hardness number under 50 g. load.
*****Standard for comparison.

9.2.10   SPECIFIC GRAVITY

The specific gravity of glasses considered for aircraft glazing varies from 2.18 to 2.63. The values for several glasses are given in Table 9.2-I, page 9-4.

9.3   THERMAL PROPERTIES

The thermal properties of principal interest include coefficient of expansion, specific heat, thermal conductivity, thermal **diffusivity,** and thermal emissivity, or more properly in this case, emittance.   A knowledge of these properties is needed mainly to calculate the temperature distribution and heat flow through the material.

9.3.1   COEFFICIENT OF EXPANSION

The coefficient of expansion for the glasses considered for aircraft glazing varies from 5.6 by 10^{-7} per deg C for fused silica to 92.0 by 10^{-7} per deg C for soda lime regular plate glass.   The values for several glasses are given in Table 9.2-I.

9.3.2   SPECIFIC HEAT

The specific heat can be measured accurately without undue difficulty and is known for some of the glasses of interest.   Because it is dependent upon thermal history, the heat treatment to which the glass has been subjected should be known and reported with specific heat values. The mean specific heats of several glasses are given in Figure 9.3-1 (Reference 28).

9.3.3   THERMAL CONDUCTIVITY, DIFFUSIVITY, AND EMISSIVITY

The thermal conductivity, thermal diffusivity, and thermal emissivity are difficult to determine, especially since they involve a transparent, diathermanous, material.   In the upper part of the temperature range of interest in aircraft glazing, the heat transfer characteristics depend in part upon radiant transmission.   When a glass plate is exposed to a radiant source, part of the energy will be absorbed in the glass while the remainder is transmitted.   Energy absorbed in the plate will affect the temperature gradient across the section.   Each side of the glass will also radiate heat at a rate dependent upon the internal temperature distribution.
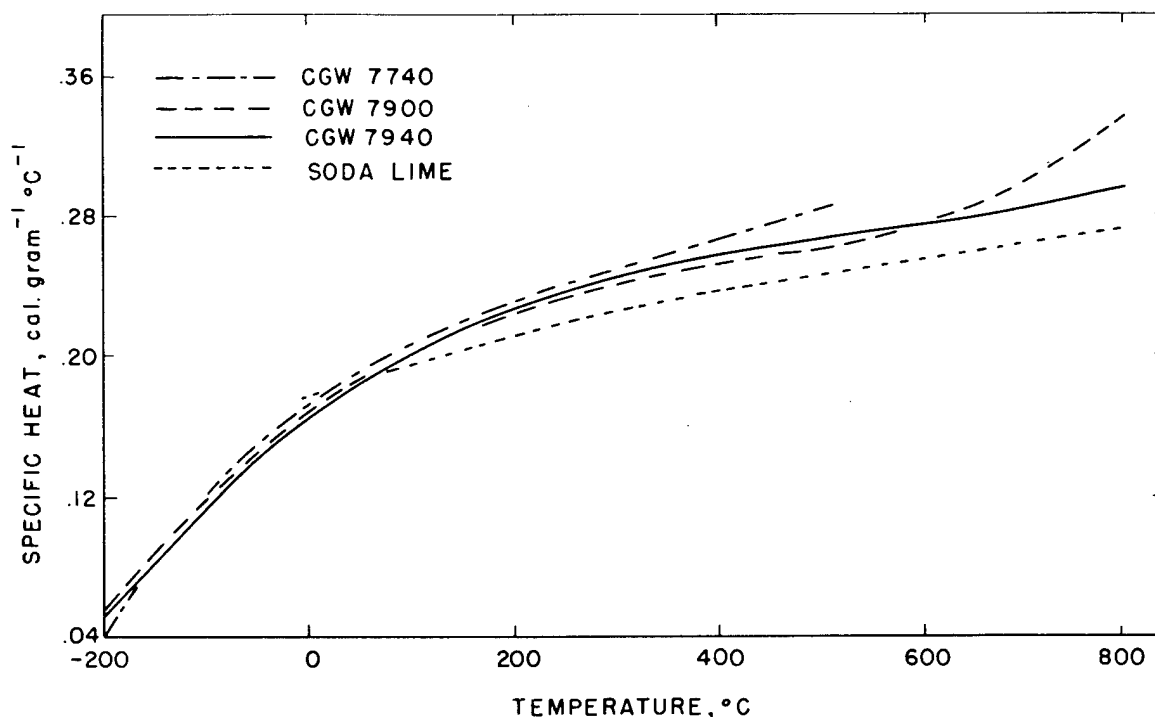
Figure 9.3-1 – Variation of Specific Heat with Temperature for Several Glasses

It has been shown that the emittance of an isothermal glass sheet can be computed if the spectral absorption coefficients of the glass are known (Reference 29). The temperature distribution within glass affects its radiation emittance at the surface and its effective internal conductivity at high temperatures. This being so, it is evident that the precise evaluation of these glass properties, by calculation or by experimental measurements, requires that they conform to the temperature distribution probable in service (Reference 30). Figure 9.3-2 shows the thermal conductivity of several glasses (Reference 28).

Table 9.3-I presents some typical thermal properties of glasses, including emissivity.

9.3.4 STEADY-STATE THERMAL GRADIENTS

Stresses caused by steady-state thermal gradients can be either innocuous or dangerous, depending entirely on the degree of constraint imposed by some parts of the item upon others by the external mounting. Thus under minimum constraint and maximum uniformity of gradient through the thickness, very large temperature differences can be tolerated.

9-27
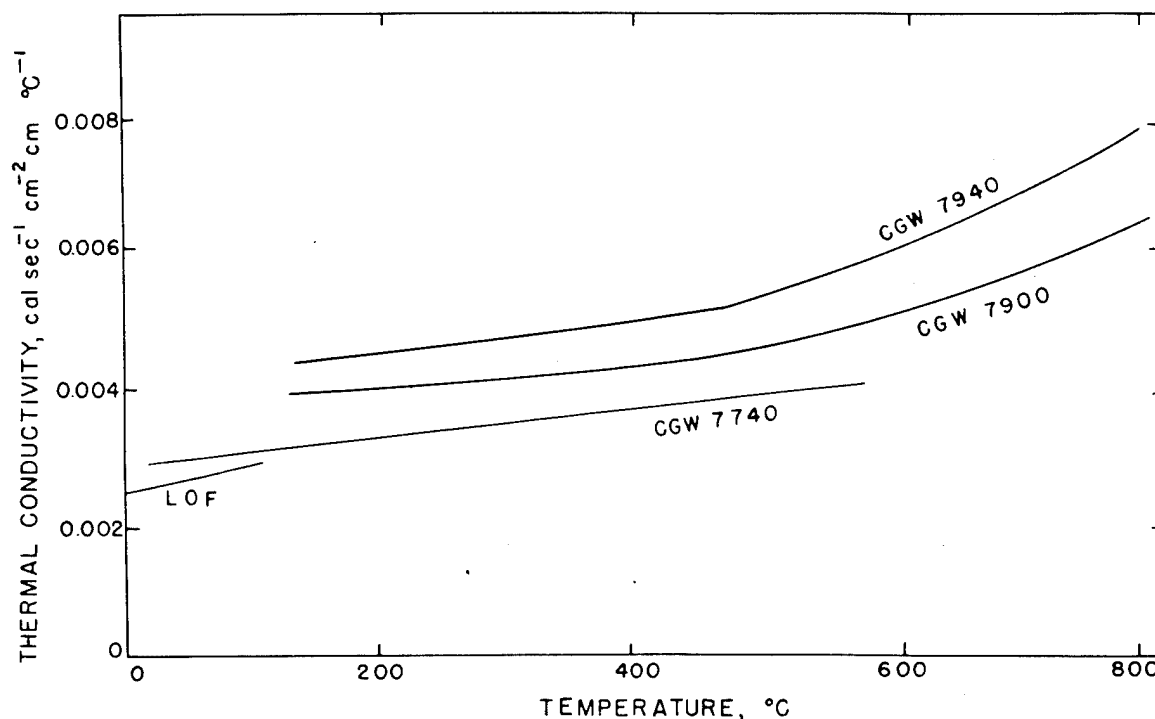
Figure 9.3-2 – Variation of Thermal Conductivity with Temperature for Several Glasses

TABLE 9.3-I – THERMAL PROPERTIES OF SEVERAL GLASSES

Property	Soda lime	Alumino-silicate	Fused silica	Chemically tempered glass
Thermal conductivity, $\dfrac{(BTU)\ (ft)}{(ft^2)\ (sec)\ (deg\ F)}$	0.65	0.72	0.67	0.6
Specific heat, BTU/lb	0.185	0.222	0.174	–
Total emissivity:				
300 deg F	0.86	0.90	0.82	–
600 deg F	0.85	0.90	0.81	–
900 deg F	0.83	0.89	0.79	–
Expansion, 10^{-7}/deg F	47.2	25.5	3.3	28-33
Softening point, deg F	1355	1674	2880	–
Annealing point, deg F	1022	1306	1967	–
Strain point, deg F	959	1238	1814	–

9-28

Under complete constraint, the face temperature differentials that will cause a tensile stress of 1,000 PSI on the cooler face is considered the maximum allowable for annealed glass. Highly tempered glasses can withstand larger temperature differentials than annealed glass. Table 9.3-II lists the maximum allowable temperature differences between opposite faces when annealed glass is under complete constraint (Reference 31).

TABLE 9.3-II – THERMAL STRESS RESISTANCE

Glass	Difference in deg F
Soda lime	64
Borosilicate	118
Aluminosilicate	84
96-percent silica	392
Fused silica	554

9.3.5 TRANSIENT THERMAL GRADIENT

When glass is suddenly heated or cooled, transient stresses are introduced that disappear when temperature uniformity is attained. Because glass fails only in tension and usually at the surface, the temporary stresses from sudden cooling are much more damaging than those resulting from thermal heating, assuming all surfaces are heated or cooled at the same rate. The transient thermal stresses increase directly with the expansion co-efficient and in a complex way with glass thickness. They also depend upon the shape of the article and on the method of chilling or heating. Thus, a complicated shape would be more severely stressed than a simple one. Because of the many factors involved, thermal shock endurance cannot be directly calculated but is generally determined by empirical testing.

Table 9.3-III gives the temperature that various glasses can be heated to and plunged into cold water without breaking. Cooling in a less severe medium, such as air, permits much higher temperatures than those listed (Reference 31).

TABLE 9.3-III – THERMAL SHOCK RESISTANCE OF ANNEALED PLATES 6 IN. BY 6 IN. *

	1/8-in. thick (deg F)	1/4-in. thick (deg F)	1/2-in. thick (deg F)
Soda lime	158	140	104
Borosilicate	356	302	212
Aluminosilicate	275	221	167
96-percent silica	2,282	1,832	1,742
Fused silica	2,287	1,832	1,742

*From Corning, "Properties of Select Glass" (Reference 31).

Tempered glass can stand considerably greater thermal shock than annealed glass; the greater the amount of temper, the greater the resistance to thermal shock. Fully tempered glass can withstand from three to four times the temperature differences for thermal shock that annealed glass can.

Thermal shock tests on 20-inch by 10-inch by 1/4-inch samples of tempered PPG 3235 and CGW 7740 were made by heating one face of the glass and then spraying water at 32 deg F on the hot face. The results show that the two glasses were able to withstand the shock with hot face temperatures as high as 850 deg F. The specimens did not fail when shocked at this temperature, but this temperature was the limit of the apparatus (Reference 32).

9.4   OPTICAL PROPERTIES

The optical properties of most interest for aircraft glazing are surface reflection, index of refraction, absorption, and over-all transmission. These values are easily measured and are readily obtainable from the manufacturer of the glass in question.

The amount of light reflected from a single polished glass surface is ordinarily small, depending on the refractive index of the glass and the angle of incidence of the light beam. For small angles of incidence the loss per glass surface generally ranges between three and

five percent. The loss is greater for large angles of incidence. Coatings and other surface treatments have been developed to reduce the reflection loss, but these are not entirely satisfactory, especially when the glass surface is not completely protected.

The refractive index of the glasses presently considered for aircraft glazing varies from about 1.46 for 96-percent silica to about 1.55 for aluminosilicate, with soda lime plate at about 1.52. The refractive index changes with temperature and with heat treatment, but these changes are not large and probably will cause difficulty only if precision instruments are sighted through the glass.

Glass absorbs energy from the light that passes through it, the amount of light absorbed depending on the type and thickness of the glass, and varies greatly with different wavelengths. The over-all transmittance of light is the ratio of the intensity of the emerging beam and the incident beam. The loss of intensity includes those of reflection and absorption. For the glasses presently considered for aircraft glazing, the over-all transmittance varies from 87 percent to 92 percent for a thickness of 1/4-inch. At this thickness, the percentage of white light absorbed by these glasses is less than that lost by reflection.

CHAPTER 10 - EDGE ATTACHMENT DESIGN

10.1 GENERAL

10.1.1 INTRODUCTION

The term "edge attachment" is commonly applied to any means of fastening or joining a glazing material to an airframe, including simple procedures such as a bolt through the glazing material into the airframe. The glazing material may be used as a canopy, window, windshield, bubble, or other structure intended to make a portion of the outer skin of an aircraft transparent.

In this chapter all discussions refer principally to canopies unless otherwise indicated; their size and specialized service requirements magnify design problems common to all aircraft glazing applications and introduce some additional problems.

10.1.2 PURPOSE OF EDGE ATTACHMENTS

The purpose of an edge attachment is usually twofold: besides the obvious purpose of joining the glazing material to the body of the aircraft, it generally serves to transmit the loads developed in the glazing material to the airframe. Such loads are commonly caused by cabin pressurization and aerodynamic loading.

10.1.3 DESIGN OF AN EDGE ATTACHMENT

10.1.3.1 IMPORTANCE OF GOOD DESIGN

The choice of the method of attachment of a glazing material to an airframe is as critical as the choice of the glazing material, for improper installation may cause local stress concentrations that exceed the allowable strength of the glazing material. The commonly used glazing materials are structurally much weaker than the other components used in aircraft, and the strength properties of plastics glazing materials are temperature dependent in the thermal range common to normal operating conditions for present-day aircraft. To make the most of the available strength of these materials and to prevent premature failures, the stresses

developed in these materials must be distributed as evenly as possible, and stress concentrations must be minimized. An inadequate edge attachment design may easily lead to greater stress concentrations than the edge attachment was intended to eliminate.

A well-designed edge attachment will distribute the common load forces uniformly from the glazing to the airframe without generating additional stresses or stress concentrations such as may result from unequal thermal expansion or induced notch effects.

10.1.3.2   CHOICE OF A DESIGN

Each edge attachment should be designed specifically for its own particular application, with due attention to the purpose of the application, the properties of the glazing material, and the probable exposure environment. The service expected from an edge attachment for a canopy may differ appreciably from that expected from an attachment for a bubble enclosure; a window attachment may be of another, wholly different nature. The style, and even the purpose, of an edge attachment for glass may be quite different than for a plastic glazing material; the characteristics of different plastics may be similarly divergent. Load conditions and probable temperature ranges are but two of many environmental factors that will affect the ultimate design of an edge attachment.

The glazing material should be securely fixed within the supports, but should be free to expand or contract with changes in temperature and with aging, without distortion of the glazing structure or impairment of the edge attachments.

10.1.3.3   PROOF OF A DESIGN

The greater complexity of aircraft enclosures and their environments requires that developmental testing accompany the design phase of any edge attachment configuration that does not have previous data support. Initial testing should concern the adhesive system's adherence to the substrate through a representative range of temperature and stressing. If an interlayer is required, it should be tested, similarly, as an adhesive. Intermediate testing should be performed on coupons which represent the complete edge attachment design with its associated hardware and transparent member. These should be tested in a thermal equilibrium state at

representative temperatures which do not exceed the calculated temperature limits the bond line will experience under flight conditions. For complex designs which will experience a severe temperature gradient, the gradient should be simulated on similar samples throughout the aircraft's thermal flight profile, which includes transient extremes (i.e., dives to more dense atmospheres). These profiles are difficult to attain with most thermal equipment, but can be approximated for a net effect. Final testing requires completed prototype parts which are subjected to cycled programs of temperatures and pressures that simulate the dynamic forces to be expected, for at least the life of the part if not of the aircraft. These parts are mounted in a test fixture by attachment to an actual glazing frame.

10.1.3.3.1 TESTING OF EDGE ATTACHMENTS

Laboratory testing of representative material interfaces are necessary, not only as a means of proving detail design, but also a way of isolating certain problem areas which may cause a total failure of the composite.

Tensile tests are the most common means of evaluating edge attachments, because the attachments generally function in tension. For most designs, this means a shear stress on the bond between the glazing and the edge attachment. These tests are generally made over the entire temperature range to which the glazing will be exposed.

Tensile tests are frequently augmented by combination tensile and bending loads and by slow, cyclic tensile fatigue tests. The slow, cyclic tensile fatigue tests simulate repeated pressurizations. The effects of weathering may be evaluated by static tensile loading outdoors.

Bending or bending fatigue tests should be made because bending may occur in yawed flight or during pressurization of relatively flat glazing areas, such as windows.

Test specimens are usually 3 inches to 5 inches wide: test data have shown little difference in results on specimens ranging from 3 to 29 inches in width. The specimens should be fabricated for the tests and not cut from canopies; specimens from canopies are difficult to test because of curvatures. The rate of straining is usually 0.05 inch per minute.

Some tests have been made on edge attachments only, apart from the glazing material. In this way the materials used, in the combinations used, may be tested apart from design factors. Common tests are coefficient of thermal expansion, tensile strength and modulus of elasticity, bending strength, bearing strength, bond strength, machining capability, and bonding characteristics.

Production control tests of finished glazing assemblies, including edge attachments, are also made. In such tests loading is at the rate of about one pound per square inch per second, approximating service loading rates.

Comparisons of test results on edge attachments must be made with considerable caution: one of the advantages of preparing specimens specifically for tests is that the method of impregnation of the edge attachment, the type and manner of bonding used, the curing conditions, and the thermal history of the finished specimen are known.

10.2   GENERAL DESIGN CONSIDERATIONS

The two major decisions in the design of an edge attachment, the choice of the structural design and the choice of the materials to be used, can be implemented by consideration of several general principles of good design. These general principles are intended to eliminate or reduce stress concentrations and, as much as possible, to reduce all stresses in the glazing and the edge attachment to pure tensile stresses. Then, depending on the design of the edge attachment, the bond between the glazing and the edge attachment would be subject to pure shear stresses. The objective is to minimize bending stresses in the glazing and edge attachment and avoid any peel stresses in the bond between them.

10.2.1   THERMAL EXPANSION

Differences in the thermal expansions of glazing materials, edge attachment materials, and metal airframes present one of the major problems in edge attachment design. An edge attachment with a coefficient of thermal expansion appreciably different from that of the glazing to which it is attached will cause warping and large stresses and stress concentrations at the bond between the glazing and edge attachment when the assembled unit is subjected to

changes in temperature. The extent of warpage and the amount of stress depend on the relative bulk of the glazing and the edge attachment, the modulus of each, and the extent of the temperature change. Any increase in the thickness or cross-sectional area of the edge attachment over the minimum required for adequate strength increases the deleterious effects, as will an edge attachment with a high modulus of elasticity.

Matching the coefficients of thermal expansion of the glazing and edge attachment materials can substantially reduce the thermally induced stresses. The coefficients of thermal expansions of many materials commonly used for edge attachments are presented in Figure 10.2-1. Similar data for glazing materials are given in Figure 4.2-9. It is apparent that the synthetic fabrics, particularly nylon, impregnated with an appropriate resin provide the best match of linear coefficients of thermal expansion.

Reasonable matching of coefficients of thermal expansion and careful design to minimize thermal effects between the glazing and edge attachment are relatively ineffective if the edge attachment is rigidly attached to the airframe. The airframe ordinarily has a linear

A MIL-P-5425
B NYLON-ACRYLICS
C 9519 DACRON-ACRYLIC
D ORLON-ACRYLIC
E 24S ALUMINUM
F 128-114 FIBERGLAS-POLYESTER
G 128-114 FIBERGLAS-ACRYLIC
H 143-114 (UNIDIRECTIONAL) FIBERGLAS-ACRYLIC, WARP DIRECTION
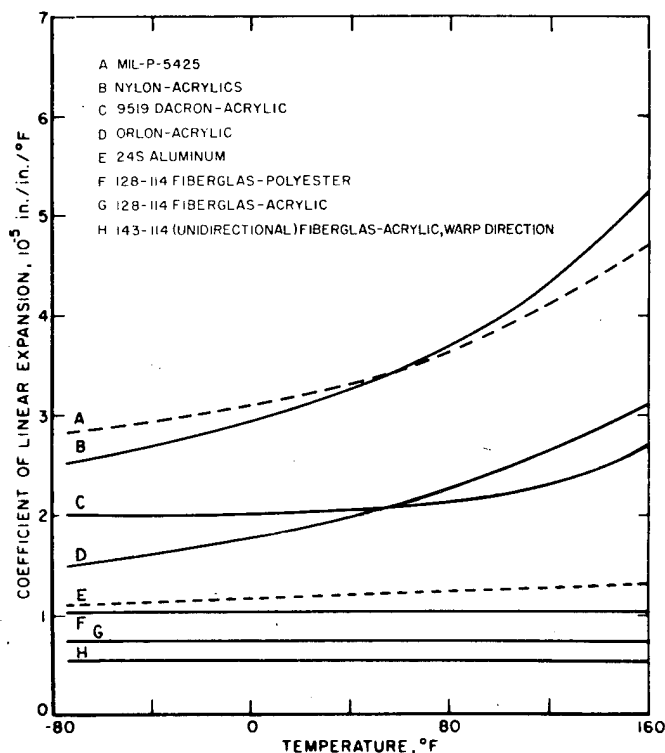
Figure 10.2-1 - Effect of Temperature on Coefficient of Linear Thermal Expansion of Various Materials

10-5

coefficient of thermal expansion much below that of the glazing or edge attachment materials. Undesirable stresses generated between the airframe and the edge attachment are transmitted to the glazing if the edge attachment is rigid. Expansion joints fore and aft, while desirable to prevent stretching or buckling of the glazing, are not sufficient. Provision must be made to allow the edge attachment to move relative to the side beams. Frictional forces should be minimized or unduly high stresses may be produced before motion between the glazing and the airframe can occur. Several methods of coping with this problem have been developed and are described in section 10.3.3. One of the simplest methods is the use of flexible loop attachments.

10.2.2 UNDERCUTS AND CHANGES IN SECTION

Undercuts in the glazing material or abrupt changes in section at the junction of the glazing material and the edge attachment are undesirable because they tend to produce stress concentrations. Where undercuts are necessary for maintenance of a smooth outer skin on the aircraft, stress concentrations may be minimized by use of large radii at the beginning of the undercut and by filling the undercut with the edge attachment to maintain good continuity; on the opposite face of the glazing material the reinforcement should extend beyond the undercut. Figure 10.2-2 (a) illustrates a good undercut, and Figure 10.2-2 (b) shows good practice in filling the undercut; Figures 10.2-2 (c) and (d) illustrate poor practice.

Photoelastic studies show that the junction of the glazing material and the edge attachment must be gradual to minimize stress concentrations in the glazing material; this is usually best accomplished with a tapered junction as in Figures 10.2-2 (b) and (d).

Annealing does not remove residual stresses in the junction between the glazing material and the edge attachment when a glass fiber reinforced edge attachment is used, but rather adds to the stresses, because of the poor match of thermal expansion coefficients and the high modulus of the glass.

10.2.3 CONCENTRIC MOUNTING

Edge attachments should be mounted concentric with the glazing material, as illustrated in Figure 10.2-3, to prevent bending stresses in the edge attachment or glazing material.

10-6

(a) LARGE RADIUS UNDERCUT ON GLAZING
    MATERIAL (GOOD).
(b) UNDERCUT FILLED BY EDGE ATTACHMENT TO
    MAINTAIN CONTINUITY OF SECTION (GOOD).
(c) SMALL RADIUS UNDERCUT ON GLAZING
    MATERIAL (UNDESIRABLE).
(d) SMALL RADIUS UNDERCUT ON GLAZING
    MATERIAL, NOT FILLED BY EDGE ATTACHMENT
    (BOTH UNDESIRABLE). IN (B) AND (D), NOTE, ON
    FACE OPPOSITE UNDERCUT, THAT REINFORCEMENT
    IS EXTENDED BEYOND UNDERCUT (GOOD).

Figure 10.2-2 – Undercut Configurations
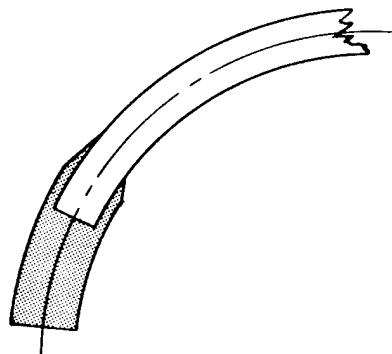
Figure 10.2-3 – Edge Attachment Concentric with Glazing Material

10-7

Glazing materials for canopies are usually formed in circular cross-section; where elliptical or parabolic cross-sections are found, the tendency on deformation is to assume a circular cross-section.

In addition to the possibility of transmitting bending stresses to the glazing when nonconcentric mounting is used, the bending stresses tend to develop peel stresses at the bonds between the edge attachment and glazing. These bonds are usually weakest in peel strength.

10.3   MONOLITHIC EDGE ATTACHMENT DESIGNS

On the following pages some structural designs are illustrated and discussed. In some instances a design is suitable only if specific materials are used; these instances are indicated. Where several designs are satisfactory for use with a particular glazing material, the advantages and disadvantages of each design are discussed. The properties of edge attachment materials are presented in Chapter 7, but sometimes specific materials are especially desirable with a particular glazing material or with a particular design; such instances are noted, with reference to Chapter 7 for data on properties.

10.3.1   BOLT-THROUGH DESIGN

Installations requiring bolts or screws through the glazing material should be avoided. Premature failure caused by excessive stress concentrations is almost certain to occur. Three exceptions are known; in such cases the mounting should comply with T/O 1-1A-12. The first exception, considered poor practice, is for slow-speed, low-altitude aircraft where there will be no loading caused by pressurization and where aerodynamic loading is minimal. The second exception is recommended as good practice; MIL-P-25690 glazing material has a longer service life when mounted with bolts through the glazing than when bonded edge attachments are used. If reinforcements are used with MIL-P-25690 material to protect the edges of the glazing, they should be bolted on, not bonded on. The third exception is a design compromise in which polycarbonate (MIL-P-83310) is the load-bearing member for a high-performance aircraft enclosure. In this case the available adhesive systems cannot repeatedly sustain the thermal and loading profiles of the operational aircraft.

Special care must be exercised to reduce stress concentrations, both in design and machine practice, when bolt-through design is used. The positions for the holes should be chosen to distribute the loads from the glazing equitably, and the number of holes should be sufficient to keep the load per hole to an acceptable level. Good shop practice is very important; the holes should be exactly centered, true, carefully aligned with the holes in the frame, and well-finished, with no radial cracks, notches, cuts, or other flaws. Overheating during machining must be avoided. Thermal expansion in the glazing material should be provided for by the use of oversized or elongated holes fit with bushings, which distribute the bolt bearing stress.

10.3.2 IMPREGNATED FABRIC LAMINATE

Figure 10.3-1 illustrates the basic design of an edge attachment incorporating impregnated fabric ears bonded to the glazing material by the impregnating resin or by an adhesive. The design is basically good for monolithic glazing materials, because the loads on the glazing can be distributed uniformly. The impregnated fabric is sufficiently strong not to be sensitive to
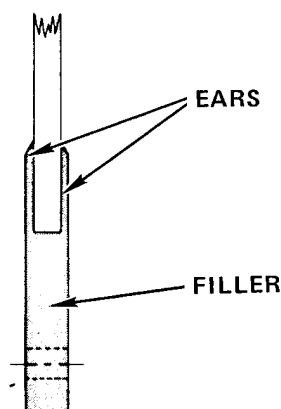
Figure 10.3-1 - Edge Attachment Design

10-9

stress concentrations of the intensity that will be developed by bolting to the airframe. The use of only one ear is undesirable, because bending or twisting of the glazing can result from the unequal transfer of the load. Consequently, two ears are used with filler in between.

When the reinforcement is glass fabric, a decrease in strength is due principally to the impregnant; when the reinforcement is a synthetic fabric, the decrease is due to the reinforcement and the impregnant. Occasionally a mixed reinforcement, consisting of layers of synthetic fabric and glass fabric, is used to obtain a compromise of their differing characteristics.

Continuous attachments for long enclosures usually require an orientation such that the fill direction of the fabric carries the load; most fabrics are stronger in the warp direction. Immersion in water has very little, if any effect on the tensile strength of these laminates.

10.3.3 FLEXIBLE ATTACHMENTS

Flexible edge attachments offer greater freedom from thermal expansion stresses than do the semirigid and rigid attachments. The flexible attachments are made of strips or loops of fabric bonded to the glazing material and looped around or gripped between bars or rods fastened to or restrained by the airframe. Figure 10.3-2 (a) illustrates the design. Friction in the joint assembly may be reduced by substitution of a nylon rod for the metal rod if it is feasible, or by bonding nylon half-rods on the outer sides of the fabric.

The load should be distributed evenly from the fabric to the airframe; care must be exercised to prevent unequal loading such as illustrated in Figures 10.3-2 (b) and (c). When bolts pass through the fabric, as in Figure 10.3-1, the load is transmitted to the airframe as a result of the clamping action and not through the bearing of the fabric on the bolts.

When flexible attachments are used, the transverse enclosure frames or expansion joints generally support the glazing, and the fabric sustains the loads developed in the glazing.

Nylon fabric is generally used for flexible loop attachments, although Dacron has been used occasionally. A synthetic fabric loop is much weaker than a glass fiber reinforced laminate in tension, flexure, and shear, but the flexibility of the synthetic fabric loop permits applied

10-10
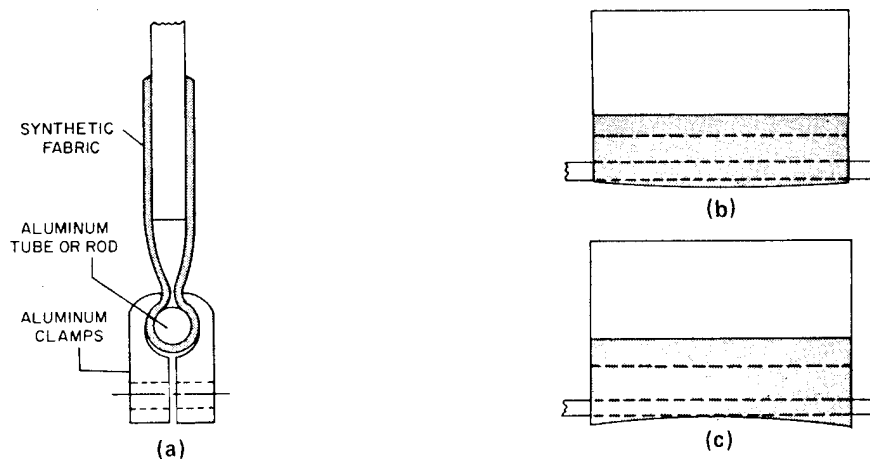
Figure 10.3-2 – Flexible Edge Attachment Design

stresses to be transferred more uniformly over the entire length of the edge attachment, resulting in reduced stress concentrations. In this respect, experience has indicated that the loop-type edge attachment is superior.

As a general rule, the static tensile strength of rigid edge attachments is higher than that of flexible attachments, but invariably the edge attachments with lower moduli exhibit superior tensile-fatigue behavior.

