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~~Phase III Proposal~~

(6) Supersonic Transport Development Program

Phase III Proposal.

BOEING MODEL 2707.

Volume II-8.

AIRFRAME DESIGN REPORT.

PART D.

MATERIALS AND PROCESSES.

(14) V2-B2707-8

September 6, 1966

(11) 6 Sep 66

(12) 225p.

PREPARED BY M. C. Kristel APPROVED BY H. Hemming

(15) Contract FA-SS-66-5

Prepared for

FEDERAL AVIATION AGENCY

Office of Supersonic Transport Development Program

402 097

THE BOEING COMPANY
SUPERSONIC TRANSPORT DIVISION

FAA

A 105

ISSUE NO. 4

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CONTENTS

1.0 INTRODUCTION

The Airframe Design Report is one of a series of documents under Volume II, Technical/Airplane, called for by The FAA Request for Proposal for Phase III of the Supersonic Transport Development Program. The Airframe Design Report is bound into five documents; V2-B2707-6-1, V2-B2707-6-2, V2-B2707-7, V2-B2707-8, and V2-B2707-9. These documents cover weight and balance, component design, design criteria, loads, aeroheat, flutter, materials and processes, and structural test. This document is in response to Section V, Paragraph C-3.

The materials and processes for the B-2707 have been evaluated by tests that reflect the new operational environment (defined in D6A10107-1) and incorporate improvements developed for subsonic airplanes. The materials and processes were selected by the application of experience and theoretical knowledge to the interpretation of test results.

This document describes the materials and processes for the particular applications and the reasons for selection together with supporting data. Details of much of the development work leading to final selection of materials and processes are reported in the bimonthly progress reports D6-18110 and are not repeated in this document. Particular emphasis is placed on new materials and requirements. Those material applications with long history of satisfactory use on commercial and military airplanes are identified, but are not discussed in detail. Discussion of materials is divided into three sections — metals, nonmetals, and standard parts. Those areas in which these technologies interface are treated in that section which is most applicable and are referenced in other appropriate sections. For example, lubricants for bearings and bushings are treated in the nonmetals lubricants section to which the reader is directed by reference in the bearings section.

Material and process information is generated by qualified and experienced materials engineers to meet specific design and service requirements. Continuing materials research assures advancements in airplane technology. All information is documented and made available to Engineering, Manufacturing, and Quality Control Departments primarily through the Boeing Corporate Document System which will be implemented for the B-2707 in accordance with the Standardization Program Document V4-B2707-19. This system ensures that positive control is exercised in materials technology during initial design concepts, design development, production, and field service. It further assures that changes to materials, processes, or standard parts are made only with the knowledge and concurrence of qualified materials specialists. The control exercised by the specifications system is extended to include Boeing subcontractors through the Materiel branch of the Operations Department. A list of Military Specifications and Handbooks applicable to this document, is included in Section 5.0.

Materials selected for the B-2707 range from relatively new materials to those used for many years in military and commercial airplanes. A summary of those materials of primary interest and their general applications are shown in Tables 1-A and 1-B.

The materials were selected on the basis of experience, research and development by Boeing, and in cooperation with the research facilities of the material producers. The parameters used in the evaluation and selection included the following:

a. Structural efficiency

b. Fracture toughness and crack growth

c. Corrosion and embrittlement phenomena

d. Fatigue

e. Thermal and environmental stability

f. Erosion and wear

g. Compatability

h. Availability and producibility

i. Fabricability

j. Cost

"A"

Table 1-A Principal Materials (Metals)

Type	Material	Application
Titanium	Ti 6Al-4V	Skins, stiffeners, formed parts, extrusions, forgings, fasteners
	Ti 4Al-3Mo-1V	Formed parts
	Ti 6Al-6V-2Sn Ti 7Al-4Mo	Forgings
	Ti 3Al-2.5V	Tubing
	Commercially Pure	Ducting, low stressed structure, formed parts
Low Alloy Steel	4340M 9Ni-4Co-.30C	Forgings Forgings
Corrosion Resistant Steel	17-4PH	Forgings, castings, bearings
	440C	Bearings
	PH 15-7 Mo	Sheet components for elevated temperature
	AISI 321 AISI 347	Ducting and Tubing
Super Alloys	A286	Fasteners
	Inconel 718 Rene' 41	High temperature fittings and sheet
	Inconel X Hastelloy X Hastelloy B	High temperature ducting

Table 1-E Principal Materials (Nonmetals)

Materials	Application
Fluorocarbons	Pressure seals System seals Fuel tank insulation Hydraulic oils Lubricants Rub strips
Fluorosilicones	Fuel tank sealants Faying surface seals Pressure seals Lubricants Aerodynamic seal
Methyl Silicones	Aerosmoothers Pressure sealants
Modified Silicones	Exterior protective heat resistant paints
Polyimide Resins	Structural adhesives Glass fabric reinforced honeycomb core Reinforced laminates Foams Electrical insulation Barrier films Rub strips Radome Dry film lubricants
Polysulfone	Interior furnishings
Nomex Polyamide	Interior wall panels, carpeting, decorative fabrics
Pasa Jell 107	Metal surface treatment for titanium bonding, and paint adhesion
Alumina Cer-Vit	Rain erosion protective shielding

Emphasis in process development has been on the refinement and modification of established practices to suit the materials selected and the design objectives. Some materials and applications however, required development and evaluation of new processes and innovations. Examples are:

a. Beta Processing of Titanium — to improve resistance to fracture toughness.

b. Dual Arc Tungsten Gas fusion welding — to substantially reduce transverse shrinkage distortion.

c. Diffusion Welding and Brazing — to provide improved joint properties where the process can be used.

d. Continuous Rolling of Titanium Alloy Strip — to improve surface quality, thickness tolerance, and reduce the number of joints required.

e. High Temperature Sandwich Fabrication — to enable the use of high volatile adhesives with non-perforated core in honeycomb sandwich manufacture.

f. Cure Forming — to accomplish forming of sandwich panel face sheets during adhesive curing.

g. Freon Vapor Degreasing — to provide for degreasing of titanium alloys with a non-chlorinated agent.

h. The Pasa Jell Process — to provide a bonding substrate which inhibits hydrolysis.

i. Polyurethane Hydroforming — to facilitate room temperature forming of small radius titanium alloy parts.

The Boeing Company has recognized the materials challenge presented by the task of airplane transportation of passengers at supersonic speeds. Material processes have been tested and selected to meet environmental requirements. Solutions have already been reached for most of them. Long-time environmental tests are in progress and are expected, with a high degree of confidence, to confirm the extrapolations which have been made.

Materials and processes controls for The Boeing Company subcontractors, and suppliers, as implemented by the Standardization Program have been established and tested.

The Boeing Company possesses the materials and process technology necessary to build a superior supersonic transport airplane and is ready to start.

2.0 METALLIC MATERIALS

Titanium alloys are the primary structural metals selected for the airframe, although steel, nickel base, and aluminum alloys will be used in certain components where their properties offer advantage.

2.1 TITANIUM

The desirable characteristics of titanium, which led to its selection, are:

a. Strength to weight ratio is considerably higher than other materials of comparable toughness.

b. Capability of being heat treated to a wide range of mechanical properties.

c. Excellent resistance to general corrosion.

d. Good welding characteristics.

e. Good metallurgical stability and creep resistance at B-2707 service temperatures.

f. Satisfactory forming, machining, and other fabrication characteristics.

g. Good fatigue properties.

h. Good thermal stress efficiency.

i. Good availability in the required primary forms; extrusions, forgings, sheet, plate, and bar.

j. Excellent service experience in Boeing and other manufacturers' products over a long period of time.

k. Excellent supplier capability.

The historical background of Boeing titanium research and development, beginning in 1951 with study programs relating to missile applications qualified Boeing as a leader in titanium technology. The early studies led to the introduction of titanium into the B-47 and B-52 airplanes, Bomarc and Minuteman missiles, and current commercial airplanes. The applications include flap track and body fittings, firewall and engine nacelle parts, spars, stiffeners, ducting, and fasteners. The alloys used were mainly Ti 4Al-4Mn and Ti 6Al-4V. Titanium has provided excellent maintenance free service life in each of these applications.

Titanium alloys were considered for Supersonic Transport (SST) applications as early as 1958. Ti 8Al-1Mo-1V was the leading titanium alloy under consideration until early 1965. At that time, results of environmental tests using a precracked Charpy specimen, rather than the conventional notched Charpy specimen, demonstrated that Ti 8Al-1Mo-1V was markedly susceptible to crack propagation when stressed in salt water and certain other aqueous environments. Variations in heat treatments were tested including special processing by the producers which showed unacceptable crack propagation resistance for thicknesses greater than 0.040 in. Also, results of thermal stability tests revealed that the good fracture toughness of duplex annealed Ti 8Al-1Mo-1V deteriorated during elevated temperature fabrication. It was discovered that an extremely fast cooling rate was necessary to develop the high fracture toughness condition in Ti 8Al-1Mo-1V. This cooling rate was found difficult to attain in manufacturing processes. The undesirable properties of Ti 8Al-1Mo-1V were found to be primarily related to alloy composition. Metallurgical analysis has shown that the eight percent aluminum content, the highest for a commercial alloy, is sufficient to reduce stress-corrosion resistance and cause an ordering reaction in the alpha phase (Ref. 1). This ordering tendency explains the instability and cooling rate sensitivity (Ref. 2).

A reevaluation of candidate alloys with emphasis on resistance to crack growth in aqueous environments showed Ti 6Al-4V and Ti 4Al-3Mo-1V to be superior to other alloys. These alloys also had good metallurgical stability and fabrication characteristics. At that time, The Boeing Company under FAA sponsorship, initiated an investigation of these two alloys. The goal of this effort was to determine the processing conditions required for the optimum combination of properties including resistance to saltwater crack growth, strength, fracture toughness, and metallurgical stability. Detailed results of this investigation were reported (Ref. 3). Based on these results Ti 6Al-4V has been selected as the primary structural alloy. Other alloys will also be used where their particular properties can be used to advantage.

2.1.1 Alloys

Superior combinations of material properties were developed for Ti 6Al-4V and Ti 4Al-3Mo-1V through new heat treatments as a result of the Boeing Titanium Development Program. Improvements of 50 to 100 percent in fracture toughness and saltwater crack growth resistance over properties of previously available mill products were achieved by beta processing. Beta processing refers to annealing or hot working above the beta transus temperature of a titanium alloy and applies to mill products other than sheets. Heretofore, beta processing was considered undesirable due to loss of tensile ductility. However, it has been shown that fracture toughness is superior to tensile ductility as a parameter for predicting structural performance. The increase in fracture toughness greatly offsets the loss of tensile ductility in applications where formability is not a major consideration. As a result of these investigations, the materials and conditions shown in Table 2-A were selected.

2.1.1.1 Availability and Producibility

Availability of Ti 6Al-4V sheet, strip, plate, bar, forgings, extrusions, and castings is assured based on over 12 years of increasing production capacity. Of the approximately 17 million pounds of titanium mill products shipped in 1965, more than 60 percent was Ti 6Al-4V in the forms listed above.

Ti 4Al-3Mo-1V, Ti 6Al-6V-2Sn, and Ti 7Al-4Mo are established commercial alloys and the suppliers have had sufficient production experience to meet the specification requirements.

Beta processing has been investigated by the titanium producers and considerable quantities of beta rolled Ti 6Al-4V plate have been made to Boeing specifications. The experience gained has demonstrated that beta annealing of alpha-beta rolled products and beta rolling are readily adapted to current mill practice. Either method provides satisfactory properties.

Beta forging of titanium alloys has also been developed by Boeing and a major forging company. The program included a thorough investigation of mechanical properties and the determination of forging criteria. Beta forging results in high fracture toughness and improved forgeability due to the higher processing temperature.

Beta processing has always been conventional practice for extruding titanium alloys and is familiar to the producers.

A study has been conducted to determine if beta processing affects the repeatability of strength properties of titanium alloys and to compare the consistency of such properties with similar values for other conventional structural alloys. Coefficient of variation is a useful parameter for such a study. This value is determined by dividing standard deviation by the mean strength and is expressed as a precentage. This has the advantage of normalizing the standard deviation so that materials with different strength ranges can be compared on a common basis. Table 2-B shows that alpha-beta processed Ti 6Al-4V (STA 1000) and beta processed Ti 6Al-4V (Beta-STA-1000) have similar repeatibility and compare favorably in this respect with the other alloy systems.

The titanium producers have improved their rolled product capability and are now manufacturing continuously rolled Ti 6Al-4V sheet and strip, and extra large heat treated plate. Continuously rolled sheet processing provides standard width material in lengths greater than fifty feet with flatness and thickness tolerances similar to those for aluminum sheet. Prior to this development, material was available in maximum lengths of approximately 12 feet, requiring splicing to provide long skins.

In addition to the standard sizes, plates of 0.750 and 1.00-in. thickness, 48-in. width by 40-ft length, have been produced to Boeing specification, including beta rolling. Flatness after heat treating, which involves a water quench, was entirely satisfactory for production. Plate material of this size will be used for wing skin material and can be readily machine sculptured and contour formed. The large sizes now available in sheet, strip, and plate minimize the number of splices required.

2.1.1.2 Properties

The proper application of alloys to design requires a careful evaluation of mechanical and metallurgical properties and the effects of the specified service environment. Tension applications require adequate fracture toughness to

Table 2-A Material Selection, Titanium

Form	Alloy Form and Condition	Selection Criteria	Availability
Sheet to 0.050 in. Thick	Ti 6Al-4V mill annealed (Condition I) 1350°F for 4 hours, slow cool.	Excellent fracture toughness to 0.050 in. Good formability Good stress corrosion resistance Moderate strength	Material available in production quantities. Continuous rolled material being produced.
Sheet from 0.050 to 0.187 in. Thick	Ti 6Al-4V duplex annealed (Condition V) 1750°F for 10 minutes air cool, then 1250°F for 4 hours, air cool	Excellent fracture toughness over 0.050 in. Moderate strength Good formability Good stress corrosion resistance	Material available in production quantities.
Sheet	Ti 6Al-4V STA-1000 (Condition III) 1725°F for 10 minutes, water quench, then 1000°F for 4 hours, air cool	High strength Moderate fracture toughness Good fatigue properties Good stress corrosion resistance	Solution treated and aged sheet is available in sheets up to 48 by 120 in. size in production quantities.
Sheet	Ti 6Al-4V STA-1250 (Condition IV) 1725°F for 10 minutes (minimum), water quench, then 1250°F for 4 hours, air cool	Higher strength than mill annealed Excellent fracture toughness Good stress corrosion resistance Good formability	Solution treated and aged sheet is available in sheets up to 48 by 120 in. size in production quantities.
Sheet	Ti 4Al-3Mo-1V STA-1050 (Condition III) 1715°F for 15 minutes, water quench, then 1050°F for 8 hours, air cool	High strength Moderate fracture toughness Good stress corrosion resistance	Available in sheets up to 48 by 120 in. size in production quantities.
Sheet	Ti 4Al-3Mo-1V STA-1150 (Condition IV) 1715°F for 15 minutes, water quench, then 1150°F for 8 hours, air cool	Excellent fracture toughness Good formability Moderate strength Good stress corrosion resistance	Available in sheets up to 48 by 120 in. size in production quantities.
Sheet	Commercially pure Titanium, annealed	Good strength to weight ratio compared to stainless steel Excellent formability Excellent weldability	Available in production quantities
Plate, Bar, Forgings, and Extrusions	Ti 6Al-4V Beta-STA-1000 (Condition III) Primary working or annealing above the beta transus, then same as Condition III, above	High strength Moderate fracture toughness Good stress corrosion resistance	Beta processed material available in production quantities.
Plate, Bar, and Extrusions	Ti 6Al-4V Beta-STA-1250 (Condition IV) Primary working or annealing above the beta transus, then same as Condition IV, above	Excellent fracture toughness Moderate strength Good stress corrosion resistance	Beta processed material available in production quantities.
Bar and Forgings	Ti 6Al-6V-2Sn (Condition III) 1600°F for 1 hour, water quench, then 1200°F for 4 hours, air cool	High strength Adequate fracture toughness Adequate stress corrosion resistance Good hardenability in thick sections	Available in production quantities.
Bar and Forgings	Ti 7Al-4Mo (Condition III) 1750°F for 1 hour, water quench, then 1150°F 8 hours, air cool	Alternate to Ti 6Al-6V-2Sn	Available in production quantities
Forgings	Ti 6Al-4V mill annealed (Condition I) beta forged, 1350°F for 4 hours, slow cooled	Excellent fracture toughness Moderate strength Good stress corrosion resistance	Readily available.
Tubing	Ti 3Al-2.5V, Annealed	Good formability Good strength to weight ratio compared to stainless steel	Available in production quantities

STA — Solution treated and aged

Table 2-8. Comparison of Mechanical Property Variation

Material	Coefficient of Variation (percent)	Reference Source
7075-T73 Rolled Bar and Rod Up to 2.5 Inches		MIL-HDBK-5 Minutes Item 62-18 (26m)
F_{tu_L}	3.46	
F_{ty_L}	5.17	
17-7PH RD 950 All Thicknesses; Sheet and Plate		MIL-HDBK-5 Minutes Item 64-4 (29a)
F_{tu_T}	2.48	
T_{ty_T}	2.96	
Rene' 41, BMS 7-95 Condition IIB		Boeing Document, D2-81281, Mechanical Properties Evaluation of Rene' 41 for X-20 Vehicle Environment
Less than 0.020: F_{tu}	4.78	
F_{ty}	5.62	
Over 0.020: F_{tu}	3.42	
F_{ty}	6.25	
Ti 6Al-4V Sheet, STA-1000 Less than 0.050		MIL-HDBK-5 Minutes Item 64-1a
F_{tu_L}	2.78	
F_{ty_L}	3.27	
F_{tu_T}	3.00	
F_{ty_T}	3.28	
Ti 6Al-4V Plate, Beta-STA-1000 0.188 - 0.750		Analysis of Titanium Metals Corporation and Reactive Metals Incorporated Material Certification Tests
F_{tu_L}	2.16	
F_{ty_L}	2.98	
F_{tu_T}	4.63	
F_{ty_T}	6.37	

insure the high degree of reliability demanded of a commercial airplane. As high strength does not necessarily result in good fatigue properties, fatigue life and fatigue crack growth rate information also influence material selection.

a. Static Mechanical Properties

Room temperature mechanical properties for Ti 6Al-4V alloy in the pertinent heat treated conditions are shown in Table 2-C. Detailed design allowables including elevated temperature properties are shown in Document D-5000, Book 84-D1, SST Structural Allowables.

b. Fatigue

The fatigue properties of conventionally processed alpha-beta titanium alloys are satisfactory for design of airframe structure. Testing was conducted to determine if the microstructural changes introduced by beta processing affected these fatigue characteristics. The new microstructures have little effect on the notched-fatigue endurance limit exhibited by an alloy. The beta-heat-treated material (Widmanstätten microstructure) produces the same fatigue S-N curves as conventionally processed material (equiaxed microstructure). Supporting evidence is given in Fig. 2-1. Similar data has been reported in Wright Aeronautical Development Division Document TR 60-489 (Ref. 4) and is shown in Fig. 2-2.

Fatigue crack growth rates of titanium alloys in air and 3.5 percent sodium chloride solution have been determined using 12 by 36 inch center-cracked panels as shown in Document D6A10065-1, Sec. III. Figure 2-3 shows the crack growth rate comparison for several titanium alloys at a stress intensity level of 45 ksi$\sqrt{\text{in}}$. Ti 6Al-4V and Ti 4Al-3Mo-1V display the lowest fatigue crack growth rate in air and are only slightly affected

Table 2-C. Strength Properties of Ti 6Al-4V Sheet and Plate

Heat Treat Condition	Gage**	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 2 in.)
I (Mill Anneal)	Sheet	134	126	9
	Plate	134	126	10
III (STA)	Sheet	157	143	5.5
	0.188-0.750	157	137	9
	0.751-1.000	150	134	7
	1.001-2.000	145	130	6
	2.001-4.000	134	126	6
IV (STA)	Sheet	144	130	7
	0.188-0.750	140	126	10
	0.751-4.000	134	126	9
V (Duplex Anneal)	Sheet	129	116	9
	Plate	134	126	10

**Sheet = Under 0.188-in. thick

**Plate = Over 0.188-in. thick

by the salt water environment. Crack growth behavior of Ti 8Al-1Mo-1V in air is only slightly poorer than the other two alloys, but is much poorer in salt water.

c. Fracture Toughness

Engineering attention, based on experience with aluminum alloy airframe development and service, has been focused on the ability of structure to withstand effects of severe stress concentrations such as appear at a fatigue crack. The fracture toughness concept has been accepted as an important criterion for evaluation of new structural materials and processes. The Boeing Company uses large test specimens to provide realistic comparisons and design information by closely simulating airframe stress conditions. Panels as large as 12 by 36 in. with centrally located fatigue cracks are employed for testing sheet. Fatigue cracked bend specimens subjected to four point loading and wide surface-flawed specimens are used for testing plate and heavy-section forms (Ref. 3 for specimen configurations) Test results obtained with surface flawed panels are used to compare fracture toughness characteristics of Ti 6Al-4V with other titanium and two aluminum alloys in Fig. 2-4. Figure 2-4 identifies the gross area stress level at which a fatigue crack of given depth becomes mechanically unstable and propagates rapidly. Figure 2-5 shows strength-toughness comparisons for various heat treatment conditions of Ti 6Al-4V, Ti 4Al-3Mo-1V, and Ti 8Al-1Mo-1V. The advantage of beta processing for Ti 6Al-4V and Ti 4Al-3Mo-1V is evident. Fracture toughness of titanium alloys increases with increasing temperature and shows no brittle transition behavior within the range of B-2707 operating temperature.

Results of fracture toughness testing show that the stress required to cause rapid propagation of fatigue cracks in Ti 6Al-4V and Ti 4Al-3Mo-1V is considerably greater than for aluminum structural alloys. Since the strength of these titanium alloys is considerably superior to that of aluminum alloys, the titanium alloys will operate at much higher stress levels in the airplane struc-

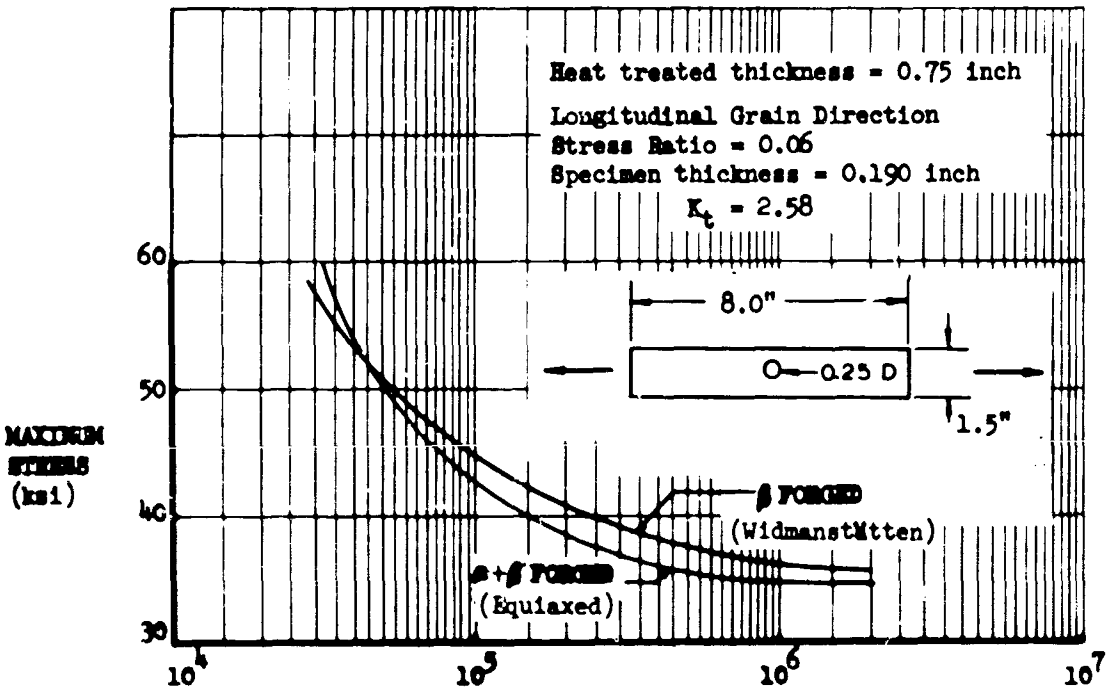

Figure 2-1. Notch Fatigue Properties Comparison of Alpha Plus Beta and Alpha Structure of Ti 6Al-4V (Boeing Data)

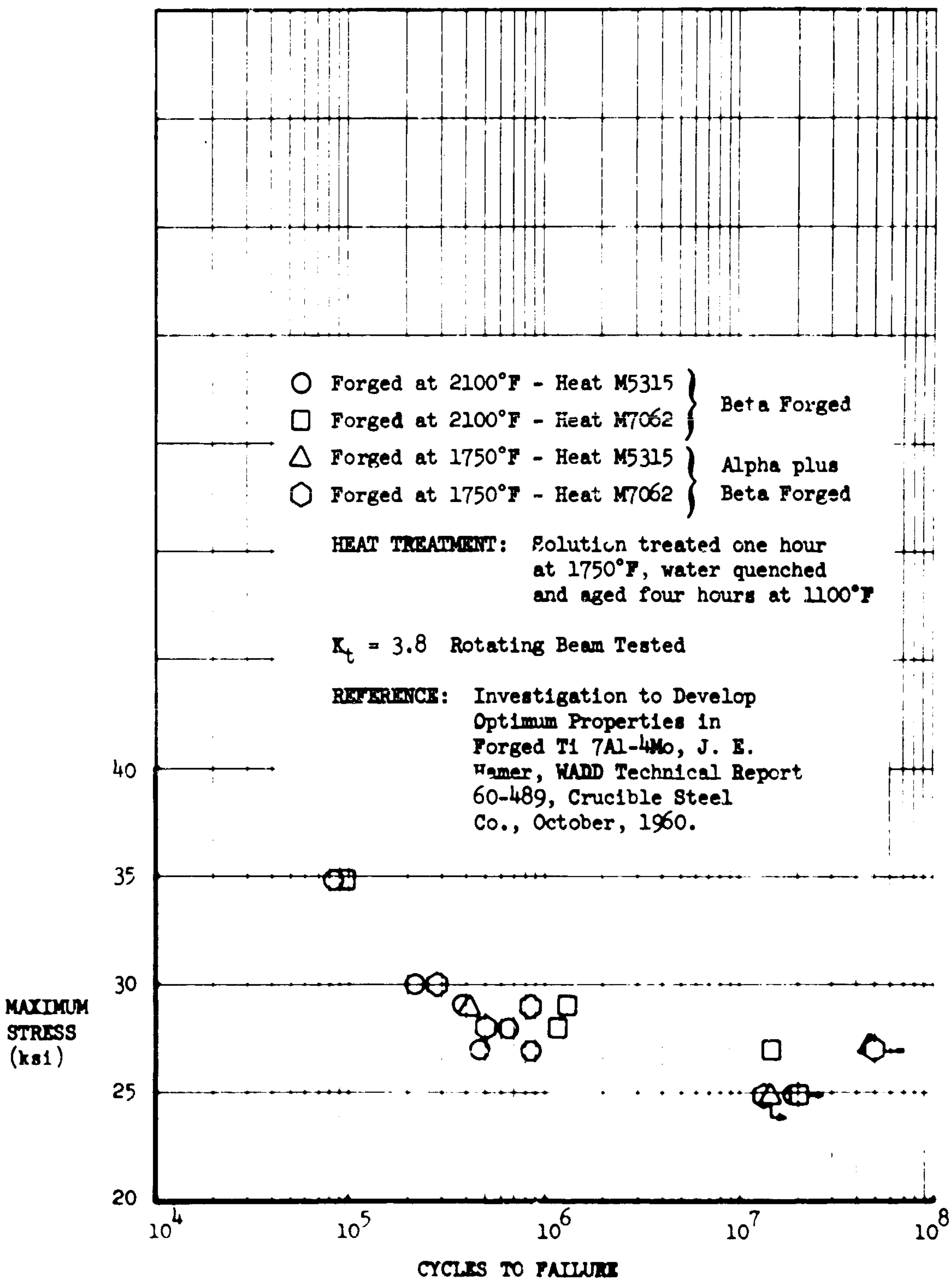

Figure 2-2. Notch Fatigue Properties Comparison of Alpha Plus Beta and Beta of Ti 7Al-4Mo (WADD Report)

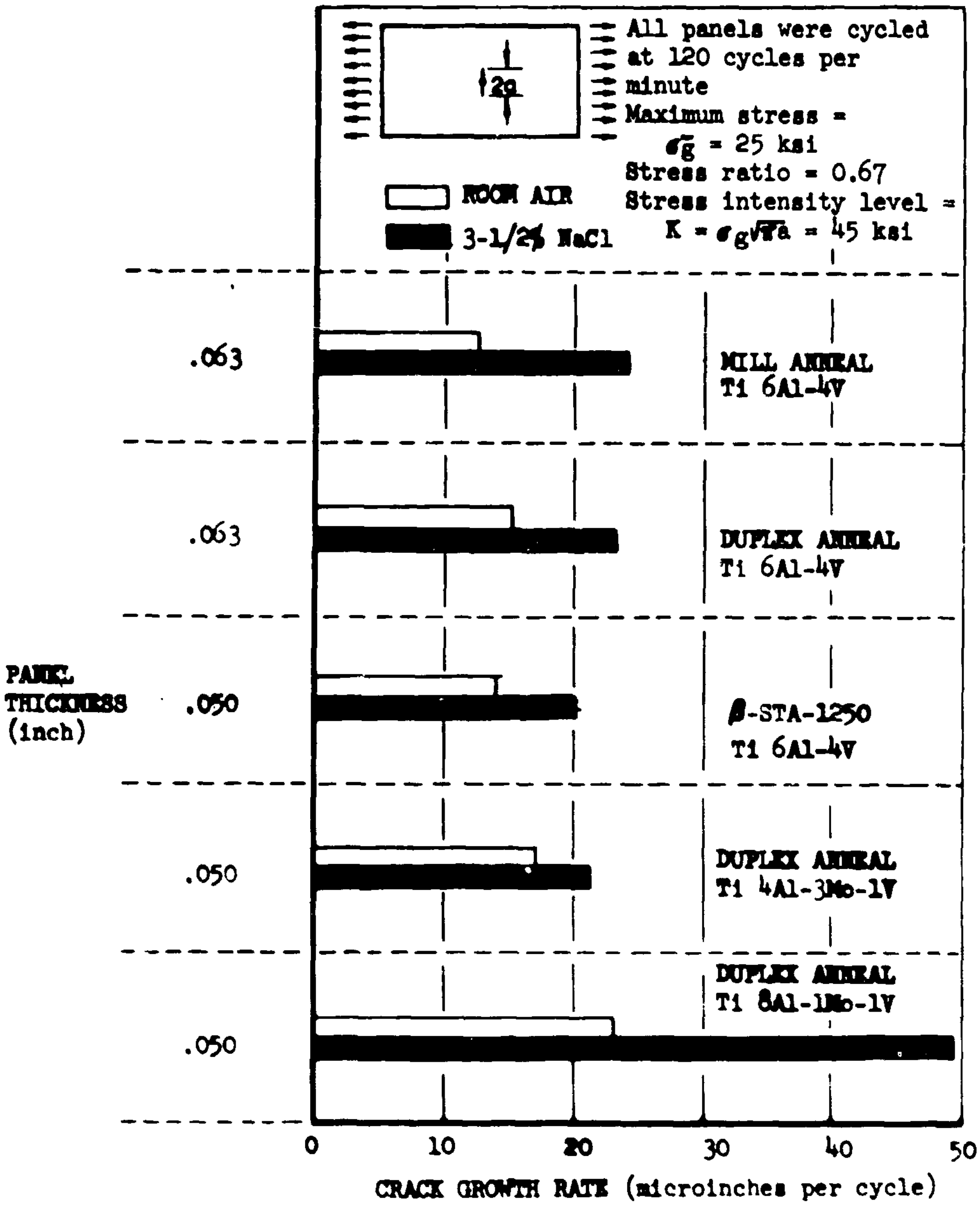

Figure 2-3. Crack Growth Rate Comparison of Three Titanium Alloys

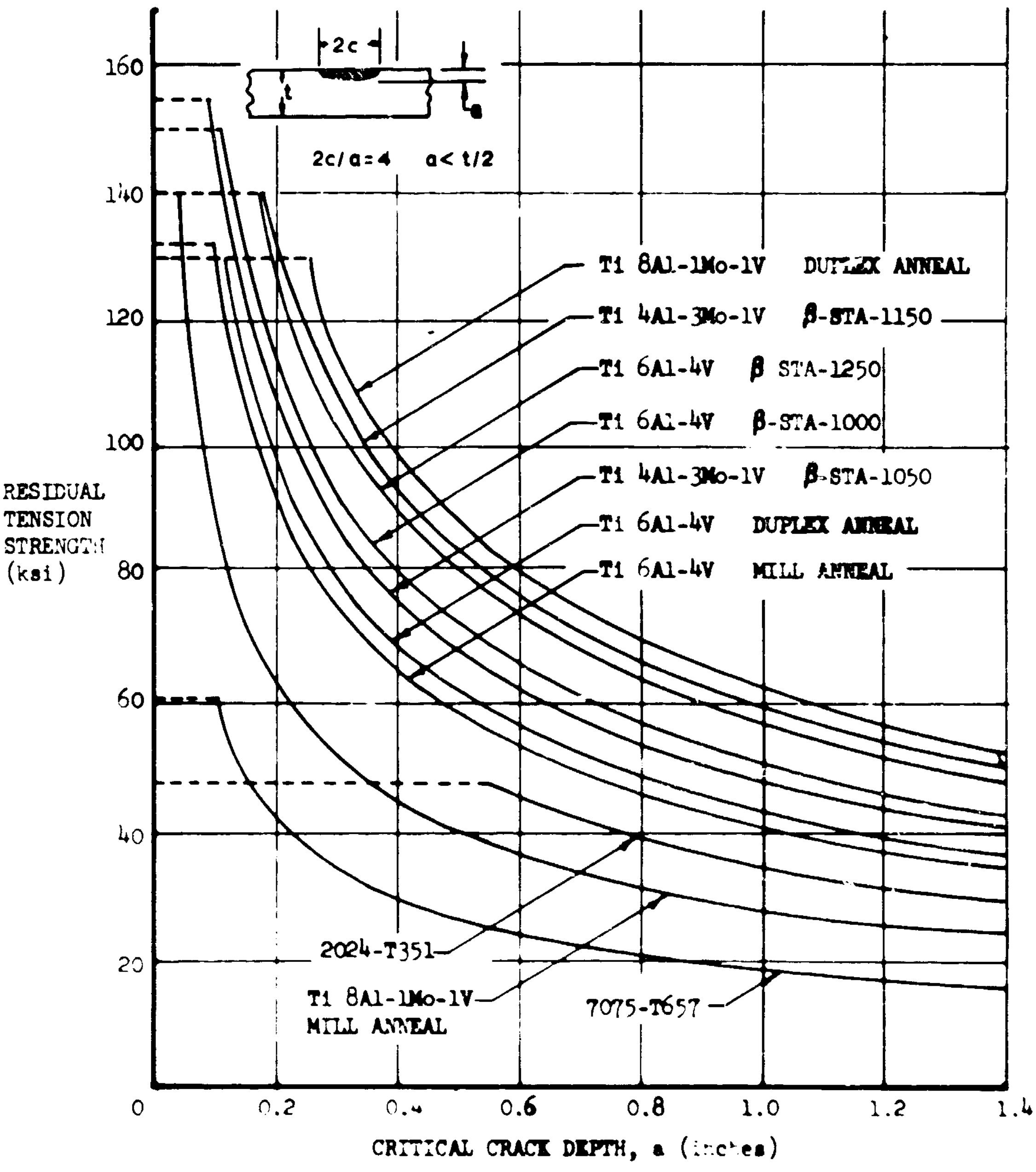

Figure 2-4. Fracture Toughness Comparison of Titanium and Aluminum Alloys

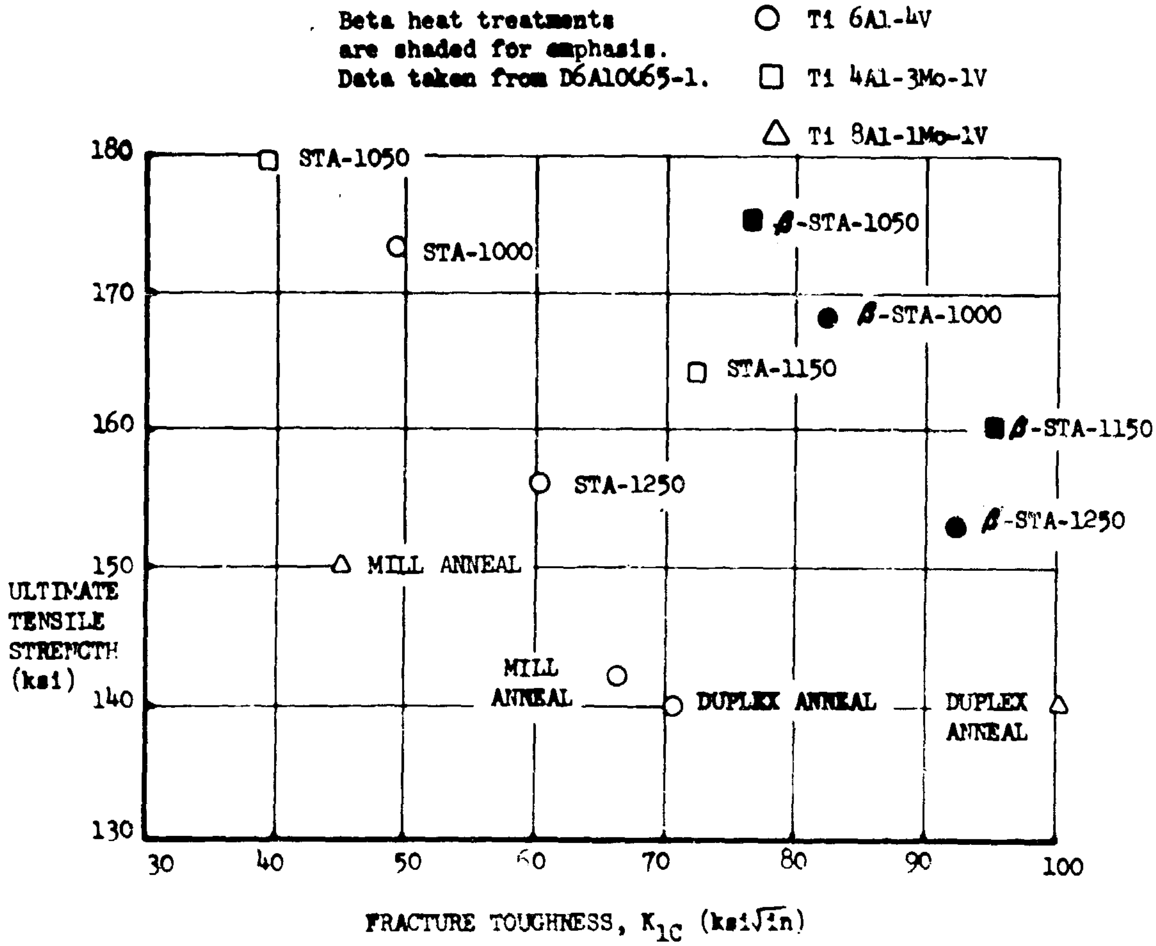

Figure 2-5. Strength Toughness Combinations for Several Titanium Alloys and Heat Treatm

ture. The operating stress levels are approximately in proportion to the ultimate strengths of the materials. Figure 2-6 accounts for these differences in operating stress levels by expressing the gross area stress required to fracture a fatigue cracked specimen as a percentage of the material's ultimate strength. On this basis, the toughness values for the selected alloys and conditions lie between 7075-T651 and 2024-T351 and are satisfactory for properly designed tension critical structure. Adjustment of stress levels and design and spacing of crack stoppers are techniques available for improving the resistance to crack propagation of assembled structure.

d. Elevated Temperature Stress Corrosion Two aspects of stress corrosion for the primary candidate alloys were investigated; hot salt embrittlement and accelerated crack-growth in certain aqueous environments. Two types of laboratory tests were used to evaluate hot salt embrittlement (Ref. 5). In one test service time-temperature-stress conditions were simulated by alternately subjecting stressed specimens to salt solution immersion and then to a temperature exposure (Fig. 2-7). In the other test, similar specimens were coated with a thick salt slurry, stressed, and subjected to a constant elevated temperature.

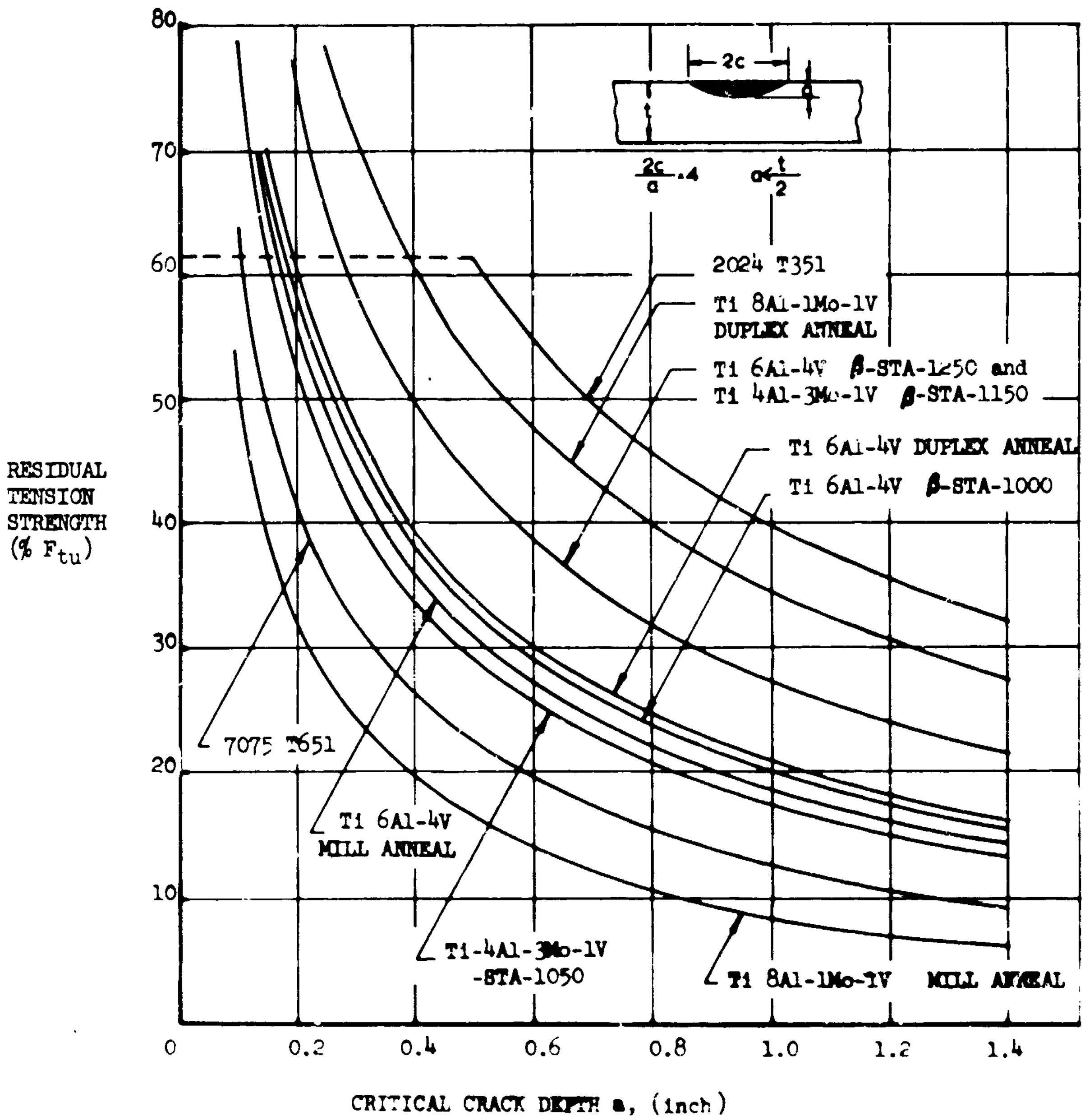

Figure 2-6. Fracture Toughness Comparison of Titanium and Aluminum Alloy Plates

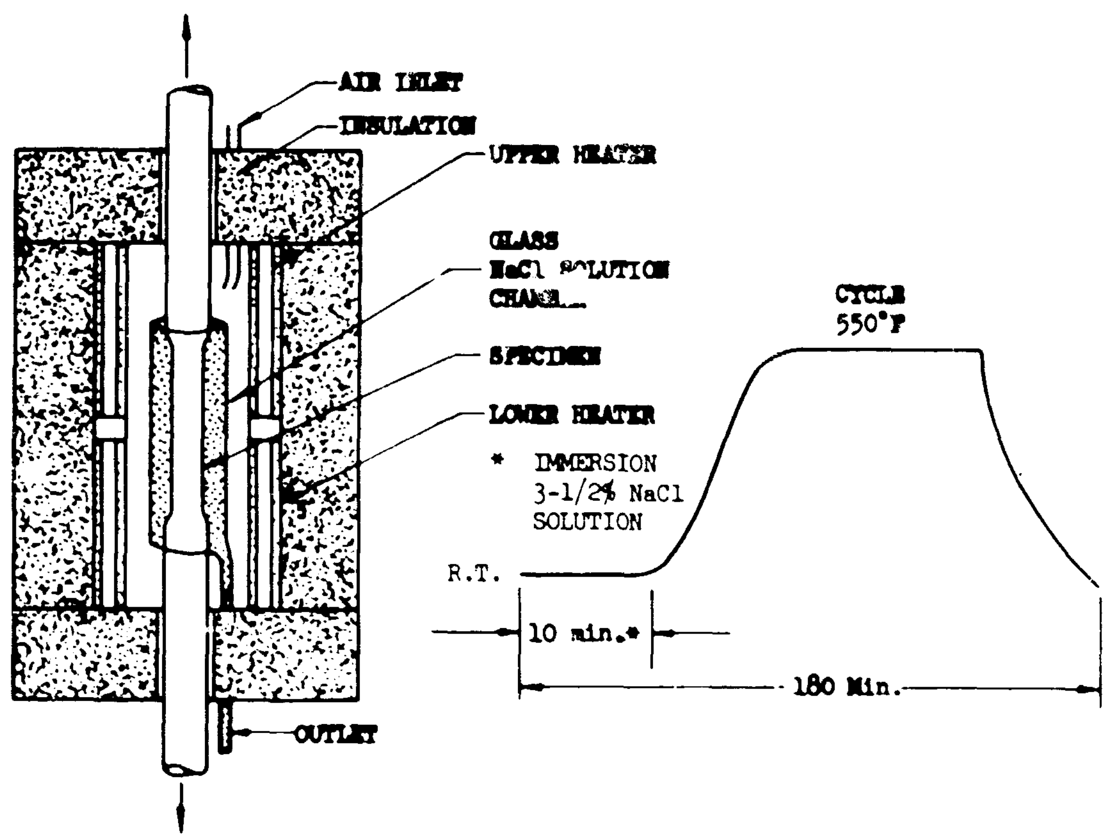

Figure 2-7. Cyclic Stress Corrosion Apparatus

The effect of temperature on the stress-corrosion susceptibility of some titanium alloys is shown in Fig. 2-8. The results demonstrate no susceptibility to strength deterioration for Ti 6Al-4V at the maximum service temperature. Hot salt stress corrosion testing by Braski and Heimerl (Ref. 6), based on a different type of specimen, shows Ti 6Al-4V and Ti 4Al-3Mo-1V to be superior to the other alloys tested.

The results for both mill and duplex annealed Ti 8Al-1Mo-1V showed deterioration due to stress corrosion did occur after 1,000 hours in the 500 to 550° F range. Increasing the time at 500° F to 2,000 and 5,000 hours was found to cause further reduction of residual tensile properties of duplex annealed Ti 8Al-1Mo-1V. However, cyclic stress corrosion tests at 550° F for both base metal and welded duplex annealed Ti 8Al-1Mo-1V (Figs. 2-9 and 2-10) produced no observable stress-corrosion effects at stresses of up to 90 percent of the tensile yield strength for similar times. Cyclic exposure data are considered the most important, being more representative of the airframe service environment. This is further substantiated by the excellent service experience of titanium alloys in jet engines which operate under cyclic temperature conditions. An explanation of this difference is based on the work by Braski (Ref. 7) on corrosion product identification. An intermediate corrosion product is involved in the elevated temperature reaction. This corrosion

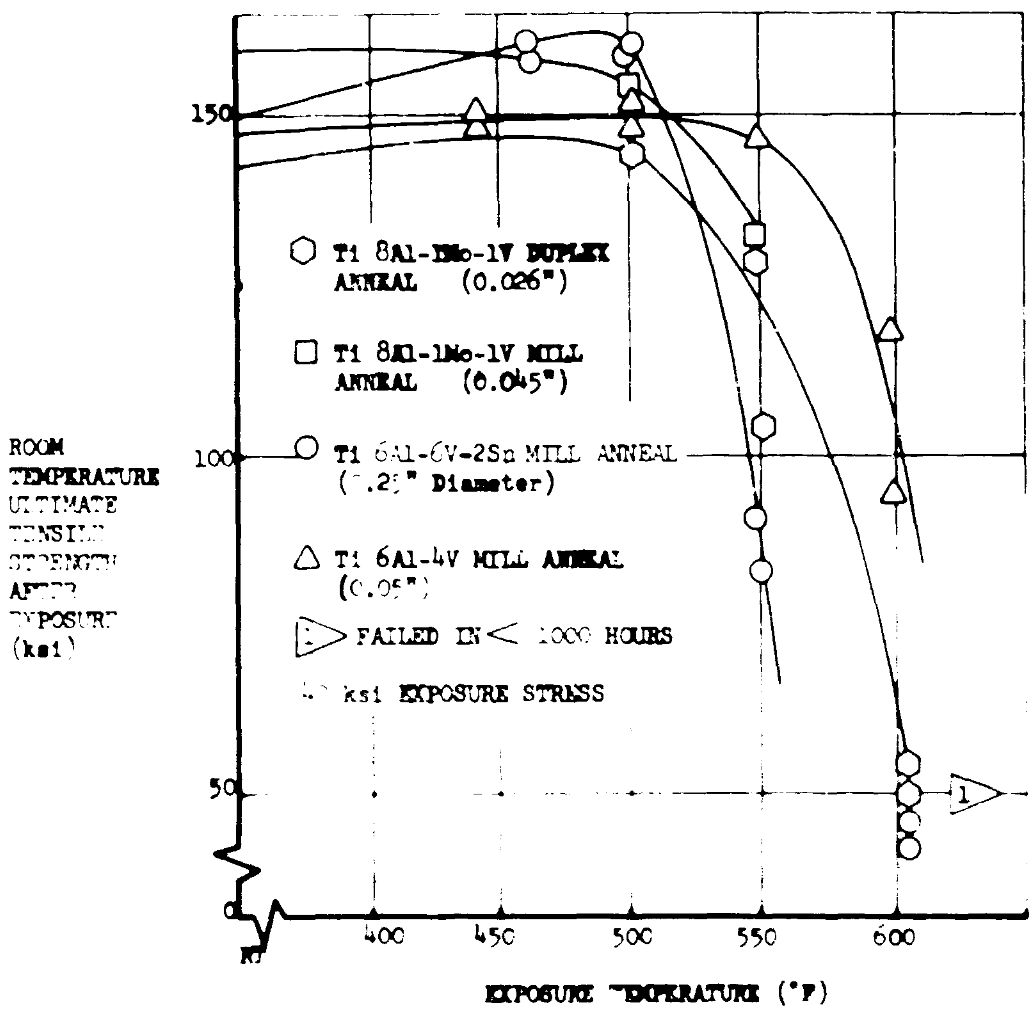

Figure 2-8. Residual Strength of Titanium Alloys after 1000 Hours Exposure to Sodium Chloride

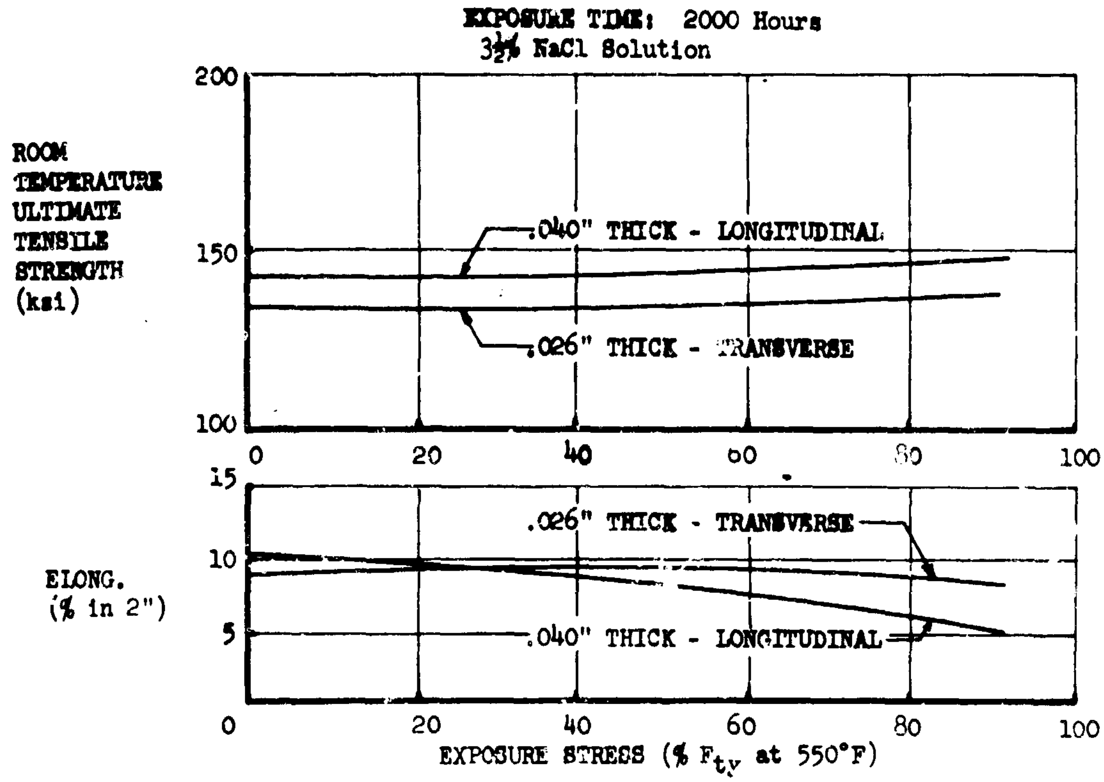

Figure 2-9. Residual Strength of Duplex Annealed Ti 8Al-1Mo-1V after Cyclic Exposure

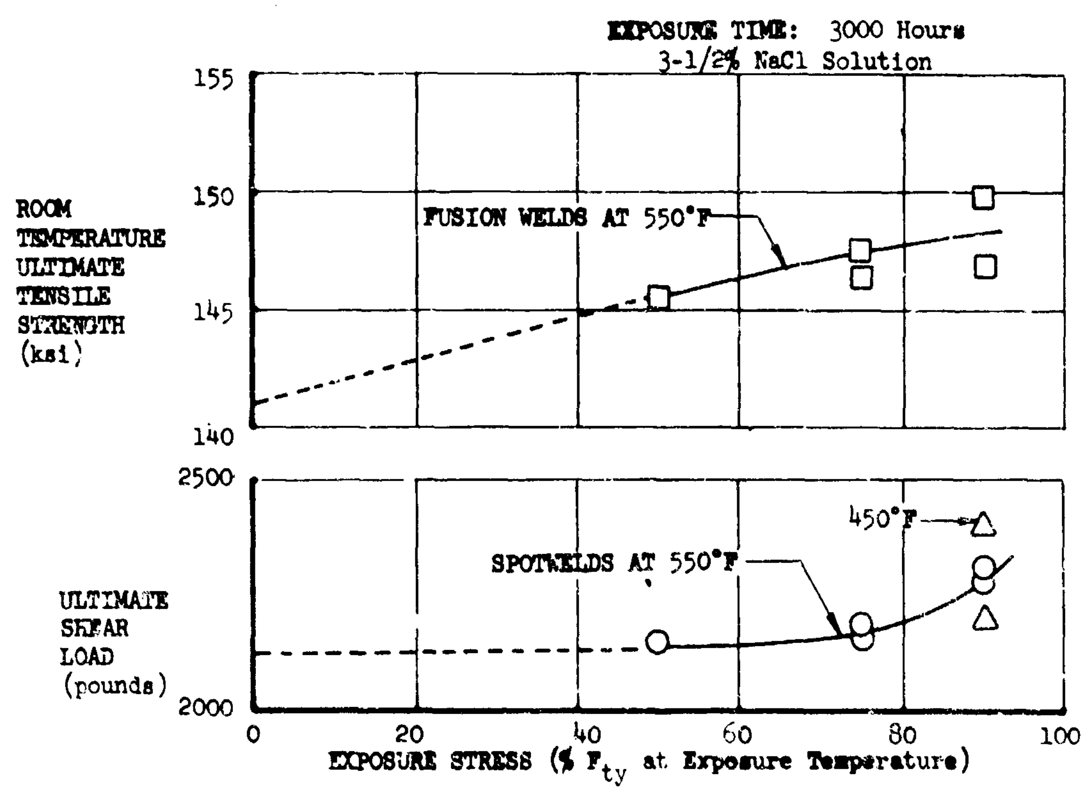

Figure 2-10. Residual Strength of Duplex Annealed Ti 8Al-1Mo-1V Welds After Cyclic Exposure

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product is unstable at normal temperatures and is removed in the presence of moisture at the low temperature portion of each temperature cycle. Further testing is being conducted at The Boeing Company to clarify this phenomenon.

e. Salt Water Crack Growth

The susceptibility of certain titanium alloys to environmental crack growth at room temperature was initially demonstrated in 3.5 percent salt solution. Recent investigations, reported in document D6A10065-1, have included other solutions representative of the operational environment, but none were found to be more severe than salt water. For this reason, tests to compare the environmental behavior of titanium alloys and heat treatment conditions were conducted in 3.5 percent salt solution.

Environmental crack growth resistance is established by sustained loading of fracture toughness specimens to stress intensity levels that are specific percentages of the critical stress intensity level of unexposed specimens. The time required for specimen failure is plotted as a function of the applied stress intensity level as illustrated in Fig. 2-11. The resulting curve represents the time required to propagate subcritical cracks to the critical size. For titanium alloys, subcritical crack growth does not occur below a particular stress intensity level. Since this level is reached before 360 minutes of loading time, the environmental crack growth resistance parameters, K_i (360 minutes) and K_{Ii} (360 minutes), are considered threshold levels.

The environmental crack growth resistance of Ti 6Al-4V is compared with other titanium alloys in Fig. 2-12 which shows the threshold stress level at which a fatigue crack of given length becomes unstable in 3.5 percent salt solution. Figure 2-13 shows strength and threshold stress intensity comparisons for various heat treatment conditions of Ti 6Al-4V, Ti 4Al-3Mo-1V, and Ti 8Al-1Mo-1V. The superior resistance of beta processed Ti 6Al-4V and Ti 4Al-3Mo-1V to environmental crack growth is evident.

Although the criteria of strength, toughness, stability, and fatigue were duly considered during selection of materials for tension structures, this additional data reflecting resistance to salt water crack growth provides strong support that Boeing selections will withstand the operating environment of the B-2707. General corrosion and material compatibility are discussed in Sec. 3.8.

f. Metallurgical Stability

The fracture toughness of duplex annealed Ti 8Al-1Mo-1V alloy sheet (0.04 inch thick) deteriorated when stressed during exposure at 500° and 650°F (Fig. 2-14). On the other hand, mill annealed Ti 6Al-4V sheet showed an increase in fracture toughness under the same exposure conditions. The tensile properties of both alloys increased during exposure. The ordering reaction in Ti 8Al-1Mo-1V probably accounts for the accompanying decrease in fracture toughness in this alloy. Thermal stability of the heat treatments for Ti 6Al-4V and Ti 4Al-3Mo-1V is being evaluated. Figure 2-15 shows 1000, 2500, and 5000 hour exposure data for Ti 6Al-4V and Fig. 2-16 for Ti 4Al-3Mo-1V. Although the data indicates some variation, no greater variance is expected for specimens now being exposed to 10,000 hours because the over aged conditions preclude further precipitation. The annealing treatments also produce near equilibrium metallurgical conditions.

2.1.2 Processing

Titanium, when first introduced to the airframe industry, quickly earned the reputation of being difficult to process. The Boeing Company and other fabricators have since developed production processes for fabrication of efficient, economical, and reliable titanium structure. These improved processes are the result of proper recognition of the material characteristics and the application of new manufacturing technology. Titanium alloys are, in fact, more amenable to high quality fabrication than other alloys with similar strength to density ratios. To assure that high quality products will result from processing, specifications have been prepared to control manufacturing variables and specify quality control requirements. Specifications are continually reviewed and revised, as necessary, to incorporate new developments. Continuing research is aimed at improving and simplifying the existing processes.

2.1.2.1 Heat Treating

In general, the titanium alloys selected will be used in the mill and duplex annealed, solution treated and aged, and beta processed conditions The specific thermal treatments are presented in Table 2-A. With the exception of beta processing, the heat treatment conditions are conventional and accepted throughout industry.

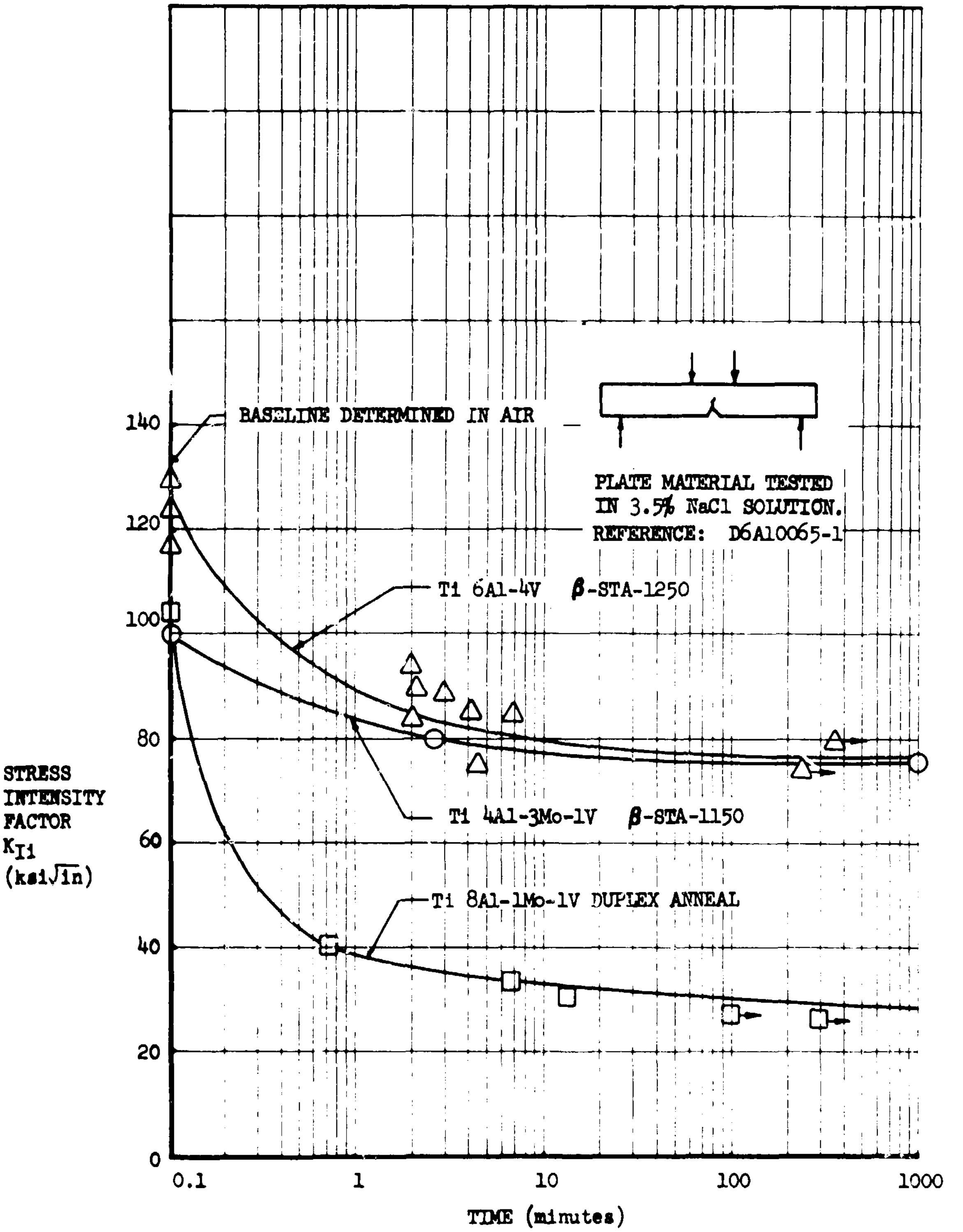

Figure 2-11. Salt Solution Crack Growth Characteristics

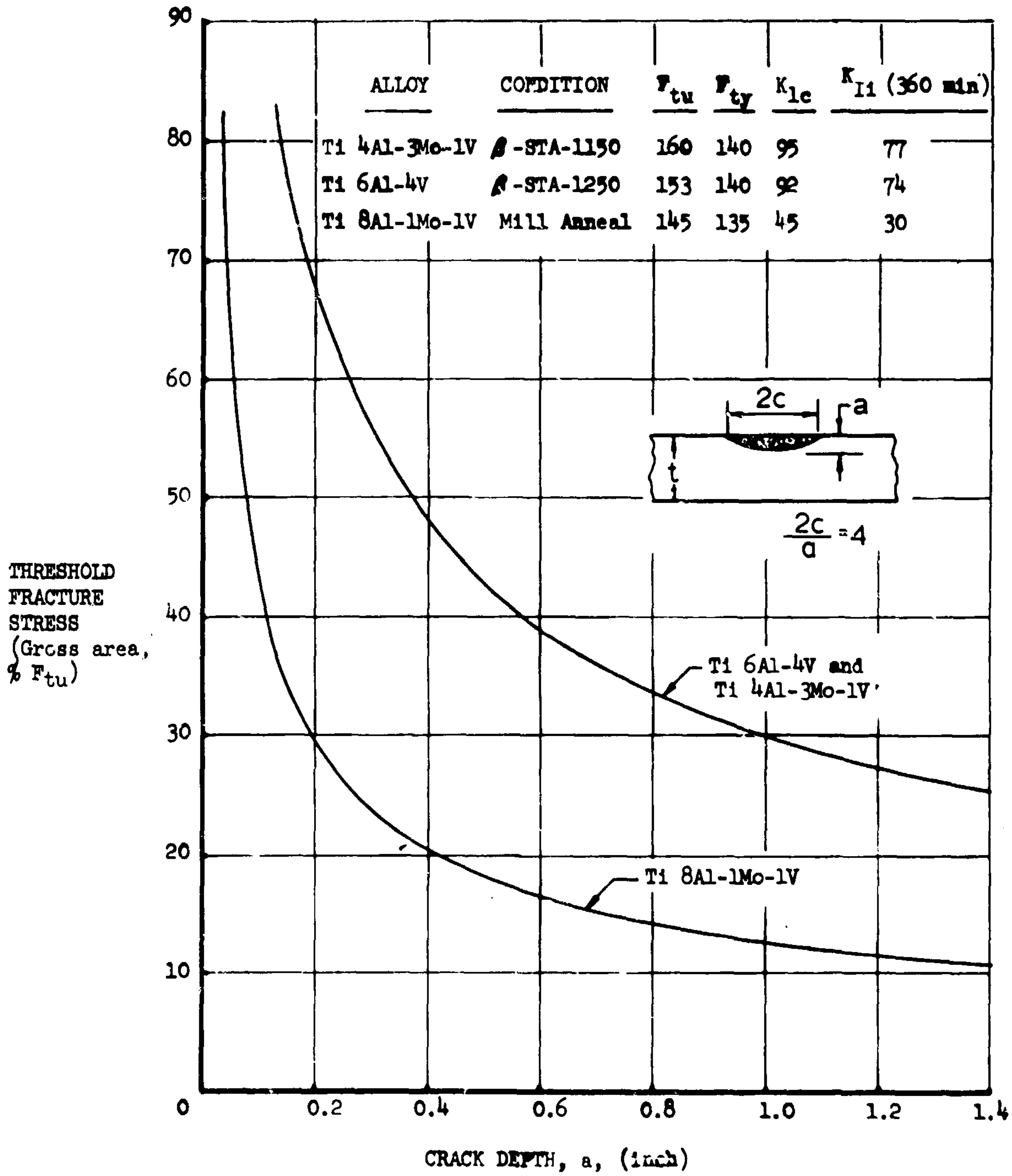

Figure 2-12. Environmental Crack Growth Resistance of Titanium Alloys

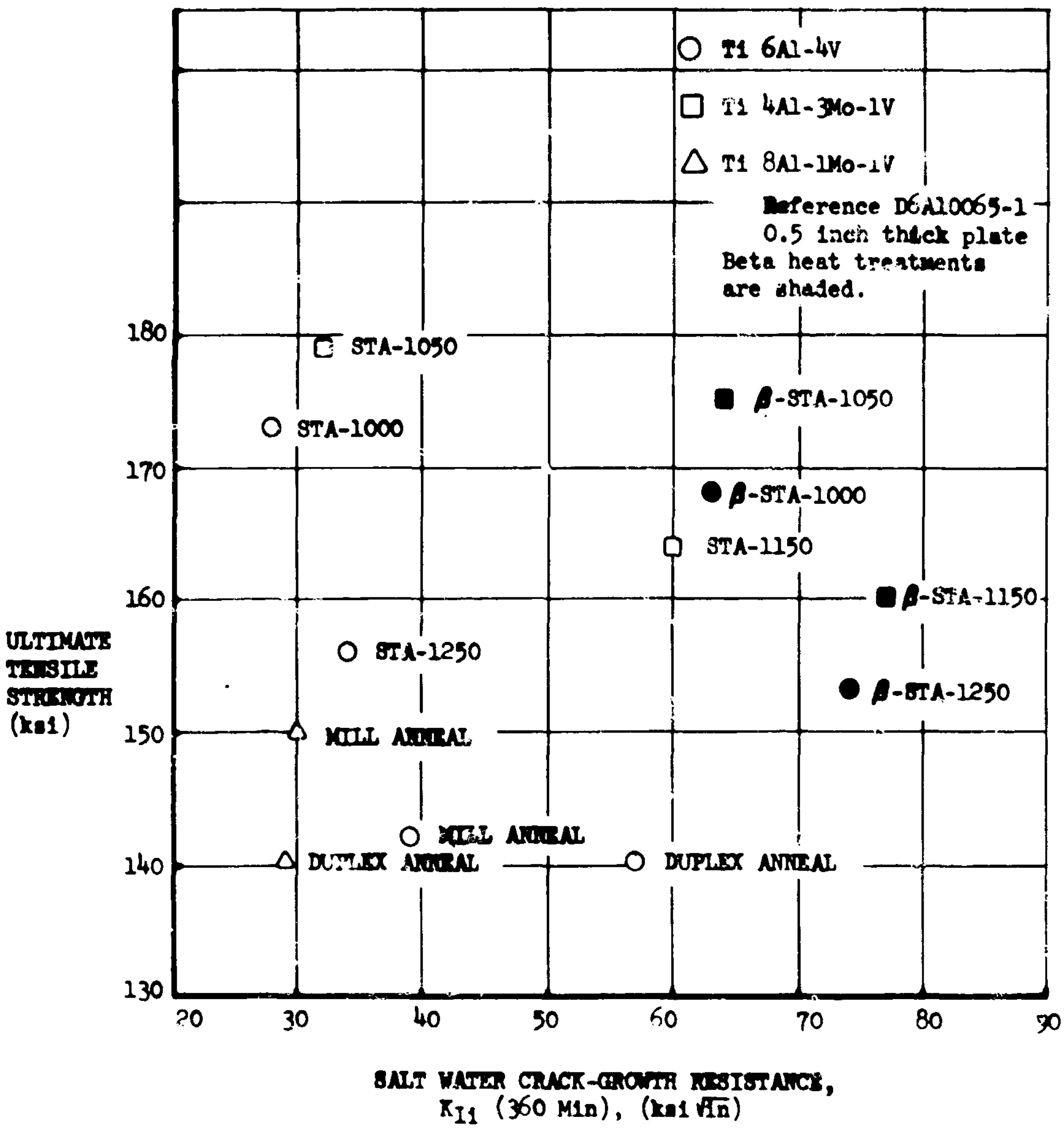

Figure 2-13. Strength and Salt Water Crack Growth Resistance of Titanium Alloys

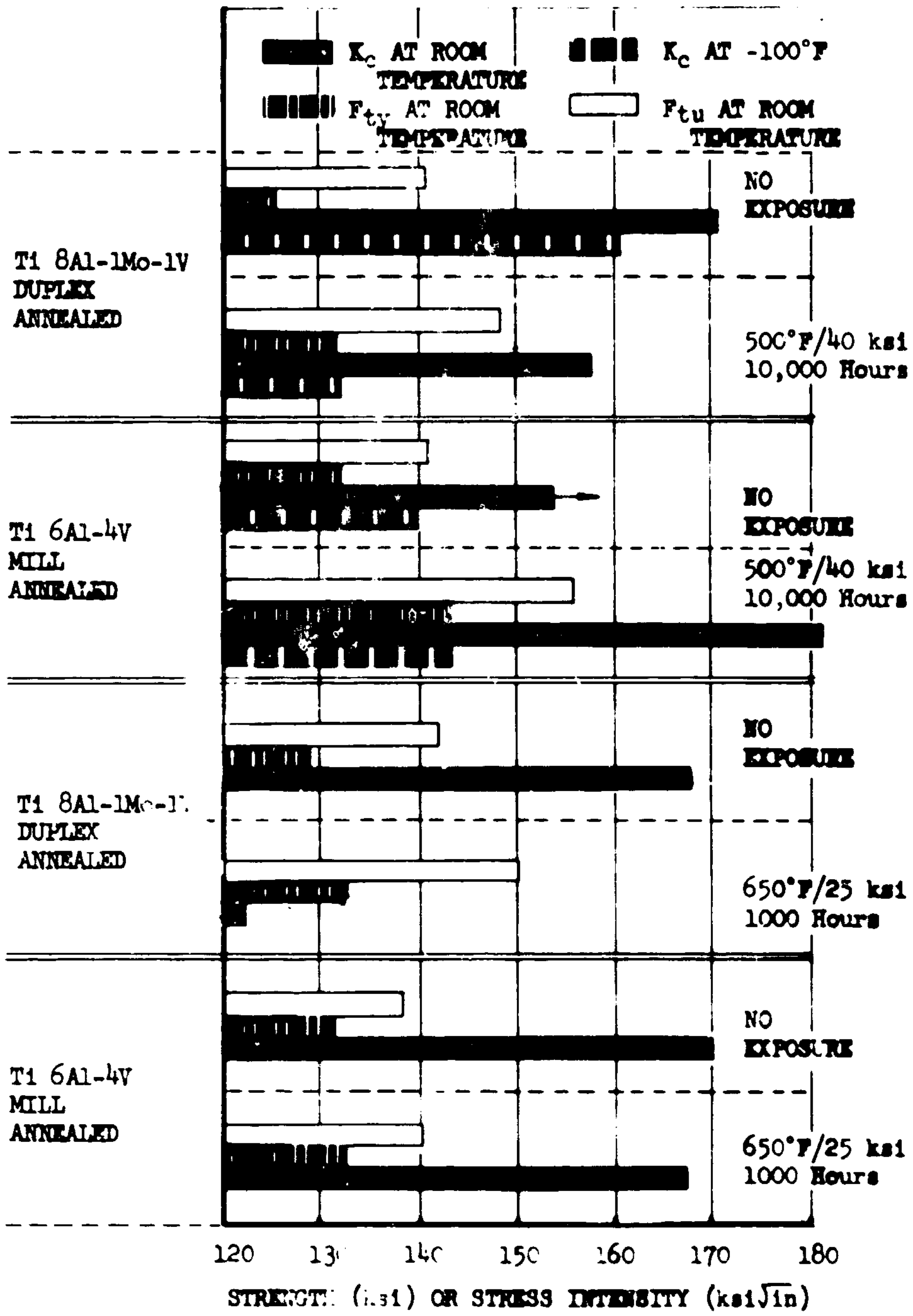

Figure 2-14. Effect of Stress and Temperature on Properties of Titanium Alloys

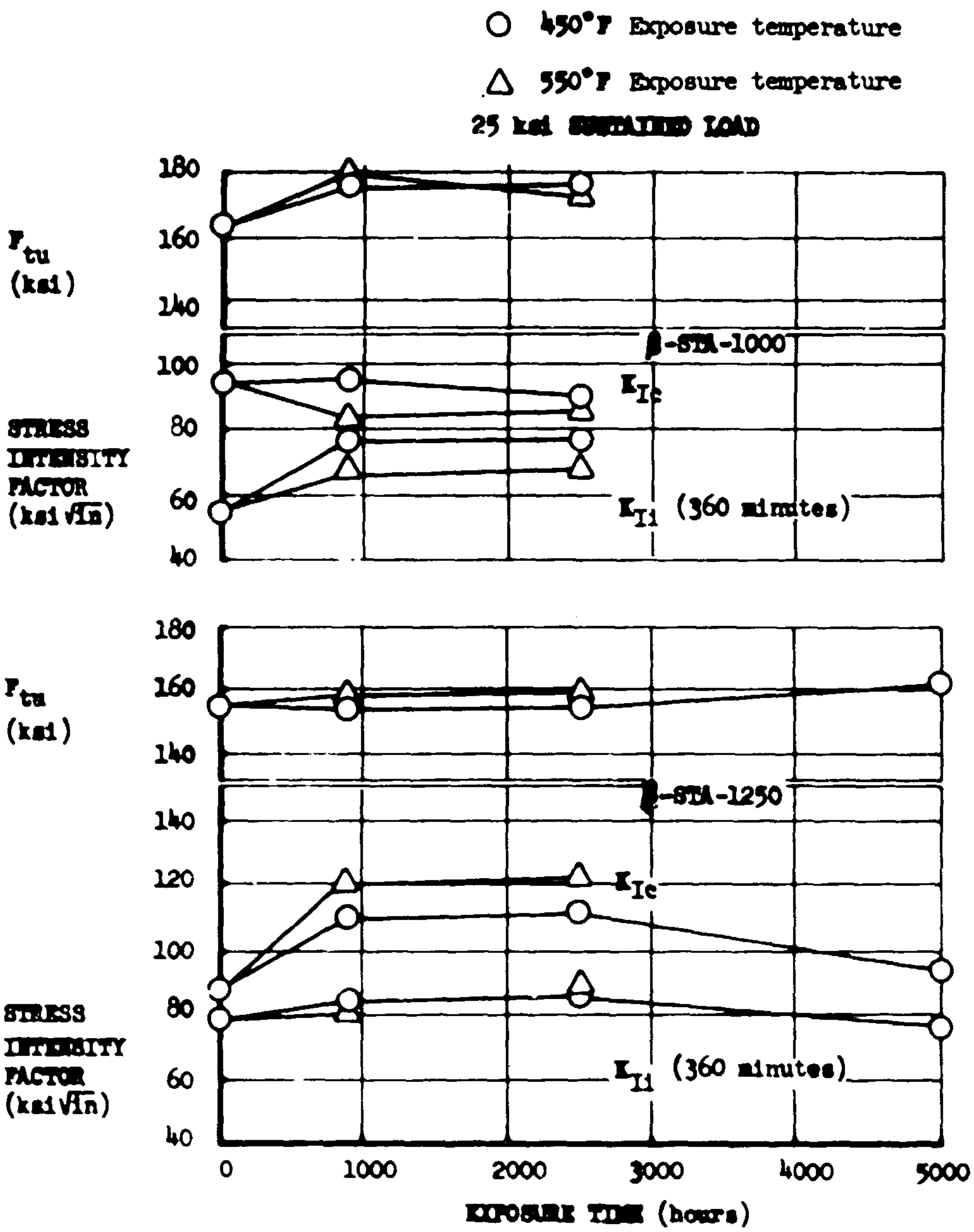

Figure 2-15. Effect of Time, Temperature, and Stress on Properties of Ti 6Al-4V Plate

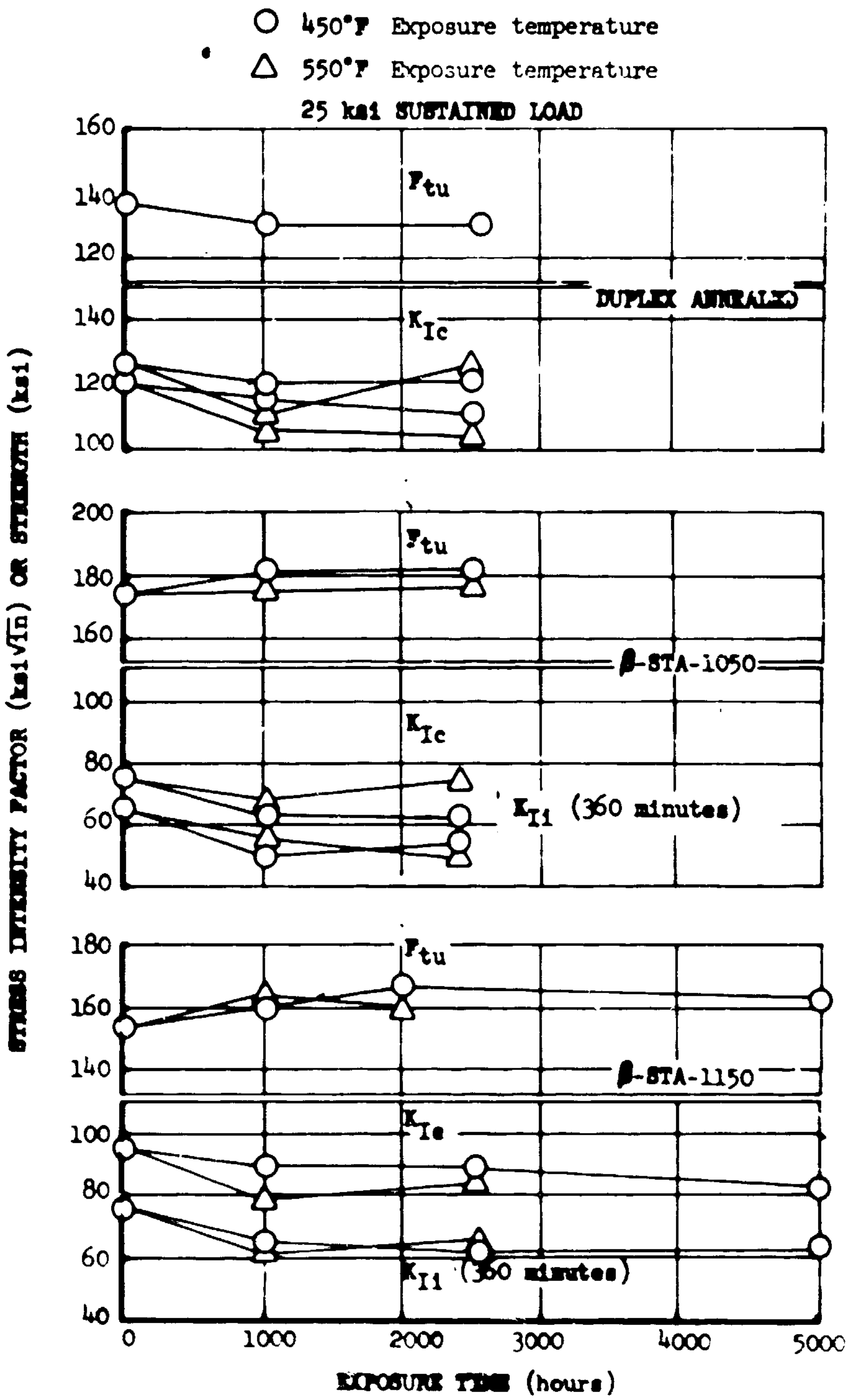

Figure 2-16. Effect of Time, Temperature, and Stress on Properties of Ti 4Al-3Mo-1V

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A comprehensive investigation of annealing, solution, and aging temperatures coupled with time and cooling rates showed the superiority of beta processing for thick section material. Beta processing provides the best properties of strength, toughness, and stress corrosion resistance.