This type of attachment has been constrained primarily to unpressurized cockpit enclosures.

10.3.4 EXPANSION JOINTS

Expansion joints, as implied by the name, are designed to provide for unrestrained expansion and contraction of the glazing material while providing the support or restraint necessary to maintain the glazing material in the desired contour. Though they do not transmit loads from the glazing material to the airframe, expansion joints are included in the general

category of edge attachments since they provide one of the many types of transition from the transparent glazing material to the airframe. Any pressure loads that exist are carried by the canopy bearing outward against the frame as well as by the edge attachments along the sides of the canopy.

Two examples of expansion joints are illustrated in Figures 10. 3-3 and 10. 3-4; numerous variations or modifications have been used. Care should be taken that clamping on the joint to ensure proper sealing action does not cause sufficient friction to preclude proper motion of the joint during temperature changes. Rigidity of the frame is essential to prevent warpage of the frame and resultant binding in the joint. When any material is bonded to the glazing material at the expansion joint, as in Figures 10.3-3 and 10.3-4, the usual precautions are necessary regarding matching of coefficients of thermal expansion.

Expansion of the rail joint requires that at least one hoop of a canopy have an expansion joint of a slotted design with the centerlines of the slots parallel to the rail direction.

10. 4   COMPOSITE DESIGNS

The basic concepts of monolithic edge attachment design hold for composite configurations as shown in Figure 10. 4-1 with the additional problem of securing multiple layers of transparent materials which have different physical responses to thermal exposure. The latter include any combination of materials discussed in the previous chapters, including glass and trans- parent metallic and nonmetallic coatings. The variation in transparent material combinations dictates edge attachment designs which often require more than one adhesive and laminate system to be capable of distributing loads properly under thermal gradient conditions.

10. 4. 1   DESIGN CONSIDERATIONS FOR PLASTIC LAMINATES

The transparent composite and its edge attachment are usually designed for a specific applica- tion, and allowable stresses undoubtedly will have to be determined by test for the particular configuration. Flight performance criteria can be further complicated by the transient types of loading, such as bird and bullet impact.

FLEXIBLE
SEALANT

METALLIC BUSHINGS

"U" CHANNEL
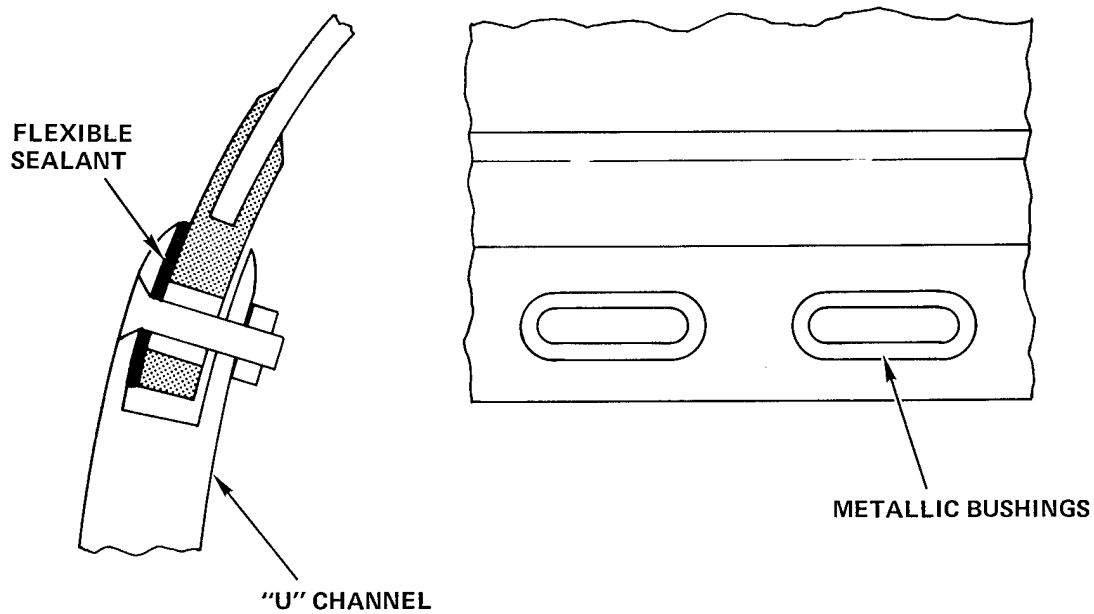
Figure 10.3-3 – "Slotted Bushing" Expansion Joint

FLEXIBLE
SEALANT

AIRFRAME   ROD
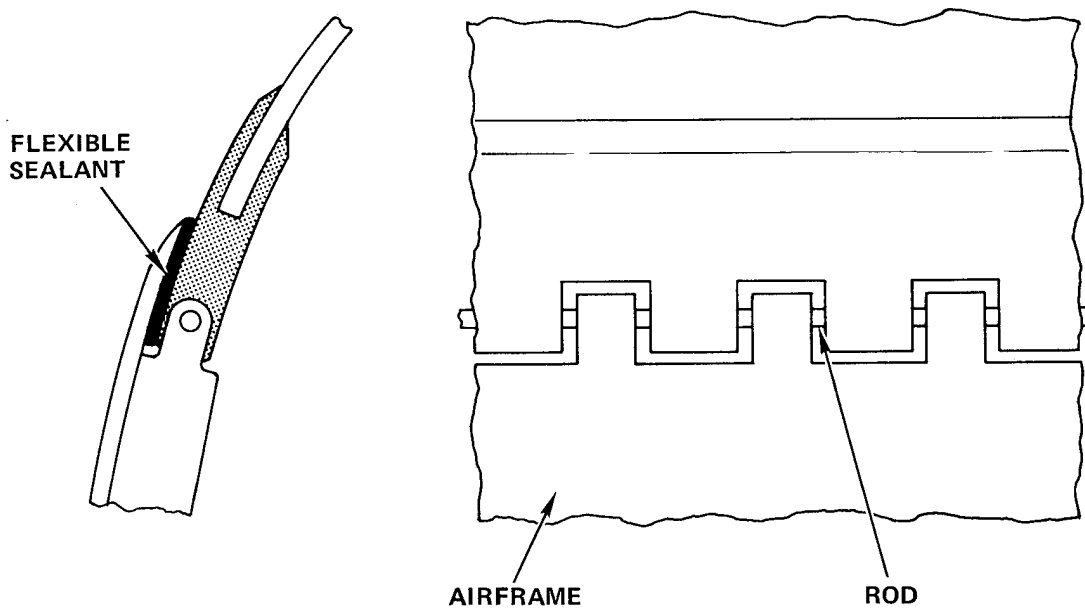
Figure 10.3-4 – "Piano Hinge" Expansion Joint

10-13

(a) EDGE ATTACHMENT USING AN IMPREGNATED
FABRIC TONGUE.
(b) EDGE ATTACHMENT USING IMPREGNATED
FABRIC EARS AND TONGUE.
(c) EDGE ATTACHMENT USING IMPREGNATED
FABRIC TONGUE AND REINFORCING STRIPS
APPLIED TO FACES OF THE GLAZING MATERIAL.
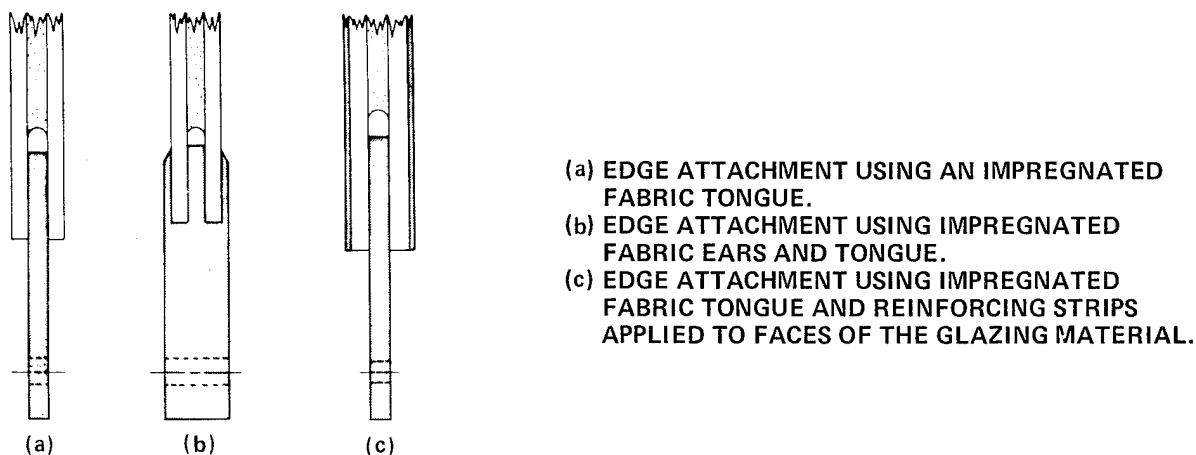
Figure 10.4-1 – Basic Concepts of Composite Edge Attachment Designs

To compensate for the various performance criteria, the transparent portion of a complex enclosure may be composed of two or more different materials. The simpler of the constructions is a thermally "clad" sheet. The more complex designs are considered laminates which incorporate transparent flexible interlayers.

Dual panes with an air gap have been used for enclosures as a means of providing a redundant safety panel (in all-glass designs) and in one case as a duct for hot air anti-icing. These constructions have been replaced for the most part by electrically conductive anti-icing systems and transparent interlayers. Dual pane construction is used for passenger window designs which provide the additional features of thermal and sound insulation.

A "clad" laminate usually consists of a thin face sheet of abrasive resistant plastic material which has been bonded on one side or both sides of a less abrasive resistant plastic substrate (i.e., MIL-P-5425 face sheets; MIL-P-83310 substrate). In this type of design, the edge

attachment is attached to the load-bearing member so that the thin face sheet or sheets are exempted except for edge sealing as shown in Figure 10.4-2.

Cladding of both sides of a substrate protects both surfaces, but has been found to be a disadvantage with polycarbonate (Reference 7) because the cladding restricts the natural ductility of the material and radically reduces its impact resistance. Cladding of the one side which would be exposed to impact has been found to be feasible. The clad type of laminate is limited to materials which are thermoplastic and have nearly identical coefficients of thermal expansion. This criterion limits the number of material combinations that can be used.

The laminate consisting of two hard face sheets and a flexible interlayer appears in its simplest form in the MIL-P-25374 specification which concerns the lamination of two MIL-P-8184 sheets with a polyvinyl butyral interlayer. The purpose of the laminate was to offer a degree of shatter resistance, but it has been since supplanted by MIL-P-25690 material
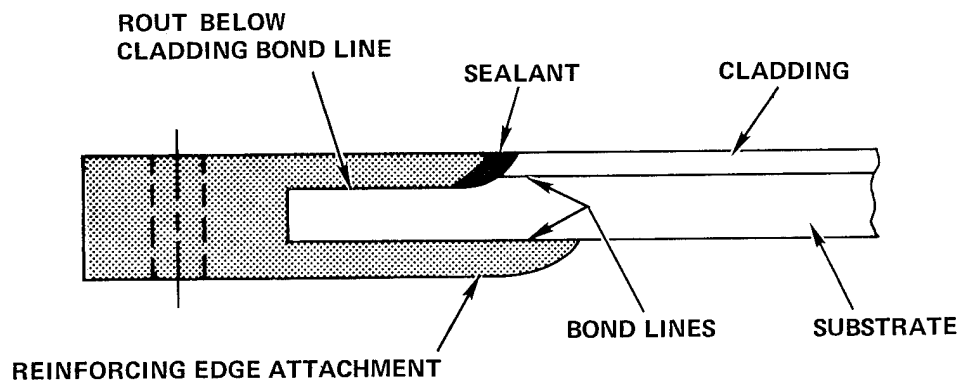
Figure 10.4-2 – Method of Exempting Cladding as a Load Bearer

10-15

(the monolithic stretched version of MIL-P-8184 material). The basic edge attachment forms for this type of laminate are sketched in Figure 10.4-1.

Available information on more recent transparent plastic laminate properties is limited because the majority of the tests are performed with edge attachment specimens of specialized configurations.

A laminate is somewhat heavier than monolithic material of equivalent strength because the interlayer contributes approximately one-third of the total weight and thickness of the laminate and is assumed to add nothing whatever to its strength. With the total thickness of the facing material as the only consideration, design could normally be based directly on the allowable stresses, but this is not the only problem.

Experience indicates that under certain conditions, the interlayer causes much of the stress because of the difference between the thermal coefficients of expansion of the interlayer material and the outer faces. Tests have shown that a compressive stress of 725 PSI was induced in the acrylic plastic outer faces of a flat laminated test specimen when its temperature was reduced from +70 to -70 F.

Conversely, it is expected that an increase in temperature would induce a tensile stress in the plastic face sheets, adding to the stresses caused by pressurization of the cabin and by flight loads. Because of the flow of some interlayers at higher temperatures, this stress may be of a lower order of magnitude.

It is also possible that either one or the other of the two outer faces may carry much more than its share of the total load because of an unsymmetrical or unbalanced edge attachment.

The balanced type of edge attachment is represented in Figure 10.4-1.

Impregnated fabric ears (see Figure 10.4-1 (a)), an impregnated fabric tongue, or both, are acceptable for laminated glazing materials. Figure 10.4-1 (b) and (c) illustrates both the tongue attachment with reinforcing strips and the combination ear and tongue attachment. Many modifications of the ear, tongue, and combination ear and tongue attachments have been used.

10-16

When only ears are used there is a tendency to bend the face sheets inwards because the inter-layer is soft; this will tend to squeeze the interlayer out from between the face sheets.

Many materials are used for the laminating resin, reinforcing fabric, and adhesive for the ear and tongue attachments. If the general requirements for a good edge attachment can be met, any combination of materials that are mutually compatible should prove satisfactory. Both rigid and moderately flexible attachments are possible.

It is generally believed that the shearing forces in the bond between the edge attachment and the glazing material are concentrated at the inner and outer extremes of the bonded areas, so that the bond need be no deeper than 3/4 to 1 inch; any increase in depth of the bonded area would not contribute materially to the strength of the bond. However, as indicated in section 10.2.2, when an undercut is used, the ear on the side opposite the undercut should extend beyond the undercut to provide additional reinforcement.

The interlayer of the laminated sheet, plasticized polyvinyl butyral for example, is rubber-like above 32 deg F, but is appears to resist compression sufficiently to space the face sheets uniformly except in the vicinity of the load and reaction point. The shear modulus is small in comparison with the modulus of elasticity of the facing material. The shear-coupling between the two face sheets is therefore small, and under load the two faces react to a large extent as a pair of individual beams. This is true, for example, in tension and under flexural loads of more than a few minutes' duration, for the interlayer will undergo cold flow. However, under bending loads of very short duration, the facings act as part of the same beam, with the interlayer inactive in bending. In acrylic face sheets, the allowable stress for long-time loading is taken as the crazing stress determined for each special application.

Erickson (Reference 33) developed formulas for estimating the components of stress in the facings of a centrally loaded beam in the vertical section of the load point, particularly the maximum stress at the juncture of the interlayer and the loaded facings. The derivations are carried out under the assumption that the elementary beam analysis of the facings yields sufficiently accurate results except in the loaded facing near the load point, that the shear-coupling force between the facings is small, and that they act under normal loads to a large

extent as a pair of individual beams. In the vicinity of the loaded facing near the load point, the perturbations in the stress components associated with concentrated loading are considered to be approximately the same as those in an ordinary beam under concentrated load.

The corrections that bring the results of elementary beam theory into coincidence with those from the more accurate analysis of stresses in the vicinity of a point of load concentration are accordingly considered applicable to the results. This analogy with ordinary beam theory is suggested by the fact that the upper facing carries the entire shear load in the vicinity of the load point, and the compressive stress transmitted to it by the interlayer is small.

The agreement found between the approximate results and the results obtained by a more exact method using a stress function in the interlayer indicates that from the point of view of analysis, this approximate approach is satisfactory. For experimental verification of the stresses predicted by the approximate formulas, comparison was made with results from photoelastic analysis. This comparison again indicated that the approximate results are satisfactory.

For formulas for the components of stress in the facings of a sandwich beam under central normal load, see Reference 33.

The tongue attachment is fairly expensive, but is provides good strength and a flush surface for the skin of the aircraft. For this design, the sheet-type interlayer should be routed out a small distance beyond the end of the insert. If any adhesive comes in contact with the interlayer, it will extract plasticizer from the interlayer. Mixing with even a very small amount of plasticizer weakens the adhesive and reduces the strength of the bond. In routing out the interlayer, it is difficult to make a slot that will fit the insert exactly. If the slot is undersized, the insert will spread the face sheets of the laminated glazing; while if the slot is oversized, and the joint is clamped during the curing of the adhesive, there will be tensile stresses in the outer surfaces of the glazing. In either case it is advisable to add thin strips of fabric reinforcement on the outside of the glazing material, as shown in Figure 10.4-1 (c). The reinforcing strips should be applied before the tongue attachment is inserted. If the insert is

10-18

assembled first and stresses are induced in the outer surfaces, these stresses are likely to lead to stress-solvent crazing when the adhesive for the reinforcements is applied.

Cast-in-place (CIP) interlayers overcome the problems of routing and solvent attack, but require great care in filling a cavity to avoid the entrapment of air or vapor bubbles.

Because the CIP casting usually occurs in the finished part, developmental and control tests will have to be performed at the fabricator's facility rather than at that of the sheet laminator.

Other than the specification laminate of MIL-P-8184 material, combinations have been used or proposed that have utilized unbalanced laminates in which the structural member was a thermoplastic such as MIL-P-8184, MIL-P-25690, or MIL-P-83310 material. The secondary member was usually a more stable thermosetting material which served as a base for an electrically conductive coating and was separated by a flexible interlayer. In these cases the edge attachment transferred the load from the structural member to the airframe, but allowed the coating substrate to float on the interlayer. An example is shown in Figure 10.4-3.

More impact resistant glazings have been constructed with a thin floating outer face sheet of acrylic, a thinner bond line of transparent interlayer, and the polycarbonate as shown in Figure 10.4-4.

Basically, the types of edge attachments in Figures 10.4-1 through 10.4-4 relate to plastic transparencies because the tensile strength of the attachment is dependent upon the shear strength of the adhesive bonds. Glass, however, is stronger in compression and consequently requires attachments of a different design.

10.4.2 DESIGN CONSIDERATIONS FOR GLASS LAMINATES

For aircraft glazing, the requirements call for resistance to thermal and mechanical stresses, and also, as far as is practicable, the elimination of both complete failure of the panel and splintering if fracture should occur. Laminating glass with a plastic interlayer is the only practical method of minimizing splintering and avoiding complete failure of a glass

CLOTH LAMINATE   ELECTRICALLY CONDUCTIVE
COATED SURFACE   MIL-P-25690

SHEAR EDGE   SEALANT   MIL-P-8257   PVB
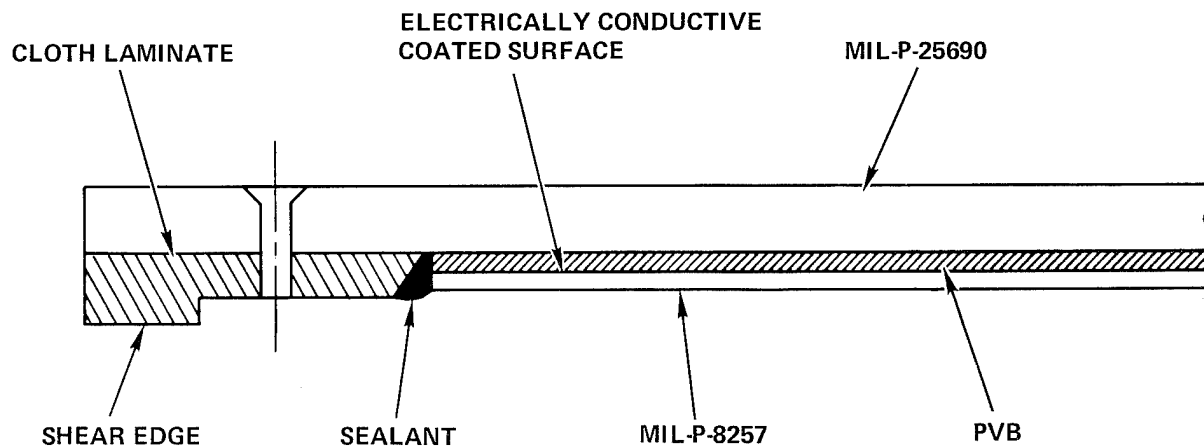
Figure 10. 4-3 - Plastic-Plastic Laminate with Electrically Conductive Coating
for Anti-Fogging

SEALANT   MIL-P-8184   PVB

FIBROUS BUSHING   MIL-P-83310
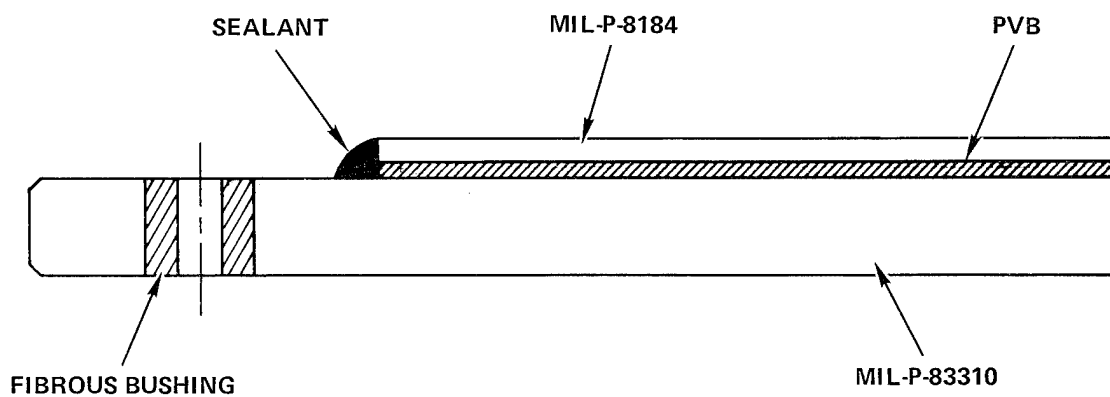
Figure 10. 4-4 - Plastic-Plastic Laminate with Abrasion Resistant Face Sheet and
Impact Resistant Construction

10-20

panel when fracture occurs. Where aerodynamic heating is severe, a sheet of tempered glass separated from the laminated glass by an air space may be required.

The load-carrying capacity of laminated glass is less than that of plate glass of corresponding thickness, and laminates with soft interlayers have lower strengths than those with hard interlayers. When the conventional interlayer material, polyvinyl butyral, is used, temperature seriously affects the load-carrying capacity of laminated glass. This is caused primarily by wide variation of the elastic modulus of this plastic with temperature. Certain other materials, such as silicones, do not vary as greatly with temperature, and therefore laminated glass containing them is not as seriously affected by temperature.

The modulus of elasticity of laminates depends on the interlayer. With a stiff interlayer the laminate has an elastic modulus close to that of plate glass, but with a soft interlayer the elastic modulus is lowered. There are apparently optimum values of the elastic moduli of the plastic interlayer which result in the greatest ability of the laminated glass to absorb energy of impact. In addition, the resistance to impact increases with the thickness of the plastic interlayer (Reference 34).

The present specification for glass laminates is contained in MIL-G-25871, which primarily concerns the polyvinyl butyral interlayer and the required properties of the laminate. Because the polyvinyl butyral has a natural affinity for glass, it acts as its own adhesive. The specification provides for other unnamed interlayers which should provide an equivalent or better laminate than the polyvinyl butyral. As mentioned in section 10.4.1, cast-in-place interlayers will require additional development and control testing at the fabricator's facility. Class B units, (curved) are also included in the specification.

10.4.2.1 FORMED LAMINATED GLASS

Forming of laminated glass has to be accomplished by preforming or bending the face sheets prior to laminating. In actual practice this process is difficult for some shapes. Sections of cylinders and cones composed of nearly straight-line elements can be formed at relatively low temperatures, although the smaller the radius of curvature, the higher the forming

temperature required. The more complex spheroidal shapes require much higher temperatures, with the resultant lower viscosity permitting the glass to stretch and flow into shape. Because of this low viscosity, the glass surfaces are more likely to be marred during the bending operation. Spheroidal shapes made by bending glass may be of poor optical quality because of the variation in thickness of the glass resulting from stretching a flat sheet to fit a spherical surface. Sections of cylinders and cones with a small radius are difficult to produce with optical properties satisfactory for aircraft glazing, particularly if viewed at high angles of incidence. Grinding and polishing after bending is not known to be practical.

10.4.2.2 LAMINATED GLASS MECHANICAL PROPERTIES

Because edge attachments for laminated glass are essentially non-load bearing, the laminate itself has to sustain its environment. As a consequence, more data are available on glass laminate properties than on transparent plastic laminates.

10.4.2.2.1 MODULUS OF RUPTURE

The modulus of rupture of laminated glass is between 50 percent and 70 percent of the modulus of rupture of an equivalent thickness of monolithic glass. Laminates with soft plastic interlayers are weaker than those with hard plastic interlayers, and laminates with thick plastic interlayers are weaker than those with thin plastic interlayers. Laminates rapidly lose their load-carrying capacity with an increase in temperature. The value of 3,500 pounds per square inch is generally accepted as the modulus of rupture at room temperature for a laminate consisting of two plates of annealed soda lime glass 7/64 inch thick and one sheet of vinyl plastic 0.020 inch thick (Reference 35).

The results of modulus of rupture tests conducted on symmetrical glass-plastic laminates made with tempered glass, and polyvinyl butyral plastic (containing 18 percent dibutyl sebacate plasticizer) in different thicknesses and tested at different temperatures are presented in Table 10.4-I. The test specimens were 3-3/4 inches wide and 11 inches long; distance between supports was 10 inches. Each result recorded is the average of six determinations (Reference 36).

TABLE 10.4-I – MODULUS OF RUPTURE OF TEMPERED LAMINATED GLASS

Glass (in.)	Thickness plastic* (in.)	Modulus of rupture (PSI)			
		–60 deg F	0 deg F	80 deg F	125 deg F
7/64	0.075	24,900	21,600	10,600	6,570
	0.120	24,300	18,500	8,340	5,190
1/8	0.075	27,100	21,600	11,700	7,030
	0.120	26,000	20,100	9,610	5,710
3/16	0.075	28,600	24,300	11,030	8,120
	0.120	22,700	17,940	8,240	7,120

*Laminates consist of two plates of glass of the indicated thickness and one
sheet of polyvinyl butyral interlayer of the indicated thickness (Reference 36).

10.4.2.2.2 PRESSURE TESTS

Pressure tests (specimens are mounted as one side of a box, and air pressure is indicated
in the box until the glass fails) show that laminated glass will withstand less pressure
than solid glass of the same thickness. Table 10.4-II gives the results of the pressure test
on annealed soda lime glass. The values presented are the average of 10 specimens, and
failure is recognized when the first crack appears. The test specimens were clamped with
gaskets at the margin (Reference 36). Nomograms suitable for determining the tensile
stress and deflection of glass-plastic-glass laminates of various sizes and thicknesses
and under different pressures are available (Reference 37).

10.4.2.2.3 SHEAR STRENGTH

The safety feature of glass-plastic laminates depends quite largely on the ability of the
adherent plastic layer to hold the composite together and thereby reduce the hazard of
flying glass when the lamination is cracked or broken. Shear strengths of various inter-
layers to glass may be found in Chapter 5, Figures 5.7-4 and 5.7-5, pages 5-24 and 5-25.

TABLE 10.4-II – PRESSURE TEST ON ANNEALED 1/4-IN. PLATE AND 1/4-IN.
LAMINATED PLATE GLASS TESTED AT 75 DEG F AND
LOADED AT A RATE OF 5 PSI/MIN

Glass	Average breaking pressure, glass size		
	12 in. by 12 in.	18 in. by 18 in.	24 in. by 24 in.
1/4 in. regular plate	14 PSI	7 PSI	4.5 PSI
1/4 in. laminated 7/64 in. glass 0.015 plastic 7/64 in. glass	11 PSI	6 PSI	3.5 PSI

10.4.2.2.4   RESISTANCE TO IMPACT FOR ANNEALED AND TEMPERED GLASS

The resistance to impact of laminated safety glass will depend on the type and stiffness of
the plastic, the thickness used in the lamination, the glass components, and the temperature
at the time of impact.   The results of falling ball impact tests conducted at 0, 75, and 120
deg F, with 1/2- and 2-pound steel spheres, on 12-inch by 12-inch specimens of 1/4-inch
laminated safety glass, made with annealed and tempered 7/64-inch plate glass and poly-
vinyl butyral interlayers 0.015, 0.030, and 0.045 inch thick, are recorded in Table 10.4-III
(Reference 36).

The "critical distance" recorded in Table 10.4-III is that distance from which the steel
sphere was allowed to fall from rest to produce failure of 50 percent of at least 20 specimens.
Specimens were classified as failures when a hole or continuous shear in the plastic inter-
layer exceeded 1-1/2 inch even though the impacting sphere failed to penetrate the lamina-
tion completely.

These results are indicative of the effects an interlayer has on impact strength, but are
obviously not representative of all aircraft laminate configurations.   Each configuration must
therefore be tested on its own merits.

TABLE 10.4-III – SUMMARY OF IMPACT TESTS ON LAMINATED SAFETY GLASS MADE
WITH POLYVINYL BUTYRAL CONTAINING 28 PERCENT DIBUTYL SEBACATE

Glass components used	Plastic thickness (in.)	Weight of steel ball (lb)	Critical distance (ft)		
			0 deg F	75 deg F	120 deg F
7/64 in. plate	0.015	1/2	18	Greater than 33-1/2	20
7/64 in. tempered plate	0.015	1/2	22	Greater than 33-1/2	27
7/64 in. plate	0.015	2	2-3/4	5-1/4	4-1/4
7/64 in. tempered plate	0.015	2	5-1/2	8	7
7/64 in. plate	0.030	2	7-1/2	22	11
7/64 in. tempered plate	0.030	2	10	33	15
7/64 in. plate	0.045	2	12	Greater than 33	33
7/64 in. tempered plate	0.045	2	21	Greater than 33	33

10.4.2.2.5   MODULUS OF ELASTICITY

The modulus of elasticity for laminated glass will depend upon the relative thickness of the glass and plastic, the type of plastic, and the temperature. For laminated glass with an over-all thickness of 1/4 inch and an inner layer of polyvinyl butyral 0.020 inch thick, the value of 5,000,000 pounds per square inch is accepted as the modulus of elasticity of laminated glass when considered as a beam and tested at 70 deg F. As the tempereture is reduced, the modulus of elasticity increases and approaches that of solid glass (Reference 22).

10.4.2.2.6   SPECIFIC GRAVITY

Laminated glass with a plastic interlayer will have a lower specific gravity than solid glass of the same thickness, the value depending on the thickness of the plastic interlayer. The specific gravity for ordinary plate glass (soda lime) is about 2.51, and the specific gravity of polyvinyl butyral is about 1.07 (Reference 36).

10.4.2.2.7 THERMAL PROPERTIES

The coefficient of thermal expansion of regular soda lime plate glass can be taken as 0.0000049 per deg F, from 0 to 570 deg F. The coefficient of expansion of the interlayer will depend on temperature but is generally considerably higher and is given in Figure 5.2-2 in Chapter 5.

Available experimental data on the thermal conductivity of glasses and plastic are not entirely consistent. The thermal conductivity of regular plate (soda lime) glass at room temperature is approximately 6.0 BTU/(hr) (ft^2) (deg F/in.) and of polyvinyl butyral is 1.5 BTU/(hr)(ft^2)(deg F/in.). The thermal conductivity of the laminated material may be estimated from these values (Reference 36). The thermal conductivities of several monolithic glasses are given in Figure 10.4-5.

A comparison between the specific heat of polyvinyl butyral plastic and plate glass is given in Figure 10.4-6.
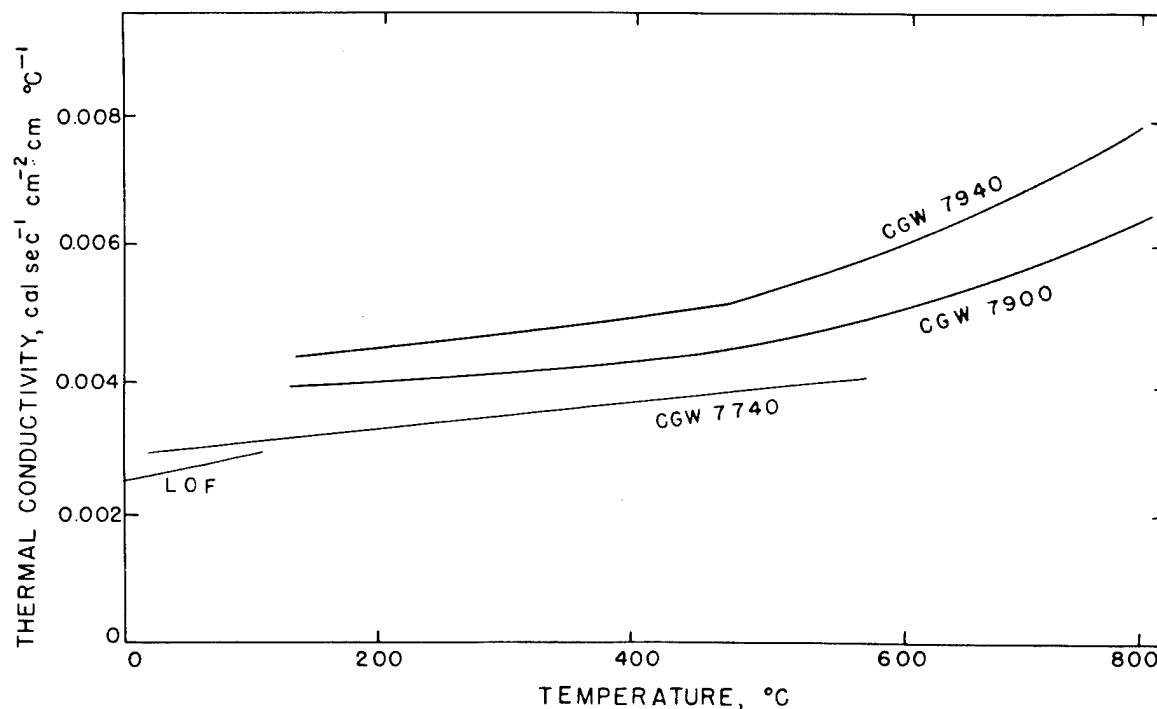
Figure 10.4-5 – Variation of Thermal Conductivity with Temperature for Several Glasses

10-26
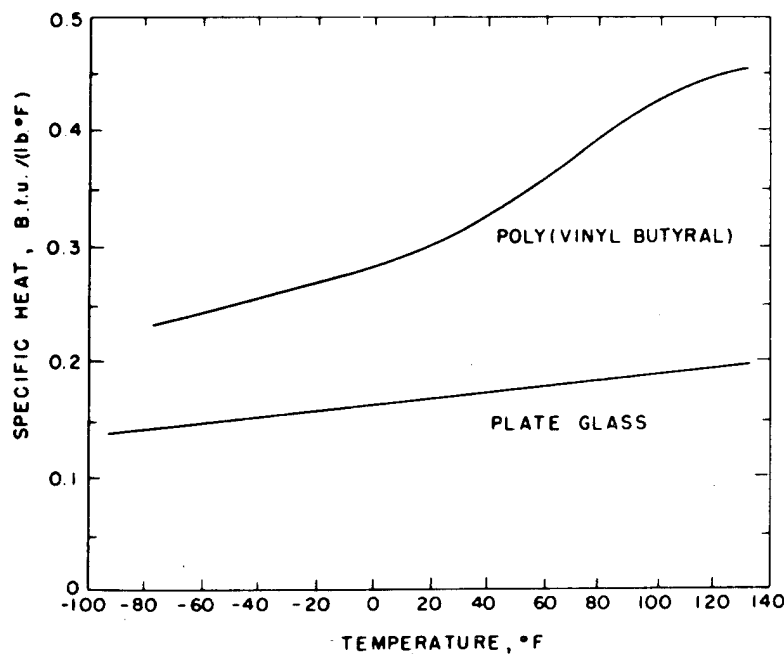
Figure 10.4-6 – Specific Heat of Plate Glass and Polyvinyl Butyral Plastic

10.4.2.2.8   OPTICAL PROPERTIES

The index of refraction of the plastic used in laminated glass is near that of glass (1.5 to 1.52), so that for most purposes the difference can be ignored (Reference 35). The haze value of laminates having 0.200-inch polyvinyl butyral interlayers is less than 2 percent (Reference 38). Optical deviation should be considered when using many interlayers and layers of glass as well as when curved glass and laminates are used. The over-all transmittance of light diminishes with the increased thickness of the laminate.

The over-all transmission of light through laminated glass is less than through plate glass. For the glasses considered for aircraft glazing, the over-all transmission is generally from 85 percent to 88 percent for 1/4-inch thickness.

10.4.2.2.9 EDGE TREATMENT

The cut edges of glass panels are sensitive areas and it is here that many fractures start. Glass panels should be carefully handled to prevent chipping or scraping of the edges.

Spontaneous failure of tempered glass is often due to injured edges. The edge may be chipped to such a depth that the compression stress layers are almost penetrated, and as a result the balance between compression and tension forces is placed in a state of delicately unstable equilibrium. At some subsequent time — from hours to months — a relatively slight stress, induced perhaps by temperature change, or a chance superimposition of thermal stresses upon normal operating stresses, may cause apparently spontaneous failure.

Care must also be taken in mounting the glass in its frame, for improper mounting may cause concentrated stresses that will cause fracture with very small additional stresses.

10.5 TYPICAL EDGE ATTACHMENTS FOR PLASTIC LAMINATES

Edge attachments for transparent plastic laminates have been tending more toward treating the structural member as a monolithic piece with a bolt-through fastening and allowing the accessory layers of transparent materials to float. The practice is consistent with MIL-P-25690 material, and although this method is also used with MIL-P-83310 material, great care has to be taken in drilling the attachment holes. A finishing procedure is mandatory for each design utilizing the MIL-P-83310 material with a bolt-through attachment, to prevent stress risers which can result in a catastrophic failure under operational conditions. A suggested hole-drilling procedure for polycarbonate is described in Section 10-8 (page 10-42).

A bolt-through fastening is sketched in Figure 6.2-3 on page 6.7.

A proposed tongue design is shown in Figure 10.5-1 which provides for thermal expansion and insulates the inner plies from heat transfer through the metallic fairing and fastenings.

For higher-performance aircraft a thermal barrier may be required to protect the structural ply. For this application a deeper rout, as shown in Figure 10.5-2, would be required to allow for insulation between the fairing and the attaching surfaces. Because the bolts would transfer heat, an insulating bushing and laminates are also required.

METALLIC FAIRING

RIVETS

MIL-P-8184

FOAM

FILLET

INTERLAYER

MIL-P-25690

NOMEX EPOXY
LAMINATE (TYPICAL)

SEAL

≈ 2.40 IN.
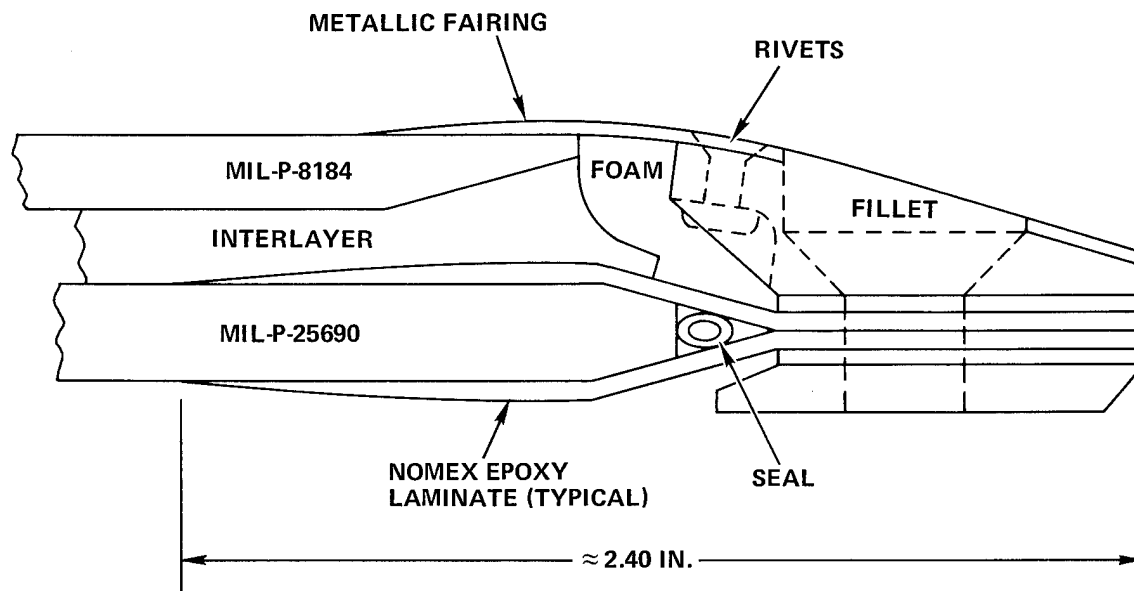
Figure 10.5-1 – Nomex Yoke Edge Design

DEEP ROUT

SEALANT

THERMAL SHIELD

INTERLAYER

ELECTRICALLY
CONDUCTIVE
COATING

INNER PLY

INSULATED BUSHING

STRUCTURAL PLY
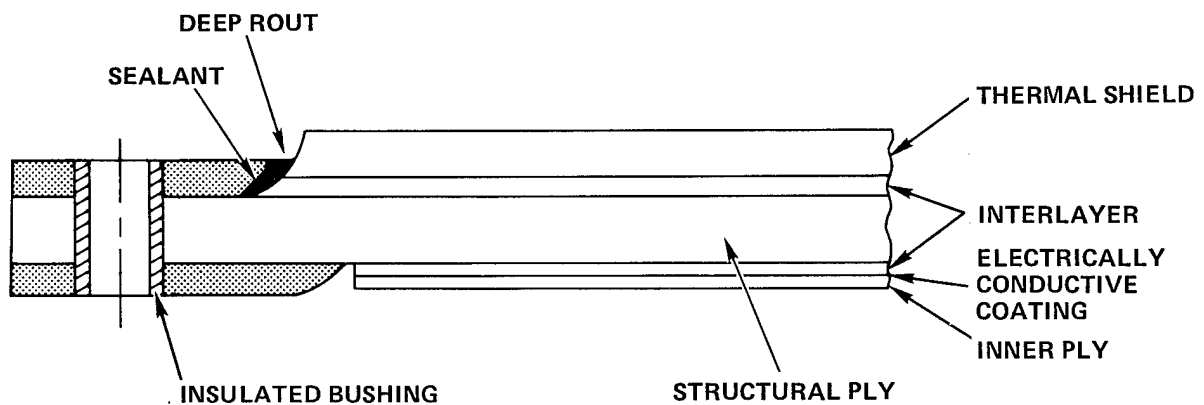
Figure 10.5-2 – Thermal Barrier Design

10-29

The advisability of using this type of design would depend upon the high-temperature portion of the aircraft's thermal profile in terms of time. Extended exposure to temperatures excessive for the structural substrate may penetrate through the bolts and bushings to the attaching hole surfaces and degrade the bearing area of the holes. Short-term exposure would be feasible.

10.6 TYPICAL ATTACHMENTS FOR GLASS LAMINATES

Current edge attachments for laminated glass are essentially nonload-bearing and generally utilize an extension of the interlayer, reinforced with a metal insert, as illustrated in Figure 10.6-1, or a U channel attachment as in Figure 10.6-2 (Reference 15). The insert is necessary because some interlayer materials soften at elevated temperatures and become brittle at low temperatures. The insert is usually 0.025 to 0.040 inch thick 24SO aluminum, for flexibility, and is frequently slotted to within 1/16 inch of the glass to increase the flexibility in the junction between the glass and the frame. The thickness of the interlayer material is not increased in the edge attachment area unless the design makes it necessary, because the wide disparity between the coefficients of thermal expansion of the glass and interlayer material causes stresses sufficient to chip the glass when the system is exposed to very low temperatures.

The parting medium in Figure 10.6-1 at the panel edge is often necessary to prevent glass chipping and delamination caused by shrinkage and hardening of an interlayer at cold temperatures. The metal insert adds to the complexity of the loading analysis in that it tends to cleave the interlayer under thermal conditions which amplify the differences in the coefficients of thermal expansion. The U channel of Figure 10.6-2 offers a "free-floating" concept which has a weight disadvantage but is simply constructed and reliable for materials that cannot be satisfactorily bonded to a tensile member or require more rigidity and room for expansion, especially for larger panels and glazings with very low coefficients of thermal expansion (i.e., high silica contents).

Other metal insert designs are sketched in Figures 10.6-3, 10.6-4, and 10.6-5 (Reference 15). Figure 10.6-6 demonstrates another channel design (Reference 15).

OUTER GLASS
(SEMI-TEMPERED)

E. C. COATING

INTERLAYER

PARTING MEDIUM

INNER GLASS
(TEMPERED)

SEALANT AND
FAIRING COMPOUND

METAL INSERT

PHENOLIC BLOCK

FRAME
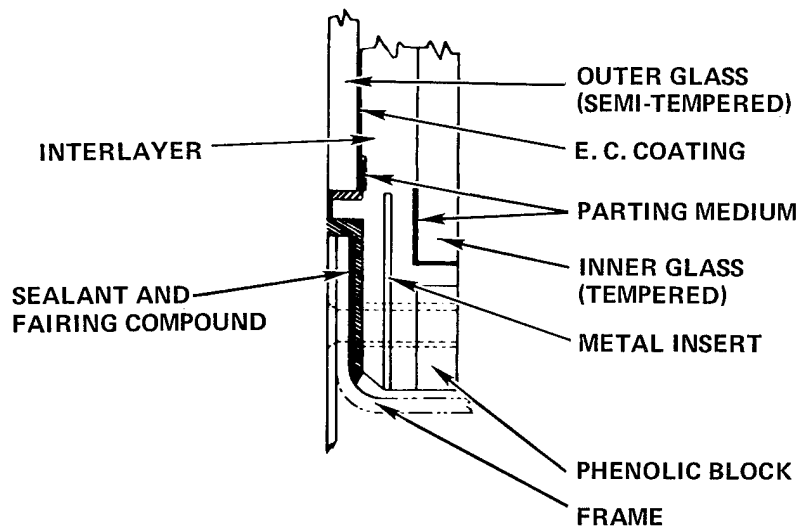
Figure 10.6-1 – Metal Insert Edge Attachment

GLASS

INTERLAYER

E. C. COATING

CUSHION AND SEAL

FRAME
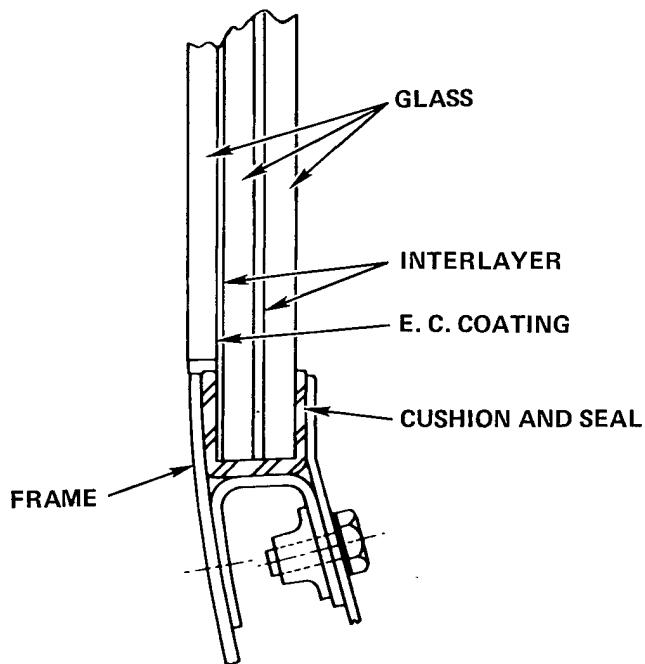
Figure 10.6-2 – U-Channel Edge Attachment

10-31

BUS BAR

3/16 IN. SEMI-TEMPERED GLASS

"NESA" SURFACE

METAL INSERT

BOLT HOLE

3/8 IN. FULL-TEMPERED GLASS
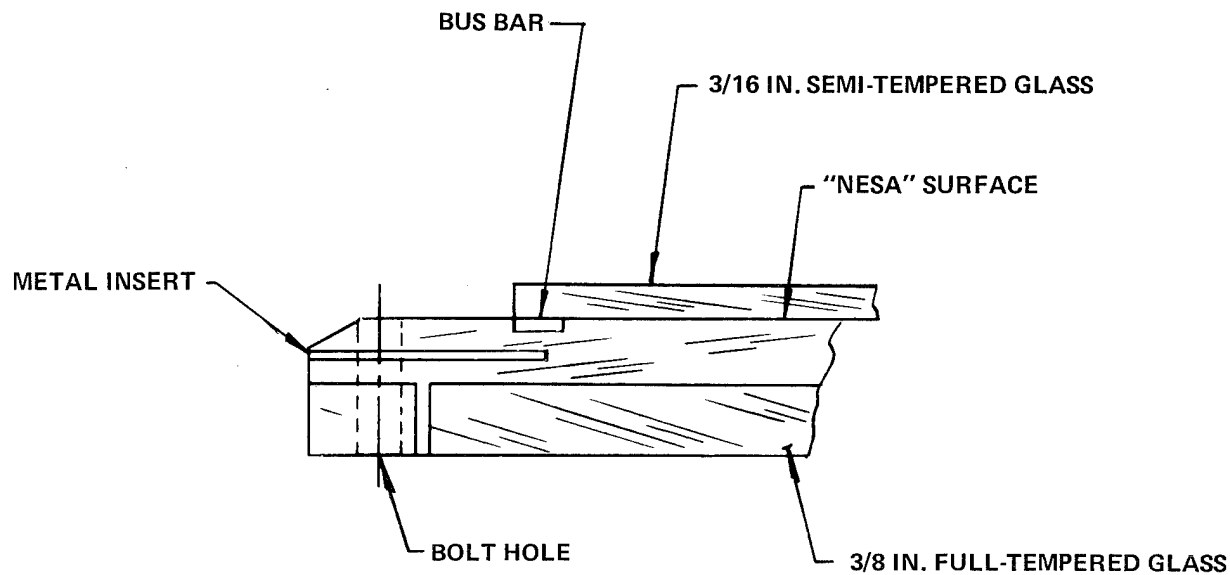
Figure 10.6-3 – Cross-Section Type for Boeing B-52 and Convair F-102/F-106 Windshields

SODA-LIME GLASS

ALUMINUM INSERTS

BONDED FIBERGLASS–REINFORCED
PLASTIC ATTACHMENT

POLYVINYL BUTYRAL INTERLAYER
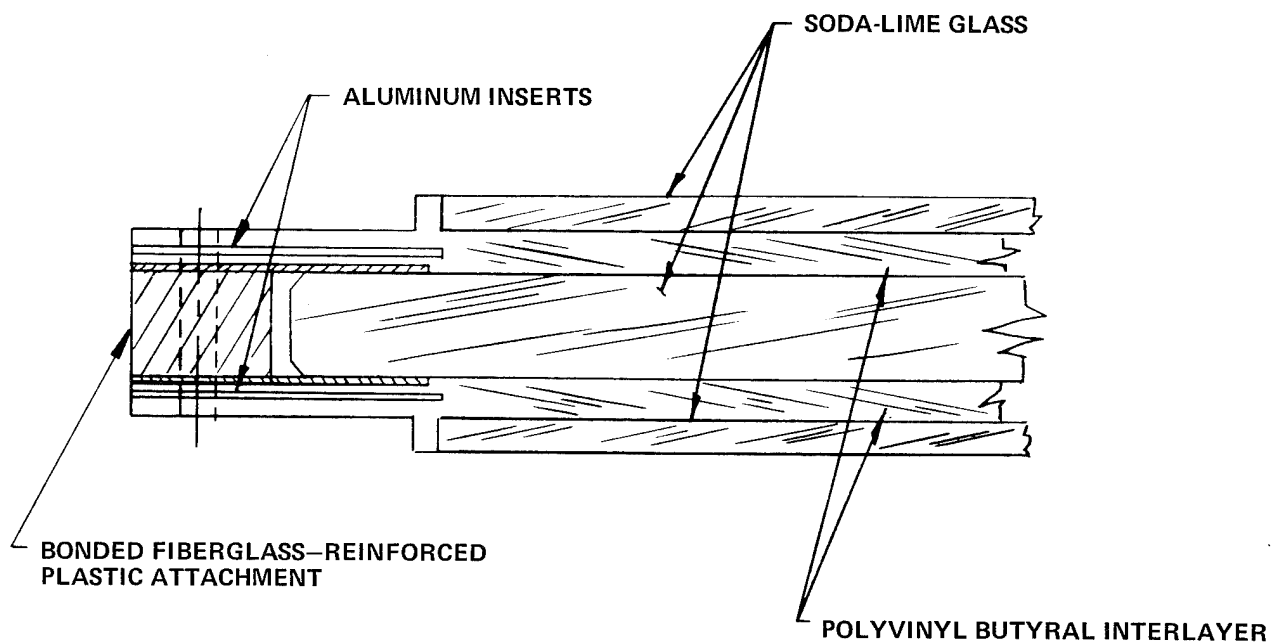
Figure 10.6-4 – Grumman A-6 Configuration
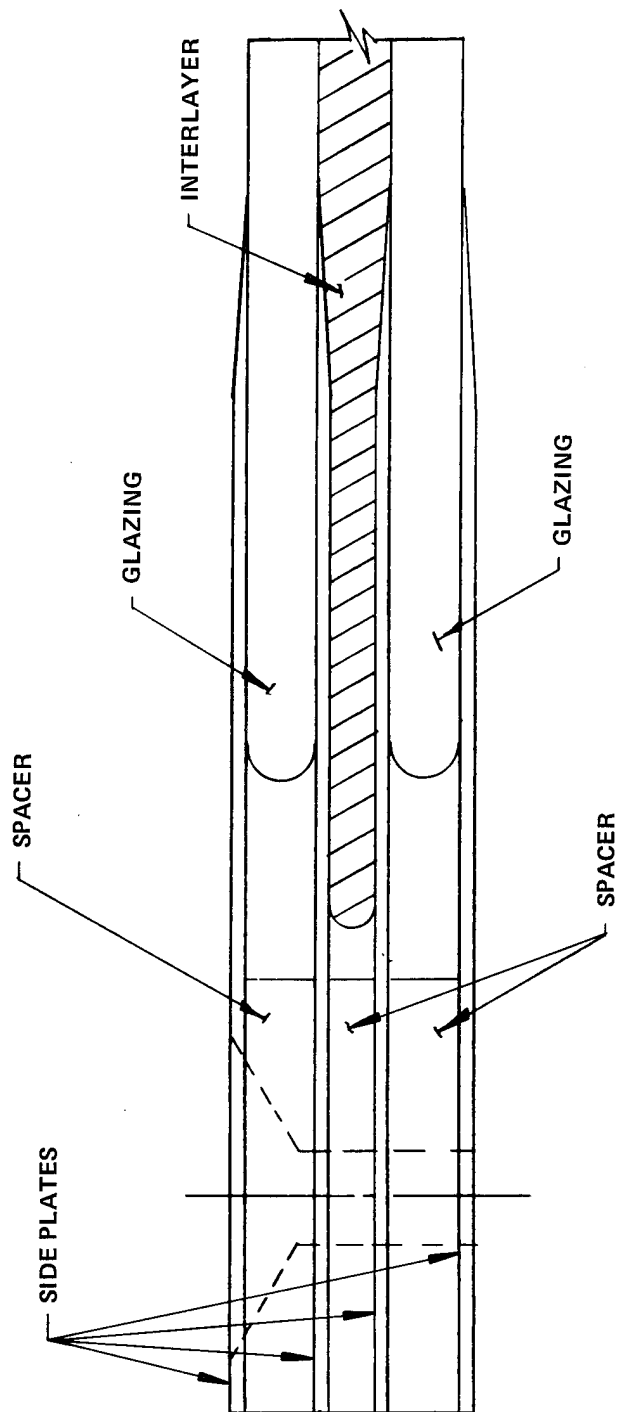
Figure 10.6-5 – High Tensile Strength Specimen Configuration
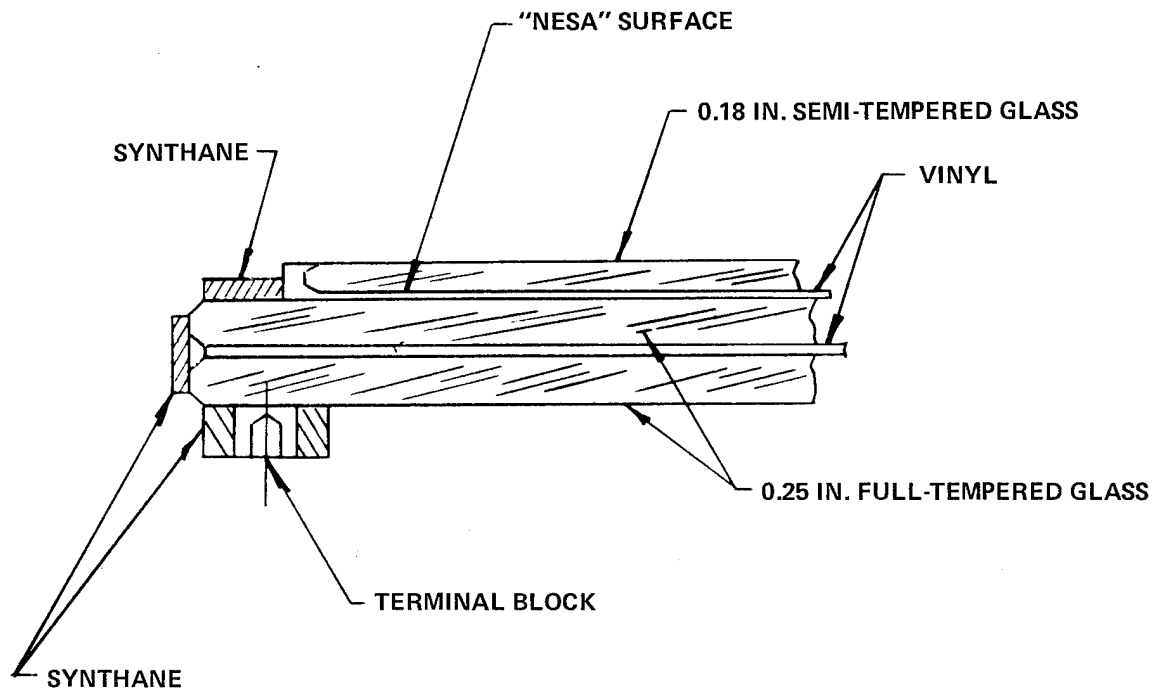
Figure 10.6-6 - F-101 Windshield Center Panel

10.7 VERY-HIGH-TEMPERATURE ATTACHMENTS

Very-high-temperature attachments are usually associated with monolithic high silica content glasses. Figures 10.7-1, 10.7-2, and 10.7-3 are examples of free floating attachments (Reference 15). Organic bonding is possible for joining specially formulated alloys to glasses with similar coefficients of thermal expansion.

Figures 10.7-4 and 10.7-5 show two such combinations of materials (Reference 15).