Current company research studies aimed at identification of the mechanism of environmental crack growth have contributed to explaining the role of beta processing in improving resistance to this phenomenon. Cracking occurs in the alpha titanium phase and the beta phase acts as a crack arrestor as illustrated in Fig. 2-17. When the microstructure includes large equiaxed grains as in the alpha-beta processed material (Fig. 2-18), the beta is not effective as a crack arrestor. However, if the beta tends to be lamellar and randomly distributed between the alpha plates as in beta processed material (Fig. 2-19), the beta is a very efficient crack arrestor.

The joint Boeing-Lockheed titanium alloy selection program showed mill annealed Ti 6Al-4V to have satisfactory resistance to salt water crack propagation in sheet thicknesses up to 0.050 in. Above this thickness, resistance gradually decreased. Therefore, application of mill annealed sheet is limited to thicknesses of 0.050 in. or less. It was found that higher annealing temperatures developed satisfactory resistance in thicker material and that beta processing provided a further improvement in both fracture toughness and environmental crack resistance. Considering the reduced tensile ductility of beta processed titanium alloys, it was established that sheet gages (up to 0.188 in. thickness) should not be beta processed because many sheet applications require good formability. Therefore, Ti 6Al-4V sheet thicker than 0.050 in. is duplex annealed. This treatment consists of a high temperature anneal (1725°F) followed by a 1250°F stabilization treatment.

Solution treated and aged conditions are also used in sheet applications where the increased strength is advantageous and where quench distortion does not present a problem. Solution treatment followed by a four hour 1000°F age is used where high strength is desired and moderate fracture toughness is satisfactory. A higher aging temperature (1250°F for four hours) is applied when increased toughness is required and strength higher than that for the annealed condition is advantageous.

All plate, forgings, and extrusions are beta processed. Because of the increased section thickness of these products, solution treatments are more readily accomplished without quench distortion. These products are therefore used in the heat-treated condition when the increased

Figure 2-17. Stress Corrosion Cracks in Alpha Terminating at Beta

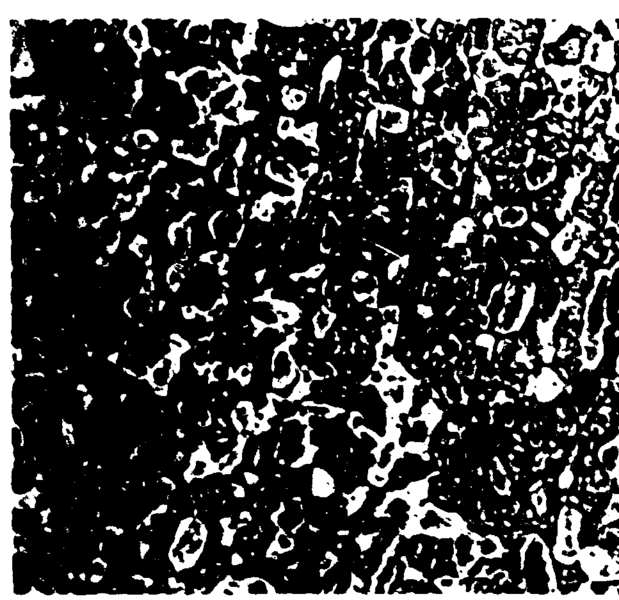

Figure 2-18. Microstructure of Alpha Beta Processed Ti 6Al-4V

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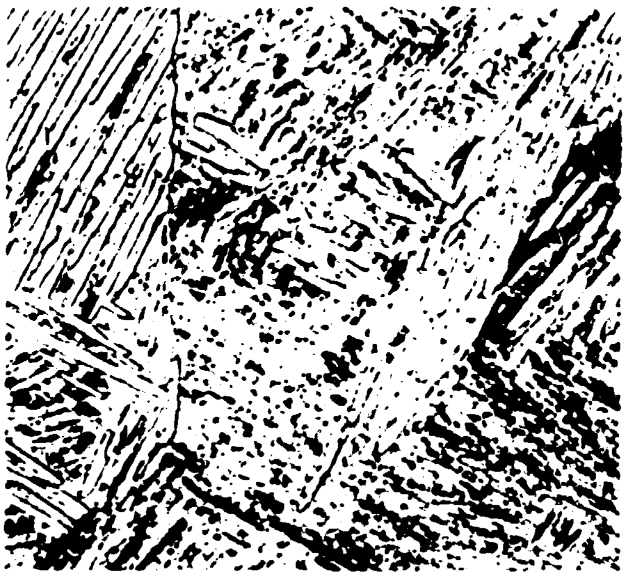

Figure 2-19. Microstructure of Beta Processed Ti 6Al-4V

strength is desired. Both the 1000° and 1250°F age conditions are used to provide the best strength-toughness combination for a specific design.

Figures 2-20 through 2-27 show the residual strength of precracked surface flawed (plane strain) and through-cracked (plane stress) panels in various conditions.

2.1.2.2 Welding

In general, the titanium alloys selected have good weldability. Welding will be used for both structural and nonstructural joining where advantages in cost, weight, and properties are realized. Fusion welding is not used in fatigue critical structure where the primary loading direction is parallel to the weld line.

a. Fusion Welding

Fusion welding is accomplished by the processes discussed below. Table 2-D shows a comparison of mechanical properties of weldments made by these processes.

1. Gas shielded tungsten arc (GTA) welding, both manual and mechanized, are used primarily for welding sheet material where complete penetration can be attained from one side of the joint. It will be used with or without the addition of filler metal as dictated by the requirements of the joint.

2. Dual gas-shielded tungsten arc (DGTA) welding is a modification of GTA welding in which both sides of the joint are welded simultaneously by two GTA torches approximately opposed. It has the advantage of balancing the shrinkage transverse to the axis of the weld, thus appreciably reducing distortion. As the entire weld area and the two torches are contained in an inert gas filled enclosure and no filler metal is used, weld contamination and defects are precluded. The nature of the DGTA process and attendant facilities limit its use to straight line butt joints in flat or gently curved details where starting and run-off tabs can be attached at the ends of the weld line. A typical application for this process is the joining of wing skins, up to a maximum of 0.5 inch thickness, to increase panel length.

3. Gas shielded metal arc (GMA) welding, mechanized only, is used when joining thicknesses in excess of 0.5 in. and electron beam welding is impractical. Figure 2-28 is a photograph of the full scale wing pivot test lug fabricated by this process. Six welds, 86-in. long and 0.87-in. thick, were made for this assembly. Properties of specimens from the certification welds are shown in Table 2-E.

4. Electron beam (EB) welding is a process conventionally accomplished in high vacuum, the process consistently produces welds without contamination, inclusions, or porosity. The large depth-to-width ratio of the weld and heat-affected-zone tends to minimize shrinkage distortion. Figure 2-29 shows a typical sine-wave beam assembly welded by melting through the cap into the web. The web path was accurately traced by a contour following system; a minimum underbead fillet size of 0.030 in. was maintained (Fig. 2-30).

The above processes have all been accorded production status for welding titanium alloys and are well documented by process specifications which meet or exceed the requirements of applicable military specifications. Additionally, the plasma arc process may be used if the advantages promised by limited tests are confirmed by the more extensive development program now in progress.

Filler metal additions for the fusion welding processes are made with commercially pure titanium weld wire. This selection was based

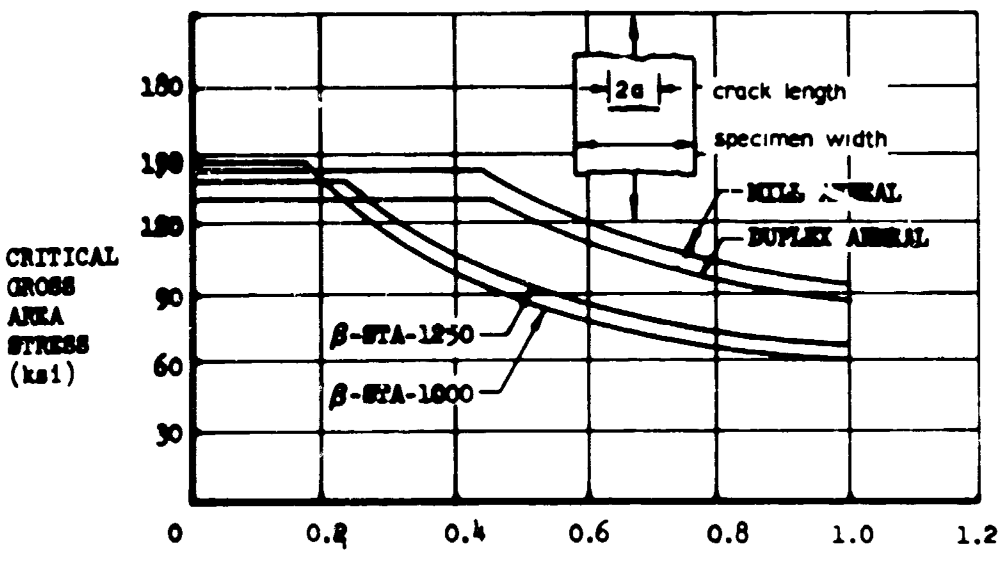

Figure 2-20. Residual Strength of Through Cracked Ti 6A1-4V

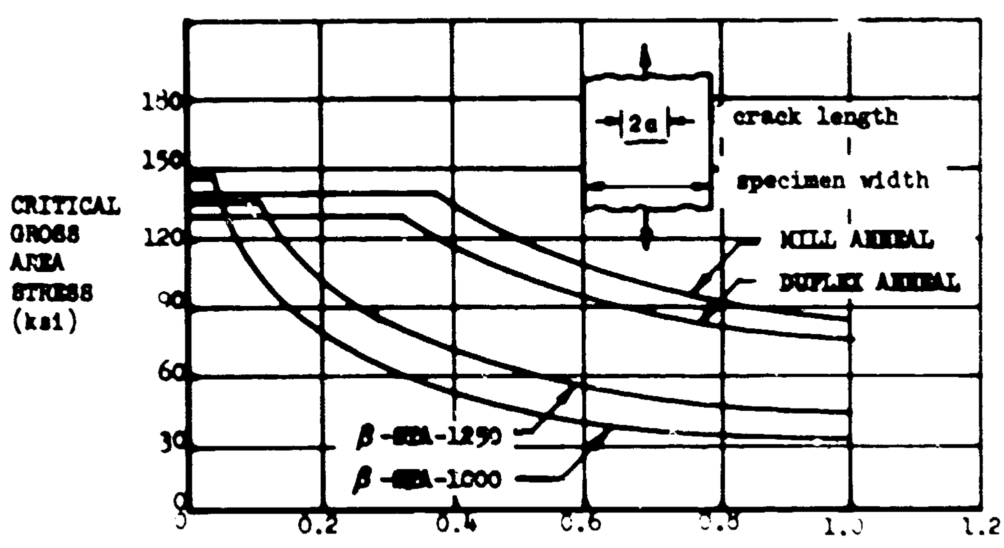

Figure 2-21. Residual Strength of Through Cracked Ti 6A1-4V in 3.5 Percent NaCl Solution

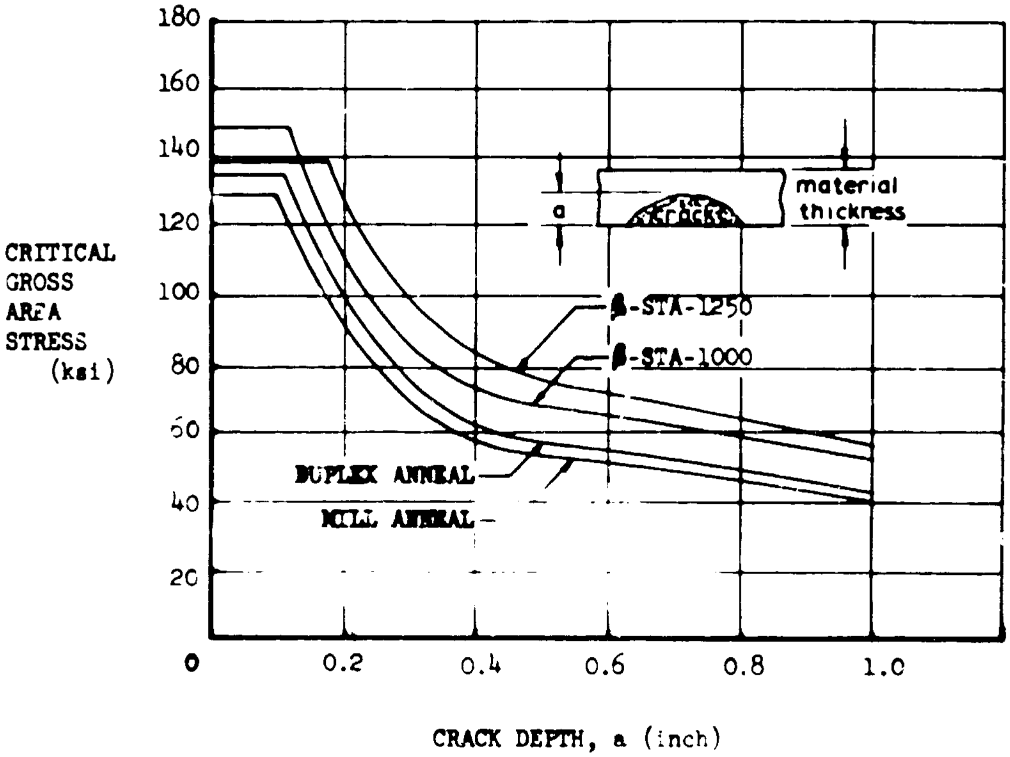

Figure 2-22. Residual Strength of Surface Flawed Ti 6Al-4V

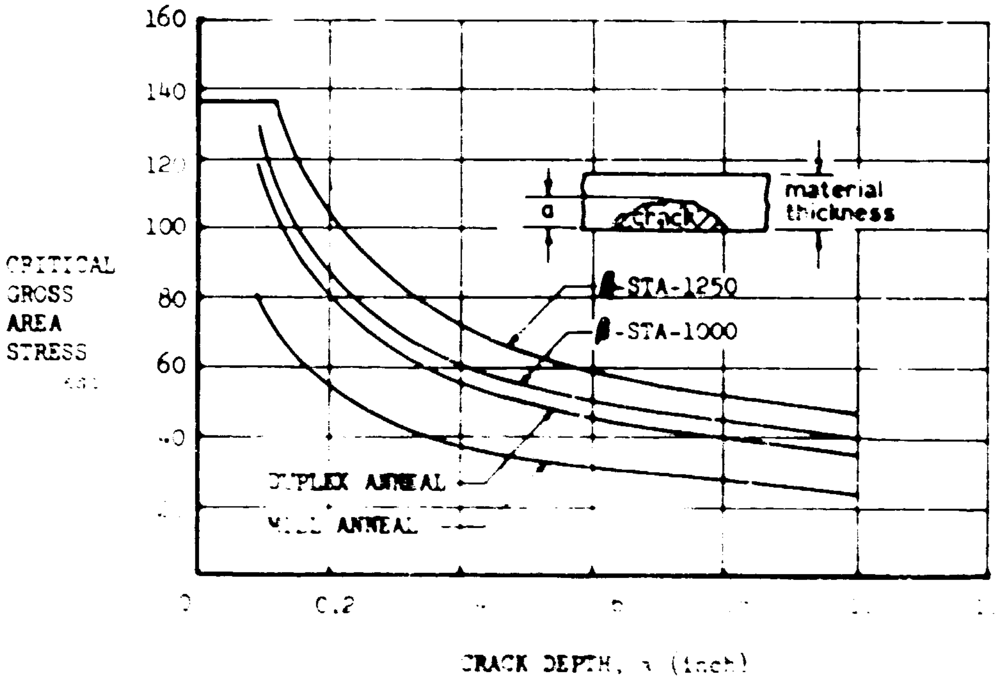

Figure 2-23 Residual Strength of Surface Flawed Ti 6Al-4V in 3.5 Percent NaCl Solution

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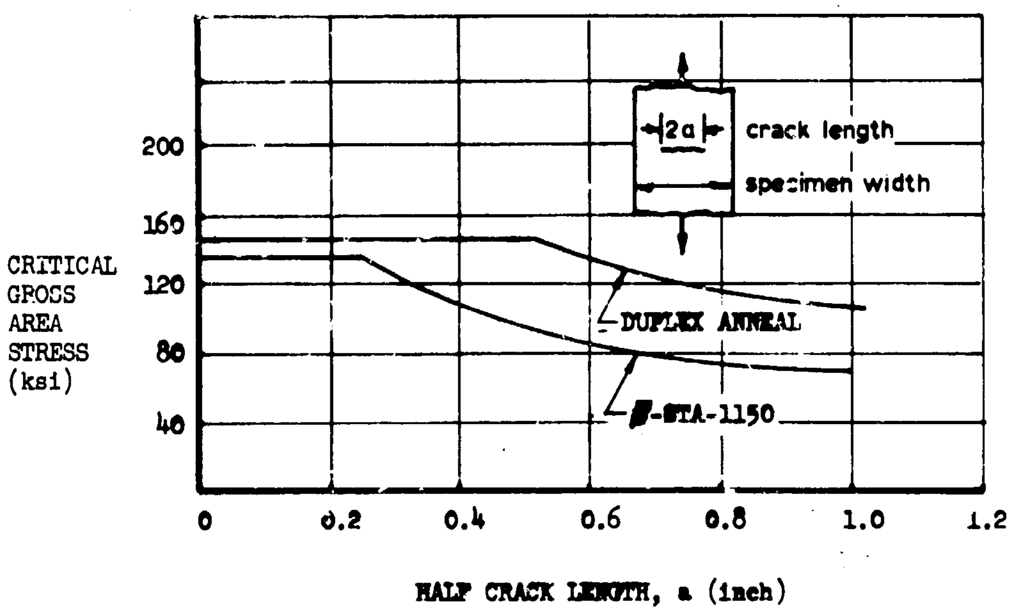

Figure 2-24. Residual Strength of Through Cracked Ti 4Al-3Mo-1V

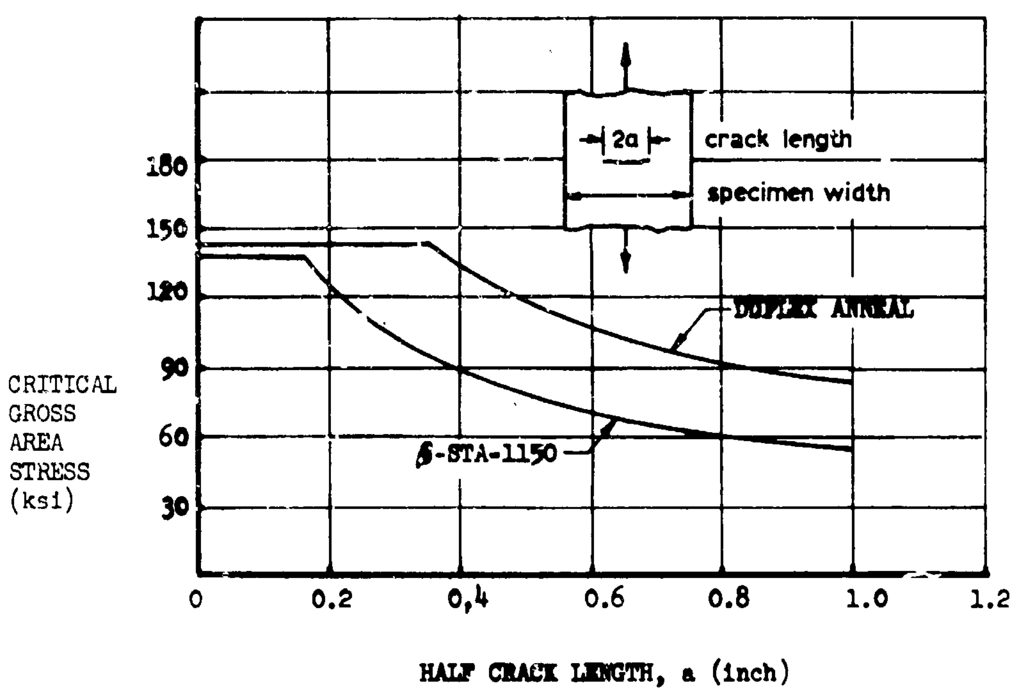

Figure 2-25. Residual Strength of Through Cracked Ti 4Al-3Mo-1V in 3.5 Percent NaCl Solution

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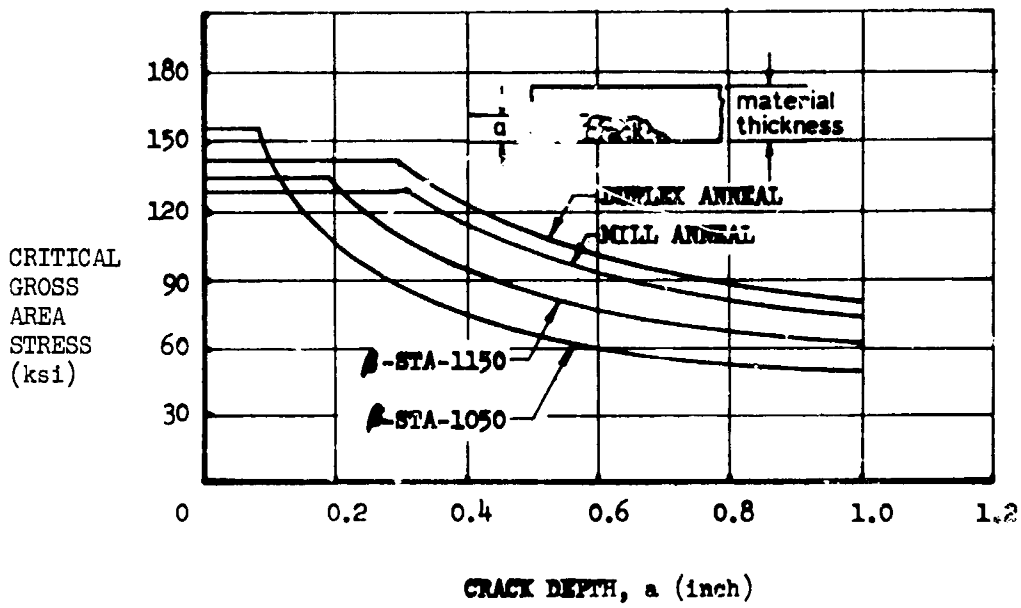


Figure 2-26. Residual Strength of Surface Flawed Ti 4A1-3Mo-1V

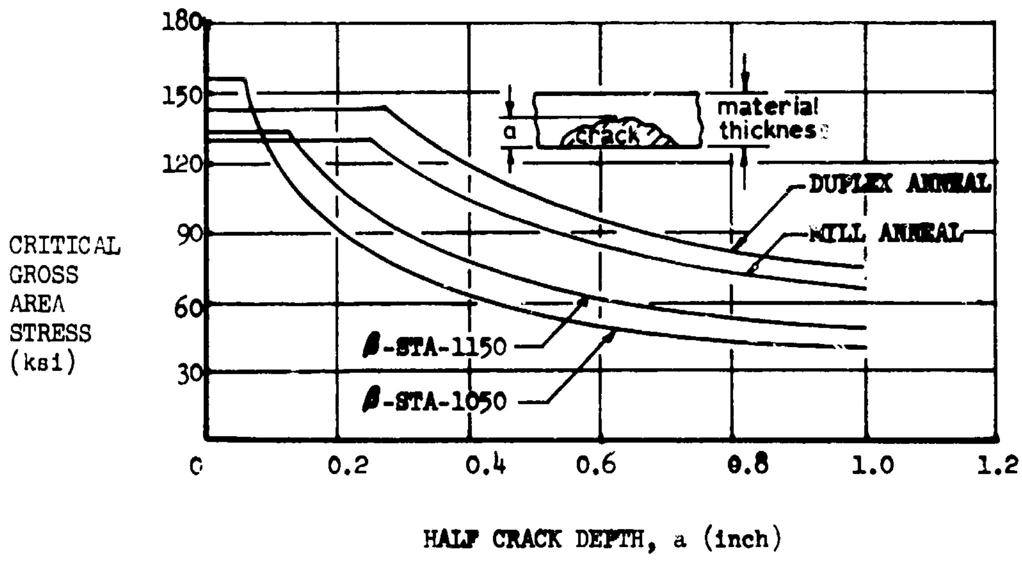


Figure 2-27. Residual Strength of Surface Flawed Ti 4A1-3Mo-1V in 3.5 Percent NaC1 Solution

Table 2-D. Mechanical Properties of GTA, DGTA, GMA, and EB Welding, Ti 6Al-4V

Weld Process	Material Thickness	Processing Sequence ▷	Filler Wire	Longitudinal Weld Tensile					Transverse Weld Tensile				
				Stress (ksi)		Joint Efficiency Percent	Percent Elongation		Stress (ksi)		Joint Efficiency Percent	Percent Elongation	
				F_{ty}	F_{tu}		1 in.	2 in.	F_{ty}	F_{tu}		1 in.	2 in.
GTA	0.060	A-W-SR	Comm. Pure	132.5	138.6	97.9	13	10	126.1	130.4	92.2	15	9.0
	0.060	A-W-SR	5Al-2.5Sn	135.6	141.5	100.0	11	8.4	127.7	131.4	93.0	16.2	10.0
	0.060	A-W-SR	6Al-4V	131.8	138.2	97.7	9	6.6	127.7	132.0	93.3	15.8	10.2
	0.060	STA-W-SR	Comm. Pure	140.6	151.9	92.4	8	6	147.5	151.3	92.0	4	2
	0.060	STA-W-SR	5Al-2.5Sn	145.2	157.2	95.6	7	5.5	153.9	159.9	97.3	5	3
	0.060	STA-W-SR	6Al-4V	146.3	155.9	94.8	5.5	4	155.7	164.1	99.8	6.5	5
	0.250	A-W-SR	Comm. Pure	130.8	140.8	100.0	13.8	11.8	111.8	127.9	90.9	8.2	4
	0.250	A-W-SR	5Al-2.5Sn	138.3	145.3	99.4	15	12	129.3	137.9	94.3	12.4	8
	0.250	A-W-SR	6Al-4V	139.7	153.1	100.0	7.2	7	132.3	142.7	100.0	2.6	5.6
DGTA	0.250	A-W-SR	None	133.0	142.1	100.0	12.5	9	143.8	149.2	100.0	16	11
GMA	0.500	A-W-SR	6Al-4V	137.5	142.9	100.0	13.8	10.3	128.3	136.2	96.5	20.6	13.5
EB	0.050	A-W	None	-	-	-	-	-	134.9	144.7	98.4	13.0	8.0
	0.155	A-W	None	-	-	-	-	-	136.6	151.0	100.0	15.4	10.3

▷ A - Mill annealed condition
STA - Solution treated and aged
W - Welded by specified process
SR - Stress relieved

GTA - Gas tungsten arc
DGTA - Dual gas tungsten arc
GMA - Gas metal arc
EB - Electron beam

Table 2-E. GMA Mechanical Properties Data

Data Source	Type of Test	Average Ultimate Tensile Strength (ksi)	Standard Deviation (ksi)	Minimum* (Tensile ksi)
Boeing	Base Metal	128.21	6.93	114.35
Vendor	Base Metal	125.37	6.23	112.91
Boeing	Welds	119.70	2.79	114.12

* Minimum = average value minus 2 times standard deviation

NOTE: GMA Certification Welds — 0.870 in thick

Ti 8Al-1Mo-1V — base metal

Commercially pure titanium filler wire

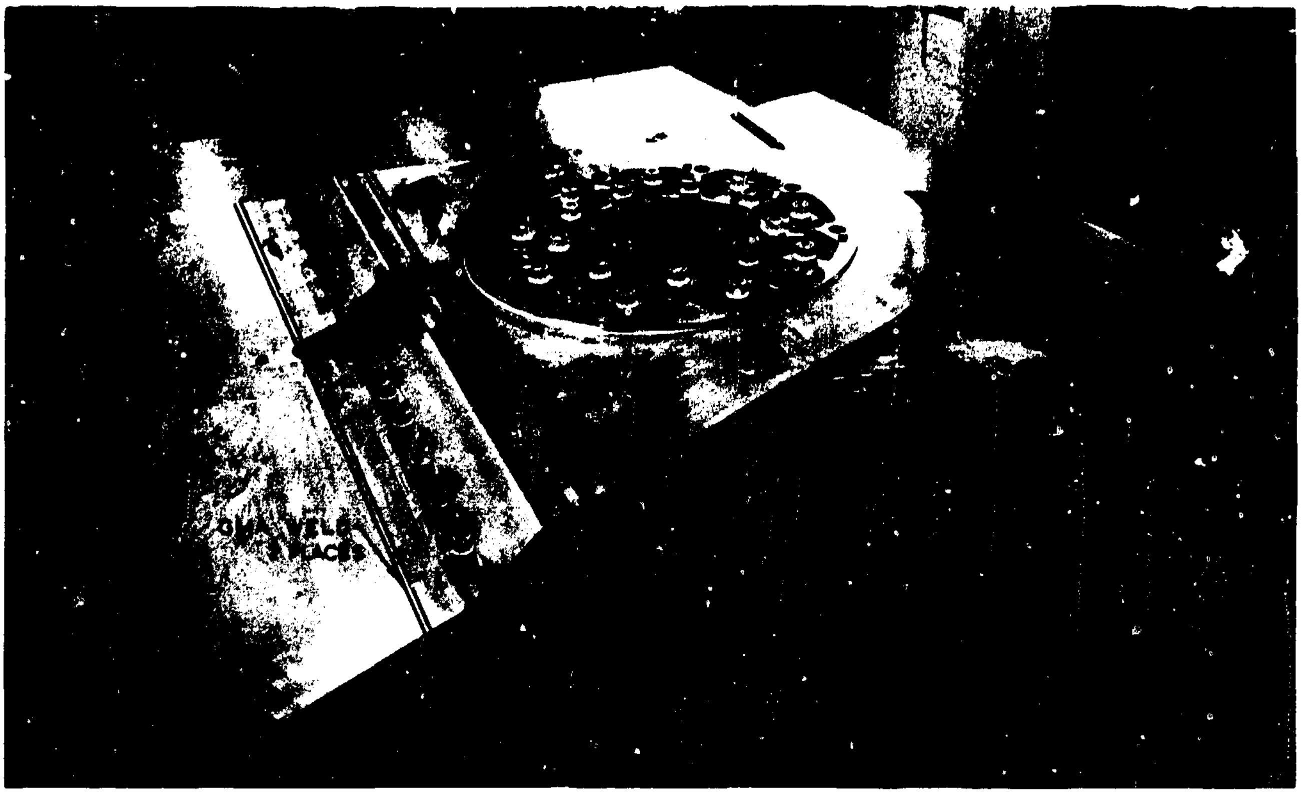


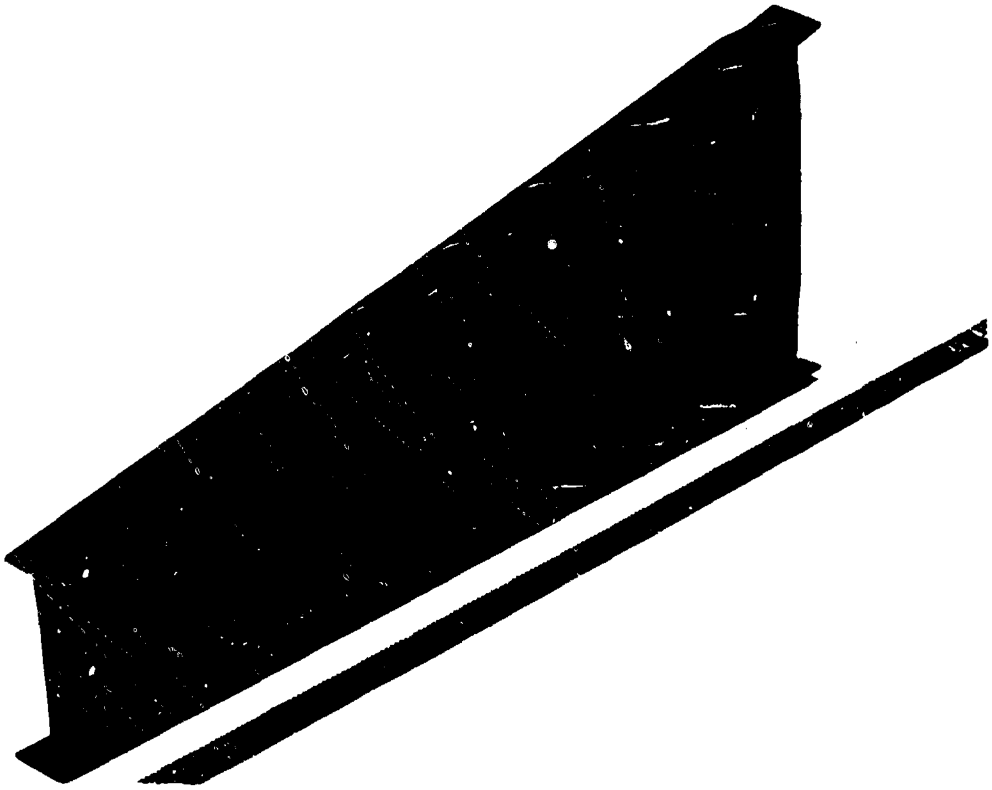
Figure 2-28. Full-Scale Wing Pivot Test Lug, GMA Fusion Welded

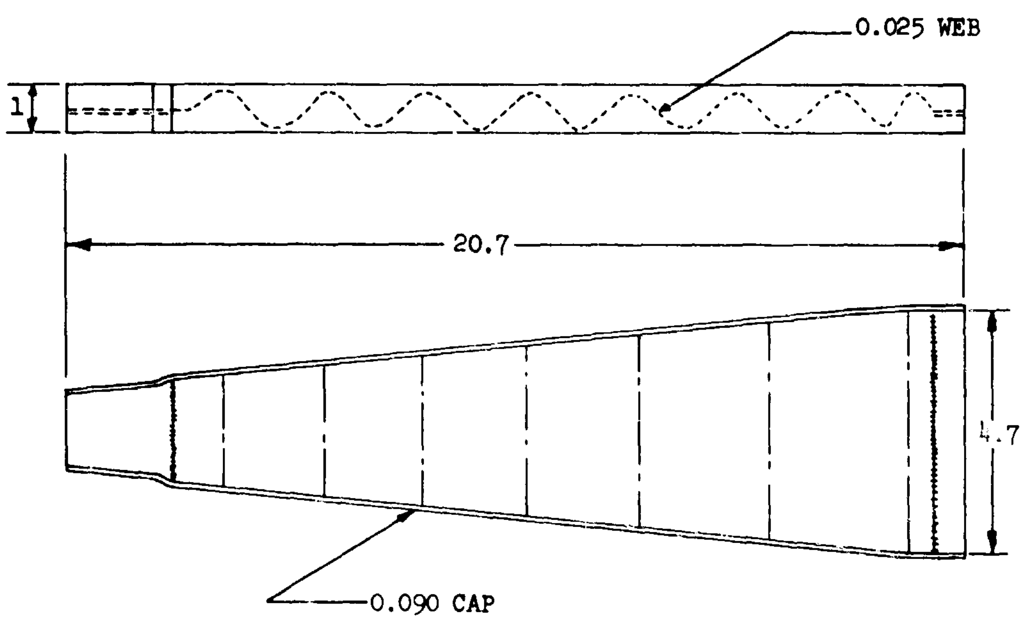
primarily on the inability, to date, of suppliers to provide alloy grade wire of consistently high quality. As the weld wire quality is improved, Boeing will take advantage of the higher joint efficiencies obtainable with Ti 6Al-4V or Ti 5Al-2.5Sn alloys. Table 2-F shows different weld wire compositions as controlled by company material specifications. Current testing is aimed at establishing the benefits to be derived from the extra low interstitial (ELI) grades of weld wire. Table 2-D shows the properties and relative joint efficiencies of welded butt joints in Ti 6Al-4V made with the various filler metal alloys.

The crack growth sensitivity of welds in aqueous salt solution was investigated. The results demonstrated that, in general, the weld metal and heat-affected zone are equal to or better than the base material. Welds in sheet material were evaluated using the 12 inch wide center cracked specimen. Figure 2-31 shows the results obtained from one such series of tests on 0.060 in. thick Ti 6Al-4V sheet. The panels were tested in air and in 3.5 percent salt solution. After the corrosion fatigue characteristics had been evaluated by cyclic loading, one panel was loaded to failure at 1000 psi per second to establish the fracture toughness of the joint. The other panel was sustained loaded in 3.5 percent salt solution to establish the threshold stress intensity level for environmental crack growth. Failure in both tests was accompanied by immediate propagation of the fatigue crack out of the weld zone into the base material.

The threshold stress intensity factor level determined by sustained loading was 143 ksi $\sqrt{in.}$ The susceptibility ratio, K_I/K_C, was 0.89 confirming other observations that this alloy in sheet thicknesses is relatively immune to environmental crack growth. The weld metal suffered no loss in resistance to fatigue crack growth in the presence of the salt water.

Typical effects of NaCl environment on crack growth in welded plate are shown in Fig. 2-32 for 0.5-in.thick Ti 6Al-4V. The 0.5 by 1.5 by 7.5-in.precracked notch-bend specimen was used. The results show that the weld metal and heat affected zone are satisfactory and similar to the base metal.





ALL DIMENSIONS ARE IN INCHES

Figure 2-29. Electron Beam Welded Sine Wave Assembly

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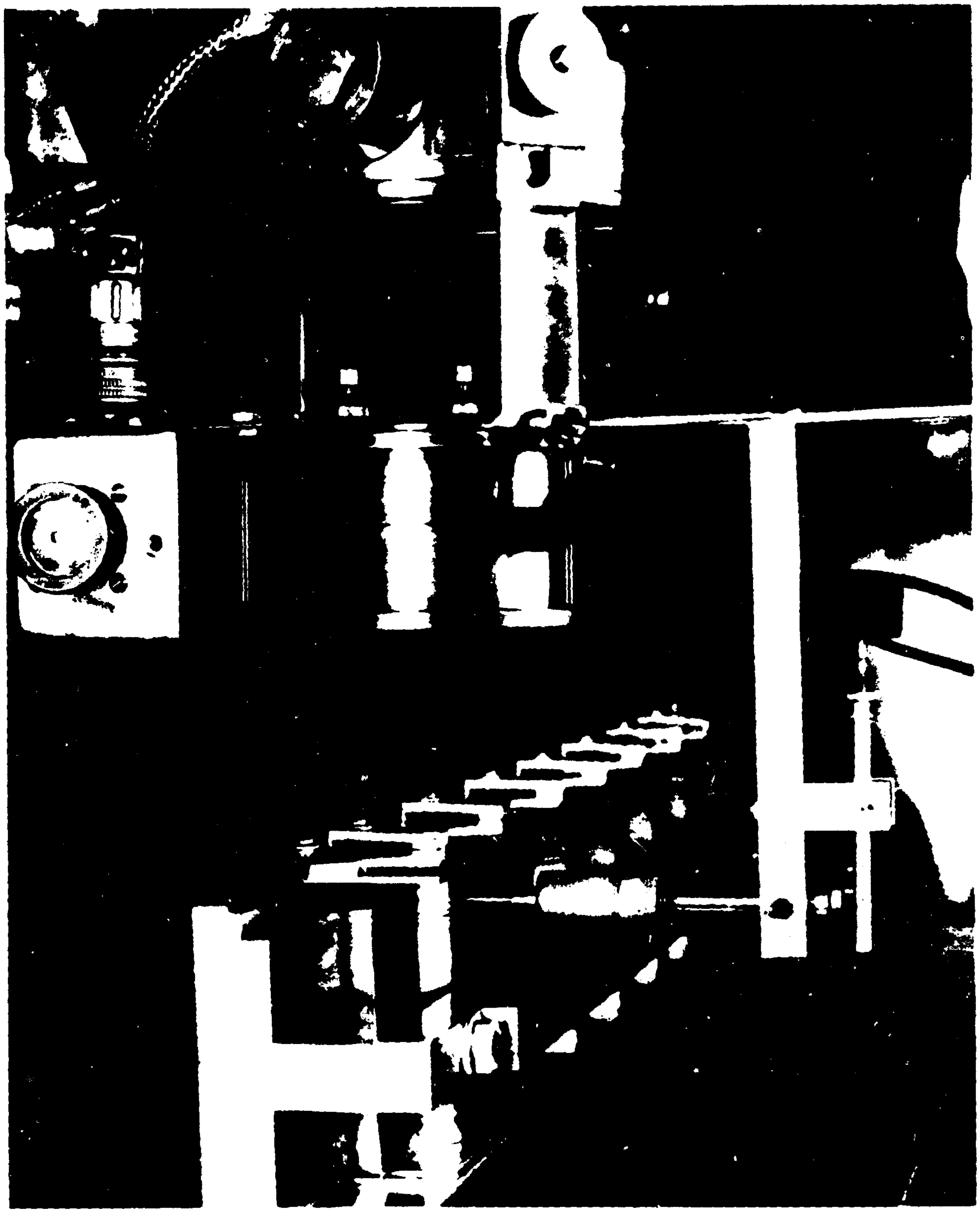

Figure 2-30. Tracer Follower for Sine Wave E. B. Weld

Table 2-F. Titanium Filler Wire Compositions

	Alloy and Grade								
	Standard	Standard	ELI	Standard	ELI	Standard	ELI	Standard	ELI
Element Percent	B120VCA	Commercial Pure	Commercial Pure	5Al-2.5Sn	5Al-2.5Sn	6Al-4V	6Al-4V	3Al	3Al
Manganese	-	0.20	0.010	-	0.010	-	0.010	-	0.010
Aluminum	2.0-4.0	-	-	4.7-5.6	4.7-5.6	5.50-6.75	5.50-6.75	2.5-3.5	2.5-3.5
Tin	-	-	-	2.0-3.0	2.0-3.0	-	-	-	-
Molybdenum	-	-	-	-	-	-	-	-	-
Chromium	10.0-12.0	-	-	-	-	-	-	-	-
Vanadium	12.0-15.0	-	-	-	-	3.5-4.50	3.5-4.50	-	-
Iron	0.50	0.30	0.15	0.15 nominal	0.15	0.25	0.15	0.3	0.15
Carbon	0.10	0.10	0.035	0.08	0.035	0.05	0.035	0.07	0.035
Nitrogen	0.07	0.07	0.009	0.05	0.009	0.015	0.009	0.05	0.009
Hydrogen	0.020	0.015	0.005	0.015	0.005	0.0125	0.005	0.015	0.005
Oxygen	-	0.18	0.09	0.12	0.09	0.12-0.17	0.09	0.150	0.09
Total, Other Elements	-	-	-	-	-	-	-	-	-
Titanium	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder

NOTE: All values maximum unless otherwise noted.
ELI = Extra-low interstitials
All values are percents

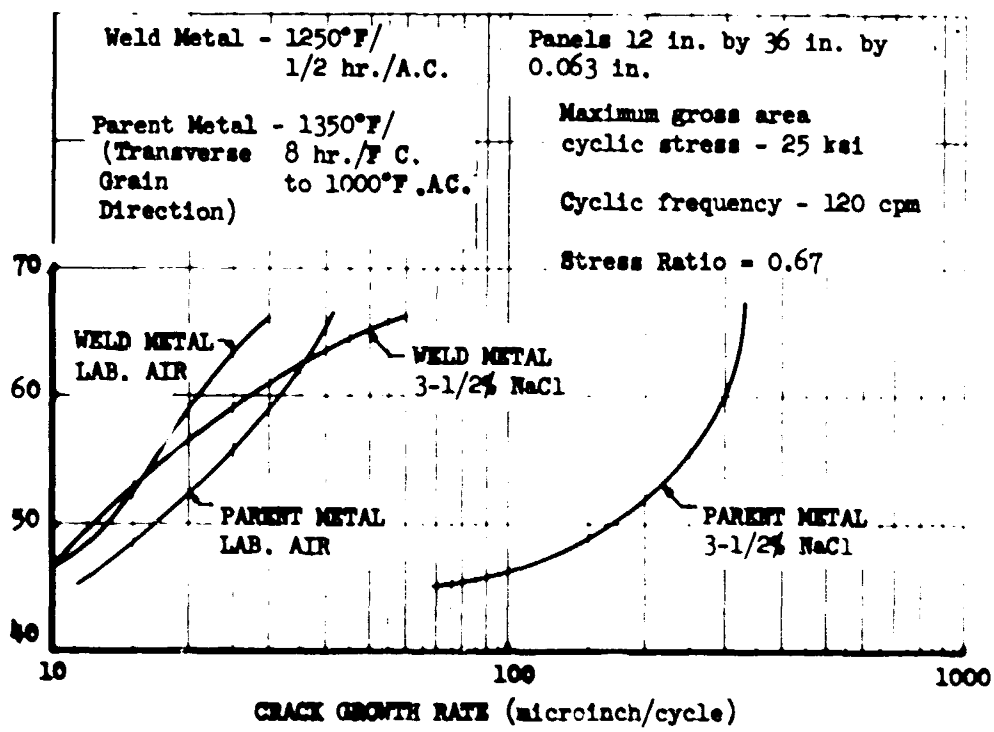

Figure 2-31. Corrosion and Fatigue Characteristics of Ti 6Al-4V Base Metal and Fusion Welds

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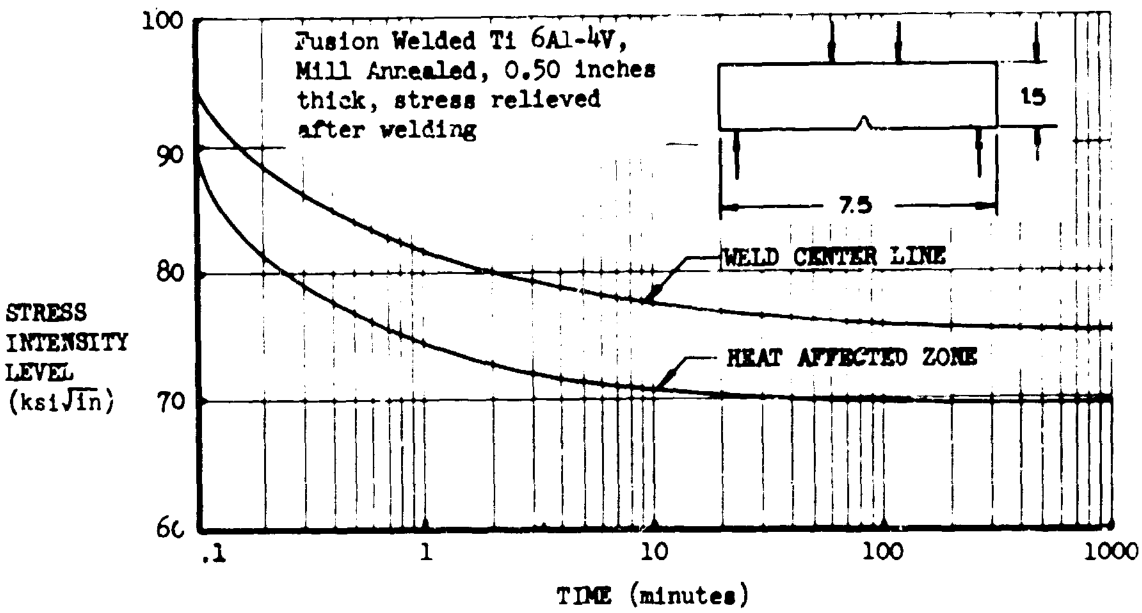


Figure 2-32. Environmental Sustained Load Characteristics of Welded Ti 6Al-4V

Weld stability tests were conducted in a Boeing—North American welding program (Ref. 8). The test specimen consisted of a 0.20-in.thick plate of mill annealed Ti 6Al-4V with a flush transverse gas shielded tungsten arc weld made without filler metal addition. The results of this program showed that a slight increase (2.3 percent) in ultimate tensile and tensile yield strengths occurred, accompanied by a very slight reduction in elongation, after exposure to 650°F for 1000 hours at a sustained stress of 25,000 psi. Since this temperature is well above the maximum temperature anticipated for titanium applications, weld stability should present no problem.

Residual stresses in welds are caused by thermally induced plastic flow due to expansion of the heated material followed by the contraction on cooling of the weld metal and adjacent area. Stresses transverse to the weld are insignificant except for multiple pass welds in thick material but the longitudinal stresses usually approach yield strength magnitude. The welding process used has little effect on the magnitude of peak residual stresses but generally speaking processes which produce narrow welds have the higher stresses; for example, electron beam welds which have the narrowest fusion zone have the highest peak stresses measured (over 100 ksi in Ti 6Al-4V).

All fusion welds in primary structure are stress relieved to minimize high residual stresses which can result in stress corrosion, delayed fracture of thick section welds, and reduction of fatigue life. Stress relief methods and supporting data are discussed in Sec. 2.6.

b. Resistance Spotwelding

Resistance spotwelding is used wherever this process is advantageous in design. Possible applications include wing rib assemblies and numerous secondary or nonstructural components. Studies have shown that the titanium alloys Ti 6Al-4V and Ti 4Al-3Mo-1V, are readily spotweldable. No special welding equipment or test facilities are required; however, part cleanliness is very important.

Certain combinations of heat treatment and welding sequence (Table 2-G) and the use of an interface metal (Table 2-H and Fig. 2-33) have resulted in mechanical properties shown. The fatigue life for lap shear joints using these combinations showed little improvement over conventional spotwelded structure. However, there is evidence that fatigue life improvement is possible with use of an interface adhesive or sealant. This technique is being investigated further (Fig. 2-34).

Table 2-G. Effect of Weld-Heat Treat Sequence on Properties of Spot Welded Ti 6Al-4V

Material Thickness	Type of Tests:	Features:	Sequence of Welding and Heat Treatments: W Only	S-W-A	S-A-W	S-A-W-A
0.060/0.060	Shear strength	Average	4791	4395	3535	3856
	Shear strength	Variation	0.033	0.114	0.066	0.158
	Tension pullout	Average	964	1213	956	1157
	Tension pullout	Variation	0.135	0.124	0.084	0.143
	Tension pullout	(T)/(S) ratio	20.1%	27.6%	27.0%	30.0%
	Impact tension	Average	27.6	36.4	27.0	35.0
	Impact tension	Variation	0.181	0.110	0.074	0.121
	Weld diameter	(Macros)	0.26"	0.25"	0.25"	0.25"
0.125/0.125	Shear strength	Average	10252	9944	8604	9300
	Shear strength	Variation	0.049	0.054	0.074	0.095
	Tension pullout	Average	3362	3414	2935	3413
	Tension pullout	Variation	0.057	0.126	0.174	0.062
	Tension pullout	(T)/(S) ratio	32.8%	34.3%	34.1%	26.7%
	Impact tension	Average	91.2	127.2	68.2	87.4
	Impact tension	Variation	0.171	0.424	0.381	0.217
	Weld diameter	(Macros)	0.345"	0.33"	0.34"	0.34"

NOTES: Shear strengths and tension pullout strengths are given in pounds.
Impact tension strengths are given in foot-pounds.
Weld diameters are given in inches.
(T)/(S) ratio = Tension shear ratio

SEQUENCE CODE FOR WELDING AND HEAT TREATMENT:

W = Weld
S = Solution heat treat (1700 ± 25°F for 15 minutes. Cold water quench)
A = Age (1250 ± 25°F for 4 hours. Cool in still air)

Table 2-H Evaluation of Interfoils in Spot Welding Titanium Alloy

Thickness (in.)	Foil Alloy	Shear(S)		Tension Pullout(T)			Impact Tension		Weld Diameter, Inches	
		Average, (lb)	Variation*	Average, (lb)	Variation*	(T)/(S) Ratio	Average, (ft lb)	Variation*	Average	Specification Minimum
0.080	Nioro	7324	0.139	1548	0.103	0.211	54.8	0.328	0.280	0.260
0.080	Comm. Pure Ti	8196	0.056	1654	0.109	0.202	58.8	0.034	0.265	0.260
0.080	None	5315		1500		0.282	55.0		0.265	0.260
0.250	Nioro	26740	0.093	9944	0.109	0.372	192.2	0.161	0.500	0.490
0.250	Comm. Pure Ti	32020	0.075	11580	0.143	0.362	212.0	0.113	0.510	0.490
0.250	None	25000		7900		0.316	180.0		0.502	0.490

NOTE: * Variation = Range/Average

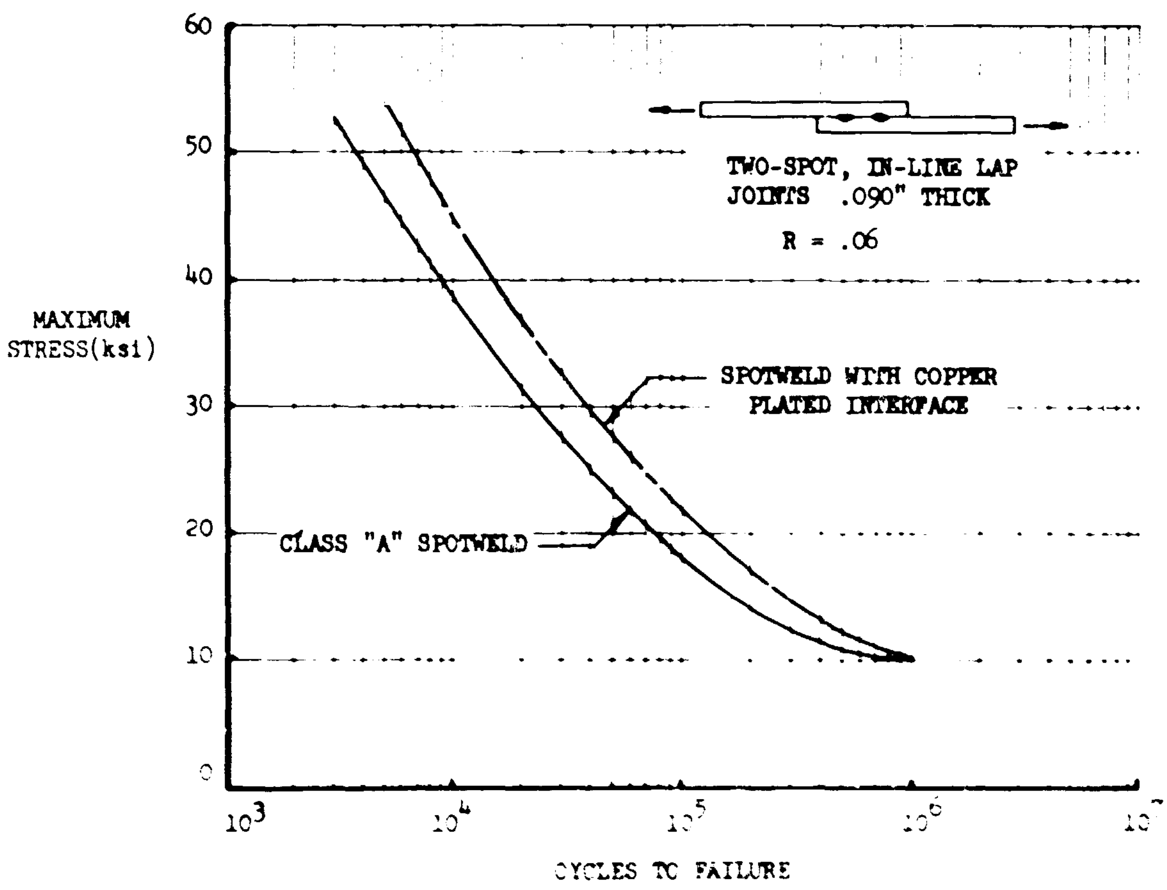


Figure 2-33. Effect of Interface Copper Plating on Fatigue Properties of Spot Welded Ti 6Al-4V

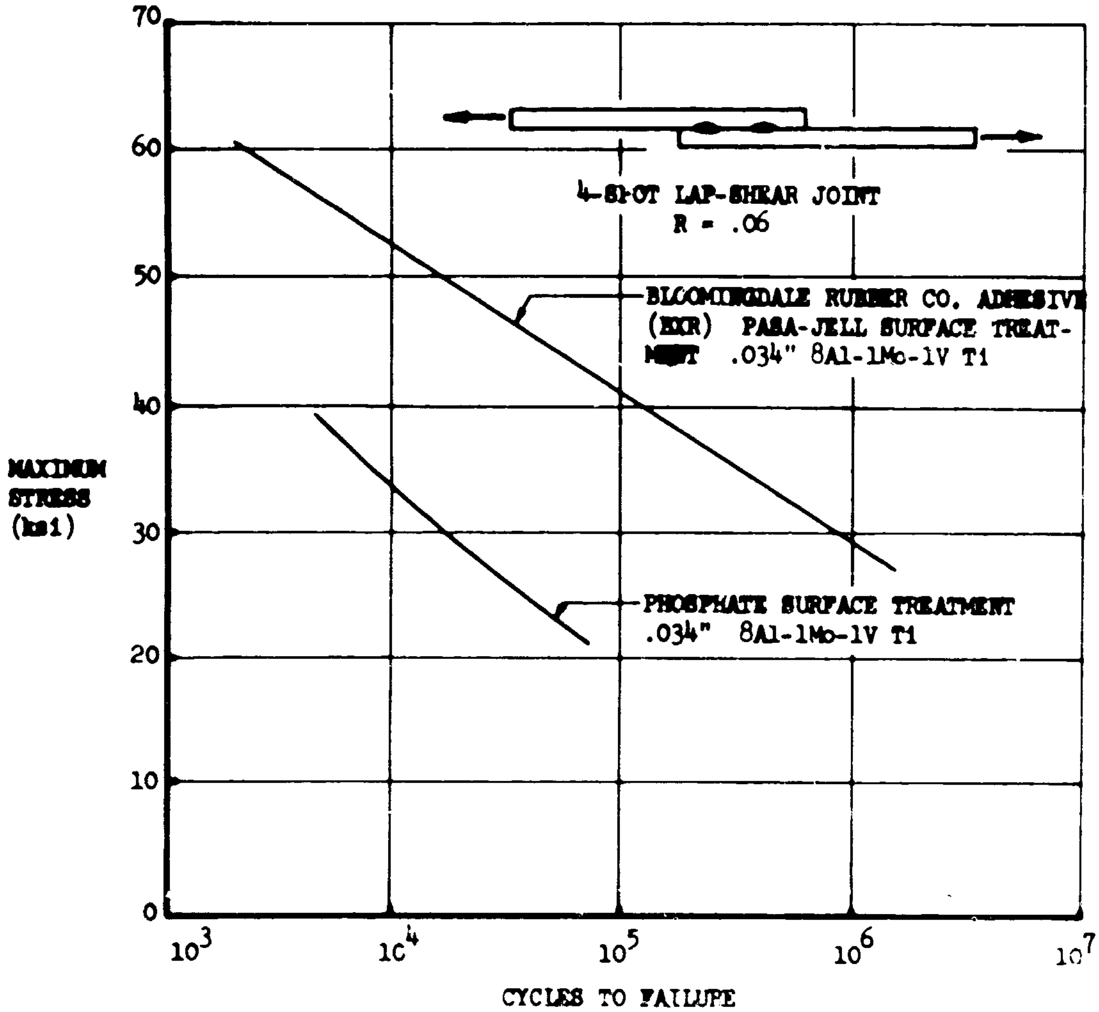


Figure 2-34. Effects of Interface Sealant on Fatigue Properties of Spot Welded Titanium Alloy

A Boeing process specification for spotwelding titanium has been prepared. This specification meets or exceeds the requirements of the applicable military specification.

c. Flashwelding

Flashwelding is used wherever this process provides design or manufacturing advantage or cost effectiveness. The process is applicable to butt joining of identical shapes; for example, stiffener extrusions, tubular landing gear joints, and rectangular bar sections. Since the entire weld is formed at one time, distortion is minimal and weld quality and reliability are excellent. Table 2-1 shows the mechanical properties of flashwelds in Ti 6Al-4V. Figure 2-35 shows fatigue data for Ti 6Al-4V specimens from which the weld reinforcement has been removed. The results indicate that the weld and base metal have nearly the same static and fatigue properties.

Flashwelding of titanium is done with conventional equipment and is controlled by a Boeing process specification. Further development of the process will be directed toward the welding of extruded shapes to determine configuration limits.

d. Pressure Welding

Pressure welding is used in applications similar to those for flashwelding. It is a solid state welding process in which coalescence is obtained while plastically upsetting the locally heated abutting ends using a constant end load. The advantage of this process is its capability for welding large cross-sectional areas with excellent metallurgical quality and high joint

Table 2-1. Mechanical Properties of Flash Welds

Weld No.	Tensile Strength, (psi)	Yield Strength, (psi)	Elongation (in 4D Percent)	Reduction of Area (Percent)
1	171,100	157,700	9	26.7
2	170,700	159,500	9	27.9
3	171,700	157,400	10	33.3
4	174,100	162,500	10	30.1
5	168,600	153,900	10.5	33.0
6	172,500	159,700	12.5	43.9
7	170,200	157,100	11.5	[illegible]1.8
Average	171,300	158,200	10.2	32.0

NOTE: Flashwelds were solution treated at 1750°F, water quenched, 900°F aged - 4 hours.

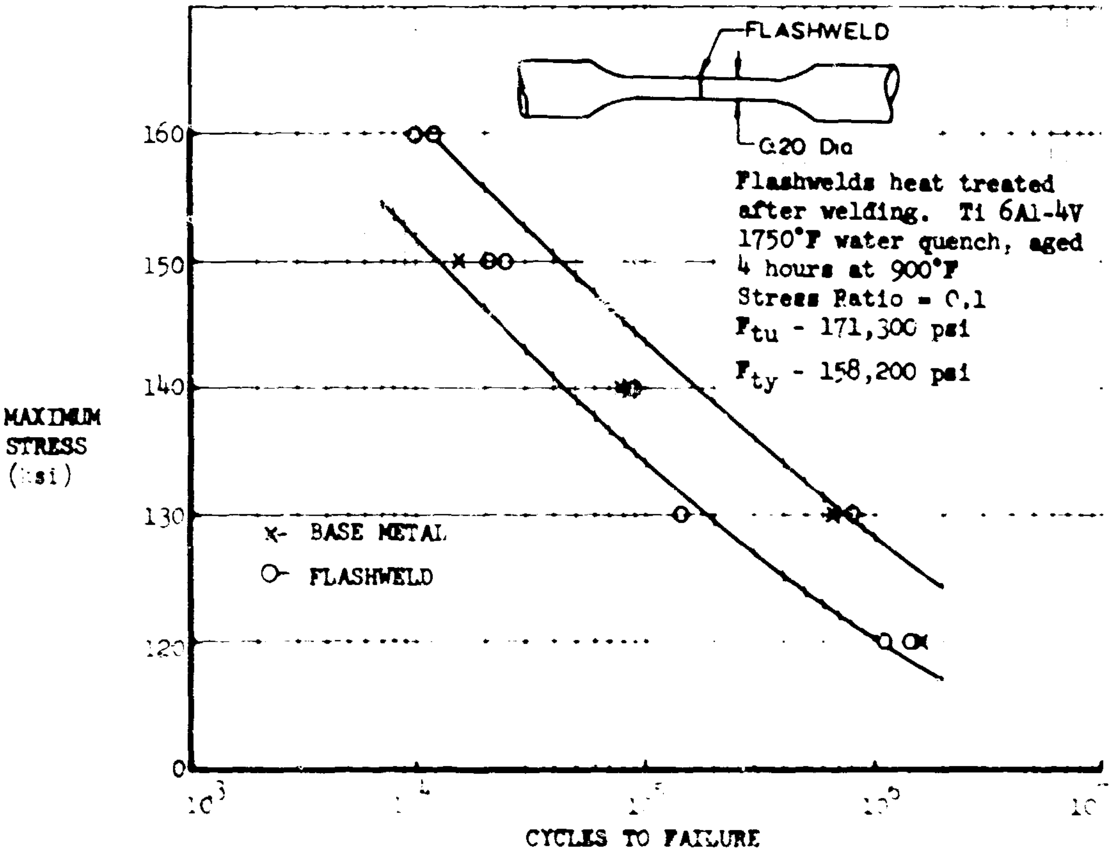


Figure 2-35. Flashweld Fatigue

strengths. Table 2-J shows a comparison of weld and base metal strengths of pressure welded Ti 6Al-4V tubes.

e. Diffusion Welding

Diffusion welding is a solid state joining process by which coalescence of the faying surface is obtained through a combination of pressure and heat with or without the use of an interface material. The process is accomplished either by roll diffusion welding or by static pressure diffusion welding at elevated temperature. Diffusion welding is considered for use in applications such as skin-stiffeners, butt joints, and lap joints where intimate faying surface contact can be assured during the weld cycle. The process results in high quality welds with shear strengths equivalent to base metal properties. Figure 2-36 is a micrograph of a void free roll-weld with a microstructure identical to that of the base metal.

Development is planned to establish quality limits with the aid of ultrasonic inspection techniques. In addition, a 31 by 96 inch panel consisting of five stiffeners is being prepared for roll welding. Structural testing of the welded panel is planned.

2.1.2.3 Copper Diffusion Brazing

Copper diffusion brazing of titanium alloys may be used in applications such as skin stiffener assemblies, butt and lap joints wherein intimate contact of the faying surfaces is assured during the brazing operation, and for thin-gage sandwich structure where temperatures preclude use of adhesives. This process differs from diffusion welding in that a copper interface material is used. The interface material forms a transient liquid phase in the joint, and therefore the process is not completely solid state. Advantages of the process are increased diffusivity and intimate contact of the liquid phase with the faying surfaces. Faying surfaces irregularities are easily filled with the liquid phase, thus enhancing the probability of void-free brazed joints.

This technique results in a manufacturing advantage in that relatively low faying surface

Table 2-J. Mechanical Properties of Ti 6Al-4V Pressure Welded Tubes

Tube No.	Type of Specimen	Ultimate Tensile Strength, Average (ksi)	Elongation Average, (percent)	Bend Angle, Average, (degrees*)	Fracture Location **
1	Weld	160.4	7.9	129	H.A.Z.
	Base Metal	166.7	10.9	150	B.M.
2	Weld	160.[illegible]	7.6	133	H.A.Z.
	Base Metal	166.4	8.[illegible]	126	B.M.
3	Weld	160.7	6.3	133	H.A.Z.
	Base Metal	158.9	12.5	139	B.M.

* Included angle at failure

** H.A.Z. = Heat-affected zone

B.M. = Base metal

Tubes were heat treated after pressure welding

1750°F/30 minutes, water quench, aged at 900°F - 4 hours, air cool

0.500 in. wall x 3.5 in. diameter welded tube

The weld reinforcement was machined flush with the base metal surfaces.

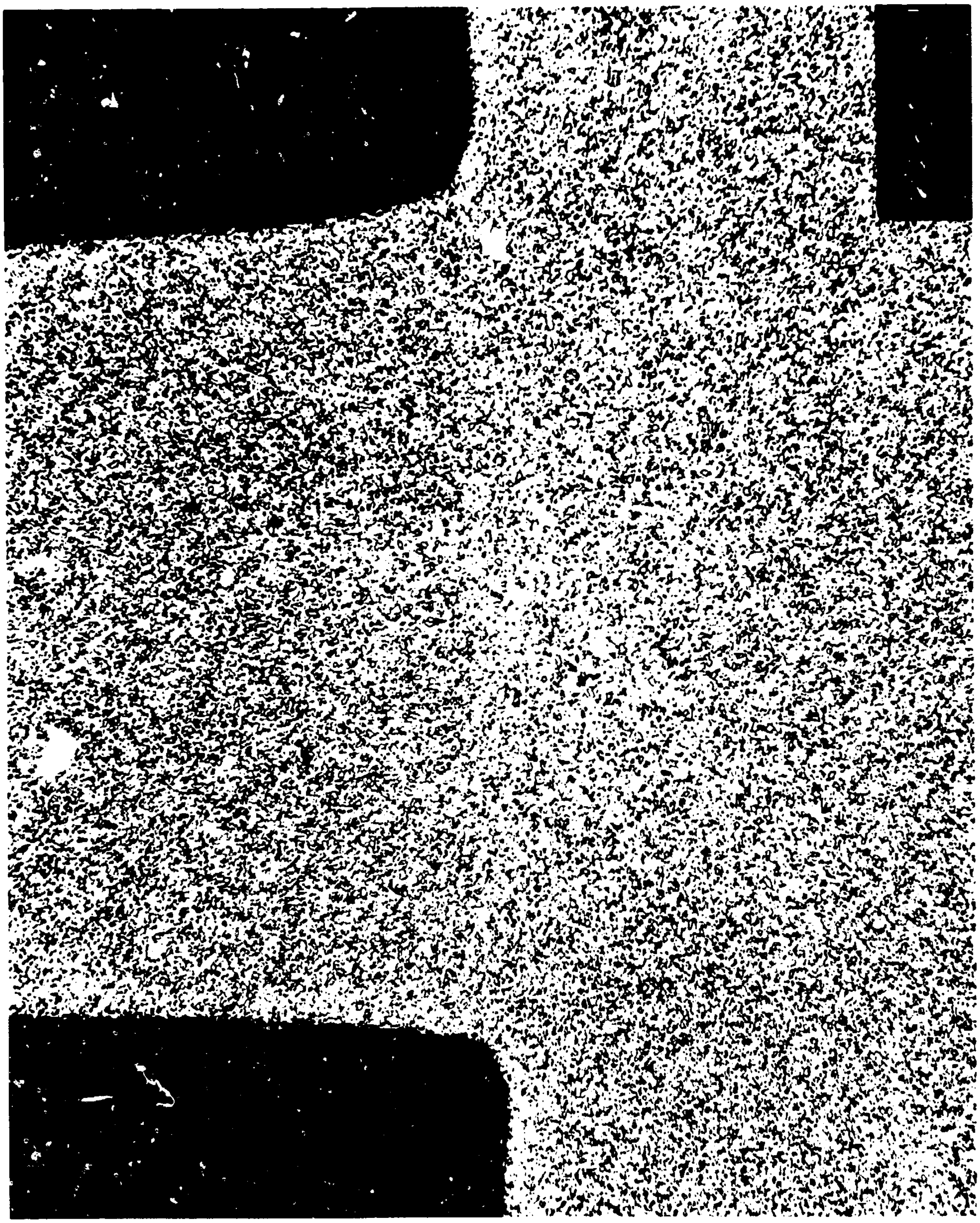


Figure 2-36. Roll Diffusion Weld in Titanium

contact pressures are required during brazing. A properly controlled process produces metallurgically homogeneous joints with the copper diffused and completely alloyed with the titanium. Tensile properties are comparable to those of the base metal before and after exposure to 600°F in the presence of salt for up to 1000 hours (see Table 2-K). The fatigue life of copper diffusion brazed Ti 6Al-4V joints and base metal is shown in Fig. 2-37.

Future work is planned in the areas of impact and fracture toughness testing, quality evaluation, and diffusion brazing of experimental test assemblies.

A Boeing preliminary process specification for copper diffusion brazing of Ti 6Al-4V has been released.

2.1.2.4 Forming
The limited formability of titanium at room temperature is generally attributed to its close packed hexagonal crystal structure. Of primary concern are the material springback characteristics, induced residual stresses, and yield strength reduction due to the Bauschinger effect. Hot forming, hot sizing, stress relieving, or a combination thereof, are frequencly necessary to minimize or eliminate these effects.