Figures 10.7-6, 10.7-7, and 10.7-8 (Reference 15) are proposed attachments which utilized an air gap for thermal control.
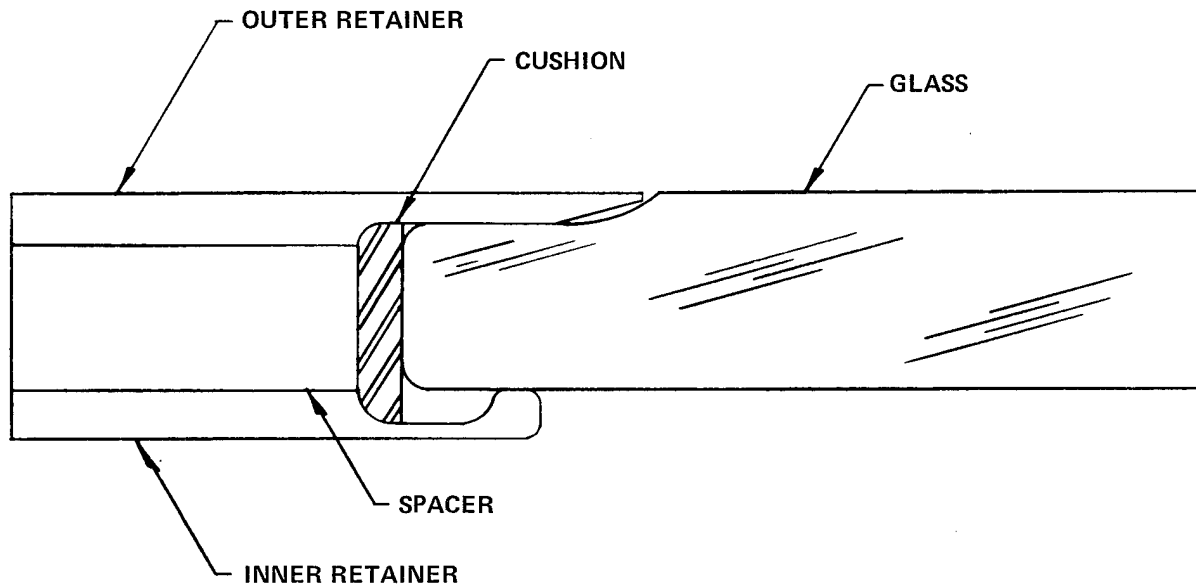
Figure 10.7-1 – Free-Floating Mounting Concept No. 1
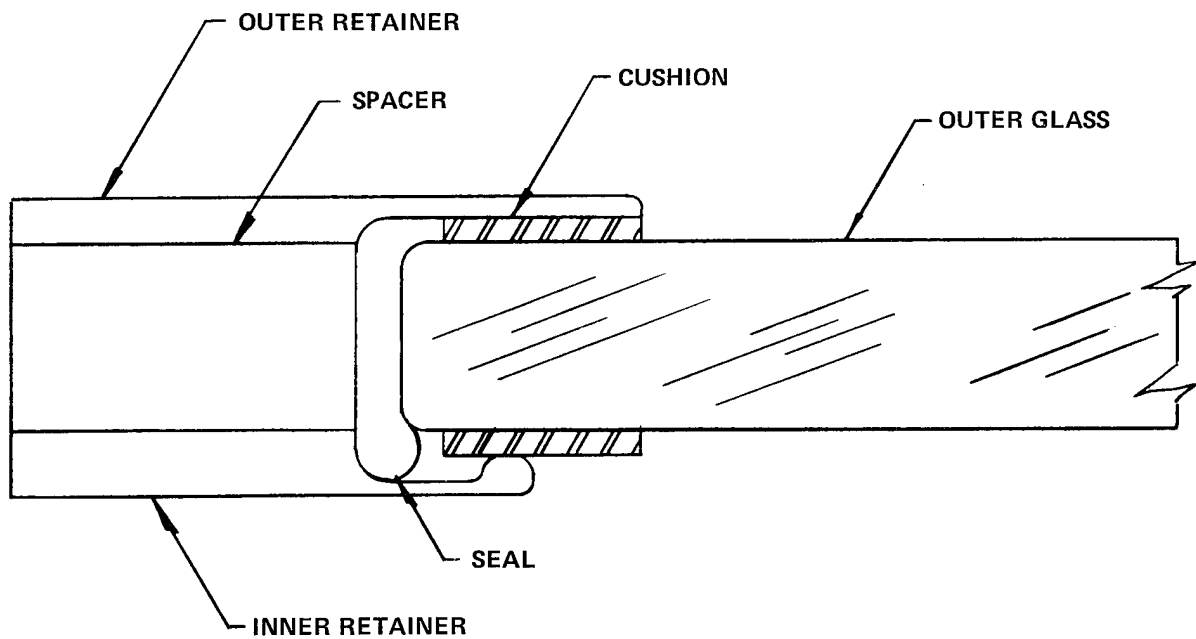
Figure 10.7-2 – Free-Floating Mounting Concept No. 2

10-35
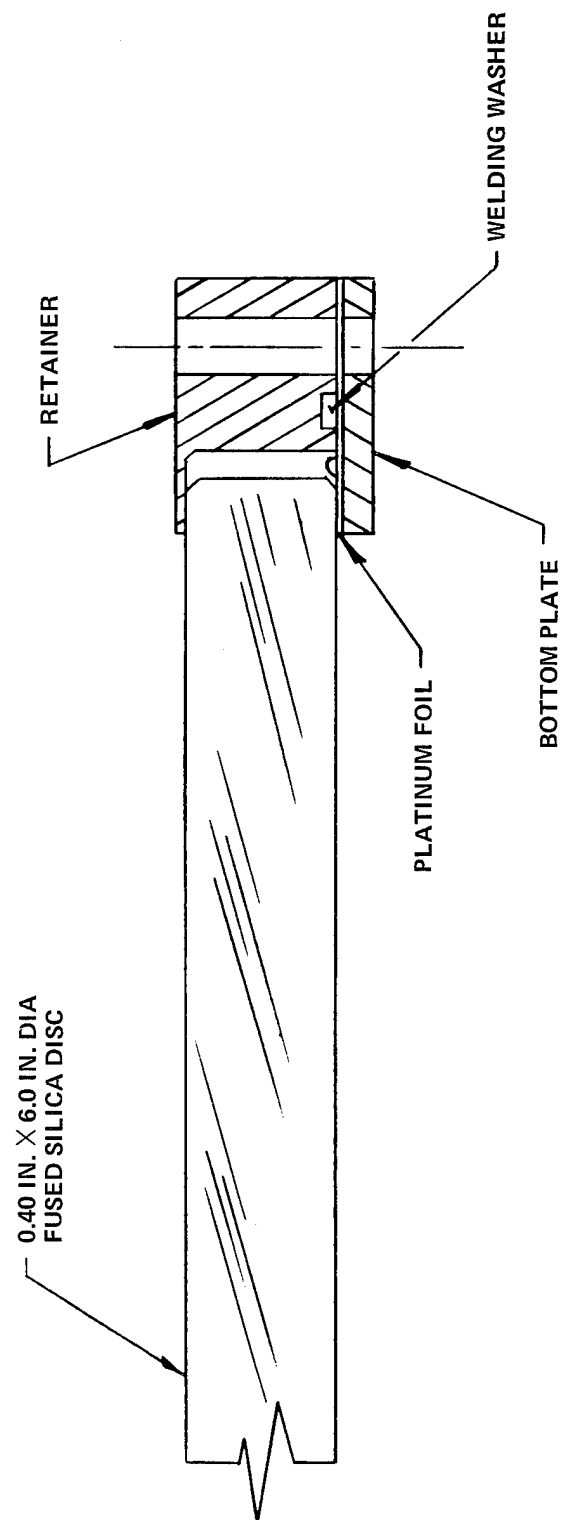
Figure 10. 7-3 – Platinum/Fused Silica Glazing Assembly

LAMINATED GLASS-FACE SHEETS:
0.312-IN.-THICK SODA LIME GLASS
TEMPERED TO 2400 MILLIMICRONS
MINIMUM. INTERLAYER 0.125-IN.-THICK
SILICONE

0.50 IN.

0.125 IN.

0.125 IN. RADIUS

GLASS-FILLED
PHENOLIC MOLDING
BONDED TO GLASS

0.020 IN. THICK ALLEGHENY
LUDLUM 4750 BONDED TO GLASS

0.060 IN. RADIUS (TYPICAL)
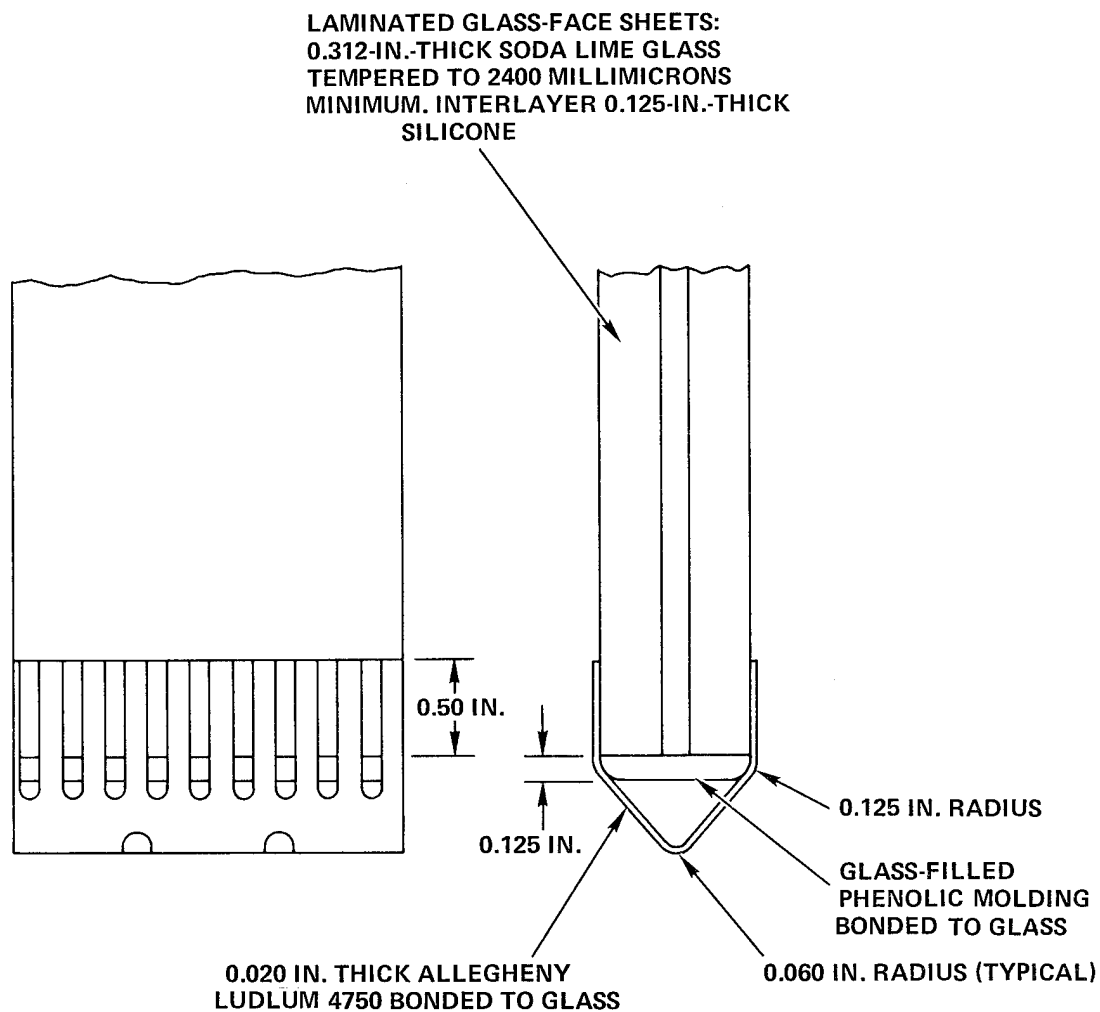
NOTE: DATA SUPPLIED BY NORTH AMERICAN ROCKWELL.

Figure 10.7-4 – Proposed Edge Attachment for B-70 Windshield

10-37

STEPPED KOVAR EDGE MEMBERS

KOVAR SPACER

ORGANIC BONDLINE

0.38 IN. × 12.0 IN. DIA ALUMINOSILICATE GLASS DISC
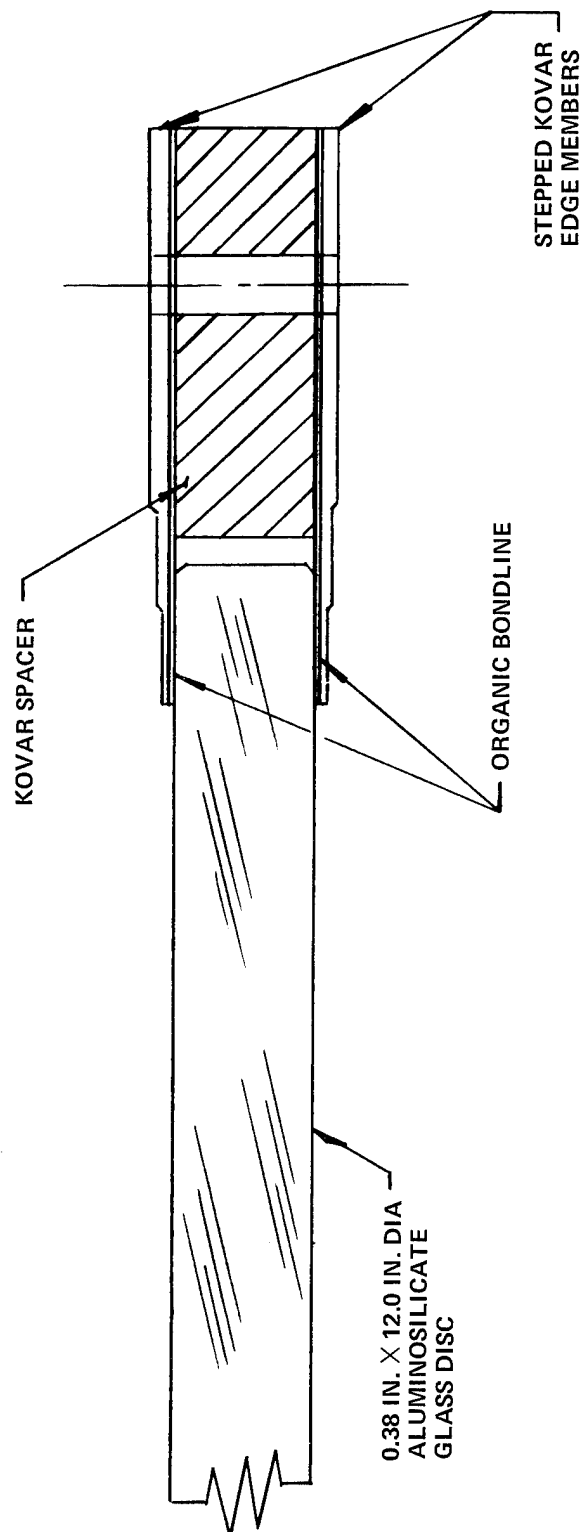
Figure 10. 7-5 - Organically Bonded Glazing Assembly

NOTE: PARTING AGENTS AND SEPARATORS OMITTED FOR CLARITY

FIBRE OR SPRING SEAL

MAIN WINDSCREEN CASTING

FRAME STRUCTURE

COOLING AIR/GAS CHANNEL

PACKER

HEAT INSULATING BUSH

METAL INSERT

RETAINING BOLT

CLAMPING FRAME

1/8" ANNEALED GLASS SPLINTER SHIELD

METALLIC FILM FOR DEMISTING(OPTIONAL)

3/4" TOUGHENED SODA LIME OR ALUMINO - SILICATE GLASS

OUTER COVER STRIP

HEAT INSULATING/SEALING STRIPS

5/8" SPECTROSIL (THERMAL SHOCK AND AERODYNAMIC LOADS ONLY)

1/2" COOLED/HEATED AIR GAP

1/4" ALUMINO - SILICATE GLASS

3/8" VINAL INTERLAYER

Figure 10.7-6 – Section through Windscreen, Using Inorganic Basic Glazings, for
Aircraft Capable of Operating at Speeds above Mach 2.5
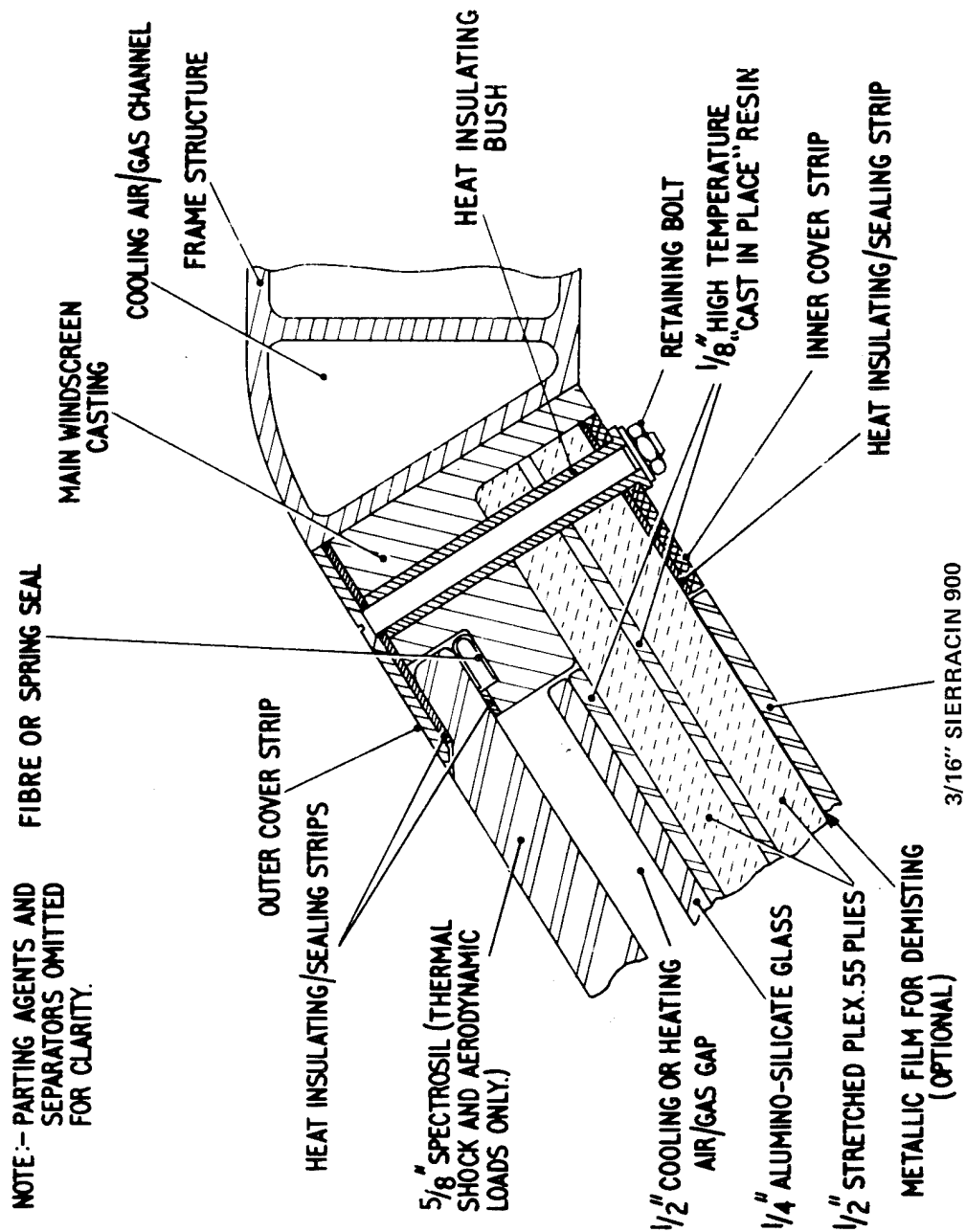
Figure 10.7-7 – Section through Windscreen, using Organic and Inorganic Basic Glazings, for Aircraft Capable of Operating at Speeds above Mach 2.5

OUTER COVER STRIP

HEAT INSULATING/SEALING STRIP

3/16" ALUMINO-SILICATE GLASS PLIES

METALLIC DEICING FILM WITH CAST IN PLACE RESIN OR 1/16" SILICONE INTERLAYER

AIR GAP FOR COOLING PURPOSES ONLY

1/4" GAP

NILO 'K' ALLOY

DIRECT BOND BETWEEN METAL AND GLASS

3/8" ALUMINO-SILICATE GLASS

AIR GAP FOR COOLING OR HEATING PURPOSES
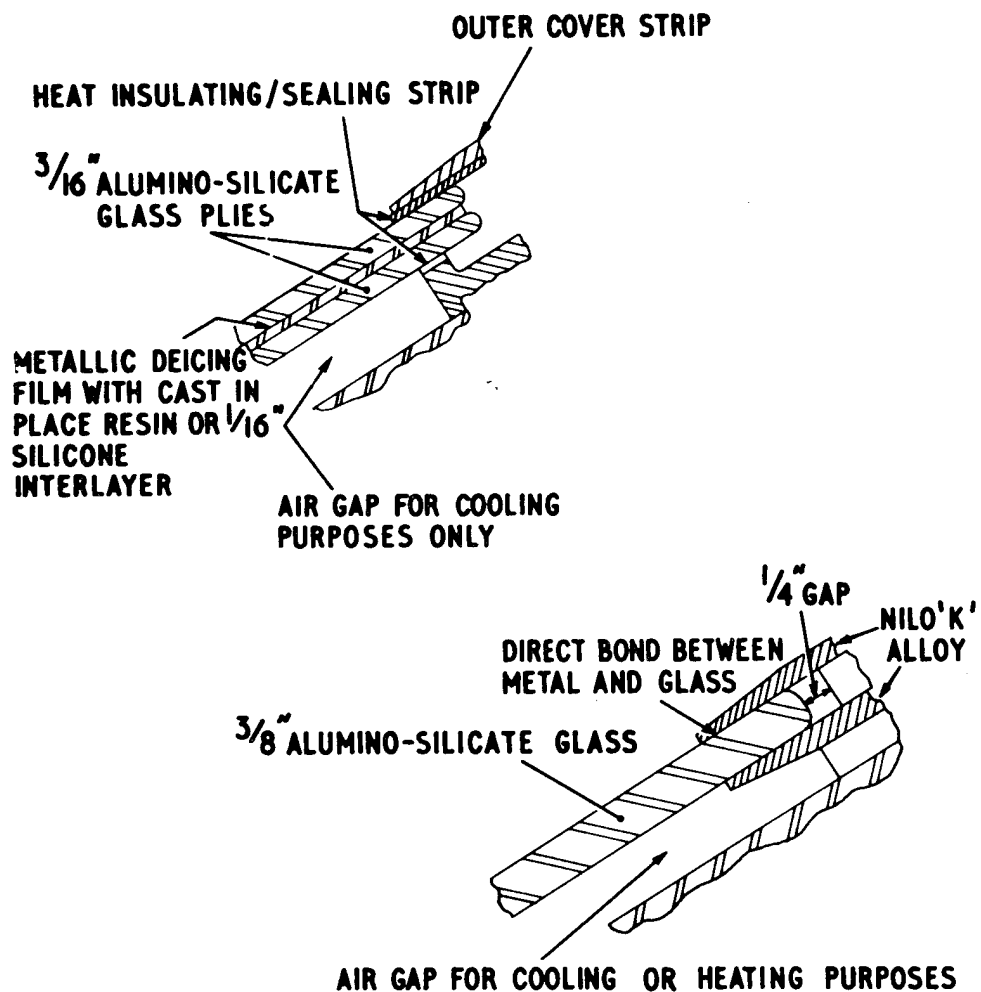
Figure 10.7-8 – Alternative Proposals for Thermal Shield if Aircraft Speed Is Not above Mach 2.5

10.8 HOLE-DRILLING PROCEDURE FOR POLYCARBONATE

Hole drilling in polycarbonate is a critical procedure, and if proper precautions are not taken, much of the material's impact resistance can be lost. The procedure outlined herein is for holes of up to 3/8-inch diameter. For larger holes, a diameter of about 3/32-inch undersize should be drilled and finished by machine to final dimensions using the procedures outlined for holes up to 3/8-inch in diameter.

Holes up to 3/8-inch in diameter should be made with an end mill, fluted, left-hand spiral at a feed rate of 0.0015 inch/revolution and a spindle speed of 1115 revolutions/minute. The coolant/lubricant should be USP grade mineral oil. It is recommended that the end mill contain holes to permit feeding the coolant directly in the hole concurrent with the machining. The end mill should have good clearance on the cutting angle and should be long enough to go through the hole to minimize "chattering" of the tool. The polycarbonate should be firmly held to also minimize chattering. A radius should be provided at each end of the hole to eliminate sharp edges which act as stress risers. It is absolutely necessary to keep tools sharp. Finish cleaning of holes should be done using aliphatic naphtha followed by an isopropyl alcohol wash. A round brush, similar to a pipette brush, should be used in cleaning of the holes. The finished holes should show no evidence of cracks. The holes should be finished to approximately a 40 to 60 RMS.

CHAPTER 11 - ENVIRONMENTAL FACTORS

11.1 GENERAL

Environmental exposures may be continuous, or may be transient during the operational life of a transparent enclosure. The design of the enclosure has to include provisions which will minimize degradation of the part from these exposures, or in the case of bird or bullet impact, protect the aircrewmen. Previous chapters have described various means of overcoming these problems; this chapter provides a more detailed insight into the environments themselves.

11.2 THERMAL EXPOSURE

Laboratory testing has shown evidence of material degradation after extended exposures to temperatures in the range of 120 to 240 F. In practice, the effects of temperature become cumulative from air friction, hot air jet removal systems for rain or ice, and solar radiation. Solar radiation is a more predominant factor for desert-based aircraft where cockpit superheat temperatures have been known to be higher than 140 F while the aircraft is parked. Figure 11.2-1 demonstrates skin temperatures which can be expected at various airspeeds. These temperatures would be also subject to variation, depending upon the glazing position, material, and cabin temperature.

Thermal shock is always a recognized problem that can occur during a rapid altitude change in which the glazing surface temperature may be at an opposite extreme from the ambient level it is entering. Ambient air temperatures versus altitude are shown in Figure 11.2-2. Electrically conductive coatings maintain a relatively stable temperature on the surface of the glazing, but hot air jet systems utilize temperatures up to +200 F which are directed by apertures that may not distribute the surface temperature evenly during flight, especially if suddenly applied on a cold windshield.

11-1
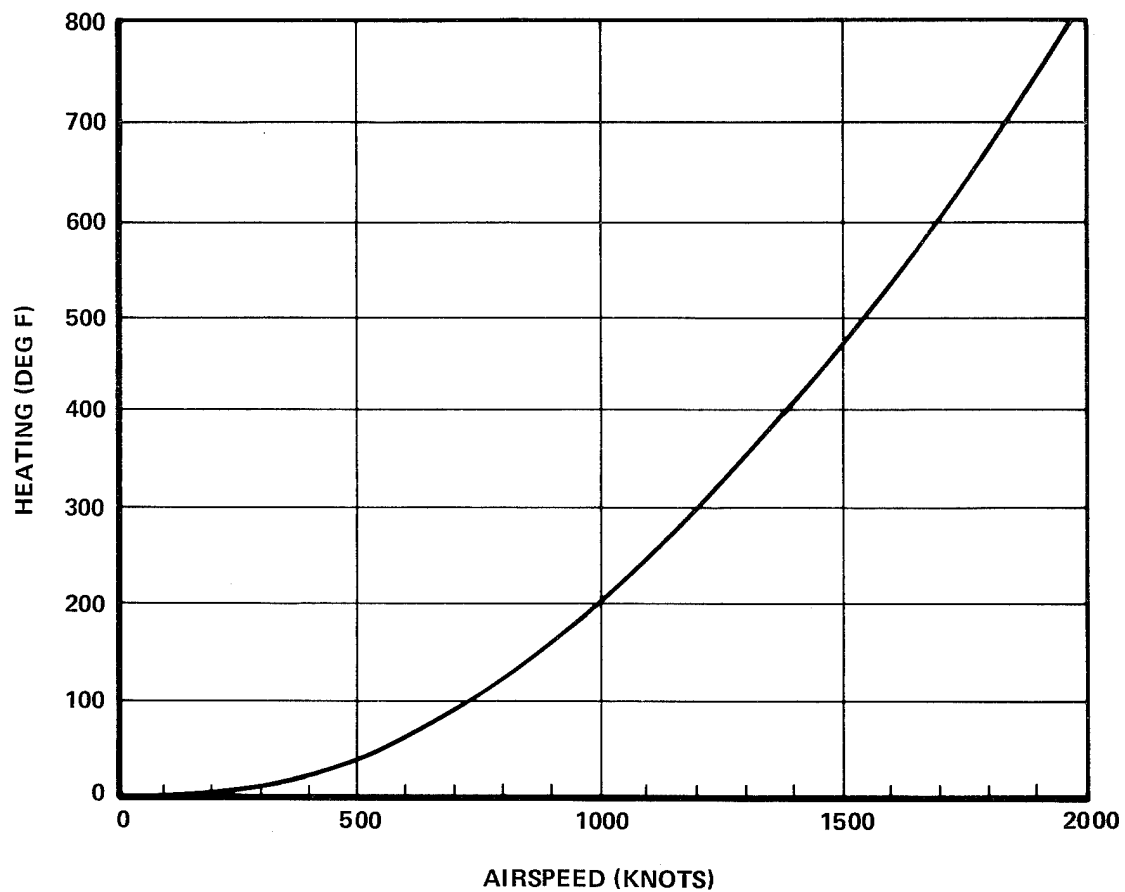
NOTE: FROM SIERRACOTE S3 ENGINEERING HANDBOOK.

Figure 11.2-1 – Aerodynamic Heating versus Airspeed
(Based upon 0.89 Recovery)

11-2
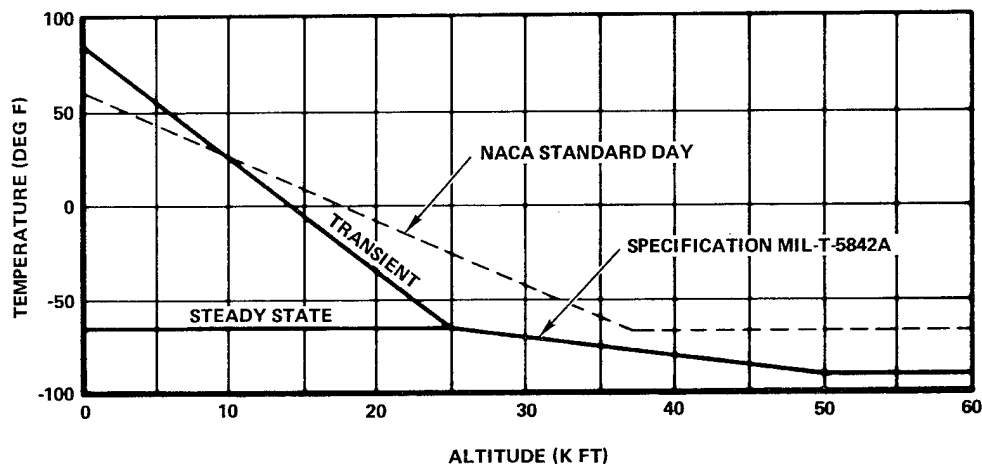
NOTE: FROM SIERRACOTE S3 ENGINEERING HANDBOOK.

Figure 11.2-2 – Ambient Air Temperature versus Altitude

Izod tests have been the principal method of determining deterioration by thermal exposure. Figure 11.2-3 provides unnotched data on unstretched (MIL-P-8184) and (75 percent) stretched (MIL-P-25690) materials along with weathering data. Table 11.2-I shows the effects of thermal aging on MIL-P-83310 material with the unusual effect of not breaking, but bending after 6 months at +160 deg F. These tests were performed edgewise.

Table 11.2-II shows that thermal aging also lowers the deflection temperature.

Figure 11.2-4 demonstrates the effect of stepped thermal aging on stretched acrylic material. Being a thermoplastic material, the MIL-P-25690 sheet tends to revert to its original sheet form and thickness as temperature is increased.

The thermal effect on the time-to-craze data at +122 deg F for MIL-P-5425 material is compared to room temperature test data in Figure 11.2-5.

11-3
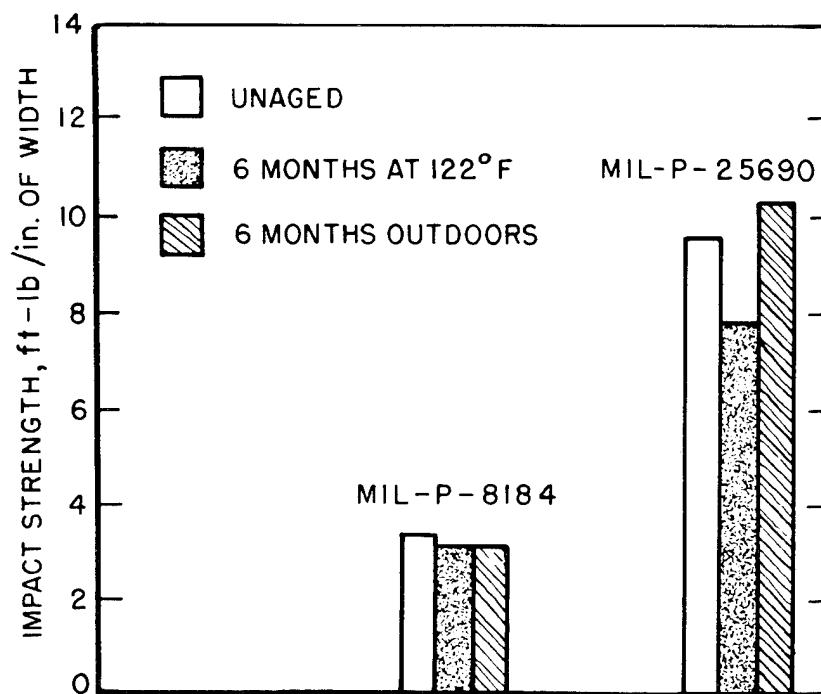
Figure 11.2-3 - Effects of Thermal Aging and Weathering Data for Unnotched Material Tested Flatwise

TABLE 11.2-I – EFFECT OF THERMAL AGING ON IZOD IMPACT STRENGTH (NOTCHED)

Exposure	Impact strength (ft-lb/in. of notch) MIL-P-83310
100 hr at +260 deg F	1.60
100 hr at +200 deg F	1.75
6 mo at +160 deg F	2.07 (no break)
Unexposed at +73 deg F	1.81

TABLE 11.2-II – EFFECT OF THERMAL AGING ON DEFLECTION TEMPERATURE
(WITH A 264-PSI OUTER FIBER STRESS)

Exposure	Deflection temperature (deg F) MIL-P-83310
Unexposed at +75 deg F	292.0
100 hr at +260 deg F	292.2
100 hr at +200 deg F	286.8
6 mo at +160 deg F	286.4
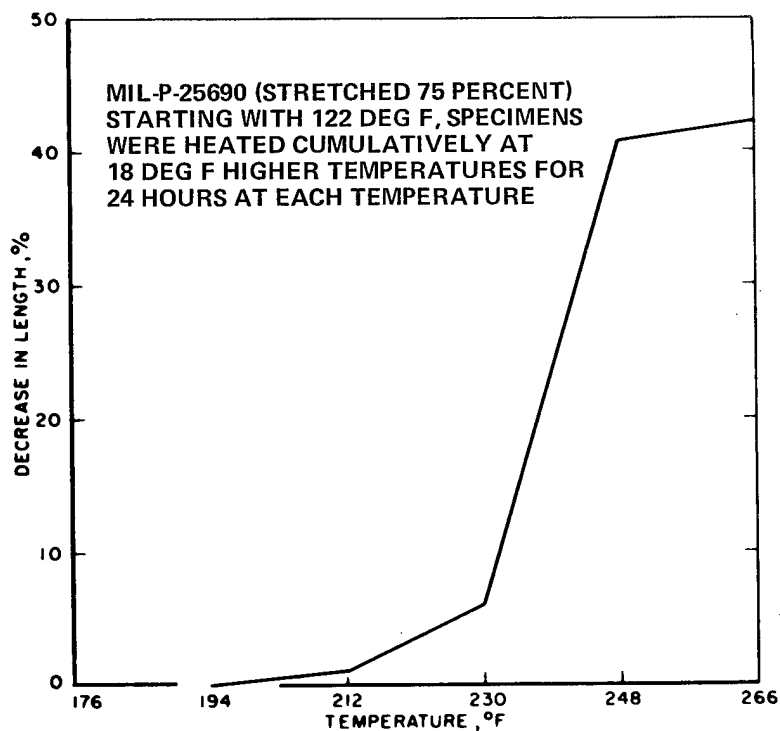
Figure 11.2-4 – Effect of Temperature on Thermal Relaxation of MIL-P-25690 Material
after Aging at 122 Deg F for Six Months

11-5
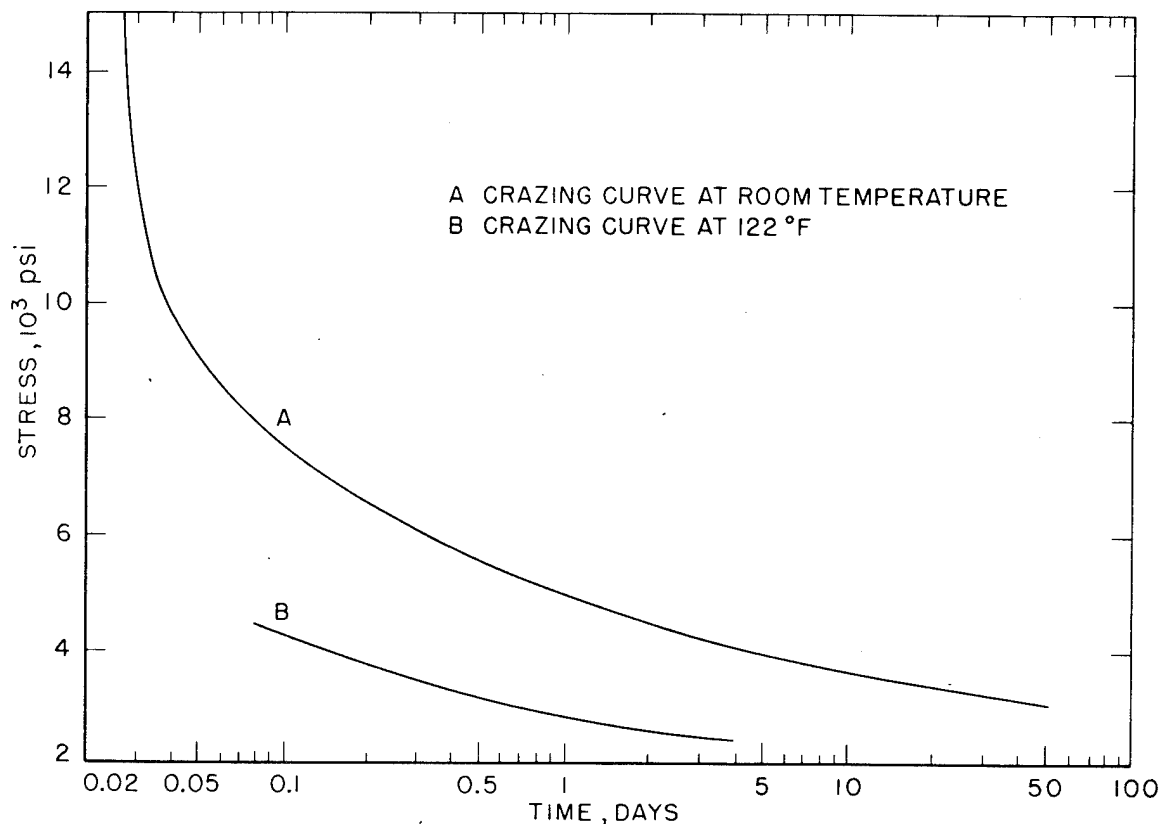
Figure 11. 2-5 – Effect of Duration of Loading on Stress-Crazing Behavior of
MIL-P-5425 Material in Long-Time Cantilever Flexure Tests at
Various Temperatures

11.3   OUTDOOR WEATHERING

Outdoor weathering is associated with thermal exposure to some extent, as mentioned in
the previous section.   The thermal component of outdoor exposure may affect plastic
materials by slowly evaporating some of the plasticizer and embrittling the material.
The remaining components of weathering are the most degrading.   Ultraviolet (UV)
exposure affects certain plastic components photochemically with the resultant discoloration
and changes in physical properties.   The erosive factors of water, ice, and of particulates
driven by air movement can be most damaging on surfaces which have already been
degraded to some extent by thermal and UV radiation.   Water absorption may aggravate
degradation, but on the whole, all of these parameters act as a single severe exposure.

Figures 11.3-1 (A) through 11.3-1 (D) are microphotographs of unprotected polycarbonate which show a progressive pitting deterioration from outdoor weathering in Arizona after six months. Figures 11.3-2, 11.3-3, and 11.3-4 show a degradation phenomenon known as "checking" over 6, 9, and 12 month periods. Noticeable surface discoloration started between six and nine months.

Figure 11.3-5 demonstrates the effect of six months' weathering on notched Izod impact tests on various thicknesses of material. Figure 11.3-6 compares the changes in light transmission and haze.

The effects of weathering on ultraviolet transmittance are demonstrated in Figure 11.3-7.

The most severe tests which involve weathering are accomplished with the exposed specimens under continual loading. Figure 11.3-8 graphs the results of tests on various materials in terms of hours-to-craze under tensile loading.

Flexural properties have also been obtained under continuous outdoor loading and are plotted for MIL-P-5425 thermoplastic material in Figure 11.3-9 in terms of a deflection-times-thickness at various stress levels. Comparable data are found in Figures 11.3-10 and 11.3-11 for MIL-P-8184 material, also a thermoplastic, and MIL-P-8257, a thermo-setting material. Flexural rupture and craze curves for MIL-P-8184 are shown in relationship in Figure 11.3-12.

Test results after six months weathering show no appreciable change in tensile strengths, plotted in Figure 11.3-13 for various thicknesses.

11.4 BIRD IMPACT

A bird resistant windshield is not a new concept, but the increased velocities of more recent aircraft designs make random collisions and penetrations of fowl more imminent. An approximation of the compressive stress imposed by the collision of a four-pound bird at a resultant impact velocity of 500 ft/sec is 1500 lb/in.^{2} compressive stress over an assumed 20-square-inch area. Such a load has to be absorbed by the windshield and the edge attachment without penetration. Excessive spall from the inside face also has to be contained.
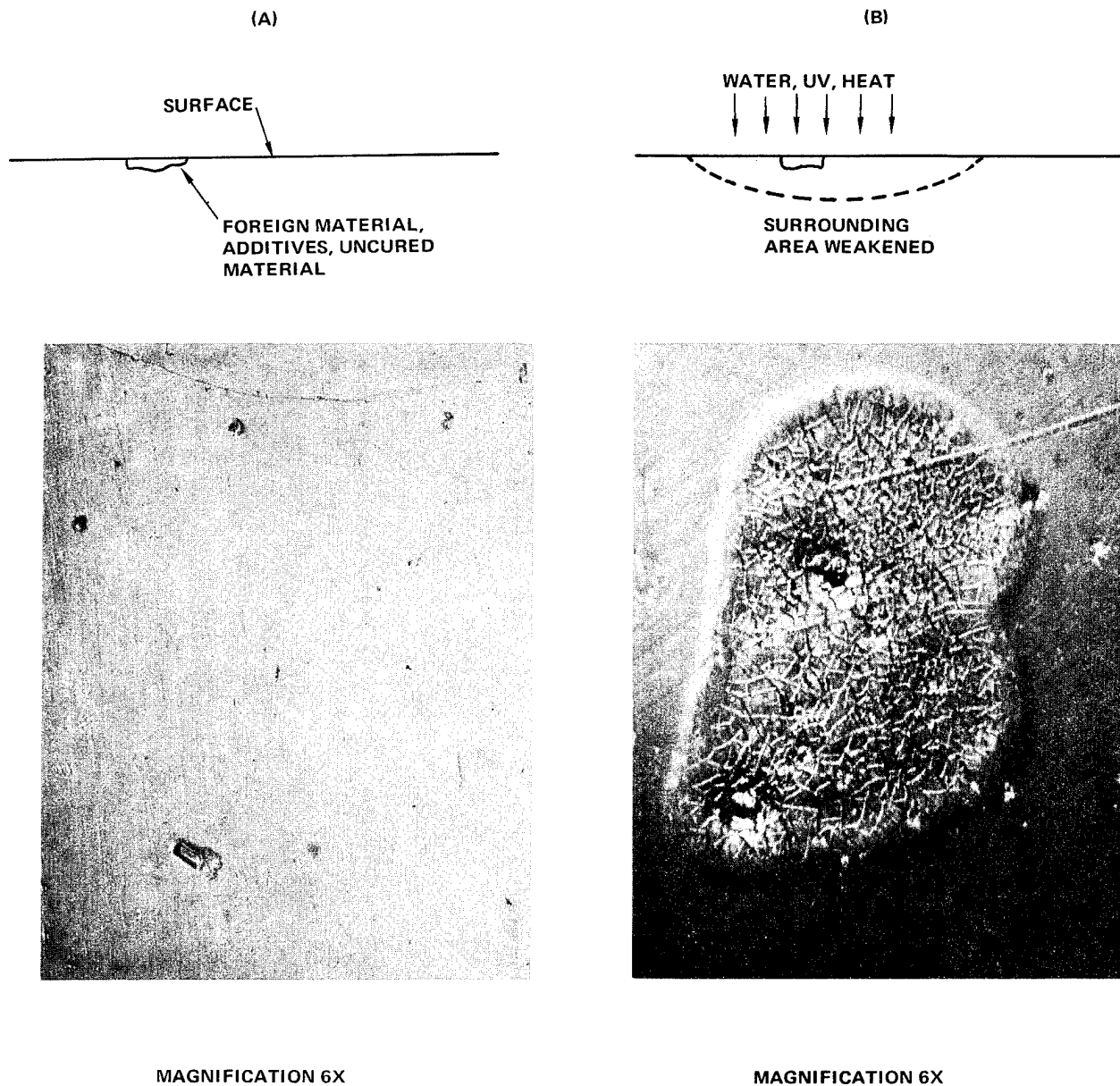
(A)

(B)

SURFACE

WATER, UV, HEAT

FOREIGN MATERIAL,
ADDITIVES, UNCURED
MATERIAL

SURROUNDING
AREA WEAKENED

MAGNIFICATION 6X

MAGNIFICATION 6X

Figure 11.3-1 – Progression of Surface Deterioration of Polycarbonate after
Six-Month Weathering (Sheet 1 of 2)

11-8

(C)

MORE WATER, UV, AND HEAT

MATERIAL CRAZED
AND BROKEN UP,
YELLOWED

(D)

BROKEN UP
RESIDUE

WIND, WATER, SAND
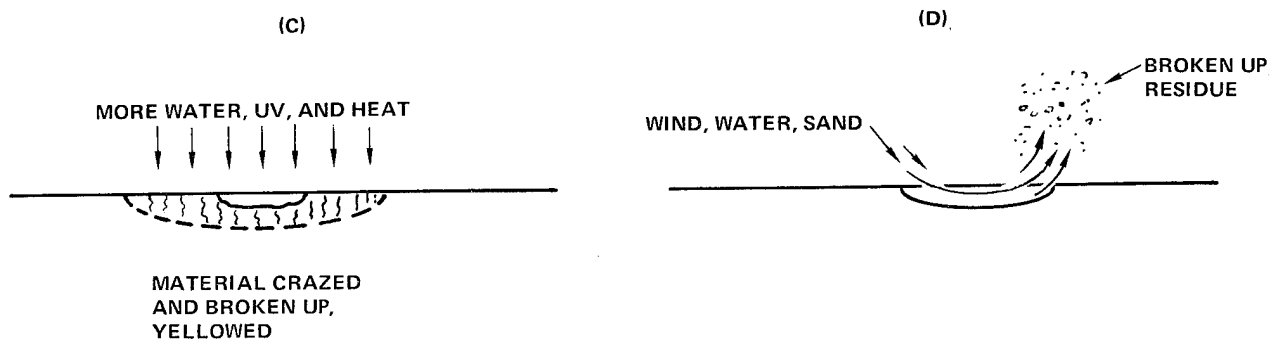
MAGNIFICATION 6X

MAGNIFICATION 6X

Figure 11.3-1 – Progression of Surface Deterioration of Polycarbonate after
Six-Month Weathering (Sheet 2 of 2)
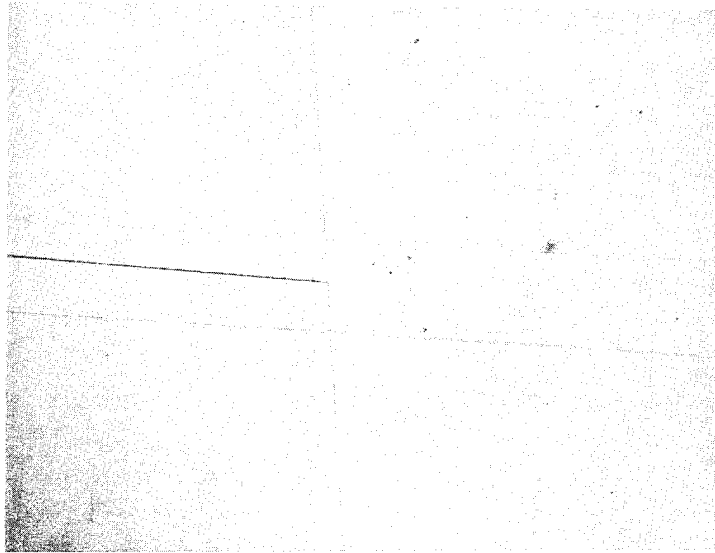
MAGNIFICATION 6X

Figure 11.3-2 - Polycarbonate after Six-Month Weathering - Start of Checking

MAGNIFICATION 6X

Figure 11.3-3 - Polycarbonate after Nine-Month Weathering -
Checking More Predominant; Surface Yellowing
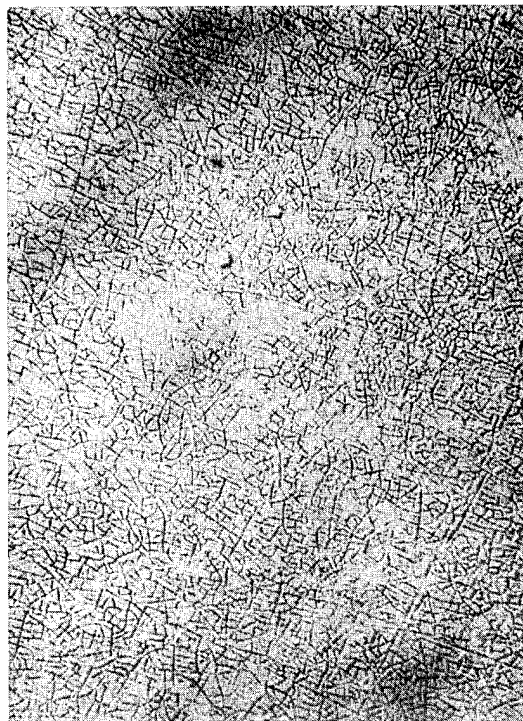
MAGNIFICATION 30X

Figure 11.3-4 - Polycarbonate after Twelve-Month Weathering
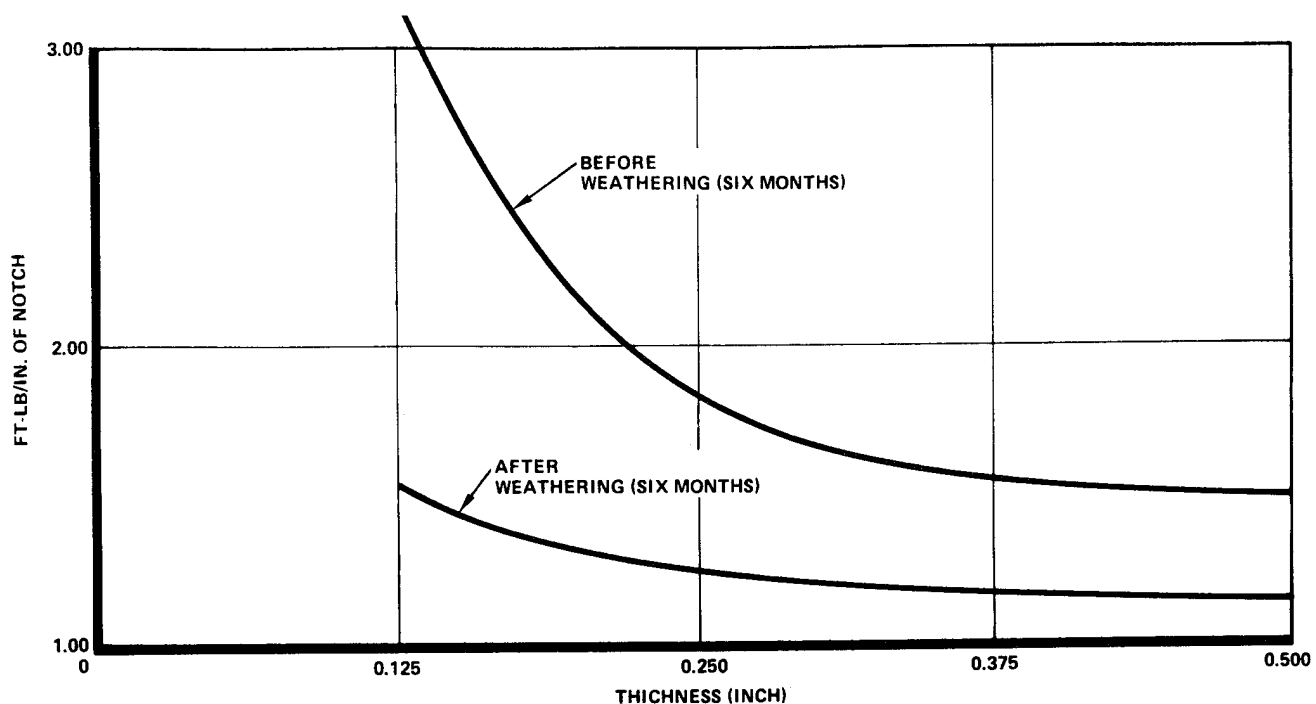
Figure 11.3-5 - Izod Impact Tests before and after Six-Month Weathering on Processed
MIL-P-83310 Material

11-11
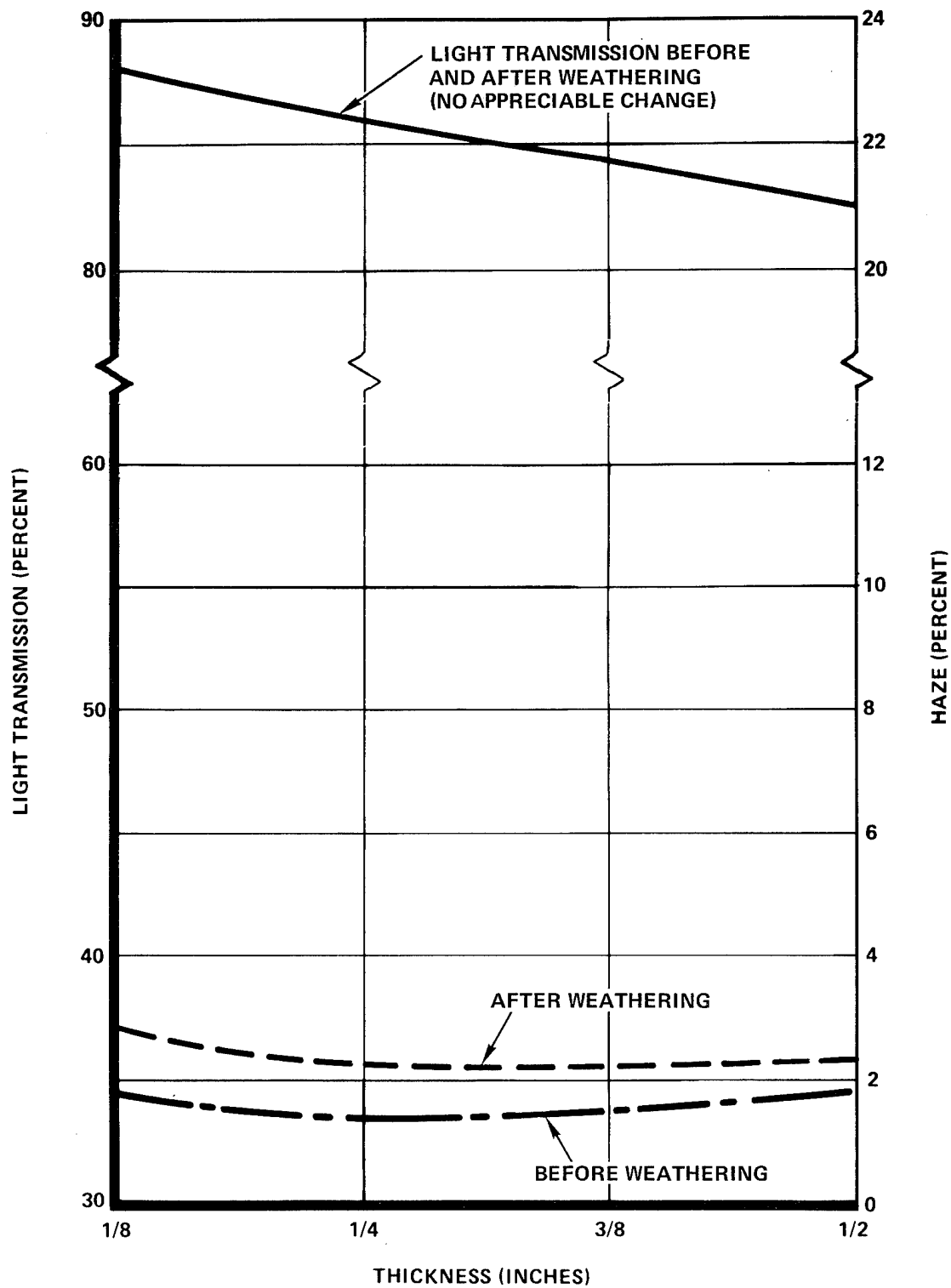
Figure 11.3-6 – Light Transmission and Haze before and after Weathering Six Months
on Processed MIL-P-83310 Material

11-12
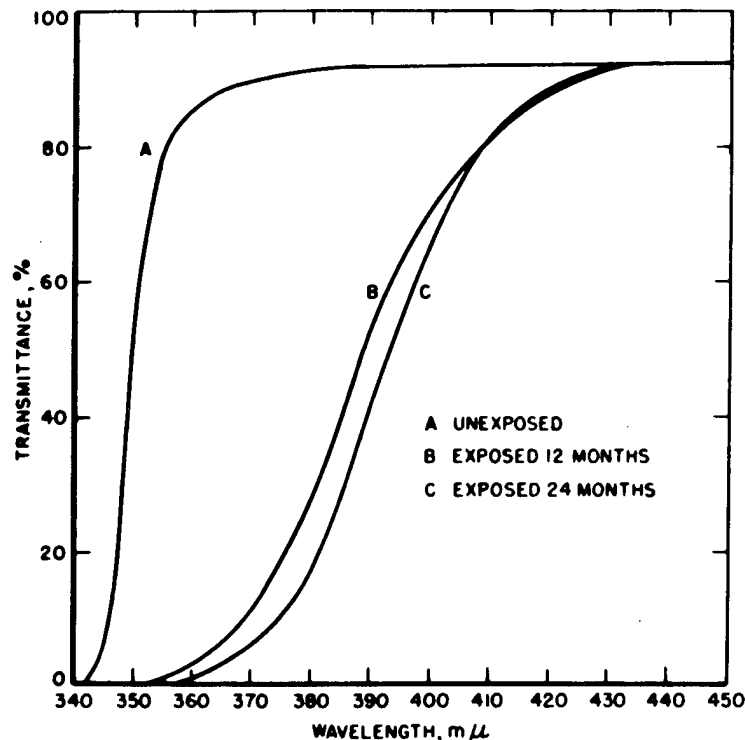
Figure 11.3-7 – Ultraviolet Light Transmittance of 0.250-Inch-Thick MIL-P-5425
Material before and after Outdoor Weathering

An impingement angle other than 0 deg of the glazing with respect to the direction of impact can be expected to reduce the load, but general design data are lacking.

Because of the difficulty in defining the semiballistic properties of a bird, various devices have been built which simulate the impact of a bird in flight by the aircraft. These devices are explained in more detail in References 39, 40, and 41.

The original birdproof designs were primarily of laminated tempered glass which utilized polyvinyl butyral interlayers. Bird impact testing of laminated windshields made with polyvinyl butyral plastic has shown that impact resistance is primarily a function of the interlayer thickness, the percent plasticizer content in the plastic interlayer, flexibility of the supporting structure, and the temperature of the plastic interlayer.
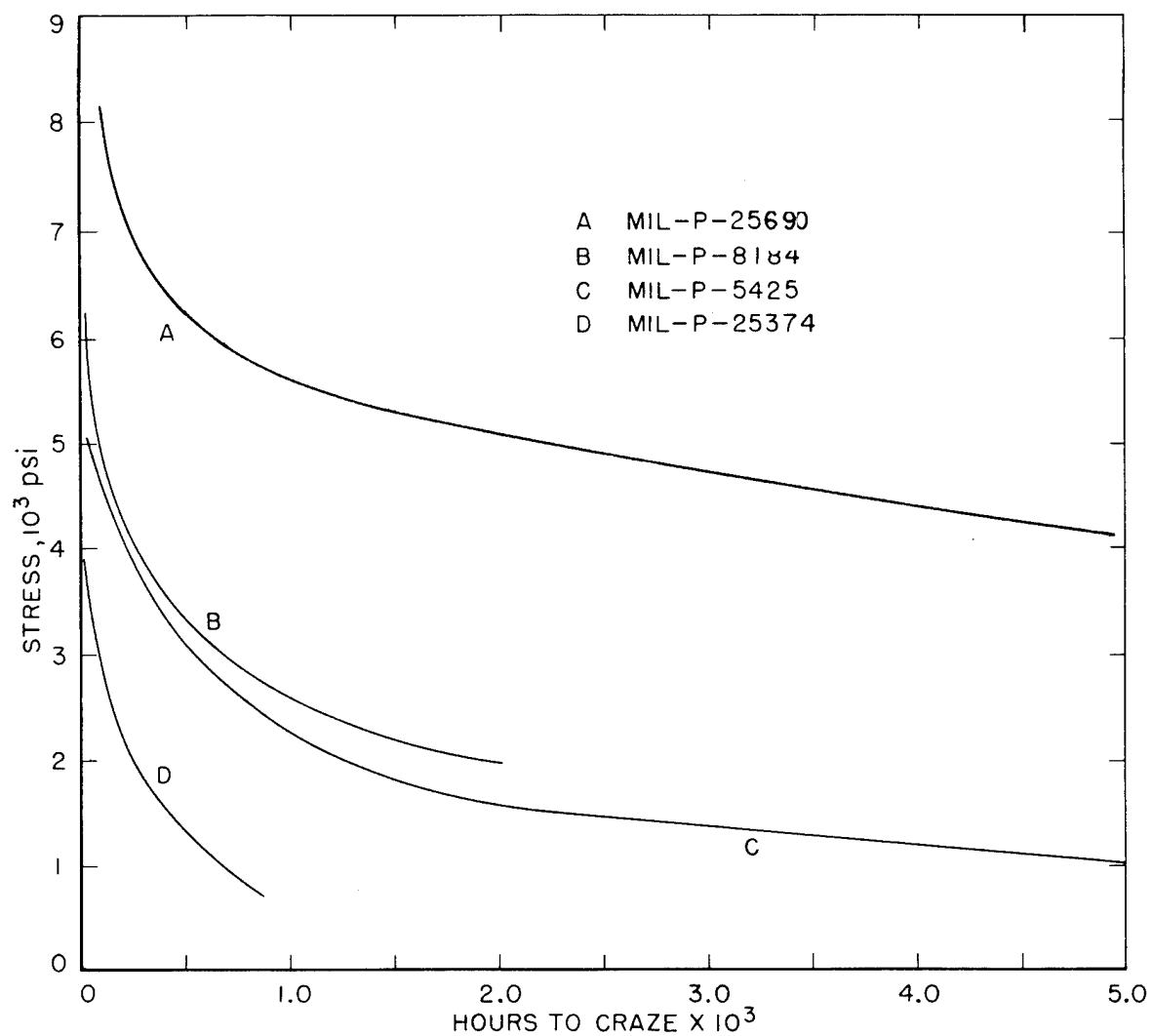
Figure 11.3-8 – Effect of Duration of Tensile Loading During Exposure Outdoors on
Crazing Behavior of Plastics Glazing Materials