Forming is accomplished at room temperature where part complexity, induced residual stresses, and Bauschinger effect permit. Hot forming or preforming followed by hot sizing is used extensively for severely formed parts. The time and temperature for hot forming and sizing are influenced by the final heat treatment condition desired. Figure 2-38 shows the bend radii and spring back of Ti 6Al-4V sheet as influenced by thermal conditions, temperature, radius to thickness ratio, and sheet thickness. The magnitude of induced residual stress resulting from bend forming at various temperatures is shown in Fig. 2-39.

The room temperature bend formability of Ti 6Al-4V has been improved by the use of a urethane pad instead of steel lower dies for brake forming. This improvement is shown in Fig. 2-40. Further work is being done to implement this improvement for room temperature forming of titanium.

The Bauschinger effect on annealed Ti 6Al-4V has been studied. It was found that as little as two percent plastic tensile strain results in a 40 percent loss in compression yield strength and the high (approximately 120 ksi) proportional limit exhibited by Ti 6Al-4V is reduced to about 30 ksi. However, almost complete recovery is obtained by thermal stress relief (see Fig. 2-41).

Table 2-K Tensile Properties of Copper Diffusion Brazed Joints, Ti 6Al-4V

Exposure Temperature, °F	None		600		600	
Exposure Time, hours	None		500		1000	
Environment	None		NaCl*		NaCl*	
	F_{tu} (ksi)	F_{ty} (ksi)	F_{tu} (ksi)	F_{ty} (ksi)	F_{tu} (ksi)	F_{ty} (ksi)
Copper Diffusion Braze (1900°F-60 min)	139	121	145	126	149	128
Ti 6Al-4V Base Metal (1900°F for 60 min)	137	117	145	126	147	127

* Aqueous NaCl slurry was applied to the specimens

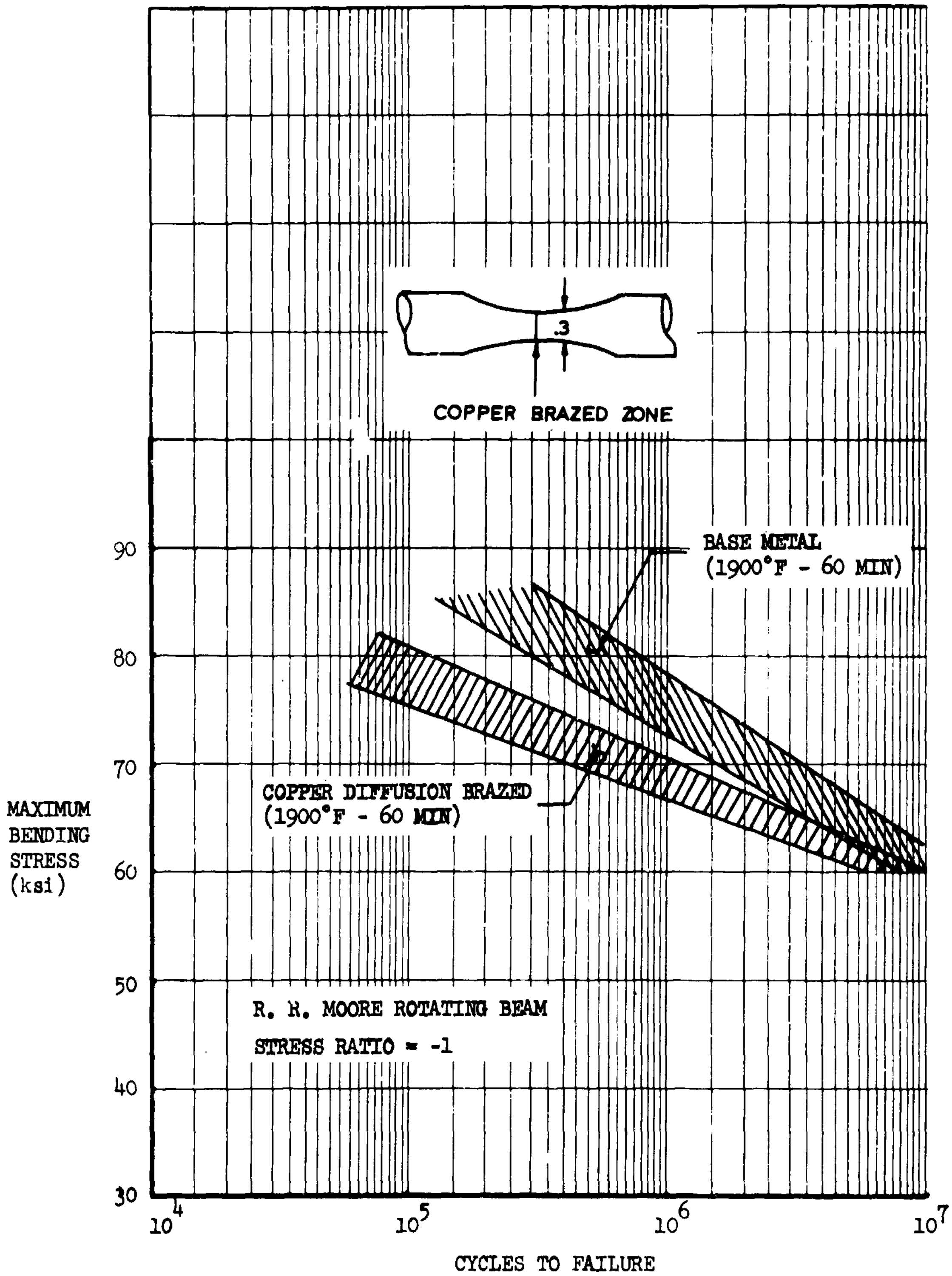


Figure 2-37. Fatigue Life of Copper Diffusion Brazed Ti 6Al-4V

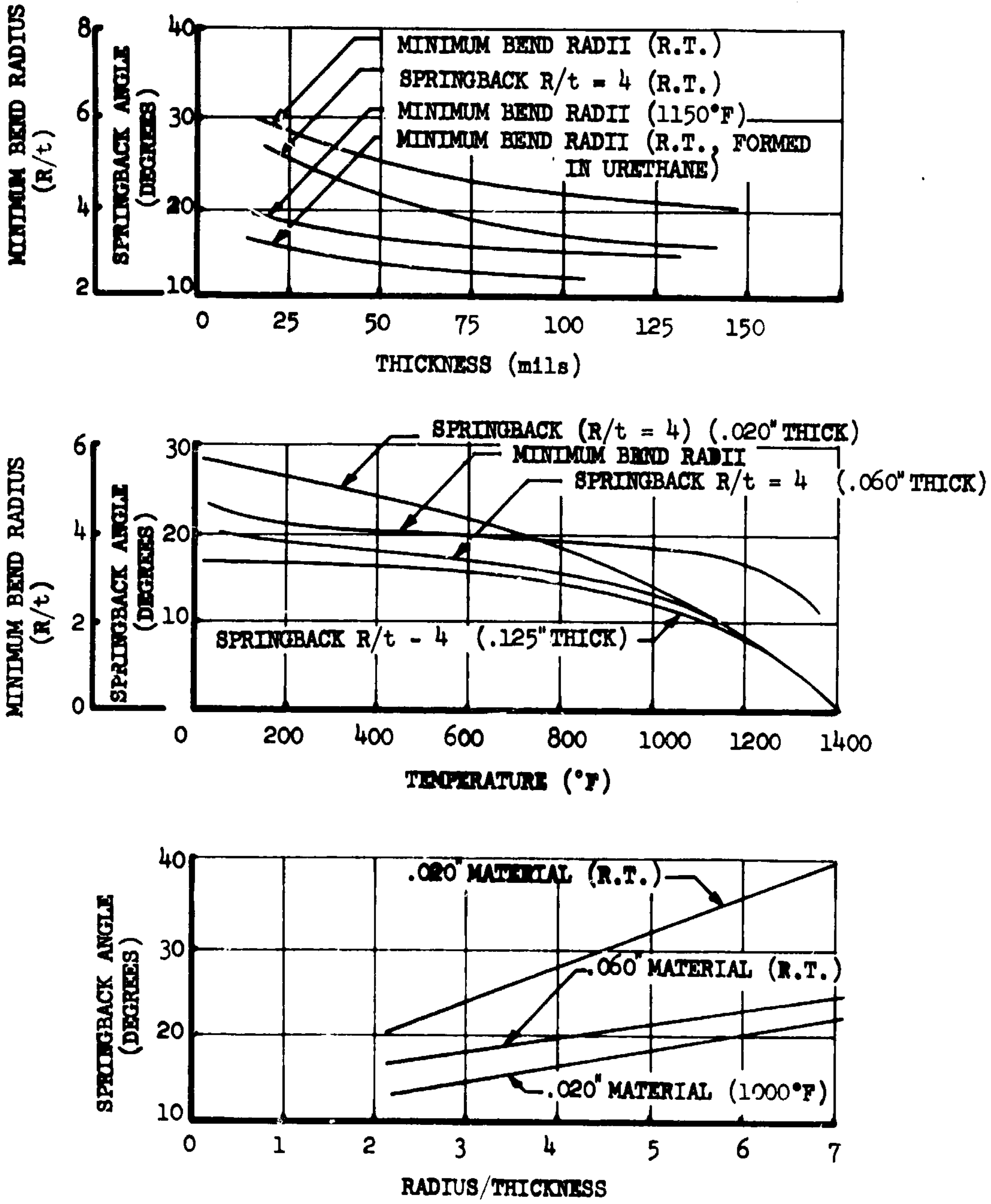
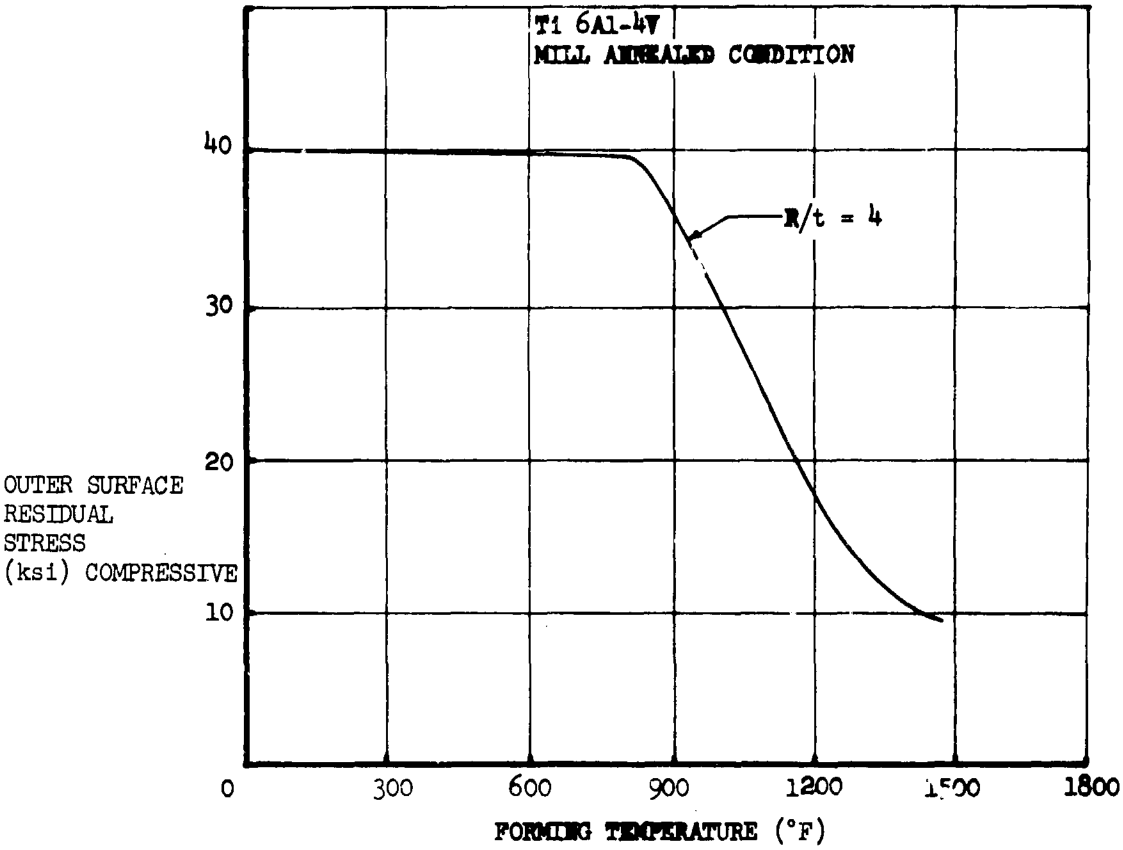


Figure 2-38. Minimum Bend Radii of Ti 6Al-4V



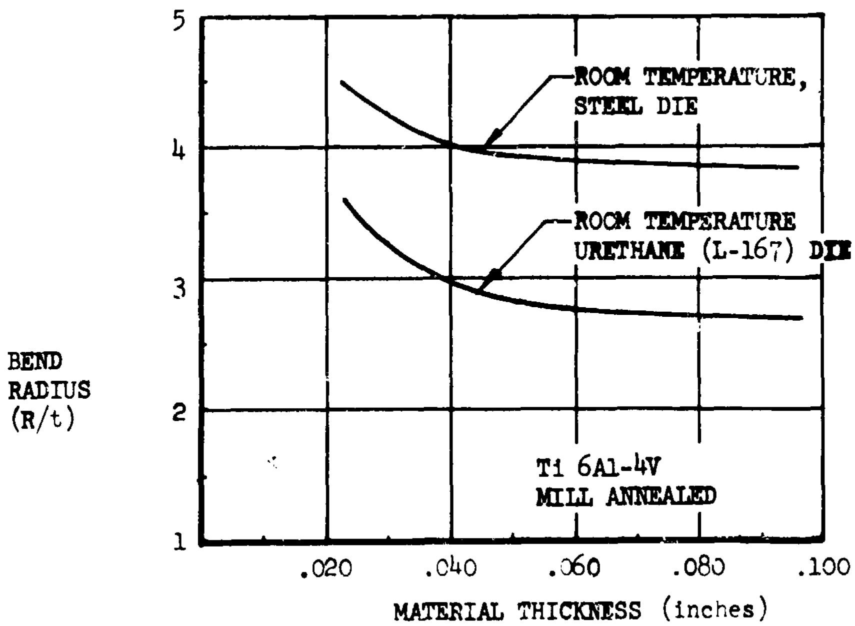


Figure 2-39. Residual Stress, Room Temperature Relationship for Formed Parts

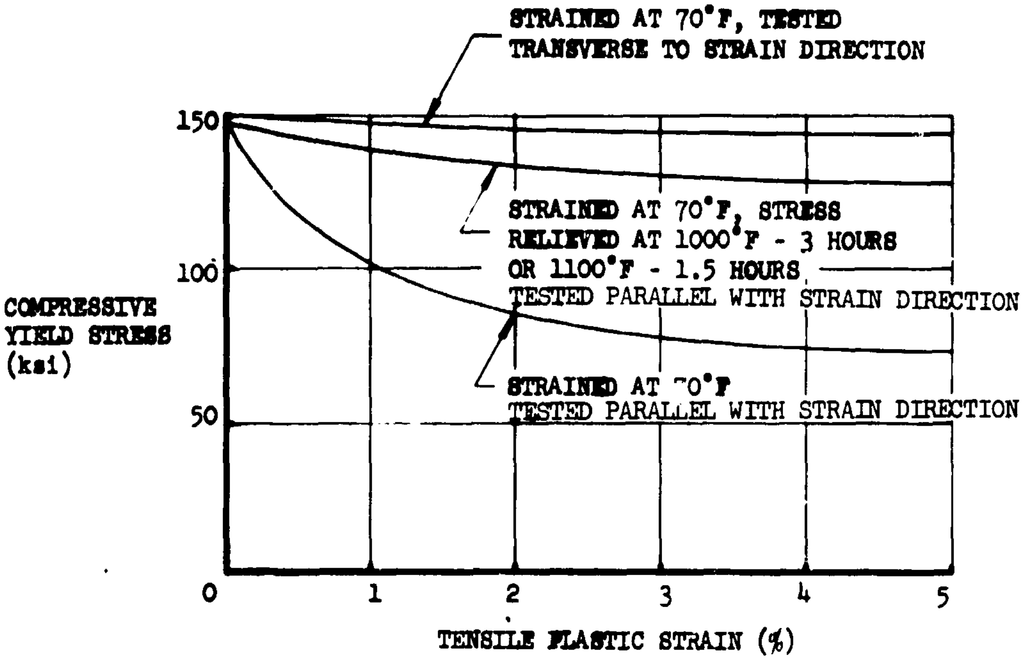


Figure 2-40. Bend Formability

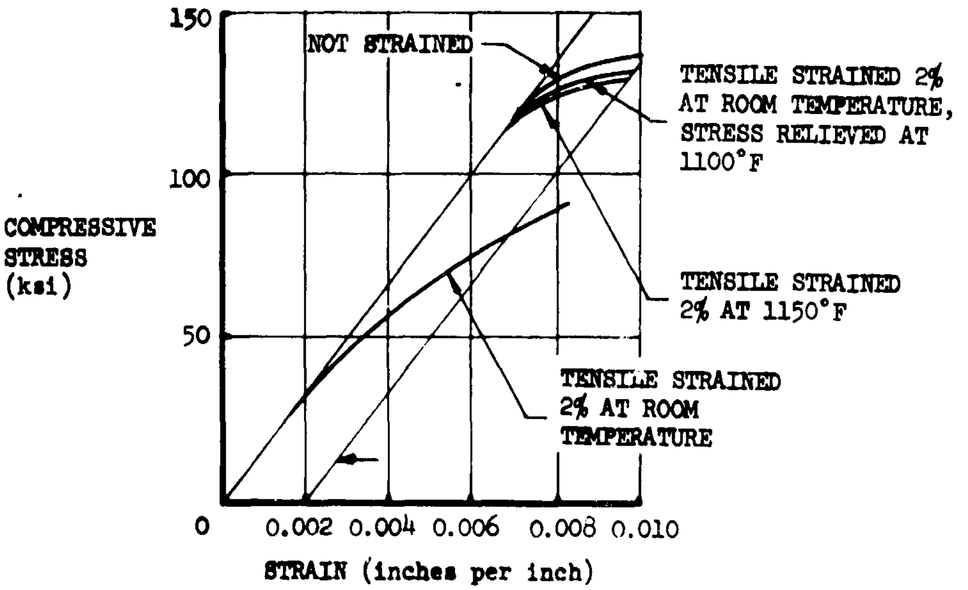


Figure 2-41. Bauschinger Effect on Ti 6Al-4V

Strength reduction due to the Bauschinger effect is not significant when forming is carried out at temperatures above 1000°F. Tests have been conducted where coupons are loaded in compression 90 degrees to the direction of tensile strain, such as might occur for formed angles or Z sections and results showed that no compression strength reduction occurs.

Measurement techniques have been developed and applied to determine the residual stress distribution through the thickness of bend formed material. Tension residual stresses at the inside surface of a 4 times radius to thickness bend at room temperature are approximately 70,000 psi as shown in Fig. 2-42. Therefore, parts formed at room temperature require stress relief.

2.1.2.5 Machining and Grinding
Mechanical machining such as face, end, or peripheral milling, and planning, are used as the primary part-shaping operations. Machining variables such as cutter geometry, feeds, and speeds have been established to provide efficient manufacturing procedures. A complete discussion of titanium machining procedures is given in Boeing document V5-B2707-9 and manufacturing manuals 6M 59-150 (Ref. 9) and 6M 59-501 (Ref. 10). Coolants for machining are discussed in Sec. 3.8.8. Test results show that no degradation of static mechanical properties or toughness resulted from mechanical machining titanium alloys. Grinding and sanding are not allowed as finishing operations for titanium alloys when the abrasive speed exceeds 800 surface ft per minute, as this significantly reduces fatigue life. This reduction is attributed to induced residual tensile stresses which have been determined to exceed 100 ksi and extend to a depth of 0.005 in. below the surface. Therefore, all ground surfaces require a minimum of 0.010 in. of metal removal by such processes as chemical milling, mechanical machining, or abrasive cleaning which do not produce adverse residual stresses. This requirement is controlled by Boeing specification. Tests indicate that the fatigue life of the finished part is improved because of the excellent surface finish produced by a controlled abrasive finishing. Nonmechanical methods of metal removal, such as chemical and electrochemical milling, electro-chemical grinding, and electrical discharge machining are discussed in Par. 3.9.2.

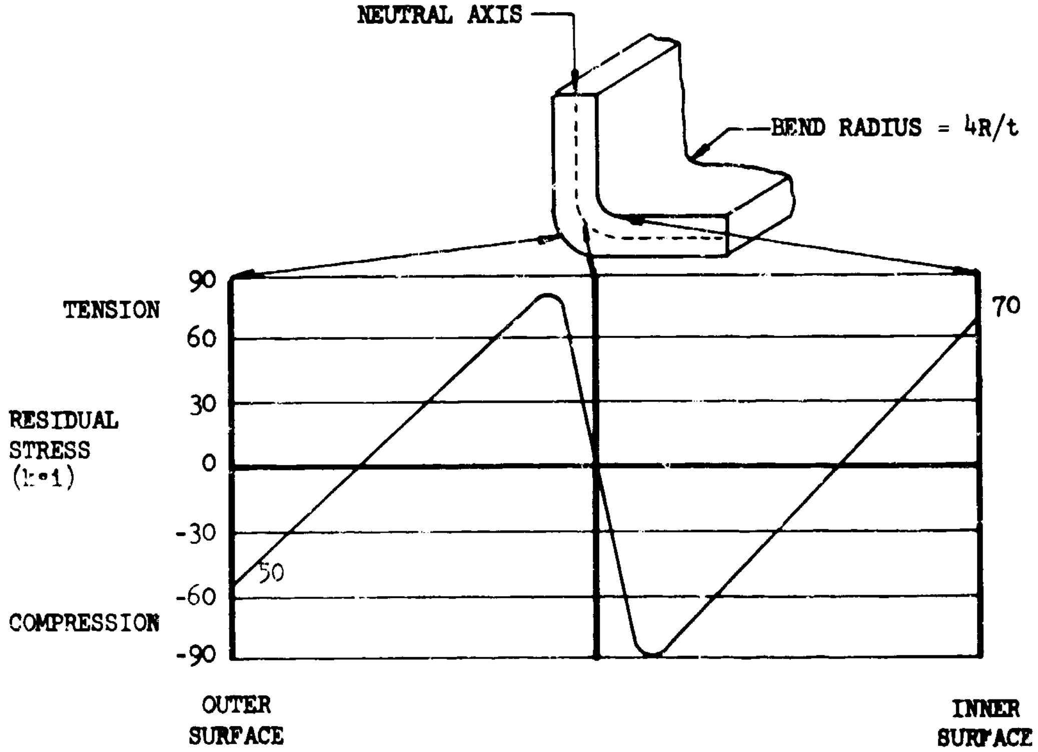


Figure 2-42. Distribution of Residual Stress in Bend Formed Ti 6Al-4V

2.1.2.6 Forgings, Extrusions, and Castings
Ti 6Al-4V is the primary alloy for forgings, extrusions, and castings. Ti 6Al-6V-2Sn and **Ti 7Al-4Mo alloys are used** where strength rather **than fracture toughness, in air and aqueous environments, is the primary design consideration. Forgings and extrusions are worked above the beta transus of the respective alloys to obtain close dimensional control, greater material utilization, lower product cost, reduce die wear, and to improve structural properties.**

The Boeing developed beta forging process has been evaluated on both flat and closed die forgings. Table 2-L lists tensile and fracture toughness properties of Ti 6Al-4V forged in the beta and the alpha beta ranges. The tensile properties of the alpha-beta and beta forged parts exceed the specification requirements listed in the applicable military specification for annealed Ti 6Al-4V. This table also shows a significant increase in fracture toughness (approximately 50 percent) of the beta worked material compared to that of the alpha beta worked material. Figure 2-1 compares the fatigue properties of alpha beta and beta worked forgings. These data show no reduction in fatigue life because of beta working as compared to the alpha beta worked forgings.

2.2 STEEL

2.2.1 Alloys
Steel is used in the airframe structure where its high strength results in weight [illegible]ings, or where other properties such as wear re[illegible]stance are required. Only proven aircraft quality steel at reliable strength levels is used. Table 2-M lists the materials selected and their applica-tions. Processing is controlled by plating and pickling specifications to preclude the possibility of hydrogen embrittlement.

Type 4340 Silicon Modified steel is used in the 270 to 300 ksi strength range because of its excellent service record as landing gear material in the Model 720 commercial jet airliner. The

Table 2-L. Properties of Beta and Alpha-Beta Pancake Forgings Ti 6Al-4V

Forging Condition	Heat (1) Treatment	Grain Direction	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (Percent in 4D)	Reduction of Area, Percent	K_{Ic} ksi in (2)
Alpha+Beta	STA-1000	Long.	167.1	154.3	12.8	47.5	45.2
Alpha+Beta	STA-1000	Trans.	167.8	154.0	13.5	46.0	46.6
Alpha+Beta	Annealed	Long.	144.6	135.2	15.2	41.0	56.3
Alpha+Beta	Annealed	Trans.	141.5	130.8	15.7	44.5	77.7
Beta	STA-1000	Long.	167.8	148.0	10.0	29.0	69.8
Beta	STA-1000	Trans.	164.0	147.0	10.5	27.5	67.7
Beta	Annealed	Long.	142.1	128.7	13.0	35.0	90.7
Beta	Annealed	Trans.	143.3	126.8	15.0	36.2	39.4

(1) Heat treated thickness = 0.75 inch
Solution treated 1725°F — 1 hr. — W.Q.: Aged 1000°F — 4 hr., Air Cooled
Annealed [illegible]°F — 2 hr. — Air Cooled

(2) K[illegible] [illegible] determined on fatigue cracked single edge notch specimens [illegible] point loading.

Table 2-M. Material Selection- High Strength Steels

Alloy and Condition	Form	Application	Selection Criteria	Availability
4340M vacuum arc remelt (270-300 ksi)	Plate, bar, and forgings	Landing gear components in temperature controlled wheel wells	High strength-density ratio Good wear resistance Good fracture toughness	Material available in production quantities
9Ni-4Co-.30C vacuum arc remelt (220-240 ksi)	Plate, bar, and forgings	Landing gear components Flap track forgings	Good Strength Excellent fracture toughness Good stress corrosion resistance Good weldability	Material available in production quantities

Model 720 fleet has flown a total of 1,949,000 hours, which include 1,185,000 landings, without a reported failure resulting from use of this steel. All the major components of the Model 720 gear are made of airmelt 4340M steel heat treated to 270 to 300 ksi with a required minimum average reduction in area of 12 percent as measured by tensile coupons cut from the midradius of the forged billet.

Type 4340M steel for the B-2707 airplane is vacuum arc remelted for premium quality. This material has a guaranteed minimum average reduction of area of 25 percent in the short transverse grain direction and a minimum of 15 ft-lbs impact strength at -65° F as measured by a Charpy V notch specimen. The vacuum arc remelt grade of 4340M steel is also used for landing gear forgings for the Boeing 737 airplane currently entering production. Results of the qualification testing of the forging are shown in Table 2-N. These tensile test results verify that the excellent properties of the vacuum arc remelt 4340M are obtained in large forgings.

The excellent service experience of the 4340M steel, at this strength level, is due to careful control of design, procurement, and processing developed over 10 years of production experience.

Type 4340M steel contains 1.5 percent silicon which retards hydrogen diffusion and reduces susceptibility to stress corrosion. The inherent resistance of this alloy to hydrogen embrittlement as compared to other alloys is shown in Fig. 2-43 (Ref. 11). The comparison is made using induced stress as a percent of notched tensile strength. The significant stress affecting hydrogen embrittlement cracking is not design stress, but residual stress induced during processing or assembly. The environmental resistance of 4340M steel is further demonstrated by comparisons using gross area stress for hydrogen embrittlement susceptibility (Fig. 2-44, Ref. 11) and extreme fiber stress for stress corrosion susceptibility (Fig. 2-45, Ref. 12).

Detailed parts are designed so that applied loads will result in uniform stress distribution. Photostress and strain gage techniques are used to insure the absence of serious stress risers. The gear assemblies are static and fatigue tested to ensure that design requirements are met. Dissimilar metals are isolated and adequate corrosion protection provided for the entire assembly as discussed (see Sec. 3.8). In addition, wear, fretting, and galling will be eliminated through the use of replaceable bushings and protective materials in faying surfaces.

Table 2-N. Tensile Properties of Vacuum Arc Remelt 4340M Forging

	Grain Direction	F_{tu}, (ksi)	F_{ty}, (ksi)	Elongation, (percent)	Reduction of Area, (percent)
	Short transverse	288.0	242.0	10.5	41.7
	Short transverse	285.0	241.0	10.5	41.4
	Longitudinal	286.0	241.0	10.5	41.7
	Short transverse	285.0	240.0	10.0	40.1
	Long transverse	287.0	242.0	10.0	42.5
	Short transverse	287.0	241.0	9.5	35.7
	Long transverse	284.0	241.0	10.5	41.4
	Long transverse	286.0	242.0	10.0	41.4
	Longitudinal	285.0	240.0	10.0	40.8
	Long transverse	287.0	244.0	10.5	42.5
	Longitudinal	286.0	243.0	10.0	41.4
	Short transverse	285.0	240.0	10.0	41.1
	Short transverse	285.0	239.0	10.0	41.7
	Short transverse	286.0	242.0	10.0	41.4
	Short transverse	284.0	238.0	10.5	40.1
	Short transverse	284.0	242.0	10.5	41.7
	Short transverse	283.0	240.0	10.5	41.7
	Short transverse	285.0	240.0	10.5	40.8
	Short transverse	287.0	243.0	9.5	41.4
	Short transverse	286.0	241.0	10.5	41.7
	Longitudinal	285.0	240.0	10.5	41.7
	Short transverse	285.0	240.0	11.0	42.5
	Short transverse	285.0	241.0	10.0	40.8
Average	Short transverse	285.3	240.7	10.2	40.9
Minimum	Short transverse	283.0	238.0	9.5	35.7
Average	Long Transverse	286.0	242.0	10.2	42.0
Minimum	Long Transverse	284.0	241.0	10.0	41.4
Average	Longitudinal	285.5	241.0	10.2	41.4
Minimum	Longitudinal	285.0	240.0	10.0	40.8
Average	All Orientations	285.5	241.0	10.2	41.1
Specification Requirements		270	220	----	25 min 30 avg

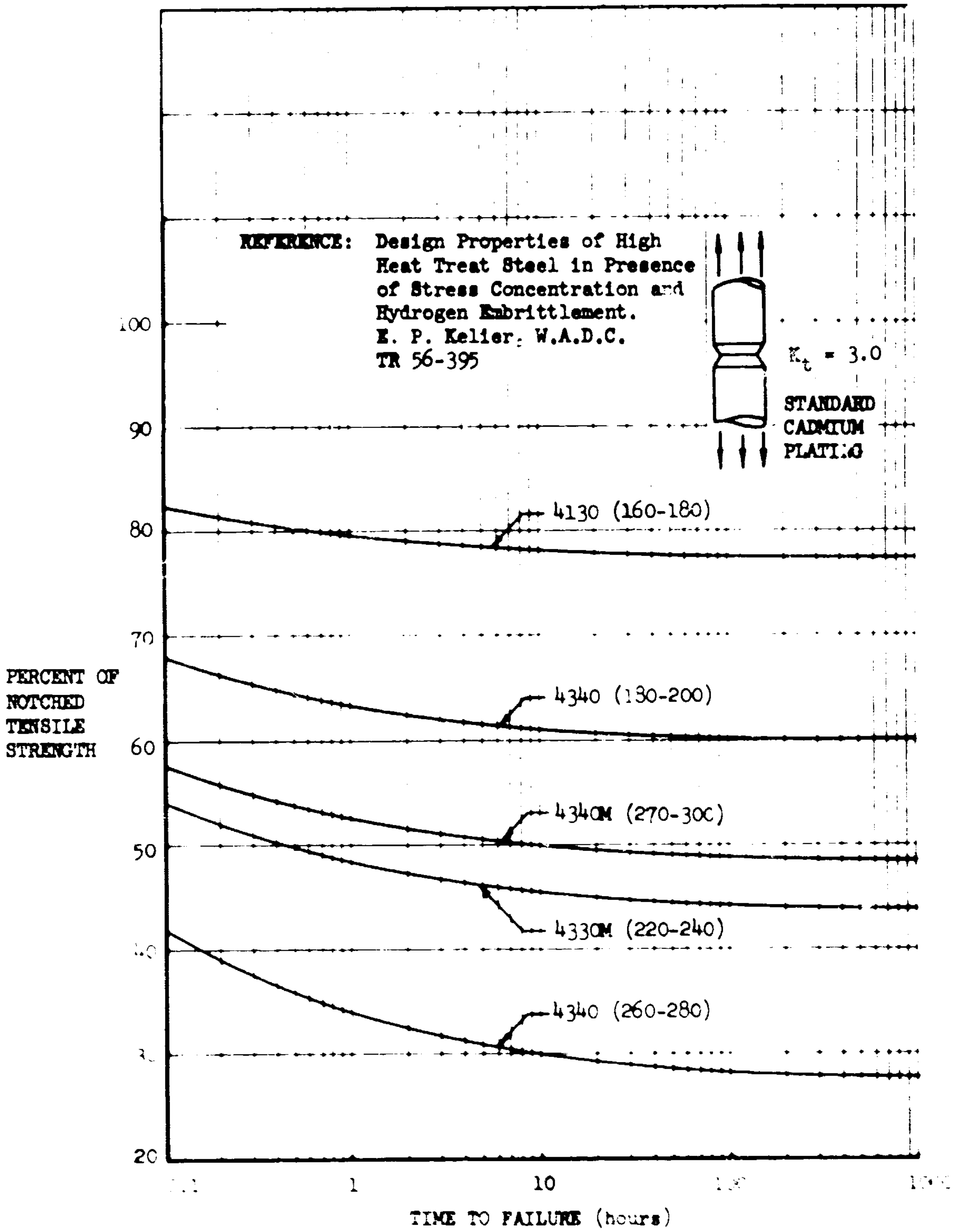


Figure 2-43. Hydrogen Embrittlement Susceptibility, Notched Tensile Strength

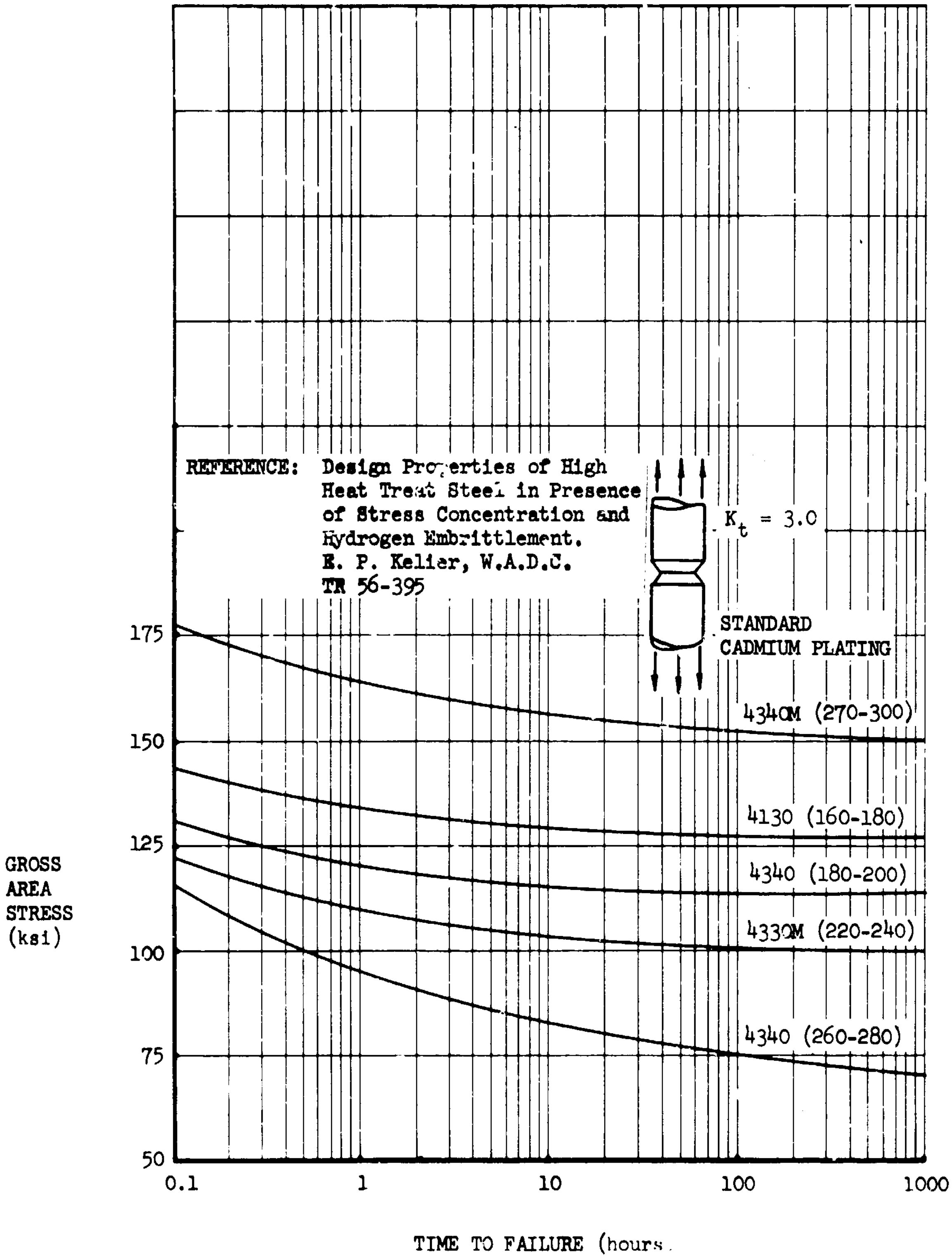


Figure 2-44. Hydrogen Embrittlement Susceptibility, Gross Area Stress

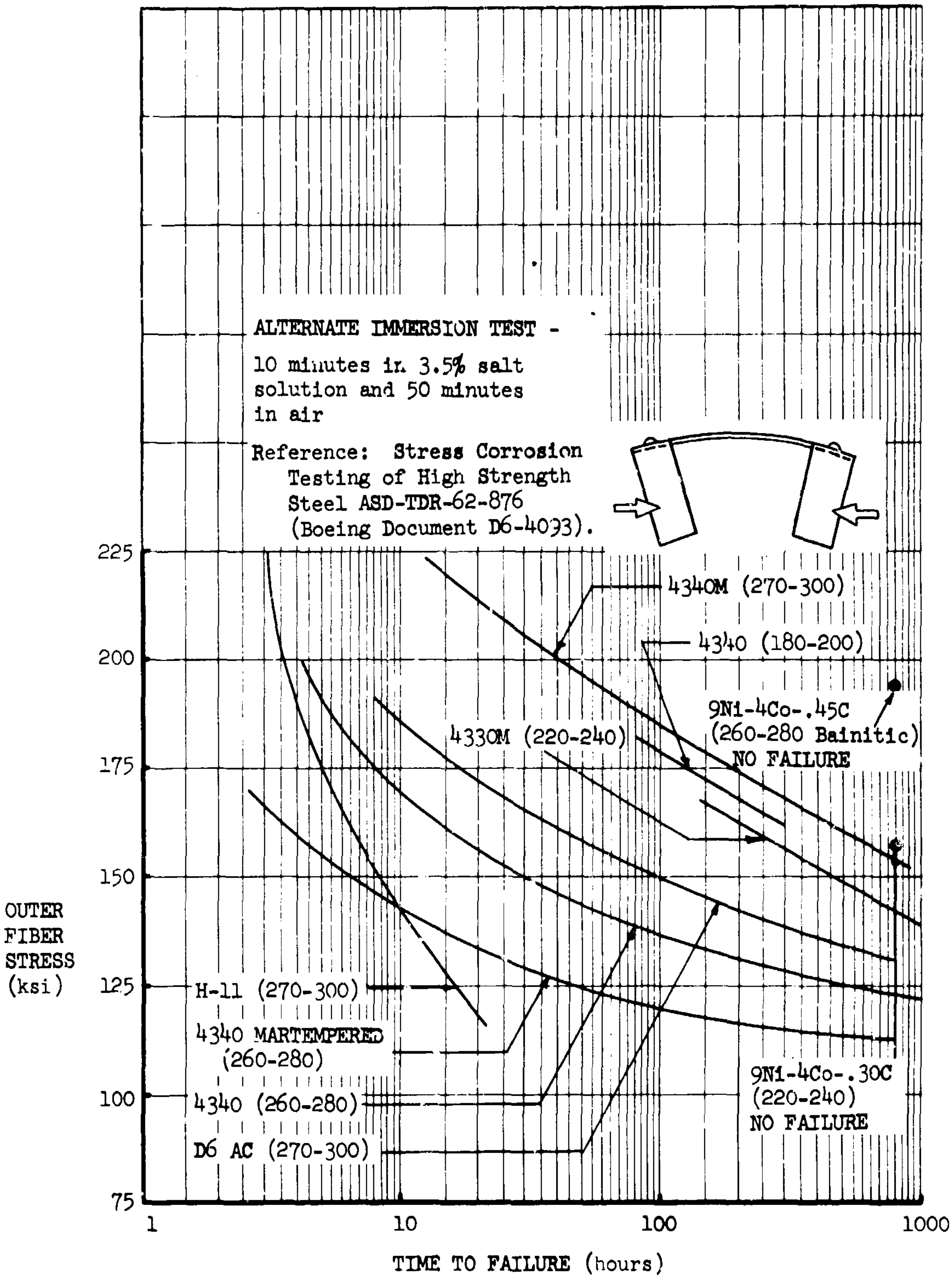


Figure 2-45. Stress Corrosion in 3.5 Percent NaCl Solution

The selection of 4340M steel was based primarily on successful Boeing utilization of this alloy. This choice has been further substantiated in a high strength steel validation program sponsored by The FAA (see Boeing document D6A10093-1, Ref. 13). This program covers the investigation of 4340M, 9Ni-4Co-.45C, and Maraging 250 steels in the 260 to 300 ksi strength range and 4330M, H-11, and 9Ni-4Co-.30C steels in the 220 to 240 ksi strength range. Although this program showed Maraging 250 to have satisfactory strength-toughness properties, it is not considered a producible alloy at this time. The 9Ni-4Co-.45C steel has satisfactory fracture toughness, but its strength is not presently competitive with that of the 4340M steel.

Of the steels evaluated for the 220 to 240 ksi strength range, the 9Ni-4Co-.30C composition is clearly the best choice based on the fracture toughness comparison shown in Fig. 2-46, and the resistance to environmental cracking as shown in Fig. 2-47. The 9Ni-4Co-.30C steel is a production alloy currently used for such applications as armor plate, forging dies, and bomb hooks. Over three million pounds of this alloy have been produced. The 4340M steel and 9Ni-4Co-.30C alloys are heat treated by conventional quench and temper processes. The mechanical properties of these two alloys are shown in Table 2-O and their fatigue properties are shown in Fig. 2-48.

2.2.2 Processing

2.2.2.1 Welding

Fusion welding of low alloy heat treatable steels is used where design and manufacturing advantages dictate its usage, and for cost effectiveness. Gas tungsten arc, gas metal arc, and coated electrode welding are accomplished in accordance with well established Boeing specifications.

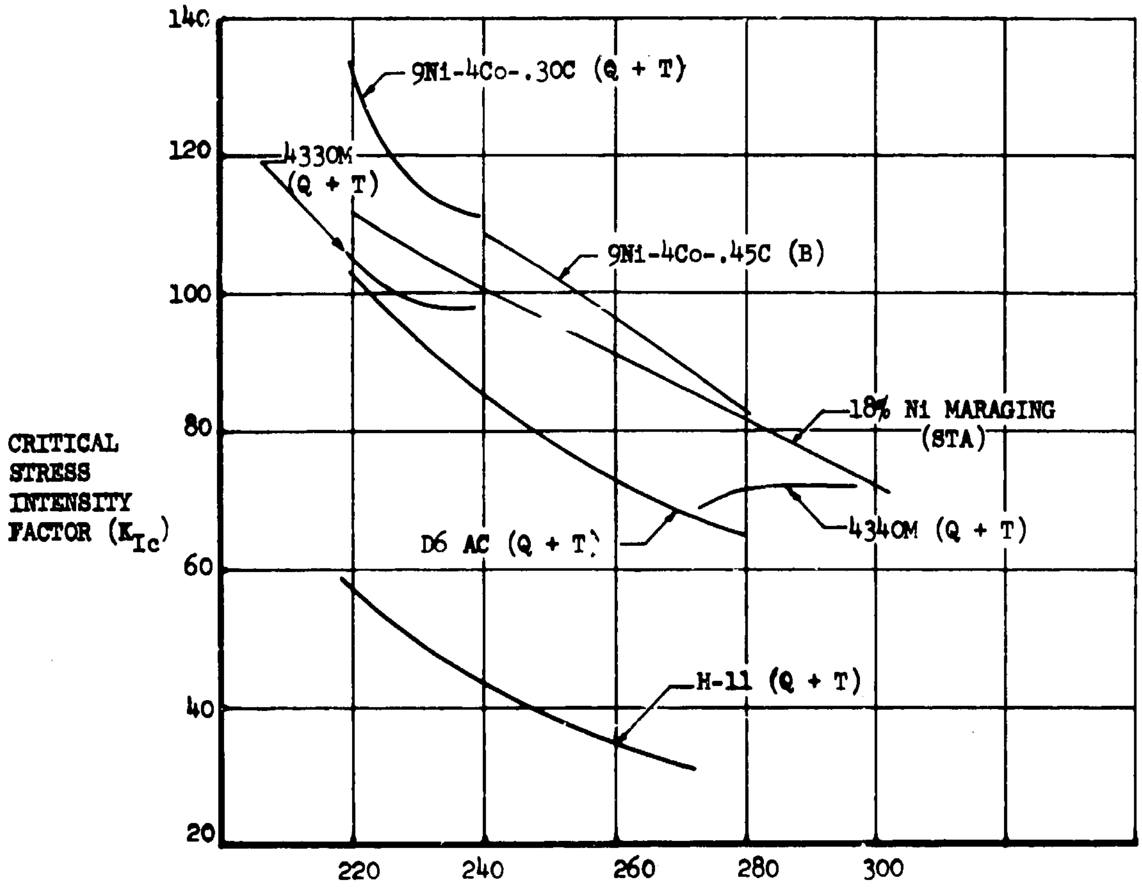


Figure 2-46. Fracture Toughness Comparison of Low Alloy Steels, in Air

AVERAGE ROOM TEMPERATURE PROPERTIES

Alloy	F_{tu}, ksi	F_{ty}, ksi	K_{Ic}, ksi$\sqrt{in}$
H-11	220	187	54
9Ni-4Co-.30C	230	204	116
4330M	235	192	100
Maraging 250	258	248	90
* 9Ni-4Co-.45C	266	218	90
4340M	285	235	72

* Bainitic heat treatment

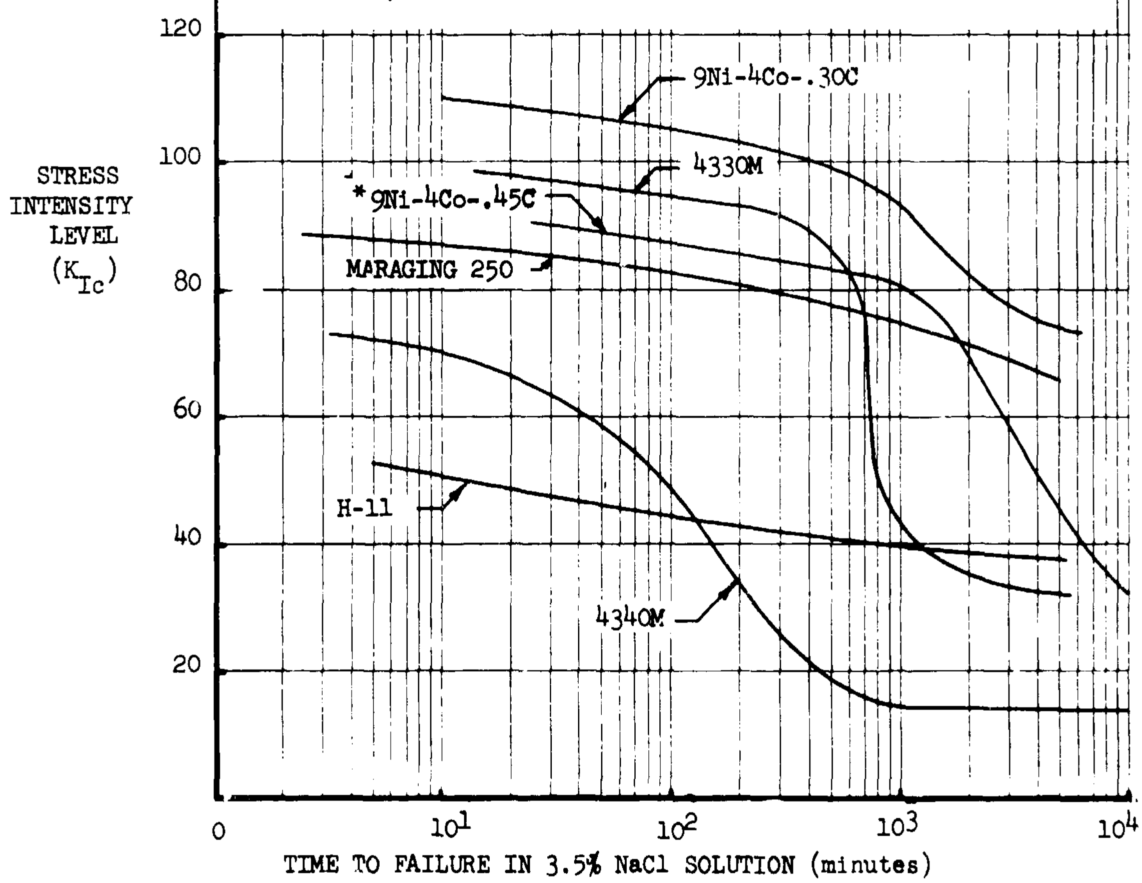


Figure 2-47. Sustained Loading Characteristics of Low Alloy Steels in 3.5 Percent NaCl Solution

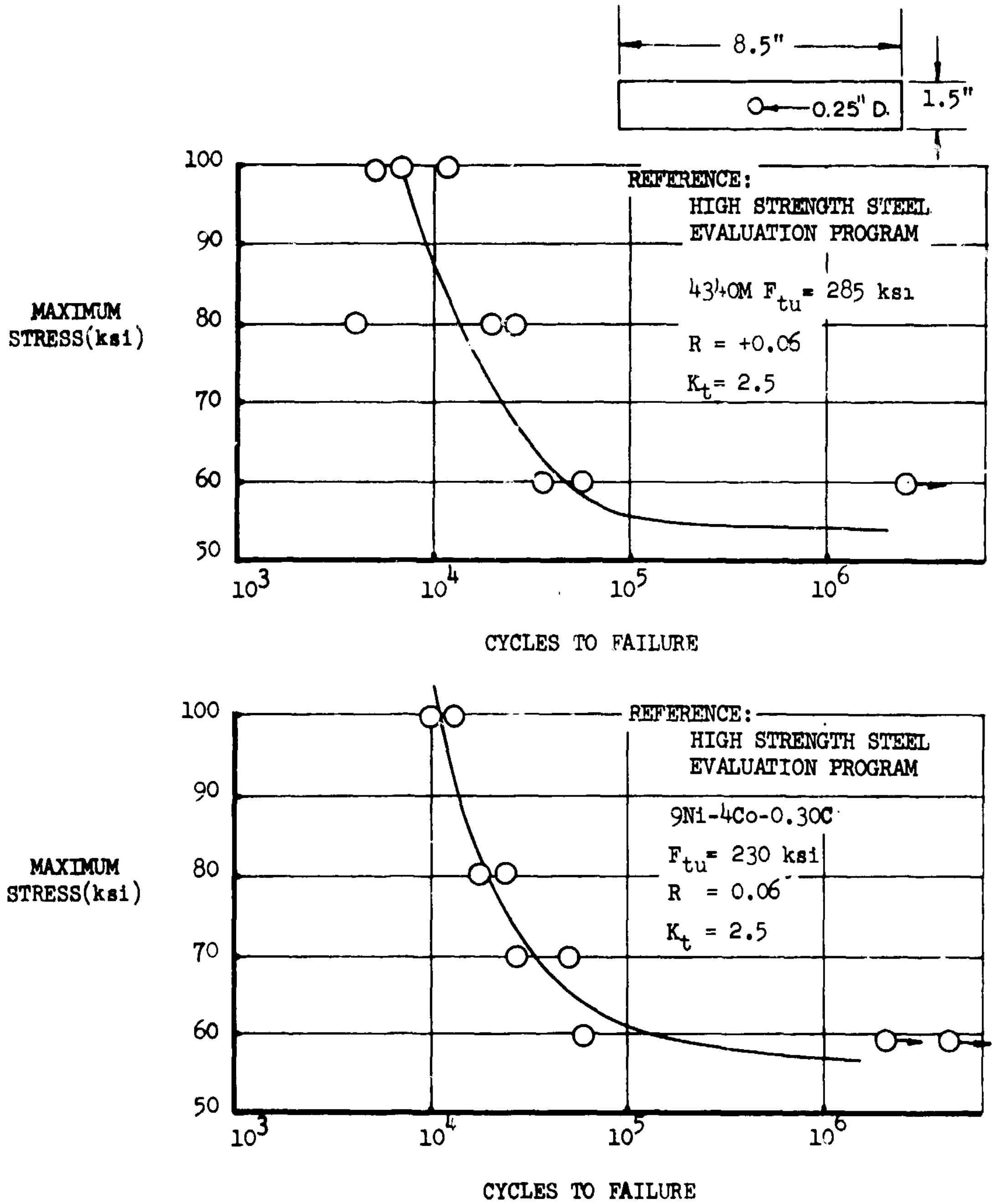


Figure 2-48. Fatigue Properties of 4340M and 9Ni-4Co-.30C Steels

Table 2-0. Strength and Toughness Data for Low Alloy Steel Forgings

Property***	Temp. (°F)	Environment	4340M*	9Ni-4Co-.30C*
F_{tu}, (ksi)	RT 300 450	Air Air	270 270 266	220 --- ---
F_{ty}, (ksi)	RT 300 450	Air Air	220 210 196	190 --- ---
F_{cy}, (ksi)	RT	Air	223	190
F_{su}, (ksi)	RT	Air	160	---
F_{bu}, (ksi)	RT	Air	456	---
RA, (%)	RT	Air	25	25
E (x 10^6 psi)	RT	Air	29	28
K_{Ic}, (ksi $\sqrt{in}$)	-65 RT	Air Air	50** 72**	105** 115**
K_{Ii}, (360 minutes), ksi$\sqrt{in}$	RT	3.5% NaCl	23**	100**
K_{Ii}, (5000 minutes), ksi$\sqrt{in}$	RT	3.5% NaCl	18**	88**

Two inch maximum section thickness

* 4340M heat treated to 270-300 ksi, 9Ni-4Co-.30C heat treated to 220-240 ksi

** Typical values

*** Properties are for two-in.maximum section thickness

All material was vacuum melted

Flash and pressure welding have been used extensively for joining low alloy, high strength steels on Boeing commercial and military airplanes. Service experience has been satisfactory. Applications on the B-2707 include such items as landing gear components, actuator assemblies, and control rods.

Preliminary test results have indicated that higher joint efficiencies are obtainable in fatigue when comparing flash welded vacuum-arc-remelt to air melt steel. The data is shown in Table 2-P. Additional testing will provide data for statistical design allowables as well as permit evaluation of the weldments for stress corrosion, hydrogen embrittlement, fracture toughness, and crack propagation characteristics.

2.2.2.2 Shot Peening
Shot peening is used under the following conditions to control surface residual stresses in heat treated steel parts:

a. As required to improve fatigue characteristics in parts heat treated to 180 to 200 ksi.

b. On all parts heat treated above 220 ksi.

c. Under chromium plating to eliminate tensile stresses.

d. Under cadmium plating to improve resistance to stress corrosion.

2.2.2.3 Machining
Proper selection of tools, speeds, and procedures are necessary to eliminate the occurrence of untempered martensite in high strength steels. These parameters have been determined and are controlled by company specification covering surface machining, drilling, reaming, honing, and grinding.

2.2.2.4 Forgings
Materials engineers work directly with the applicable design projects to ensure that all steel forgings are designed to have optimum structural integrity in the final machined part. This integrity is obtained by ensuring that the forging properties are compatible with the design requirements.

Table 2-P. Properties of Flash Welded Steel

	4340M (Vacuum Arc Remelt)			4330M (Air Melt)		
	Flashweld	Base Metal	Efficiency Percent	Flashweld (ksi)	Base Metal (ksi)	Efficiency Percent
Ultimate tensile strength, ksi	290	291	100	229	230	99
Tensile yield, ksi	239	238	100	203	206	98
Elongation % in 2 in.	10	11	91	7	13	53
Reduction in area, percent	39	42	93	21	58	36
Precracked charpy impact, in.-lb/in.^{2}	312	353	88	321	505	63
Rotating beam fatigue, cycles	75,333*	78,222*	96	33,500**	67,000**	50

*Maximum Stress 150 ksi, Stress Ratio -1

**Maximum Stress 120 ksi

4340M — Heat treated to 270-300 ksi

4330M — Heat treated to 220-240 ksi

One forging from the first production heat is metallurgically examined. Details of this procedure are as specified in Par. 2.1.2.6.

Die forgings provide good structural integrity because of the favorable grain flow that is provided in parts with transitions in section size and shape. They are generally used in preference to hog-outs from plate, bar, or extrusions. In cases where flashless closed die forgings are impractical, closed die forgings are designed with particular attention to parting line location so that loads are minimal across the parting line. Proper forging design coupled with manufacturing techniques such as sequenced machining and heat treating are used to reduce residual stress to acceptable levels.

2.3 CORROSION AND HEAT RESISTANT ALLOYS

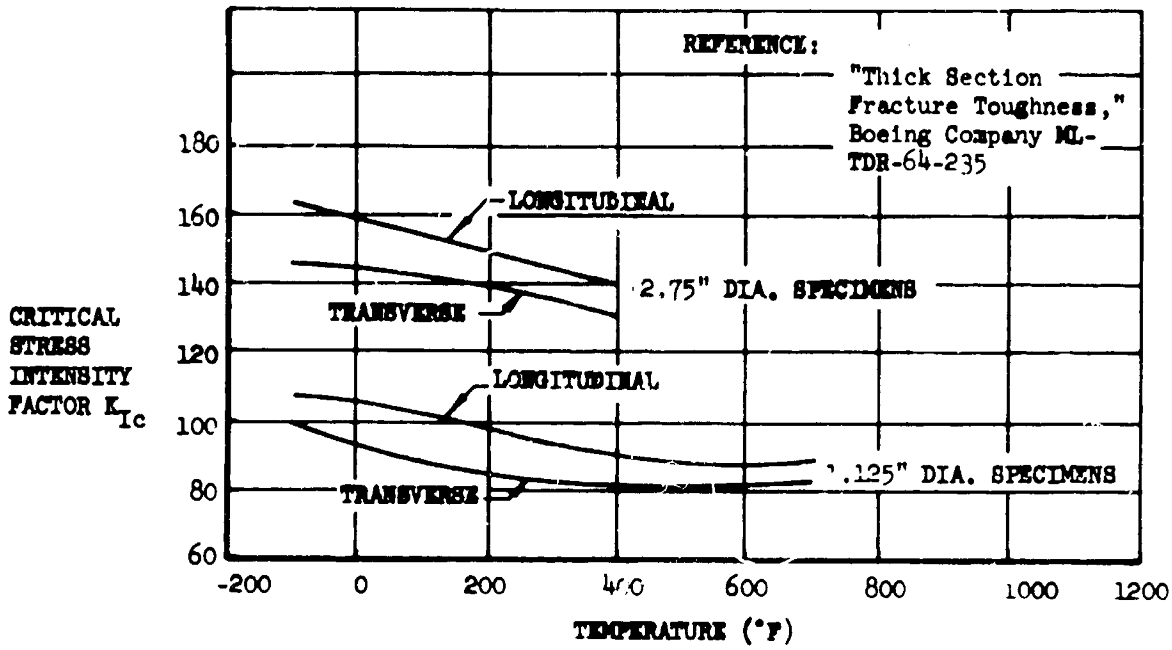
2.3.1 Alloys

The corrosion and heat resistant alloys listed in Table 2-Q are used when required by operational environment. These materials are being successfully used on current Boeing commercial airplanes for such applications as pneumatic ducting and engine hardware where elevated temperature strength, oxidation resistance, and excellent thermal stability are required.

Properties of the austenitic stainless steels are well established and are published in industry and military standard handbooks. The primary super alloy selected for use is Inconel 718. Figure 2 49 (Ref. 14) shows the elevated temperature static strength and toughness properties of Inconel 718, and Fig. 2-50, (Ref. 15) and 2-51 show the fatigue and creep rupture properties, respectively.

Table 2-Q. Material Selection, Corrosion and Heat Resistant Alloys

Selected Alloy and Condition		Form	Application	Selection Criteria	Availability
Stainless Steels	17-4PH PH 15-7Mo	Plate, Bar, Forgings, Castings	Fittings and engine hardware	High strength Wear resistance Corr. resistance	No limitations
	AISI Type 321 or 347	Sheet and Tubing	Ducting	Excellent formability Corrosion resistance Excellent toughness	No limitations
Super Alloys	A286	Bar and Forgings	Fasteners	High strength Corrosion resistance Forgeable	No limitations
	Inconel 718 Inconel X Hastelloy X Hastelloy B Rene' 41	Plate, Bar, Sheet and Forgings	High temperature fittings	High strength at temp. Corr. resistance Oxidation resistance	No limitations



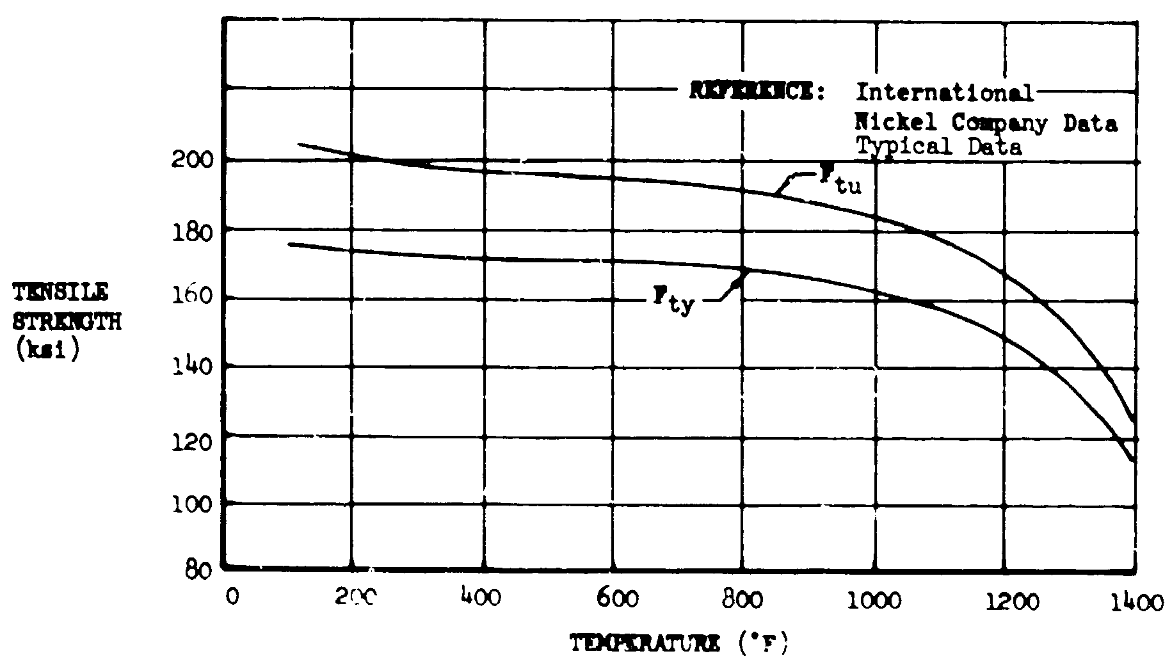


Figure 2-49 Strength and Toughness of Inconel 718

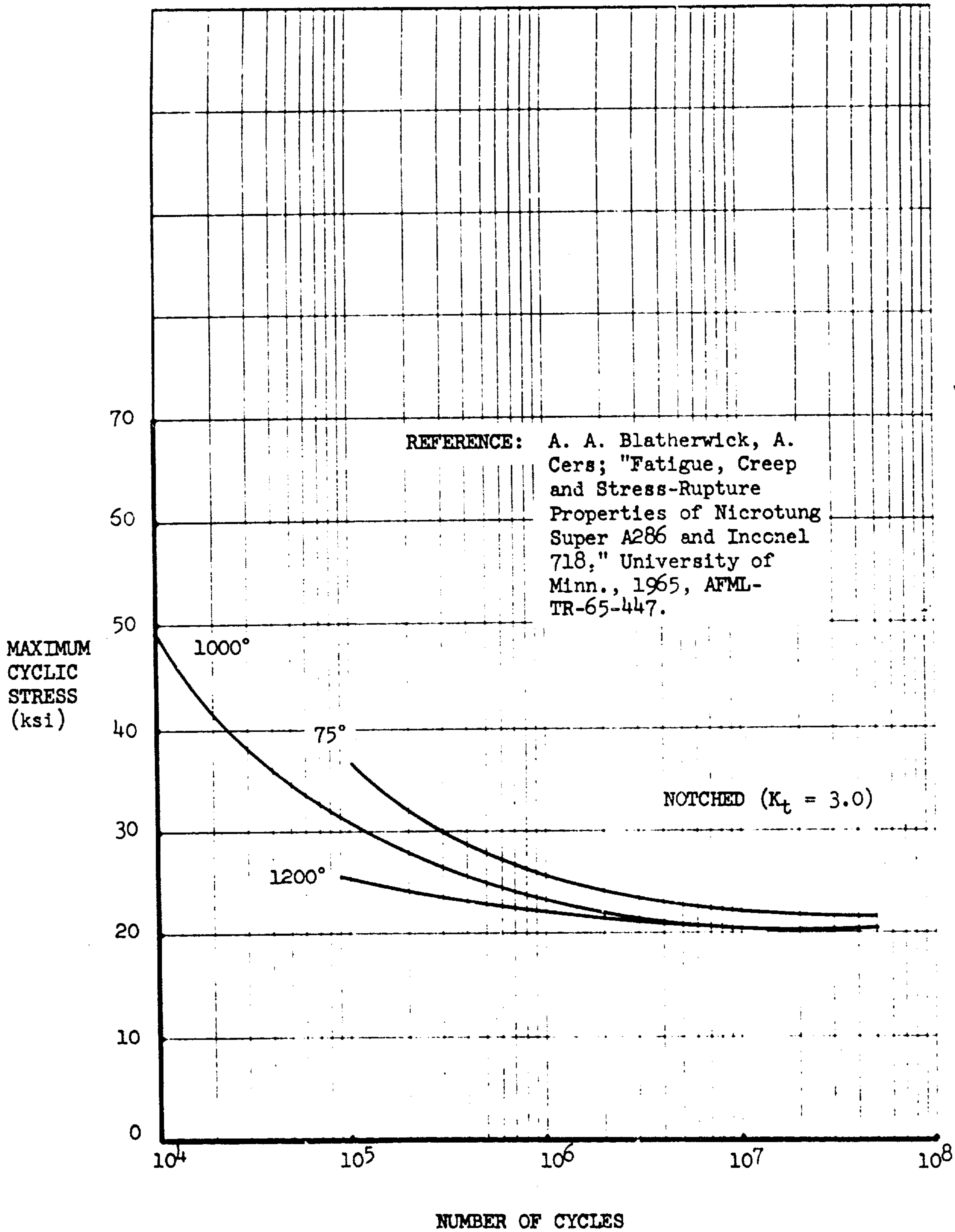


Figure 2-50. Fatigue Behavior of Inconel 718

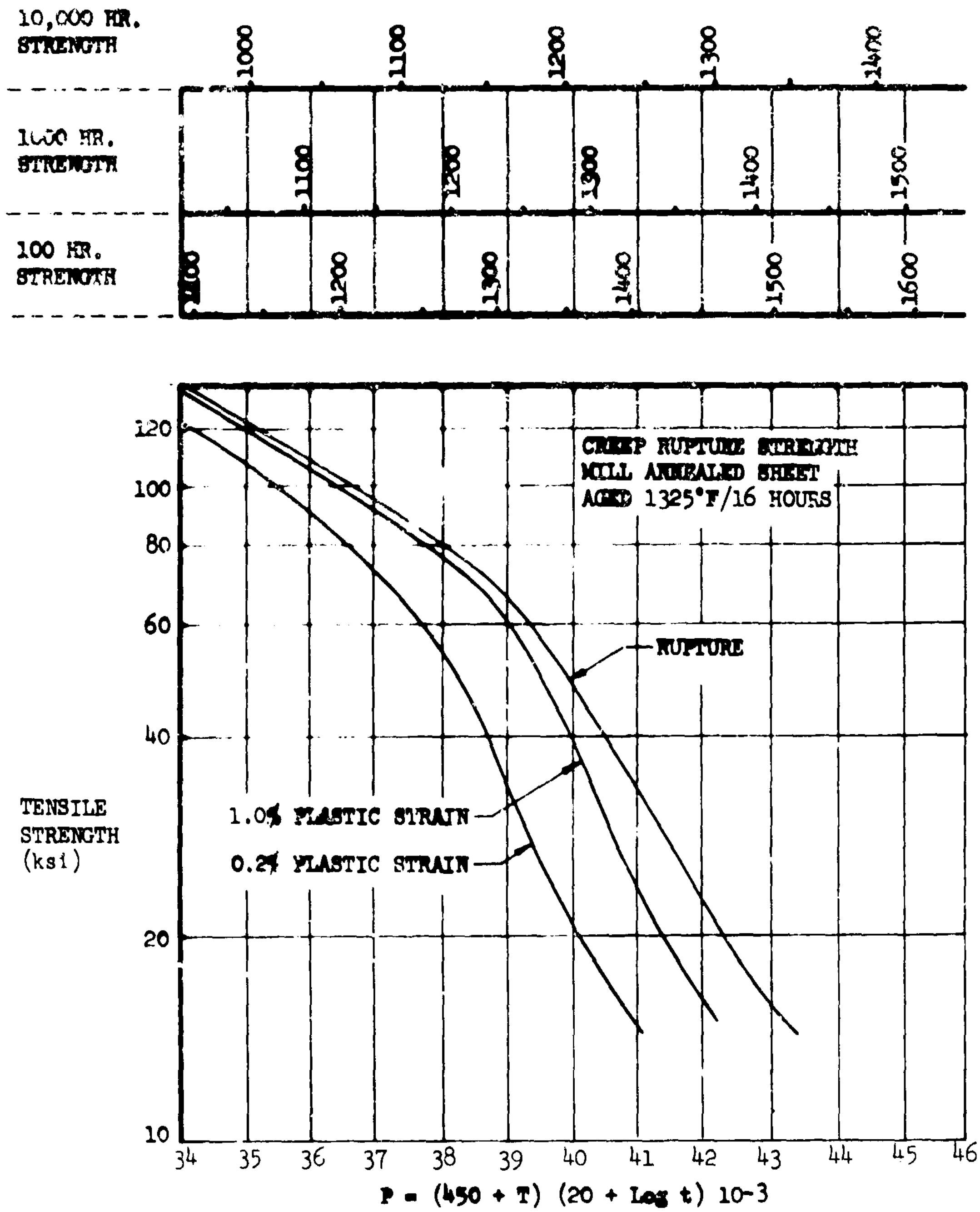


Figure 2-51. Creep-Rupture Strength of Inconel 718

2.3.2 Processing

2.3.2.1 Heat Treatment
Thermal treatments for corrosion and heat resistant alloys are conventional and are controlled by company or military specifications.

2.3.2.2 Welding and Brazing

a. Fusion welding of stainless steel alloys is used as required for conventional applications. Company specifications limit such welding to the stabilized and extra low carbon grades of 300 series alloys unless the welding is followed by suitable annealing heat treatment. Boeing specifications also control the welding of higher strength stainless alloys and super alloys such as PH 15-7Mo, 17-4 PH, and Hastelloy X and Hastelloy B. Weldments of these alloys in engine and thrust reverser applications have performed satisfactorily. The development and evaluation of welds in Inconel 718 as reported in TDR No. ML-TDR-64-237 (Ref. 8) confirms the good weldability of this alloy.

b. Resistance spot and seam welding, projection welding, and flash welding are used in conventional applications.

c. Brazing of these alloys is accomplished by torch, induction, or furnace methods, as applicable, and in accordance with Boeing specifications.

2.4 ALUMINUM

2.4.1 Alloys
Aluminum alloys are used for applications in areas where temperatures do not exceed 200°F. Alloy 7075 in the -T73 condition is used for most aluminum forgings. The 2000-series alloys exhibit excellent fatigue resistance and fracture toughness properties and are used for tension-loaded structure. The 6000-series alloys are selected for ductwork, because of their good weldability, corrosion resistance, and fatigue characteristics. Thermal treatments, stability, and properties are well documented in industry and military specifications and handbooks.

2.4.2 Processing
Processing of aluminum alloys will be controlled by existing specifications. Since the aluminum alloys to be used are those with which Boeing has had extensive experience, no new fabrication innovations are required.

2.5 CONTROL OF RESIDUAL STRESSES
It is recognized that service life of structural components can be influenced by residual stresses induced during fabrication such as welding and room temperature forming.

Residual stresses are controlled during fabrication to ensure a level below the maximum acceptable sustained stress. The effectiveness of residual stress control methods for welded and formed titanium is illustrated in Fig. 2-52.

The Boeing Company has developed the compliance technique for residual stress measurement to determine the effectiveness of stress control methods. This method permits measurements of residual stress distribution through the thickness of the part being examined. It is not limited to average values or surface values as are other commonly employed techniques. A complete discussion of the technique is presented in Boeing document D6-16266 (Ref. 16).

2.5.1 Stress Prevention
Mechanical prestress has been shown to be a highly effective means of preventing weld-induced residual stress. Although the limitations imposed by the process preclude extensive application, it will be used wherever practicable. The process is accomplished by applying a load so that the two parts to be joined are strained elastically along the weld line. This strain is maintained during the welding process and released after the weld has solidified and cooled. Figure 2-53 shows the effectiveness of the process as reflected by the change in flatness for different amounts of prestrain. For large parts it is not required to load the panel over a width greater than the length of the weld.

Preheating does not generally lower the residual stresses to an acceptable level. It is not a substitute for the more effective methods but will be used as necessary to prevent in process cracking.

2.5.2 Stress Relief
Relief of residual stresses can be accomplished in several ways. The selection of the appropriate method will be based on the configuration, material, and application of the component.