11-14
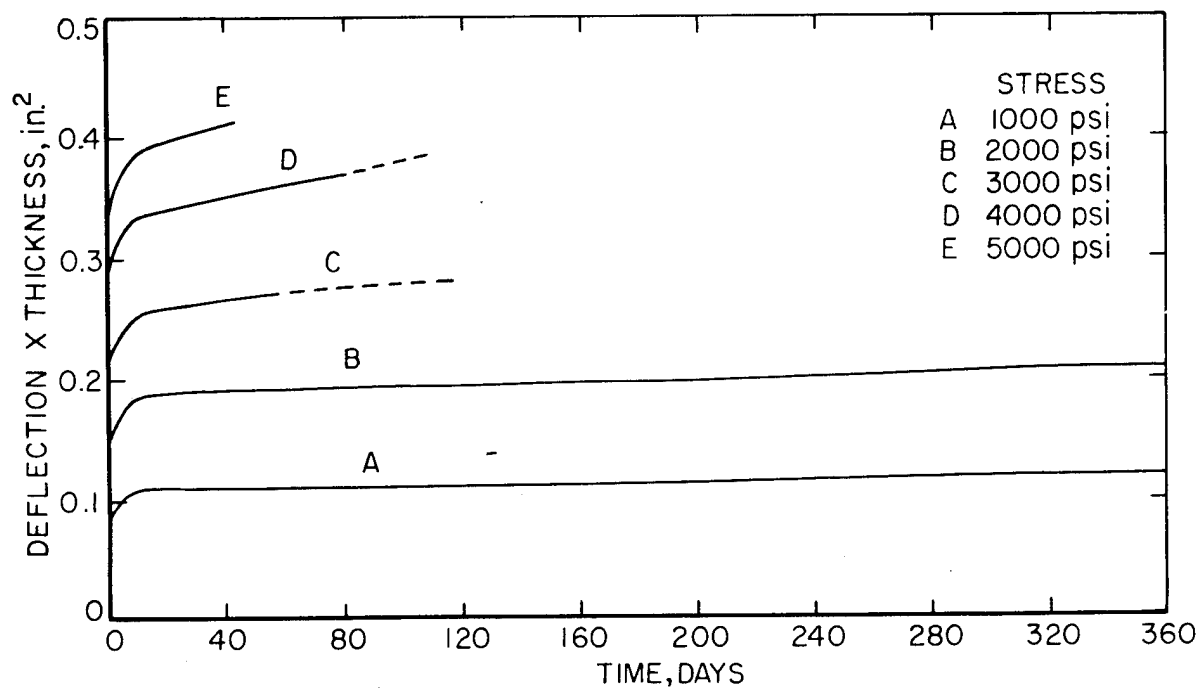
Figure 11.3-9 – Flexural Deflection of MIL-P-5425 Material in Long-Time Outdoor
Cantilever Tests
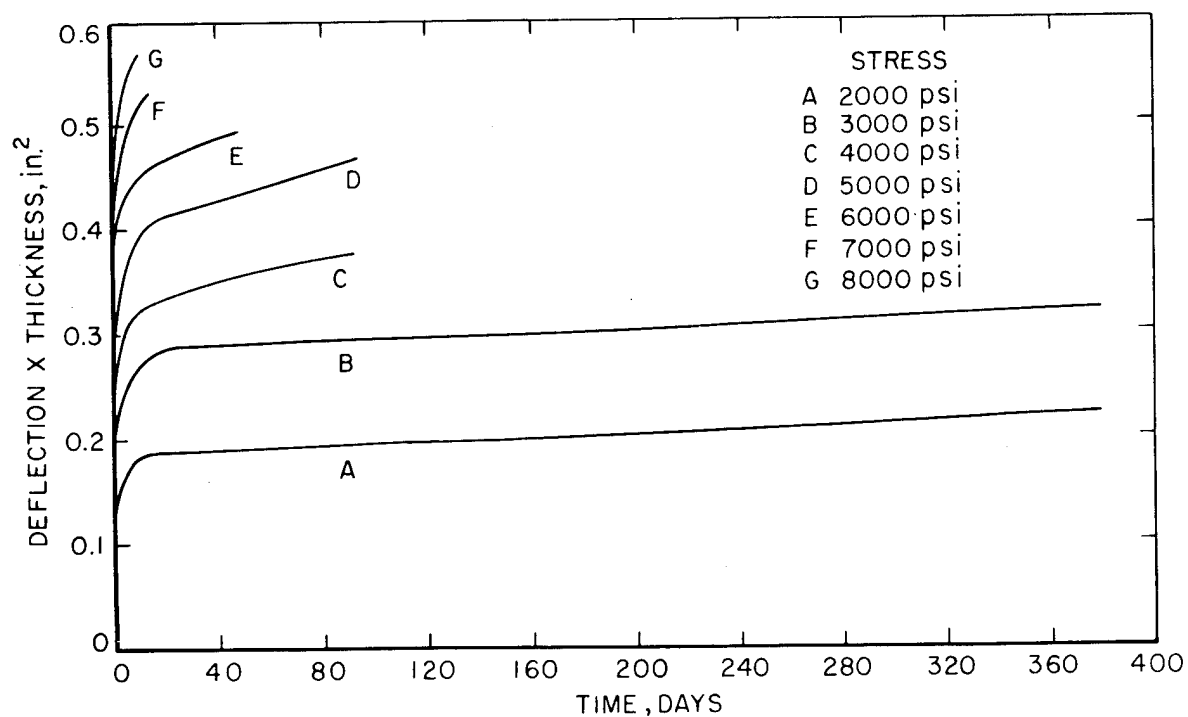
Figure 11.3-10 – Flexural Deflection of MIL-P-8184 Material in Long-Time Outdoor
Cantilever Tests

11-15
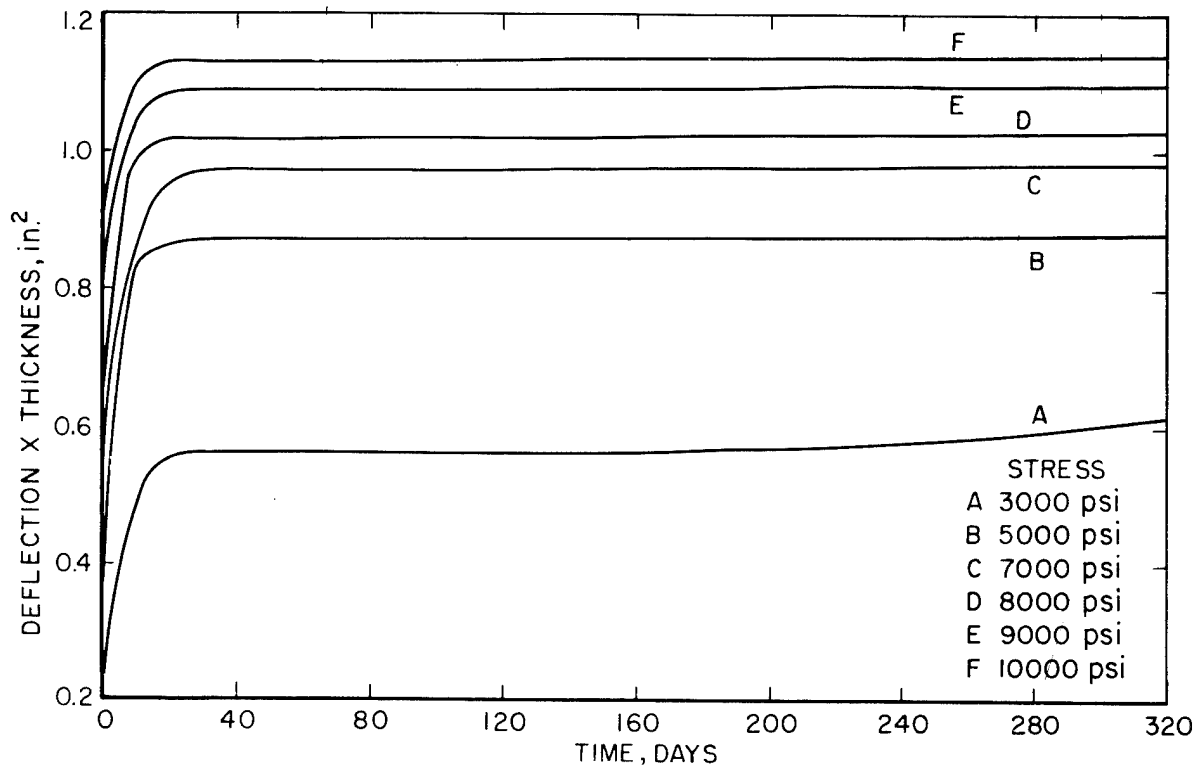
Figure 11.3-11 – Flexural Deflection of MIL-P-8257 Material in Long-Time
Outdoor Cantilever Tests
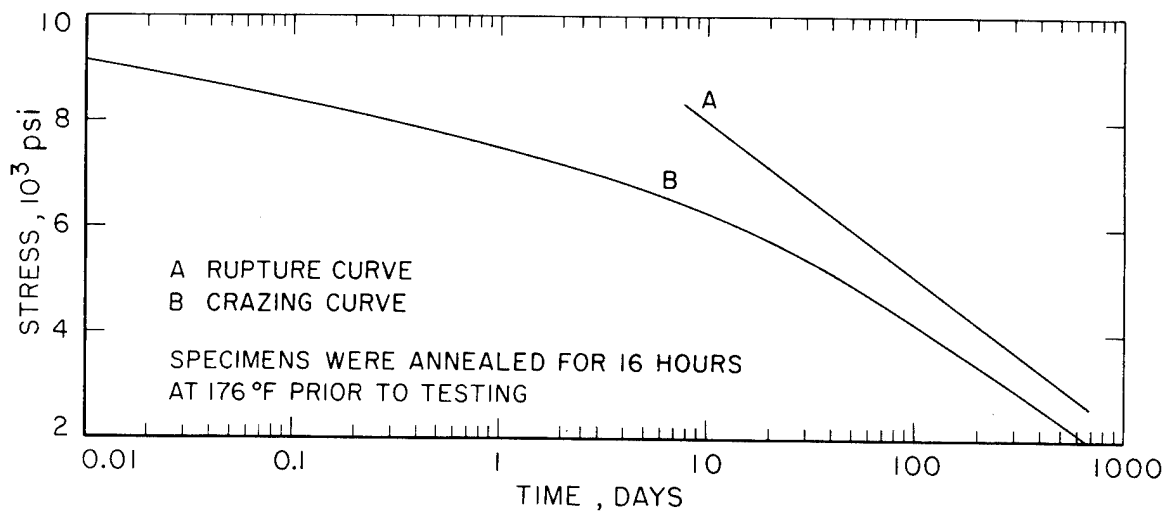
Figure 11.3-12 – Effect of Duration of Loading on Flexural Properties of 0.250-Inch-Thick
MIL-P-8184 Material Tested Outdoors

11-16
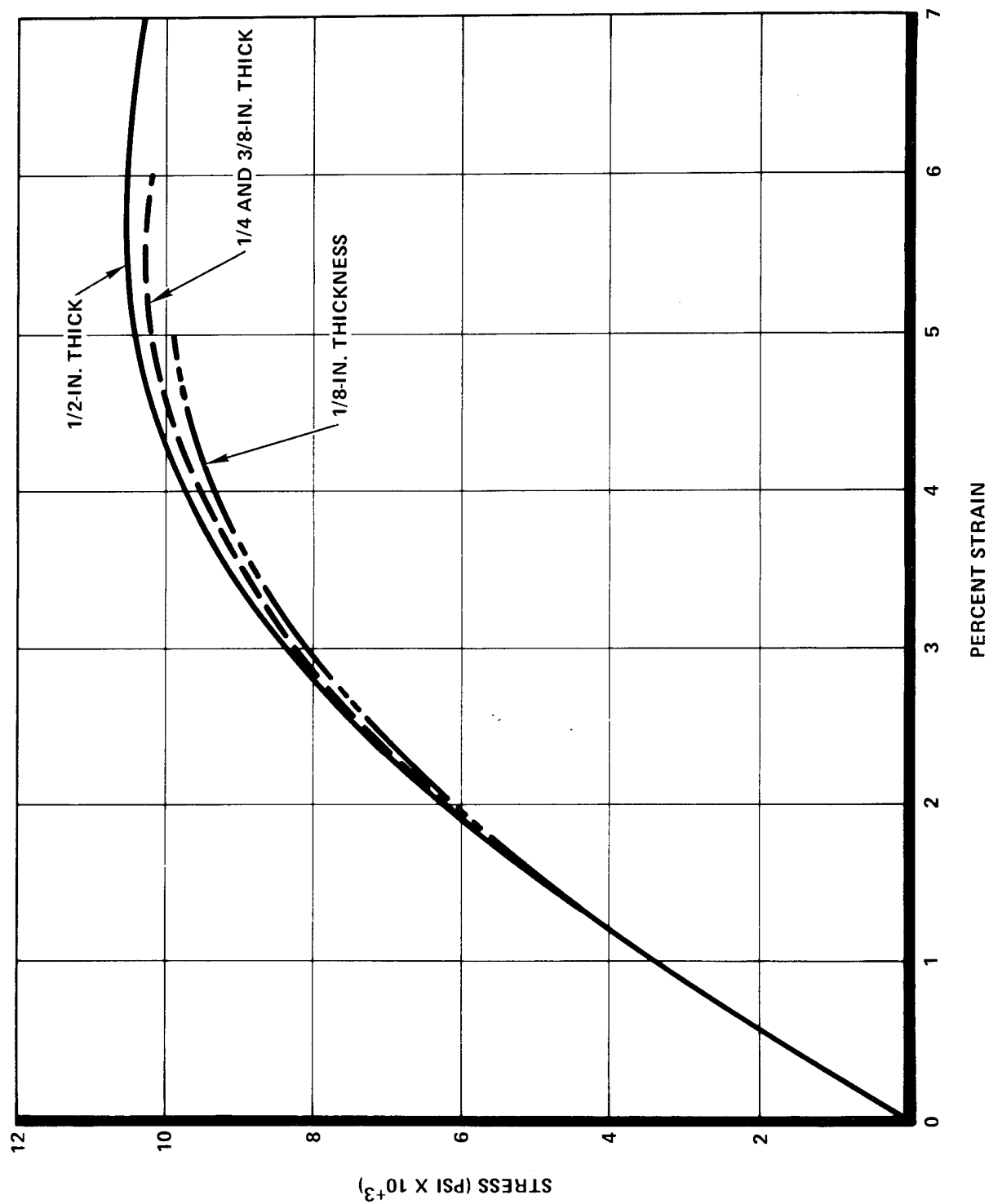
Figure 11.3-13 – Tensile; MIL-P-25690 Material after Processing; +75 Deg F;
Weathered 6 Months

The plastic interlayer has generally been polyvinyl butyral with 21 parts per hundred plasticizer, although some testing has been done with interlayer containing 15 and 30 parts per hundred plasticizer. The primary purpose of the change in plasticizer content is to shift to temperature ranges at which maximum penetration protection is obtained. The thicknesses of the tempered glass faces of the laminate have little effect on impact strength within reasonable limits, while the polyvinyl butyral plastic interlayer thickness has a predominant effect, the plastic (21 parts per hundred plasticizer) interlayer being most effective when the temperature maintained by the imbedded electrical heating element (coating) is about 90 to 100 F. But at lower or higher temperatures beyond this range, the impact strength decreases rapidly (Reference 42).

In a number of laboratory tests, windshields mounted in the more flexible supporting structures resisted penetration at velocities about 100 MPH greater than did identical panes mounted in the more rigid cockpit structure (Reference 42).

Edge attachments were developed which better utilized the flexible properties of the inter-layer. Electrically conductive coatings which were primarily for anti-fogging or anti-icing had the secondary advantage of keeping the interlayer at its best operating temperature for a deterrent to bird strike penetration. Figure 11.4-1 demonstrates the reactive forces of the panel, and Figure 11.4-2 shows a typical glass laminate with its edge attachment.

The load is transferred through the interlayer to the aluminum insert, through the bushing, and to the bolt. The reinforcements act as a retainer for the interlayer as well as a thermal insulator and sealing surface for pressurization. The "parting medium" allows a slight flexing at the panel edges under pressurization loads and avoids high shear stresses at the panel edges which can occur at very low temperatures when the electrical coating is operative.

The use of glass laminates with electrically conductive coatings has been predominantly limited to flat panels. Where aircraft profiles require curved panels, plastic materials become an obvious choice. With the advent of polycarbonate and its superior impact resistance, curved birdproof designs became more practical. To date, monolithic

ATTACHMENT
BOLT
LOCATION

SHATTERED
GLASS PLIES

VINYL
PLY

BIRD STRIKE IMPACT LOAD

VINYL PLY ABSORBS IMPACT
ENERGY BY STRETCHING AND
DEFORMING. SHATTERED
GLASS PLIES REMAIN
ADHERING TO VINYL.
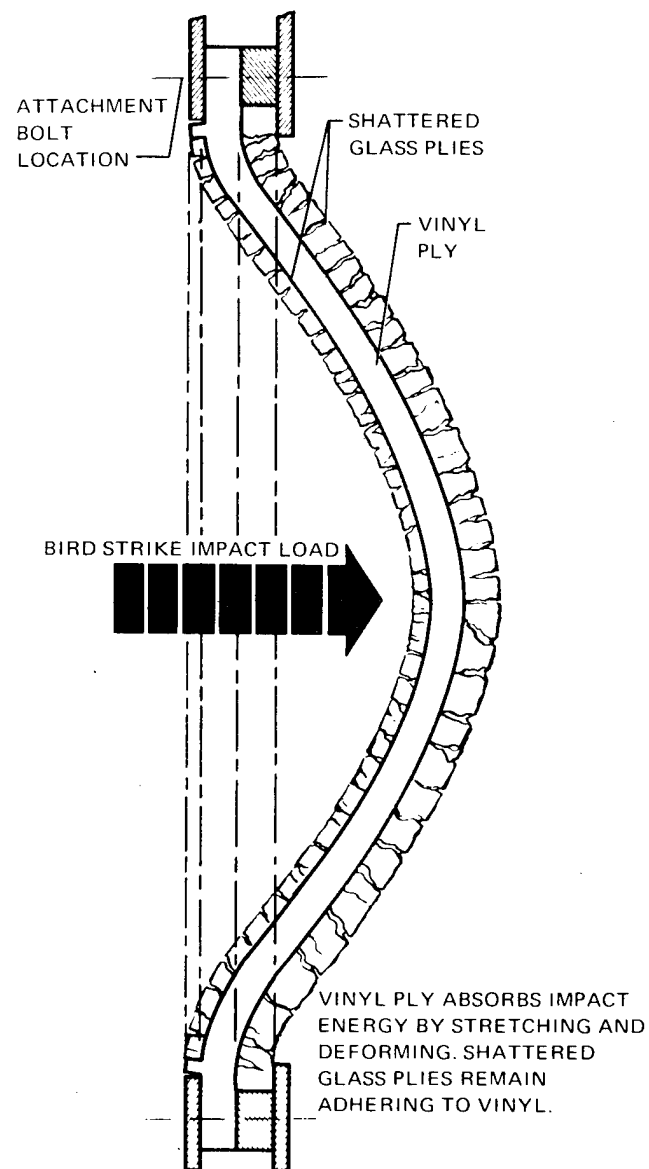
NOTE: DATA SUPPLIED BY LOCKHEED.

Figure 11.4-1 – Manner in which a Birdproof Windshield Panel Resists a Bird Strike

PHENOLIC EDGING
ALUMINUM SPACER
PHENOLIC RETAINER
ALUMINUM INSERT
SEALANT
PARTING MEDIUM
CONDUCTIVE COATING

1 OUTER GLASS PLY · (3/16 INCH)
2 OUTER VINYL PLY (APPROX 0.290 INCH ON FORWARD PANEL; APPROX 0.265 INCH ON CENTER PANEL)
3 MAIN GLASS PLY (1/2 INCH ON FORWARD PANEL; 3/8 INCH ON CENTER PANEL)
4 INNER VINYL PLY (APPROX. 0.120 INCH)
5 INNER GLASS PLY (1/8 INCH)

1 2 3 4 5

FORWARD PANEL
A

NOTE: DATA SUPPLIED BY LOCKHEED.

Figure 11. 4-2 - Typical Glass Laminate with Edge Attachment

polycarbonate in the order of one-half inch thick with a bolt-through attachment has had successes for particular aircraft applications. Stretched acrylic combinations which have been tested successfully at 345 knots velocity are shown in Figures 11. 4-3 and 11. 4-4.

Currently, an Air Force-sponsored birdproofing design and testing program is underway to establish higher velocity design parameters for general usage.

11. 5   BULLET IMPACT

Transparent armor is a very specialized form of glazing, and as such, its design is of a classified nature. More information can be found in References 43, 44, and 45. The environment of projectile susceptibility is complex for aircraft because tactical situations change. In the broad sense, however, a threat level has to be determined to design the armor cross-section which will be adequate and of the lightest weight. The threat level involves the types of projectiles used in the tactical areas, their probable muzzle velocities,
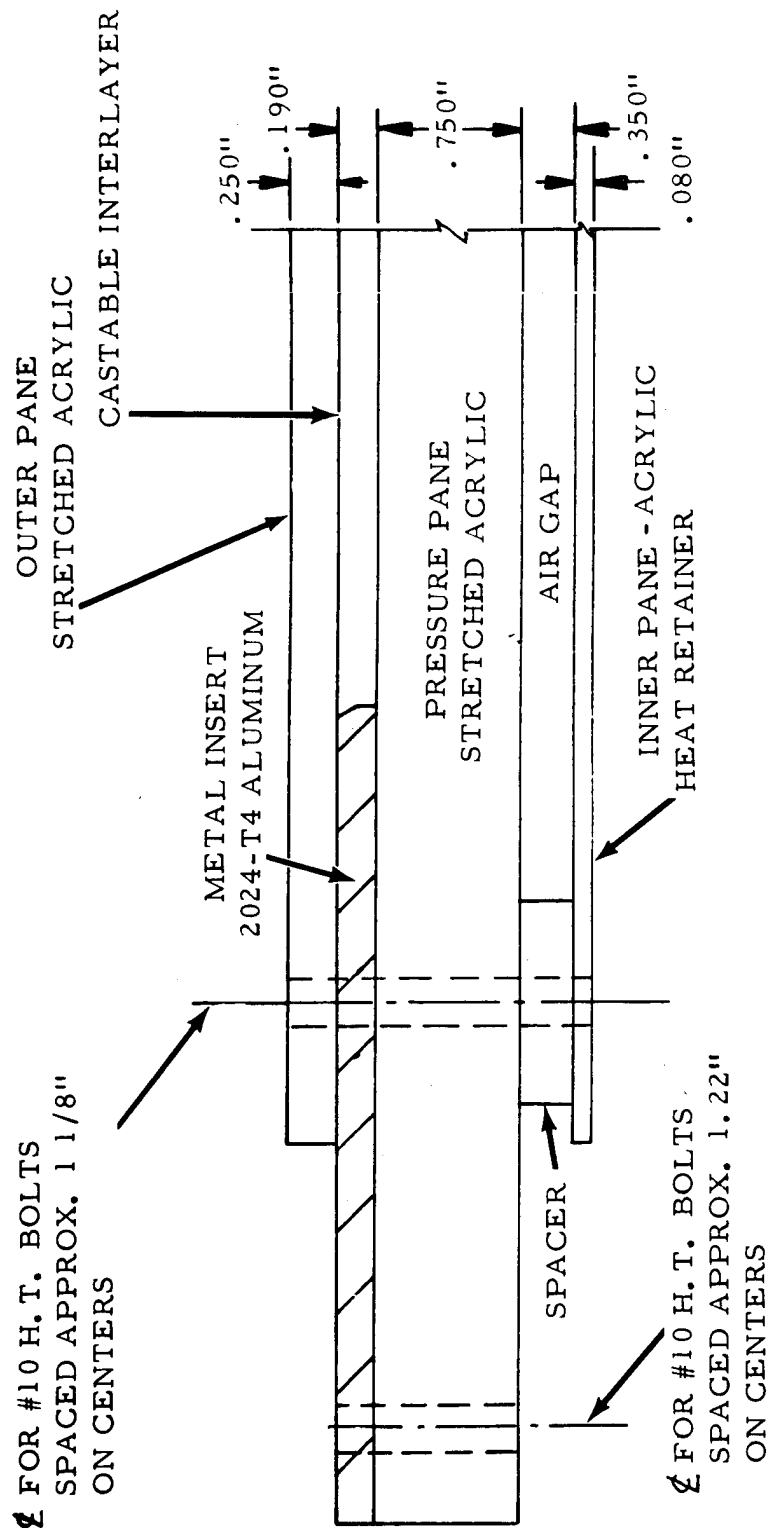
Figure 11.4-3 – Acrylic-Castable Interlayer-Acrylic Design

11-21

CONDUCTIVE COATING

.325"

.750"

OUTER PANE
.062" POLYESTER
PLASTIC

POLY VINYL BUTYRAL

STRETCHED ACRYLIC
PRESSURE PANE

METAL INSERT
.061" THICK
7178 ST ALUMINUM

¢ FOR #10 H.T. BOLTS
SPACED AT 1 1/8"
ON CENTERS + 1/4" DIA.
METAL SPACER EACH HOLE

V_C = 350 KNOTS MIN.
NOM. WINDOW SIZE - 19" x 35"
MAX. V_{Test} = 345 KNOTS (NO PENETRATION)
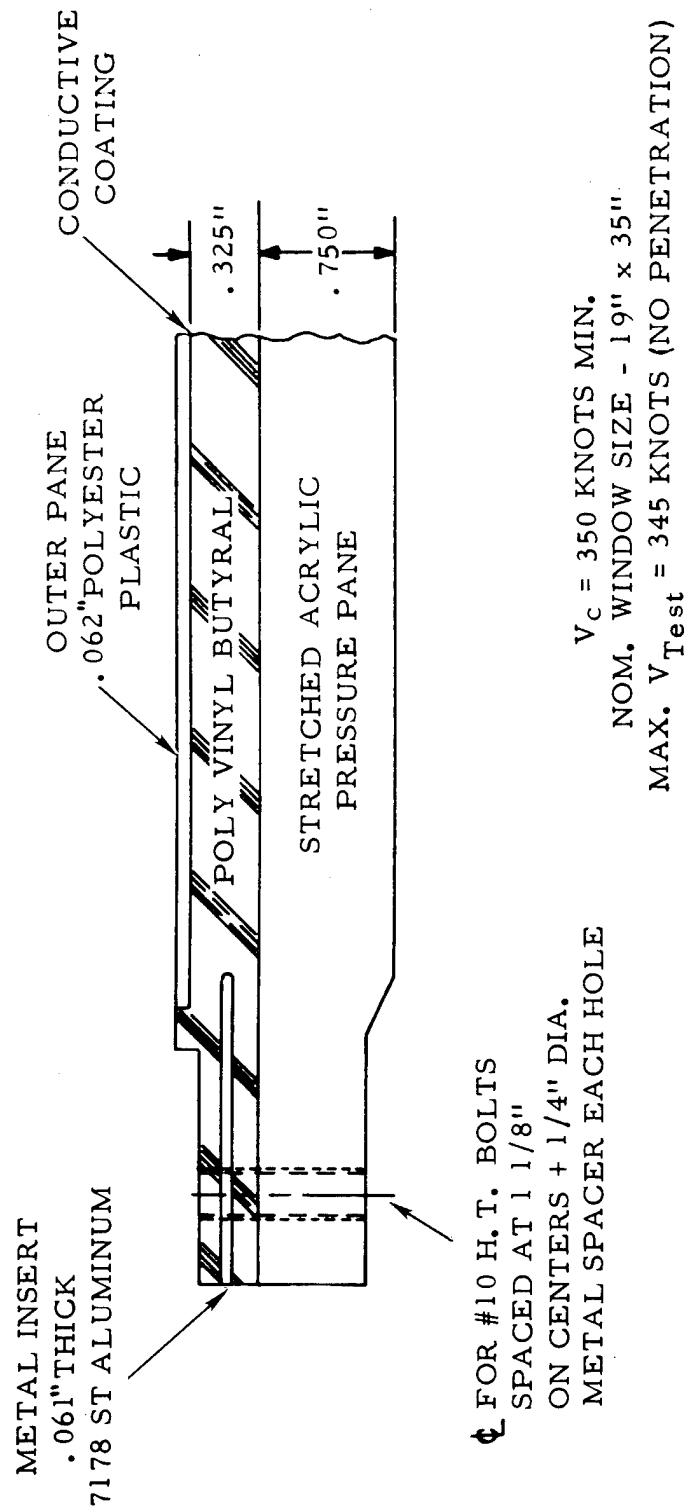
NOTE: DATA SUPPLIED BY LOCKHEED.

Figure 11.4-4 – Plastic Laminate Construction for Forward Vision Window

11-22

the altitude and attitude of the aircraft when entering the ballistic environment, and the position of the transparent armor with relation to the direction of the threat. From this information the velocities and obliquities of certain expected types of ammunition have to be determined at the point of impact on the armor. This portion of the design parameter is usually specified by the procuring agency as a "protection ballistic limit" (V50) and threat level.

The definition of the ballistic limit (V50 protection ballistic limit, BL(P)) is as follows. The protection V50 ballistic limit is defined as the average of four fair impact velocities comprising the two lowest velocities resulting in complete penetration and the two highest velocities resulting in partial penetration. The maximum spread of 150 feet per second will be permitted between the lowest and highest velocities used in determination of ballistic limits.

The basic principles of armor design require that the kinetic energy of impact be diverted, transferred into heat, and absorbed. Diversion is usually accomplished with a hard face sheet which will shatter on impact. The brittle conchoidal type of fracture requires that energy be expended radially and 90 degrees from the direction of impact if a 0-degree obliquity angle is involved. The hard face also has a tendency to break up the projectile and throw it sideways. Certain softer materials do not crack on impact and create a frictional component which transforms into heat and distributes the load over a larger area. The third member, usually plastic, acts as a spall shield and contains the residual energies of the broken face sheet and the projectile by absorption. More layers may be required if the threat level is higher.

The resulting design for any threat level will have to be qualified by ballistic test with the ammunition chosen for the threat level. Specifications MIL-G-5485C, "Glass, Laminated, Flat, Bullet-Resistant"; and MIL-A-46108A, "Armor: Transparent, Laminated Glass-Faced Plastic Composite" provide the parameters involved in armor design.

11.6   ELECTROMAGNETIC EXPOSURE

Electromagnetic exposure of an enclosure can come from two primary sources. The more probable source is from the discharge of electrostatically acquired potentials from charged particles in the air (dust, ice, etc.). The least probable source is that of a lightning strike. The phenomena of corona, streamering, and sparking are of most concern because of their visual display, possible injury to a crewman, and premature triggering of an ejection mechanism.

Frictional charges (triboelectric effects) are discussed in Chapter 6, section 6.4.4. Their discharges cause some of the electrical interference known as static.

The visual manifestations of corona and streamering are dependent upon the ionization of air and the potential which promotes it. Corona is a glow which accompanies the initial ionization of air without a complete breakdown of the air gap. A potential of approximately 275 volts is needed for this to occur. The phenomenon appears more readily at higher altitudes because of lower pressures. Potentials which are higher, but still less than the breakdown voltage for air (approximately 330 volts), tend to form a luminous tube which may spread out into a forklike pattern referred to as streamering. These two types of phenomena are referred to as field emissions.

Thermal emissions are more damaging and are referred to as sparks or arcs. Lightning strikes are essentially sparks of tremendous power and unpredictability. In considering a glazing as the struck part, the glass or plastic can be punctured if the strike is of sufficient magnitude to overcome the dielectric strength of the material through its thickness. Experimentation with simulated lightning strikes (Reference 46), which utilized a 1,400,000-volt spark, indicated that 1/8-inch polycarbonate sheet could not be penetrated. It is conceivable, however, that a transparency with an anti-icing conductive coating under a transparent protective coating covering of less than 1/8 inch could be penetrated, with a resulting burn-out of the coating. The spark, should it penetrate a glazing without a coating, may attach itself to an internal piece of operating electronic equipment, destroy insulation, and force an arc-over or self-sustained electrical path to any other conducting surface of different potential. These

11-24

arcs are highly ionized streams of hot gas which conduct the strike current nearly as well as metallic wire, and can be perpetuated by the potentials of damaged electrical equipment.

Because very strong electromagnetic fields are established in lightning, field emissions can be expected to also occur in the vicinity.

11.7   OPERATIONAL CONDITIONS

Other than the previously discussed environmental factors, aircraft glazings are often subject to concentrated agents which can destroy the optical integrity and possibly weaken the part rather rapidly.   Any repetitively applied fluids for cleaning, anti-icing, rain removal, etc. are required to be chemically inert to the glazing on which they are applied.

Unfortunately, many other fluids used in aircraft maintenance procedures are often in the vicinity of a glazing and may accidently contact it.   A repainting operation, as an example, can be expected to require the application of a paint remover as well as new paint to the framing adjacent to the glazing.   Although the glazing would be masked, the strong vapors from the solvents and possible penetration of fluid at the edge of the masking could be deleterious.   Because aircraft with both glass and plastic surfaced enclosures may be serviced at the same facility, the opportunity of accidently interchanging fluids which are safe to use on one and not the other also has to be considered.