The conventional methods of stress relief are by heating the entire part in a furnace or locally heating the region to be stress relieved. Figure 2-54 shows the maximum residual stress remaining after various time-temperature com-

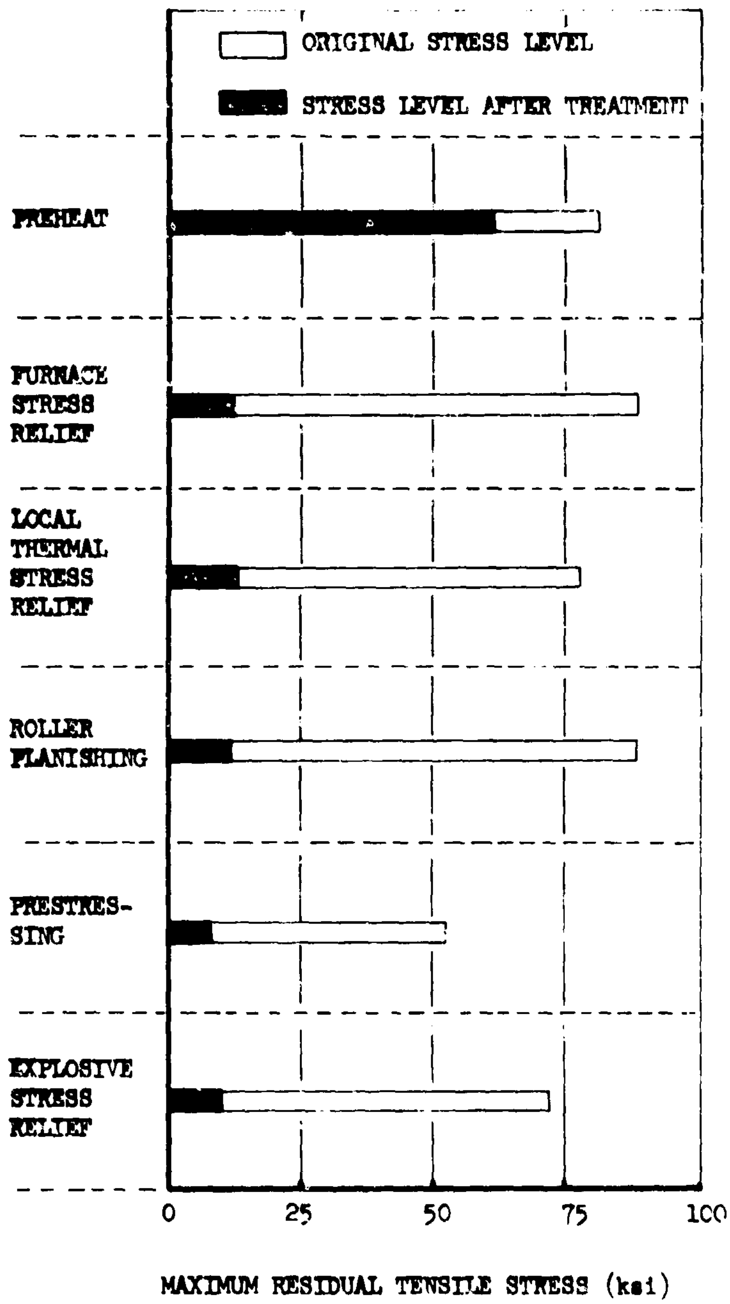


Figure 2-52. Typical Results of Stress Control Measures on Various Alloys and Specimen Configurations

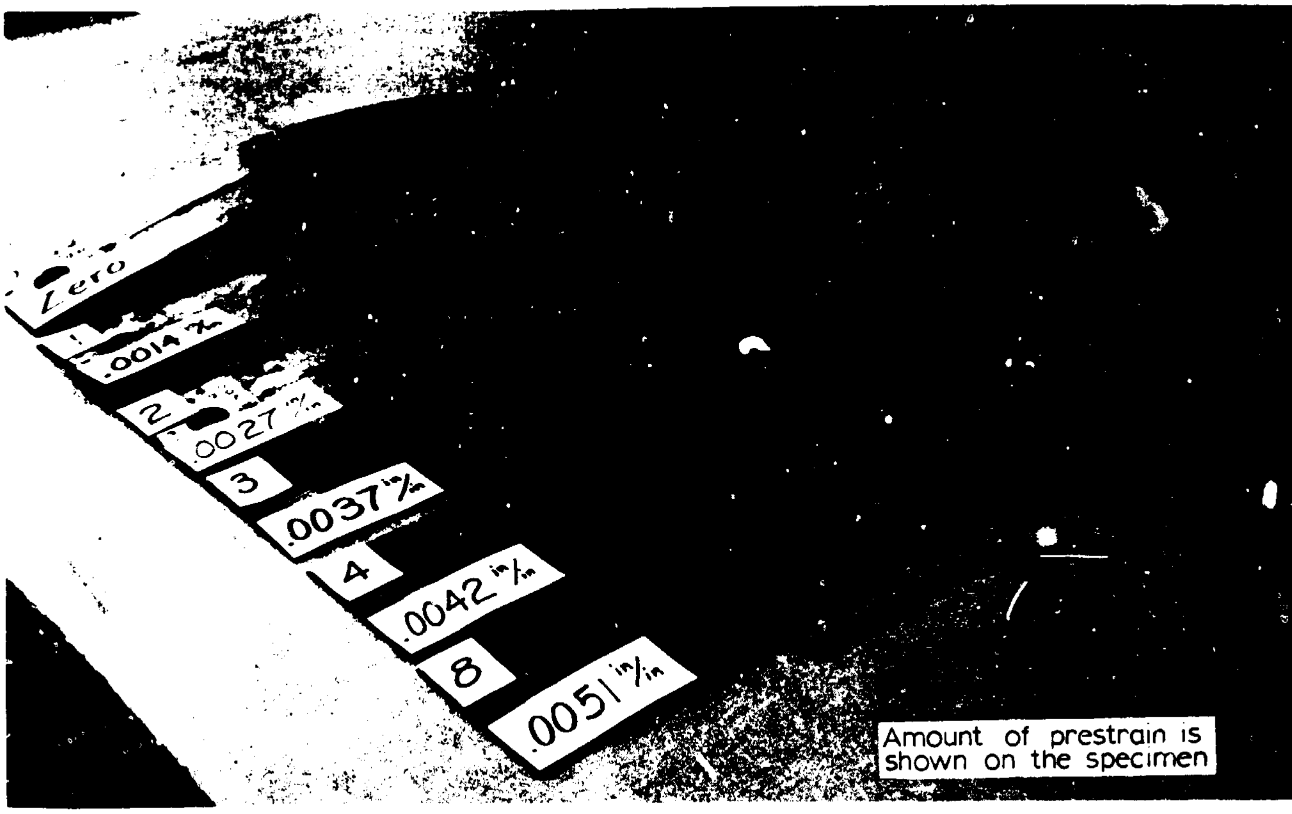


Figure 2-53. Effects of Mechanical Prestrain Variations on Weld Shrinkage Distortion

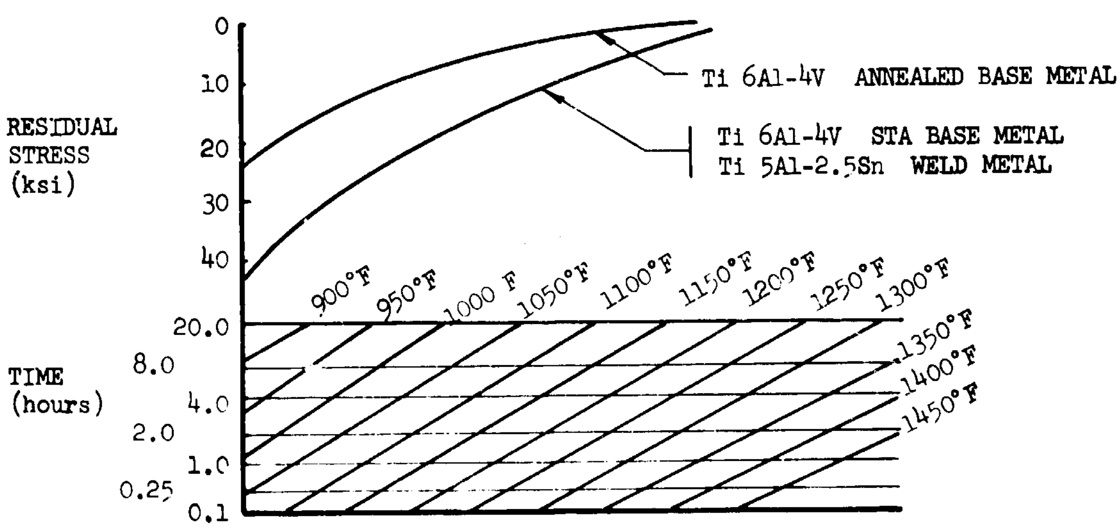


Figure 2-54. Time Temperature Parameters for Stress Relief

binations for furnace stress relief. The curves are also valid for local thermal stress relief when care is taken to minimize stresses created by temperature gradients adjacent to the locally heated zone.

Relief of residual welding stresses can be effected in flat sections by roller planishing either at room temperature or at elevated temperature using local heating. Roller pressure sufficient to elongate the rolled area about two percent is employed. This reduction must take place over the entire region of high stress. If the planished width is too narrow, the stress distribution shown in Fig. 2-55 is obtained. This is quite similar to the original distribution except for stresses in the planished zone. Roller planishing presents distortion problems when used on thin gage metals because the residual compressive stress introduced by it may result in local buckling. In sections thicker than about 0.125 inch this problem does not exist. No noticeable effect on tensile and ultimate strength has been observed.

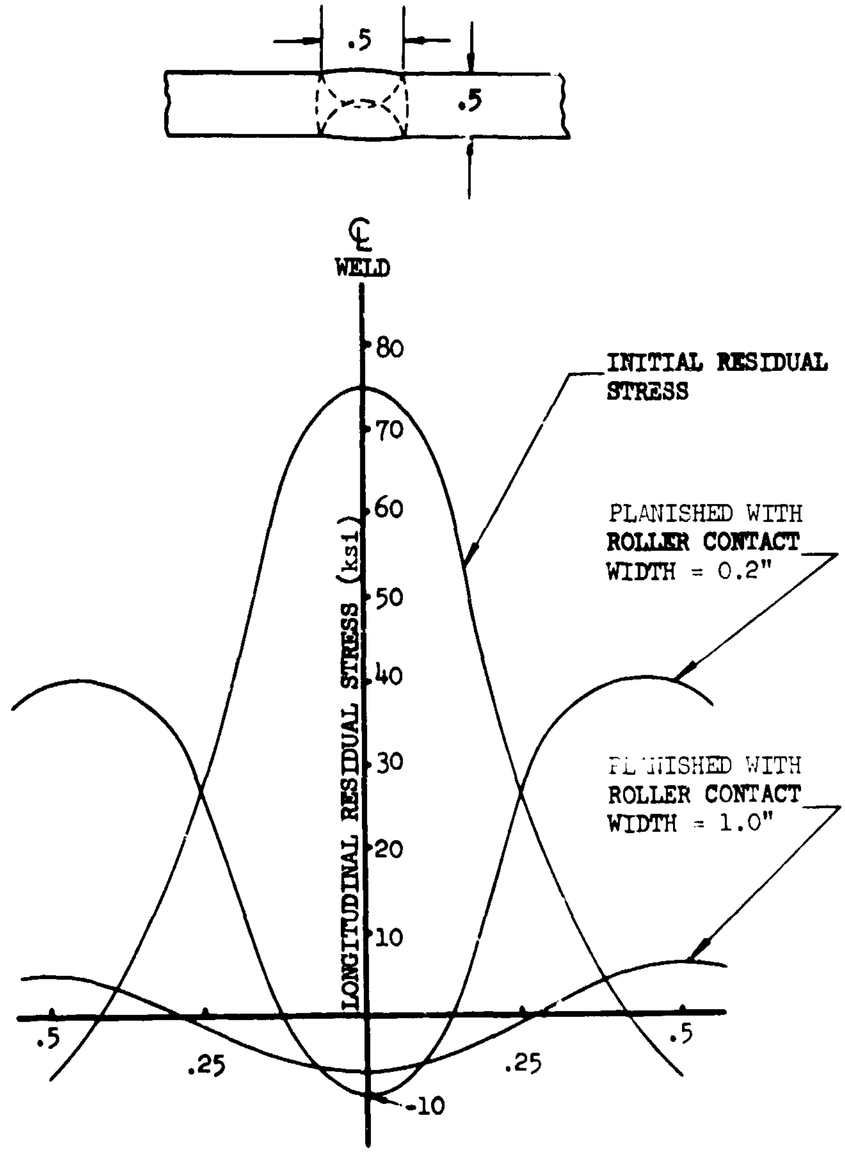


Figure 2-55. Residual Stress Distribution after Hot Planishing

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Preliminary results of a program to investigate explosive stress relieving indicate it is an effective method with potential time and cost reduction. It has been used on both welded and formed sections and is accomplished by a very high, short duration, pressure pulse caused by detonation of explosives. Figure 2-56 shows the average residual stress in the weld zone in 0.250 inch thickness Ti 6Al-4V after explosive stress relief using various dynamic pressures. The process has no effect on strength and ductility.

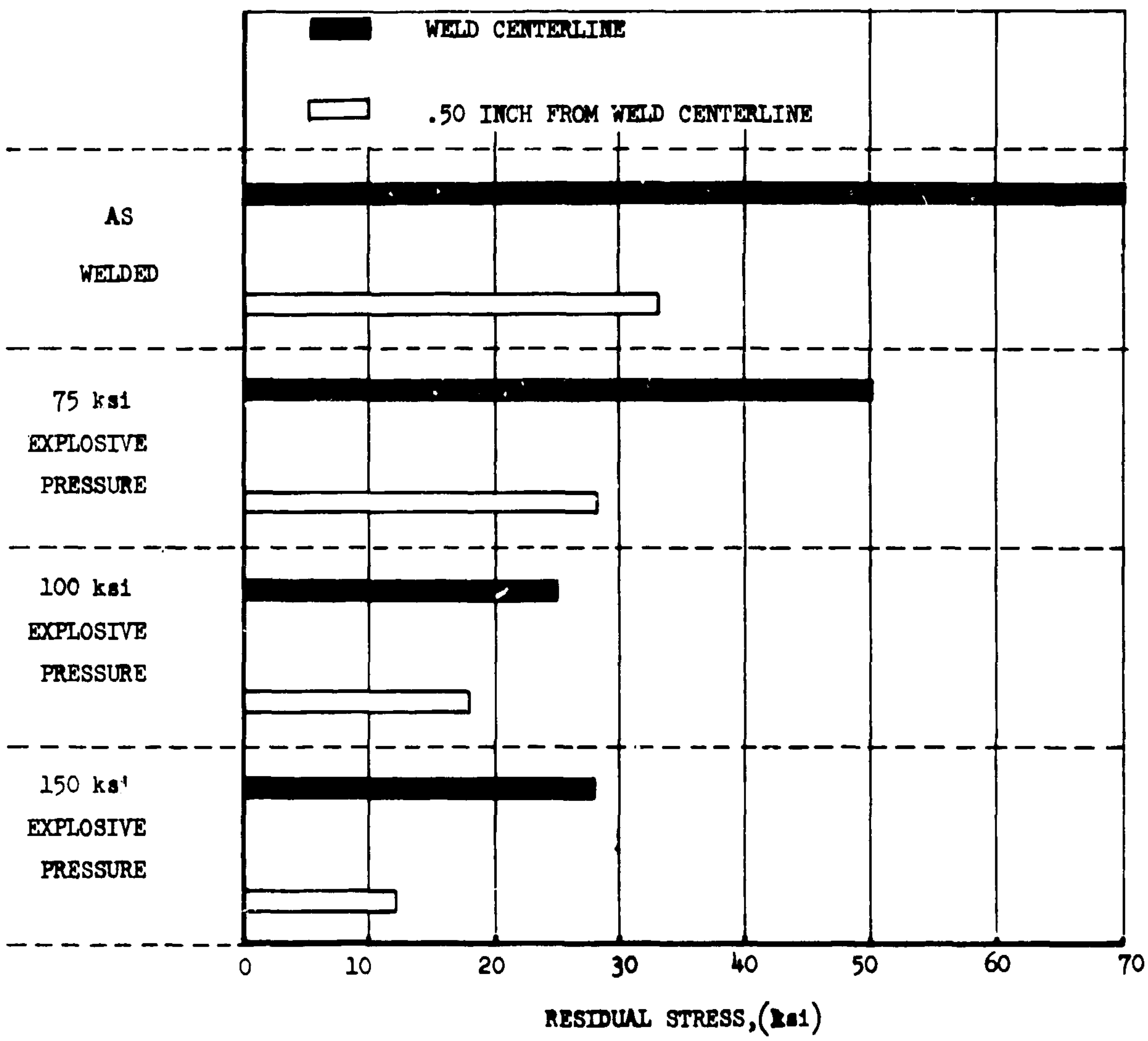

Figure 2-56. Explosive Stress Relief Data

3.0 NONMETALS

Nonmetallic materials are used for a variety of applications on the interior and exterior of the B-2707. These applications include structural components such as adhesively bonded panels, windshields, and radomes and nonstructural components such as ducts, insulation, seals, sealants, coatings, ceramics, lubricants, hydraulic fluids, interior furnishings, and supporting hardware.

Materials are selected on the basis of the requirements of the specific application, weight, availability, maintainability, producibility, service life, cost and compatibility with other materials.

3.1 ADHESIVE BONDING

Structural adhesive bonding capitalizes on the elevated temperature strength and inherent thermal stability of polyimide resin adhesives. Structural bonds, with bonded shear strengths of 3500 psi, are readily obtained on the titanium alloys used for construction of the B-2707. Resistance to thermal degradation is achieved by incorporating fillers and anti-oxidants in the adhesive and by proper surface treatment of the titanium adherents. Bonds with shear strengths exceeding 2,000 psi after 15,000 hr of continuous exposure at 500°F are achieved.

The above structural capabilities of polyimide adhesives ensures bonded structure having sufficient integrity to withstand the temperature environment imposed by the flight regime of the B-2707.

Polyimide adhesive bonded designs offer the following advantages:

a. Fatigue life of joints is increased when bonding is used in conjunction with mechanical fasteners.

b. Bonding enables use of light weight structure in areas of high energy sonic environment.

c. A weight saving is realized by reduction of size and number of mechanical fasteners.

d. Bonding performs a dual function of joining and sealing.

e. Adhesive bonded structure is less costly than brazed structure.

f. Bonding isolates dissimilar metals, thus preventing galvanic corrosion.

3.1.1 High Temperature Structural Bonding

Metal-to-metal bonding of titanium structure for elevated temperature usage will be accomplished with commercially available polyimide resin adhesive systems.

The selected polyimide adhesive system, chosen primarily on the basis of its strength retention after thermal aging, was compared with polybenzimidazoles, modified epoxies, and other polyimide adhesives prior to its final selection. Results of the comparative heat aging tests utilizing phosphate fluoride pretreatment are shown in Fig. 3-1 and 3-2. The superior strength retention of the polyimide adhesives is readily apparent.

Design criteria for bonded titanium structure are comparable to those used on current commercial airplanes since titanium lap shear values exceeded 1,800 psi after 12,000 hours of aging at 400 to 500°F. The development of suitable metal-to-metal bonding included evaluations of metal cleaning and surface treating processes. The process selected using Pasa Jell 107 precludes degradation of the bond by reaction products of the adhesive during cure, and from thermal and hydrolytic effects during the life of the product. Figure 3-3 and Table 3-A show the effects of the selected cleaning and surface treating procedures on bond strengths after environmental exposure. The Pasa Jell 107 pretreatment provides superior thermal and hydrolytic degradation protection and will be employed as the surface preparation.

The procedure used for joining metal-to-metal structural components is a Boeing-developed, low-pressure, two-phase, bonding process. The initial or bonding phase utilizes hot air circulating pressure vessels wherein an accurately sequenced

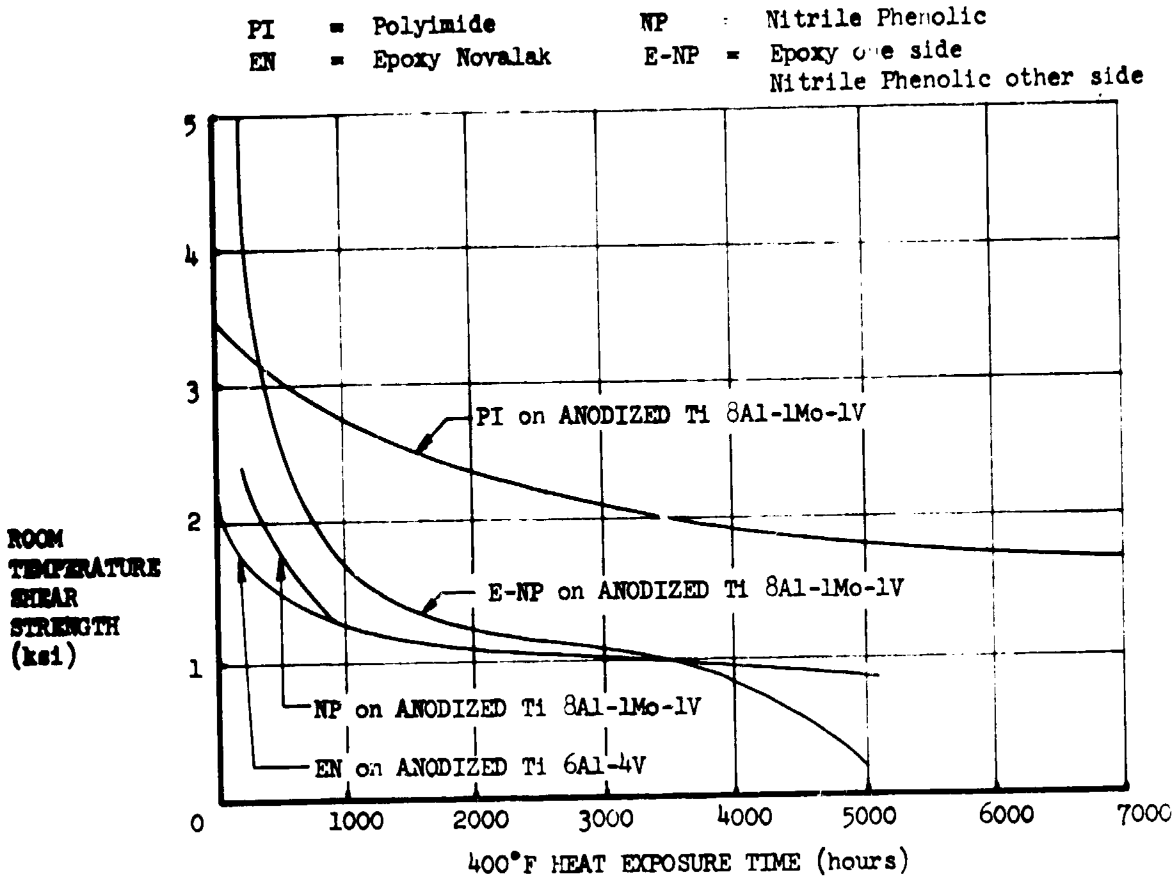

Figure 3-1. Adhesive Heat Aging, Comparative Data, 400° F

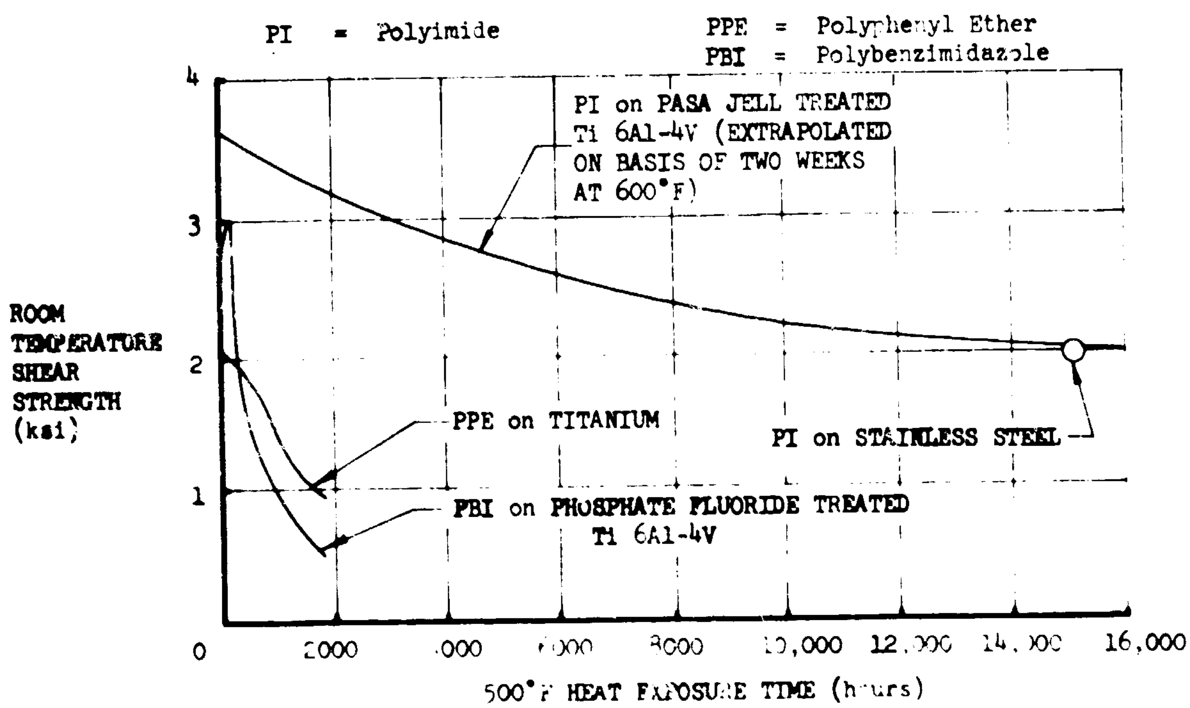

Figure 3-2. Adhesive Heat Aging, Comparative Data, 500° F

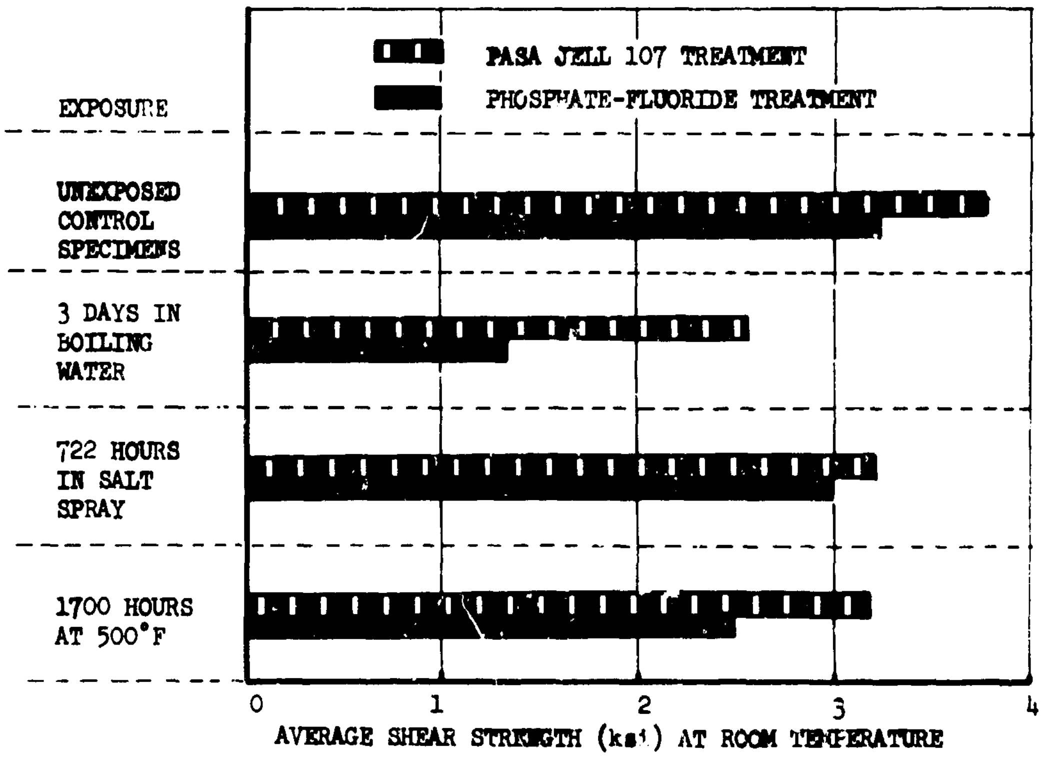

Figure 3-3. Effects of Environment and Surface Treatments on Lap Bonded Specimens

Table 3-A. Lap Shear Strength of Titanium Alloy Adhesive Bonds After Various Exposure Conditions

Surface Treatment	Remaining Bond Strength (Percent Original)		
	After 186 hours at 600°F in Nitrogen	After 186 hours at 600°F in Air	After 3 days in Boiling Water
Pasa Jell 107 (Dichromate Chemical Conversion Coating)	105 (c)	88 (c)	59 (b)
Alkaline Anodizing Process	94 (c)	76 (c)	52 (b)
Phosphate-Fluoride Chemical Conversion Coating	55 (b)	33 (a)	34 (a)
Cleaned by Chemical Etching in Nitric-Hydrofluoric Acid	27 (a)	24 (a)	23 (a)

(a) Adhesive failure
(b) Partially adhesive failure
(c) Cohesive failure within the adhesive

application of heat and pressure produces an intermediate cure condition in the polyimide resin. A subsequent post curing phase using air heated ovens, chemically stabilizes the polyimide resin and imparts optimum strength to the adhesive.

The above two phase cure process results in the most economical use of pressurized and unpressurized heating equipment and allows maximum flexibility in manufacturing. In addition, two phase curing allows maximum integration of the metal-to-metal bonding process with such allied bonding operations as polyimide laminate fabrication, polyimide structural sandwich composite bonding, and high temperature polyimide foam processing. As a result outstanding success has been achieved in production of polyimide bonding structures.

Inspection procedures to ensure quality metal-to-metal bonding do not differ significantly from existing procedures employed on current commercial airplane.

Quality assurance provisions as dilineated in Boeing specifications include the following:

a. Control of adhesive procurement, storage, and use.

b. In process inspection.

c. Processing of test articles simultaneously with production hardware.

d. Nondestructive testing.

Figures 3-4 and 3-5 show, respectively, the costs and weights of various bonded aluminum structures found by previous experience to be sonic fatigue resistant. Cost of similar titanium structure is higher due to raw material costs.

3.1.2 General Adhesive Bonding

General bonding will be accomplished using a variety of adhesives which have been used successfully for 15 years for bonding metals, plastics and other materials such as fabrics, felt, cork, wood, rubber, and glass. Adhesive systems are selected for use on the basis of environmental resistance, strength, and processing characteristics. Typical adhesive systems are:

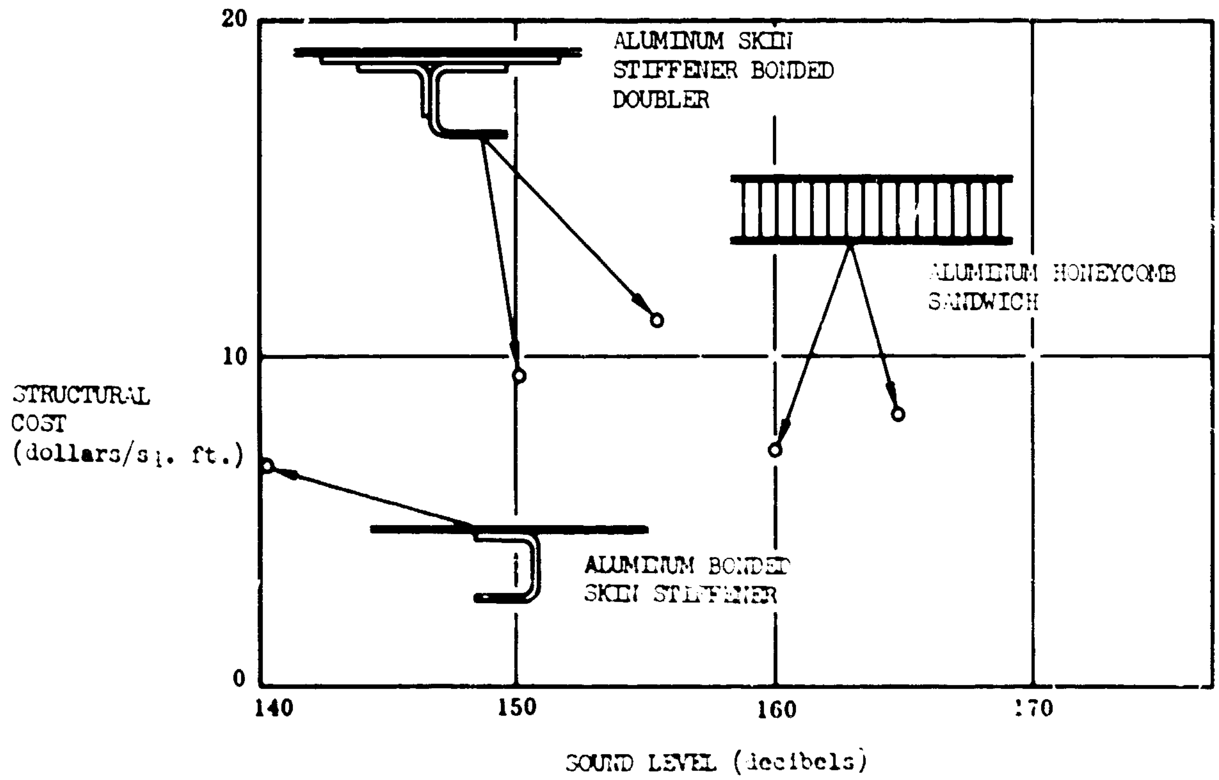

Figure 3-4. Cost of Typical Structure for Use in Sonic Environments

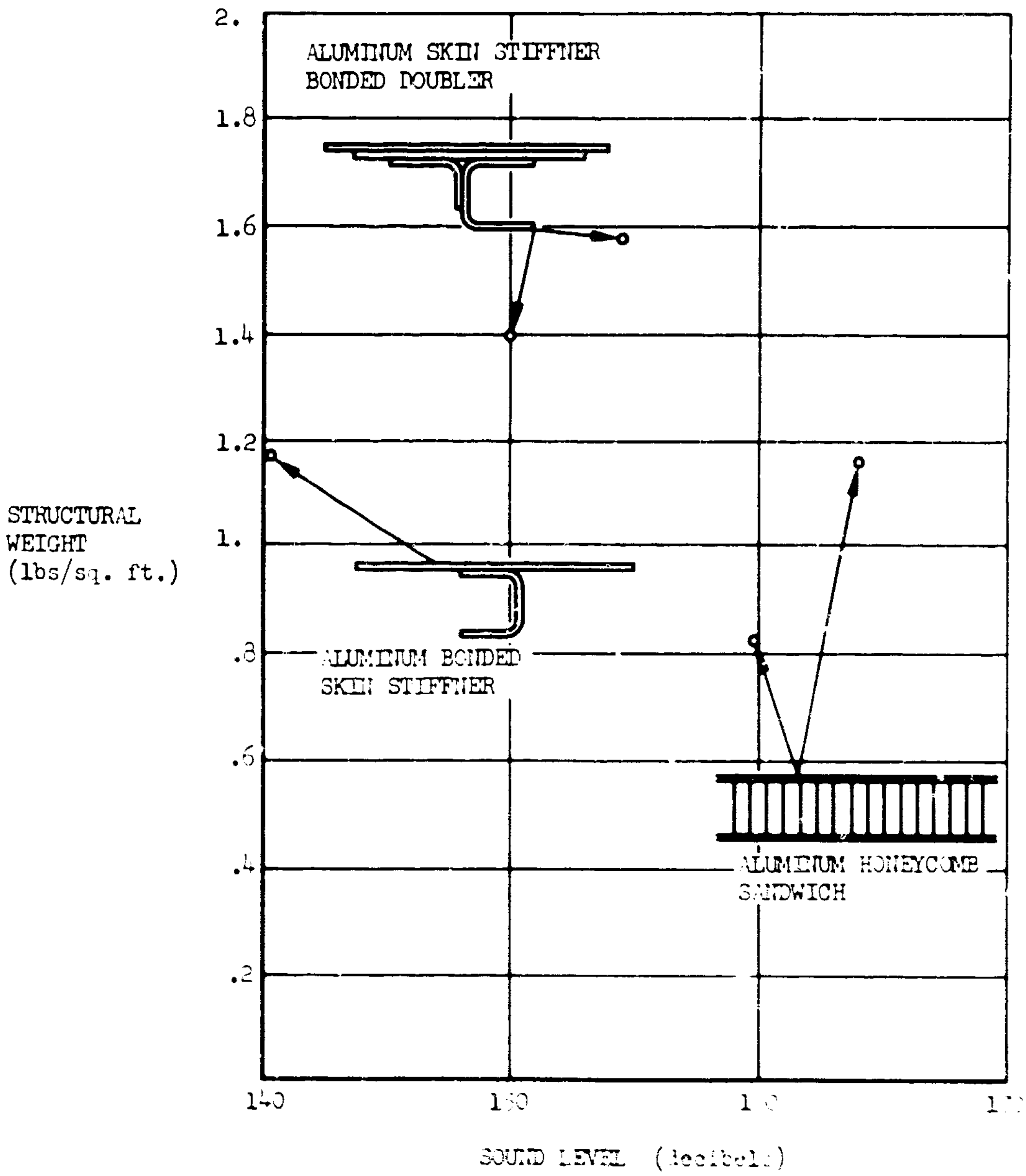

Figure 3-5. Weight of Typical Structures for Use in Sonic Environments

a. Epoxy-polyamide such as a combination of Shell Chemical Company's Epon 812 and 828 with General Mill's Versamid 115 and 125.

b. Buna N rubber-based such as Coast Pro-Seal's 590M.

c. Polysulfide-based such as Coast Pro-Seal's 719B.

d. Silicone-based such as Dow Corning's RTV Silastic 501 with A-4094 primer.

For load carrying applications requiring lap shear strengths greater than 1000 psi and where the temperature does not exceed 260°F, the adhesives listed in Table 3-B are typical of those to be used.

3.2 STRUCTURAL SANDWICH

Sandwich structure is used for applications including load bearing surfaces of the wing, body, and empennage. Sandwich structure for other than microwave applications will have titanium exterior faces, glass fabric reinforced polyimide core, and inner surfaces of titanium or glass reinforced polyimide laminate. Sandwich assemblies possess the following advantages:

a. High strength.

b. Lightweight structure for maximum stiffness.

c. Maximum aerodynamic smoothness.

Sandwich structure configurations take advantage of the knowledge gained in almost 15 years of

Table 3-B. General Adhesive Systems

Adhesive	Type	Typical Lap Shear Strength		
		Room Temp. lb/in.^{2}	180°F lb/in.^{2}	-67°F lb/in.^{2}
AF 30	Nitrile Phenolic	3400	2100	3700
FM-61	Nitrile Phenolic	3200	3800	3700
Epon 927	Epoxy	3200	500	3200
Aerobond 3013	Epoxy	3200	500	3200
HT-424	Epoxy Phenolic	3800	3100	3700
FM-58	Nitrile Phenolic Epoxy	3800	2700	4300
AF-204	Epoxy Phenolic	3000	2800	3700
AF-126	Epoxy	5000	1500	4500
Redux 775	Vinyl Phenolic	4500	2000	4000
FM-47	Vinyl Phenolic	4500	3600	3200
FM-1000	Polyamide Epoxy	7000	3670	7400
FM-34	Polyimide	3600	----	----

experience in designing and producing honeycomb structures. Analysis has been made of previous service experience and successful applications have been utilized; the less desirable avoided. For example, the adhesive systems used at the time honeycomb sandwich construction was introduced required the use of perforated core to allow removal of adhesive volatiles during cure. As a result, moisture ingression occurred. Today's sandwich panels are constructed with nonperforated, impermeable core, processed by a method which removes the volatiles prior to gelation of the adhesive, and incorporate edge sealing. Comparison of the conditions are shown in Fig. 3-6.

Wedge close outs are designed with a foam filled core and seam welded trailing edges to provide a positive seal with maximum durability at the interface of the face sheets. A comparison between earlier designs and the present one is shown schematically in Fig. 3-7.

3.2.1 Resin System

The selection of a high temperature resistant organic polymer matrix for bonded structural sandwich is based on comprehensive evaluation of existing candidate materials. The polymers were intially screened on the basis of chemical structure. The investigation covered a review of all applicable research in the field including the Whittaker Corporation's work under Contract No. AF33(615)-2283 (Ref. 17) and Westinghouse Research Laboratory's work reported in AFML-TR-65-188 (Ref. 18). The more aromatic polymer structures are generally more resistant to elevated temperature environments. These polymers include polyimides, polybenzimidazoles, silicones, and phenolics. Factors which significantly influence the selection of a suitable polymer system are thermal stability in air at 400 to 500°F for the service life of the B-2707, processing characteristics, availability, and cost.

Polyimide resins exceed the requirements established for the B-2707. Current polybenzimidazole resin systems, although possessing temperature strength retention for intermediate time exposures, lack the necessary thermal stability for service life requirements. Phenolics have inferior thermal stability. Silicone resins, although possessing good thermal stability, do not have adequate structural properties.

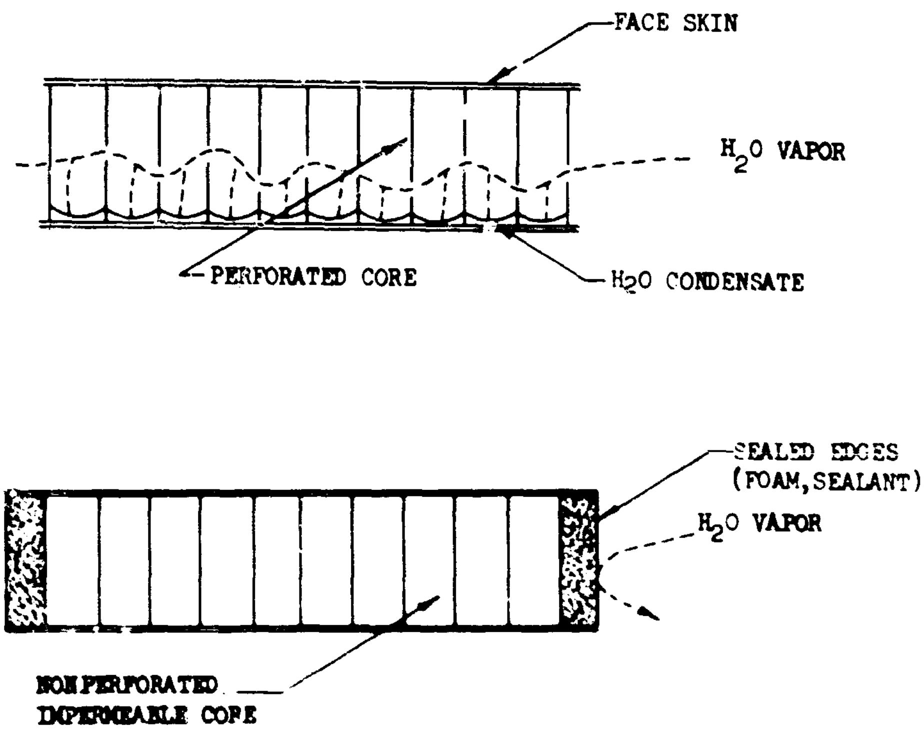

Figure 3-6. Sandwich Design

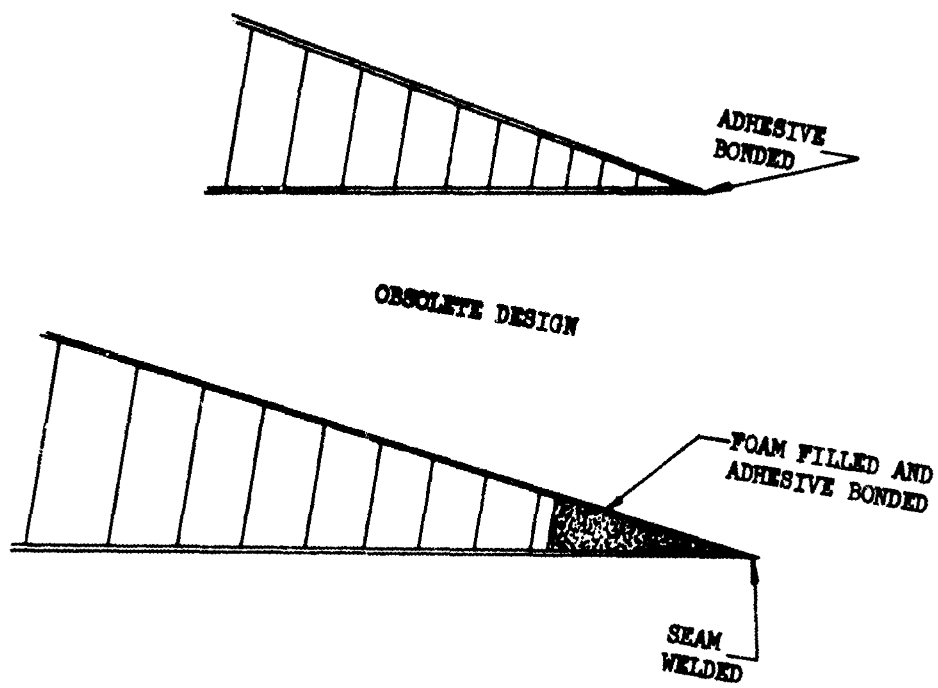

Figure 3-7. Panel Close Out Comparison

A limited investigation was conducted on pyrrone polymer (a hybrid of polyimide and polybenzimidazole) supplied by NASA Langley Research Center, Hampton, Virginia. The tests indicate that pyrrone possesses about the same thermal resistance properties as polyimides. However, the relative scarcity and high cost of pyrrone polymers restricts their consideration for B-2707 reinforced plastic structure at this time.

Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) are used as screening tests to predict thermal properties of resin systems. TGA simultaneously measures the temperature and mass of a material subjected to increasing or constant heat. DTA measures the temperature imbalance between reference material (alumina) and the test material as heat is applied. Cure and burn-off temperatures of polymeric materials are estimated from TGA and DTA test results. Materials are tested in air, inert atmosphere or vacuum. Figure 3-8 illustrates the TGA of several polymer systems and the DTA of polyimide resin. The outstanding polymers on the basis of TGA and DTA can be narrowed to polybenzimidazoles, polyphenylenes, and polyimides. Thermal stability of these resins is demonstrated by their superior weight stability at elevated temperature conditions. The initial polyimide cure (270 to 400°F) is indicated by DTA endothermic reaction caused by release of solvent and water. Polyimide burn-off is evident at about 800°F by the exothermic reaction as a result of oxidation and cleaving of chemical bonds. Polyphenylenes have not been considered as matrix materials because of their relative scarcity and high cost.

Polymer thermal stability is also determined from strength and weight loss of laminate structure after aging at elevated temperatures. Figures 3-9 and 3-10 illustrate strength and weight loss characteristics of some of the more thermally stable resins. Both figures demonstrate the superiority of the polyimide system.

Polyimide resins such as Skybond 700 (Monsanto), PI-4701 (DuPont), or Imidite 1850 (Narmco) will be used for structural adhesive, reinforced plastic faces, reinforced plastic honeycomb core, and structural foam in sandwich assemblies.

Glass fabric reinforcement for polyimide sandwich faces, polyimide honeycomb sandwich core, and polyimide laminates will be E and S glass. Environmental resistance of reinforced plastic structure at elevated temperature and high humidity conditions is dependent on the glass

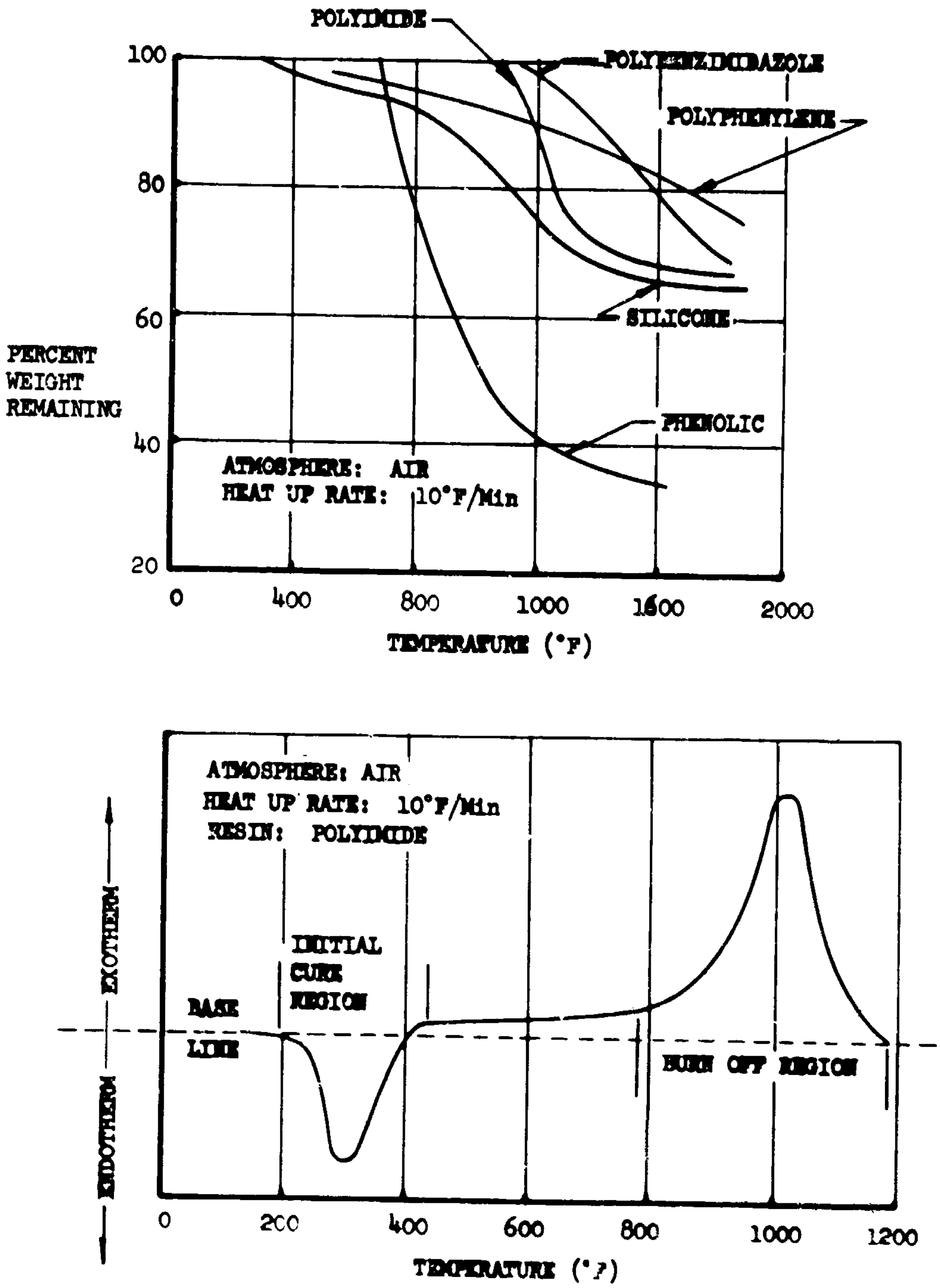

Figure 3-8. Thermogravimetric and Differential Thermal Analyses of Resin Systems

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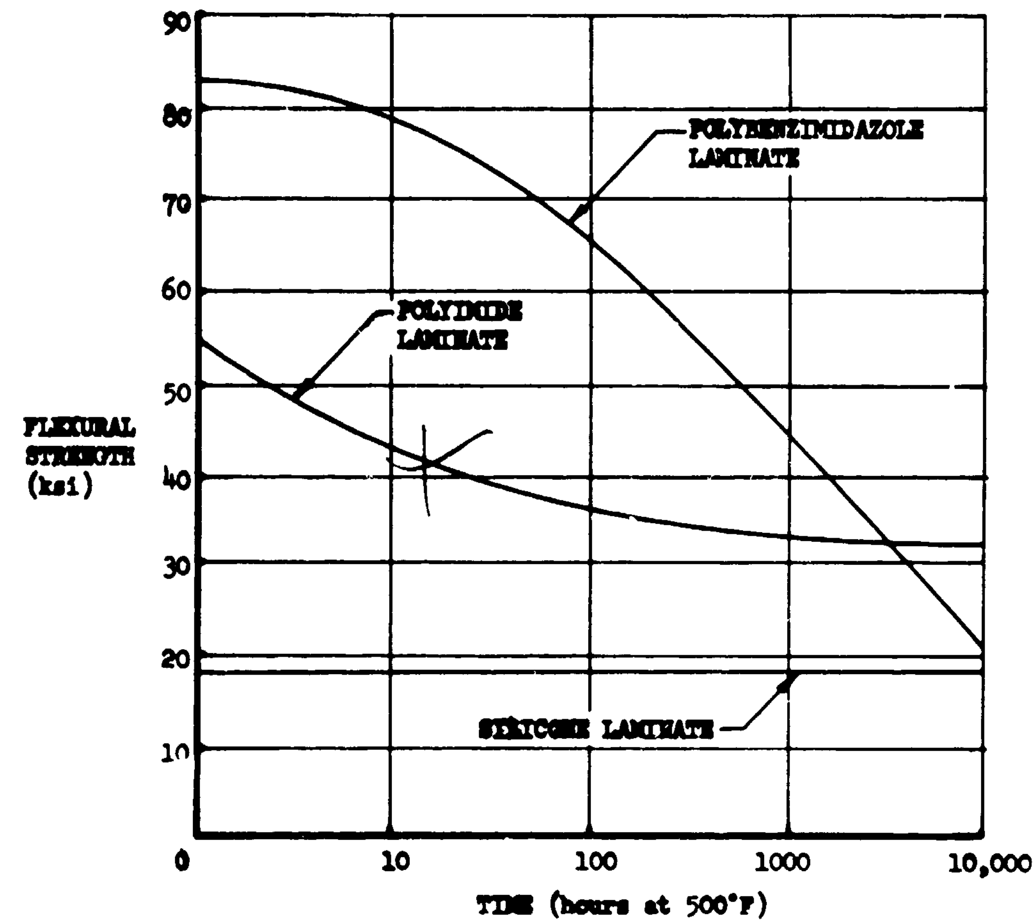

Figure 3-9. Thermal Stability, Strength Basis

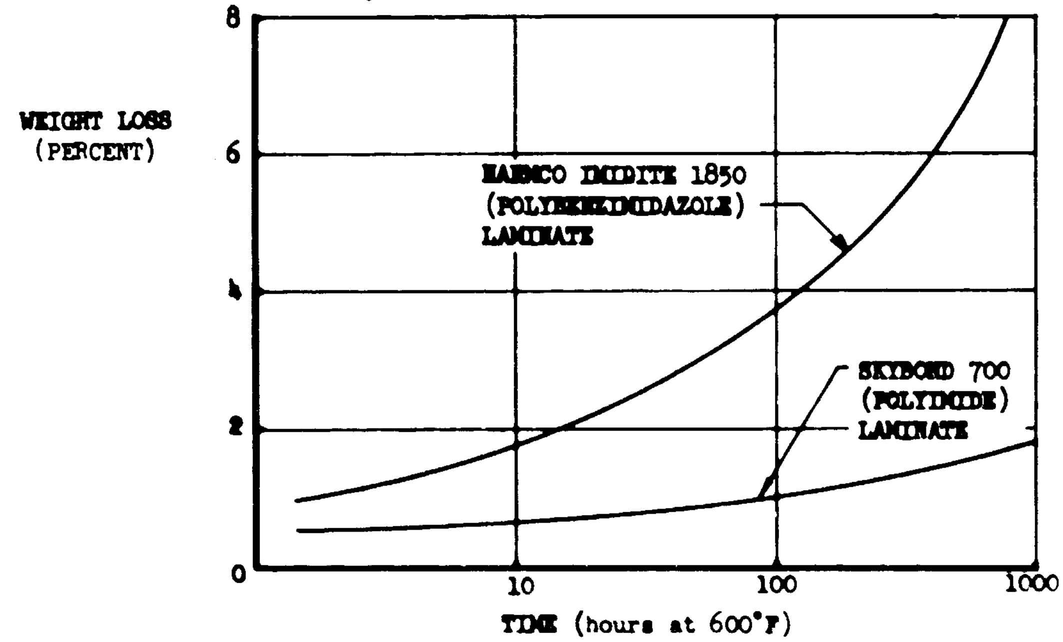

Figure 3-10. Thermal Stability, Weight Loss Basis

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finish. E glass with A1100 (aminopropylsilane) finish is more compatible with the polyimide system than other glass-polyimide finishes. Although S glass is 30 percent stronger than E glass, the finishes available do not provide any significant advantages after long time thermal exposure. Coordinated programs with Owens-Corning, Union Carbide, DuPont, and other companies have been established to evaluate developments in glass finishes which are more compatible to both E and S glass reinforcement. In addition, the coupling agents developed for S glass polybenzimidazole systems under Air Force Contract No. AF33(615)-1163 (Ref. 19) will be evaluated for the polyimide resin system in cooperation with Owens-Corning.

3.2.2 Core Material

Fiberglass reinforced polyimide resins, have been selected for the honeycomb core. In a cooperative program established between Boeing and Hexcel, several types of core materials were developed and evaluated including phenolic and polyarylene ether phenol with and without polyimide coatings. These materials were aged and tested at 400, 450, and 500°F. The comparative mechanical properties of the test core materials are shown in Figs. 3-11 through 3-13. These figures illustrate effects of thermal exposure on polyimide core at 450 and 500°F. Mechanical properties of polyimide core are not affected by continuous exposure to 400°F and exhibit only a slight decrease after 5000 hours at 450 and 500°F. Polyimide resin is the basic component that provides elevated temperature stability in laminates, honeycomb core, and adhesive. The stability of the mechanical properties of reinforced polyimide structures and adhesives at 450°F from 1000 to 15,000 hours substantiates engineering design decisions for the polyimide system. The mechanical properties of polyimide structures are expected to remain constant at flight conditions

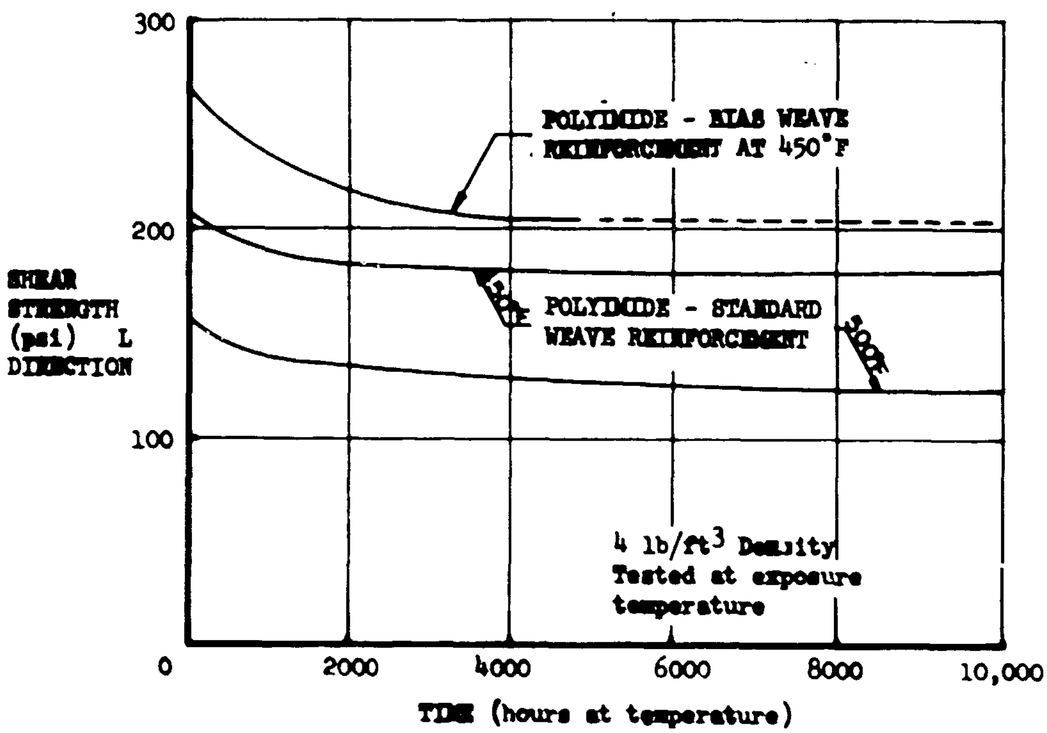


Figure 3-11. Reinforced Plastic Honeycomb Core Material Shear Strength, L Direction Versus Time at Temperature

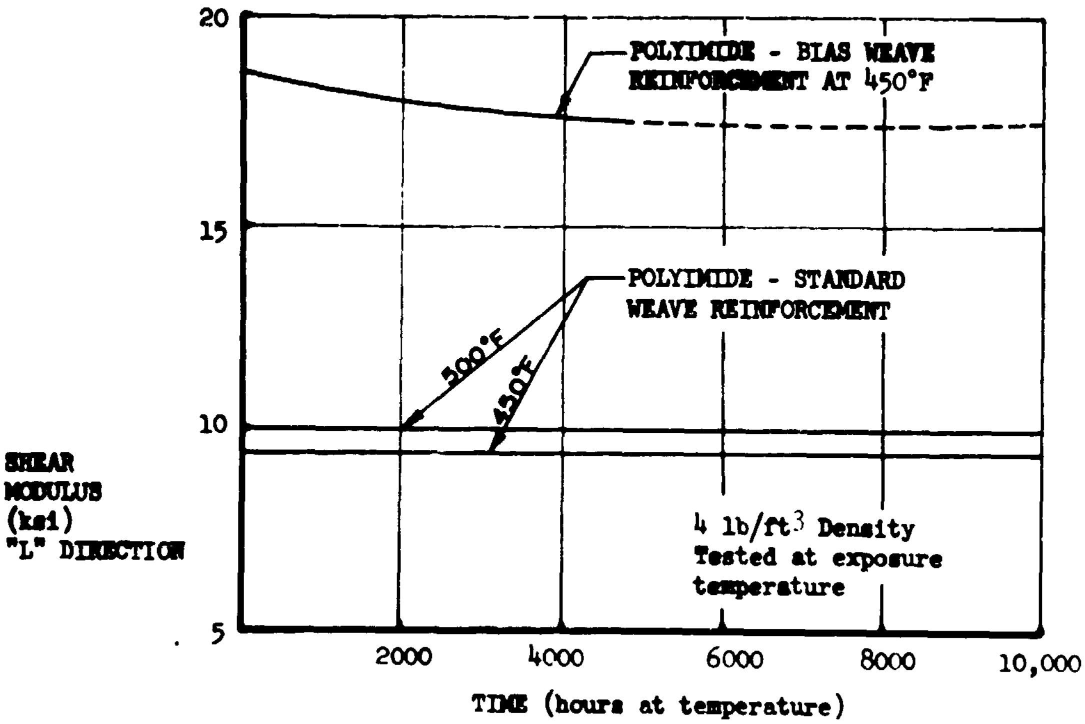


Figure 3-12. Reinforced Plastic Honeycomb Core Materials Shear Modulus (psi) L Direction Versus Time at Temperature

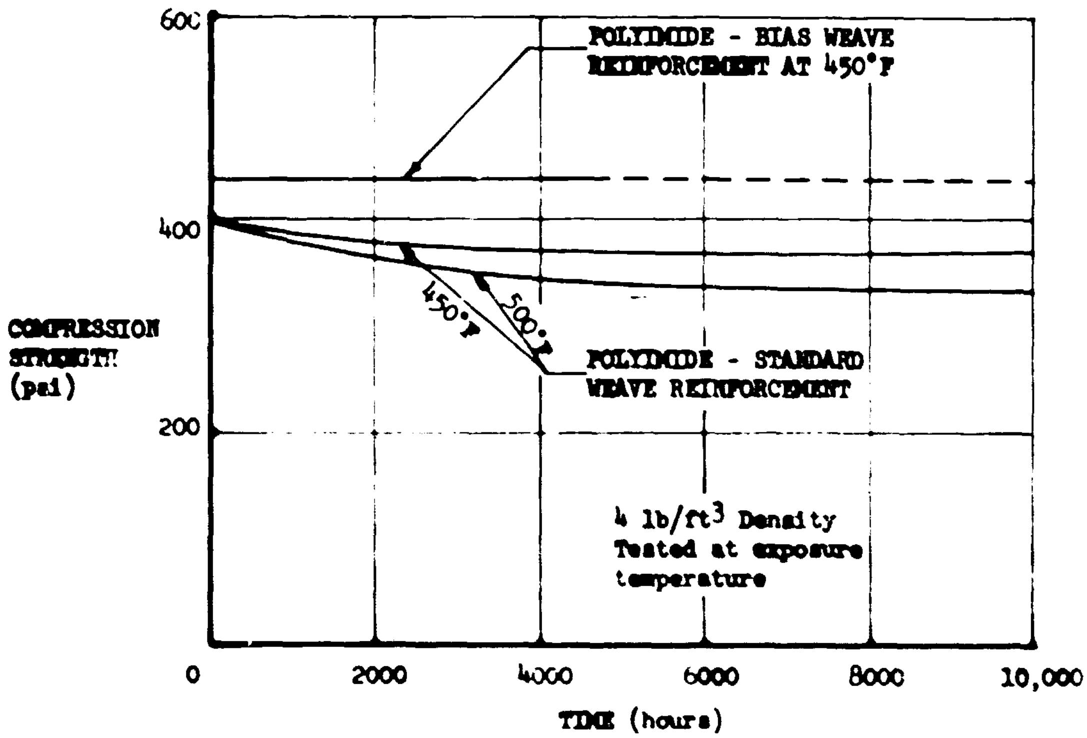


Figure 3-13. Reinforced Plastic Honeycomb Core Materials Compressive Strength (psi) Versus Time at Temperature

in excess of 30,000 hours. The polyimide cores were the only ones retaining adequate strength after 1500 hours of exposure.

Use of bias weave reinforcements offers distinct mechanical strength and modulus advantages over the standard weave. The impermeability of the core is assured through proper selection of fabric weave, optimum glass to resin ratios and closely controlled manufacturing procedures.

Resistance welded and diffusion bonded commercially pure titanium core is available and company processes utilizing polyimide adhesive have been developed for sandwich structure. Diffusion bonded titanium honeycomb core was developed under NASA Contract No. NAS 7-273 (Ref. 20) by Hexcel Products, Incorporated. Preliminary evaluation indicates that it will be similar in mechanical properties to resistance welded core. The mechanical properties of resistance welded commercially pure titanium and bias weave reinforced polyimide core are listed in Table 3-C.

3.2.3 Reinforced Plastic Faces

Plastic laminate sandwich face material is composed of polyimide resin such as Skybond 700 (Monsanto), PI-4701 (DuPont) or Imidite 1830 (Narmco) reinforced with glass fabric having A1100 finish. The polyimide laminate material selections have been previously discussed.

Retention of structural integrity at B-2707 service temperatures is being established by thermal aging tests of laminates. Exposure of polyimide laminates to temperatures of 400°, 500°, and 550°F for 30,000 hours is in progress. Mechanical properties for both E and S glass

Table 3-C. Strength and Cost Comparison, Titanium/Polyimide Core

Mechanical Properties of Resistance Welded C. P. Titanium Square Cell Honeycomb Core

Density ft^3	Core Designation	Shear Strength (psi)		Compression Strength, psi	Approximate Cost \$/ft^2 3/4-in. Thick
		L Direction	W Direction		
2.3	4 - 1	100	75	133	20
4.5	4 - 2	270	178	400	25
6.7	4 - 3	435	330	908	35
7.3	3 - 2	480	370	1070	35

Mechanical Properties of Bias Weave Glass Fabric
Reinforced 3/16 Inch Hexagonal Cell Honeycomb Core

Density ft^3	Core Designation	Shear Strength (psi)		Compression Strength, psi	Approximate Cost \$/ft^2 3/4-in. Thick
		L Direction	W Direction		
4	HRH-327	284	160	600	16
5	HRH-327	355	200	751	18
6	HRH-327	425	240	900	20

laminates to 10,000 hours of thermal aging are illustrated in Fig. 3-14 through 3-25. These data indicate the capability of the polyimide system to withstand B-2707 requirements.

Sandwich structures having reinforced plastic laminate facings will require sealing if they are exposed to moisture or fuel containing environments. Minnesota Mining's EC 1937 is an effective sealer for polyimide laminates and withstands temperature environments to 500°F. Two additional materials which can be used for the sealing application are DC 7146 (Dow Corning) silicone resin and RS 5660 (Monsanto) polyimide resin. These two materials have shown the desired properties to provide a positive seal on polyimide laminates. In addition, Narmco reported in AFML-TR-65-146 (Ref. 21), Vol. I that DC 7146 was the outstanding antioxidation sealer for their polybenzimidazole laminates and Brunswick Corporation have indicated in Document BR-862-122-003 (Ref. 22) that RS 5660 polyimide resin can be used to provide a moisture barrier for the SST radome.

Films such as FEP coated Kapton (DuPont) and polyimide resin coated Nomex paper (DuPont) have also been successfully utilized as moisture and fuel barriers on polyimide laminates.

3.2.4 Metal Faces
Structural sandwich in most applications will be metal faced with Ti 6Al-4V alloy on both sides. The adhesive resin system and titanium cleaning and pretreatment processes to be used are discussed in Sec. 3.8.1. The selection of metal faces is based on weight advantages.

3.2.5 Adhesives
The adhesive used for structural core-to-skin bonding is formulated from a polyimide base resin as discussed in Sec. 3.1.1. Thermal exposure of test specimens at 500°F to 12,000 hours has been completed. Adhesive lap shear strengths of bonded titanium joints with various surface treatments are compared in Fig. 3-26.

The adhesives designated in Fig. 3-27 are identical except for exclusion of antioxidant and filler. It is apparent that advantages are gained with the additives except for the loss of strength after exposure to moisture. This deficiency may be overcome by use of primer as illustrated by Fig. 3-28. The use of a combination primer and film adhesive system is selected as the optimum method of achieving maximum strength and heat stability of the bond.

3.2.6 Edge Potting and Sealing
Structural sandwich edge potting compounds are

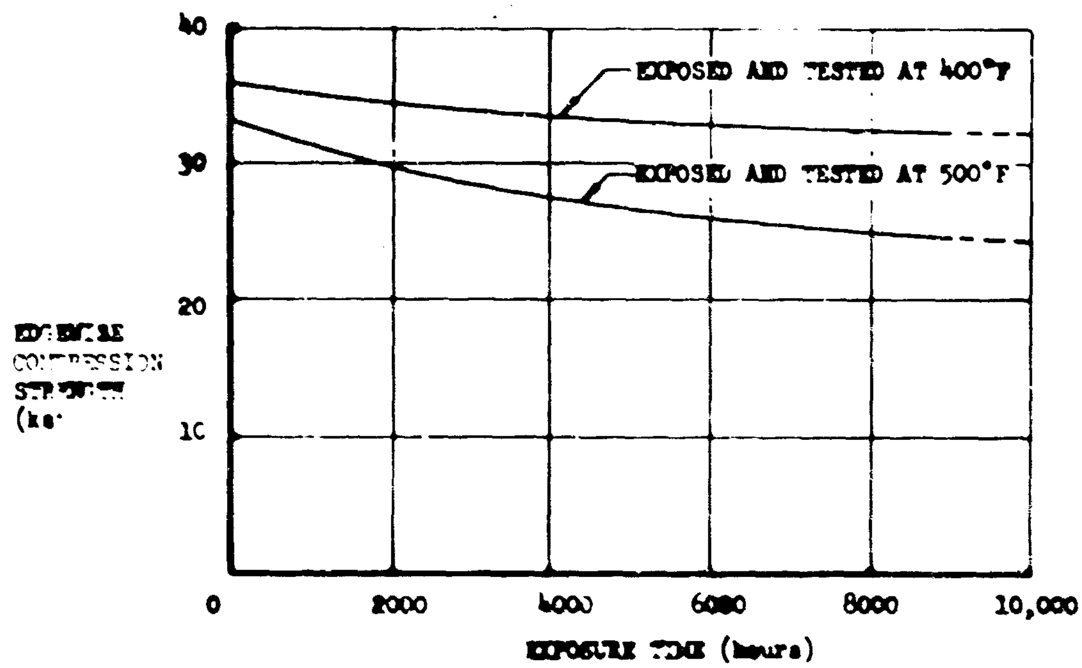


Figure 3-14. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Edgewise Compression Strength

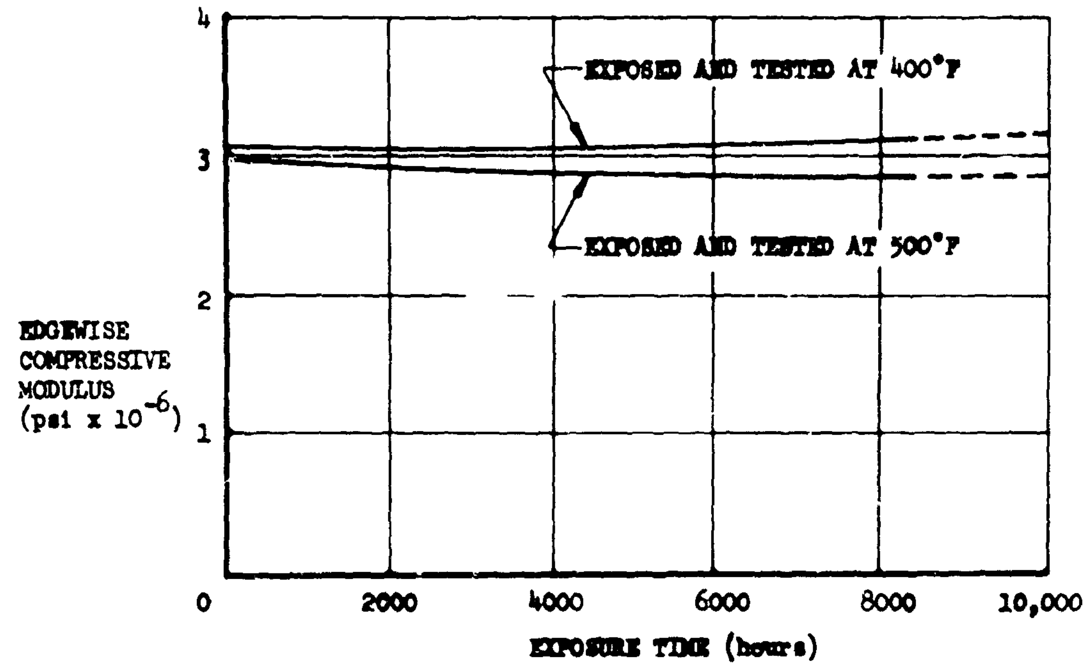


Figure 3-15. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Edgewise Compression Modulus

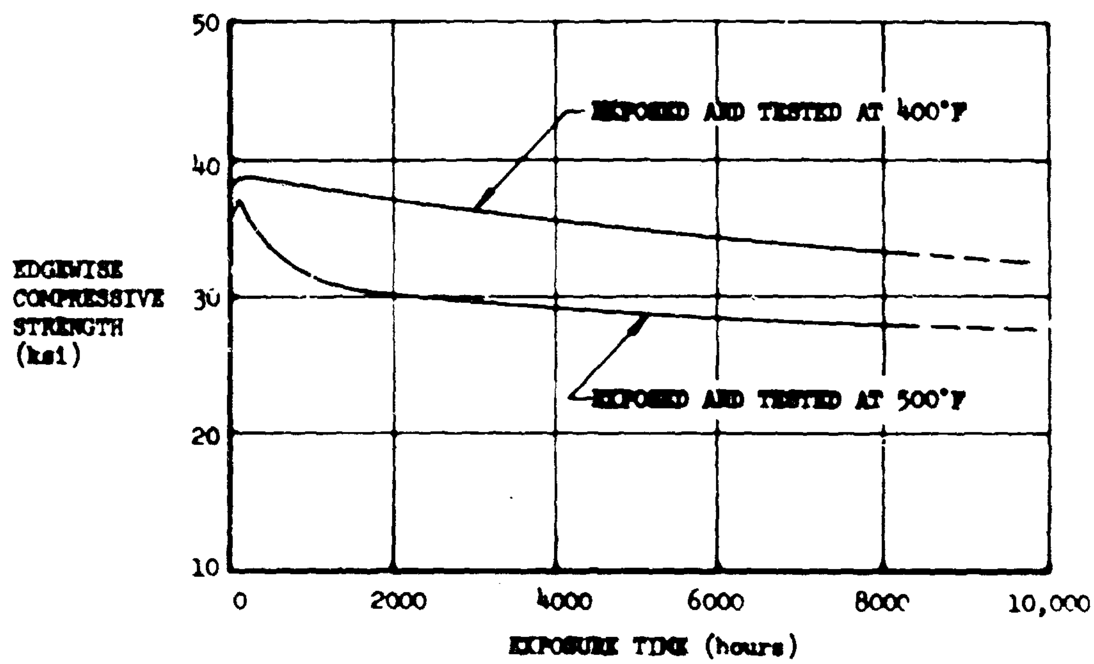


Figure 3-16. Thermal Exposure Effects on S Glass Reinforced Polyimide Laminate Edgewise Compression Strength

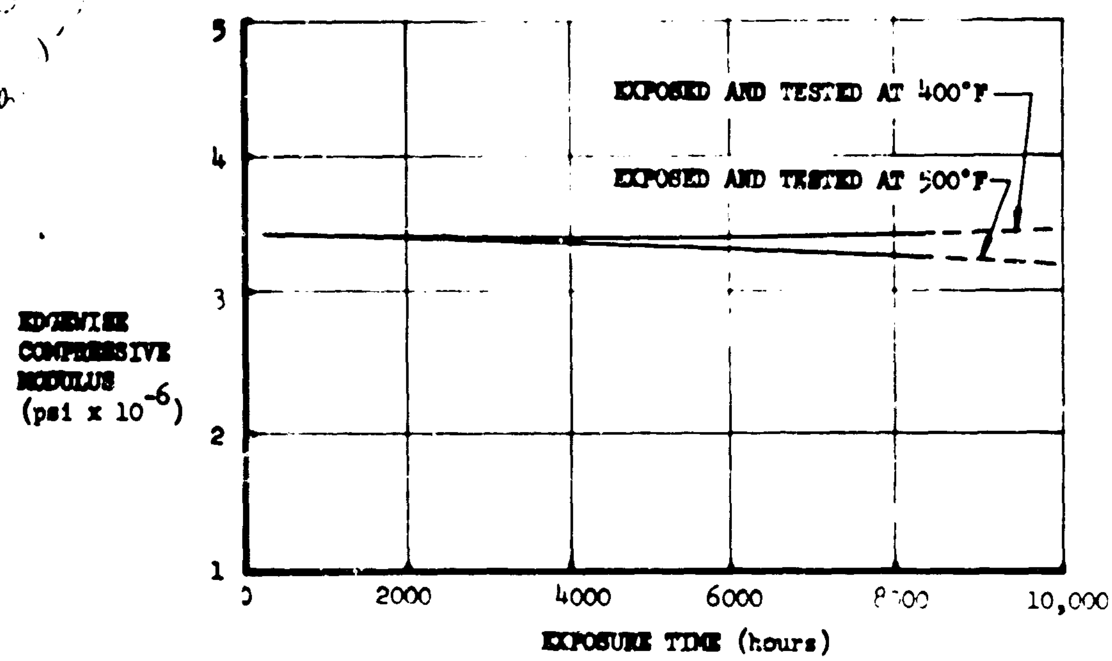


Figure 3-17. Thermal Exposure Effects on S Glass Reinforced Polyimide Laminate Edgewise Compression Modulus

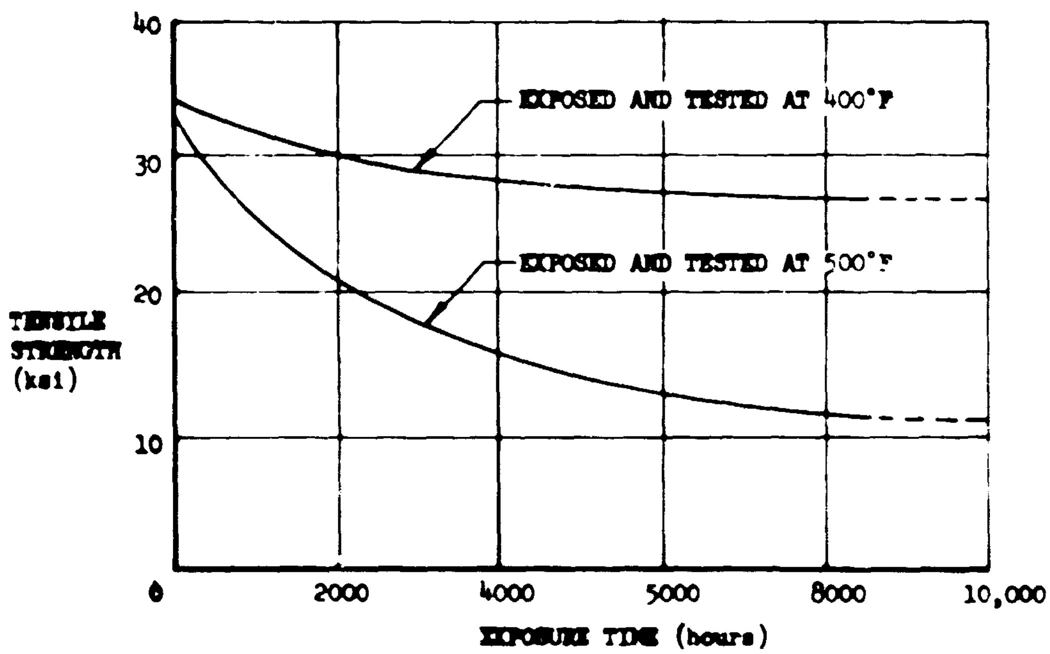


Figure 3-18. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Tensile Strength

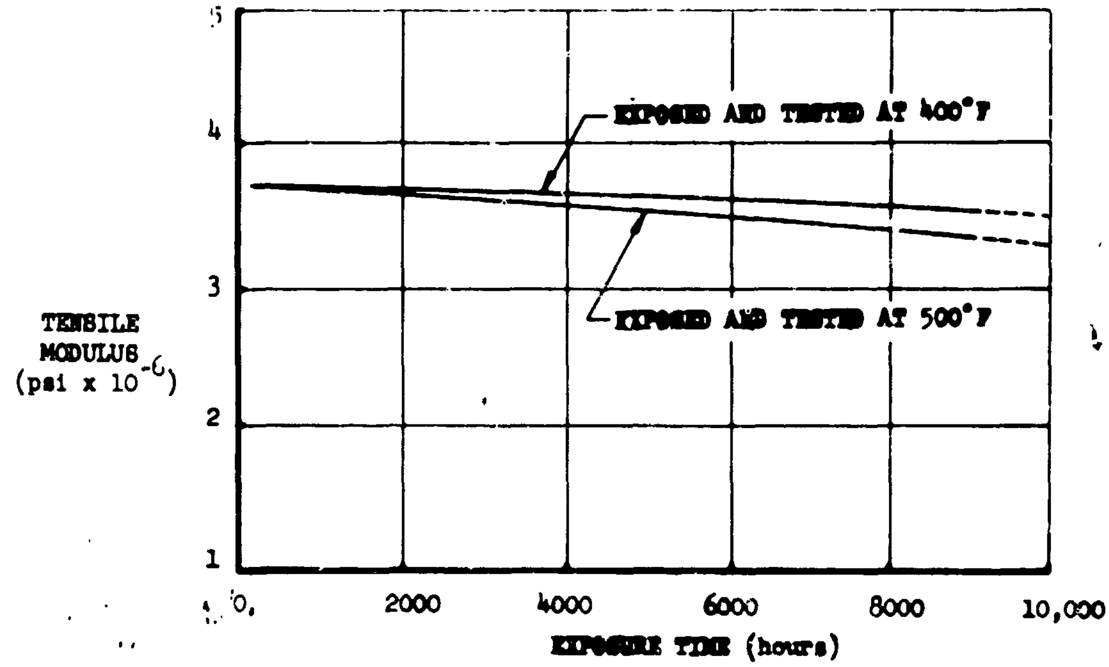


Figure 3-19. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Tensile Modulus

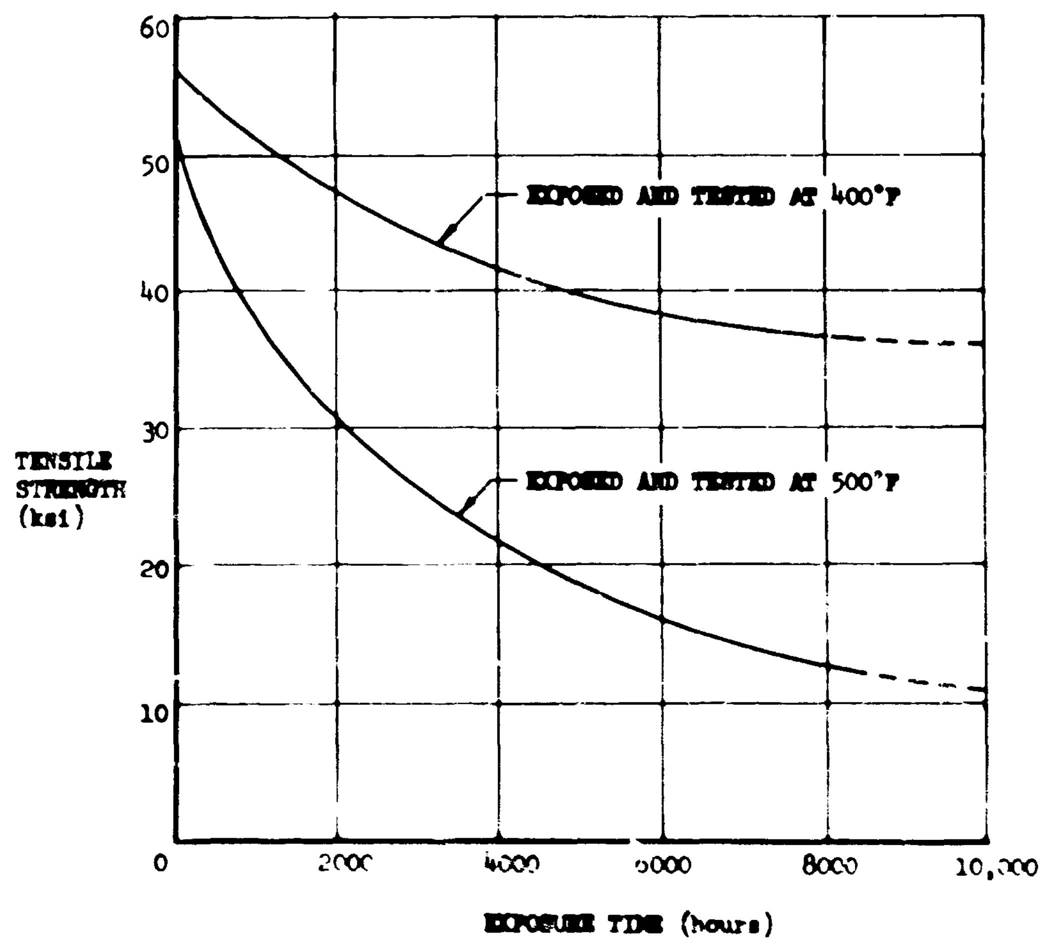


Figure 3-20. Thermal Exposure Effect on S Glass Reinforced Polyimide Laminate Tensile Strength

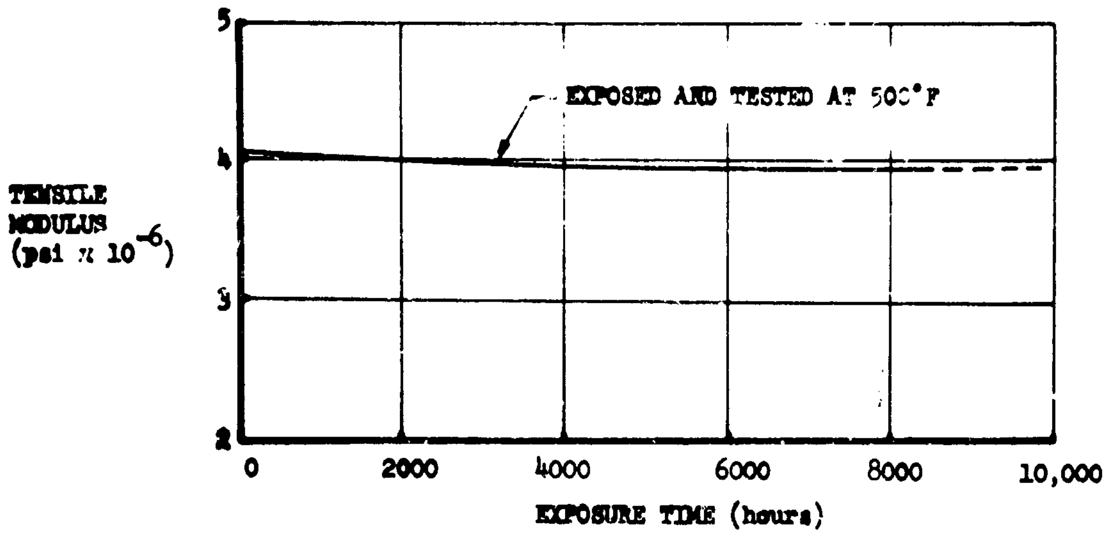


Figure 3-21. Thermal Exposure Effects on S Glass Reinforced Polyimide Laminate Tensile Modulus

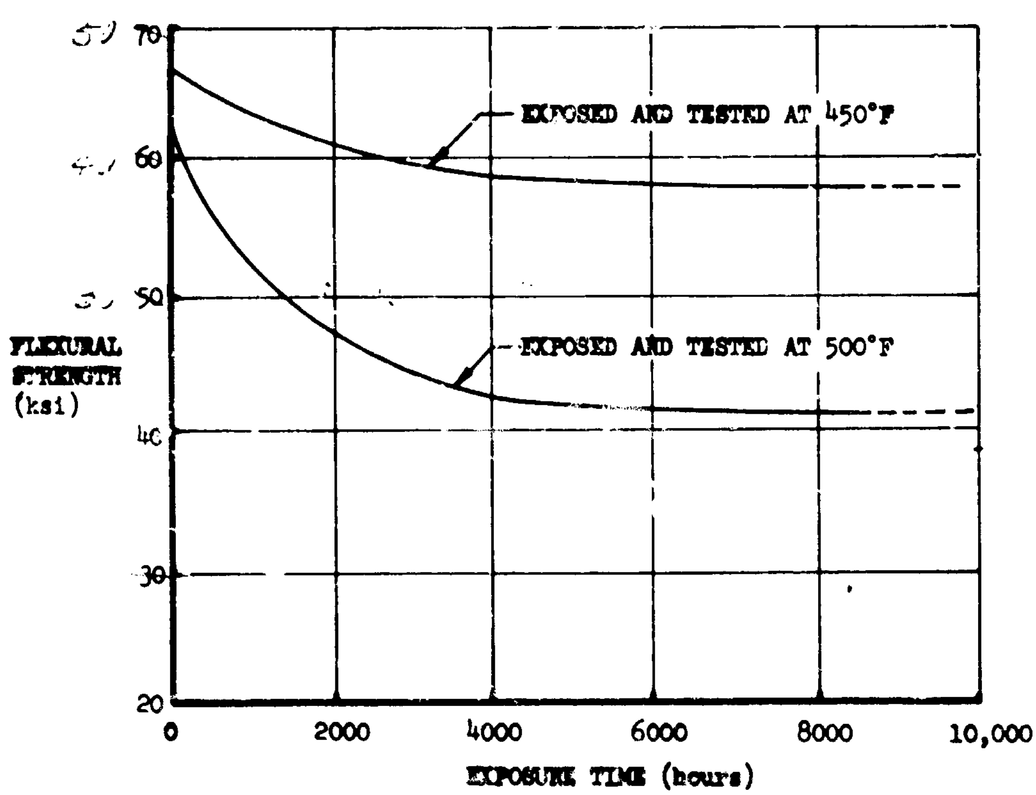


Figure 3-22. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Flexural Strength

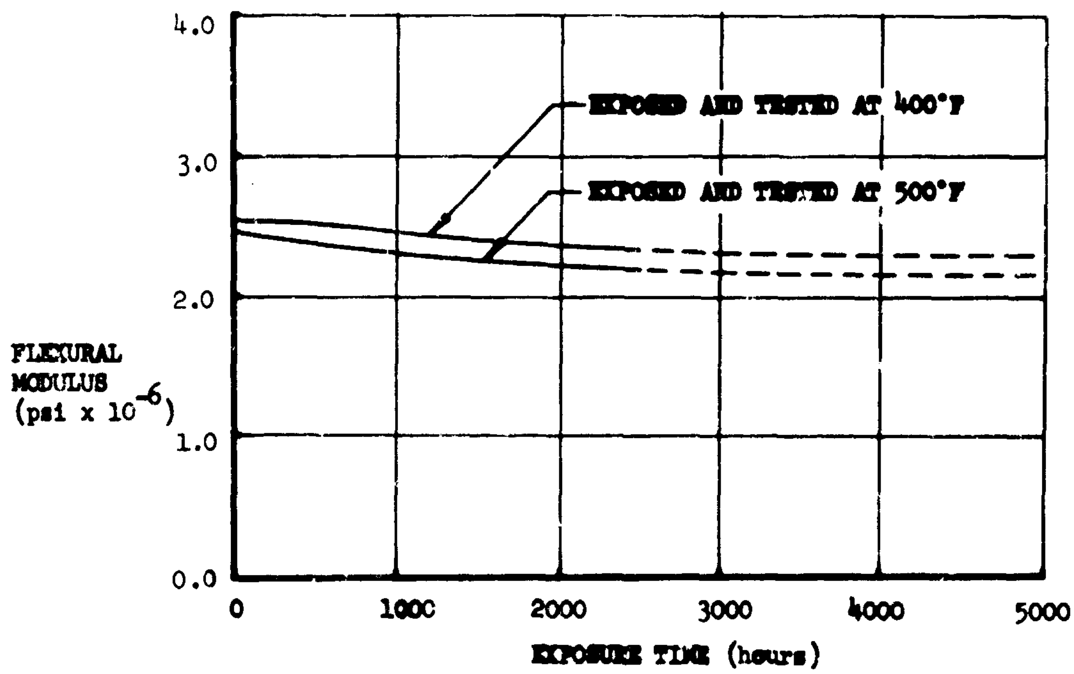


Figure 3-23. Thermal Exposure Effects on E Glass Reinforced Polyimide Laminate Flexural Modulus

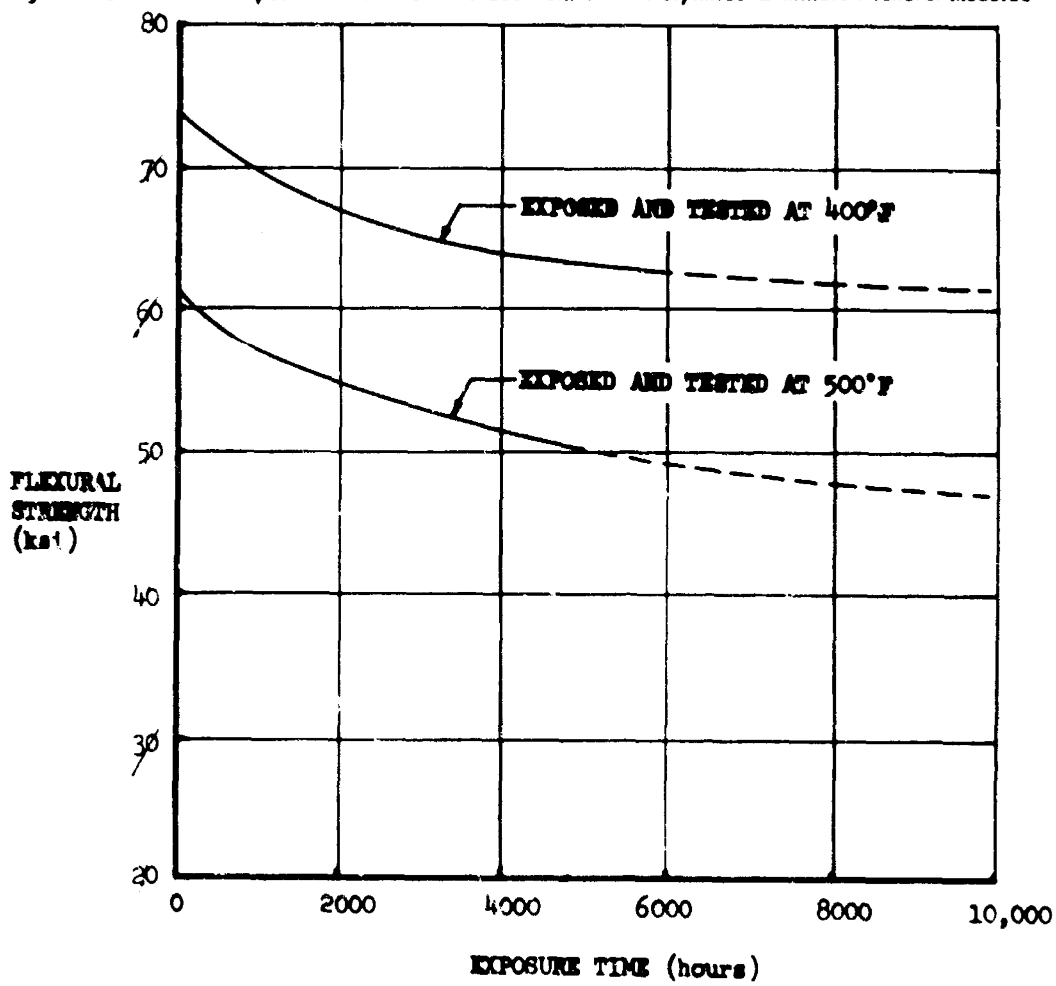


Figure 3-24. Thermal Exposure Effects on S Glass Reinforced Polyimide Laminate Flexural Strength

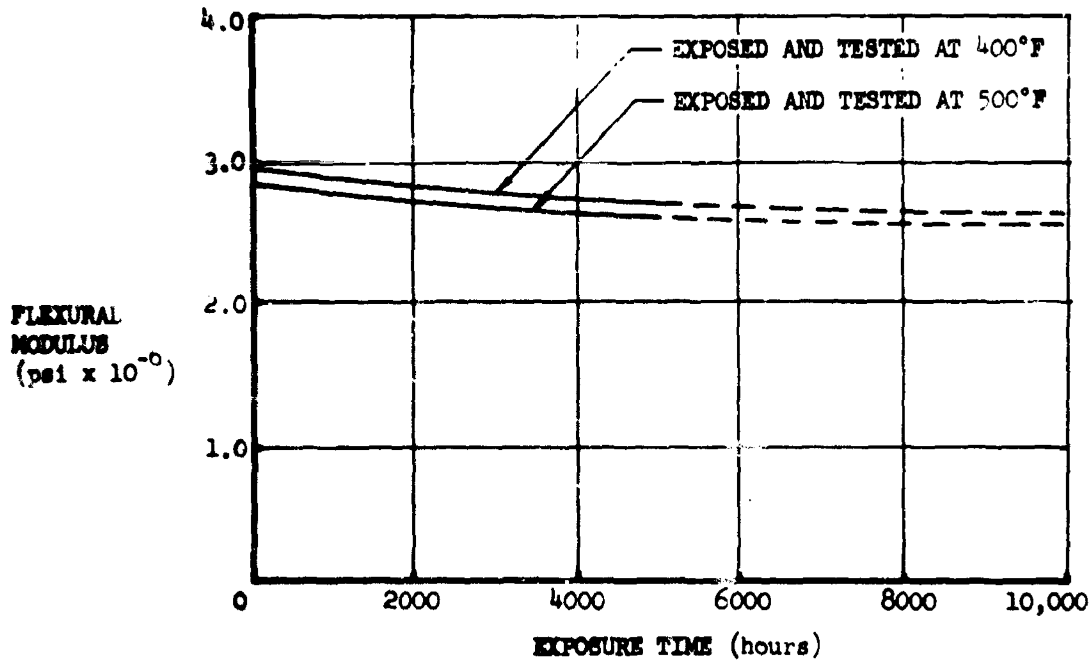


Figure 3-25. Thermal Exposure Effects on S Glass Reinforced Polyimide Laminate Flexural Modulus

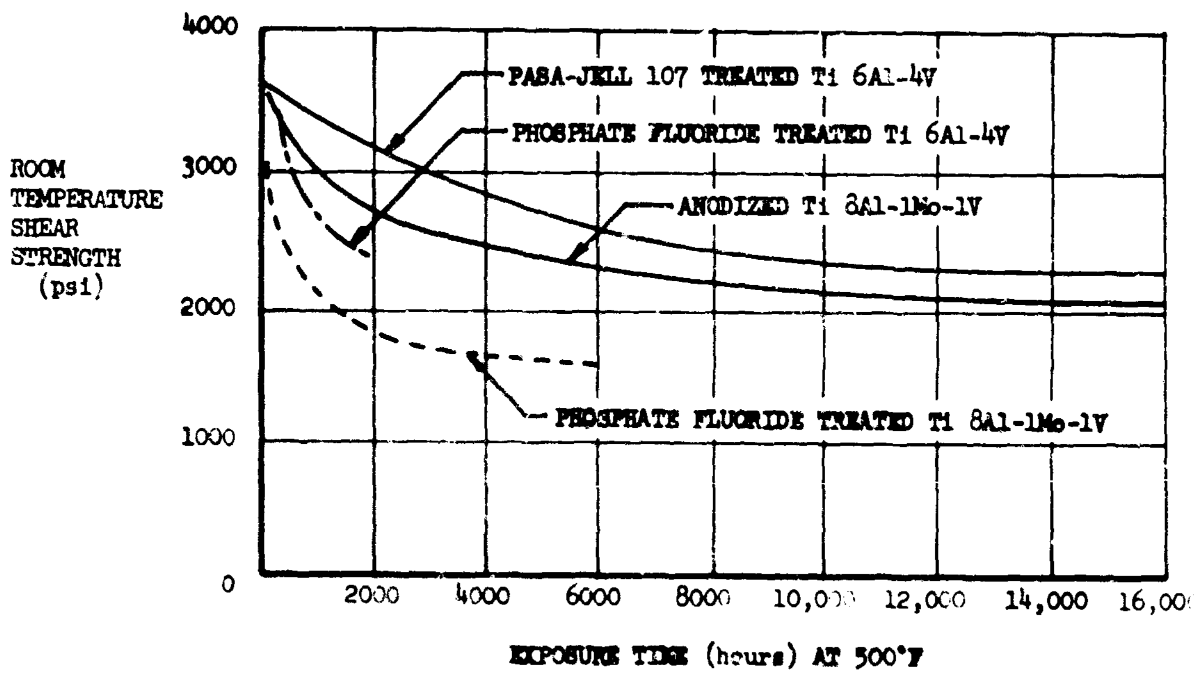


Figure 3-26. Effect of Temperature Exposure on Bond Strength of FM-34 Adhesive Using Various Surface Treatments

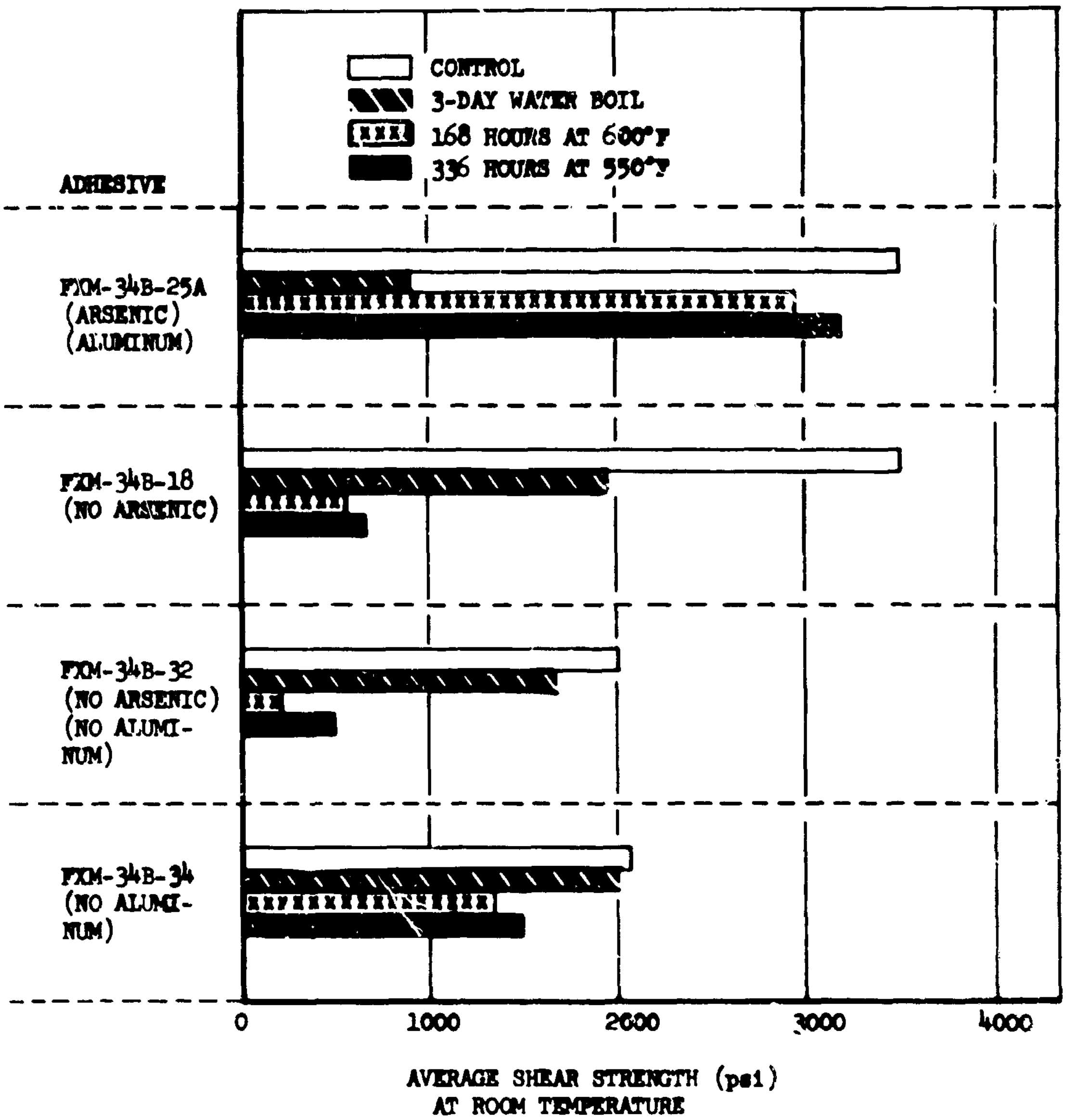


Figure 3-27. Effect of Additives on Bond Properties

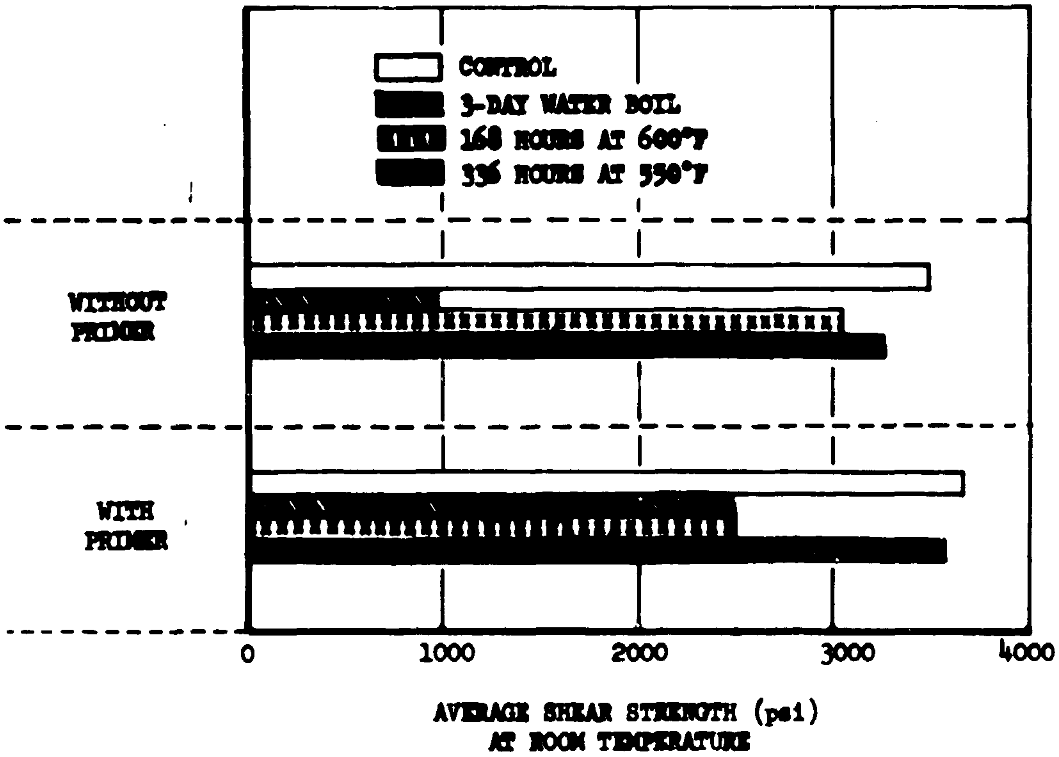


Figure 3-28. Effect of Primer on Bond Properties

utilized in areas where sealing of open edge sandwich is required or where reinforcement of hardware to the sandwich is necessary. The material for this application will be a polyimide or silicone base compound.

A syntactic foam, formulated from a DuPont polyimide resin and Emerson and Cuming glass spheres, has been developed for edge filling, vent hole sealing, and sealing of tool holes and fastener heads in sandwich assemblies. It can also be used to encapsulate electrical components. Unlike conventional syntactic foams of epoxy resins with phenolic spheres that are thermally stable to 300°F, the polyimide glass sphere syntactic foam is suitable for continuous use at elevated temperatures to 550°F.

The syntactic foam prior to curing is putty like in consistency. Thus it can be trowelled onto surfaces, molded to shape, or injected into cavities. The material is heat cured in a manner similar to the structural polyimide foam. Foams in densities ranging from 10 to 30 lbs/ft^3 have been prepared. The syntactic foams have compressive strengths of 10,000 to 20,000 psi and tensile shear strengths of 1000 to 2000 psi at 500°F.

A Boeing developed temperature resistant structural polyimide foam will be used for composite structure where bonding to extrusions such as spars, rib caps, and fittings as required. Some other applications are core splicing, core stabilization, and gap filling.

The foam has been successfully utilized in test hardware fabrication such as the leading edge slat and the leading edge wedge depicted in Figs. 3-29 and 3-30. Structural polyimide foam adhesive in tape form was used to bond the titanium spar to the core on both assemblies. Pourable foam was used to bond fittings in-place and to stabilize the core cells at the forward edge of the wedge assembly. Tape structural foam was used to bond extrusions to honeycomb core in the fuel cell door assembly as shown in Fig. 3-31. These parts will be tested under various conditions simulating supersonic flight environments.

Structural foam compressive and embedment strengths have been determined on specimens fabricated from assemblies in which metal strips were foam bonded in a block of honeycomb core. The embedment strength was determined by pulling the strips from the core. The compressive

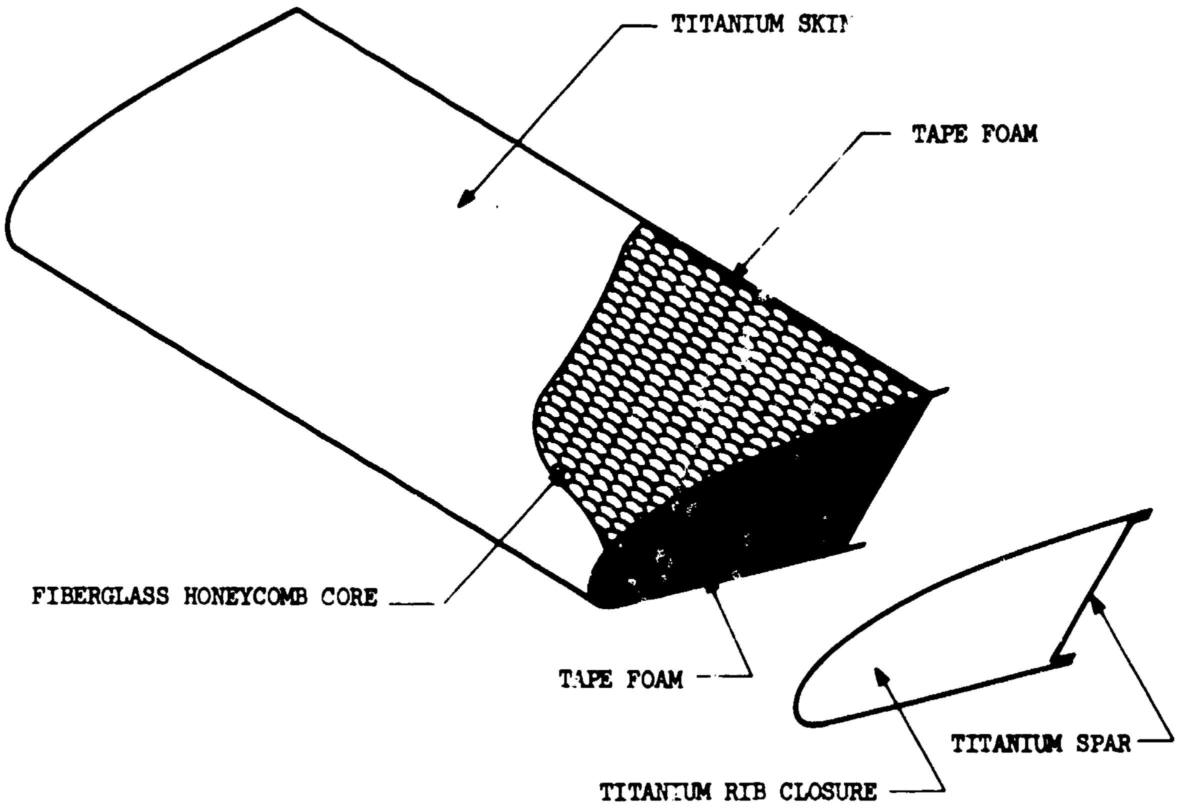


Figure 3-29. Leading Edge Slat

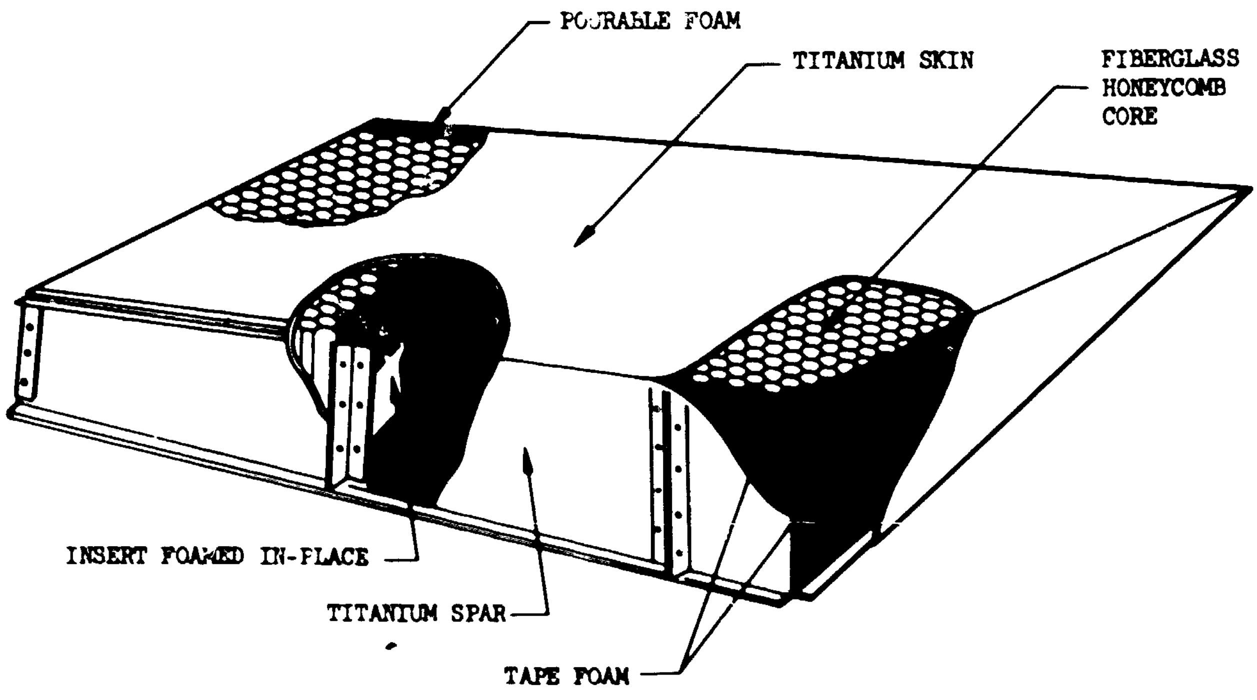


Figure 3-30. Leading Edge Wedge

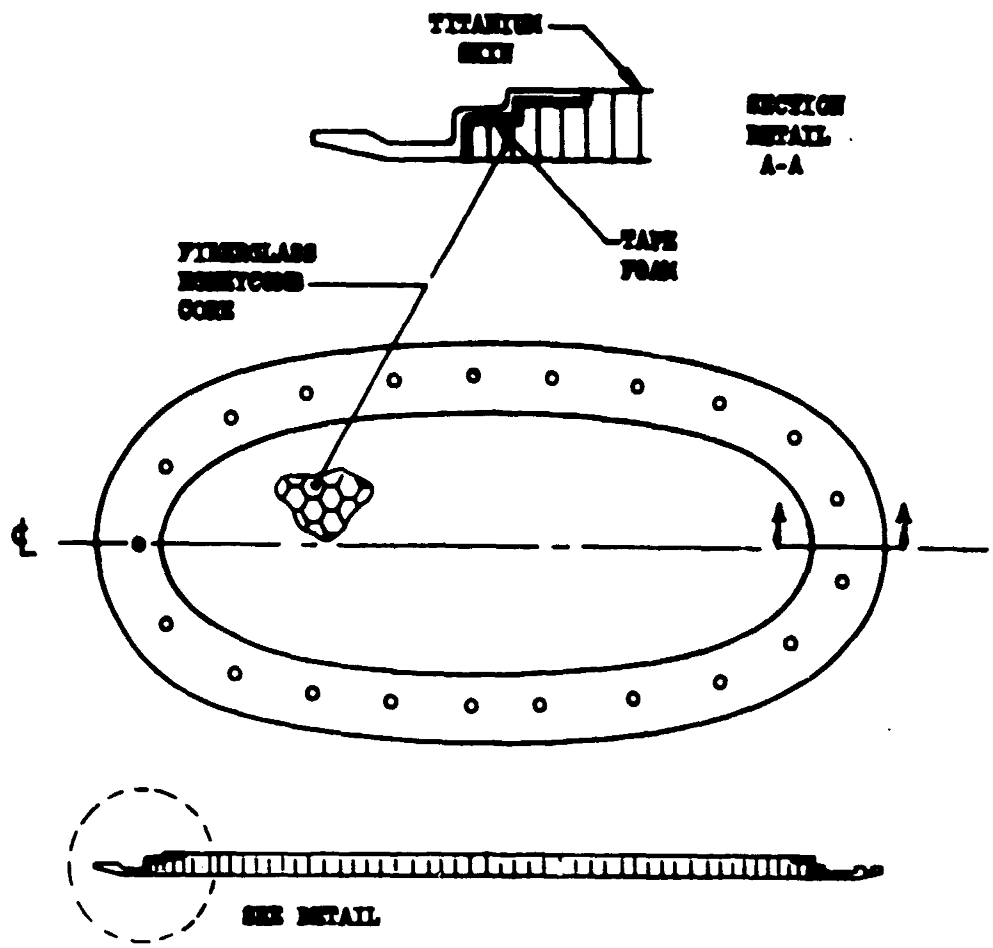


Figure 3-31. Fuel Cell Door

strength specimens were also used for density determination. Embedment and compressive strengths are tabulated in Table 3-D. The currently used structural foam requirements are included in this table for comparison. It can be seen that structural polyimide foam far exceeds the existing requirements. These foams can be applied either before or after the sandwich structure is cured. The cure cycles for the polyimide based foams are similar to those used on other polyimide structure.

3.2.7 Sandwich Properties
Typical honeycomb sandwich properties are shown in Table 3-E.

Sandwich panels were fabricated to B-2707 design requirements using polyimide, polybenzimidazole, and phenolic resin systems. These structures were sonic fatigue tested at room temperature and after thermal exposure. Results of these tests are shown in Table 3-F (Ref. 23). The superiority of polyimide resin systems is clearly demonstrated. After 3434 hours of exposure, only the polyimide resin system retained a measurable resistance to sonic vibration. Additional sonic testing results are shown in V2-B2707-9.

A representative sandwich edge bond cross section configuration is schematically illustrated in Fig. 3-32. In simulated lightning strike tests this configuration resisted a charge transfer of 400 coulombs as shown in Fig. 3-33. By comparison, an all titanium bonded sandwich was punctured by a charge of 100 coulombs as shown in Fig. 3-34.

3.2.8 Inspection Techniques
The quality of bonded honeycomb sandwich is assured by control of raw materials, in process inspection, statistical sampling and testing of

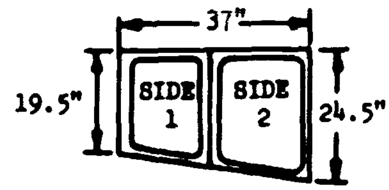
Table 3-D. Mechanical Properties of Foams

Foam Type And Tests	Current Structural Foam Requirements For Commercial Airplanes	Structural Polyimide Foam Properties
Pourable Foam		
Embedment	1600 lbs	2200 lbs
Compression	2400 psi	3900 psi
Tape Foam		
Embedment	1400 lbs	3200 lbs
Compression	2400 psi	4600 psi

Table 3-E. Typical Sandwich Properties

	Psi at Room Temp.	Psi at 450°F
Flatwise Tension	700	500
Edgewise Compression	140,000	104,000
Long Beam Flexure, Strength		
Glass Face Compression Stress	45,000	27,000
Glass Face Tension Stress	51,000	

Table 3-F. Sandwich Sonic Fatigue Test Results



Panel No.	Construction Materials	Test Data - Side 1	Test Data - Side 2
1	Resin-Narmco 1850 Adhesive- Polybenzimidazole	<u>255 cps</u> 60 Min at 160 db 60 Min at 165 db 16 Min at 168 db Failed skin to core bond	<u>200 cps</u> 60 Min at 160 db 39 Min at 165 db Failed skin to core bond
2	Resin-Polyimide Adhesive-Parent Resin	<u>200 cps</u> 60 Min at 160 db 60 Min at 165 db 60 Min at 168 db 37 Min at 170 db Inner skin cracked	* <u>175 cps</u> 60 Min at 160 db 39 Min at 165 db 1 Min at 168 db Inner skin cracked
3	Resin-Narmco 1850 Adhesive- Polybenzimidazole	<u>286 cps</u> 30 Min at 160 db 120 Min at 165 db 120 Min at 168 db 22 Min at 172 db Failed skin to core bond	* No strength remained after soak
4	Resin-Fiberite 1255 Adhesive-Parent Resin	<u>236 cps</u> 60 Min at 160 db 60 Min at 165 db 2 Min at 168 db Failed skin to core bond	* No strength remained after soak

* These Three Panels Soaked for 3,434 Hours at 450°F
Ref. 23.

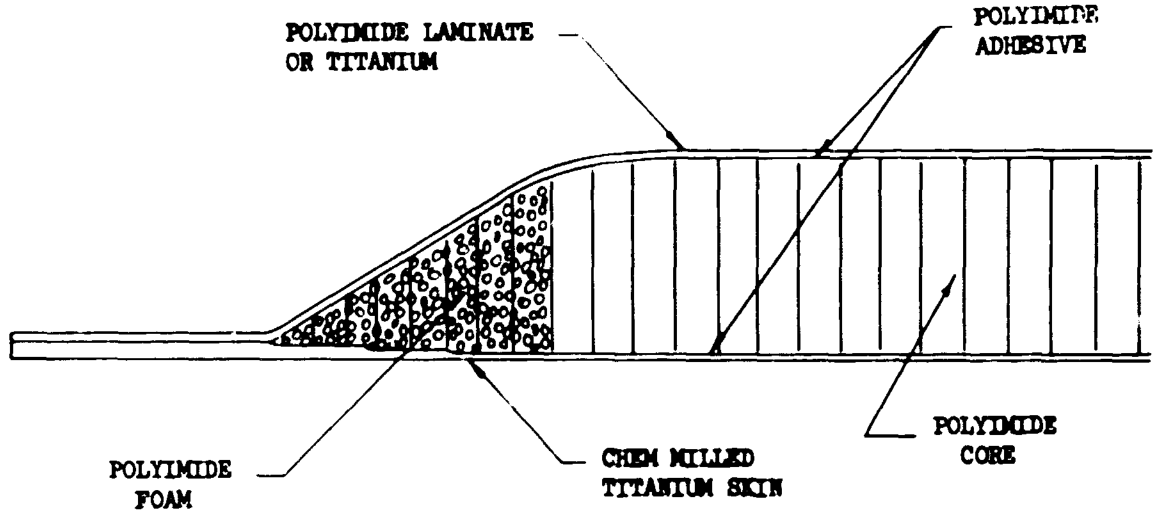
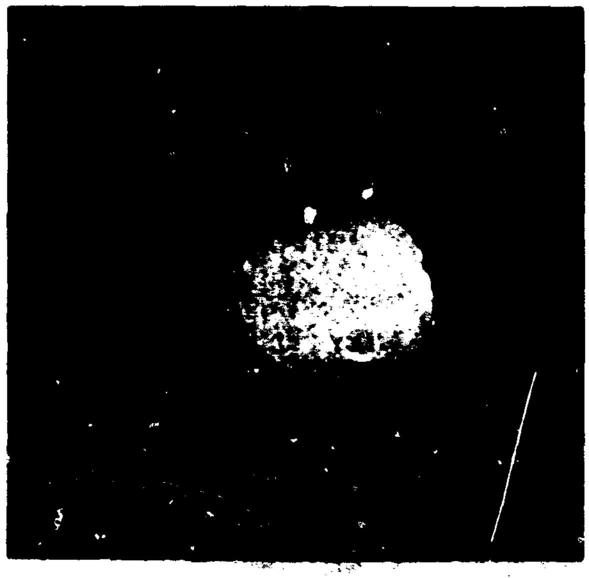


Figure 3-32. Typical Sandwich Construction

(IMPINGED FACE) .005 Ti 6Al-4V INNER SKIN
.500 POLYIMIDE HONEYCOMB CORE
.010 Ti 6Al-4V EXTERIOR SKIN
100 COULOMB OF CHARGE

Figure 3-33. Lightning Strike Test Panel (Polyimide Honeycomb Core)



(IMPINGED FACE) .010 Ti 6Al-4V INNER SKIN
.50 TITANIUM CORE
.010 Ti 6Al-4V EXTERIOR SKIN
(100 COULOMB OF CHARGE)

Figure 3-34. Lightning Strike Test Panel (Titanium Honeycomb Core) simulated production parts, and non-destructive testing. Boeing philosophy is to continue to develop nondestructive testing techniques to effect as reliable quality as is presently maintained but at decreased costs.

The methods and equipment under investigation for nondestructive testing of bonded sandwich structure include:

a. Sonic resonator techniques

b. Fokker Bond Tester techniques

c. Liquid crystal methods

d. X-ray techniques

e. Test coupons

f. Tap test

A sonic resonator is currently undergoing evaluation with the following objectives:

- To develop it for optimum sensitivity to defects in bonded sandwich structures.
- To implement inspection of production panels.
- To establish a statistical confidence level for the instrument and operators as an inspection system.

The resonator consists of a piezoelectric crystal probe connected to a central control module with a tunable signal generator, impedance bridge, amplifier, and null detector. Its operation requires that the transducer be placed on a known standard structure using a coupling agent such as glycerin. The detector is zeroed, then the crystal probe is placed on the area to be inspected. A damaged or unbonded area will cause an electrical imbalance resulting in an up-scale reading on the detector. The instrument response to voids in bond line of metal faced sandwich is excellent. Unbonded areas can be detected by testing from either side. Fractured polyimide core can also be detected.

The limits of defect detection and operator reliability were evaluated by dropping a steel ball, one inch in diameter, from known heights onto a bonded panel assembly. Results obtained were taken from a meter with a scale range from 0 to 100 (see Table 3-G).

Table 3-G. Sonic Resonator Calibration

Height of Ball Dropped (Inches)	Average Reading
0	2
8	5
12	7
16	15
24	31
28	54

In most instances the instrument showed excellent reproducibility for different operators. The maximum deviation from the average was ±4 units.

The Fokker Bond Tester operates in much the same manner as the sonic resonator. This equipment has been automated and is capable of testing large panel areas with high reliability and minimum personnel.

Thermal transmission techniques represent an entirely different approach to nondestructive test procedures. Surface temperature measurements are used to detect internal flaws in metal and nonmetal bonded structures. Variations in surface temperatures arise due to distortions of normal heat flow patterns as a result of voids and other bonding defects. Infrared radiometers have been frequently used for surface temperature measurements needed to discover these flaws. However, radiometers are limited to point or line measurements and, because of this, are time consuming when inspecting large areas. The application of a heat sensitive coating to the surface being studied represents the more practical approach to this test method. Cholesteric crystals represent a group of heat sensitive compounds which can be easily adapted to thermal transmission techniques. These compounds in the liquid state, exhibit optical properties normally associated with solids. They may be divided into nematic, smetic, and cholesteric mesophases. The cholesteric mesophases have the most striking optical characteristics; for example, the color response has a sensitivity such that a difference of 1°F changes a red background to blue. The application of liquid crystals involves the use of a black, water soluble, background paint. The crystal mixture is brushed or sprayed over the background of the part to be tested. To check the surface for bonding defects, the crystals are heated slightly above their transition range and are then cooled by air. Rapid heating and cooling of the surface results in greatest sensitivity to bonding anomalies. If the part is free of bonding defects, the color consistently changes from violet to red. Heat transmission through defective areas is slower than through an area of acceptable bond when the ambient temperature is quickly lowered. Quality of the bond is indicated by the color differential.

Liquid crystal techniques offer the following advantages:

a. Relatively simple procedures.

b. Fast response.

c. Reversibility-color transition may be noted as the materials are heated or cooled.

d. Reproducibility — a given mixture will exhibit the same color at the same temperature.

e. Permanent records may be kept by taking still or movie camera photographs of the color transition.

f. Low cost — expensive equipment is not required.

Successful tests have been conducted on titanium faced — polyimide core — polyimide faced sandwich structure fabricated with known defect areas.

Acoustic testing techniques or tap test as a method for nondestructive testing is being investigated to determine if a modest amount of automation might make the test more quantitative and meaningful. A metal plunger attached to a special holder is moved by a spring loaded screw. The noise developed, as the part is struck, is detected by an Astatic microphone whose output is filtered, amplified, and displayed on an oscilloscope. This apparatus has been used to detect the presence of localized loosely bonded areas in a honeycomb panel which gave a characteristic dull response when struck. Good correlation of sound, oscilloscope pattern, and panel area defect is found when this procedure.

X-ray techniques, as a nondestructive test method, are useful in examination of small assemblies. However, the high cost and inability to analyze large structures severely limits its use in preference to other methods.

3.3 PLASTICS

Application of plastics include heat resistant reinforced plastic parts, radomes, and thermoplastic decorative materials. They have many useful characteristics such as good electrical and thermal insulation, transparency to microwaves, light weight, resistance to fatigue, and exceptional formability. Criteria for selection are based on these properties.

With the exception of the materials specifically engineered to meet the thermal environments of the B-2707 exterior, the majority of these materials have been successfully used on previous commercial airplanes. New materials have been tested and their suitability verified.

These materials are controlled by existing Military, Federal, and company specifications.

3.3.1 Thermosetting Glass Reinforced Laminates

Glass fiber reinforced plastics (GFRP) will find extensive use. The choice of these materials is based on consideration of weight, resistance to the physical and chemical environment, cost, and maintainability. In all cases the selected composites have proven superior to other materials by service experience and laboratory testing. New high temperature resistant polymers are being introduced to meet the thermal, fatigue, and strength requirements.

Woven glass fabric style 181-E with an aminopropylsilane (A-1100) finish, and matrix of polyimide resin has been selected for most applications. Polyimide resins are heat reactive aromatic polymers which can be fabricated by press molding or vacuum bag/autoclave methods. From a manufacturing standpoint the latter method offers several advantages such as lower tooling costs.

Polyimide resin woven glass fabric laminates are used in areas such as the cabin windshield structure and window spacers and window frames primarily because of their insulating properties shown in Fig. 3-35. Polyimide resin in filament wound and woven fabric laminates will be used in the fabrication of radomes. The processing of polymide laminates 0.125 in. thick or thicker allows 20 percent of the plies to be dry fabric. The excess resin is uniformly absorbed in the dry fabric and efficient removal of volatiles is required to produce strong polyimide laminates.

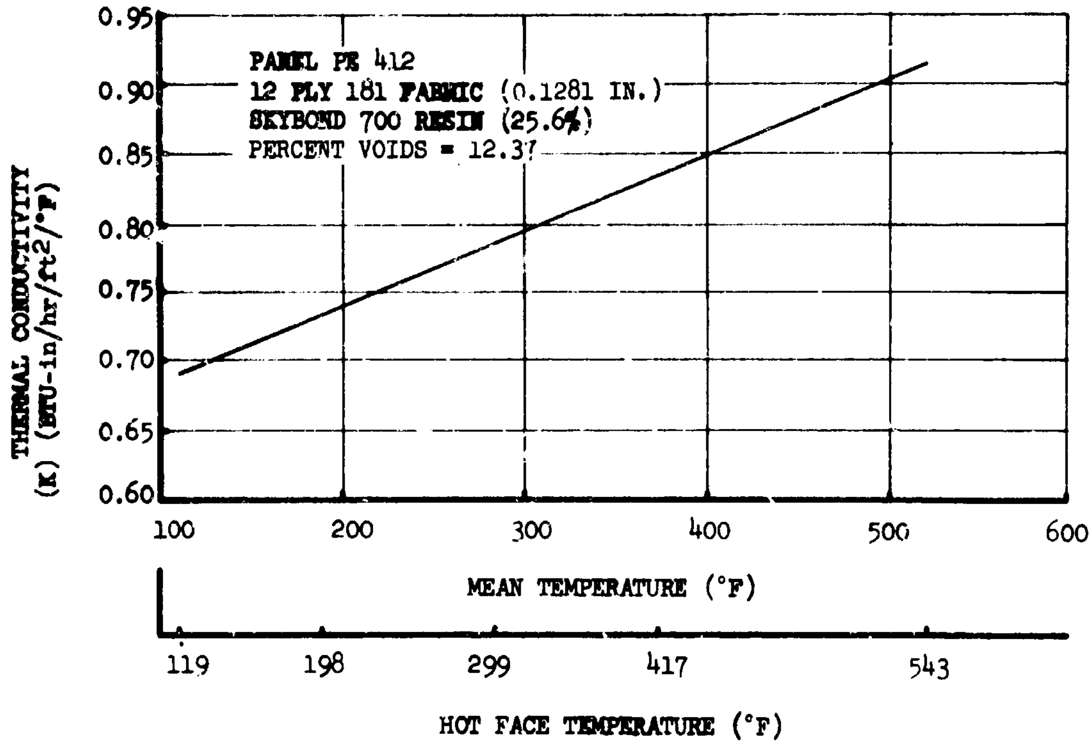


Figure 3-35. Thermal Conductivity, Polyimide Laminates

The ability to reduce the amount of prepreg through the use of dry glass fabric plies reduces the material cost to the level of phenolic and epoxy systems which are used in present commercial airplane. Table 3-H illustrates the physical and mechanical properties of a polyimide laminate 1.11 inches thick with every fifth ply of dry fabric.

Other resin systems such as phenolics meeting requirements of Military Specification MIL-R-9299 and epoxies meeting requirements of Military Specification MIL-R-9300 will be used where the maximum temperatures encountered are below 250°F. Non-woven glass fabric will be used where high directional strengths, abrasion resistance, and impact strength are required. These materials are readily available and design properties are described in Boeing Design Manual, Document D-5000.

3.3.2 Radomes

Woven glass cloth or glass filaments, laminated with a thermosetting resin, are customarily used for airplane radome construction. These composites can be tailored to make a satisfactory compromise between structural and electrical requirements.

Polyimide resins were selected for use in the radome. Candidate resin systems included diphenyl oxides, polybenzimidazoles, polyarylene ether phenols, and silicones. Only polyimides and silicones had the required thermal stability. Silicone resin systems were inferior to polyimides in mechanical strength as shown in Fig. 3-36.

Electrically, the polyimide laminate system is a superior radome material. Data presented in Fig. 3-37 indicate a good level and good stability of dielectric properties from room temperature to 500°F.

The polyimide resin system is adaptable to the glass filament winding process. Excellent results with the polyimide glass filament winding process have been obtained and verified in the fabrication of subscale radomes having good mechanical and electrical properties as shown in Table 3-I.

Materials and processes are also available for the polyimide glass fiber honeycomb sandwich design. Polyimide glass fabric honeycomb core has been developed with excellent mechanical properties at elevated temperatures. Section 3.2.2 provides a detailed discussion of reinforced polyimide core material. Adhesives suitable for

Table 3-H. Physical Properties of Thick Polyimide Laminates

Panel Area	Resin Content Percent	Specific Gravity	Interlaminar Shear Strength	Interlaminar Shear After 3 Hrs. Water Boil — Avg. PSI
Top	23.9	1.59	2324	1860
Center	23.6	1.58	2360	2272
Bottom	22.9	1.61	2390	2108

Panel thickness 1.11 inch, 93 plies of polyimide impregnated 181 E glass fabric, plus 23 dry plies of 181 E glass fabric. All values shown are the average of 4 or more specimens.

Table 3-I. Properties of Polyimide NOL Rings, S Glass

EDGEWISE COMPRESSION STRENGTH (Circ Direction)	
No previous exposure, tested at room temperature	51,000 psi
No previous exposure, tested at 500° F	49,000 psi
Exposed 1,000 hours at 500° F, tested at room temperature	31,000 psi
Exposed 1,000 hours at 500° F, tested at 500° F	29,000 psi
TENSILE STRENGTH (Circ Direction)	
No previous exposure, tested at room temperature	87,000 psi
DIELECTRIC CONSTANT (9,375 MC)	
No previous exposure, tested at room temperature	3.9
No previous exposure, tested at 500° F	4.0
NOL INTERLAMINAR SHEAR	
No previous exposure, tested at 500° F	3,000 psi
Exposed 500 hours at 500° F, tested at 500° F	3,000 psi

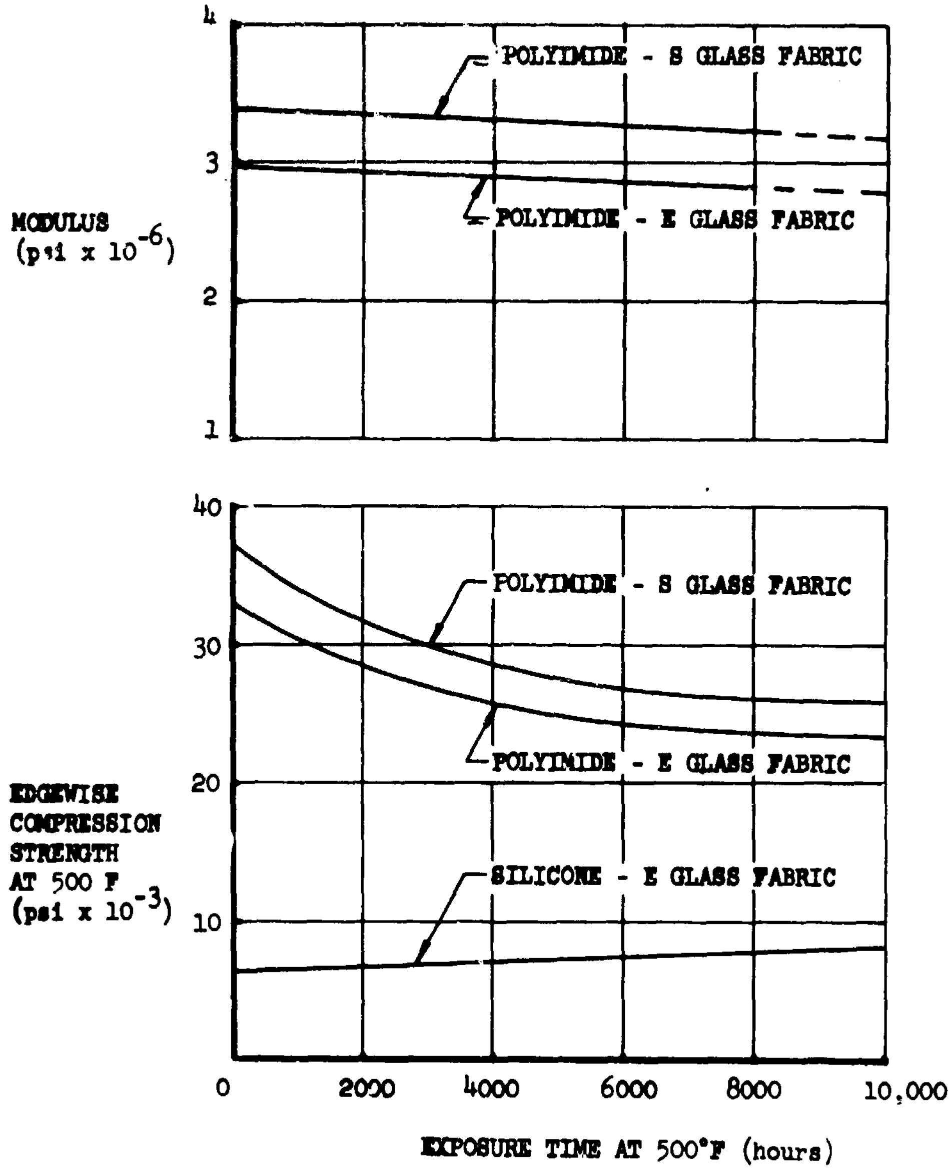


Figure 3-36. Mechanical Properties, Silicone and Polyimide Laminates

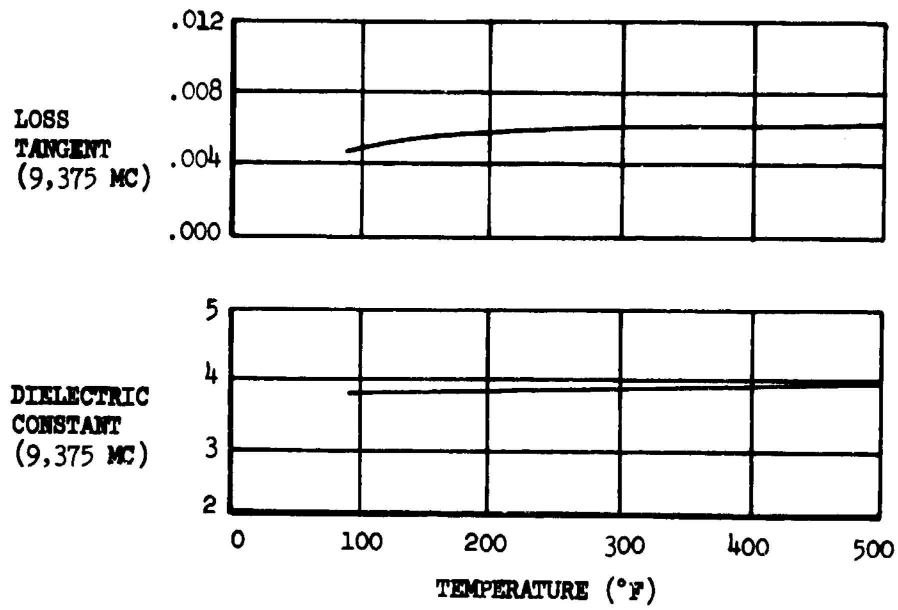


Figure 3-37. Dielectric Properties, E Glass Laminates

bonding honeycomb to faces have developed a tensile lap shear strength of 3300 psi and a honeycomb sandwich climbing peel strength of 28 in.-lb per 3-in. width at room temperature. This is the same adhesive (without additives) proposed for structural sandwich bonding.

Polyimide prepregs can be readily used in the layup of contoured assemblies and honeycomb sandwich end closures. The material is easily tacked, draped, and formed into position in the curing tool.

Rain erosion materials and anti-static coating for applications on radomes are described in Par. 3.8.5, and 3.8.6.

Sealing of solid laminate radomes is accomplished by repeated applications of polyimide resin to the surface followed by a primary cure cycle. Reduction of void content to a level below 5 percent is achieved and a process development utilizing a pressure impregnation technique is expected to result in improvement beyond this level.

The Boeing Company subcontracted with Brunswick Corporation for the design and fabrication of a nose weather radar radome under Contract No. 6-221427 and controlled by Boeing Document D6-9881. The material selection was made from a literature survey by both Brunswick and Boeing personnel from data available under company and Air Force funded programs. The studies were based upon selection of resin and reinforcements with respect to predicted:

- Electrical performance
- Structural performance
- Weight
- Costs of materials
- Ease of manufacture
- Reliability
- Availability of material

A polyimide resin system which indicated superior strength after exposure to environment of the B-2707 was PI 3301, a DuPont resin, with high strength glass filament S-1014. Two glass finishes are being evaluated with this reinforcement, a diphenyl oxide and a polyimide. These finishes were developed by Ironsides Resin Co.

The data generated during the development phase indicates the design objectives of the weather radar radome can be met. The design data generated has been obtained from analysis of flat panels, subscale models, and standard test specimens. Typical test results are presented in Table 3-I.

3.3.3 Molding Compounds

Press-molded glass-fiber reinforced plastics will be used for nonstructural equipment boxes and covers where the primary considerations include dielectric strength and electrical resistivity.

Low-pressure molded-glass fiber reinforced plastics will be used for air ducts. Except in areas requiring the thermal resistance provided by the polyimide resin system, conventional resin systems meeting requirements of current military specifications will be used. Glass fabric reinforced plastic air ducts offer maximum rigidity, minimum weight, and low cost in designs that require abrupt changes in cross sectional shape or contour. Boeing developed GFRP surfaced foam ducts offer an efficient low pressure air distribution system at minimum noise and vibration levels.

These materials have been successfully used on military and commercial airplanes.

3.3.4 Potting and Casting

High and low temperature resistant electrical potting and casting materials are available to fulfill all requirements established by B-2707 environments. Silicones and epoxies are used extensively. Materials and process specifications have been written for these materials. Syntactic polyimide pottings have been developed for use in areas where strength at elevated temperatures are required. Advanced materials, such as metacarborane based polysiloxane, are also being investigated for elevated temperature potting applications. For additional information on electrical potting and sealing compounds, see Par. 3.6.2(c).

3.3.5 Thermoplastics

Thermoplastic materials will, in general, be used in nonstructural applications such as interior decorative surfacing and edging, electrical insulators, electrical thermal strips, wire bundle clamps, hangers, retainer clips, and equipment housings. They are available at low cost with a variety of properties, are light weight, and can be fabricated by injection molding, extruding, blow molding, and heat forming. They will be selected for the specific applications to satisfy design criteria and will be procured to existing specification. For interior applications of thermoplastics refer to Sec. 3.5.

3.4 TRANSPARENCIES

Requirements of the transparent areas vary depending upon the location. Windshields must allow excellent visibility at all times, must be provided with rain removal, deicing, and defogging systems, and be resistant to impact by birds and hail.

Pilot compartment and passenger windows have less severe requirements imposed and are designed accordingly. An additional feature for passenger convenience is use of light polarizing acrylic panes for manual adjustment of light intensity.

Design allowables properties of window materials appear in Document D-5000, Book 84D1, SST Structural Allowables.

3.4.1 Windshields

Windshields are mounted in the movable nose section, referred to as the forebody, and the crew compartment or cabin. The main purpose of the forebody glazings it to provide visibility during supersonic flight.

Operational temperatures in the windshields will range from -50° to 450°F.

The crew compartment windshields, as shown in Fig. 3-38, will be a combination of monolithic glass, laminated glass, and monolithic plastic panes.

3.4.1.1 Glass

a. Chemically Strengthened Glass

The ion-exchange strengthening technique has greatly increased the usable strength of glass. Preliminary design allowables for chemically strengthened glass are 40,000 psi, which gives a large weight efficiency advantage over chill tempered soda-lime glass.

A limited number of specimens of an improved glass of this type was tested. The minimum measured modulus of rupture was 79,000 psi, an indication that even higher strengths may be realized in the future. Properties at maximum operating temperature of 450°F will be established.

The size of the fracture pieces of chemically strengthened glass can be controlled, making it suitable for use as a spall shield.

b. Tempered Soda Lime Glass

Chill tempered soda lime glass is readily available and is proven in service. This glass has a strength allowable of 20,000 psi from 75° to 500°F.

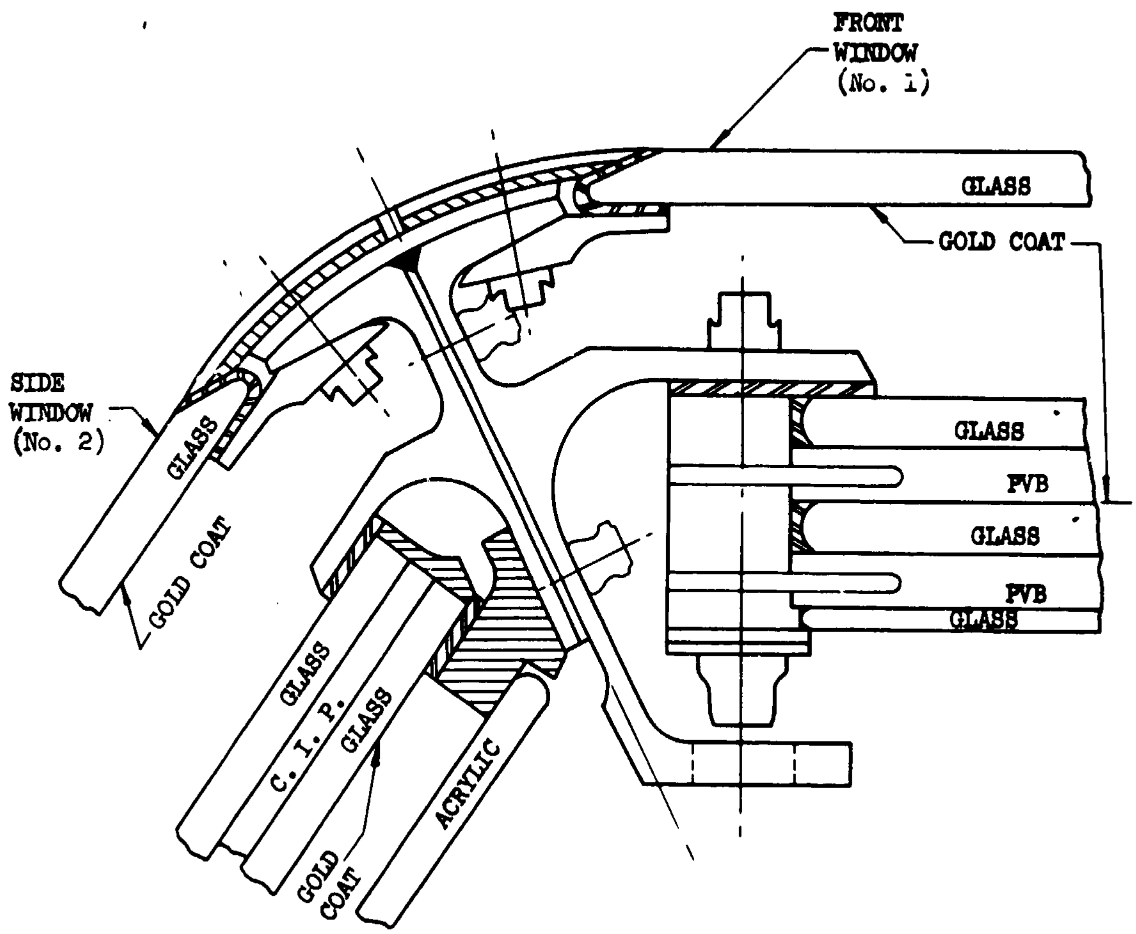


Figure 3-38. Windshield Configuration

c. Aluminosilicate Glass
Aluminosilicate glass, which is more expensive than soda lime glass, may be used where there is a requirement for high thermal shock resistance. This resistance is inherent in aluminosilicate glass because of its low coefficient of thermal expansion. A comparison of thermal expansion of soda lime and aluminosilicate glass is shown in Fig. 3-39.

The aluminosilicate glass used will be chill tempered to the same strength (20,000 psi) as soda lime glass.

3.4.1.2 Interlayers
The interlayers of the laminated glazings are required to perform the following functions:

- Retain chips in case of glass breakage.
- Prevent the carcass from entering the control cabin after the bird breaks the glass plies.
- Reduce heat flux through the windshields.
- Reduce reflections.
- Protect delicate electrically conductive coatings.

a. Polyvinyl Butyraldehyde
Polyvinyl butyraldehyde (PVB) is the only interlayer material currently available which has proven birdproofing capability. PVB has known birdproofing capability over a controlled temperature range. The windshield will have an electrically conductive coating to keep the PVB within the birdproofing temperature range during subsonic flight.

b. Silicone
Dow Corning XR 63449 is the leading candidate for the interlayer to be used in all forebody windshields. Although this is a relatively new material,

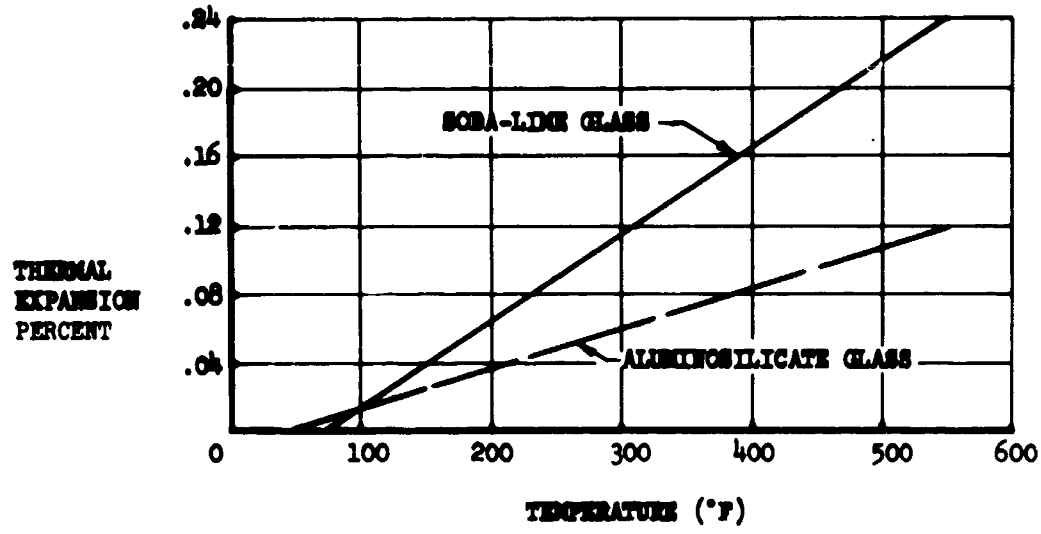


Figure 3-39. Thermal Expansion Soda-Lime and Aluminosilicate Glasses

preliminary test results indicate it is superior to Silastic types K and M interlayer as shown in Table 3-J (Ref. 24).

c. Cast-in-Place

Although cast-in-place (CIP) interlayers have been available for several years, it is only recently that CIP materials have shown promise of attaining the strength-elongation properties required for a birdproof interlayer. These newer interlayers are being evaluated.

3.4.1.3 Coatings

The defogging and deicing coatings are of vapor deposited gold. The very low emittance value of these gold coatings acts to reduce heat flux. Coating quality is monitored using the power factors concept in general use throughout the windshield industry. In order that the spectral light transmission through the No. 1 windshield be maintained as high as possible, PE-81-E coating supplied by Liberty Mirror Division of Libbey-Owens-Ford Glass Co. is used for deicing or defogging. Where light transmission requirements are not so severe, the heavier IR-81-E coating will be used because of its superior low emittance properties (0.08 as compared to 0.21). Preliminary light transmission values of these coatings are compared in Fig. 3-40.

On the inner surface of some of the forebody glazings a stannous oxide coating will be used as an IR reflective film. Stannous oxide is more durable and has greater light transmission than gold.

3.4.1.4 Acrylic Sheet Glazing

The interior plies of the side windows will be monolithic stretched acrylic sheets. These inner plies have no pressure retention requirement and their primary function is to provide a second air gap to reduce the temperature of the interior surfaces of the side windows and protect the gold coating. The light weight and superior craze and crack propagation resistance of the stretched acrylic make it especially advantageous.

3.4.1.5 Inserts

Polyimide glass laminates are used for interlayer inserts (for interlayer to frame attachment). Their low thermal conductivity and adhesion to PVB has been verified by tests.