Glass is essentially inert to any of the aircraft operational or maintenance fluids and can be excluded from the problem.   Plastics, however, are highly susceptible to certain fluids are are consequently tested to determine sensitivity.   The cantilevered craze test of FTMS 406 Method 6053 is the most accepted procedure, although variations in loading, fluids, and fluid application have been used to accumulate more data.   Tables 11.7-I through 11.7-IV show the extent of testing performed on various materials.

Figures 11.7-1 through 11.7-3 provide additional crazing data concerning the materials with unprotected surfaces.   Table 11.7-V shows the protection offered by a particular type of coating on polycarbonate.   In relation to other structural transparent plastics, poly-carbonate has the least solvent craze resistance.   Without protection, polycarbonate is sus-ceptible to attack from most fluids used in an aircraft proximity as shown in Tables 11.7-III, -IV, and -V.

TABLE 11.7-I - TIME TO CRAZE OF PLASTIC GLAZING MATERIALS IN CANTILEVER
STRESS-SOLVENT CRAZING TESTS AT ROOM TEMPERATURE

Solvent	Applied stress (PSI)	Time to craze for		
		MIL-P-5425	MIL-P-8184	MIL-P-8257
Isopropyl alcohol	1,000	30 min	6 hr, no crazing	
	2,000	15 min	50 min	
	3,000	3 min	17 min	
	4,000	Immediate	1 min	1 hr, no crazing
	5,000	do	Immediate	24 hr, no crazing
Toluene	1,000	3 min		
	2,000	1 min	3 to 23 hr	
	3,000	Immediate	63 min	
	4,000	do	48 min	
	5,000	do	1 min	24 hr, no crazing
Methyl ethyl ketone	1,000	do	4 hr, no crazing	
	2,000	do	1 min	
	3,000	do	Immediate	18 hr, no crazing
	4,000	do	do	18 hr, no crazing
	4,500			
	5,000	do	do	18 hr, no crazing
Acetone	500	5 min, no crazing		
	1,000	3 min	4 to 5 min	
	1,500	1 min		
	2,000	Immediate	2 min	
	12,000	Immediate	Immediate	37 min
Ethylene glycol	2,000	1 hr, no crazing		
	4,000	25 min		1 hr, no crazing
Propylene glycol	2,000	1 hr, no crazing		
	4,000	10 min		1 hr, no crazing

11-26

TABLE 11.7-I - TIME TO CRAZE OF PLASTIC GLAZING MATERIALS IN CANTILEVER STRESS-SOLVENT CRAZING TESTS AT ROOM TEMPERATURE (CONT)

Solvent	Applied stress (PSI)	Time to craze for		
		MIL-P-5425	MIL-P-8184	MIL-P-8257
Lacquer thinner	1,000	25 min	1 hr, no crazing	(No Data)
	2,000	1 min	32 min	
	3,000	Immediate	2 min	
	4,000	Immediate	Immediate	
Glass wax	2,000	4 hr, no crazing		
	5,000	7 min	5 hr, no crazing	(No Data)

TABLE 11.7-II - EFFECT OF STRETCHING ON THE STRESS-SOLVENT CRAZING PROPERTIES OF ACRYLICS IN LONG-TIME CANTILEVER TESTS*

Material	Degree of multiaxial stretch (percent)	Outer fiber stress to cause crazing in contact with			
		Isopropyl alcohol**		Lacquer thinner***	
		Unaged (10^3 PSI)	Aged**** (10^3 PSI)	Unaged (10^3 PSI)	Aged**** (10^3 PSI)
MIL-P-5425	0	14	9	11	6
	50	22	18	14	11
	75	35	23	29	15
	100	41	33	36	25
MIL-P-8184	0	21	16	19	17
	50	31	21	31	22
	75	42	31	44	26

*Tests conducted on cantilever beams stressed 10 minutes without solvent followed by 30 minutes with solvent. Distance from load to crazing was measured and the outer fiber stress to cause crazing was calculated.
**Specification MIL-F-5566
***Federal Specification TT-T-266a.
****Aged for six months outdoors in a temperate climate.

TABLE 11.7-III – RESULTS OF 30-MINUTE EXPOSURE TESTS ON POLYCARBONATE

Substance	Results
MIL-H-5606 hydraulic oil	No reaction
JP-4 jet fuel	No reaction
JP-5 jet fuel	No reaction
MIL-A-8243 deicing fluid	Thin white surface film and deep cracking
MIL-23699 lubricant	No reaction
TT-M-261 methyl ethyl ketone	White surface film and shallow cracking
TT-T-548 toluene	White surface film and shallow cracking
TTN-95 aliphatic naphtha	No reaction
Brush alodine (MIL-C-5541)	No reaction
020-038 polyurethane thinner	Translucent surface film and shallow cracking
MMS-401 solvent cleaner (aromatic petroleum naphtha, ethylacetate, methyl ethyl ketone, isopropanol)	Thin translucent surface film and immediate total fracture
Masking tape (Tuck Tape No. 123)	No reaction
Turco 5351 paint stripper	White surface film
Delchem 2236A acid stripper	White surface film
Turco 4377	Crazed white surface film
Turco 3878 and steam	No reaction
5 percent sodium chloride solution	No reaction

Note: Data supplied by McDonnell Douglas.

TABLE 11.7-IV - RESULTS OF 24-HR EXPOSURE TESTS ON POLYCARBONATE

Substance	Results
MIL-H-5606 hydraulic oil	No reaction
JP-4 jet fuel	No reaction
JP-5 jet fuel	No reaction
MIL-A-8243 deicing fluid	Thin transparent surface film and deep cracking
MIL-23699 lubricant	No reaction
TT-M-261 methyl ethyl ketone	White surface film and shallow cracking
TT-T-548 toluene	White surface film and shallow cracking
TFN-95 aliphatic naphtha	No reaction
Brush alodine (MIL-C-5541)	No reaction
020-038 polyurethane thinner	Thin translucent surface film and deep cracking
MMS-401 solvent cleaner (aromatic petroleum naphtha, ethylacetate, methyl ethyl ketone, isopropanol)	Thin translucent surface film and deep cracking
Masking tape (Tuck Tape No. 123)	No reaction
Turco 5351 paint stripper	Yellow pitted film
Delchem 2236A acid stripper	White pitted film
Turco 4377	Crazed yellow surface film
Turco 3878 and steam	No reaction
5 percent sodium chloride solution	No reaction

Note: Data supplied by McDonnell Douglas.
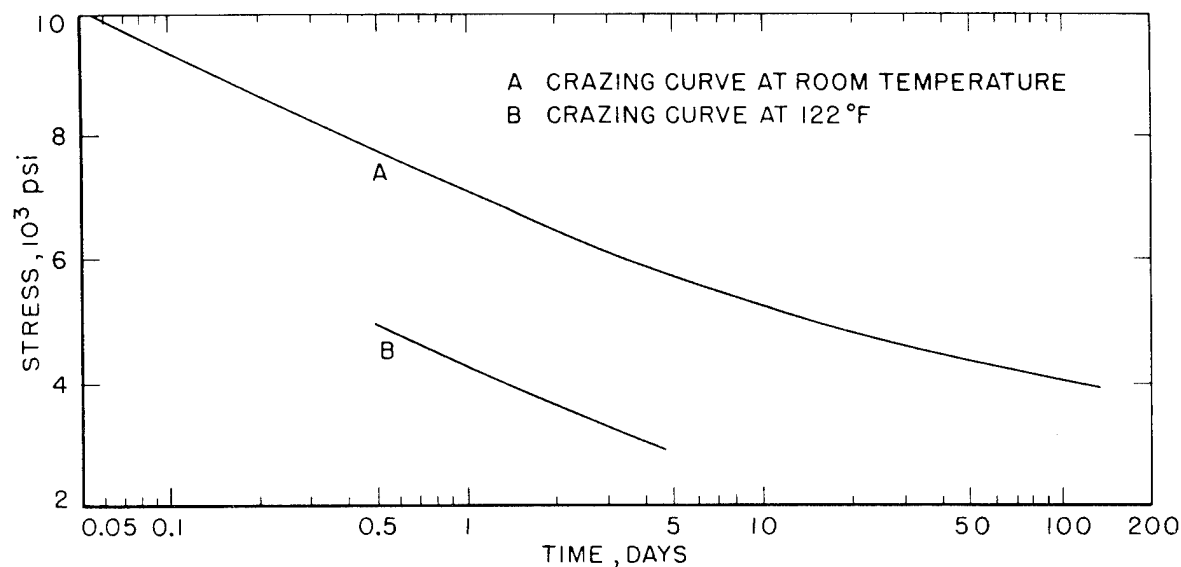
Figure 11. 7-1 - Effect of Duration of Loading on Stress-Crazing Behavior of MIL-P-8184
Material in Long-Time Cantilever Flexure Tests at Various Temperatures
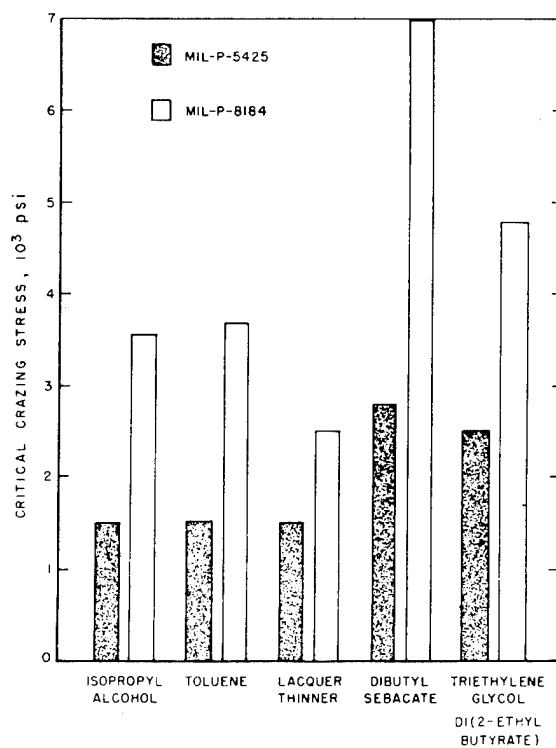
Figure 11. 7-2 - Stress-Solvent Crazing Behavior of MIL-P-5425 and MIL-P-8184
Materials with Various Solvents

11-30
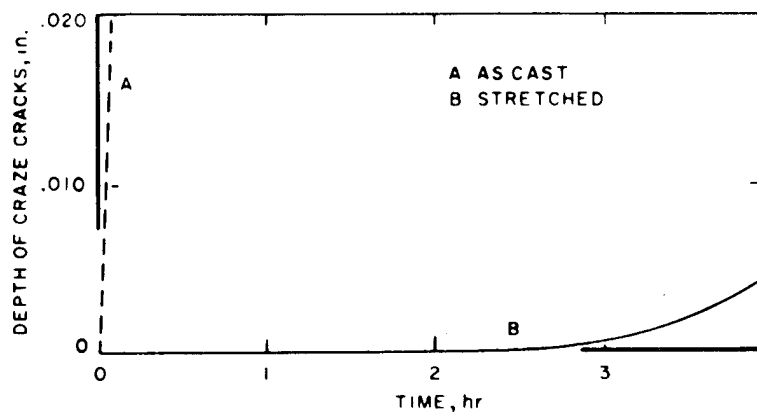
Figure 11.7-3 - Effect of Flexural Stress and Simultaneous Solvent Action on the Depth
of Craze Cracks in MIL-P-8184 Material (Applied Stress - 2,500 PSI;
Solvent - Lacquer Thinner)

TABLE 11.7-V - SUMMARY OF TESTS - STRESS-SOLVENT CRAZING OF
LEXAN POLYCARBONATE TYPE 9030-112

Solvent	Uncoated		Abcite coated	
	Threshold stress (PSI)	Time to craze (minutes)	Threshold stress (PSI)	Time to craze (minutes)
Isopropyl alcohol	4000	20	5000	1
Lacquer thinner	Any	On contact	Any	On contact
Kerosene	3000	60	5000	3
10-percent "Cinch"[a] in H_2O	5000	12	5000	20
JP-4 jet fuel	3000	60	4000	60
Hydraulic fluid MIL-H-5606	5000	20	5000	No craze
Skydrol 7000	2000	3	3000	8

[a]TM, Proctor and Gamble Co., Cincinnati, Ohio 45201.

The testing summarized in Table 11.7-V illustrates that the Abcite coating can provide some degree of chemical protection to the polycarbonate sheet. However, it will not provide complete protection, and for very penetrating solvents such as lacquer thinner, the protection is nil.

Dust and abrasion are particular problems of helicopter operations. Where temporary or permanent landing pads are not available, the downward vortices of the blades raise a considerable volume of dust which adheres to the glazing surfaces. Although windshield washers and wipers are available, experience has shown that their use on heavy dust concentrations act abrasively and destructively on plastic surfaces to the extent that panel replacement can become necessary. This is one reason abrasion resistant coatings have become of great importance.

Hand cleaning of the panels under field conditions cannot be expected to be accomplished with white-room care. Operational expediency and the probable unavailability of specially prepared cleaning materials in front line positions preempts detailed cleaning procedures and requires that the glazings be designed for a minimum of maintenance.

11.8   OPTICAL ENVIRONMENT[a]

The optical environment is that which has to be faithfully transmitted to the pilot and crew through the glazing with minimal light loss, deviation, and distortion. The protections against all of the previous environments may have to be minimized to provide a well-designed optical part.

Once the cross-sectional profile of a glazing has been established, it should be recognized that the transparent sheet stock prior to forming may not have perfectly parallel surfaces. The resulting prismatic bending of light rays causes a condition of deviation as shown in Figures 11.8-1 and 11.8-2.

---

[a]Photographs and drawings in this section taken from Reference 47 except where noted otherwise.
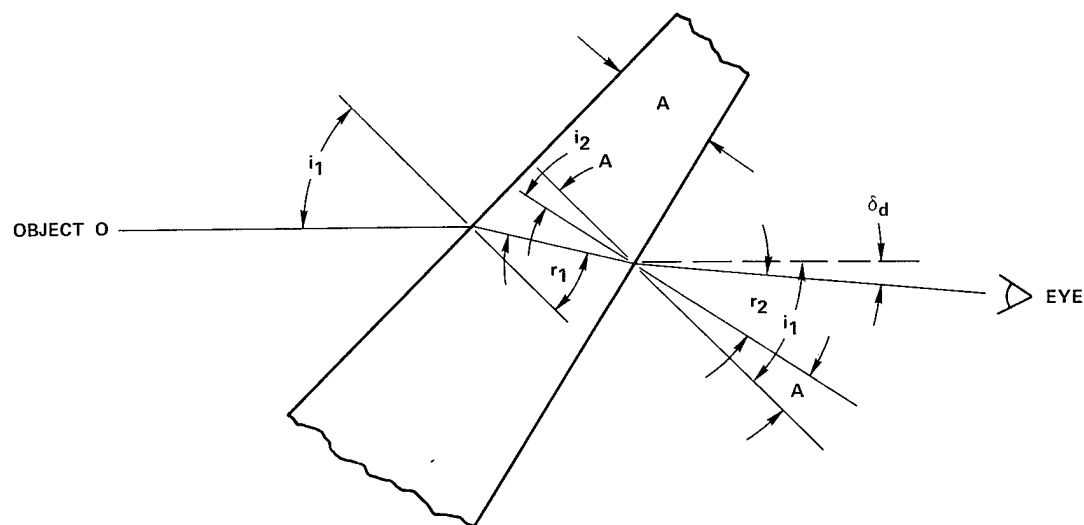
11-32

$$i_2 = r_1 - A$$
$$r_2 = SIN^{-1} N SIN (R_1 - A)$$
$$r_1 = SIN^{-1} \left(\frac{SIN\ i_1}{n} \right)$$
$$\delta_u = i_1 - A - r_2$$

i_1 = ANGLE OF INCIDENCE AT OUTBOARD SURFACE
i_2 = ANGLE OF INCIDENCE AT INBOARD SURFACE
r_1 = ANGLE OF RAY REFRACTED BY OUTBOARD SURFACE
r_2 = ANGLE OF RAY REFRACTED BY INBOARD SURFACE
δ_u = ANGLE OF DEVIATION OF THE RAY
A = WEDGE ANGLE
n = INDEX OF REFRACTION

4601-231

Figure 11.8-1 – Ray Trace through Panel (Wedge Apex up)
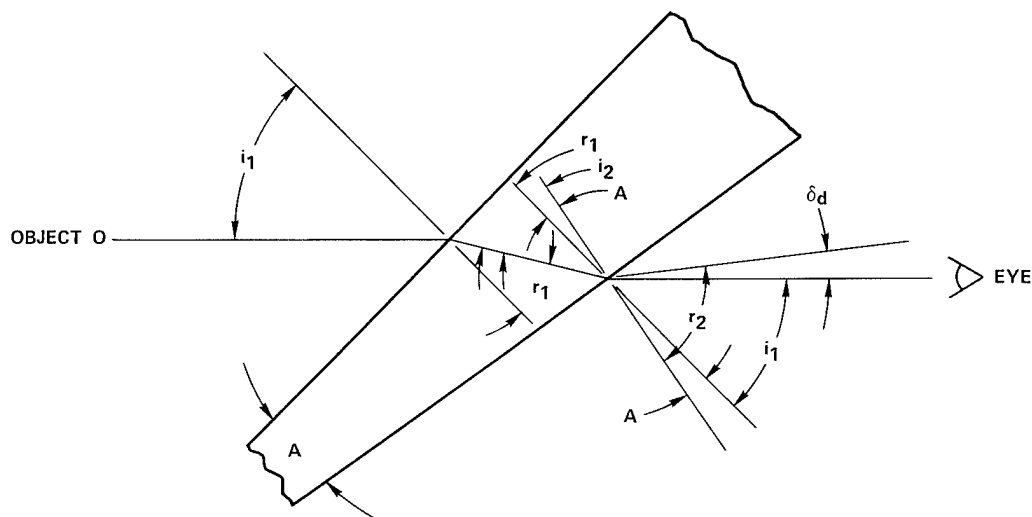
11-33

OBJECT O

EYE

i_1

r_1

i_2

A

r_1

δ_d

r_2

i_1

A

A

$$r_1 = SIN^{-1} \frac{SIN\ i_1}{n}$$
$$i_2 = r_1 + A$$
$$r_2 = SIN^{-1}\ N\ SIN\ (R_1 + A)$$
$$\delta_d = R_2 - A - i_1$$

i_1 = ANGLE OF INCIDENCE AT OUTBOARD SURFACE
i_2 = ANGLE OF INCIDENCE AT INBOARD SURFACE
r_1 = ANGLE OF RAY REFRACTED BY OUTBOARD SURFACE
r_2 = ANGLE OF RAY REFRACTED BY INBOARD SURFACE
δ_d = ANGLE OF DEVIATION OF THE RAY
A = WEDGE ANGLE
n = INDEX OF REFRACTION

4601-232

Figure 11.8-2 – Ray Trace through Panel (Wedge Apex down)

Deviation may be further magnified by a forming operation prior to fabrication. Figure 11.8-3 presents the calculations for the curved case.

After fabrication, a transparent panel may exhibit operational effects. Relatively thin panels mounted in frames which react to aerodynamic loading have been known to accentuate deviations through mechanical movement. Electrically heated coatings have been observed to cause deviations, when powered, because of stressing and changing of the index of refraction. Figure 11.8-4 demonstrates the latter phenomenon photographically.

The previously discussed deviations may all occur at a 0-degree angle of incidence. Considering that most glazing mountings are angular, Figure 11.8-5 graphically illustrates the changes in deviation and distortion that can be expected for a particular mounting angle which has been translated into the angle of incidence. Figures 11.8-6 and 11.8-7 show photographically the effect on deviation.

Distortion is defined as the incremental change in deviation. Figure 11.8-8 photographically shows the effect of a rapid change in deviation which identifies a "bullseye" distortion. Another form of distortion is shown as "orange peel." Orange peel is characterized by an uneven surface of small shallow depressions which are usually caused by mold contact during forming operations. These would produce wavy grid lines in a photograph. Some distortions from inclusions or bubbles are small and are allowable in certain areas with a size and number-per-square-foot limit placed by specification. Edge distortions can occur from strains caused by forming mold hold-downs during processing.

The criticality of deviation and distortion varies with the position of the glazing on the aircraft. Optical design considerations for these positions may be found in MIL-STD-850, "Aircrew Station Vision Requirements for Military Aircraft."

Light transmission and haze are functions of thicknesses as well as the quality of the material. Multiple layers of several materials with different indices of refraction usually result in more loss than the additive absorption values because of interface reflections. Measurement of light transmission and haze should be performed on a representative specimen of the designed cross-section in accordance with Method 3022 of FTMS 406.

11-35
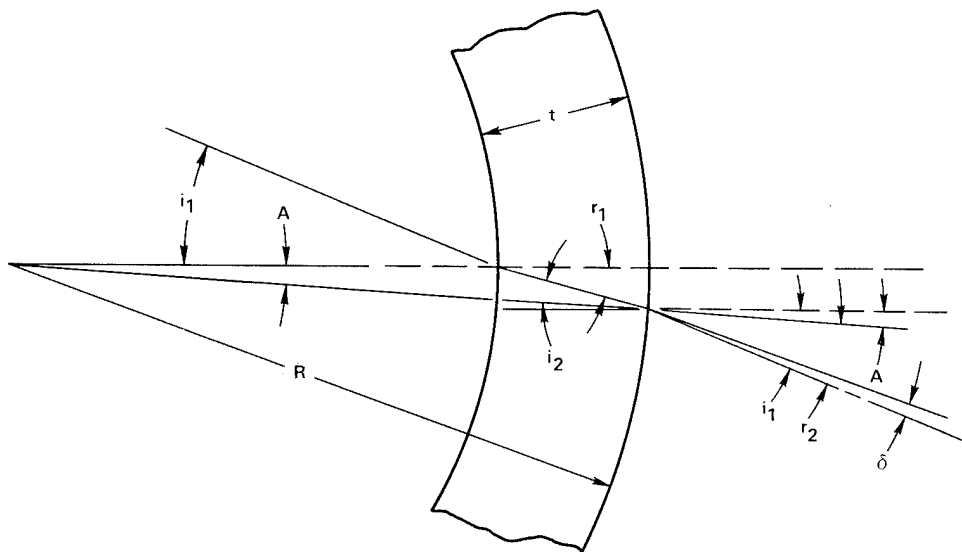
DEVIATION IN A CURVED WINDSHIELD VERSUS ANGLE OF INCIDENCE AND RATIO
OF THICKNESS TO OUTSIDE RADIUS.

$$SIN\ r_1 = \frac{SIN\ i_1}{n}\ ,\ r_1 = SIN^{-1}\ \frac{SIN\ i_1}{n}\quad A = \frac{t\ tan\ r_1}{R}$$

$$i_2 = r_1 - A = R_1 - \frac{t\ tan\ r_1}{R}\quad SIN\ r_2 = n\ SIN\ i_2$$

DEVIATION: $\qquad r_2 = SIN^{-1}\ n\ SIN\ i_2$

$$\delta = i_1 - A - R_2$$

$$\delta = i_1\ \frac{t\ tan\ r_1}{R} - SIN^{-1}\ n\ SIN\ i_2$$

$$\delta = i_1 - \frac{t}{R}\ tan\ r_1 - SIN^{-1}\ n\ SIN\ (r_1 - A)$$

n = INDEX OF REFRACTION

4601-233

Figure 11.8-3 – Ray Trace through Curved Windshield

11-36
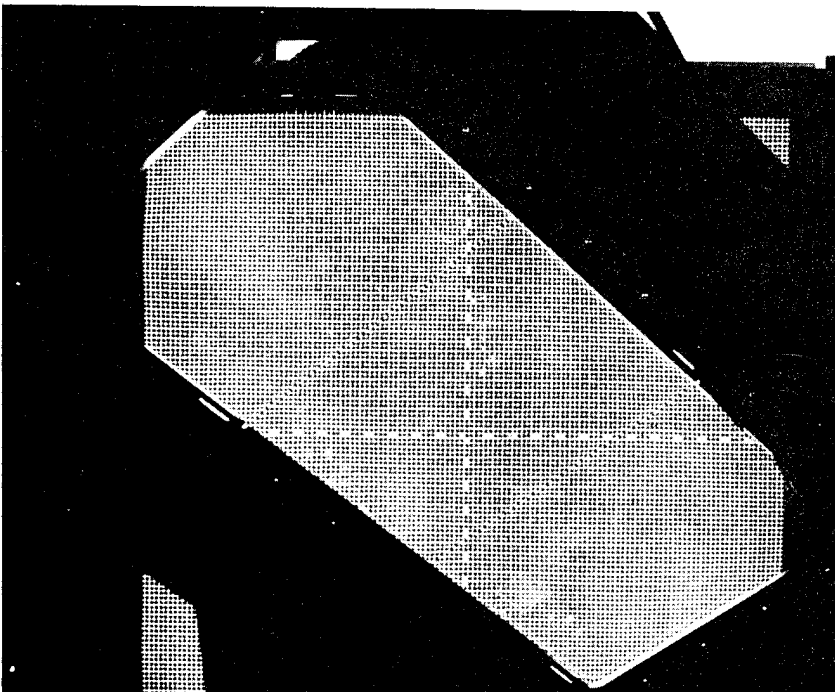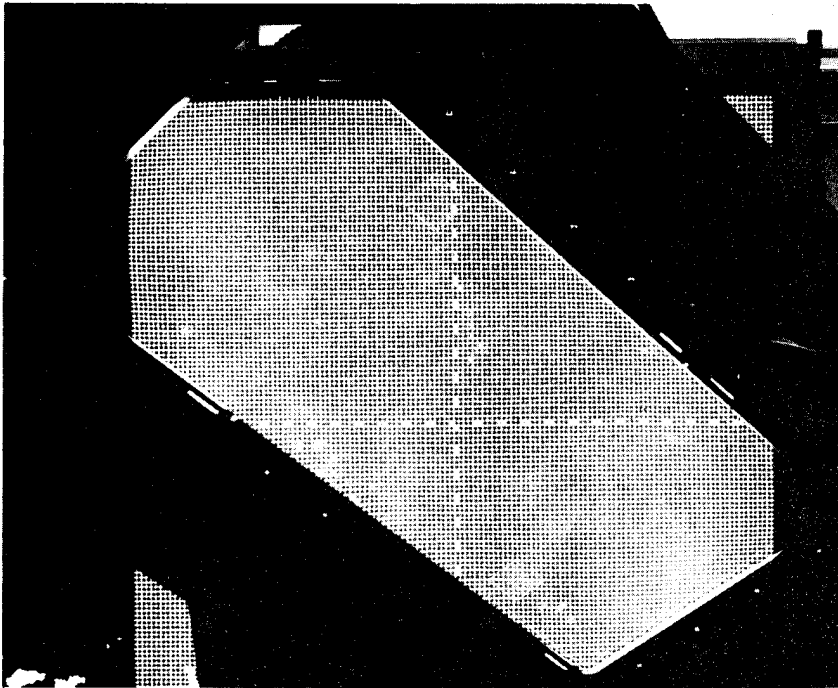
Figure 11.8-4 – The Optical Effects of Heating with Electrically Conductive Coatings
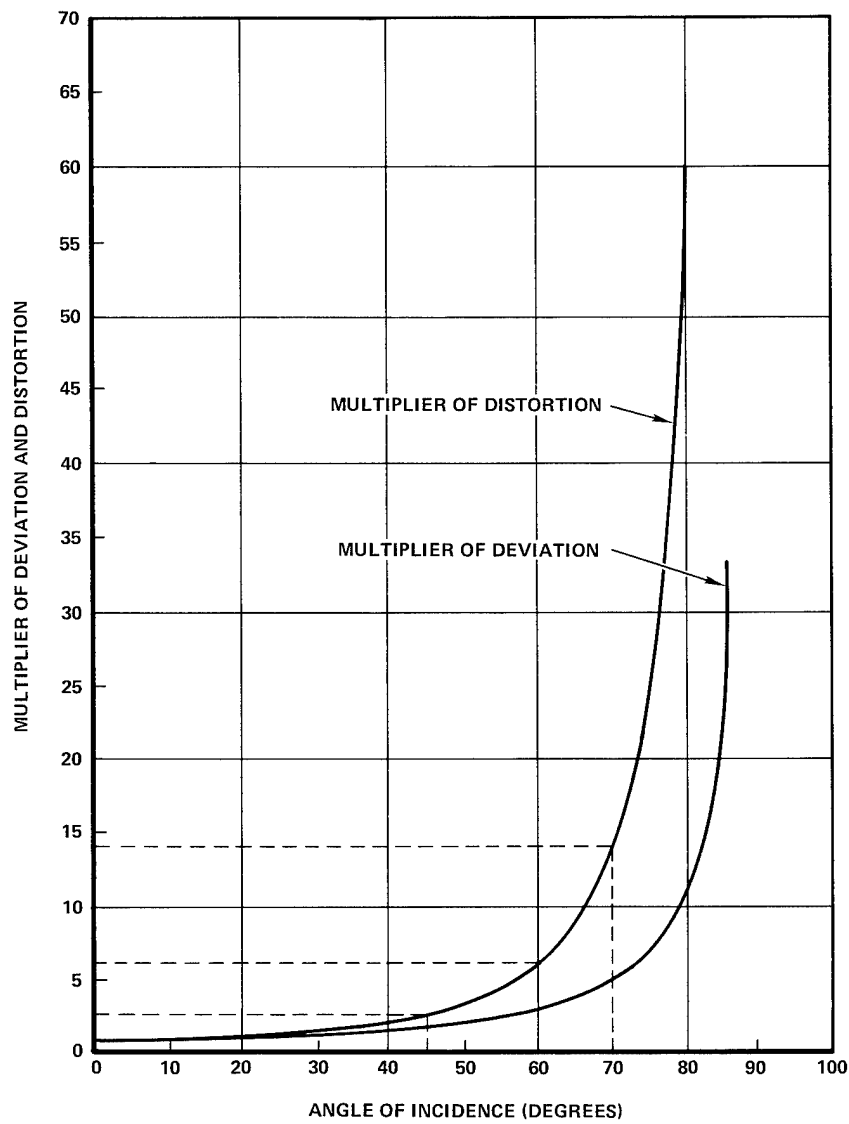
Figure 11.8-5 - Magnification of Deviation and Distortion versus Angle of Incidence
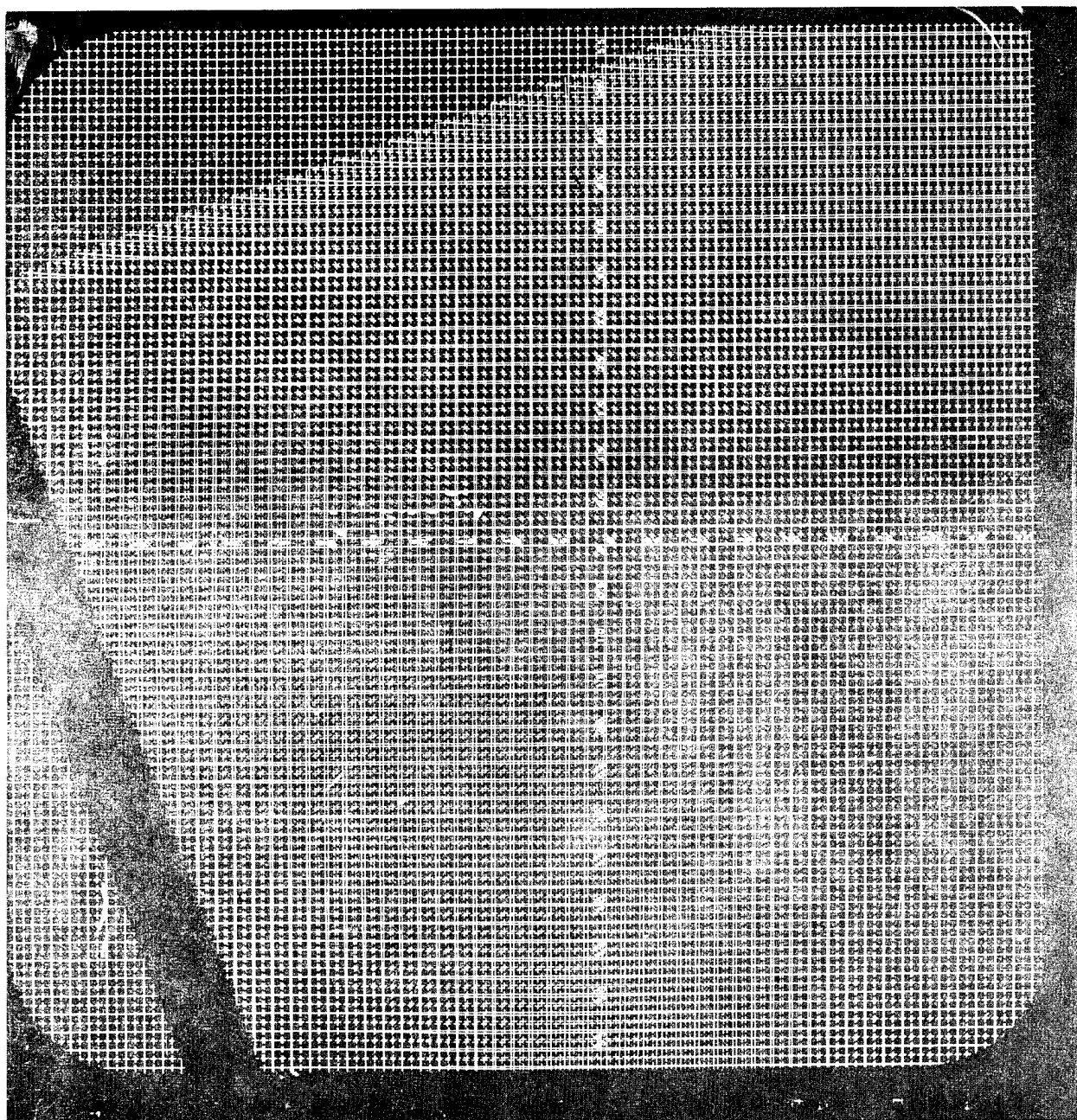
Figure 11. 8-6 – Double-Exposure Photograph (Deviation and Distortion Acceptable)
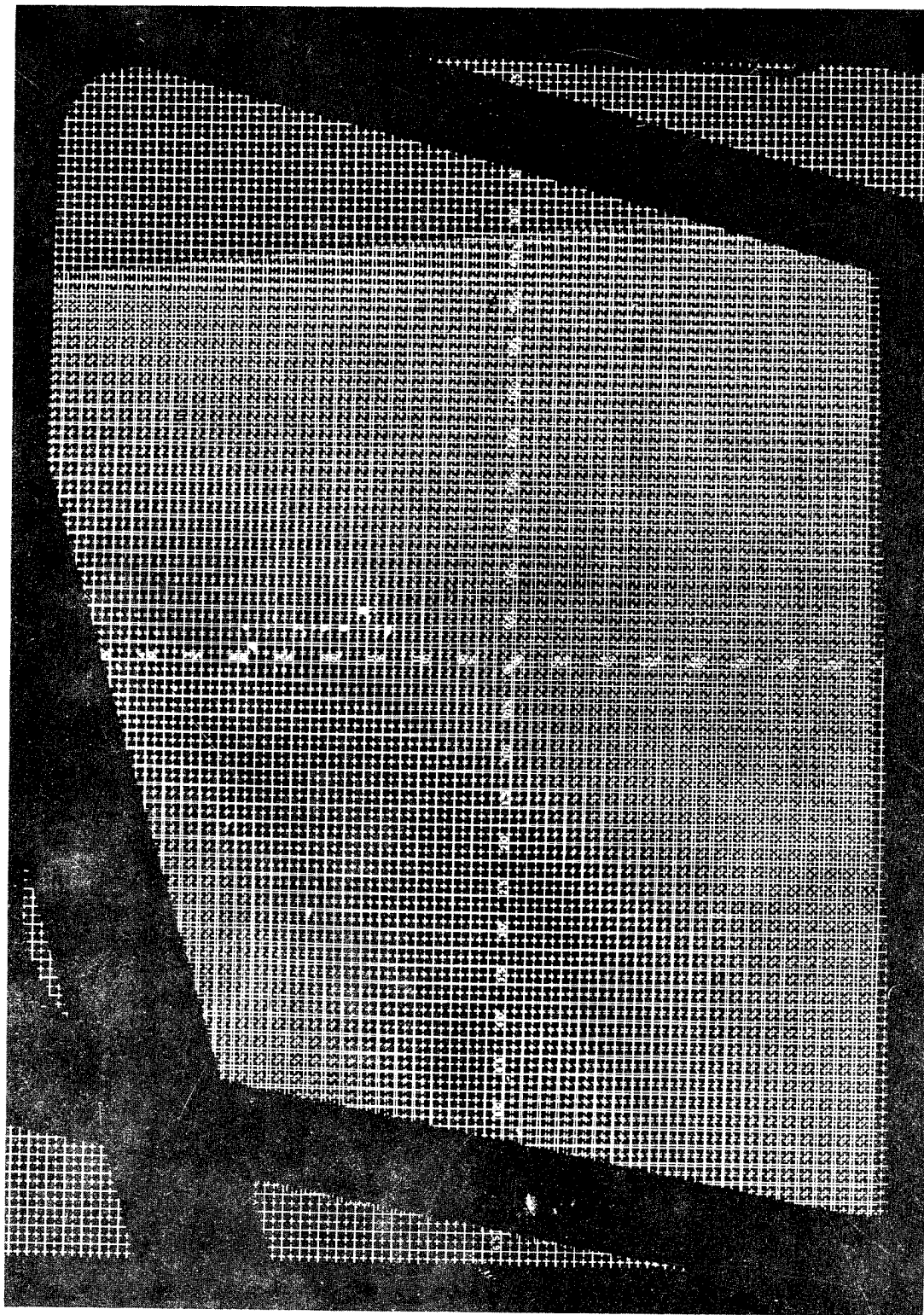
Figure 11.8-7 - Double-Exposure Photograph (Installed Angle Shows Accentuated Deviation)