3.4.2 Passenger Windows

The configuration of the passenger windows is shown in Fig. 3-41. Each component has the following features:

a. Outboard Pane

Chilled tempered soda lime glass to withstand cabin pressure in case of failure of the center pane. It will have a low emittance gold coating (IR-81-E) over the inboard surface to restrict transmission of heat toward the passenger cabin.

b. Middle Pane

Chemically strengthened glass. A low emittance gold coating (IR-81-E) will be applied.

c. Inner Pane

Two plies of stretched acrylic each with a light

Table 3-J. Comparative Properties, Silastic Interlayers

Property	Type K	Type* M	XR63449
Maximum continuous use temperature without discoloration or other degradation.	300° F	325° F	400° F
"As laminated" resistance to thermal degradation.	Good	Good	Superior
Resistance to SO_2. ultra-violet light degradation.	Poor	Poor	Good
Maximum use temperature with glass fiber bleeders for outgassing.	-----	400° F	None required
Adhesion to glass	Good	Good	Superior

Ref. 24

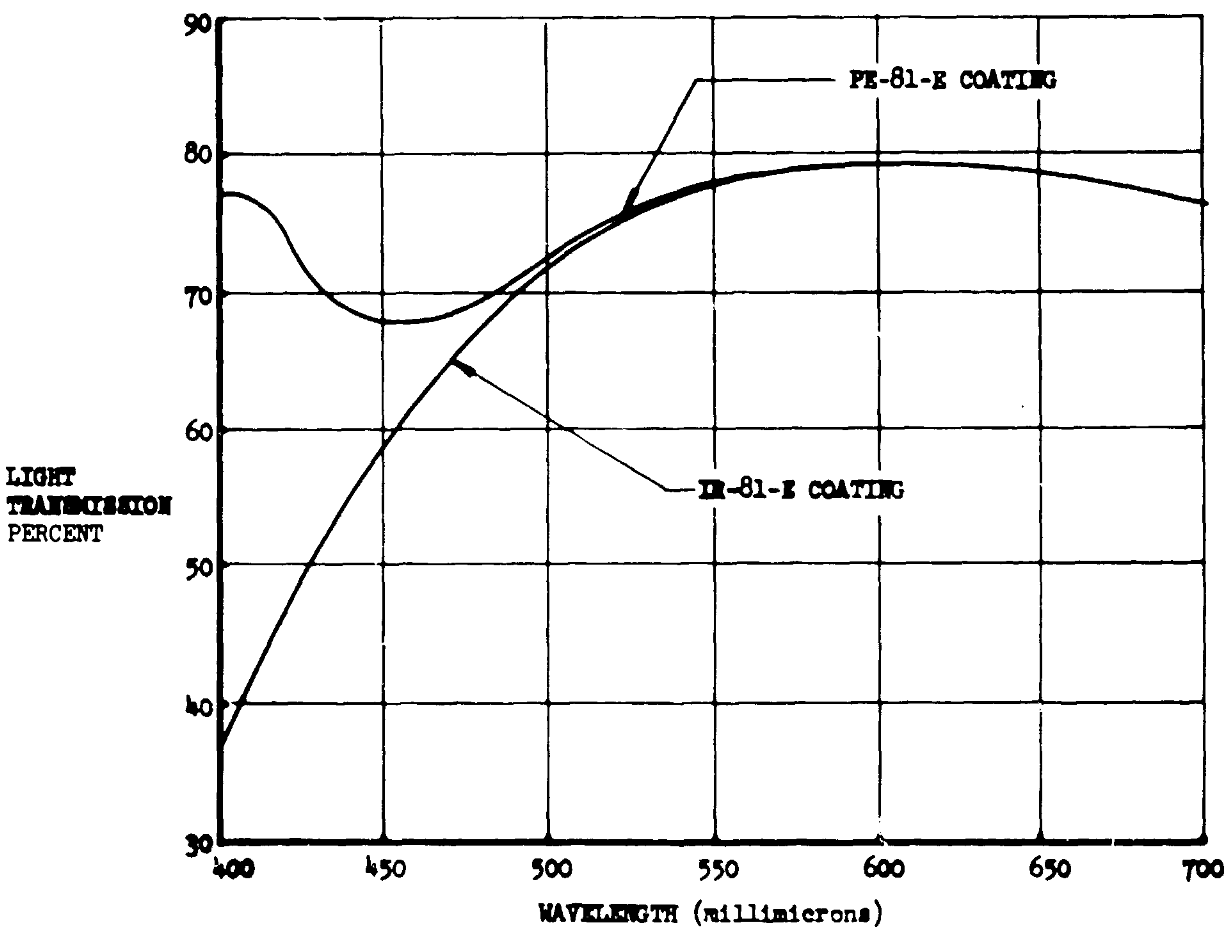


Figure 3-40. Light Transmission of Gold Coating

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X

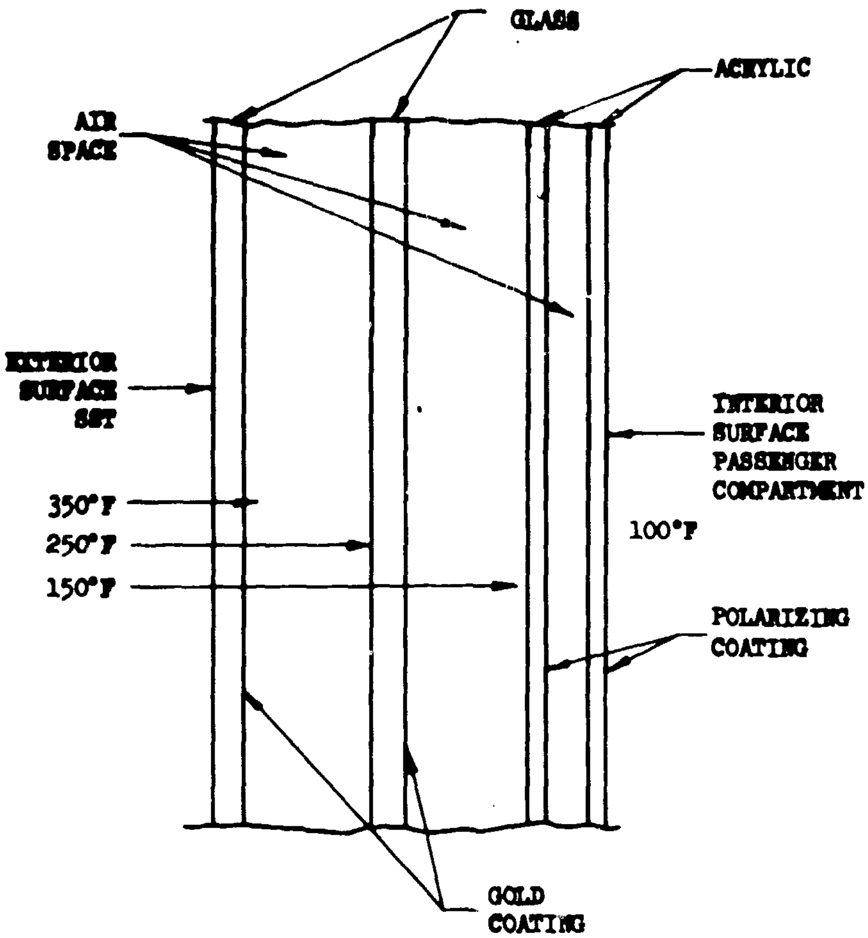

Figure 3-41. Passenger Window Configuration

polarizing film coating, one ply rigidly mounted and the other rotatable by the passenger for the purpose of varying light intensity.

3.5 INTERIOR MATERIALS

The primary consideration for interior materials is that their flammability characteristics must provide ample time for evacuation in case of fire. They are especially selected so that their combustion or decomposition products produce a minimum of smoke, odor, toxic gases, or combustibles. These materials include seat cushions, passenger service units, ceiling and wall panels, vent extrusions, floor coverings, upholstery, fabric coverings, and provisions for comfort or esthetic effects. The cabin and cargo areas have the same environment as present commercial airplane and, in general, the criteria for material selection are identical.

Although thermal and acoustical insulations are not customarily considered interior materials, they must meet the same rigid safety requirements while performing their function of controlling temperature gradients.

3.5.1 Interior Furnishings

Testing of over 2,000 individually different materials for use as interior furnishings has been performed by The Boeing Company during the past decade. The objective has been to make available to the customer a wide variety of materials that meet all safety requirements, are easily maintained, have long life, and are esthetically attractive.

The results of these tests have been evaluated, published, and submitted to The FAA by Boeing Document D6-1084 (Ref. 25), Evaluation of

Interior Materials. The specific properties obtained for the materials tested are used for comparative purposes when evaluating candidate materials.

Increased emphasis is being placed on passenger safety from crash fires. The Bunsen burner type tests required by Federal Standards Service Release (FSSR) No. 453 (Ref. 26) are now used merely for materials screening. These are followed by similar tests on the material in its airplane use attitude; if it is a material for side panels, it is tested in the vertical position rather than horizontal. In addition the 30-30 Inclined Tunnel Test or the ASTM E-84 Tunnel Test, which more realistically simulate cabin fire conditions, are conducted. Tests of candidate materials are in process. Selected materials are tested by firing of a typical furnished cabin interior.

Physical properties and comparisons of candidate materials are given in Table 3-K. The burning, staining, and maintenance characteristics are compared in Table 3-L. These materials are all commercially available in the required forms and conditions for fabrication by conventional methods. They are procured and processed to meet the requirements of military and company specifications.

a. Polysulfone
Polysulfone is a thermoplastic material formulated to provide high temperature resistance and easy fabrication at relatively low temperatures. Injection molding, extrusion, blow molding, and heat forming are used to make such parts as passenger service units, air deflectors, and edgings.

b. Acrylonitrile Butadiene Styrene Polymers (ABS)
The material, better known by the trademarks such as Royalite (U.S. Rubber) and Cycolac (Borg-Warner), is primarily used for large complex interior parts which are fabricated by heat forming.

c. Acrylic Polyvinylchloride Alloy
This material marketed by Rohm and Haas as Kydex is an alloy of acrylic and vinyl chloride polymers. It is available only in sheets for heat forming into decorative components. In general, Kydex can be formed and shaped into components by heat forming methods similar to those of the ABS materials. However, it is capable of being formed to deeper contours, is more fire resistant, and has higher impact strength than other comparable materials.

d. Nylon
Nylon is the generic name for synthetic polyimides principally fabricated by extrusion and injection molding. The material has high impact strength, abrasion resistance, and is extremely resistant to most organic materials. It is generally used for small detail parts where the above properties are design requirements. The polymer is also available in continuous filament and fiber form and is used to produce fabrics and carpeting. It is classed as self extinguishing and generally melts at a temperature below 500°F.

e. High Temperature Resistant Nylon (Nomex)
High temperature resistant nylon is marketed by DuPont under the trademark of Nomex. It is available in short fibers (floc) and smaller particles (fibrids) which can be further processed into paper and felts or continuous filament yarns for weaving into fabrics. These product forms can then be further fabricated to produce component parts such as honeycomb core panels and sheet stock. This material in either form has excellent heat and flame resistance and dimensional stability. It does not melt, but degrades above 700°F to a friable char at a rate proportional to the heat supplied. Any flame produced during oxidation is self extinguishing when the initiating flame is removed. Nomex will be used as surfacing sheets and honeycomb core for wall and ceiling panels, upholstery fabrics, and rug material.

Table 3-K Physical Properties of Interior Materials

Property and Test Method	Polysulfone	Nylon	ABS	High Temperature Resistant Nylon (NOMEX)	Acrylic-Vinyl (KYDEX)
Specific Gravity D 792	1.24	1.13	1.15	1.3	1.35
Heat Deflection Temp., °F D 648	345	186	180	540	170
Tensile Strength, psi D 638	10,200	10,000	6000	22,000	6,500
Tensile Elongation, % D 628	50	50	100	--	100
Flexural Strength, psi D 790	15,400	No break	10,000	24,600	10,700
Compressive Strength, psi D 695	13,000	12,000	6000	30,000	8,400
Modulus of Elasticity, psi D 638	390,000	175,000	150,000	790,000	350,000
Coefficient Thermal Expansion in/in. x 10^{-5}/°F D 696	3.1	4.0	5.0	1.0	3.5
Coefficient of Thermal Conductivity Btu/ ft^2/in/°F C 177	1.8	1.4	1.3	0.9	1.01
Abrasion wt. loss in grams D 1044	0.043	0.008	0.2	0.046	0.073

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Table 3-L Fire Resistance and Maintainability of Interior Materials

Material Property	Polysulfone	Nylon	ABS	High Temperature Resistant Nylon (NOMEX)	Acrylic Vinyl (KYDEX)
Flammability	S. E.	S. E.	S. E.	S. E.	S. E.
Smoke	Low	Moderate	High	Very low	High
Burn Dripping	No	Yes	Yes	No	Yes
Staining	N. A.	N. A.	N. A.	[1]	N. A. [2]
Maintenance	Good	Good	Good	[1]	Good

S. E. = Self-extinguishing as defined by ASTM D635. material which does not burn the full length of [illegible] in. after two ignitions.

N. A. = Not affected by typical staining agents such as nicotine, mustard, coffee, catsup and ballpoint pen ink

[1] Fibers woven into rugs and fabrics are maintained in the same manner as other synthetic materials. Papers used as honeycomb facings are subject to staining and will require an overlay of Polyvinyl Fluoride for low maintainability.

[2] Not affected by staining agents except ballpoint pen ink.

f. Overlay Films

Films are used to improve abrasion and flame resistance, maintainability, stain resistance, and ease of cleaning. The materials to be used include the following:

- Polyimide film — A high temperature resistant material which does not melt at 800°F and provides excellent barrier properties.
- Fluorocarbon films — Tetrafluorethylene, vinylidene fluoride, and fluoronated ethylene propylene provides flexible flame resistant coverings for polyurethane cushioning and upholstery.
- Polyvinyl fluoride film — Provides ease of cleaning and abrasion resistance for ceiling and side wall panels.

Properties of flammability, abrasion resistance, and cleanability for these materials are shown in Table 3-M.

3.5.2 Thermal Acoustical Insulation

The thermal-acoustical insulation will consist of fiberglass blankets covered with a metalized coated glass fabric. The fabric metalizing gives it a highly reflective (low emissivity) surface to reflect heat. Densities of this enclosed batting will be 1.0 lb per cubic ft (0.25 lb/ft² for a three inch thickness) in passenger areas, and 0.6 lb per cubic ft (0.05 lb/ft² for a one inch thickness) in cargo areas. This material incorporates a low emissivity additive to decrease thermal conductivity.

Tests have shown that the thermal stability, fire resistance, and water wicking and pickup resistance of the fiberglass batting are satisfactory for use in B-2707 flight environment.

Materials development and selection, including properties, for the fuselage insulation are presented in Document No. V2-B2707-10, Environmental Control.

Table 3-M Properties of Overlay Films

Property	Materials			
	Polyimide	Polyvinyl Fluoride	Tetrafluoro-ethylene	Fluorinated Ethylene-Propylene
Abrasion Resistance Weight loss grams/1000 cycles	0.004	0.08	0.01	0.01
Flammability	Non-burning to 800° F	Self-extinguishing	Non-burning to 600° F	Non-burning to 500° F
Cleanability	Good	Excellent	Excellent nonstick surface	Excellent nonstick surface

Discussion of acoustical requirements and acoustical performance of the insulation is contained in Document No. V4-B2707-5, Internal Noise.

3.6 SEALANTS, SEALS, AND ELASTOMERS

Materials for the various forms of sealing are discussed in this section. Basically, the purposes of sealing are to contain fluids or to protect components or structure from adverse environments. Objectives as to the level of containment include zero leakage, the maintaining of pressure differentials within specified limits, and the prevention of fluid flow.

The containment of fluids encompasses a variety of requirements. Fluids which must be contained include fuel and fuel vapor, engine oil, hydraulic fluid, acids, caustics, water, and air or other gases required for the operation of the airplane.

Electrical components must be sealed and stabilized for protection against the effects of shock, vibration, moisture, and other adverse environments. Discontinuities on the airplane surfaces must be sealed to provide aerodynamic smoothness. Failure to achieve maximum surface smoothness will locally magnify the effects of aerodynamic heating and drag. Various locations on the airplane exterior must also be sealed to prevent the entry of water and other fluids.

Fuel tank thermal insulation is used to control the temperature of the fuel resulting from aerodynamic heating. This is necessary to prevent fuel degradation and coking and also to allow the fuel to be used as a heat sink for subsystems.

Sealants, seals, and elastomers will be procured and processed in accordance with company specifications. A Boeing document will define specific design criteria and process requirements for sealing. These specifications will ensure that only proven materials and manufacturing techniques are used.

3.6.1 Fuel Tank Sealants and Insulation

a. Fuel Tank Sealing

Fluorosilicone sealant materials have been selected for sealing integral fuel tanks and other areas requiring fuel resistance.

Fillet, faying surface, injection, and isolation seals will be used in conjunction with self sealing rivets. The basic method is fillet sealing since it is a post assembly operation and does not require the close scheduling of faying surface sealing and is easily repaired in service.

Integral fuel tank design criteria are based on extensive experience in design and sealing of commercial airplanes. This sealing process has been successfully demonstrated on a full scale outboard wing box and several subscale fuel tanks.

Fuel sealants are exposed to temperatures ranging from -50 to 450°F, fuel with fuel vapor at the higher temperatures, and structural flexing. Bulk fuel temperatures do not exceed 180°F, but the small quantities of fuel remaining in tanks that are emptied early in the flight are at an average temperature of approximately 250°F.

A functional screening test was devised to test fuel sealants. It consists of environmental exposure, shear loading, and leak testing of a sealed panel. A typical panel is shown in Fig. 3-42. The environmental cycle consists of 72 hours at 250°F in referee fuel conforming to requirements of military specification MIL-J-5161 grade II followed by 16 hours at 400°F in a nitrogen-fuel vapor atmosphere. The 250°F fuel exposure temperature was chosen as an average value for the residual fuel. Nitrogen used for maintaining the inert atmosphere contains a small percentage of oxygen approximating the concentration encountered at the cruising altitude. After several cycles of environmental exposure, the panel is shear loaded at -65°F to produce joint deflections of 0.010 inch and subsequently leak tested. If leakage is not detected, the panel is recycled and tested until leakage occurs. Results of testing are given in Fig. 3-43. Dow Corning 94-002 fluorosilicone fillet sealant has completed 5000 hours of simulated service with no leakage. The test is continuing.

Physical properties of Dow Corning 94-002 filleting sealant before and after environmental cycling are shown in Fig. 3-44. This sealant passed a low temperature flexibility test in accordance with Military Specification MIL-S-8802 after 1344 hours of exposure. Tests for adhesion have shown that solvent cleaning and priming of Ti 6Al-4V are sufficient to promote adhesive strengths which exceed the cohesive strengths before and after environmental exposure.

Dow Corning 94-002 is capable of withstanding the operating temperature environment of the B-2707. Variations in behavior at elevated temperature have been observed. However, data shown in Fig. 3-43 are indicative of achievements possible by improvements in control of compositional limits and processing.

The Boeing Company and Dow Corning are actively engaged in a joint development and evaluation program and are confident that by 1967 a new fluorosilicone sealant formulation will consistently exhibit a 50° to 100°F improvement in thermal capability. A minimum service life of 50,000 hours at a fuel tank temperature of 430° to 450°F is expected.

Tests have been conducted to determine if candidate sealant materials have any detrimental effect on Ti 6Al-4V. The tests involve compression loading of metal strips coated with sealant. Specimens are prepared in the following manner:

- Two metal strips (1 by 4 by 0.050) are cleaned and primed as required.
- Sealant is applied to one side of each strip in a nominal 0.20-in.thickness and cured.
- The two strips are wired tightly together at both ends with the sealant on the outside.
- A 3/8-inch diameter dowel is inserted in the center to bow the specimen and thus stress the metal.

Deflections required to fail the coated specimens before and after exposure to water boil and heat aging are then compared to the values obtained for uncoated specimens. Test results shown in Fig. 3-45 indicate most fuel sealant materials affect Ti 6Al-4V to some degree. Tests are being conducted to determine if Ti 6Al-4V fatigue life is reduced by sealant material and what coatings may be applied to protect the titanium.

Fluorosilicone sealant materials were chosen because of their excellent service life, retention of physical properties, and satisfactory performance in sealing test hardware. Results of the functional test proved fluorosilicone sealants superior to other polymer types.

Viton based sealants were rejected because of unsatisfactory performance in functional tests, detrimental effect on titanium, and poor adhesion.

The Air Force Materials Laboratory is conducting a program to improve Viton based sealant materials with emphasis on additives to protect titanium from attack by sealant degradation products.

Other programs under direction of AFML are aimed at producing new base polymers, such as triazine and polyether elastomers, which are

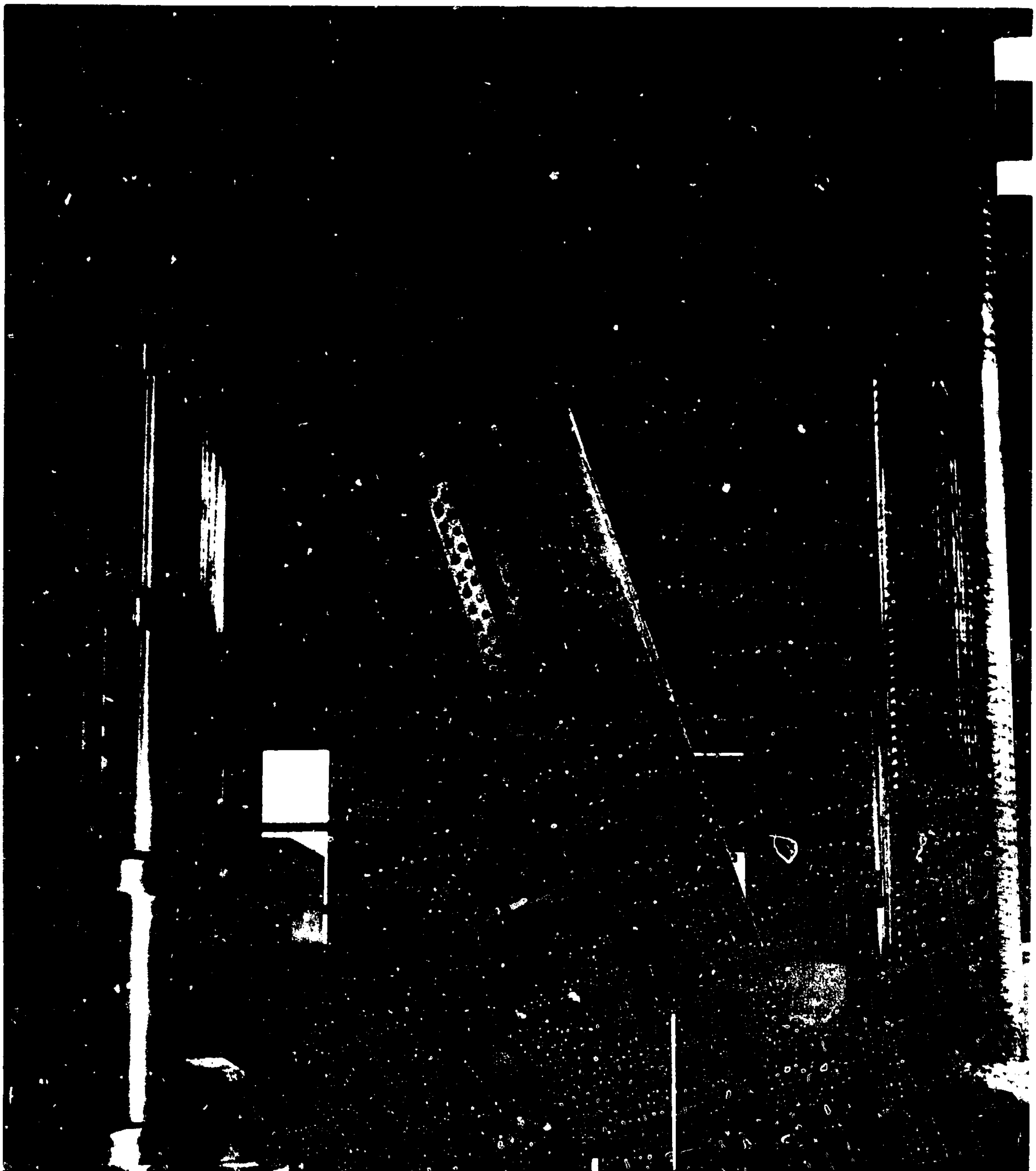

Figure 3-42. Functional Test Device

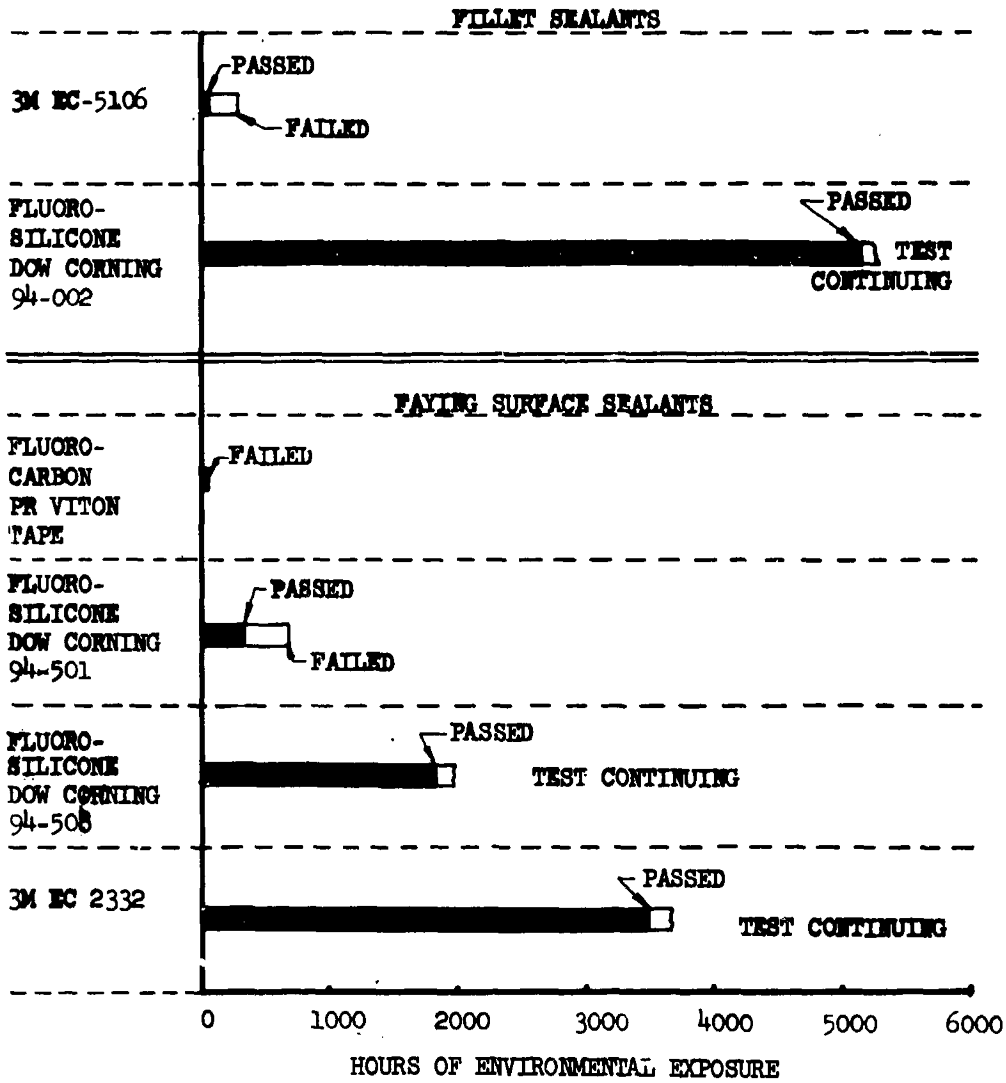

Figure 3-43. Functional Test Results, Fuel Tank Sealants

expected to provide improved high temperature capability and extended service life. Small scale polymerization of bis (iodoperfluoroalkyl) triazines and bis (perfluoroalkenyl) triazines was successfully performed by Denver Research Institute under Contract No. AF 33(615)-1367. These materials will be given a cursory evaluation, in cooperation with AFML, by The Boeing Company as soon as experimental quantities are available.

b. Fuel Tank Insulating

A lightweight fluorinated synthetic material designated as B-5037 is selected for insulating the integral fuel tanks. The density of this material is controlled by the use of lightweight evacuated glass microspheres. The base material used for compounding this insulation is commercially available and can be formulated into sprayable or trowelable forms with various viscosities. The density of the insulation including the fuel barrier is limited to 10 lbs/ft^3.

The basic function of the fuel tank insulation is to prevent the bulk fuel temperature from exceeding 180°F at any time during supersonic cruise. This must be accomplished with a minimum of insulation weight.

It is necessary that the insulation be capable of withstanding the following conditions:

- Exposure to temperatures of 430° to 450°F.
- Exposure to kerosene fuels at temperatures up to 250°F.
- Compression load of the fuel.
- Deflection imposed by the movements of the wing under loads.

The B-5037 insulation is resistant to the indicated environmental conditions such that the service life of the insulation will equal or exceed that of the airplane.

Satisfactory adhesion to Ti 6Al-4V alloy is obtained by solvent cleaning of the surfaces to be insulated. An aromatic naphtha based solvent mixture is used for this purpose. After application and cure of the insulation, a fuel barrier material is applied and cured.

Significant physical properties of the selected material are presented in Table 3-N. In addition, the material did not crack or lose adhesion to Ti 6Al-4V alloy when a simulated outboard wing panel was subjected to the following test.

- The insulated panel is subjected to an environmental exposure cycle consisting of 72 hours in JP-5 fuel at 250°F followed by 96 hours in N_2 fuel vapor at 435°F° Subsequent to this exposure the panel is subjected to stresses of 60 ksi tension and 60 ksi compression over a temperature range of -65°F to 450°F at a rate of 60 cycles per minute for 10 hours.

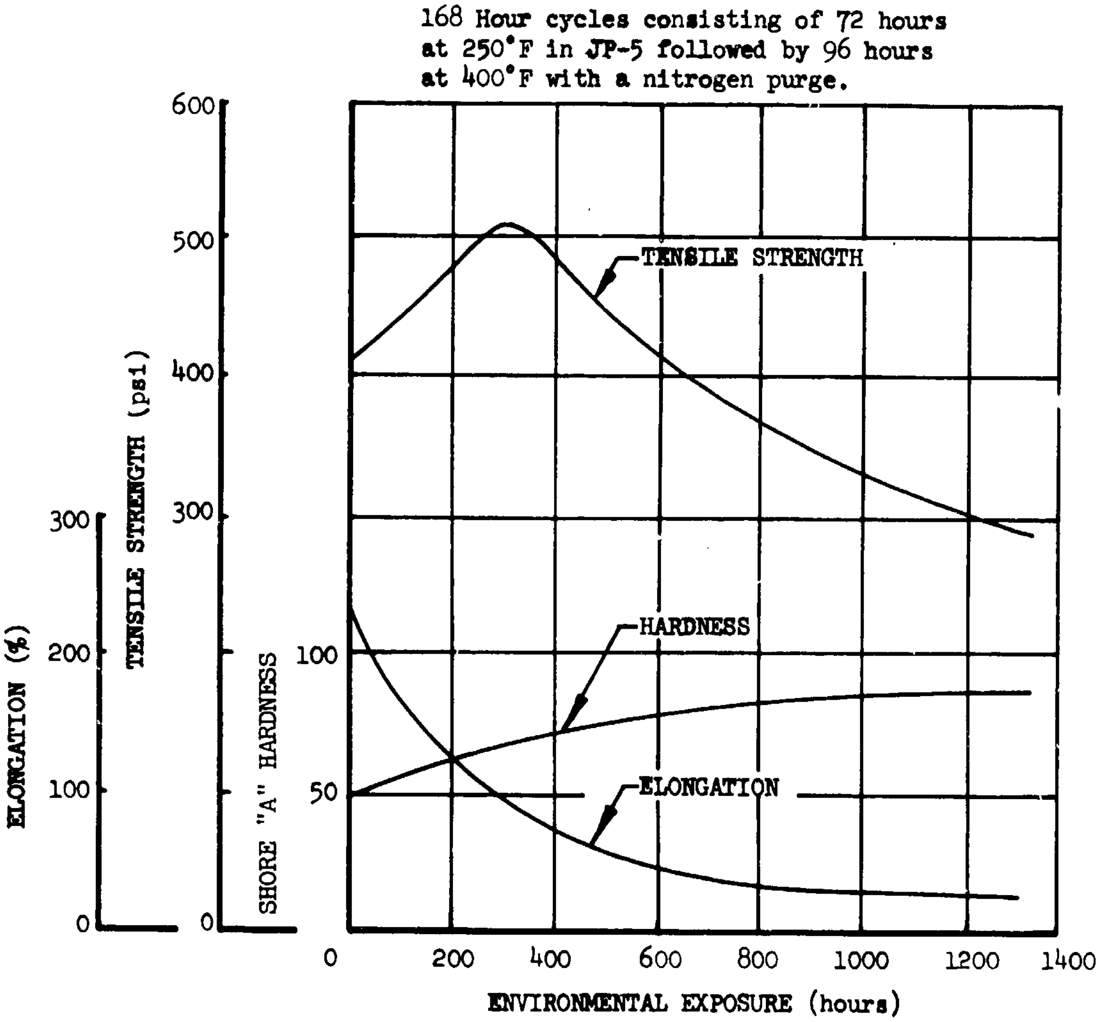

Figure 3-44. Properties of DC 94-002 Sealant

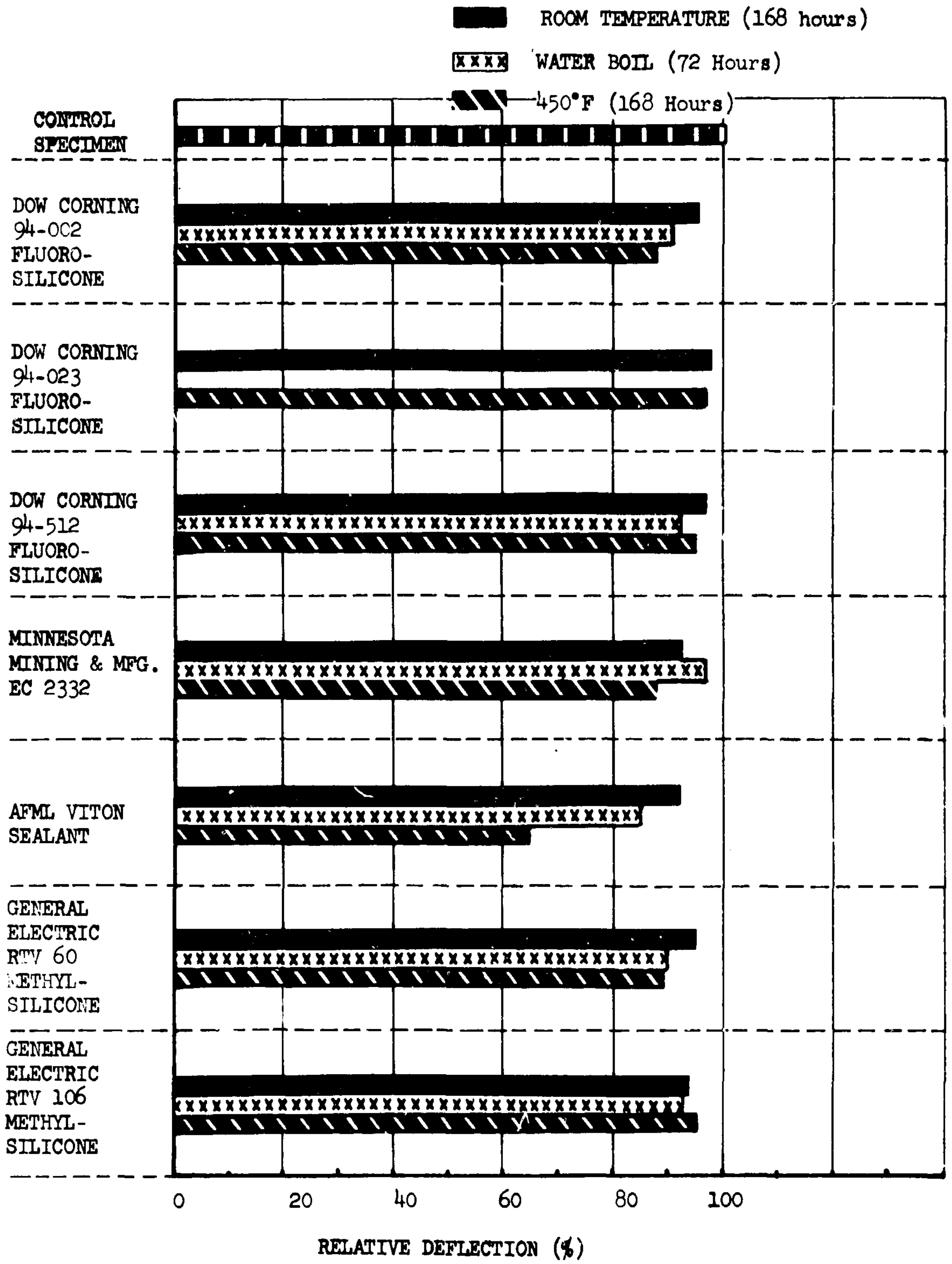

Figure 3-45. Compatibility of Titanium and Sealants

Table 3-N. Fuel Tank Insulation Properties

DENSITY	<10 lb/ft^3
SPECIFIC GRAVITY (MEAN)	0.16
THERMAL CONDUCTIVITY, BTU/in/hr/ft^2/°F	0.35
Determined at a mean temperature of 250°F	
FLEXIBILITY AT -65°F (5% strain)	No cracking
FUEL RESISTANCE	
14 days at 250°F in JP-5	<3 percent weight gain
Cycling for 72 hours in JP-5 at 250°F and 96 hours in JP-5 vapor and N_2 at 435°F	15 cycles, no loss of adhesion or flexibility
ADHESION TO TITANIUM (Lap Shear), psi	
at 450°F	45, cohesive failure
at 70°F	85, cohesive failure
at -65°F	200, cohesive failure
FLUID RESISTANCE (14 days exposure)	
(a) JP-5 Fuel at 180°F	<3 percent weight gain
(b) Salt water at 200°F	<5 percent weight gain
(c) Water at 200°F	<5 percent weight gain

Recently, Monsanto Chemical Company submitted a sample of a newly developed open cell polyimide foam which can be produced in any desired thickness. Favorable properties exhibited include extremely low density (0.5 to 4.0 lb/cu. ft) and the outstanding thermal stability which is characteristic of the polyimide systems. The foam should be capable of continuous operation at temperatures up to 500°F.

Dow Corning has submitted a foam in place fluorosilicone material which holds promise of meeting thermal and fuel resistance requirements. Although density of the fluorosilicone foam (26 lbs./cu. ft.) is considered too high, it is expected that satisfactory densities will be achieved by incorporation of a light weight filler.

Additional developmental work at The Boeing Company will include the investigation of a foam in place system using honeycomb core for reinforcement. Preliminary results indicate densities of 6 to 8 lbs/ft^3 with a resulting compressive strength of 90 psi are attainable. The foam is thermally stable up to 500°F for extended periods. Metallic foils or nonmetallic film such as DuPont's polyimide Kapton film, will be investigated to enhance fuel barrier characteristics.

3.6.2 General Sealing

a. Pressure Sealing

Methyl silicone sealant materials have been selected for sealing pressurized areas of the fuselage. These materials will provide reliable seals for the service life of the B-2707.

Fillet sealing is normally used because it is a post-assembly operation and avoids the close scheduling required by faying surface sealing. Fillet seals are capable of withstanding high structural deflections and also have the advantage of being easily repaired in service. Faying surface seals are used in low deflection areas when their advantages in simplicity and weight savings outweigh their disadvantages. The pressure sealing methods described are standard on present commercial airplanes and have proved reliable in service.

The environment encountered by the pressure sealants includes temperatures from -50°to 450°F and pressure differentials of up to 15 psi. Screening tests were conducted at temperatures of 600°F for periods up to 500 hours. The higher temperature was chosen for screening tests to accelerate thermal degradation and eliminate marginal materials.

Physical properties of three methyl silicone sealants before and after 600°F aging are shown in Fig. 3-46 through 3-48. General Electric RTV-60 is a two component material suitable for use in faying surfaces or other confined areas. General Electric RTV-106 and Dow Corning 92-024 are one component systems which depend on atmospheric moisture for cure. This restricts their use to fillet sealing applications. Results show that all three materials retain satisfactory physical properties at 600°F and indefinite service life at 450°F is indicated. All other materials considered fell short of this objective.

Solvent cleaning and priming of the surface are required for adhesion to titanium. Qualitative tests for adhesion have shown that adhesive strength of these sealants to titanium exceeds the cohesive strengths of the sealants before and after aging at 600°F.

Tests have been conducted to determine if methyl silicone sealant materials have any detrimental effect on titanium. Results of testing of RTV-60 and RTV-106 in accordance with Par. 3.6.1 are shown in Fig. 3-45. Some effect is evident, but its magnitude is no greater than that for the other types of sealants tested. Fatigue tests as

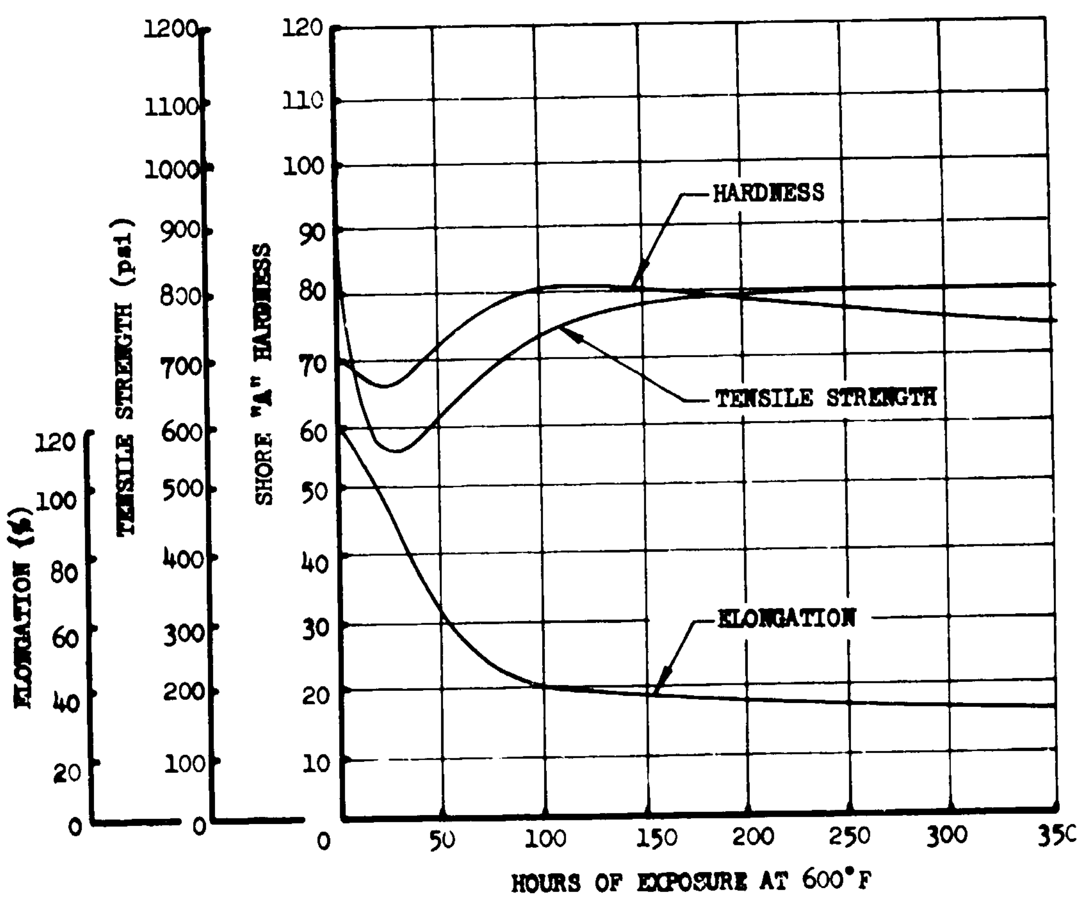

Figure 3-46. Properties of RTV-60, 600° F

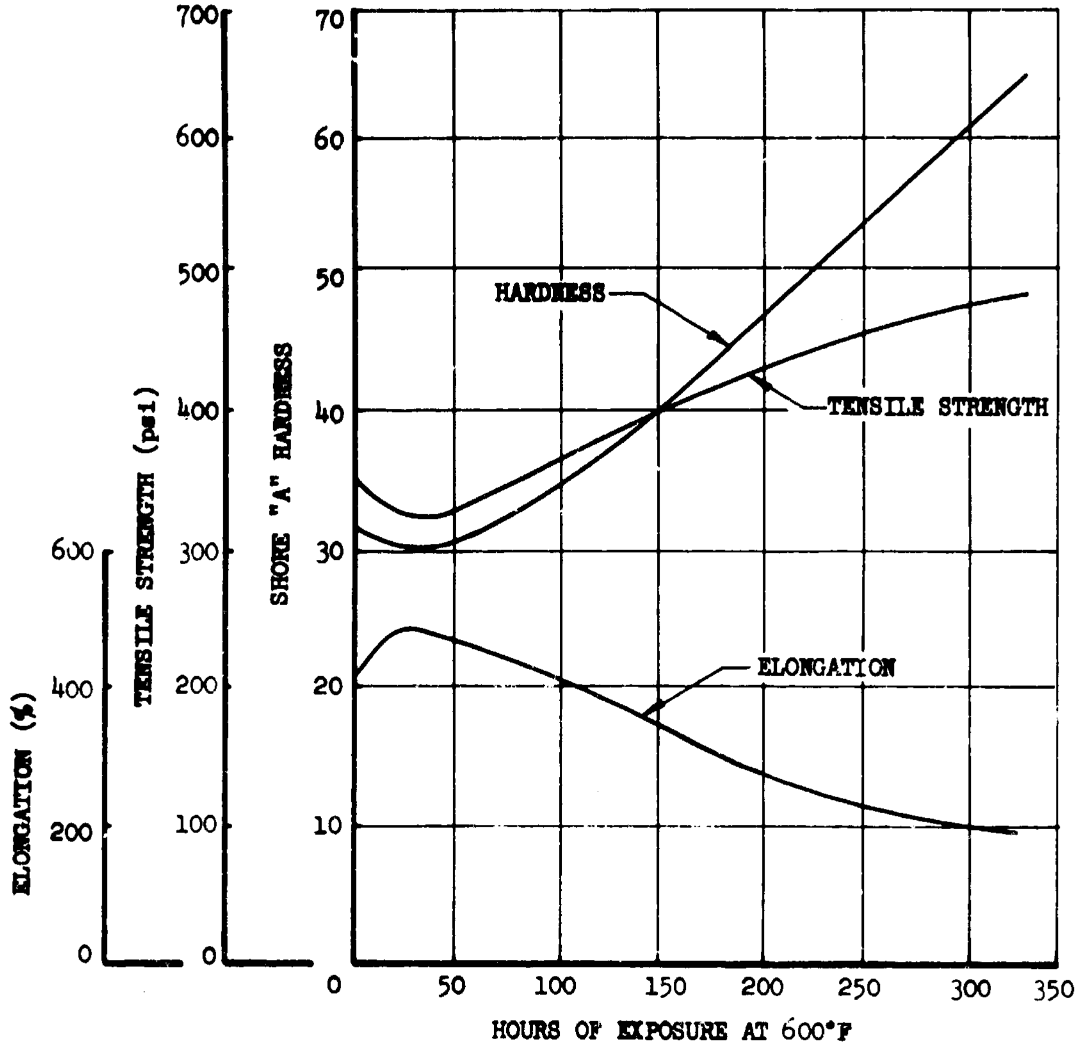

Figure 3-47. Properties of RTV-106, 600 F

previously described will determine the significance, if any, of the indicated differences in specimen deflection.

b. Battery and Toilet Sealing

Polysulfide sealant materials have been selected for sealing the battery compartment and toilet areas.

The environment encountered by these sealants includes exposure to uric acid in the toilet areas and fluid containing up to 30 percent by weight potassium hydroxide in the battery compartment. Since these areas are enclosed within controlled temperature compartments of the airframe, no exceptional heat resistance is required of the sealant materials.

Testing has shown that polysulfide sealant materials have superior resistance to the acid and alkaline fluids and provide sufficient protection for the structure.

Polysulfide sealant materials are used on present commercial airplanes and the use of these materials conforms with standard practice.

c. Electrical Sealing and Potting

Methyl silicone sealant materials are used for sealing and potting when a flexible material is required and temperatures do not exceed 500°F for continuous operation or 600°F for intermittent operation.

Typical room temperature electrical properties of a cured methyl silicone sealant material are listed below:

Dielectric Strength, Volts/mil	
0.040 in. thickness	600
0.075 in. thickness	500
Dielectric Constant	
60 cps	3.8
10^6 cps	3.5
Dissipation Factor	
60 cps	0.020
10^6 cps	0.003
Volume Resistivity, Ohm per cm	1.3×10^{14}

Methyl silicone sealant materials are used for flexible electrical sealing and potting on present commercial airplanes where heat resistance is required.

3.6.3 Compartment Pressure and Access Door Seals

The term compartment pressure seals, as used herein, refers to any device used to seal doors or other closures for the containment of pressure. Access door seals may serve to contain either pressure or fuel.

Doors or closures may be divided into two categories as follows:

a. Category I covers doors which are bolted or otherwise mechanically fastened in position and remain secured throughout most routine loading and servicing operations.

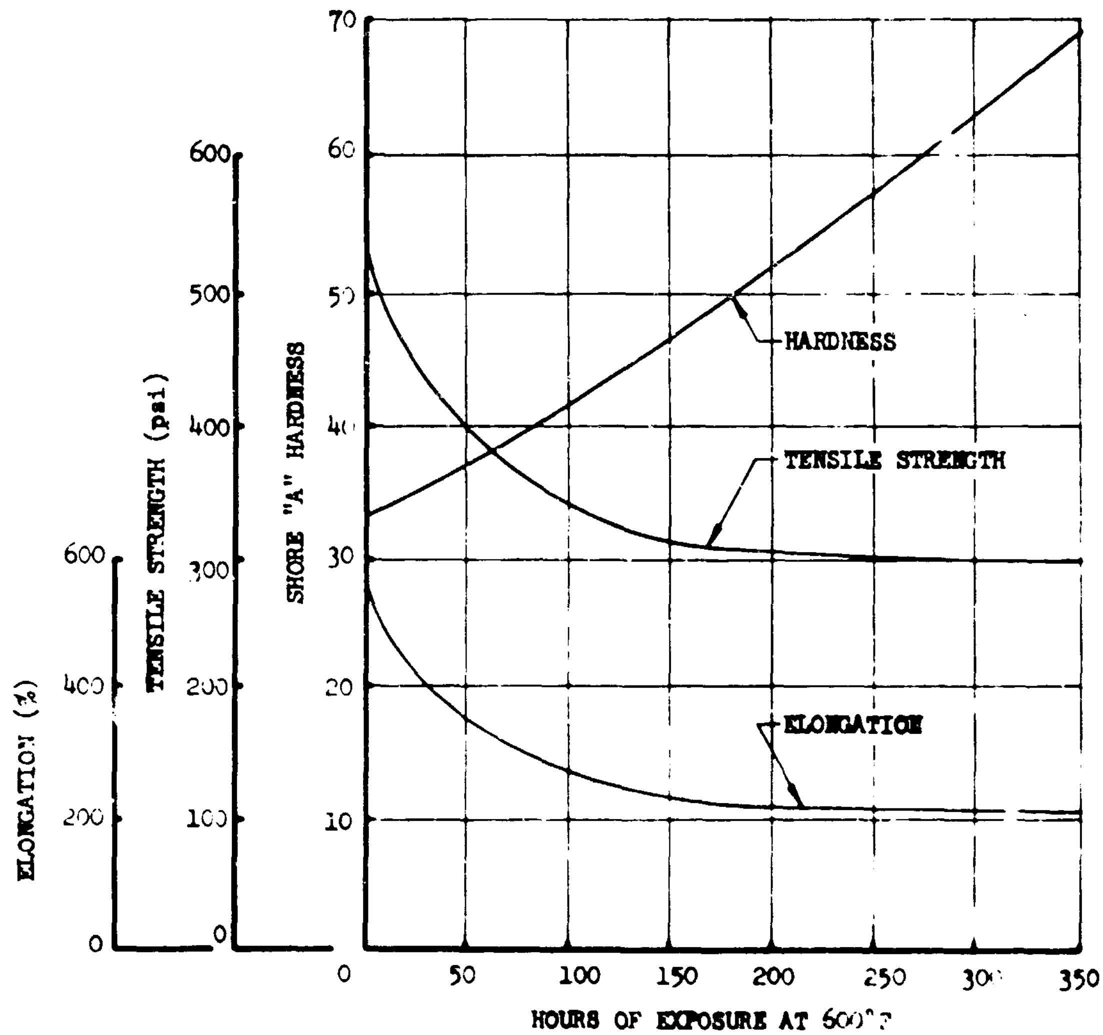

Figure 3-48. Properties of DC 92-024, 600 F

Examples are access doors which must be removed at various time intervals for routine inspection and maintenance of systems or structure.

b. Category II covers doors which are regularly opened and closed as a part of routine operations. Examples are passenger, cargo, crew, and landing gear doors.

Seals used on category I doors, whether they are intended to contain pressure or liquids, rely to a large extent for their effectiveness on the compressive forces produced by the mechanical fastening of the door to the structure. Such seals serve a strictly static function in that they are under constant compression at all operating conditions. Thus, the elastomer chosen must have good compression set properties at environmental temperatures of 400° to 450°F and under conditions of fuel exposure at temperatures up to 250°F. On the other hand, flexibility at low temperatures is of relatively little importance.

Seals fabricated from fluorocarbon rubber best meet the static sealing requirements described. A Viton polymer, designated 77-545 and manufactured by Parker Seal Company, shows the most promising physical property values after aging in air at 400°, 500° and 600°F and after aging in JP-5 fuel at 250°F.

Physical property values for 77-545 are listed in Table 3-O. Compression set after 24 hours at 400°F is only 30 percent. Volume swell is quite low, four percent after seven days in Dow Corning XF1-0294 hydraulic fluid at 430°F. Compatibility with other candidate hydraulic fluids is comparable. All physical properties meet or exceed existing specification requirements for the indicated exposure conditions.

Four other fluorocarbon seal materials are available as alternate candidates. These are Plastic and Rubber Product's 975-75, Precision Company's 17107A, and Stillman Rubber Company's SR-276-70 and EX 999-41.

Tensile properties of the five leading candidates, after aging seven days in JP-5 fuel at 250°F, are shown in Fig. 3-49. Hardness change and percent volume swell under the same conditions were as indicated in Fig. 3-50. Compression set data, after aging seven days in air at 350°F, are shown in Fig. 3-51.

It is evident from the referenced data that each of the candidate materials exhibits superior performance with regard to one or more physical properties. Although the Parker 77-545 compound has the best balance of properties, the different combinations of properties available with the candidate materials are sufficient to satisfy design requirements.

Seals used on category II doors are subjected to flexing at temperatures as low as -50°F. They are under compression at temperatures of 400° to 450°F. Sealing efficiency is such that required pressures are maintained at all times during operation of the airplane.

To meet these requirements, seals fabricated from dimethyl silicone elastomers or fluorosilicone elastomers are used. The seals are reinforced with Nomex or glass fabric and covered with Teflon (TFE) to meet low friction requirements. Pressurized or spring loaded seals are used, as required, to help compensate for elastomer compression set caused by long term heat exposure.

3.6.4 Aerodynamic Seals and Smoothers

a. Aerodynamic Seals

Aerodynamic seals are used to control air flow from one aerodynamic surface to another. These seals must maintain their flexibility and other physical properties after prolonged exposure to operating temperatures of 400° to 450°F. They must also remain flexible at -50°F and resist effects of exposure to kerosene type fuel, engine oil, and hydraulic fluids.

A Nomex or glass cloth reinforced fluorosilicone rubber satisfactorily meets these requirements. The fluorosilicone polymer was chosen because of its favorable aging characteristics at 450°F and because of its fluid resistance. Typical fluorosilicone rubber compounds are Dow Corning LS-53 and LS-2311U, Parker Seal 6-375-7, and Hadbar 1000-81.

The 450°F environmental temperature is well within the thermal capabilities of both Nomex and glass fabrics. Nomex has an advantage in that it does not exhibit the self abrasive behavior which is typical of woven glass fabrics. Where low friction properties are required, a Teflon (TFE) cover will be incorporated. A single type of seal design was chosen for high temperature break out pressure tests at several different deflections. This design consists of a fabric

Table 3-0. Resistance of Fluorocarbon Rubber to Selected Environments

Properties	Typical Requirements	Values Obtained
ORIGINAL PHYSICAL PROPERTIES		
Hardness, pts (Shore A)	75 ± 5	75
Tensile strength, psi	1500 Min	2,150
Elongation (percent)	125 Min	201
Modulus at 100 percent Elongation (psi)	350 Min	780
Compressive Load at 20 percent Deflection (psi)		
At 70° to 85°		300
At 500° F		140
Specific gravity		1.87
AIR AGING: 70 HRS. AT 500° F		
Hardness change Δ H. pts (Shore "A")	0 to +15	83 (+5)
Tensile change (percent)	-35 Max	1,845 (-14.2)
Elongation change (percent)	-50 Max	176 (-12.4)
Weight Loss (percent)	-8.0 Max	-4.7
AIR AGING: 16 HRS. AT 600° F		
Hardness change Δ H. pts (Shore "A")	0 to +15	85 (+10)
Tensile strength change (percent)	-35	-15.3
Elongation change (percent)	-55	-29.0
Weight Loss (percent)	10 Max	-4.5
FLUID AGING: 7 DAYS AT 430° F IN XF 1-0294		
Hardness change Δ H. pts (Shore "A")	0 to ±5	0
Tensile strength change (percent)		1,980 (-8.0)
Elongation change (percent)		188 (-6.5)
Volume Swell	0 to -10	4.2
COMPRESSION SET PER ASTM D 395		
24 Hrs. at 400° F — 25 percent Deflection used		
Percent of original deflection	50 Max	30.2
TEMPERATURE RETRACTION, 50 PERCENT ELONGATION		
TR-10 °F	+5 Max	-2° F

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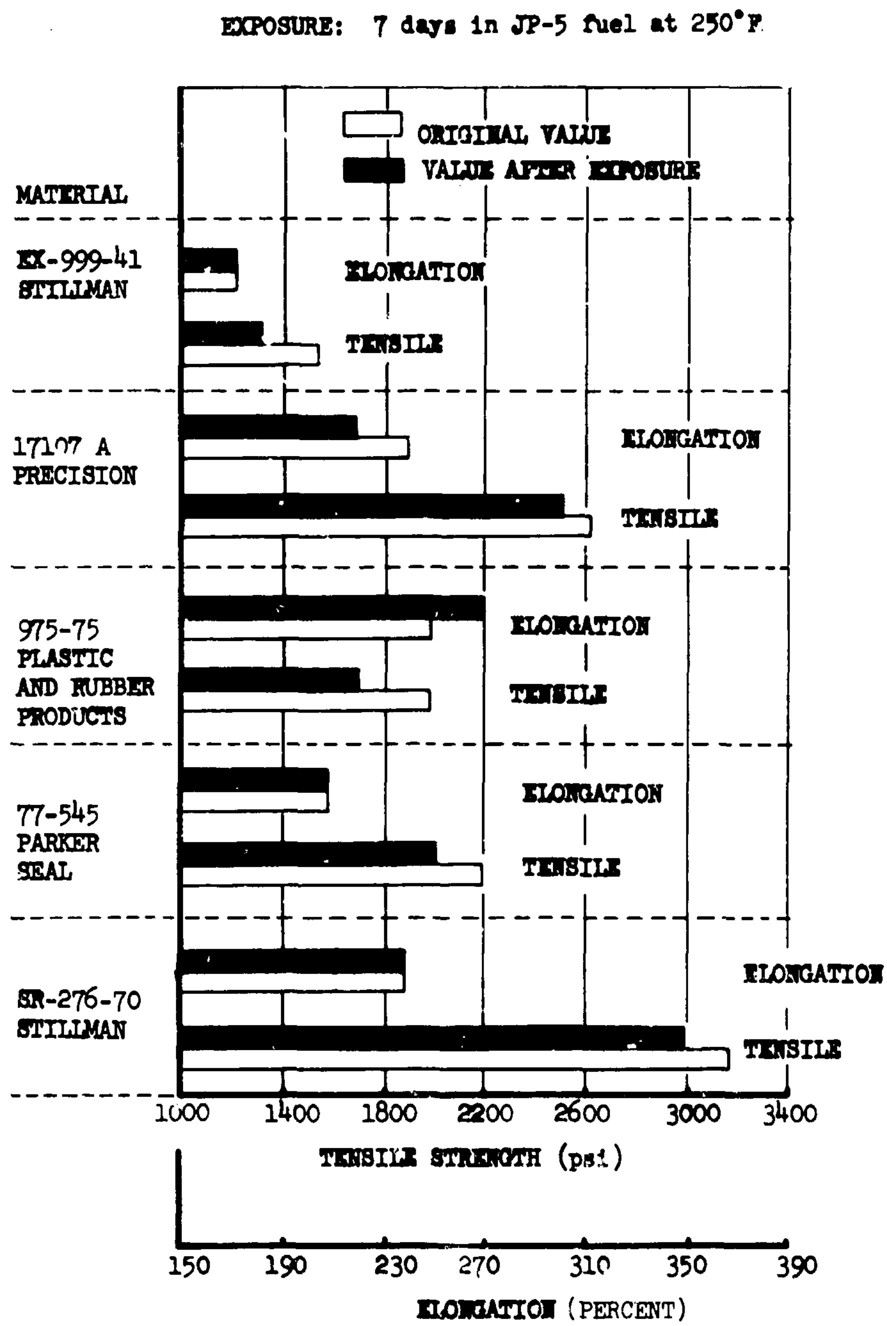

Figure 3-49. Tensile Properties of Fluorocarbon Rubber, Fuel Aging

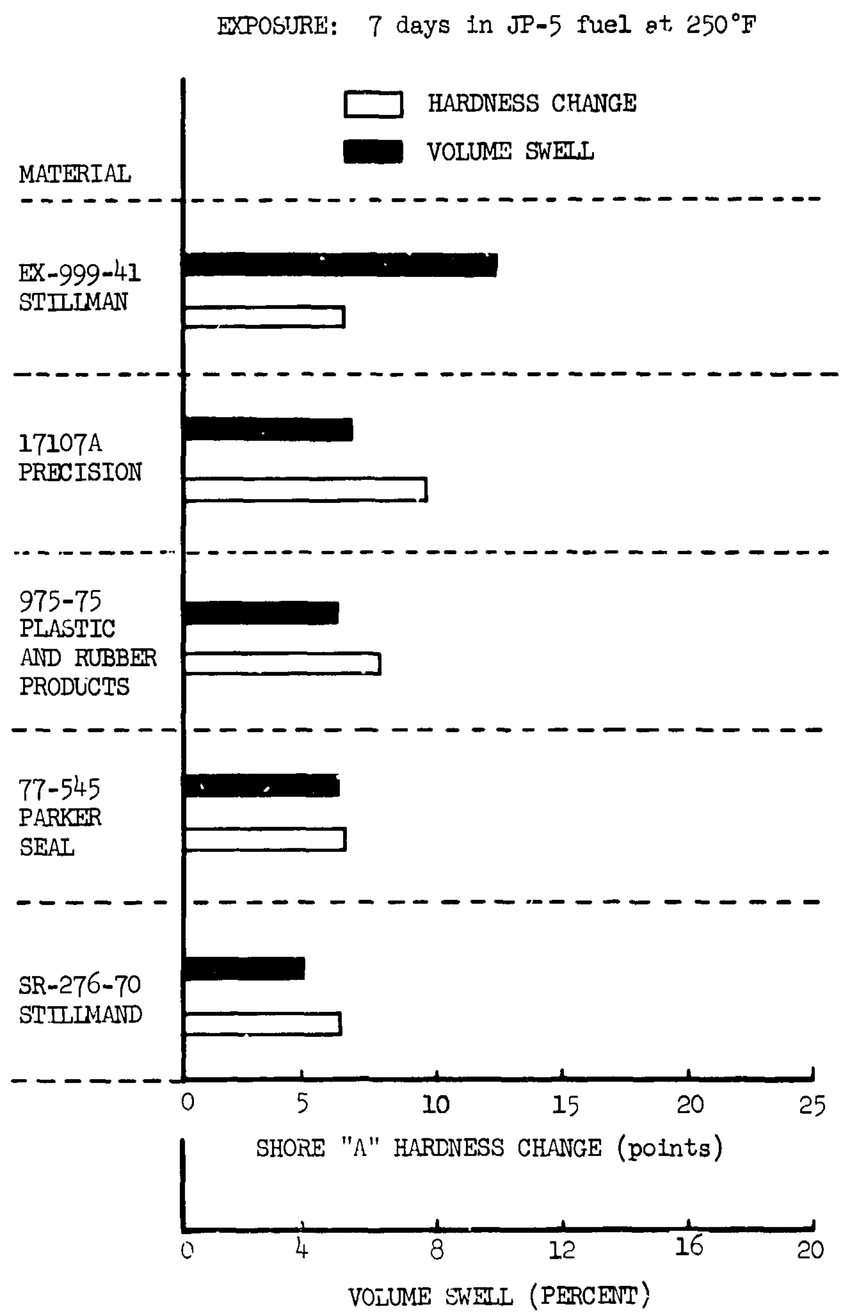

Figure 3-50. Flurocarbon Rubber, Hardness and Volume Change

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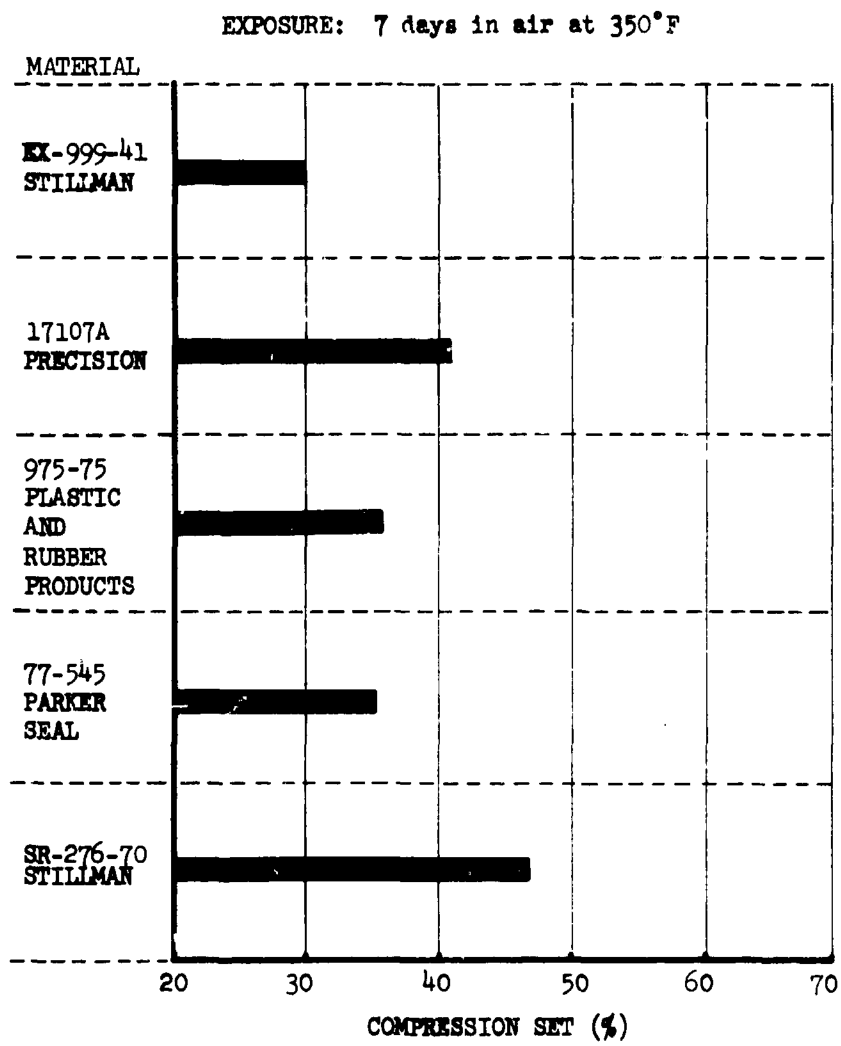

Figure 3-51. Fluorocarbon Rubber, Compression Set, 350°F

reinforced length of tubing built upon a flat short-width base manufactured from the same fabric. The design is shown in Fig. 3-52.

To establish the fuel resistance of the fluorosilicone polymer, Parker Seal's 6-372-7 compound was immersed in JP-5 fuel at 250°F for seven days. After the immersion period, tensile properties and Shore "A" hardness were determined and compared to original values. Percent volume swell was also calculated. Results of the fuel immersion tests are shown in Fig. 3-53. A 30 percent reduction in tensile strength and 25 percent reduction in elongation are indicated. Shore "A" hardness has dropped from 68 to 60 and the volume swell was eight percent. These data indicate that the fuel resistance of the elastomer is adequate.

High temperature aging data indicate that there will be no significant degradation of the fluorosilicone elastomers in the 400° to 450°F temperature range. After high temperature aging, tensile strength, elongation, compression set, and stress relaxation values are within acceptable limits. Dow Corning LS-2311L has the best high temperature compression set properties while Hadbar 1000-81 exhibits the lowest stress relaxation values.

The strength of the composite seal is largely dependent upon the reinforcement. Similarly, tensile elongation is limited by the reinforcement, but this is of no importance as long as compressive flexibility and the capability of meeting design deflections are obtained.

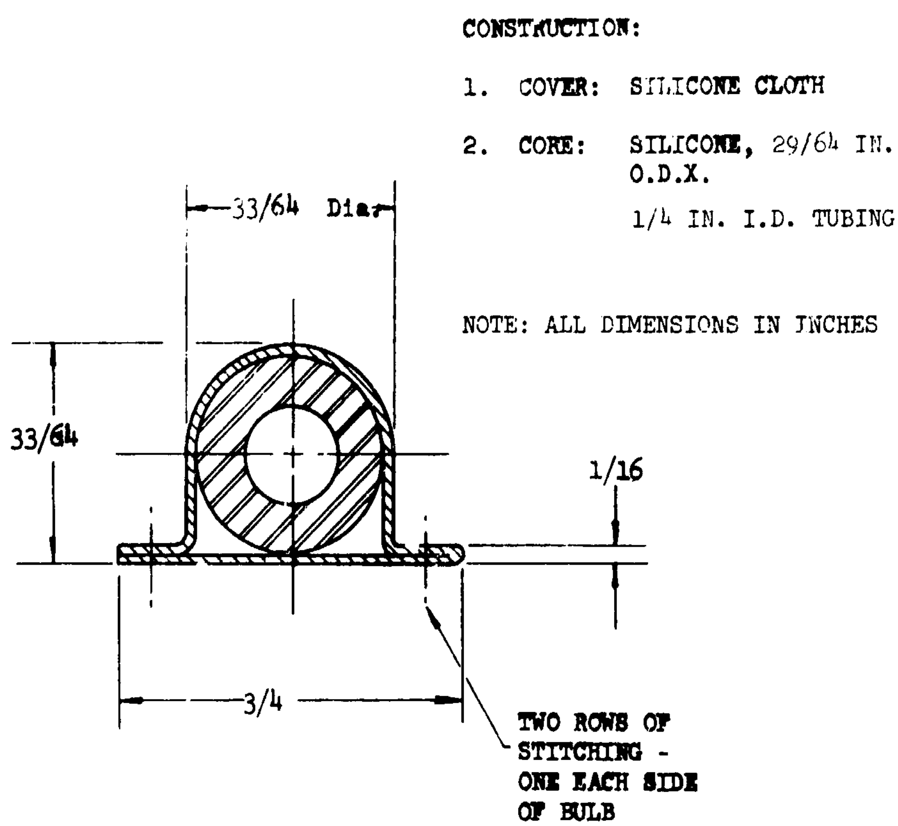

Figure 3-52. Aerodynamic Seal, Test Configuration

b. Aerodynamic Smoothers

A dimethyl silicone compound is used to smooth aerodynamic surfaces of the airplane. The material selected is available in either plain or pigmented colors from the General Electric Company, and is designated RTV-1071 (plain) and RTV-1072 (pigmented). It has demonstrated satisfactory shaving and sanding characteristics.

This material is applied manually or with the use of an extrusion gun. After cure, the material is shaved and sanded, either manually or with a mechanical sander to a smooth, level, continuous surface. The material does not roll or tear during working. This provides a distinct cost reduction by eliminating the need for rework.

The material cures in 24 hours at room temperature, requiring no expensive temperature or humidity controls. When cured, the two versions of the material are virtually identical in composition. There are no differences in hardness or other physical properties. Cure is accomplished by chemical reaction with an accelerator blended into the base material before application.

Satisfactory adhesion to Ti 6Al-4V alloy is obtained by solvent cleaning and application of a primer. An aromatic naphtha or ketone based solvent mixture is used for cleaning. Brush application and room temperature air drying of a solvent based primer ensures satisfactory adhesion to the metal at all operating temperatures and weather conditions.

Properties of the smoothing and fairing compound enable it to satisfactorily withstand the temperatures and weathering of supersonic flight. Exposure to temperatures in excess of 500°F results in no significant degradation of the material.

A satisfactory alternate smoother is a one-part mica, silicone, and crystobolite solids loaded paste. This compound, designated CA9R and available from Englehard Industries, is applied in exactly the same manner as the dimethyl silicone. Cure is accomplished by solvent evaporation concurrent with chemical reaction initiated by an accelerator. It requires two hours of air drying, followed by two hours of baking at 300°F.

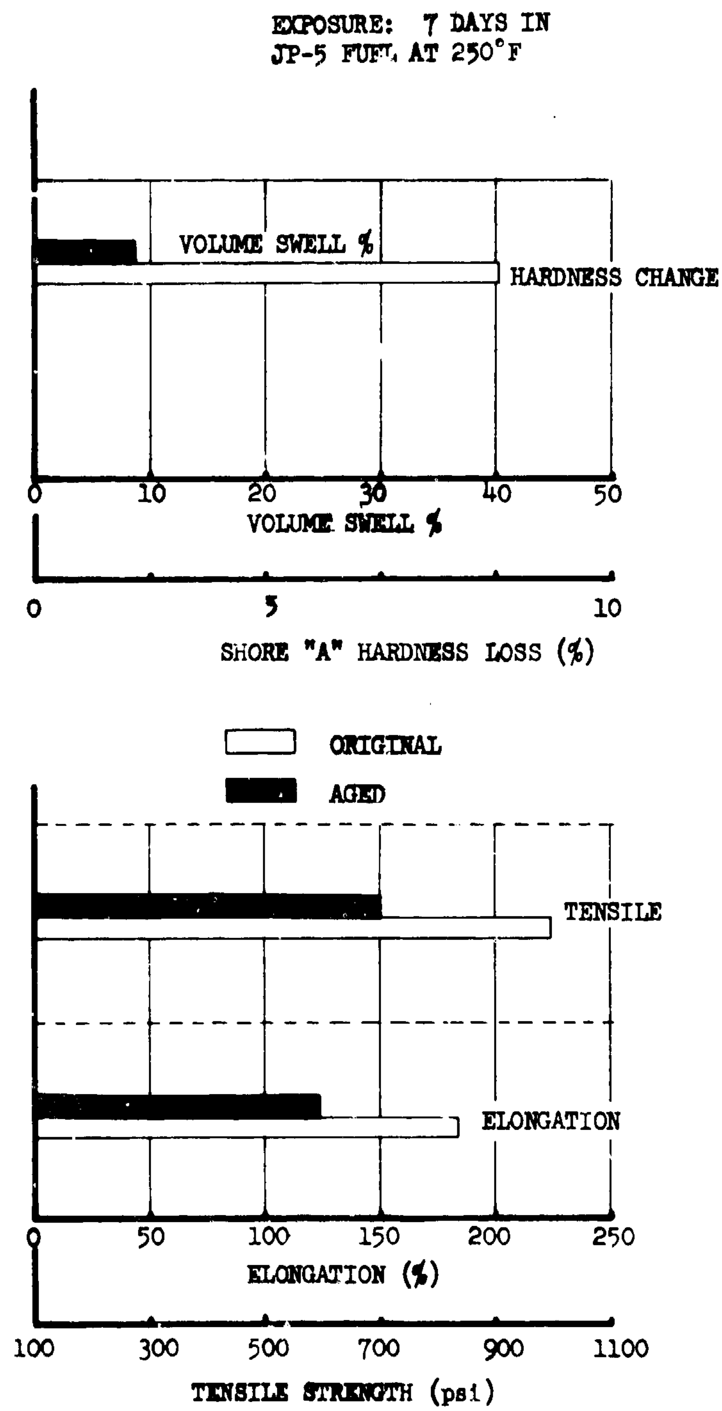

Figure 3-53. Fluorosilicone Seals, Aging in JP-5 Fuel

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Satisfactory adhesion to Ti 6Al-4V alloy is obtained by solvent cleaning of the surfaces to be filled. An aromatic naphtha or ketone based solvent mixture is used for this purpose. No primer application to the clean metal is required. Exposure to temperatures in excess of 500°F results in no degradation of the material. It was originally developed for use in applications where temperatures up to 1000°F are encountered.

Effects of temperature on hardness of the aerodynamic smoother materials are shown in Fig. 3-54.

3.6.5 Fluid System Seals

a. Fuel and Engine Oil Seals

Fluorocarbon (Viton) elastomers will be used for fuel and engine oil seals. These seals will be subjected to a temperature range of -50° to 400°F with low fluid pressures.

Physical properties of several vendor fluorocarbon and fluorosilicone formulations have been determined and are listed in Figs. 3-49, 3-50 and 3-55. In simulated service tests of O-rings and rubber-in-metal groove seals fabricated from Parker 77-545, no leaks were detected after 480 hours of aging. The aging consist d of 120 hours in JP-5 referee fuel at 250°F and 360 hours at 475°F with leak testing done at -65°F.

Fluorocarbon elastomers were chosen over fluorosilicone elastomers because of their better physical properties. The fluorocarbons have much lower compression set which is a particularly important characteristic for seals.

Since the seal designs are standard, no problems are expected in installing seals.

b. Hydraulic System Seals

Seals used in the hydraulic system must be capable of withstanding continuous exposure to the system fluid at operating temperatures of 425° to 450°F. Important seal properties include dimensional stability, low stress relaxation, low compression set and compressive creep, low coefficient of friction, and tear and abrasion resistance. In general, tear and abrasion resistance are more important for dynamic than for static applications where damage during seal installation is the primary concern.

For static seal applications, Viton elastomeric O-rings and filled Teflon (TFE) back-up rings are used in conjunction with silver plated stainless steel rings of the V and K types. The TFE back-up rings will be filled with 15 percent glass fibers and five percent molybdenum disulfide. Cast iron step-cut rings and 15 percent graphite filled TFE rings will be used in dynamic sealing applications.

The Viton elastomer and the filled TFE compounds were selected for use as nonmetallic seals in the hydraulic system on the basis of the requirements outlined. Performance of these materials in comparative physical property tests and functional tests has been superior to that of other candidates. Parker 77-545, a Viton compound, has demonstrated the best performance of any material tested for use as a static O-ring configuration seal. Fluorosilicones and dimethyl silicones were among other classes of materials evaluated for this purpose.

General physical properties of the candidate nonmetallic seal materials are listed in Tables 3-0 and 3-P, and shown graphically in Fig. 3-56 through 3-61. These data, along with results of fluid compatibility studies and service application tests provided the criteria for materials selection.

Figures 3-62 and 3-63 show the effects of aging at 430°F in three candidate hydraulic fluids on two Viton based elastomers. Figure 3-64 provides a direct comparison of the five compounds in terms of resistance to a fluorosilicone hydraulic fluid, Dow Corning XF1-0294. Volume swell was determined along with changes in tensile strength, elongation, and hardness.

The selected materials have performed satisfactorily in simulated service testing of a hydraulic actuator. Results of these tests are presented in Table 3-Q. Seals fabricated from the Viton and filled teflon materials have experienced up to 426 hours and more than 6,400,000 cycles of testing without failure.

Assuming materials compatibility, a post-cure at elevated temperature in the applicable hydraulic fluid results in a worthwhile improvement in the physical properties of elastomeric seal materials. In particular, a significant reduction in compression set values has been noted. In order to exploit this characteristic, all Viton seals will receive a suitable post cure in the hydraulic fluid prior to installation.

EACH DATA POINT IS BASED ON 168 HOURS OF EXPOSURE.

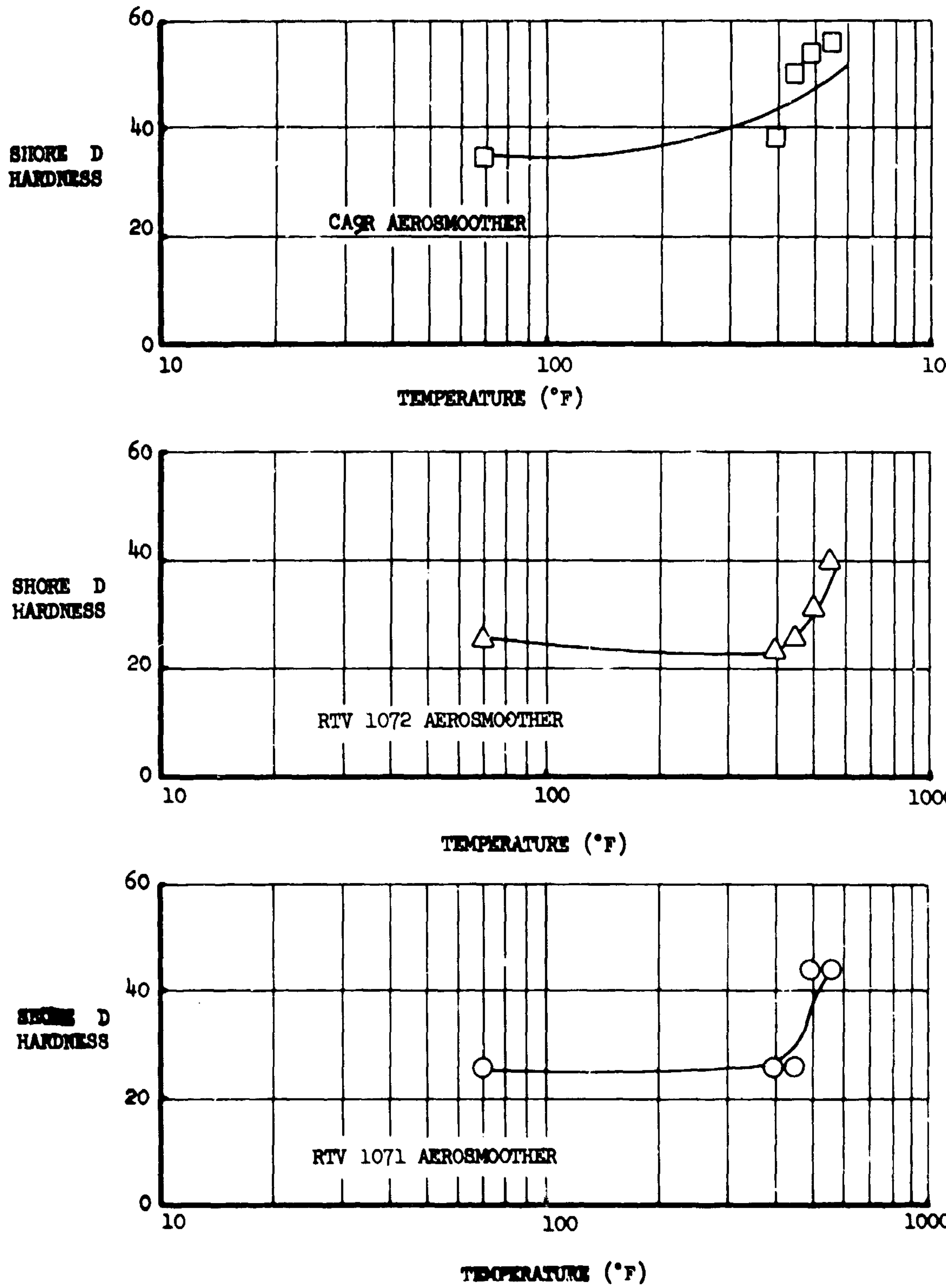

Figure 3-54. Shore D Hardness, Aerodynamic Smoothers

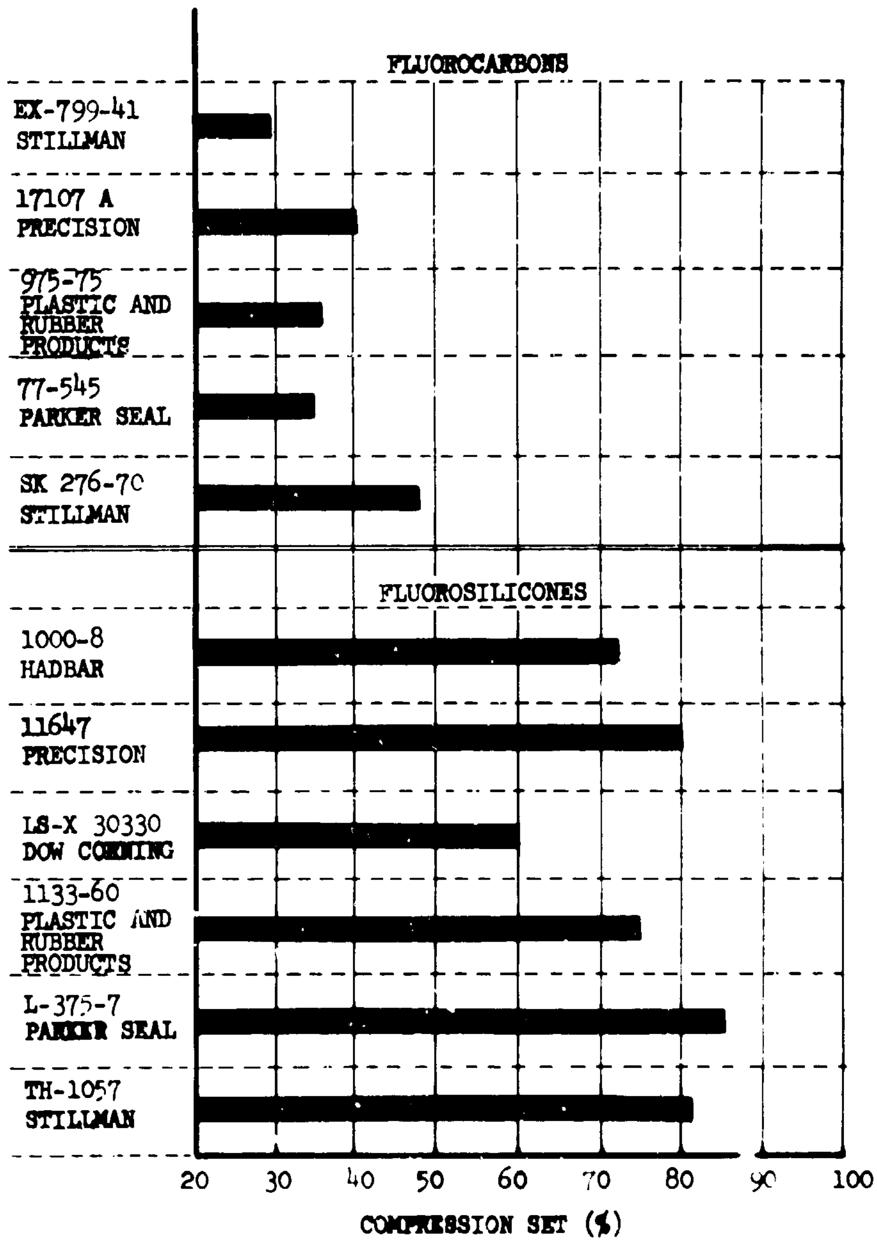

Figure 3-55. Compression Set Properties, Fluorosilicones and Fluorocarbons, 7 Days at 350°F

Table 3-P. Properties of Filled TFE Materials

Room Temperature Properties	Glass Filled TFE	Graphite Filled TFE	
		Parallel to Molding Direction	Perpendicular to Molding Direction
Tensile strength, psi	2,000-3,000	4,700	2,200
Elongation, percent	50	70	60
Compressive strength, psi			
50 percent deflection	5,100		
Stress at 1 percent strain		1,500	1,200
0.2 percent offset yield stress		1,600	1,200
Modulus x 10^{-4}		15.0	12.0
Flexural properties, psi			
Modulus x 10^{-5}			1.70
0.2 percent offset yield stress			1,375
Compressive creep, percent			
78°F and 2,000 psi for 24 hours			
Initial		2.9	4.8
Retained or permanent		0.4	2.1
122°F and 2,000 psi for 85 hours	2.9		
500°F and 600 psi for 24 hours			
Initial		2.6	10.8
Retained or permanent		1.8	7.1
Impact strength, ft lbs/in.	2.01		
Hardness, shore D	60-70	66	66
Coefficient of thermal expansion 10^{-5} in./in./°F	3.6		
75° to 200°F		4.7	4.0
200° to 300°F		5.2	4.3
300° to 400°F		5.9	4.7
400° to 500°F		7.5	5.4
Limiting PV factor	5,000-10,000		
10 FPM		15,000	
100 FPM		15,000	
1000 FPM		12,000	
Wear Factor, K, $10^{-10} \left(\frac{in.^3 - min}{lb - ft - hr}\right)$		6	
Coefficient of friction			
Static 33.3 psi	0.15	0.11	
Dynamic 33.3 psi, 150 fpm			

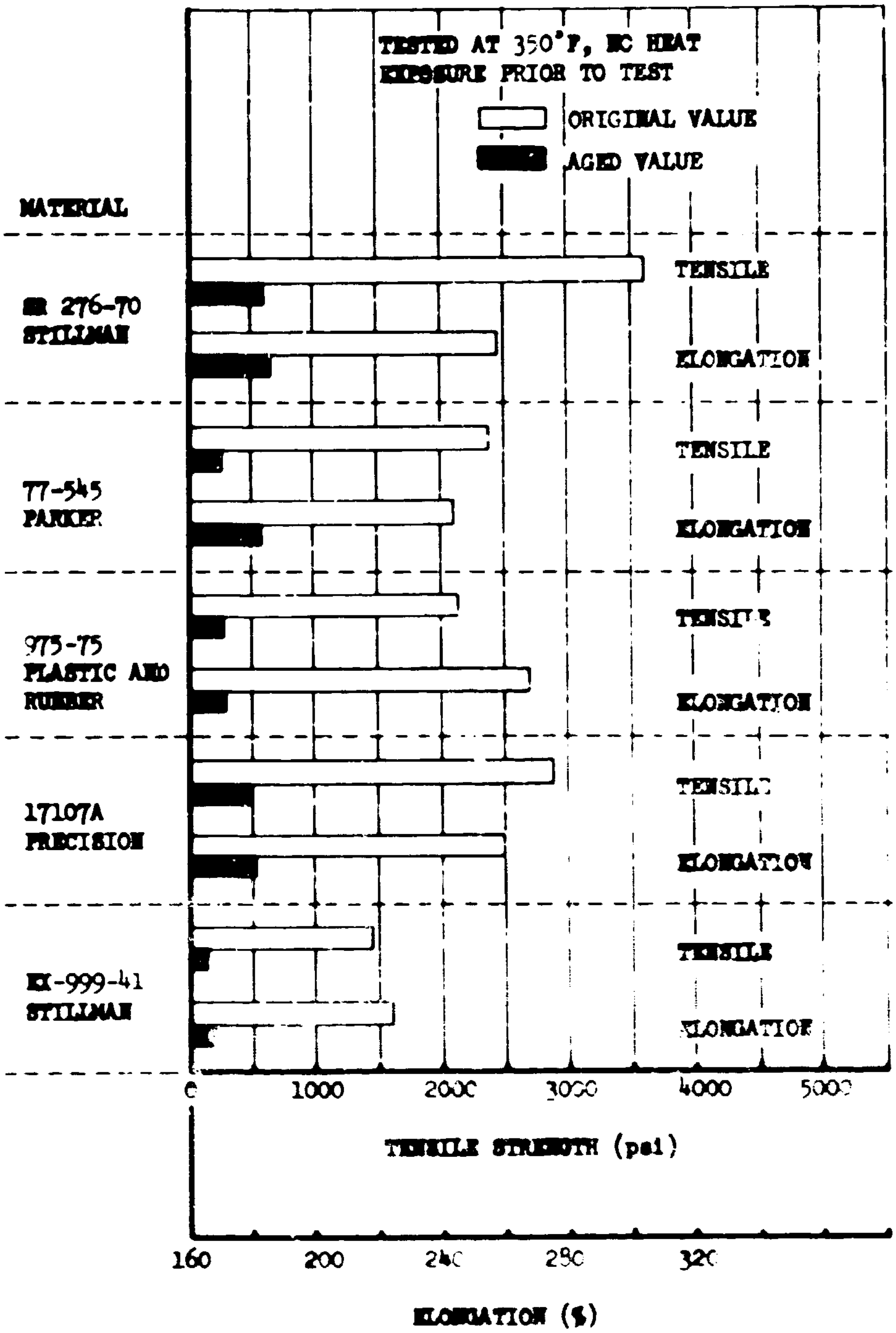

Figure 3-56. Tensile Properties of Viton Seal Materials, 350°F

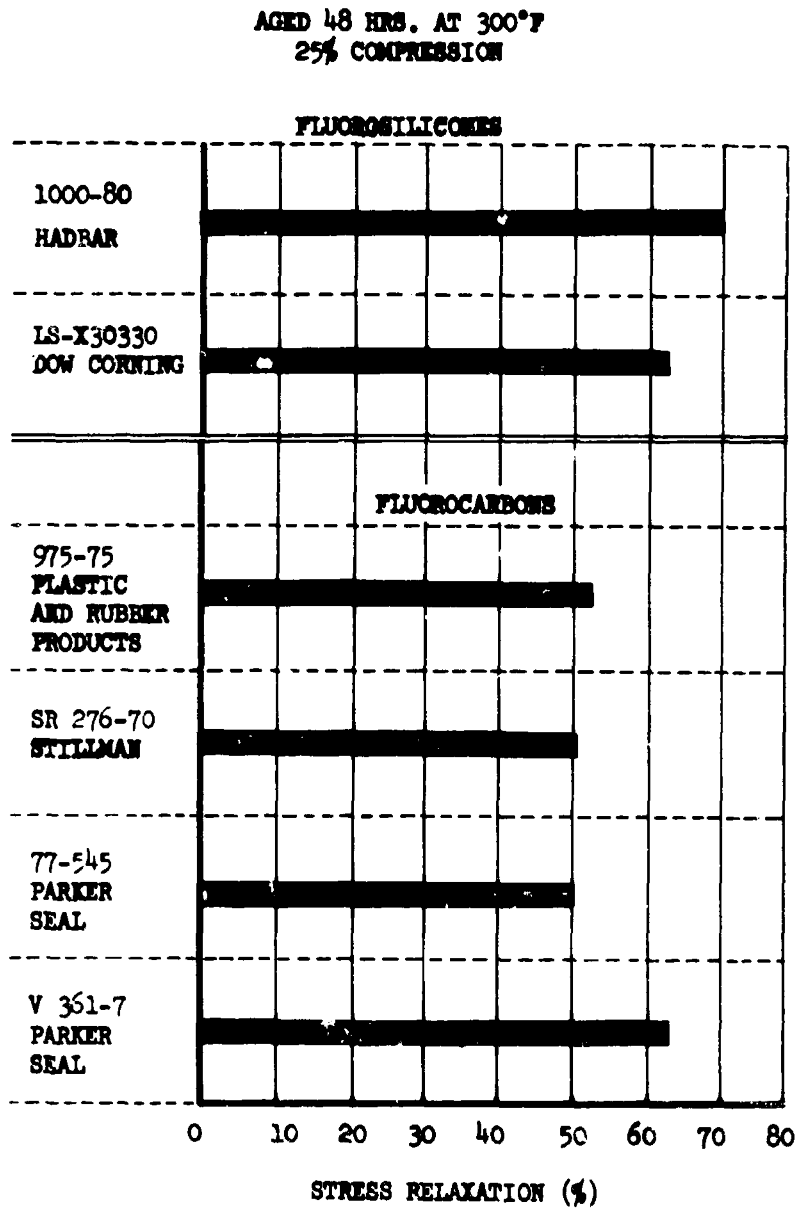

Figure 3-57. Stress Relaxation, Fluorocarbon (Viton) and Fluorosilicones

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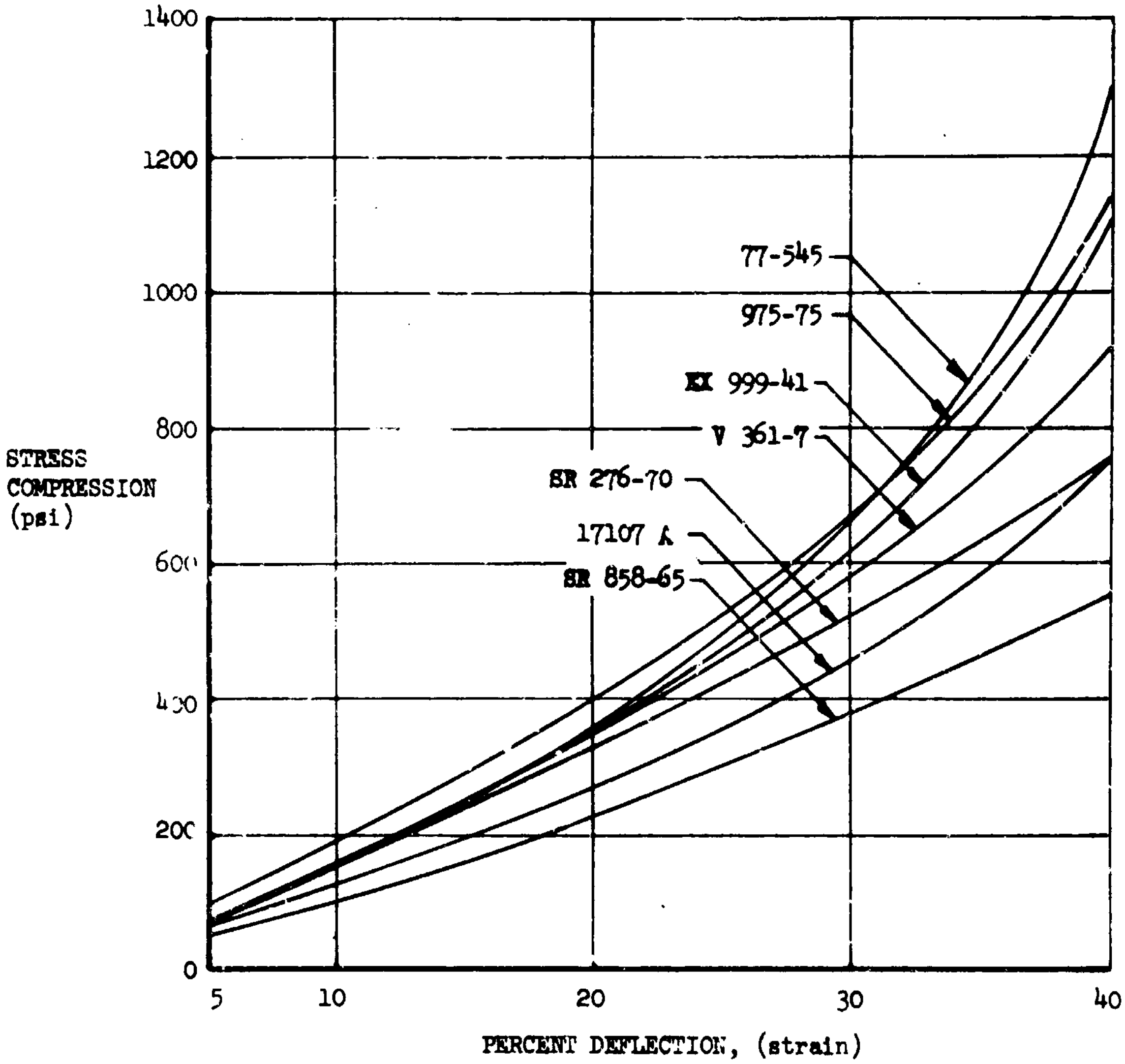

Figure 3-58. Compression-Deflection Properties, Vitons

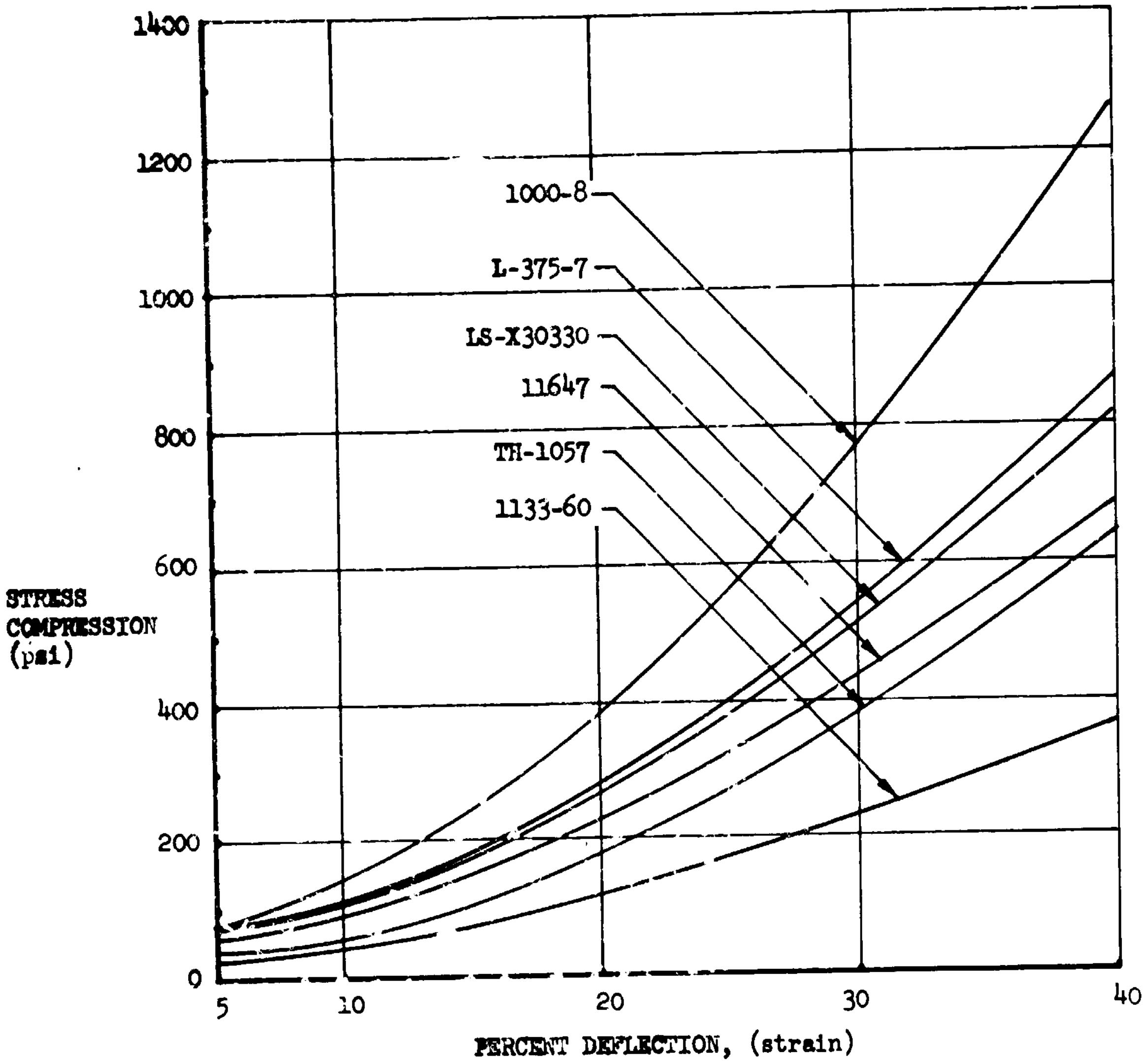

Figure 3-59. Compression-Deflection Properties, Fluorosilicones

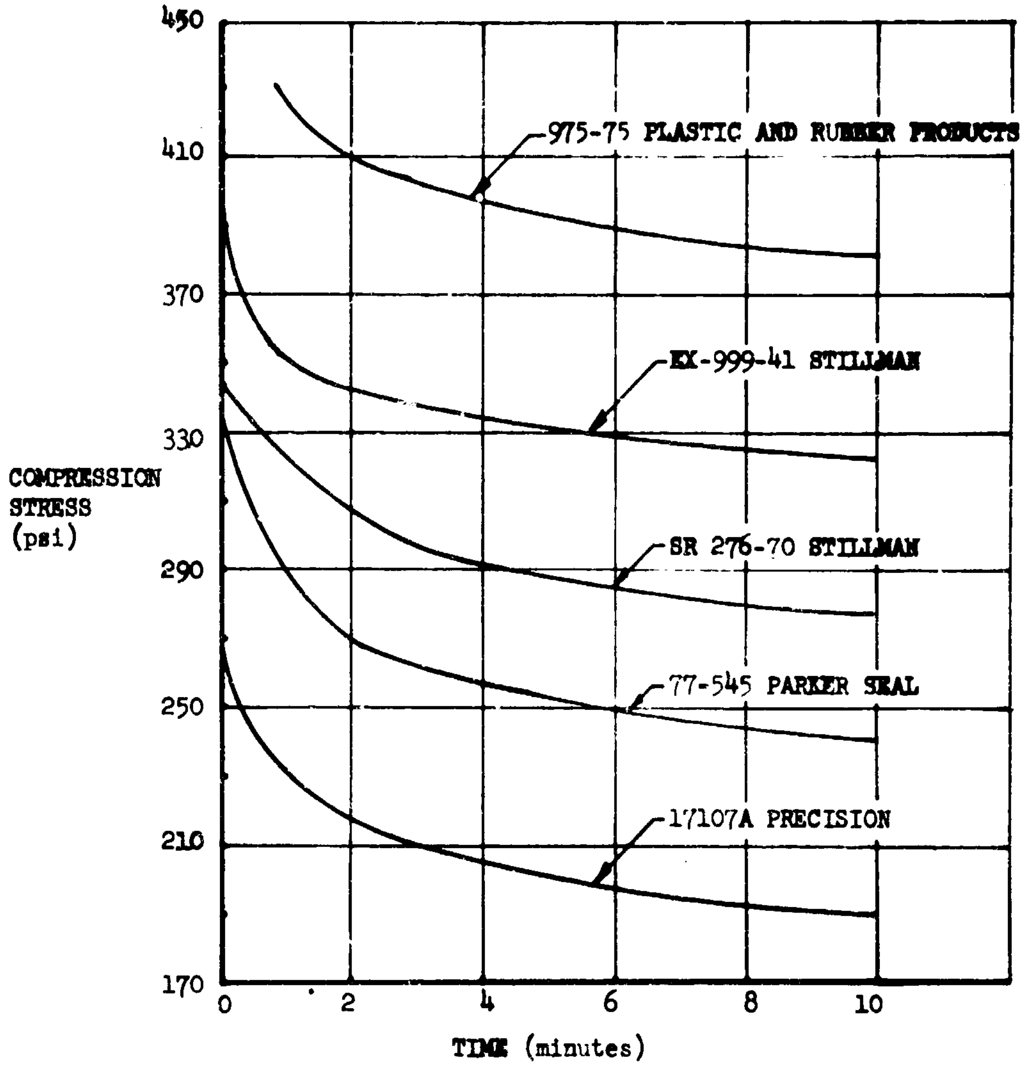

Figure 3-60. Room Temperature Creep, Vitons

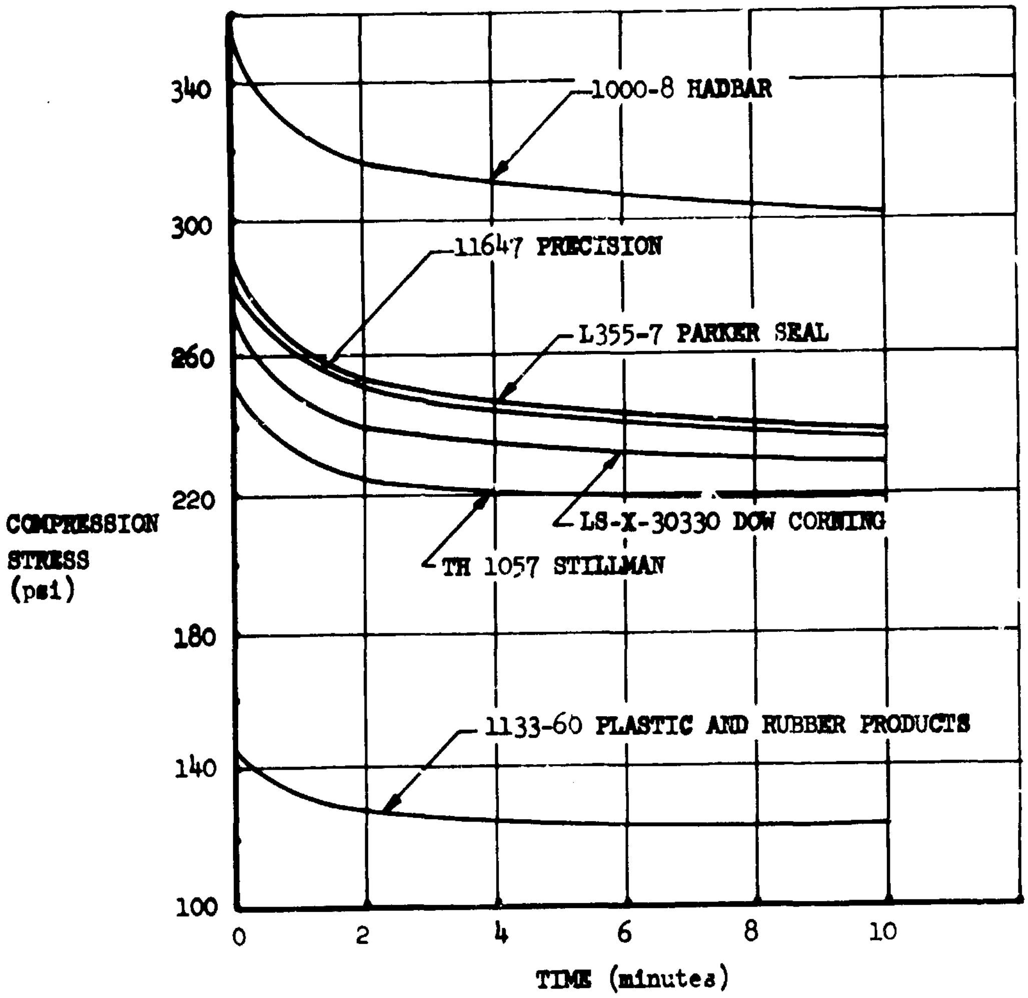

Figure 3-61. Room Temperature Creep, Fluorosilicones

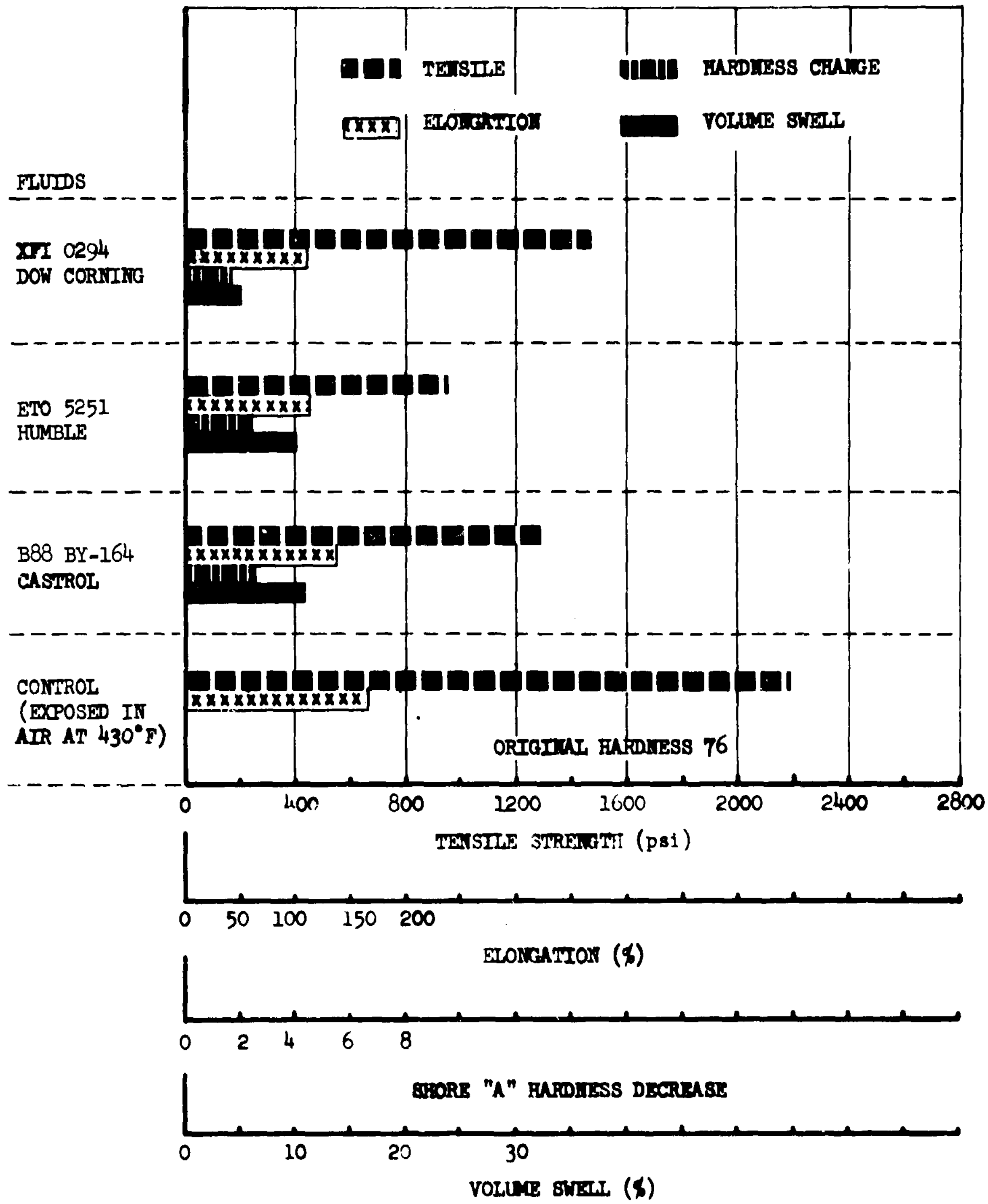

Figure 3-62. Fluorocarbon (Stillman SR-276-70) Compound Compatibility (7 Days in Fluid at 430° F)

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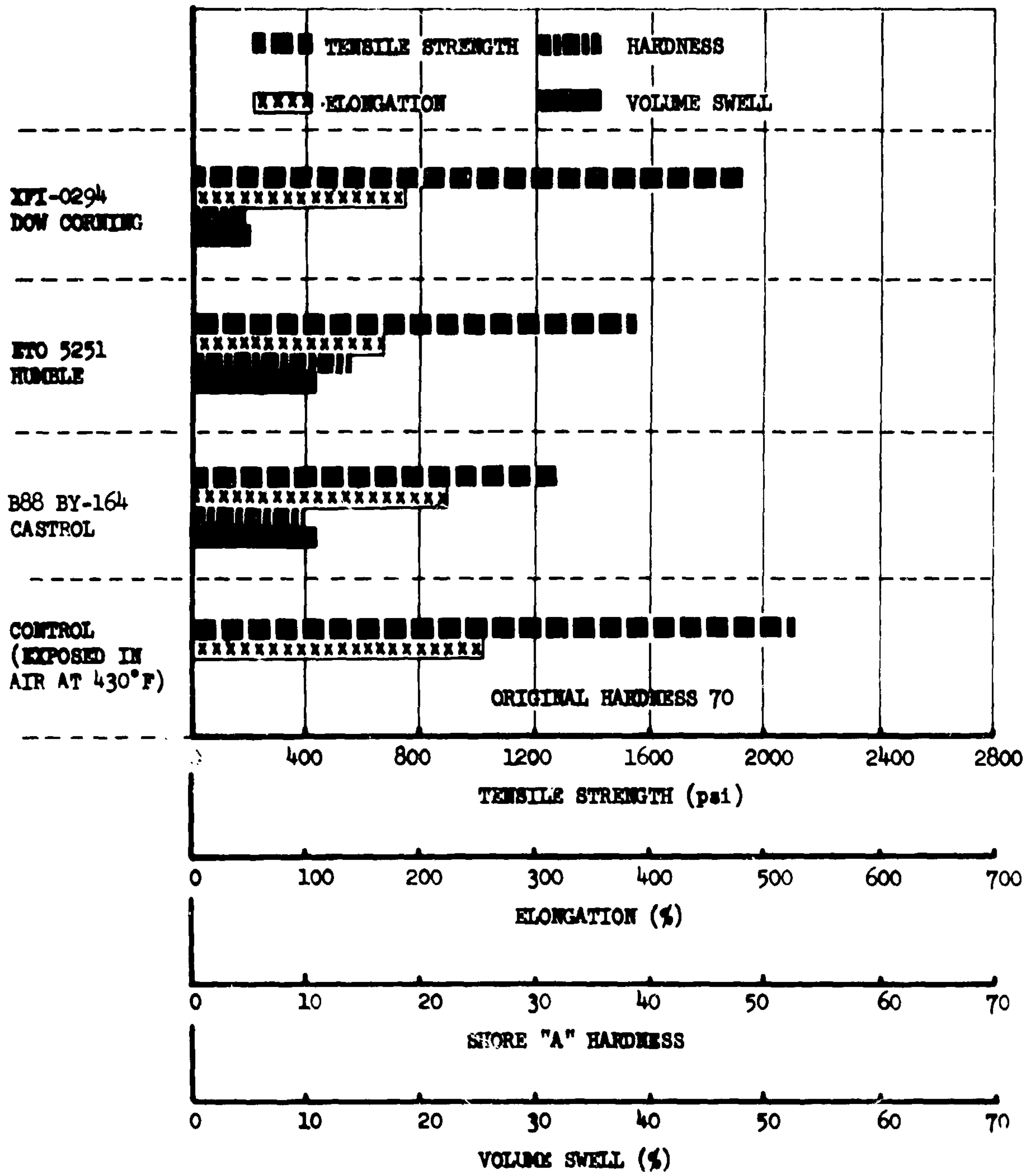

Figure 3-63. Fluorocarbon (Parker 77-545, Viton) Compound Compatibility (7 Days in Fluid at 430° F)

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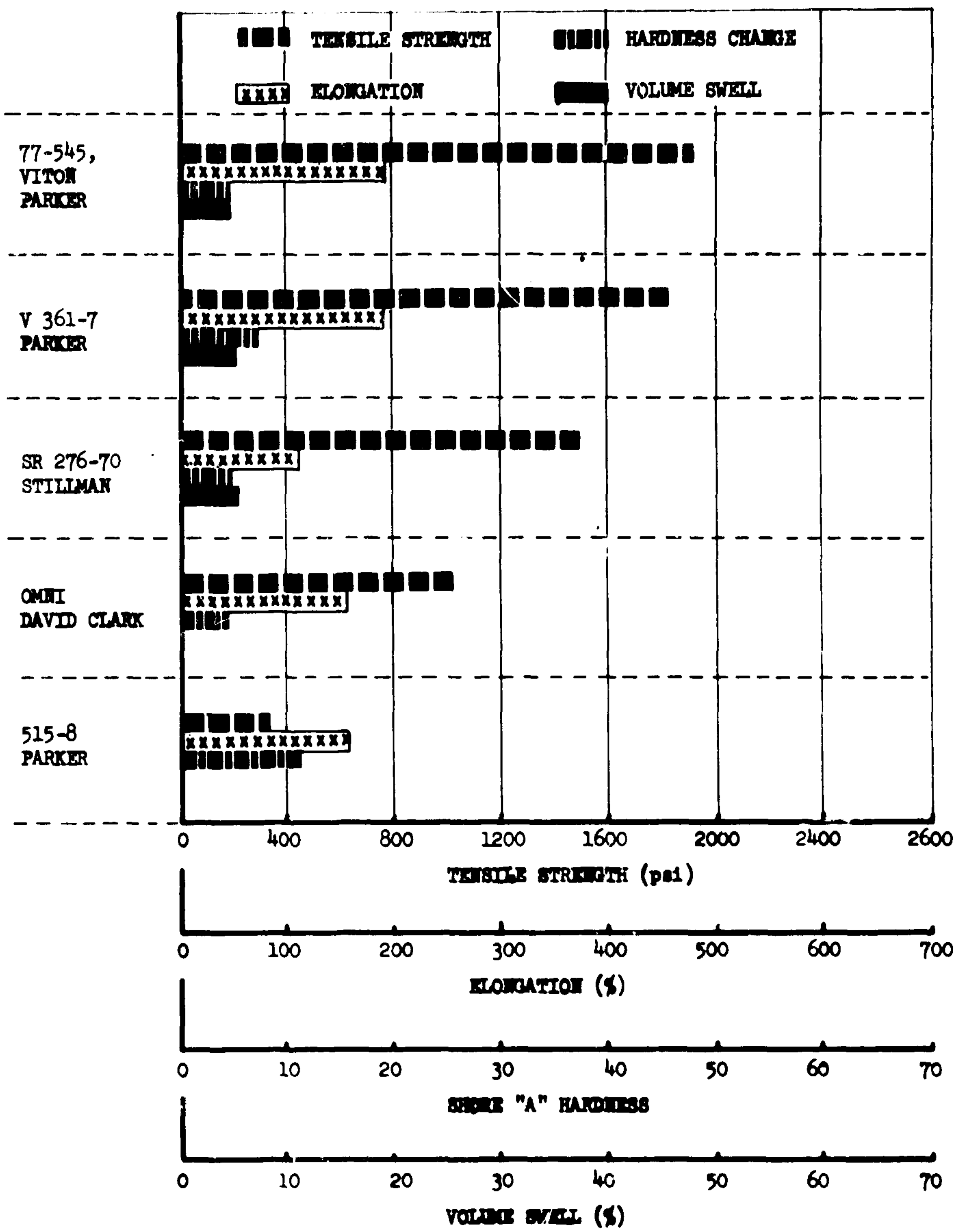

Figure 3-64. Fluorocarbon Compounds in XF1-0294 Hydraulic Fluid (7 Days at 430° F)

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Table 3-Q. Actuator Seal Test Performance Data

Application	Seal Material	Test Hours	Long Stroke Cycles	Short Stroke Cycles	Comments
Static Primary seal	Viton "A" O-rings (Parker 77-545)	426	--	--	Satisfactory performance
Backup rings	25% Glass filled Teflon (TFE)	280	--	--	Satisfactory performance
Dynamic Piston Seal	K6E Cast iron step cut ring	426	97,400	6,347,000	Satisfactory performance. Considerable wear life left.
Rod seal 1st stage	K6E Cast iron step cut ring	426	97,400	6,347,000	Satisfactory performance. Very low leak-age.
2nd stage	15% Graphite filled Teflon (TFE) Foot-seal with Viton "A" loading O-ring	427	97,400	6,347,000	Satisfactory performance
	15% Graphite filled Teflon DynaBak with Viton "A" O-ring	182	47,400	2,412,000	Satisfactory performance

Test Conditions:
Temperature: 400° to 475° F
Pressure: 3000 psi

Filled polyimides have exhibited considerable promise for dynamic seal applications. These materials are quite rigid but provide excellent thermal stability and should offer extended service life at system operating temperatures. Research on a material of this type (Polymer SP) was performed by the Republic Aviation Division of Fairchild Hiller under a NASA contract (NAS 3-7264 Ref. 27). Graphite is the most common filler, but others could be incorporated as required to improve friction characteristics.

Other composites based on a Teflon (TFE) matrix, with fillers such as bronze or carbon, are under investigation.

Materials presently being studied for possible static seal applications include the meta-carborane based polysiloxanes. Recently developed poly m carboranylenesiloxane polymers display elastom eric properties over the temperature range of -80° to 800°F. These experimental polymers are available only in very limited quantities at the present time. However, small samples are being evaluated for compatibility with hydraulic system fluids at elevated temperatures. Other experimental elastomers will be investigated as their development progresses and samples become available for evaluation.

3.7 LUBRICANTS

Performance analysis and selection of lubricants is based primarily on wear life evaluation of the lubricant at temperatures and loads anticipated in specific applications. Friction coefficient, load carrying capability, and thermal stability are also considered. In addition, compatibility and corrosivity of the candidate lubricants with system materials are established.

Typical applications where oils, greases, and solid lubricating materials may be used include plain bearings, rolling element bearings, gears, pulleys, cables, variable diameter engine centerbodies, variable geometry nose sections, wing hinge faying surfaces, access doors, fasteners, pin or hinge joints, and overlapping wing control surfaces such as flaps, slats, spoilers, elevons, and ailerons.

Many of the lubricant applications for the B-2707 have temperature and load requirements consistent with the requirements of commercial jet powered airplanes. In these applications, oils, greases, and solid lubricants qualified to military and company specifications are employed. Lubricants for the new high temperature environments of the B-2707 have been evaluated and selected.

3.7.1 Greases

The use of conventional airplane lubricants qualified to military specifications will satisfy the temperature requirements for many bearing lubricant applications. Greases qualified under Military Specification MIL-G-23827 are general purpose greases with a service temperature range of -65° to 250° F These greases contain an extreme pressure additive and are used in antifriction bearings, instruments, gears, and actuator screws. Grease conforming to Military Specification MIL-G-25760 is used in temperature environments of -65° to 350° F for the lubrication of antifriction bearings. Conventional grease lubricants are used for control pulley bearings, fair leads, control stands, and other bearing applications.

High temperature resistant greases are used to lubricate ball, roller, and plain bearings operating through a temperature range of -65° to 450° F They have the ability to lubricate modified 440C stainless steel bearing materials at high unit loads under conditions of oscillating or rotating motions. In addition, lubricants provide corrosion and oxidation resistance, are compatible with surrounding structure, have a low evaporation rate, and are water resistant. Bearings requiring high temperature resistant grease are located on control surfaces, flaps, flap tracks, spoilers, and leading edge wing slats.

The preliminary evaluation of 33 candidate lubricants recommended for high temperature bearing applications indicates the following four chemical classifications of greases are superior on the basis of minimum wear and low coefficients of friction on 440C stainless steel at 400° F.

	Grease	Fluid	Thickener
1.	Marlin Rockwell EG 551	High molecular weight hydrocarbon	Organic
2.	Dow Corning E4 3025	Fluorosilicone	Arylurea
3.	Du Pont PR 240AC	Fluorocarbon	Telomer dispersion
4.	McGee Chemical McLube 1195	Polyalkaline glycol	Contains MoS_2

Figure 3-65 presents the load carrying capacities of these four types which have been selected for bearing tests.

Oscillating bearing tests on an AN200K5ST shielded bearing at 450° F with 1,405-lb radial load at ±30 degrees oscillating and 20 cpm have been run. The bearing with the Marlin Rockwell EG 551 grease ran for a total of 100,700 cycles (75 hours). Failure was caused by bleeding and thermal decomposition of the hydrocarbon fluid in the grease resulting in excessive torque and scoring of the balls and races in the bearing.

The other three materials are being similarly tested.

3.7.2 Self Lubricating Materials

Areas exist where relative movement of contacting surfaces occur and long intervals between relubrication is a requirement. Self-lubricating rub strip materials are used in these applications.

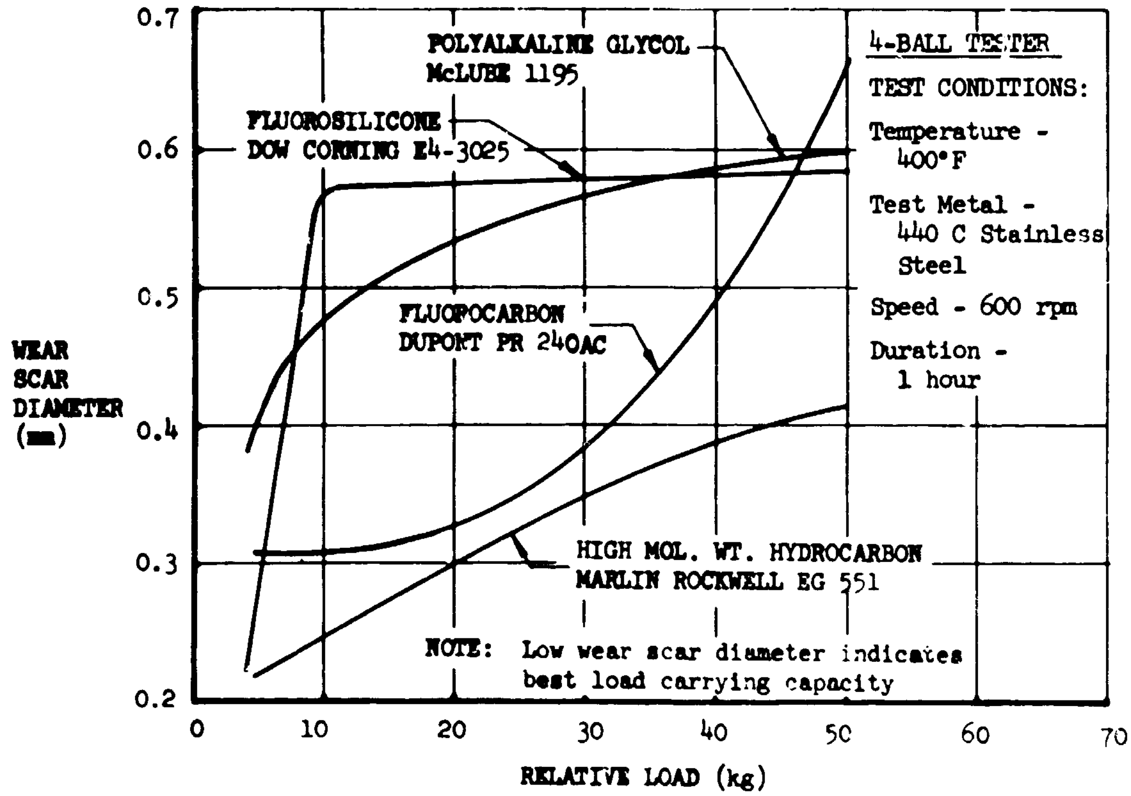

Figure 3-65. Relative Load Carrying Capacity of Synthetic Greases

a. Boeing Developed Solid Lubricant Compacts

Lubricant compact materials have been developed that are capable of providing low friction and wear resistance when in contact with metal surfaces at temperatures from -65° to 700°F under loads to 10,000 psi. Original development by The Boeing Company was done in 1961-62 under Air Force Contract AF33(616)-7395 (Ref. 28). Development of Design Criteria of a Dry Film Lubricated Bearing System. Additional work has been done by subcontract for Midwest Research Institute under Air Force Contract AF33(657)-10384 Task Number 30404 (Ref. 29)

Boeing lubricant compacts provide superior wear resistance, especially through the 450° to 650°F temperature range, over reinforced tetrafluoroethylenes and are considered to represent a major break through in self lubricating materials. They are used in applications where flexing and impact resistance is not a major consideration. Physical, mechanical, lubricity, and material compatability properties of the compact materials selected are shown in Table 3-R. Figure 3-66 illustrates typical part configurations and uses in which Boeing solid lubricant compact materials have been successfully applied.

Table 3-R. Properties of Boeing Developed Lubricant Compacts

Property	Compact Designation			
	108	108-67	108-67-75	?46-40
Physical Properties				
Density, Gm/cc	5.40	5.54	6.13	5.5
Coefficient of Thermal Exp. (0° to 1,800°F) in/in/°F	5×10^{-6}	5×10^{-6}	5×10^{-6}	5×10^{-6}
Max. Operating Temp. in Nonoxidizing Atmosphere				
Inert gas or vacuum	1,500°F	2,000°F	2,500°F	2,500°F
In air	700°F	700°F	700°F	700°F
Mechanical Properties (RT.)				
Flexural Strength, psi	9,000	13,000	16,375	28,000
Compressive Strength, psi	14,000	22,000	36,800	112,000
Friction & Wear				
Max. Surface Speed, ft/min	15,000	12,000	12,000	2,900
Max. PV (pressure in psi x velocity ft/min [1]	4,000,000	4,000,000	4,000,000	4,000,000
Friction Coefficient in air and in vacuum	0.02 to 0.3	0.02 to 0.3	0.02 to 0.3	0.02 to 0.3
Wear Rate in/hr in air at 2,900 ft/min (PV = 3,000,000)	0.0175	0.0020	0.0002	
Wear Rate (in/3) - reciprocating at 450°F				
at 200 psi	---	3.7×10^{-7}	---	---
at 10,000 psi	---	---	---	5×10^{-7}

Material Compatibility - No corrosion evident after 30 day exposure to water, salt spray, MIL-D-5251 oil, Versilube F-50, Freon E3, Conc. HCl, & Conc H_2SO_4.
- Dissolved in two day exposure to conc. HNO_3.
- No stress corrosion at 550°F when rubbed on titanium surfaces (see Section 3.8.1).

[1] Temperature stabilized and no galling evident at 12,000 ft/min.

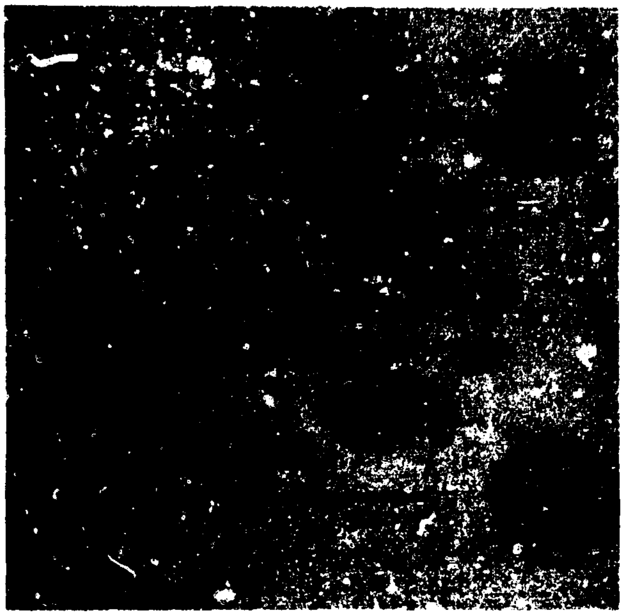

Figure 3-66. Typical Application of Boeing Lubricant Compacts

Composition and sintering temperature and pressures of these compact materials can be adjusted to produce different strengths and other desired properties to meet requirements of specific applications. For example, lubricant compact number 108-67 has been developed for use as moveable seals rubbing against titanium in the engine inlet centerbody where loads are approximately 200 psi and temperatures to 620°F are expected. Friction and wear tests simulating the engine centerbody application have been conducted. Wear of this material was less than 0.012 in. after 1,400,000 cycles (46,000 ft total travel) at temperatures of 535°F and 620°F. Maximum wear allowed is 0.030 in. No galling or scoring of the titanium mating surface occurred in these tests and the friction coefficient was 0.15 to 0.20. Wear resistant properties of this material and a filled Teflon rub strip material (Rulon LD), subsequently discussed are shown in Fig. 3-67. Rulon LD may be used in areas where flexure and impact resistance is required.

Table 3-R shows properties of other compact materials with higher strengths which can be used for journal bearing liners and track sliders where optimum life is required at temperatures between -65° and 700°F.

b. Teflon Fiberglass Reinforced Cloth
At temperatures below 400°F, exceptional wear life of plain and spherical bearings is obtained using liners made of Teflon fiberglass reinforced cloth adhesively bonded to the races. The friction coefficient of this Teflon material ranges from 0.02 to 0.10 depending on the load. Additional information covering wear life and load limitations are presented in Sec. 4.2.

c. Filled Teflon Materials
Self lubricating materials such as Dixon Corporation Rulon LD and bronze or glass filled Teflons are used in faying surfaces such as flaps, slats, and ailerons where titanium or steel are in contact under light loads. Reciprocating tests have been conducted on Rulon LD at temperatures of 335° and 400°F to determine the friction coefficient and wear rate properties. Coefficient of friction ranged from 0.10 to 0.25 at a 200 psi load and was less than 0.10 at a 1000 psi load. Average wear rates found for the Rulon LD were 0.12 x 10^{-5} in./ft of travel at the 200 psi load and 6 x 10^{-5} to 12 x 10^{-5} in./ft of travel at 1,000 psi loading. These values are based on dimensional measurements of the wear specimen before and after testing.

3.7.3 Solid Films
Solid lubricating materials are used in applications when relubrication is not possible or desired, dirt cannot be kept away from the lubricated area, or large exposed metal surfaces preclude the use of oils or greases.

a. Applications Below 250°F
Products qualified under a company solid film material specification and meeting requirements of Military Specification MIL-L-8937 are used in applications where they have been proven by commercial and military airplane experience. Room temperature evaluation of one of these lubricants applied to a steel alloy had a wear life in excess of 12,000 ft and a friction coefficient less than 0.10 at 10,000 psi load with no measureable wear.

b. Applications for Temperatures Between -65° and 700°F
A solid film lubricant coating with excellent friction and wear life properties at temperatures to 700°F was developed by North American Aviation. This lubricant, designated Vitro-Lube 1220, was developed for use on the XB-70 airplane under Air Force Contract AF33(600)-42058 (Ref. 30). It consists of molybdenum disulphide, graphite, and silver powders dispersed in a glass frit. Bonding is achieved in one minute when the part to which it is applied is raised to a temperature

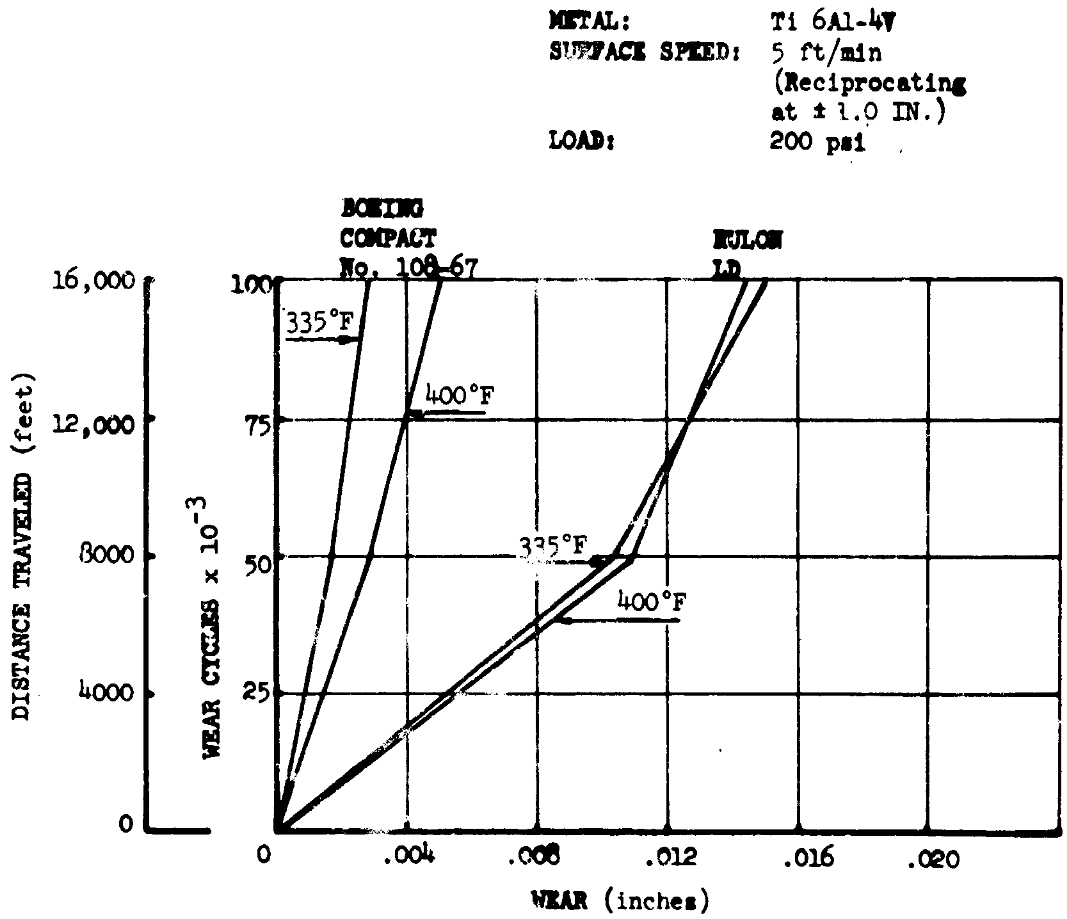

Figure 3-67. Wear Rate of Boeing Compact and Rulon LD

of 975°F. This material is commercially available from National Process Industries.

The Boeing Company has made extensive evaluations of the Vitro-Lube 1220 lubricant coating. It is used for prevention of galling and fretting of metal-to-metal interfaces in the temperature range from -65° to 700°F. This choice is made for the following reasons.

- Wear life is superior (lowest wear rate) to 23 other commercially available solid film lubricants which were evaluated at 450°F with applied loads of 200 and 10,000 psi. Figures 3-68 and 3-69 show a comparison of some of the materials tested.
- Coefficient of friction of Vitro-Lube 1220 at 450°F is less than 0.30 under a load of 200 psi and less than 0.10 under 10,000 psi load.
- Vitro-Lube 1220 has been used successfully for XB-70 applications.
- The Vitro-Lube 1220 coating has received extensive evaluation by North American Aviation to determine the effects of batch variations, process variations, corrosive atmospheres, curing in nonoxidizing atmosphere, coating of one versus two surfaces, cure temperature, coating thickness, substrate material, bearing clearance, fluid contamination, cure time, and spray versus dip applications.
- Repeatable results have been obtained in The Boeing Company evaluation.
- Compatibility of the Vitro Lube 1220 coating with titanium alloys has been found to be acceptable at 450°F (see Par. 3.8.1).

When the effects of the 975°F cure temperature cannot be tolerated or wear life of the lubricant is not a critical factor, Everlube 811 (a sodium silicate bonded MoS_2-graphite solid lubricant

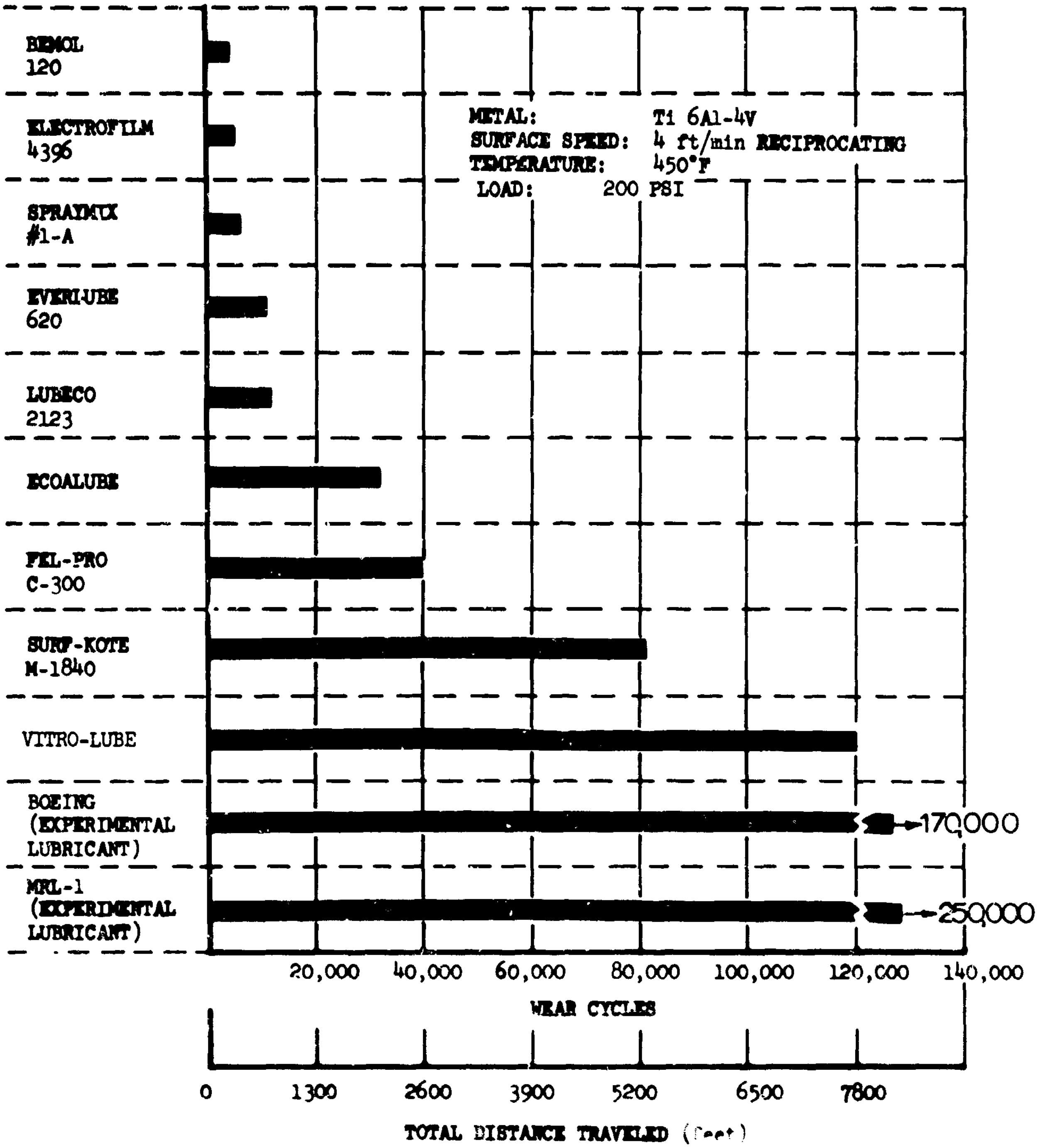

Figure 3-68. Relative Wear of Solid Film Lubricants, 200 psi

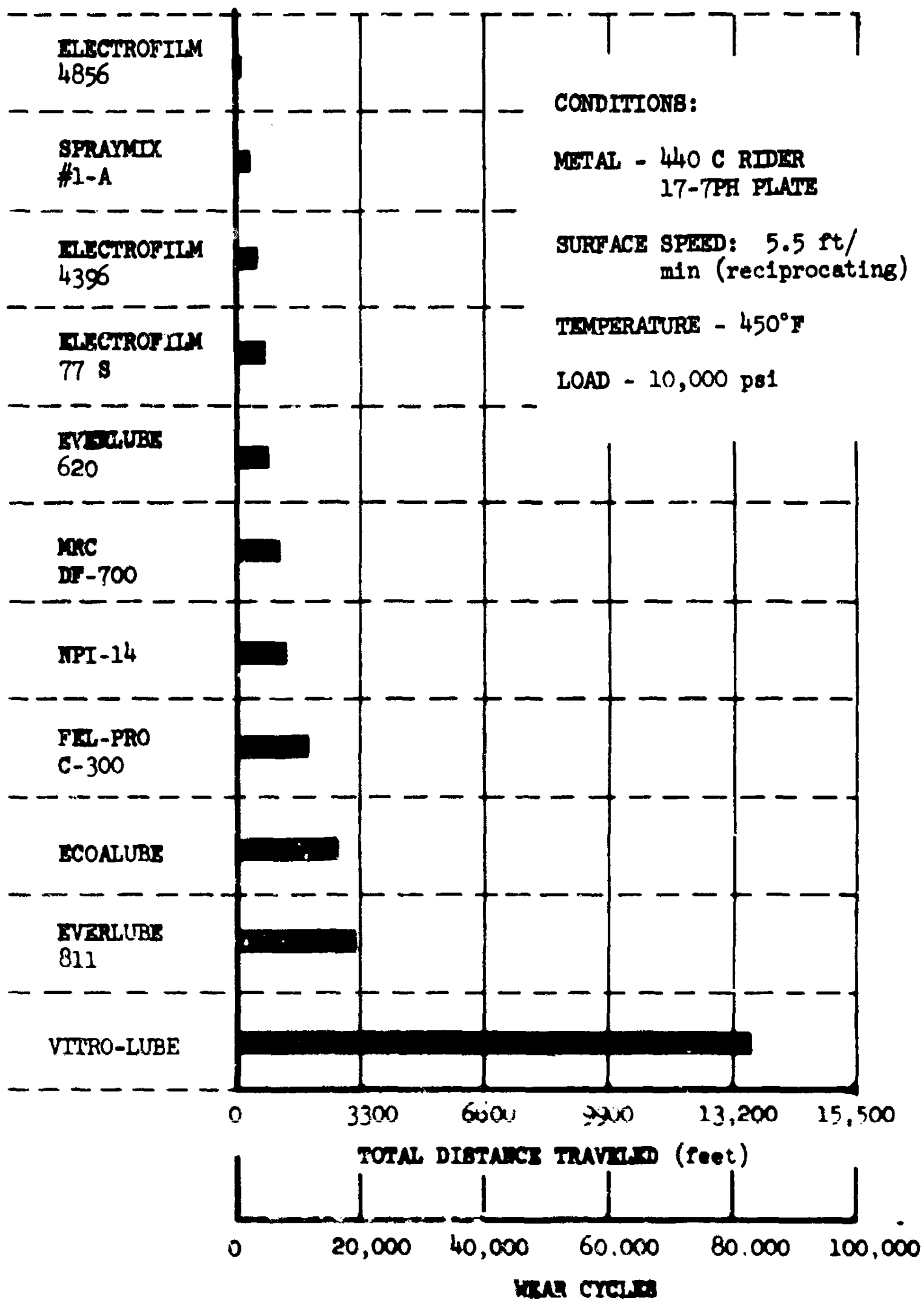

Figure 3-69. Relative Wear of Solid Film Lubricants, 10,000 psi

V2-B2707-8

coating) is used. This use is based on reproducibility of test results and wear life determinations as shown in Fig. 3-69.

Figure 3-68 indicates that a developmental coating designated MRL-1 and a Boeing experimental lubricant utilizing a polyimide resin binder have exceptional wear lives at 450°F and 200 psi load. These coatings are still in experimental stages and will be further evaluated.

c. Applications for -65° to 1200°F
Solid lubricating pigments such as lead monoxide and graphite will be used in lubricating films for applications where temperatures exceed 700°F on engine mounts and thrust reversers. These materials exhibit good lubricity to 1200°F. Lubeco 2023, Fel-Pro C-300, Electrofilm 1000, and Sermetel (Type 11) are solid films containing these lubricating pigments dispersed in high temperature stable inorganic binders and are used where environmental temperatures exceed 700°F.

d. Applications for Fasteners
Solid film lubricants such as Lubeco 2123 and Fel-Pro C-300 are used on fasteners to facilitate installation in interference fit holes and as thread lubricants. It has been demonstrated that fasteners coated with these lubricants can be installed into holes with interferences as great as 0.006 inches. Installation forces for interference fits are shown in Fig. 3-70. Section 4.1 covers additional details concerning the use of solid film lubricants in fastener applications.

3.7.4 Oils

Neopentyl polyolester oil with additives is used for lubricating mechanical systems such as accessory drives, gear boxes, actuators, generators, and compressors. This oil is readily available and is procured in accordance with Military Specification MIL-L-23699. It is presently used in applications such as turbojets, turboprops, and turboshaft engines for commercial and military airplanes. Neopentyl polyolester oil has superior oxidation resistance, thermal stability, bearing and gear load capacity, and low volatility in the temperature range of -65° to 400°F.

3.8 CORROSION AND DETERIORATION PREVENTION AND CONTROL

The prevention of corrosion and material deterioration is a very important consideration in the design, production, and maintenance of airplane structures. Proper investigation, analysis, and control will be implemented during development, design, and manufacturing to assure satisfactory service life for the B-2707. As a result of extensive testing and in-service subsonic experience, The Boeing Company will provide effective preventive measures against corrosion and other deterioration processes.

These measures consider all forms of corrosion mechanisms as well as other deteriorating reactions such as thermal degradation, reduced pressure, ultraviolet radiation, wear, erosion, scratches, dents, abrasion, and electrical damage. Controls are being established that will ensure compatibility of airplane materials with each other as well as with:

a. Manufacturing materials such as forming lubricants.

b. Service environment including deicing and snow removal aids.

c. Maintenance materials such as cleaning fluids.

Surface treatments, plating systems, special systems for such items as erosion protection and elimination of static charges, and paint systems have been developed and their use is controlled by Document D6A10072-1, Protective Finishes, Detailed Requirements for Model B-2707.

3.8.1 Materials Compatibility

The factors causing corrosion and deterioration of commonly used structural airplane materials as well as their interaction with other materials, are well understood from long experience with subsonic airplanes. The effective methods used on current airplanes to control these problems will be applied to the B-2707.

The transition from conventional structural materials to titanium alloys requires special attention. Very little information exists concerning interaction of titanium with other materials under anticipated environmental conditions. The position of titanium in the electromotive series (Table 3-S) establishes that titanium is a relatively noble metal when passivated, but when activated it becomes anodic to most of the commonly used airplane metals. A passive condition is dependent on the compatibility with the environment and with the other materials. All materials, metals and nonmetals, that are anticipated to come in contact with titanium are being environmentally tested and this program will continue.

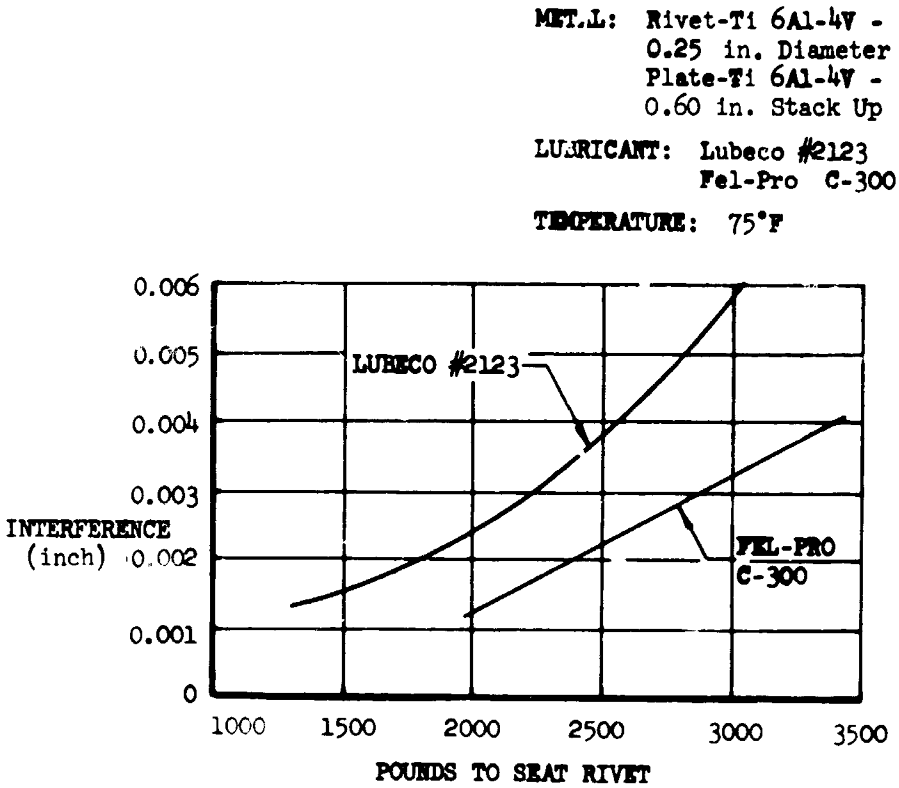

Figure 3-70. Installation Forces for Lubricated Fasteners

The test procedures selected include a bend test as a screening procedure for identifying the problem materials. It is very sensitive to surface embrittlement and discontinuities. This is a modification of the test described by G. J. Heimerl and D. N. Braski (Ref. 31). The bend test requires stressing in the plastic region and thus does not relate directly to airplane structures. More sophisticated test procedures are necessary to quantitatively evaluate the problem areas in each material system.

A tension-tension fatigue test is used to quantitatively evaluate surface embrittlement. The center section of the fatigue specimen is coated with the material in question and exposed to that environment which caused the surface embrittlement detected by the bend test. After exposure, the specimens are fatigue tested at room temperature to determine fatigue life compared to control specimens.