11-40
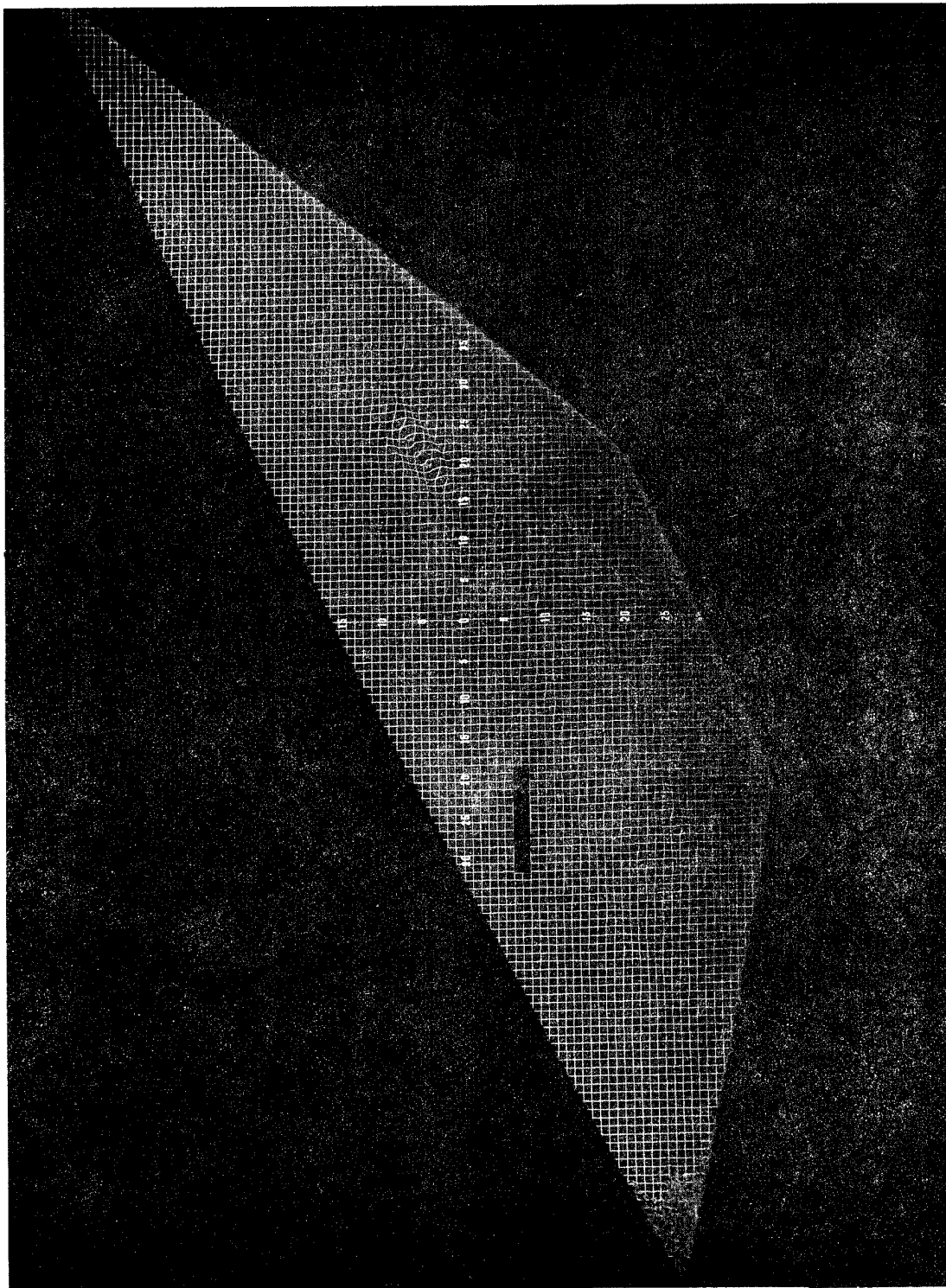
Figure 11.8-8 - Severe Distortion at Low Viewing Angle

Methods of optical testing for deviation and distortion are contained in specifications MIL-G-5485C, MIL-G-25667A (ASG), and MIL-G-25871A (ASG). These describe measurements by the projected line or concentric target methods. Both methods are of low precision and have been largely superceded by photographic methods which provide a permanent record of the inspection. Reference 47 provides a survey of optical test methods.

Should the optical area of complex panel not meet the requirements of optical deviation and distortion in its installed position, it may be necessary to have the sheet stock ground and polished prior to forming or addition of an edge attachment. The processing is expensive, but not impossible. Grinding of both sides provides parallelism, and polishing adds the necessary gloss finish.

BIBLIOGRAPHY

1. Modern Plastics Encyclopedia, Vol. 48, No. 10A. McGraw-Hill Publishing Co., New York, New York (1971-1972).

2. Hall, H. W., and Russell, E. W., "Polymethyl Methacrylate (Perspex Type) Plastics; Crazing, Thermal, and Mechanical Properties," Report No. Chem. 454, British R.A.E. (Farnborough) (October 1949).

3. Russell, E. W., "Crazing of Cast Polymethyl Methacrylate," Nature (London) 165, No. 4186, 91 (January 21, 1950); also available as Report No. Chem. 447, British R.A.E. (Farnborough) (August 1948).

4. Kies, J. A., and Smith, H. L., "Aircraft Glazing Materials. Resistance to Crack Propagation," Naval Research Laboratory Memorandum Report 372 (1954).

5. Kies, J. A., and Smith, H. L., "Toughness Testing of Hot Stretched Acrylics," Materials Laboratory, Directorate of Research, Wright Air Development Center, Air Research and Development Command, Summary of Joint AIA-WADC Transparent Materials Conference, Dayton, Ohio (March 1955).

6. Smith, H. L., and Kies, J. A., "Engineering Applicability of Toughness Values," in "Transparent Materials for Aircraft Enclosures, WADC-University of Dayton Joint Conference," by R. E. Wittman, Wright Air Development Center Technical Report 57-421, pp 7-19 (October 1957).

7. Hassard, R. S., "Design Criteria - Transparent Polycarbonate Plastics Sheet," AFML Technical Report 72-117 (August 1972).

8. Bartoe, W. F., and Robertson, E. N., "Laminated Plexiglas in Aircraft," Aero Digest 56, 42 (May); 68 (July 1948).

9. Matimoe, P. T., "Properties of Laminated Safety Glass Made With Silicone Interlayers," in "Transparent Materials for Aircraft Enclosures, WADC-University of Dayton Joint Conference," by R. E. Wittman, Wright Air Development Center Technical Report 57-421, pp 105-127 (October 1957).

10. Folk, J. L., and Iler, K. R., "Evaluation of Materials for Gunsighting Domes," Wright Air Development Center Technical Report 54-128, Part I (1954).

BIBLIOGRAPHY (CONT)

11. Chen, P., Giacoppe, S., Halpern, B. D., Karo, W., Levine, P., and Tibery, C. L., "Interlayer Material Development," Wright Air Development Center Technical Report 55-217 (January 1956).

12. The Sierracin Corporation, Burbank, California, "Sierracote 3 Engineering Handbook" (December 1957).

13. Mann, M. J., Lt. USAF, "Radar Reflection of Transparent Materials," pp 38-48 from Wittman, R. E., "Transparent Materials for Aerospace Enclosures" AFML-TR-65-212 (September 1965).

14. Maxwell, H., "Development of a Structural Organic Bonded Edge Attachment for Inner Panels of Double Glazed Windshield and Canopy Units." North American Rockwell, Los Angeles, California, NA-60-352 (March 1960).

15. Mochel, Ellen L., "Strong Glass," from "Transparent Materials for Aerospace Enclosures" by Robert E. Wittman, AFML Technical Report 65-212 (September 1965).

16. Kerper, M. J., Diller, C. C., and Eimer, E. H., "Properties of Glasses at Elevated Temperatures," WADC Technical Report 56-645 Part II (1957).

17. Brown, F. G. J., and Ellis, J., "The Strength of Annealed and Heat Treated Glass," Reports and Memoranda No. 3003, Aeronautical Research Council, Her Majesty's Stationary Office, London (1957).

18. Black, L. V., "Effect of the Rate of Loading on the Breaking Strength of Glass," Bull. Amer. Ceram. Soc., Vol. 15, pp 274-275 (1936).

19. Holland, A. J. and Turner, W. E. S., "The Effect of Sustained Loading on the Breaking Strength of Sheet Glass," J. Soc. Glass Tech., Vol. 24, pp 46-57 (1940).

20. Howard, R. N., "The Behavior of Glass Under Impact and Static Loading," J. Soc. Glass Tech., Vol. 28, p 5 (1944).

21. Kerper, M. J., Diller, C. C., and Eimer, E. H., "Properties of Glass at Elevated Temperatures," WADC Technical Report 56-645 Part III (1958).

22. Pittsburgh Plate Glass Co., "Herculite Fabrication," Technical Glass, Bulletin No. 13 (1948).

BIBLIOGRAPHY (CONT)

23. Baker, T. C., and Preston, F. W., "Effect of Water on the Strength of Glass," J. of Applied Physics, Vol. 17, p 179 (1946).

24. Holland, A. J. and Turner, W. E. S. "Breaking Strength of Glass—Effect of Flaws and Scratches," J. Soc. Glass Tech. Trans., Vol. 20, p 72 (1936).

25. Libbey-Owens-Ford Glass Co., "Aircraft Glass," Technical Manual (1956).

26. Shand, E. B., "Glass Engineering Handbook," Corning Glass Works, Corning, N. Y. (1955).

27. Shoemaker, A. F., Quarterly Report No. 1. "High Temperature Aircraft Windshield Development Program." Corning Glass Works (1958).

28. Lucks, C. F., Matolich, J., and Van Velzor, J. A., "The Experimental Measurement of Thermal Conductivities, Specific Heats, and Densities of Metallic, Transparent, and Protective Materials," AF Technical Report 6145, Part II and Part II (1952 and 1954).

29. Gardon, Robert, "The Emissivity of Transparent Materials," J. Amer. Ceram. Soc., Vol. 39, p 278 (1956).

30. Hahner, C. H. and Kerper, M. J., "Inorganic Transparencies for Aircraft Enclosures," Report 161, North Atlantic Treaty Organization Advisory Group for Aeronautical Research and Development (1957).

31. Corning Glass Works, "Properties of Selected Commercial Glasses," (1957).

32. Horowitz, David, "Determination of Thermal Shock Characteristics of Glass," WADC Technical Report 55-24 (1955).

33. Erickson, W. S., "Deflection and Distribution of Stresses in the Facings of a Centrally Loaded Transparent Sandwich Beam," Wright Air Development Center Technical Report 52-185, Supplement I (1952).

34. Shand, E. B., "Glass Engineering Handbook," Corning Glass Works, Corning, N. Y. (1955).

35. Pittsburgh Plate Glass Co., "Strength of Plate and Laminated Glass," Bulletin No. 6 (1941).

BIBLIOGRAPHY (CONT)

36. Libbey-Owens-Ford Glass Co., "Aircraft Glass," Technical Manual (1956).

37. Islinger, J. S., "Engineering Design Factors for Laminated Aircraft Windshields," WADC Technical Report 53-99 (1954).

38. Mattimoe, P. T., "Properties of Laminated Safety Glass Made With Interlayers," WADC-University of Dayton Joint Conference (1956).

39. Foster, L. E.; Johnson, R. G., "Bird Impact Tests of the Model 188 Forward Windshield," Lockheed-California Co., Burbank, California, LR 11859 (March 1958).

40. Reinert, R. P. "S-3A Flight Station Fatigue, Fail Safe and Windshield Bird Impact Test Results," Lockheed-California Co., Burbank, California, LR 25118 (March 1972).

41. GERA-1861: "Test Procedure for the Response of Transparent Aircraft Windshield Materials to Bird Impact." Goodyear Aerospace Corporation, Litchfield Park, Arizona (October 1972).

42. Civil Aeronautics Administration, Technical Development and Evaluation Center, Indianapolis, Indiana, "Development of Aircraft Windshields to Resist Impact with Birds in Flight"—Part II, "Investigation of Windshield Materials and Methods of Windshield Mounting," Technical Development Report No. 74—Part III, "Impact Characteristics of Aircraft Windshield Incorporating Polyvinyl Butyral Plastics Interlayer," Technical Development Report No. 105.

43. Shorr, N.; Littell, H. E., Jr., "Ancillary Properties of Transparent Armor" (U), Final Report, Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania. AMMRC-CR 69-03(F) (March 1969) (Restricted Distribution).

44. Shorr, N.; Littell, H. E., Jr., "Transparent Armor (Glass-Plastic Composite)" (U), Final Report, Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania, AMMRC-CR 69-06(F) (May 1969) (Restricted Distribution).

45. Littell, H. E., Jr., "Transparent Armor Shields" (U), Final Report, Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania, AMMRC-CR 71-12 (August 1971) (Restricted Distribution).

BIBLIOGRAPHY (CONT)

46. Aston, R; Gorton, R; Weinstock, G. L., "Lightning Protection Techniques for Large Canopies on High-Speed Aircraft," McDonnell Douglas Corporation, St. Louis, Missouri, AFAL-TR-72-49 (February 1972) (Restricted Distribution).

47. Holloway, R. A., "Survey of Optical Test Procedures for Aircraft Transparencies," Lockheed-California Co., Burbank, California, LR 23771 (September 1970).

48. Murray, William D., Slote, Lawrence, "Determining Skin Friction Temperature," Missile Science, pp 33-36, 38, 42 (June 1954).

49. Starkweather, H. W., Jr; Adicoff, A; Eirich, F. R., "Heat Resistant Allyl Resins," Institite of Polymer Research, Polytechnic Institute of Brooklyn, Brooklyn, N. Y. (October 1954).

50. Von Hippel, A., Molecular Science and Molecular Engineering, Technology Press, MIT (1959).

51. Maxwell, H. G., "Development of Ceramic Bonded Windshield Edge Attachments for Model XB70 Airplane," North American-Rockwell, Los Angeles, California, NA-62-47 (January 1962).

52. GER-10680: Evaluation of High-Temperature Cast-in-Place Transparent Plastic Laminates Suitable for Canopies on Supersonic Fighter Aircraft," Goodyear Aerospace Corporation, Akron, Ohio (May 1962).

53. Christopher, W. F.; Fox, D. W., Polycarbonates, Reinhold Publishing Corporation, New York, New York (1962).

54. Schnell, Herman, Chemistry and Physics of Polycarbonates, J. Wiley and Sons, New York, New York (June 1964).

55. Chinn, J. L.; Ewbank, N. M., Jr.; Gigas, G., "Charged Particle Radiation Effects on Selected Transparent Materials for Aerospace Enclosures," Atomics International, Canoga Park, California. From Wittman, R. E., AFML-TR-65-212.

56. Wittman, R. E., "Transparent Materials for Aerospace Enclosures" AFML-TR-65-212 (September 1965).

BIBLIOGRAPHY (CONT)

57. Stachiw, J. D.; Gray, K. O., "Windows for External or Internal Hydrostatic Pressure Vessels," Part I, "Conical Acrylic Windows under Short-Term Pressure Application," NCEL-R512 (January 1967).

58. Stachiw, J. D.; Dunn, G. M.; Gray, K. O., "Windows for External or Internal Hydrostatic Pressure Vessels," Part II, "Flat Acrylic Windows under Short-Term Pressure Application," NCEL-R527 (May 1967).

59. Shumaker, R. E.; Lair, R. C., "F-111 Canopy Laminated Acrylic Composite and Edge Member Design and Development Sample Test Program," Goodyear Aerospace Corporation, Akron, Ohio, GER-13430 (August 1967).

60. Lair, R. C., "Stress Distribution in Glass-Acrylic Composites," Goodyear Aerospace Corporation, Akron, Ohio, GER-13024 (December 1967).

61. "A Comparative Evaluation of Several Cast-in-Place Interlayer Systems Useful in Windshield Transparencies," Goodyear Aerospace Corporation, Akron, Ohio, GER-13673, Rev. A (January 1968).

62. Mayer, Robert H., "Temporary Increase in the Creep Rate of Polycarbonate During Irradiation," Massachusetts Institute of Technology, Class No. 6K (April 1969).

63. Cully, D. C.; Locke, J. D., "Criteria for Toughness ("K" Factor) Requirement of Transparent Materials," Goodyear Aerospace Corporation, Litchfield Park, Arizona (June 1969).

64. Montgomery, R. L.; Gaiser, C. J., "Sierracin (R) 311 Transparent Protective Coating for Plastics," The Sierracin Corporation, Sylmar, California (June 1969).

65. Stachiw, J. D.; Brier, F. W., "Windows for External or Internal Hydrostatic Pressure Vessels," Part III, "Critical Pressure of Acrylic Spherical Shell Windows under Short-Term Pressure Applications," NCEL-R631 (June 1969).

66. Wiser, George L., "Sierracin (R) Glass-Plastic Composite Windshields," The Sierracin Corporation, Sylmar, California (June 1969).

67. Voss, David L., "Polycarbonate for Advanced Aircraft Transparencies," McDonnell Aircraft Company, St. Louis, Missouri, MDC 69-013 (June 1969).

BIBLIOGRAPHY (CONT)

68. Wahl, Norman E., "Supersonic Rain and Sand Erosion Research," Part I, Tektron's Bell Aerosystems Company, Buffalo, N. Y., AFML-TR-60-287 (September 1969) (Restricted Distribution).

69. Stachiw, J. D., "Windows for External or Internal Hydrostatic Pressure Vessels," Part IV, "Conical Acrylic Windows under Long-Term Pressure Application at 20,000 PSI," NCEL-R645 (October 1969).

70. Bauer, R. G.; Pierson, R. M.; Mast, W. C.; Bletso, N. C.; Shepherd, L., "New Transparent Impact-Resistant Polymer Blends from Resins and Rubbers Having Minimized Compositional Heterogeneities," The Goodyear Tire & Rubber Co., Research Division, Akron, Ohio, "Advances in Chemistry Series," Number 99, pp 251-259, Report 17 (January 1970).

71. Process Bulletin, "Photographic Inspection of Transparent Glazing," Lockheed-California Co., Burbank, California, C-52-I(1) (January 1970).

72. 11TR1 Staff Report, "How to Make Glass Stronger," Ceramic Industry Magazine, pp 83-84 (April 1970).

73. Ball, G. L., III; Wojtowicz, A.; Salyer, I. O., "Evaluation of Improved Transparent Materials and Adhesives for Ballistic and Impact Shields," Monsanto Research Corporation, AFML-TR-70-167 (June 1970).

74. Lockheed-California Company, Issue 22, "Orion Service Digest," (September 1970).

75. Product Specification, "Special LEXAN (R) Sheet No. SL-2000-111," General Electric Company (December 1970).

76. Stachiw, J. D.; Moody, W. A, "Windows for External or Internal Hydrostatic Pressure Vessels," Part V, "Conical Acrylic Windows under Long-Term Pressure Application of 10,000 PSI," NCEL-R708 (January 1971).

77. DeBeneditto, A. T.; Trachte, K. L., "The Brittle Fracture of Amorphous Thermoplastic Polymers," Monsanto Research Corporation, ONR-HPC70-109 (April 1971).

78. Grimm, Nelson, "See-Through Ceramics," General Electric Co., Industrial Research, pp 40-43 (May 1971).

79. Ball, G. L., III; Wilken, P. H.; North, C. J.; Salyer, I. O., "A Thermoplastic Transparent Adhesive for Bonding Polycarbonate to Glass," Monsanto Research Corporation, AMMRC-CR-71-10 (July 1971).

BIBLIOGRAPHY (CONT)

80. Stachiw, J. D., "Failure Modes of Spherical Acrylic Shells under External Hydrostatic Loading," International Association for Shell Structures Paper No. 4-1 (October 1971).

81. Zimmerman, R. L., "Engineer's Guide to ABS Plastics," Materials Engineering (October 1971).

82. McLoughlin, F. M., "Windshield Bird Impact Development Tests (CM-9)," North American Rockwell, Los Angeles, California, Structural Test Summary Report T.A. 290-0040 (November 1971).

83. Stachiw, J. D.; Gray, K. O., "Windows for External or Internal Hydrostatic Pressure Vessels," Part VI, "Conical Acrylic Windows under Long-Term Pressure Application at 5000 PSI," NCEL-R747 (November 1971).

84. Verbeck, J. W., Jr.; Paseck, R. A., "B-1 Windshield Acrylic Thermal Conductivity for Anti-Icing Analysis," North American-Rockwell, Los Angeles, California, NA-71-1076 (November 1971).

85. Keig, G. A. and Watts, J. M. J., "Development of a Process for the Growth of Large Sheets of Single Crystal Aluminum Oxide," AMMRC-CR 71-23 (December 1971).

86. "S-3A Escape System Qualification," Lockheed-California Co., Burbank, California, LR24887 (February 1972).

87. Miller, Phillip A., "Anti-Icing Aspects of Helicopter Windshield Design," The Sierracin Corporation, Sylmar, California (May 1972).

88. Ball, G. L., III; Salyer, I. O.; North, C. J.; Wilken, P. H., "Engineering Data on Ethylene Terpolymer as an Adhesive for Polycarbonate Composite Aircraft Transparencies," Monsanto Research Corporation, AFML-TR-72-109 (July 1972).

89. Maltenieks, O. J., "Improved Rain Repellent Coatings for Aircraft Windshields, Canopies, and other Non-Metallic Components," Lockheed-Georgia Company, AFML-TR-70-199 (August 1972).

90. Stachiw, J. D., "Effect of Bubble Inclusions on the Mechanical Properties of Cast Polymethyl Methacrylate," Naval Undersea Center, NUC TP 305 (August 1972).

BIBLIOGRAPHY (CONT)

91. Stachiw, J. D.; McKay, J. R., "Windows for External or Internal Hydrostatic Pressure Vessels," Part VII, "Effect of Temperature and Flange Configurations on Critical Pressure of 90 Degree Conical Acrylic under Short-Term Loading," NCEL-R773 (August 1972).

92. Stachiw, J. D., "Transparent Materials in the Sea," Naval Undersea Research and Development Center, NUC-TN732 (October 1972).

93. Ernsberger, F. M., "Fundamentals Relating to the Use of Load Bearing Glass Transparencies in Aircraft," Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania, Report No. 2.

94. Gillery, F. H., "Nesatron (R) Glass—A New Material for Aircraft Transparencies," Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania, Report No. 4.

95. Mazza, J. S.; Shorr, N.; Yelle, M., "Helicopter and Other VTOL Transparencies," Pittsburgh Plate Glass Industries, Pittsburgh, Pennsylvania, Report No. 5.

96. James, H. C.; Ingelse, A. O.; Huyett, R., "Design Test and Acceptance Criteria for Army Helicopter Transparent Structures," Final Report, Goodyear Aerospace Corporation, Litchfield Park, Arizona, GERA-1864 (November 1972).

97. Borg-Warner, Marbon Division, Washington, West Virginia, "Clear Cycolac (R), Grade CIT," Technical Report P-168.

98. Eastman Chemical Products, Inc., Kingsport, Tennessee, "TENITE (R) Polyterephthlate 7DR0."

99. Goodyear Aerospace Corporation, Litchfield Park, Arizona, "Stretched Acrylic Plastic."

100. Minnesota Mining and Manufacturing Co. Chemical Division, St. Paul, Minnesota, "ASTREL (R) 360 Plastic."

101. Optical Coating Laboratory, Incorporated, Santa Rosa, California, "Multilayer Antireflection Coatings."

102. Rohm and Haas Company, Philadelphia, Pennsylvania, "Plexiglas Technical Handbook."

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

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

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Goodyear Aerospace Corporation Litchfield Park, Arizona	Unclassified
	2b. GROUP N/A

3. REPORT TITLE

PLASTICS FOR FLIGHT VEHICLES
　　　　PART II
TRANSPARENT GLAZING MATERIALS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
MIL-HDBK-17A, January 1973

5. AUTHOR(S) *(First name, middle initial, last name)*

Richard S. Hassard

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1973	382	101

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
F33615-71-C-1465	
b. PROJECT NO. 7381	GERA-1863
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for Public Release, Distribution Unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Revision of MIL-HDBK-17, Part II 14 August 1961	Air Force Materials Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

The information in this handbook includes and augments the contents of the previous revision by expanding the data to embrace the more recent material innovations and design complexities. The format treats the facets of transparent enclosure design in a sequence which starts with material properties and logically progresses to the ultimate composites complete with edge attachments. Explanations are interspersed which provide an understanding of various, and possibly unfamiliar, technical disciplines which have become more apparent as the sophistication of aircraft design and mission increases.

DD FORM 1473
1 NOV 65

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Enclosures, Aircraft Transparent						
Glazing Materials, Transparent						
Glass, Monolithic, Transparent						
Plastic, Monolithic, Transparent						
Glass, Laminated, Clear						
Plastic, Laminated, Clear						
Composites, Laminated, Clear						
Interlayers, Transparent						
Coatings, Transparent						
Edge Attachments, Aircraft Enclosure						