A precracked Charpy specimen, under sustained load conditions, is used to evaluate the effect of liquid or soluble decomposition products on the crack propogation rate. The fatigue cracked specimen is immersed in the solution under a sustained load until failure occurs. The stress required to produce failure in six hours is compared with that for control specimens tested in distilled water and in 3.5 percent salt solution. This test is similar to those used for materials selection as discussed in Sec. 2.1.

Results of the materials compatibility program to date are presented in Table 3-T.

3.8.2 Paints

a. Exterior Coatings

Silicone based paints have been established for use on exterior surfaces. These paints are available in a variety of colors and extensive formulation information is available. High emittance and good decorative properties will be maintained through repeated flight and ground service exposures. Four manufacturers are qualified to supply material to The Boeing Company material specification.

Table 3-S. Electromotive Series

Magnesium	Lead
Magnesium-base alloys	Tin
Titanium (active)	Nickel (active)
Aluminum (active)	Inconel 600 (active)
Zinc	Chromium and martensitic stainless steels (passive)
Chromium (active)	Yellow brass
Galvanized steel	Copper
Aluminum	70-30 Cupronickel
Aluminum-base alloys (5000 series)	Inconel 600 (passive)
Cadmium	Nickel (passive)
Aluminum-base alloys (2000 series)	Titanium (passive)
Mild steel	Monel
Wrought iron	Austenitic stainless steels (passive)
Cast iron	Silver
Austenitic stainless steels (active)	Gold

The selection, based on screening tests of 31 vendor supplied paints established a clear superiority for silicone based paints. Properties determined in these tests included:

- Resistance to system fluids
- Adhesion after heat and water exposure
- Emittance as cured
- Emittance after heat and water exposure
- Elevated temperature hardness as cured
- Elevated temperature hardness after heat exposure
- Appearance
- Ease of application and cure temperatures

The results showed silicones with the highest ratings, an epoxy with the next highest rating, and urethanes and polyimides with the lowest ratings. In addition to superior performance in the screening study, silicones have advantages in availability and color retention, and they cure without baking.

Screening study properties of the top ranked paints are listed in Table 3-U.

The air dry silicone paints qualified for use will be applied by air spraying and cured by conventional means. A satisfactory cure is obtained in seven days of room temperature exposure, or cure may be accelerated by use of heat lamps.

Cleaning of the silicone paints, in difficult areas such as wheel wells, will be easier than cleaning of currently used airplane paints. Fluorocarbon coatings (Teflon) will be used in any areas presenting particularly difficult cleaning problems.

High temperature coating materials are available to perform the coating functions required on exterior surfaces subject to temperatures above 450°F such as leading edges, nose, and engine areas. The coating materials shown in Table 3-V (Refs. 32, 33, 34, and 35) will be used for these applications.

b. Interior Paint

The interior paints selected for various service requirements are shown in Table 3-W. Paints for use at temperatures up to 150°F are used on current airplanes and are readily available. Their effectiveness has been well established in service. An exception is the substitution of polyurethane for vinyl chloride paints, because of the toxicity hazard of vinyl chloride in fires.

Table 3-T Compatibility of Titanium Alloys With Other Materials

Material in Contact with Stressed Titanium Sheet during Exposure ▷	Reduction in Bend Characteristic of Titanium Sheet after Exposure Cycles			
	NIL	SLIGHT (<10%)	SIGNIFICANT (10% - 25%)	DRASTIC (>25%)
Aerodynamic smoother				
CA9R	X			
RTV 1071		X		
RTV 1072		X		
Adhesive				
FXM 34B25A	X			
Air-strip Deicer				
K_3PO_4-$HCONH_2$	X			
Electroplated Steel				
Cadmium	X			
Chromium		750°F		
Copper		750°F		
Nickel		750°F		
Nickel-Cadmium	750°F		900°F	
Silver	600°F			750°F
Hydraulic Fluid				
Castrol	X			
ETO 5251	X			
XF 1-0294	X			
Insulation				
XA 5910		X		
Lubricant				
Compact (Ta + MoS_2)		550°F		
Lubeco 2123		X		
Vitro-lube		X		
Metals				
Aluminum	550°F	600°F		
Paints and Primers				
DC 808	X			
Midland 9 x 414	X			
De Soto Super Koropon	X			
DCXP-7-1359		X		
DCXR-6-2165	X			
Plastics				
DuPont 2501		X		
Epon 957 (Teflon-glass)		X		
Monsanto Skygard 700		X		
Sealants				
AFML Viton		RT	212°F	450°F
EC 2332		X		
RTV 60		X		
RTV 106		X		
94-002		X		
94-023		X		
94-512		X		

▷ Exposure cycles unless otherwise noted are as follows.

1. 95 ksi, 168 hours at RT
2. 95 ksi, 72 hours in boiling water
3. 90 ksi, 168 hours at 450°F

Table 3-U. Properties of White Silicone Paints

Paint	Bend Adhesion [4]			Total Normal Emittance		Pencil Hardness			
	[1]	[2]	[3]	[1]	[3]	RT [1]	450°F [1]	RT [3]	450°F [3]
Midland 84-410	2	0	0	0.75	0.74	3B	6B	4H	2B
Rinshed-Mason Q36W809	0	0	0.9	0.80	0.80	2H	2B	4H	HB
Dow Corning DC XP-7-1359	0	0	0.5	0.79	0.79	2B	6B	H	HB
Markal SR-4	0	0	0	0.76	0.76	B	6B	3H	2B

Condition:

[1] As sprayed and cured

[2] Immersed in water for 168 hours

[3] Exposed at 450°F and 30 torr for 168 hours

[4] The numbers in each column indicate inches of paint adhesion failure as measured from the smallest bend radius on an ASTM conical mandrel, 0 indicates optimum adhesion

Table 3-V. Extreme High Temperature Resistant Finishes

Paint Type	Maximum Service Temperature	Function	Application Method	Data and/or Reference
Aluminized Polyimide	1,000°F	Abrasion protection corrosion protection and decoration	Conventional spraying	(1) A pencil hardness above 5H is maintained by polyimide coatings (2) Ref. 32
Silicate	500°F	Thermal control corrosion protection and decoration	Conventional spraying	Ref. 33
Rokide A	3,600°F	Thermal control and decoration	Flame spraying	Ref. 34
Aluminized Silicone	1,200°F	Decoration and corrosion protection	Conventional spraying	Paint practice based on service exposures Ref. 35

Table 3-W. Interior Paints

Function	Service Temperature -65°F to 150°F	-65°F to 300°F	-65°F to 400°F
General Corrosion Protection	Epoxy - chromate primer	Epoxy - chromate primer	Air dry silicone - chromate primer (suitable to 450°F)
Impact and abrasion protection	(1) Polyurethane Enamel (2) Vinylidene fluoride coating [1]	Silicone elastomer dispersion coating	(1) Silicone elastomer dispersion coating (2) Flurocarbon elastomer coating [2]
Chemical resistance	Epoxy enamel over epoxy chromate primer	Epoxy enamel over epoxy chromate primer	(No requirement for chemical resistance anticipated) [3]
General decoration	Acrylic - Nitrocellulose lacquer	Air dry silicone topcoat	Air dry silicone topcoat
Stress corrosion protection	Activated, metal rich primer - silicone based		

[1] Alternate material to be evaluated for impact, abrasion and fire resistance.

[2] Alternate material to be evaluated for impact and abrasion resistance.

[3] If need arises fluorocarbon paints will be used.

Satisfactory performance of paint during actual aircraft service is the most reliable criteria for paint selection. However, when paints must be selected to meet new requirements, considerable reliance can be placed on simulated environmental tests. These tests have shown good correlation with service history. Tests which Boeing specification materials must pass are listed below:

(1) All paint material

- Adhesion under water immersion
- Adhesion under condensing humidity
- Resistance to system and maintenance fluids, flamability and toxicity
- Resistance to South Florida exposure
- Adhesion and flexibility at -65°F

(2) Primers - Corrosion protection under salt spray.

(3) Elevated Temperature Resistant Paints

- Adhesion in boiling distilled water
- Resistance to hydraulic fluid at 350°F
- Resistance to Military Specification MIL-L-23699 Jet Engine Oil at 300°F

Interior paint materials will be applied and cured by conventional means. Application will be by air spraying, brushing, dipping, or flow coating. All interior paint materials are capable of obtaining full cure at room temperatures. Acceleration of cure by heating will be possible with all the selected elevated temperature resistant paints.

3.8.3 Plating
Model B-2707 presents the usual airplane requirements for corrosion resistance, anti-galling coatings, and bearing surfaces protection. In addition, the higher temperatures involved and the need for compatibility with titanium components require special consideration.

Combinations of materials which would be susceptible to electrochemical or galvanic attack will be avoided. Where this is not possible, sacrificial or barrier coatings will be applied to prevent corrosion. Plated coatings will also be used to prevent direct chemical attack, intergranular attack, and stress corrosion of critical components.

Platings which are used, their applications and limitations, are detailed in Boeing document D6A10072-1 (Ref. 36), Protective Finishes, Detailed Requirements for Model B-2707. As noted in this document, many of the platings are the same as those in use on current airplanes, because the requirements are the same. The increased temperatures of operation and the widespread use of titanium impose new requirements for plated coatings. Low alloy, high strength steels are plated with low embrittlement cadmium or cadmium-titanium alloy for corrosion protection provided they are not in contact with titanium. These coatings are used for components operating to a maximum of 350°F only, in order to avoid embrittlement and cadmium toxicity problems. At temperatures above 350°F, a special diffused cadmium nickel coating is applied, subject to the same restriction against titanium contact. Electroless and electrodeposited nickel are used where the plating must be compatible with titanium.

Special attention is given to hydrogen residuals of plated materials in contact with titanium and titanium alloys. It has been found that plated parts which have not been baked for hydrogen reduction lose their hydrogen to titanium metal in contact with them causing embrittlement of the titanium at elevated temperatures.

The plating of titanium and titanium alloys requires close control of processing parameters. The ability of these materials to rapidly passivate makes the production of adherent metal coatings difficult.

The activation method currently used is an anodic treatment in a bath composed of glacial acetic acid and hydrofluoric acid. This pretreatment has produced consistently high adhesion of nickel and copper coatings. Overlay plating of any desired material is then made to the initial coat by standard methods. Coatings produced on titanium by this method have been used successfully. An example of such usage was the titanium helium reservoirs on the Saturn booster. Adhesion of the coatings was found to be excellent. Gas residuals for the various steps in the pretreatment and plating processes were determined and found to be well below the limits established as damaging to titanium. Details of the project are available in Test Report T2-3350-1 (Ref. 37). Special processing will be employed for those titanium alloys which prove difficult to plate by normal methods. Specific cases are well covered by previous work in the field. McGargar, Pohl, Hyink, and Hanrahan (Ref. 38) report adhesion of electroless nickel suitable for gears on a number of alloys after a treatment involving vapor blast cleaning, alkaline electroless nickel, diffusion bake at 1550°F for four hours, and shot peening. The same process was employed by Levy and Romuld (Ref. 39) to produce coatings resistant to seizing and galling on army weapons. The post plating diffusion treatment must be compatible with the heat treatment of the alloy. Baking for

adhesion of nickel has reportedly been done at temperatures as low as 750°F for 15 minutes in an argon atmosphere. Diffusion layers of three to six mils are reported after diffusion at 1550°F (Ref. 40).
These latter processes are applicable to a wide variety of titanium alloys. The ability to produce an adherent coating by these methods permits application of almost any follow-on coating.

3.8.4 Surface Treatment
Surface preparation is a key factor for adhesion of structural adhesives and protective finishes, corrosion protection, and avoidance of galling. It is also a factor in welding and in appearance control of unpainted metal surfaces. Surface treatments for aluminum, steel, and magnesium are the same as those currently used and proven successful on commercial airplanes.

3.8.4.1 Titanium Surface Preparation for Bonding
The Pasa Jell 107 process has been selected for general prepaint preparation in view of its ease of application and controllability. The ability to either immerse large details or manually apply the treatment for prepaint preparation of assemblies or to complete airplanes is an added advantage.

Since Pasa Jell 107 has been selected as the surface preparation prior to adhesive bonding, many manufacturing problems are simplified because common cleaning and treatment facilities can be used. The treatment is compatible for sealing.

3.8.4.2 Titanium Coatings to Minimize Galling
The adverse galling properties of titanium are well known and lubricative coatings are required to minimize the problem where titanium surfaces rub against each other. The conversion coatings which minimize galling are Battelle phosphate fluoride coatings, several proprietary anodic coatings including one of The Boeing Company's, and Watervliet Arsenal anodic hard coating. These coatings minimize galling under light frictional loading. Their primary function is to promote retention of standard lubricants, since adhesion of the lubricant to bare titanium is not sufficient to produce adequate lubricity under heavy loading.

For most applications, the easily applied phosphate fluoride coating promotes satisfactory adhesion to dry film or fluid lubricants. Abrasive blasting produces good adhesion of lubricant and subsequent lubricity although the surfaces obtained are not suitable for many types of parts.

The use of lubricants to minimize galling is discussed in Sec. 3.7.

3.8.4.3 Titanium Surface Preparation, Appearance Control
Normal cleaning and pickling processes for titanium produce an acceptable appearance after fabrication. Nitric hydrofluoric acid pickling, for scale removal or prewelding surface preparation, produces a smooth and lustrous surface. Pickling to remove one to three mils per surface of metal also produces appearance uniformity on machined surfaces when the machine marks are not overly prominent. When surfaces are chemically milled during fabrication, they have acceptable appearance equivalent to those after pickling.

3.8.5 Erosion Protection
The problem of erosion manifests itself in the flight of the airplane through rain. Rain erosion is a direct function of impingement velocity and angle, drop size, and rate of rainfall. Rain impingement will produce erosion damage by exerting extremely high pressures over the area of impact and by an outward tangential flow at high velocities along surfaces.

a. Supersonic Rain Erosion Protection
Above 40,000 feet, the expected droplet size is less than one mm in diameter (Refs. 41 and 42). At altitudes below 40,000 feet, rain droplets greater than two mm in diameter are rarely encountered. It was predicted that droplets would fragment and vaporize behind a shock wave in air (Ref. 43). It was later shown on the supersonic sled investigation by Sandia Corporation at the Holloman AFB sled facility that droplets less than one mm in diameter did fragment causing no erosion damage; droplets one to three mm in diameter did not fragment and caused erosion damage (Ref. 44).

It has been shown (Refs. 45 and 46) that the rate of erosion decreases sharply as the impingement angle is decreased and approaches zero, if the impact angle is less than 15 degrees. During supersonic flight, critical areas with respect to rain erosion are wing leading edges, empennage leading edges such as stabilizer and vertical fin, and the radome tip. In supersonic flight the wing

leading edges will be swept back to 18 degrees. Hence, erosion damage is not expected even from rain droplets which are not fragmented behind the shock wave. Although the impact angle for the empennage leading edges is greater, this area will also be resistant to damage. Wahl (Ref. 47) has shown that titanium has over three times the rain erosion resistance of aluminum and aluminum performs satisfactorily on leading edges at Mach 0.9. Brunton (Ref. 48) as well as De Corso and Kothmann (Ref. 49) indicate impact pressures from rain drops at Mach 3 will be about three times the impact pressures at Mach 1. Thus, titanium should give satisfactory protection to all leading edges.

The tip of the nose radome is the most susceptible area to rain erosion damage and must be given maximum protection. A preformed ceramic cap is used to protect the fiberglass reinforced polyimide radome. Candidate protective cap materials available are alumina and Cer-vit. Cer-vit is a recrystallized glass developed by Owen-Illinois, Toledo, Ohio. Both alumina and Cer-vit are suitable as electromagnetic windows in the radar transmission frequency range. Alumina has repeatedly shown its resistance to rain erosion at supersonic speeds (Refs. 50, 51, and 52). Extrapolation of existing data predicts high density alumina will resist rain erosion at velocities up to Mach 10 (Refs. 52 and 53). The advantages of Cer-vit, compared to alumina, are its ease of fabrication where glass forming techniques are used, its zero porosity, and mirror finish. The latter two advantages minimize erosion caused by the tangential shear forces due to water flow along the surface.

The protective cap will be bonded to the fiberglass reinforced polyimide radome. Both alumina and Cer-vit appear to be compatible with the high temperature organic adhesives.

The Boeing Company is participating in the joint Air-Force Materials Laboratory — Naval Air Development Center 1966 program for evaluation of rain erosion resistant materials at supersonic speeds. The tests are conducted at the Holloman Air Force Base rocket sled facility. Test specimens are mounted on a wedge (Fig. 3-71) which is designed to present faces at angles of 13.5, 30°, 45°, 60°, and 90° to the sled direction and rain field. These cover the spectrum of leading edge frontal angles of the B-2707. Materials are tested at Mach 1.5, 2.0, 2.5, and 3.0.

Materials representative of the exterior of the B-2707 are being tested as well as candidates for rain erosion protective coatings. The materials are:

a. Titanium skins — on polyimide honeycomb core.

b. Glass reinforced plastic skins — on polyimide honeycomb core sandwich.

c. Sealed surface of glass reinforced polyimide laminate.

d. Alumina-bonded to a polyimide laminate.

e. Cer-vit 106 (devitrified glass).

A representative from The Boeing Company is assisting in the testing of those specimens submitted by The Boeing Company. This enables the company to have first hand, immediate data from tests of all materials including those from the results of work done by the Brunswick Corporation under AF Contract AF 33(615)3342. Materials will be characterized as to physical properties, such as hardness, surface finish, tensile and flexural strength, density, porosity, and modulus. Attempts will be made to correlate test performance with these characteristics. Flat ceramic coated polyimide test specimens have been tested at the Holloman supersonic sled test facility at Mach 1.5 with a rainfall rate of 2.6 in./hr using two mm rain droplets. This is a very severe environment and is not expected to be encountered in actual flight. Both the alumina and Cer-vit samples showed no signs of rain erosion damage.

Tests are being conducted to determine the bond strength, thermal shock characteristics, and impact characteristics of ceramic coated polyimide laminate systems. These tests will be performed at temperatures up to 550°F and bond strengths are expected to be at least 1,000 psi at 550°F. Room temperature bond strengths of 3,300 psi are attained. Thermal shock resistance is predicted to be good since the thermal expansions of the laminate and ceramic materials are of the same magnitude. Impact resistance is evaluated by firing projectiles at velocities up to Mach 4 at test specimens.

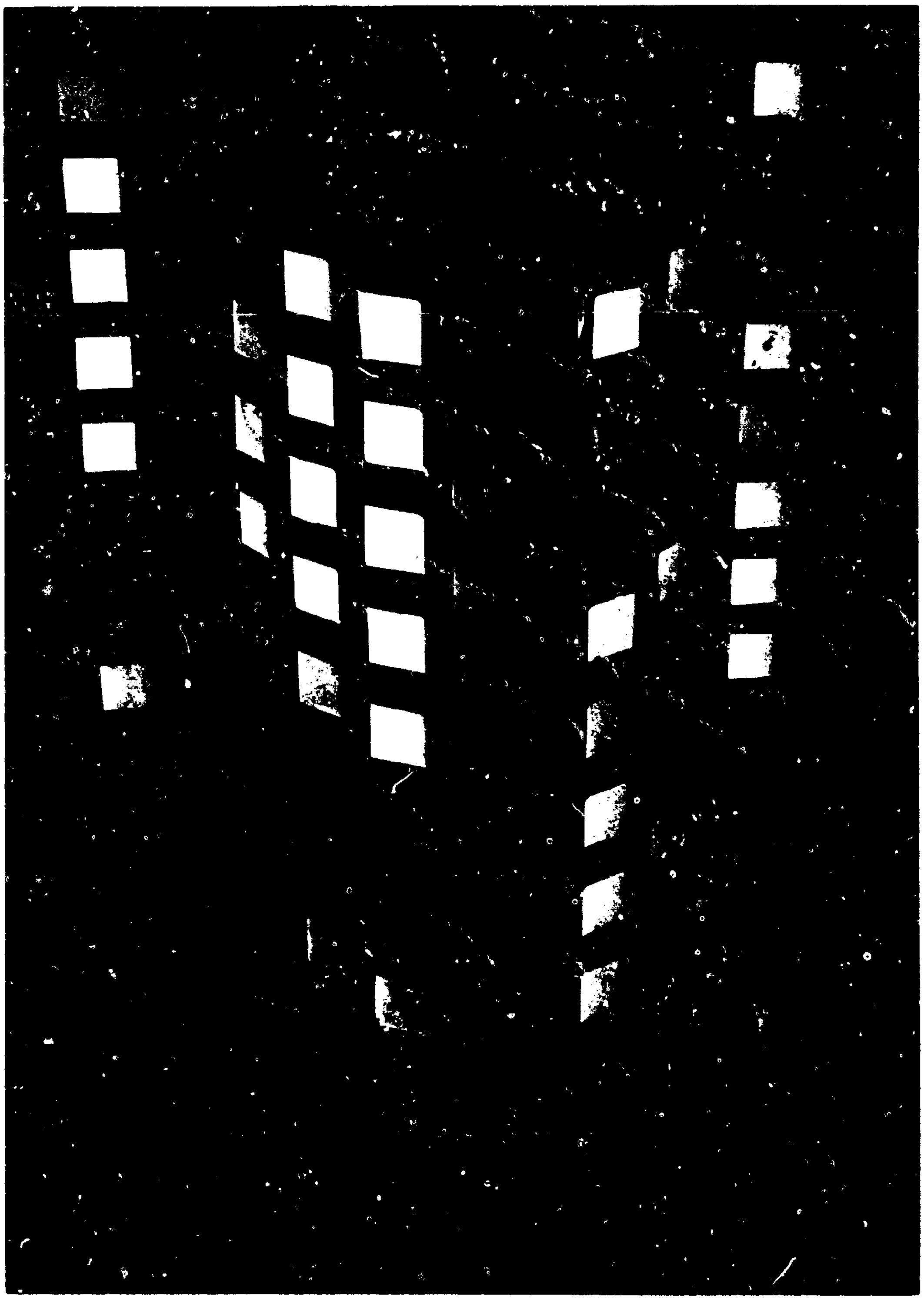

Figure 3-71. Wedge Test Jig for Rain Erosion Sled Tests

The physical properties for alumina and Cer-vit are shown in Table 3-X.

Elevated temperature resistant elastomeric materials are used for subsonic rain erosion protection. Elastomeric materials applied as thick coatings or adhesively bonded shields have been effective in protecting laminate structures from damage by rain at subsonic speeds. Currently used neoprene materials are not satisfactory since elevated temperatures to 550°F will be experienced. Therefore, heat resistant elastomers, such as fluorocarbon and silicone rubbers are selected. A comparison of the essential properties of a neoprene rain erosion protective coating (Gaco N-79) and a filled fluorocarbon elastomeric coating (Viton A) is shown in Table 3-Y (Refs. 54 and 55). The data show that such materials will provide satisfactory subsonic rain erosion resistance. The abrasion resistance and tensile strength of Viton A is comparable to that demonstrated by the Gaco material.

Surfaces are abraded and solvent cleaned in preparation for bonding rain erosion protective coatings and caps. Coating application is by brush or spray. Shields are formed by conventional deep drawing or calendering and adhesively bonded to the radome.

3.8.6 Elimination of Precipitation, Static Charges
Protection from static charge buildup will be afforded to reinforced polymeric materials used on exterior surfaces by application of conductive

Table 3-X. Properties of Rain Erosion Protective Materials

Properties	Alumina	CER-VIT
Coefficient of thermal expansion 65 to 500°F	1.1×10^{-5}/°F	*
Porosity	0.6	0
Density	3.4	2.5
Modulus of Rupture, psi	60,000	70,000
Hardness, Knoop	900	600
	(500 gm load)	(200 gm load)
Young's modulus, psi x 10^{-6}	50.0	13.3
Poisson's Ratio	0.26	0.25
Dielectric Constant	at 77°F at 932°F	at 77°F
1 Mc	9.5 11.3	5.4
10 Gc	9.4 10.0	-
Loss Tangent		
1 Mc	0.0007 0.0047	0.005
10 Gc	0.0002 0.0002	

* The thermal expansion can be tailored from -30 to + 140 x 10^{-7}/°F over a wide temperature range.

Table 3-Y. Properties of Subsonic Rain Erosion Coatings

Ref. 54 Material	Exposure	Ref. 55 Abrasion Index	Tensile Strength, psi	Elongation at Break, percent	Energy of Rupture, lb/in^3
Gaco N-79	None	2-4-2.9	1000	1150	4280
Viton A + Purecal U	None	2.2	820	270	1300
Viton A + Purecal U	550°F	2.8	-	-	-

coatings. The conductive coating will be either Du Pont P.I. 5200 or Boeing developed carbon black modified silicone elastomeric coating. Conductive coatings have a surface resistance no greater than 100 megohms per square to assure bleedoff of static electricity before discharge damage can take place. To prevent radar interference associated with highly conductive materials, conductive coatings applied to radomes have a surface resistance greater than one megohm per square. In addition to meeting the conductivity requirements, conductive coatings are resistant to temperatures in the 450 to 500°F range. Table 3-Z shows pertinent properties for the selected coating. Polymer reinforced laminates will be prepared for coating by sealing, sanding, and solvent wiping. Conventional air spraying or brushing will be used to apply the conductive coatings

3.8.7 Marking Materials

a. Permanent Markings

Permanent marking will be required on parts and assemblies to assure proper identification during final assembly, maintenance, repair, and storage. Certain areas of the airplane will require markings for identification, decoration, and instructional purposes. Permanent markings used on current commercial airplanes are used and are shown in Table 3-AA. Part identification markings suited for elevated temperature exposure are shown in Table 3-AB.

Stenciling and silk screening with air dry silicone paint is employed for decorative and instructional marking on surfaces subject to temperatures above 300°F. Stenciled exterior markings will have the color range and durability required and will resist the exterior elevated temperature reduced pressure environment.

b. Temporary Markings

Temporary markings are used to identify parts during manufacturing. Materials and methods established on current airplanes will be used for temporary marking on aluminum, steel, and stainless steel surfaces. For titanium alloys, temporary markings are applied by rubber stamping utilizing the inks listed in Table 3-AC. The selected inks are free from halides and are

Table 3-Z Properties, Anti-Static Coatings

Material	Surface Resistance Megohms/Square	Cure	Resin System	Percent Pigment By Weight	Exposure Test
PI 5200	0.5 to 15	200° F 15 to 20min., 500° F 30 min.	Polyimide	7.5	500° F with no failure
Boeing ANST -XC-7	1	Room temperature	Silastic	14	450° F 30 torr, with no failure

Table 3-AA Permanent Markings

		Metal-CAL	Nameplate	Plastic Film Decal (Mylar)	Paint Film Decals	Stencil (Etched Metal or Machine Cut)	Silk Screening
DESCRIPTIVE PROPERTIES (TYPICAL VALUES)	Material	0.002 to 0.003 Al Color anodized	0.040 1100 or 3003 Al	Polyester	Lacquer or enamel	Lacquer, ink or enamel	Lacquer, ink or enamel
	Adhesive	Pressure sensitive rubber base, 0.001 thick or solvent activated	Mechanically attached; 15,363	Pressure sensitive	Varnish or dextrin	---	---
	Total thickness	0.004	0.040 plus screw heads or crimped "fingers"	Less than 0.0045	0.002 to 0.004	0.001 to 0.003	0.0002 to 0.0015
	Flexibility	Satisfactory	Low	Satisfactory	Satisfactory	Satisfactory	Satisfactory
	Weight	Satisfactory	Relatively high	Satisfactory	Satisfactory	Satisfactory	Satisfactory
APPLICA-BILITY	Legibility	Excellent	Excellent	Excellent	Excellent	Poor to excellent [1]	Excellent
	Ease of Modification or replacement	Fair	Good to fair	Fair	Fair	Good to fair [1]	Fair
	Cost	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory	Satisfactory
RESISTANCE PROPERTIES	Abrasion	Excellent	Excellent	Excellent	Satisfactory	Fair	Fair
	Cleaning	Excellent	Excellent	Excellent	Fair	Fair	Fair
	Fuel	Satisfactory	Excellent	Satisfactory	Satisfactory	Satisfactory	---
	Temperature Limit	300 F	375 F	300 F	175 F	160° to 500° F	175 F
	Humidity	Excellent	Excellent	Excellent	Fair	Fair	---
	Water	Excellent	Excellent	Excellent	Satisfactory	Satisfactory	---
	Weather	Excellent	Excellent	Excellent	Poor to satisfactory	Poor to satisfactory	---

[1] Depends on stencil type and background

Table 3-AB Elevated Temperature Markings

Marking Method	Marking Material: Service Temperature -65 to 300° F	Marking Material: Service Temperature -65 to 450° F	Material Selection Based On	Exceptions
1. Rubber Stamping	Polyurethane resin base ink	Silicone resin base ink	1. Temperature resistance 2. Appearance retention tests (See Table 3.8.7.1-3) 3. Exterior paint qualification tests (See section 3.8.2.1)	None
2. Electric Etching	temperature limitation same as part material		707, 720 and 727 experience	Titanium Alloys
3. Electrochemical Etching	Temperature limitation Same as part material		707, 720 and 727 experience	Nonmetals

Table 3-AC Temporary Marking Inks, Titanium

	Material ▷1	Color	Source
Category I	(Max temperature 300° F)		
	DX-100	Purple	Dykem Ink Co.
	DX-296	Red	Dykem Ink Co.
	512	Black	Meyercord Co.
	73X-NW	Black	Independent Ink Co.
	S-1141	Black	Marking Device Manuf. Co.
	WE 43	Yellow	General Printing Ink Co.
	Paul Bunyan	Purple	Dickson Ink and Chemical Co.
Category II	(Principally for use above 300° F)		
	Paul Bunyan water-soluble inks plus 10 percent sodium silicate		

▷1 Removability effected by conventional shop solvents. e.g., acetone, methyl ethyl ketone or alkaline cleaner adaptable to rubber stamping. Tagging is used where ink markings would be subjected to abrasion or where methods of ink removal are incompatible with part materials. Use of these materials and methods is controlled by a company specification.

3.8.8 Processing and Manufacturing Aid Materials
Processing and manufacturing aids such as marking materials, protective coatings, machining lubricants, and processing chemicals have been evaluated for compatibility with titanium. The materials were evaluated by:

- Chemical analysis of the material for halide content (principally chloride ion).
- Short time exposure of stressed titanium alloy specimens at elevated temperature (850°F)
- Exposure of flat specimens of titanium alloy at 500° to 550° F.

Subsequent analysis of exposed titanium specimens included Allison bend testing for surface embrittlement, vacuum fusion gas analysis for detection of hydrogen or oxygen pickup, and metallographic examination for evidence of intergranular attack. Results of the tests are shown in Table 3-AD.

3.9 CHEMICAL AND ELECTROCHEMICAL PROCESSES
The electrochemical processes are electrochemical milling, electrochemical grinding, and electrical discharge machining; all are used to remove metal and to shape metal parts. Thus, they supplement mechanical machining processes and provide increased flexibility in part design and economy in part production. Aircraft industry experience has proven the value and reliability of the electrochemical machining processes for producing complex shapes from high strength materials.

Chemical processes are chemical milling, cleaning, and descaling. In usage, chemical milling is similar to the electrochemical processes but the processing method and controls required are more closely related to cleaning and descaling.

Chemical processing of steel and aluminum alloys is well understood and has been widely employed for many years. The procedures used for the B-2707 will be the same as those successfully used throughout the industry. For titanium alloys, the danger of hydrogen embrittlement and chloride contamination has, in the past, caused considerable concern about chemical processing of titanium. While close control of these processes must be exercised, experience has proven the compatability of chemical processing methods for titanium.

3.9.1 Cleaning and Descaling
Degreasing and alkaline detergent cleaning materials are used for removal of oily and water soluble soils. This class of cleaners are firmly established and their use is quite routine. However, before any specific commercial cleaner is approved for use by The Boeing Company, it is tested for cleaning efficiency and material compatibility. For example, Freon PCA* solvent is selected for vapor degreasing of titanium in lieu of the commonly used trichlorethylene which can induce stress corrosion cracking.

A variety of acid pickling processes is used for the removal of scale formed during heat treating or hot forming metal. Deoxidizing solutions for aluminum are efficient with low etch rates and minimum metal attack. For steels, although tenacious heat treat scales are common, safe and efficient descaling methods have long been established. Descaling of titanium is complex, but test and production experience (since 1950) has established effective methods directly applicable to the B-2707. Recent investigations have updated this technology for the new applications to be encountered.

a. Pickling Solution for Titanium
Nitric hydrofluoric acid mixtures continue to be the standard solutions for descaling, general surface preparation, and light etching to remove contaminated metal. The nitric to hydrofluoric ratio and bath temperature must be controlled to avoid input of hydrogen to the base metal and selective etching during descaling. High nitric to hydrofluoric ratios result in low etch rates, whereas low ratios result in hydrogen embrittlement. The proper nitric to hydrofluoric ratio can be maintained by hydrofluoric acid additions; controlled either by analysis of free hydrofluoric acid or by determination of etch rate. Figure 3-72 shows the effect of hydrofluoric acid concentration on etch rate for titanium pickling solutions. The etch rate range used is 2 to 5 mils per surface per hr. This produces effective descaling and minimizes selective etching. With this etch rate range and the proper nitric acid concentration, the

*1, 1, 2 - Trichloro - 2, 2, 1 - Trifluoroethane

Table 3-AD. Compatibility of Manufacturing Aid Materials

Tapes and Temporary Coatings	Approved	Not Approved
Protex 50 tape	X	
Mystik 6223 tape	X	
Mystik 6250 tape	X	
Tuck 90T tape	X	
Mystik 5863 tape (black and olive drab)	X	
Permacel 95 tape	X	
Shuford Mills CP11 tape		X
Shuford Mills RP52 tape		X
Tuck 90W tape		X
Vinyl chloride strippable protective coatings		X
Spraylat SC-1071 coating	X	
Inks		
Meyercord 512 black ink	X	
Sigmund Ullman W-E-yellow 43 ink	X	
Paul Bunyan purple ink	X	
DyKem DX 100 ink	X	
DyKem DX 296 ink	X	
Cado Flomaster black and purple ink	X	
Independent Ink #68 red ink		X
Independent Ink 73 x NW black ink	X	
Marco S-1141 black ink	X	
Machining and Forming Lubricants		
5 percent Barium Hydroxide solution	X	
Freon Butyl Cellosolve mixture	X	
Mineral Oil (Chevron white oil #3, NF)	X	
Sodium Nitrite solution, 5 to 10 percent	X	
Mobile TJ-73	X	
Cut Max 569		X
Rapid Tap		X
Everlube T-50	X	
Fel-Pro C-300	X	
Solvac NP	X	
Solvac 2032	X	
Hocut 237	X	
Tapzol 410	X	
Grind Tex B 410		X
Mobile Met 25		X
Habcool 318		X
Tap Magic		X
Mobil C-250		X

Table 3-AD. (Concluded)

Solvents	Approved	Not Approved
Naphtha	X	
Acetone (and other ketones)	X	
Stoddard solvent	X	
Alcohols	X	
Toluene, Xylene	X	
Butyl Carbitol	X	
Butyl Cellosolve	X	
Freon PCA	X	
Carbon tetrachloride		X
Trichlorethylene (above 600° F)		X
Methyl chloroform		X
Methylene chloride		X
Miscellaneous Material		
Turco Pre-Treat (heat treat coating)	X	
Turco 4316 (scale conditioner)	X	
Turco 4338 (scale conditioner)	X	
ZL-2 (penetrant inspection fluid)	X	

hydrogen evolved is not significantly absorbed in the titanium. Any hydrogen pickup encountered is small relative to established allowable levels for the various alloys. The data plotted in Figs. 3-73 and 3-74 show the relationship between etch rate and hydrogen pickup.

Selective etching can be avoided by techniques such as repeated cycles of immersion and air-water blasting. Unusually tenacious scale may be removed by abrasive blasting. However, use of heat treat protective coatings or scale conditioners minimize the need for this type of descaling.

b. Heat Treat Protective Coatings for Titanium

Several coatings have been selected on the basis of effectively minimizing scale formation in different temperature ranges, for removability, and for minimizing oxygen alpha case. These coatings and their special characteristics are:

- Pre-Treat, Turco Products, Inc — This is a special kaolin-resin combination applied by spraying to a controlled thickness on cleaned surfaces. Protection to 1,900° F is afforded with best effectiveness to 1,725° F. After application, the coating dries and has moderate resistance to handling.
- T-50, Everlube Corporation of America — This molybdenum disulfide graphite filled silicone material is applied by spraying and affords protection to 1,900° F for a few hours. This coating is the particular selection for parts to be hot formed since it lubricates and minimizes scale and resists being scraped off.
- Boeing Ceramic Coating — This sprayed on coating is used above 1,400° F to minimize oxygen alpha case.
- Fuller Hi-Heat 171-A28 — This is an aluminum silicone paint. Its application and use are similar to the Boeing ceramic coating but slightly less effective in minimizing alpha case.
- Boeing Crystalline Coating — This aqueous solution includes a nitrate and carbonate. When brushed on titanium to be heated to 1,500° F, it causes formation of scale consisting largely of a titanate. This scale is considerably less tenacious than normal oxide scale.

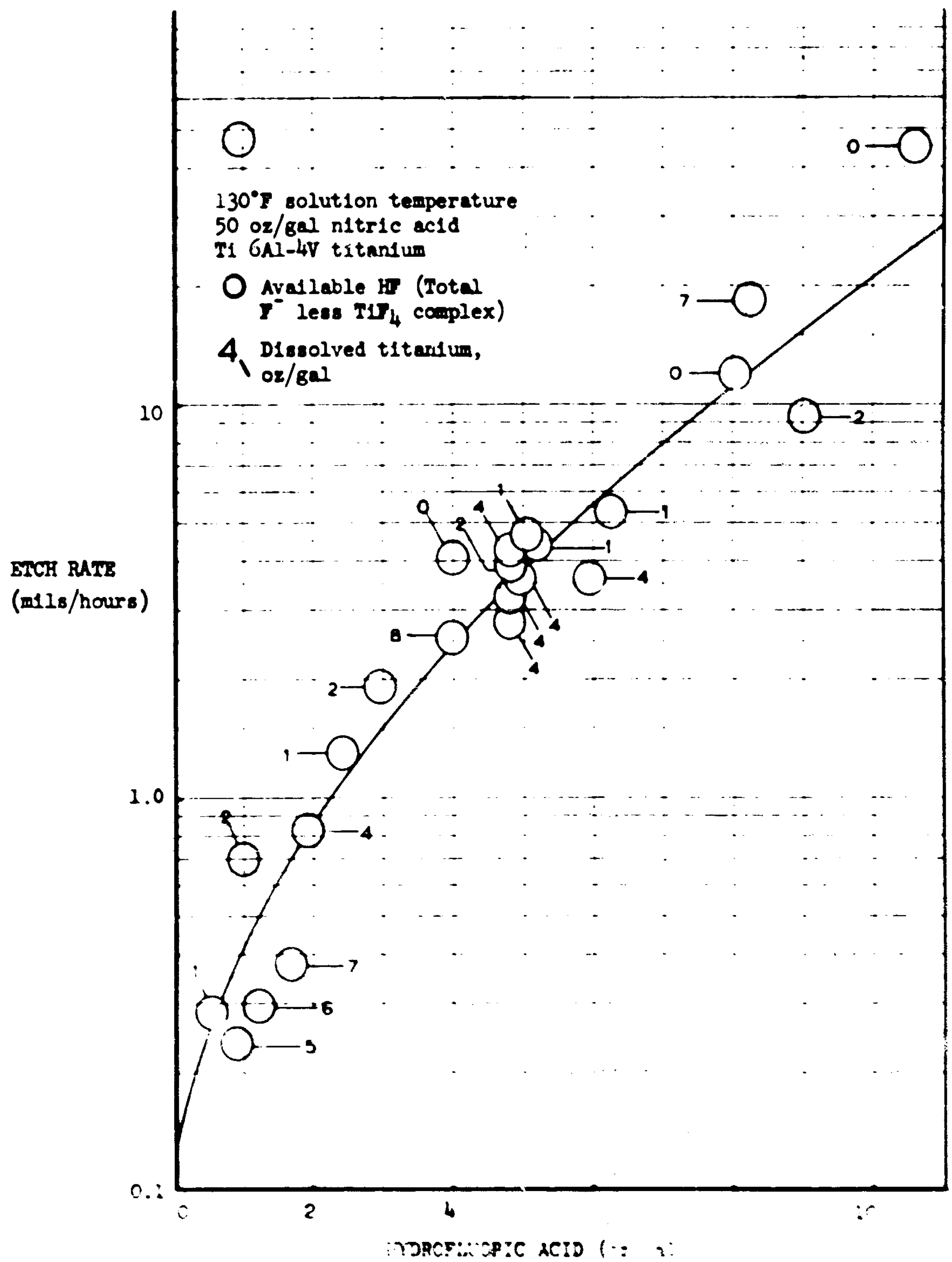

Figure 3-72. Titanium Pickling Solutions, Variations in Etch Rates

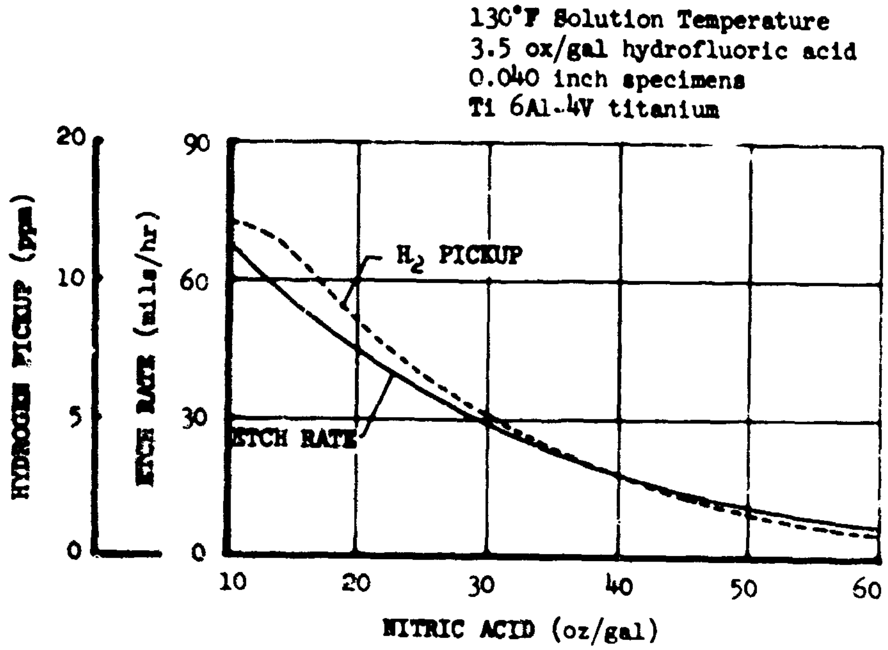

Figure 3-73. Effect of Acid Ratios on Hydrogen Pickup

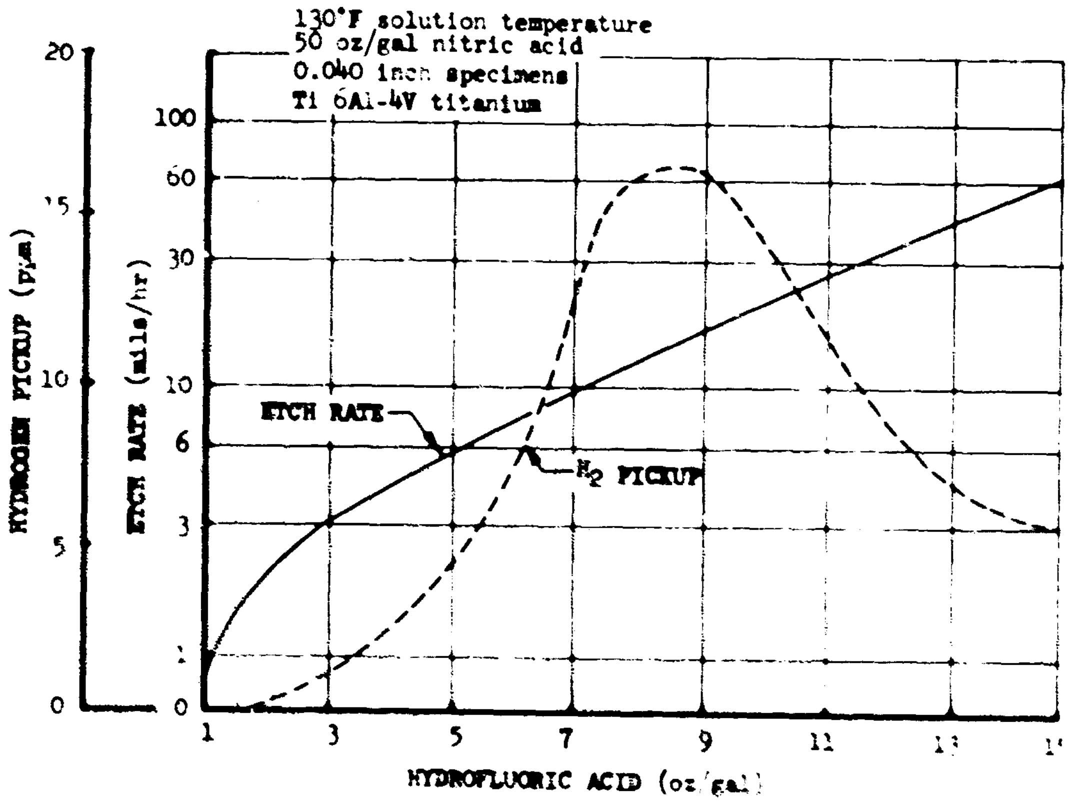

Figure 3-74. Effect of Etch Rate on Hydrogen Pickup

c. Titanium Scale Conditioners

Scale conditioners operate by altering the scale after formation for easier removal. When a coating and a scale conditioner are used, maximum scale removal efficiency and uniformity of metal removal are achieved.

Several commercial molten salt baths have demonstrated effective scale conditioning and material compatibilities, but their high operating temperatures have prevented their adoption. A newer low temperature molten bath, Kolene Corporation Alko-N which operates at 425°F, is being investigated.

Two aqueous solution scale conditioners manufactured by Turco Products, Inc., have the following applications:

- Turco 4338, a concentrated caustic permanganate solution operating at 200°F — This effectively removes residue of ceramic and Everlube T-50 coatings before pickling, but does not chemically alter titanium scale itself. It is primarily designed to condition scale on stainless steel and certain nickel cobalt alloys. This material is currently used at Boeing for titanium and steel.

- Turco 4316, a concentrated caustic solution operating at 270°F — This solution removes ceramic and Everlube T-50 residue after heat treatment and chemically alters titanium scale. It is effective on scale formed over a wide heat treat range and considerably simplifies pickling. It is used only for titanium.

d. Descaling of Steels

Carbon steels at strength levels less than 220 ksi are descaled in inhibited hydrochloric acid. Higher strength steels are abrasively descaled.

Austenitic or martensitic stainless steels are most readily descaled in nitric hydrofluoric acid. The 10 to 1 nitric to hydrofluoric solution as used for titanium is satisfactory although a lower ratio (4 to 1) is somewhat more effective for descaling and does not produce excessive steel etching. Because high heat treat temperatures are common, heat treat protective coatings are definitely advantageous. For this purpose, Turco Pre-Treat or a silicone coating developed by Boeing are used.

Precipitation hardening stainless steels require pickling in low etch rate solutions to avoid intergranular attack. A high nitric low hydrofluoric solution can be used, but parts descaled in inhibited hdyrochloric solution are generally more free of attack. Turco 4338 scale conditioner is used to facilitate scale removal.

e. Descaling of Aluminum

A large number of commercial deoxidizers are available for descaling aluminum. These materials are in current use, have been proven effective, and are economical.

3.9.2 Chemical and Electrochemical Metal Removal

Chemical and electrochemical techniques will be used to produce pockets, multiple holes and complex three dimensional shapes when conventional machining is difficult or extremely expensive. The following processes will permit designing a part to an optimum configuration for weight reduction:

- Chemical Milling.
- Electrochemical Machining (ECM).
- Electrical Discharge Machining (EDM).
- Electrolytic Grinding (EG).

Each of these techniques have been thoroughly evaluated with regard to dimensional tolerances, reproducibility, surface finish, and effects on material properties and is controlled by company specifications.

Chemically and electrochemically milled surfaces are free from induced residual stresses. They exhibit fatigue characteristics similar to those resulting from end milling with sharp tools to a standard RHR 125 finish as shown in Fig. 3-75.

Electrolytic grinding removes 90 percent of the metal electrochemically and 10 percent abrasively; producing surfaces with a slight residual tensile stress. Stress measurements on titanium parts indicate that residual stresses from electrolytic grinding are only 10 to 20 percent as high as those introduced during conventional grinding. Electrolytically ground parts can usually be used as produced.

Electrical discharge machining introduces high residual tensile stresses, and a remelted and oxygen contaminated surface as shown in Fig. 3-76. The contaminated surface is removed by chemical or conventional machining techniques.

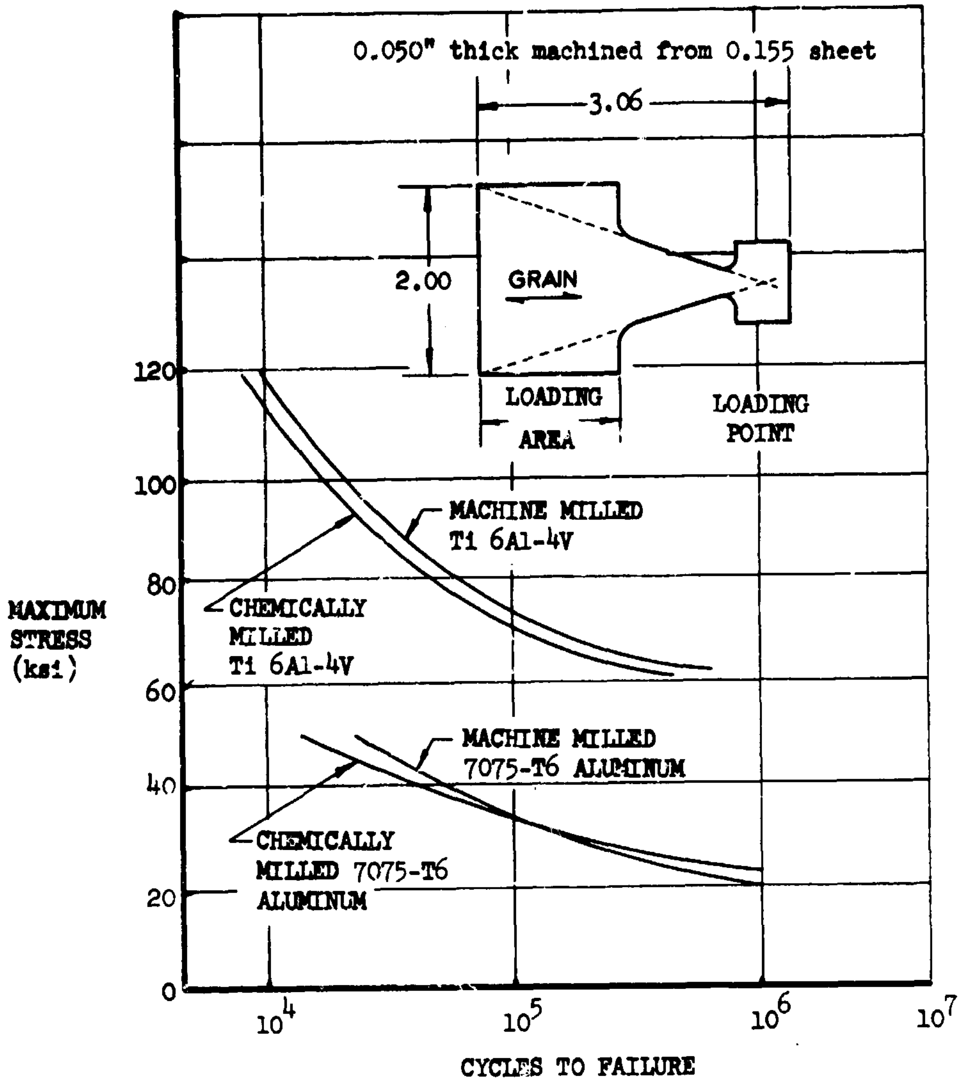

Figure 3-75. Fatigue Life of Chemically Produced Surfaces

a. Chemical Milling

Chemical milling is used on wing and body skin sections to reduce gage of sheet metal and to produce desired shapes. Chemical milling is used to remove metallurgically disturbed surfaces such as those produced by grinding.

Approved chemical milling processes have been developed and sources established for aluminum, magnesium, ferrous alloys, Rene' 41 or M-252, titanium, and titanium alloys.

Surfaces generated by chemical milling and conventional machining in any combination are used as dictated by design or manufacturing economy. The specification requirements control the surface finish, dimensional tolerances, fillet radii, transition zone, preferential attack, and hydrogen pickup.

Chemical milling can be used to reduce thickness tolerances, thereby providing a minimum weight structure at a reasonable cost. A potential weight saving of 0.08 pounds per square foot may be realized by decreasing chemical milling thickness tolerances from the usual ±0.005 in. to the weight-equivalent of ±0.002 in.

Chemical milling and light etching of titanium parts will be accomplished in a nitric hydrofluoric acid solution or in a chromic hydrofluoric acid solution. Hydrofluoric acid is the etching solution

Figure 3-76. Micrograph of EDM Produced Surface

and the nitric acid or chromic acid limits hydrogen absorption and moderates the etch rate. A wetting agent is used to lower the surface tension, thus reducing the contact angle of the solution with the metal. This allows the reactant gas to escape from the surface as small bubbles and eliminates surface roughening.

Hydrogen contamination of titanium will be controlled by maintaining a high concentration of nitric acid in the solution and a solution etch rate which is greater than the diffusion rate of hydrogen in the metal. The following relations have been established:

- The etch rate and the hydrogen pickup will decrease exponentially and will approach zero as the concentration of nitric acid increases.
- Increasing the concentration of the available hydrofluoric acid will increase the etch rate exponentially and will increase the hydrogen pickup to a maximum value which will then decrease as the etch rate greatly exceeds the hydrogen diffusion rate.
- Dissolved titanium combines with the fluoride and decreases the available hydrofluoric acid, decreasing the etch rate.
- The etch rate will increase exponentially as the temperature increases.
- The temperature and wetting agent have little effect on hydrogen pickup.

Etch rate and hydrogen pickup are shown in Figs. 3-73 and 3-74.

b. Electrochemical Milling (ECM)
Electrochemical milling is essentially reverse plating. The metal is dissolved in an electrolyte flowing between the part and an electrically charged tool. Since current density is very much higher on the surface near the tool, the metal is preferentially dissolved to duplicate the shape of the tool. The dissolved metal is carried away by the electrolyte. The machining rate is determined by the chemistry of the metal and the current density and is completely independent of part hardness.

The principal use of electrochemical machining has been to generate holes and cavities in titanium, nickel, and ferrous alloy parts that would be impossible or impractical to machine by other methods. This technique may also be used to machine extrusions.

The J extrusion shown in Fig. 3-77 can be produced by electrochemical milling as well as conventional machining. The I extrusion shown can only be produced by electrochemical milling, because the thin webs would distort as a result of residual stresses induced if the part were machined.

c. Electrolytic Grinding (EG)
Electrolytic grinding is similar to electrochemical milling except that a charged metal composite or metal backed grinding wheel is used as the tool. Ninety percent of the part machining is accomplished electrochemically, the remainder by grinding.

Most of the advantages and restrictions of electrochemical milling also apply to electrolytic grinding. Multiple-pass electrolytic grinding of large surfaces is not feasible; if passes do not overlap ridges are left, otherwise adjacent areas are undercut.

d. Electrical Discharge Machining (EDM)
Electrical discharge machining utilizes a charged tool and high frequency sparking to vaporize the

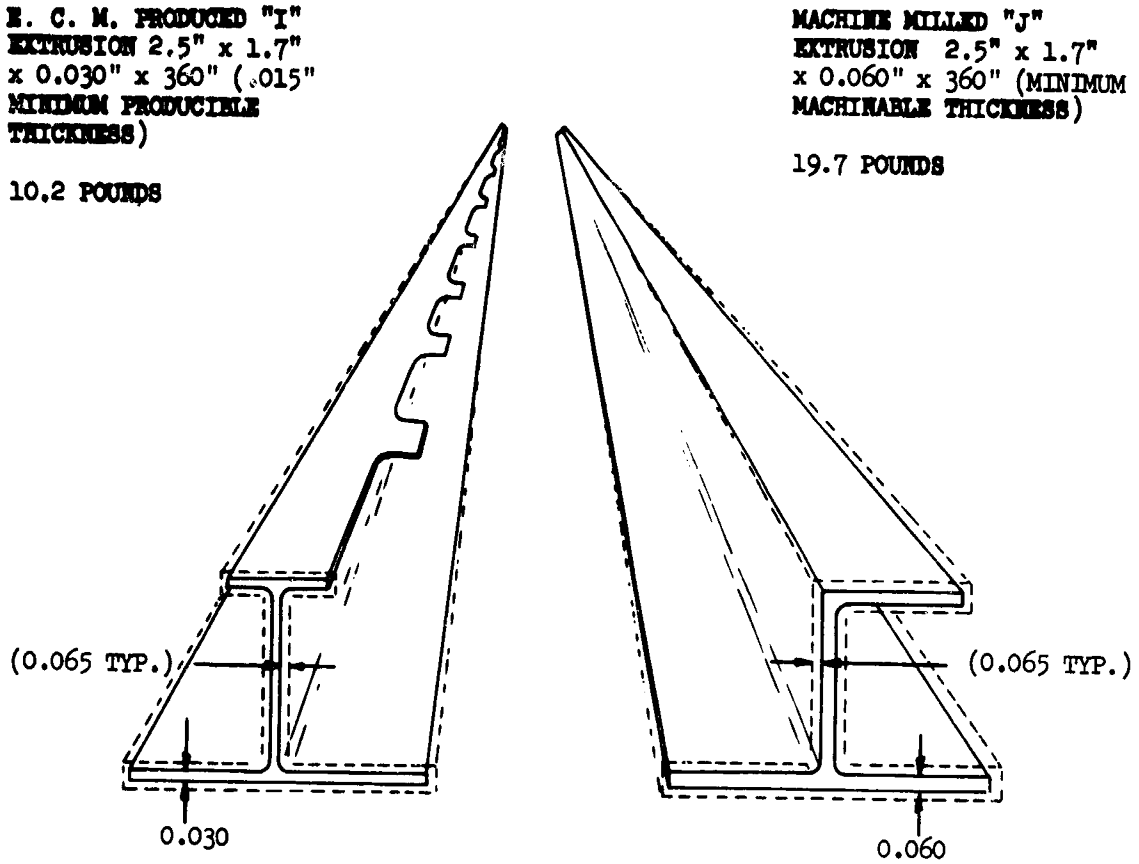

Figure 3-77. Applications of Electro Chemical Milling-Extrusions

nearest metal surface until a cavity is formed which duplicates the shape of the tool. The part is submerged in a dielectric and additional dielectric is pumped through the tool to prevent forming a stable arc, to carry away metal particles, and to cool the part thus limiting the depth of heat affected metal. The copper cutting tools are simple and inexpensive, but are consumed at a relatively high rate frequently requiring separate tools for the roughing and finishing cuts. Machining rates are slow but are completely independent of part hardness.

Electrical discharge machining will be used to produce blind or through holes in difficult to machine metals. The damaged surface produced will be removed by chemical or conventional machining methods.

3.10 ENVIRONMENTAL FACTORS

The atmospheric environmental factors including ozone, radiation, and particulate matter must be considered for their effect on the structural materials, passengers, and crew during flight. A summary of these factors is presented here. A more complete discussion appears in Operations Suitability V4-B2707-1.

a. Ozone

The ozone concentration in the stratosphere can exceed 10 ppm by volume. Ozone resistant materials have been selected on the basis of present knowledge. If long term evaluation tests, now in progress, show detrimental effects, suitable protection will be provided.

b. Radiation

Solar ultraviolet is the only radiation that should affect materials. It will be a factor only for organic materials on the exterior surfaces. Materials which might be affected are being evaluated under simulated flight conditions including temperature, reduced pressure, and ultraviolet radiation.

c. Particulate Matter

The concentration of aerosol particles in the stratosphere is so small that they are not expected to cause any gross effects by erosion or chemical action to the surfaces.

3.11 HYDRAULIC FLUID

Humble WSX-6885 hydraulic fluid, manufactured by the Humble Oil and Refining Co., Linden, New Jersey, has been tentatively selected as the hydraulic fluid material for the B-2707 hydraulic system use. This is a trimethylolpropane ester material which possesses physical and chemical properties necessary for efficient hydraulic system operation at both low and elevated temperatures.

Complete hydraulic fluid properties and evaluation which include tables and graphs depicting thermal, hydrolytic, and oxidative stability corrosion characteristics, and other property data, as well as extensive pump loop and systems test data on ETO 5251 fluid (chemically identical to WSX-6885) are presented in Systems Report Part B, V2-B2707-11. Comparable data are also included for other promising candidate hydraulic fluids.

4.0 FASTENERS, BEARINGS, AND SYSTEMS COMPONENTS

4.1 FASTENERS

General

The factors which were considered in the fastener type and material selection include the following:

a. Required strength levels

b. Fastener configuration

c. Weight

d. Corrosion resistance

e. Compatibility with structural material

(1) Coefficient of expansion

(2) Galling

(3) Coatings and lubricants

f. Thermal effects on fastener material

(1) Properties at temperature

(2) Properties after exposure

(3) Metallurgical stability

g. Cost

h. Production installation characteristics

i. Producibility and availability. Table 4-A shows comparison of fastener materials.

4.1.1 Bolts and Nuts

Bolts selected for general use are Ti 6Al-4V. Bolts are heat treated to 160,000 psi minimum ultimate tensile strength and 95,000 psi minimum shear strength. Higher strength bolts for use at temperatures of -65°to 500°F are A286 processed to 200,000 psi minimum ultimate tensile strength. Table 4-B shows representative tensile and shear data for bolts of these materials when tested at room temperature and at 500°F before and after exposure at 500°F.

Bolts and nuts are unplated and are lubricated, when required, with a solid film lubricant suitable for high temperature service. For most applications, protruding head bolts are the external wrenching type (12 point or spline configuration); some bolts are of the hexagon head type. Bolts with 100 degree countersunk heads are the Hi-Torque recess type. High fatigue bolts have rolled threads in compliance with Military Specification MIL-S-8879.

A286 nuts are used in sizes and types not available in titanium in production quantities. Torque tension data have been developed for the various bolt-nut material and solid film lubricant combinations. Figure 4-1 illustrates the variation in preload obtained with lubricated and unlubricated bolts before and after exposure at 500°F. Figure 4-2 shows the effect of specific lubricants on the torque to tension relationship.

Figure 4-3 illustrates the type of data developed for establishing torque-tension design information. Data obtained from residual tension relaxation tests after elevated temperature exposure are used in establishing installation torque values. Established torque values result in optimum preload or clamp up after any relaxation. Preload indicating washers are used where closer control of initial preload is required. Titanium 6Al-4V or corrosion resistant steel plain washers conforming to NAS 1587 are used under hexagon or 12 point external wrenching nuts. Countersunk washers (NAS 1587) from these materials are used under bolt heads, or the structure is countersunk to provide clearance for the bolt head-to-shank fillet radius. Materials and lubricants are selected to provide maximum corrosion resistance.

High strength corrosion and heat resistant alloys such as Inconel 718 and Udimet 630 are used for applications where ultimate tensile strength over 200,000 psi is required.

4.1.2 Taper Shank Fasteners

Taper shank fasteners are used rather than straight shank fasteners where high joint fatigue life in bolted joints is required. The taper shank

Table 4-A. Comparison of Fastener Materials

Fastener Material		6A1-4V	A 286	Monel
Density		0.160	0.286	0.319
Coefficient of Expansion (500° F)		5.2×10^{-6}	9.5×10^{-6}	9.0×10^{-6}
Corrosion Resistance		Excellent	Good	Excellent
Stability at Temperature (500° F)		Good	Good	Good
Compatibility With Structure		Excellent	Good	Good
Galling		Extreme	Severe	Moderate
Metallurgical Stability		Good	Good	Good
Availability		Good	Excellent	Excellent
Suitable Lubricant Available		Yes	Yes	Yes
Driveability (Rivets)	GUN	Fair	Good	Excellent
	SQUEEZE	Excellent	Excellent	Excellent
Shear Strength (Rivets)				
Room Temperature		90,000 psi	90,000 psi	49,000 psi
500° F		69,000 psi	82,000 psi	
After 1000-Hr. Soak at 500° F			82,000 psi	

Table 4-B. Room and Elevated Temperature Strengths of 0.25 Inch Diameter Bolts

Bolt Material	Room Temperature Tensile Strength (lb)		
	Unexposed	After 500-Hours Soak at 500° F	After 1000-Hours Soak at 500° F
Ti 6A1-4V	7,110	7,130	7,050
A286	8,715	8,625	8,490

Bolt Material	500° F Tensile Strength (lb)		
	Unexposed	After 500-Hours Soak at 500° F	After 1000-Hours Soak at 500° F
Ti 6A1-4V	5,620	5,690	5,580
A286	7,740	7,735	7,600

Bolt Material	Room Temperature Shear Strength (lb)		500° F Shear Strength (lb)
	Unexposed	After 1,000-Hours Soak at 500° F	After 1000-Hours Soak at 500° F
Ti 6A1-4V	5,155	5,185	4,230
A286	5,805	5,745	5,070

NOTE: Bolts were tension loaded to 50 percent of their 500° F tensile strength during the 500 and 1,000-hour exposures.

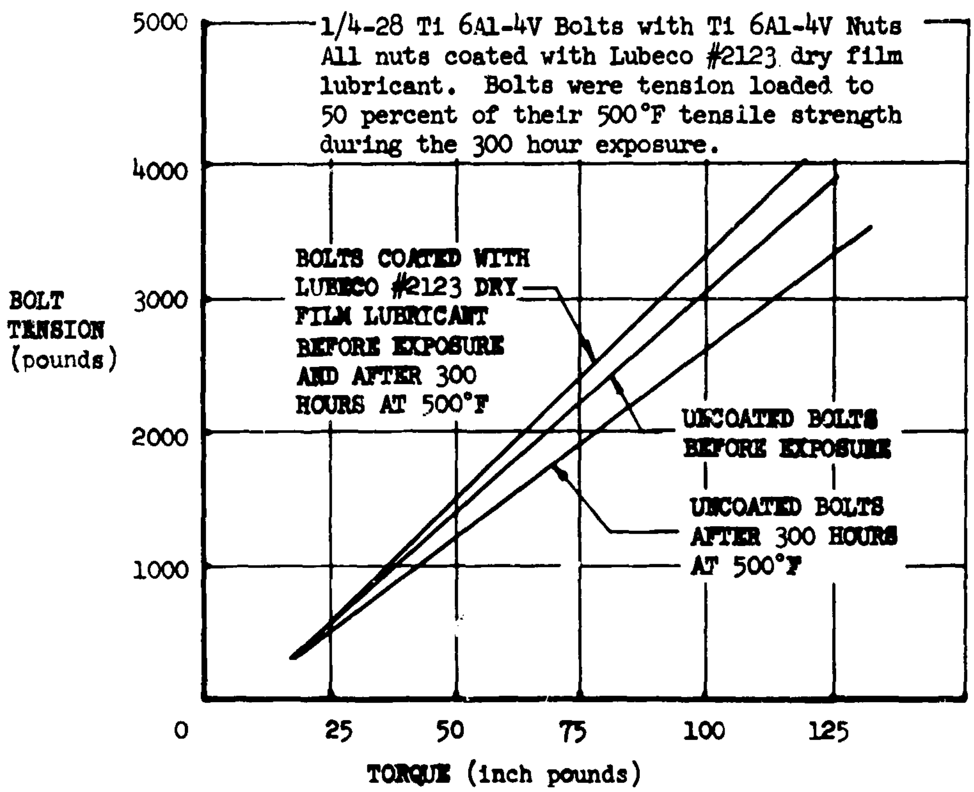

Figure 4-1. Torque-Tension Curves, Lubricated and Unlubricated Titanium Bolts and Nuts

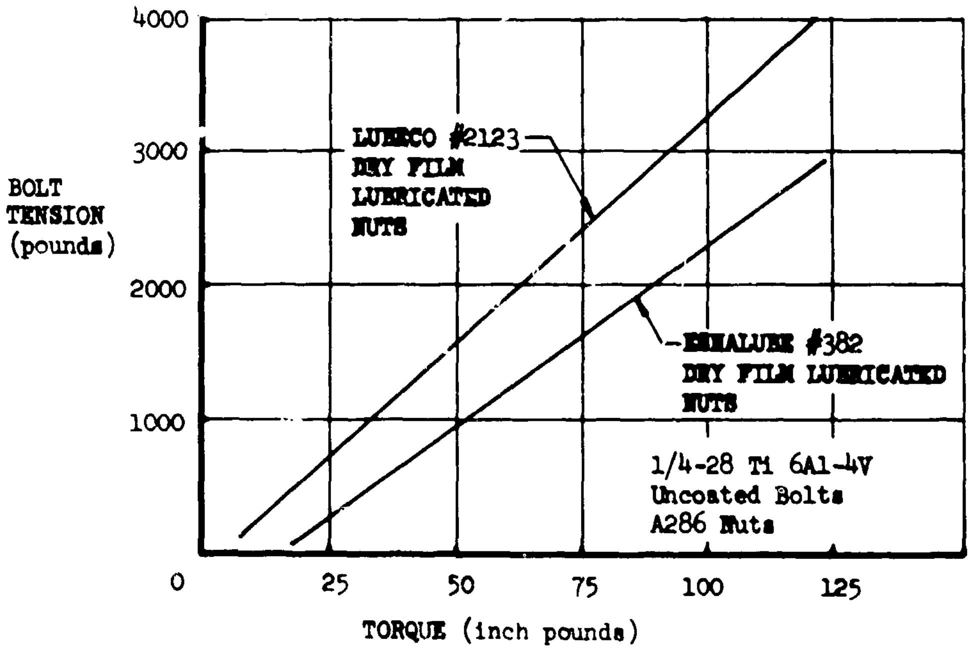

Figure 4-2. Torque-Tension Curves, Uncoated Ti-6Al-4V Bolts and Lubricated A286 Nuts

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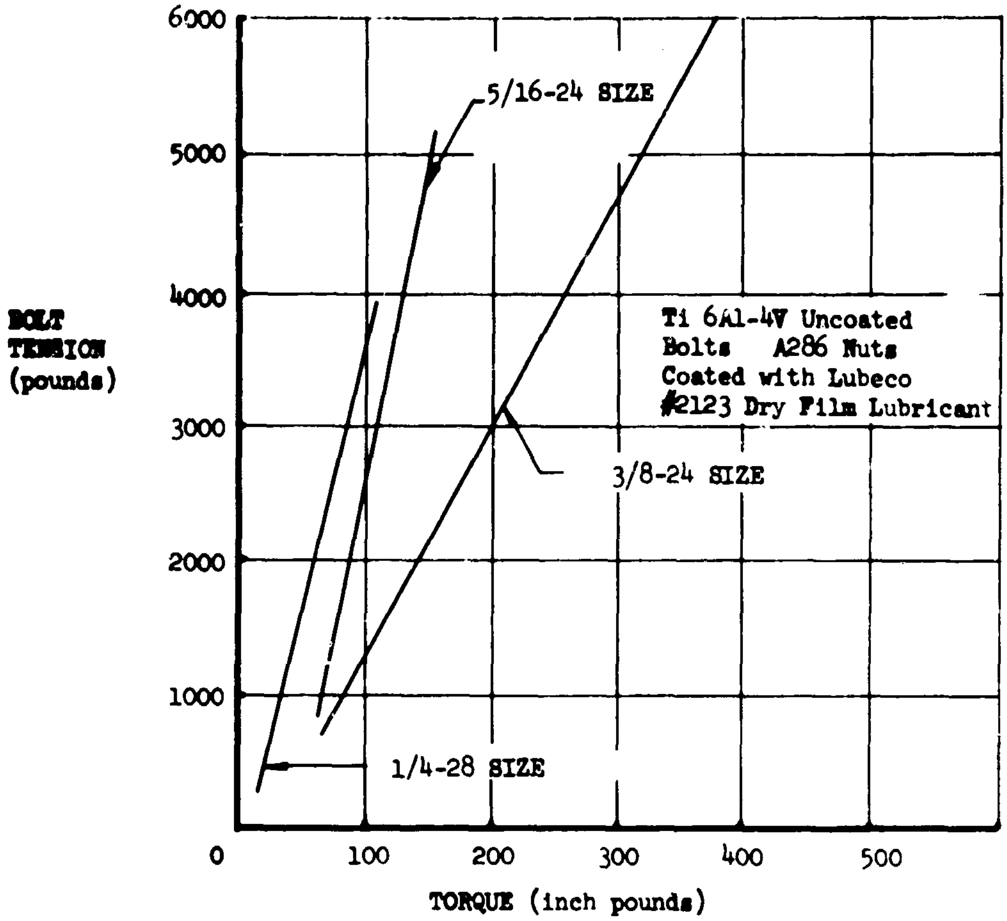


Figure 4-3. Torque-Tension Curves, Uncoated Ti-6Al-4V Bolts with A286 Nuts, Size Evaluation

fasteners are Ti 6Al-4V coated with a solid film lubricant to prevent galling and seizing in the hole during installation. Figure 4-4 is representative of data developed to compare the fatigue life of joints fastened with taper shank bolts with that of joints fastened with straight shank bolts.

4.1.3 Hex Drive Fasteners

Shear head hex drive bolts with controlled preload type collars are used in primary shear joints which are not fatigue critical. These bolts are Ti 6Al-4V coated with a solid film lubricant. Collar materials are A286 and Ti 6Al-4V (when available) coated with a solid film lubricant.

Installation processes are controlled by Company process specifications. Company standards are used for control of standard fasteners not covered by service or industry drawings.

4.1.4 Rivets

Materials selected for solid rivets are Ti 6Al-4V, A286, and Monel. Titanium 6Al-4V and A286 rivets have a minimum shear strength of 90,000 psi. Monel rivets have a minimum shear strength of 49,000 psi. Reduced and standard 100 degree head, and standard universal head types are used in 1/8- to 3/8-in. diameters. In joints subjected to high fatigue loads, rivets are installed by a room temperature squeezing process. In joints which are not fatigue critical or are nonstructural, rivets are installed either at room temperature or hot by squeezing or gun driving. Squeezing and gun driving installation procedures have been established by extensive testing, and are controlled by company process specifications. Fluid tight riveting procedures are also controlled by a company specification.

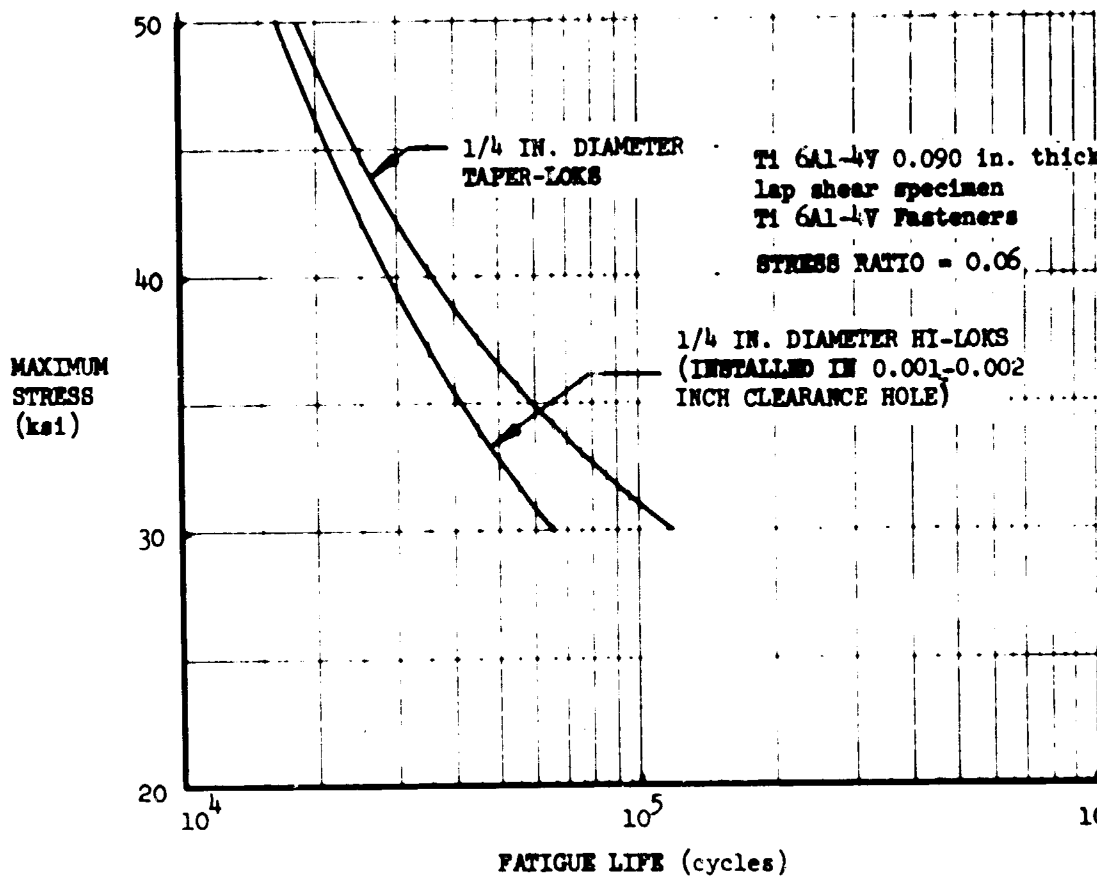


Figure 4-4. Comparison of Joint Fatigue Life, Taper and Straight Shank Bolts

4.1.4.1 Titanium Rivets

Titanium 6Al-4V rivet material is used for high fatigue resistant structural joints, where installation can be accomplished by compression heading (squeezing).

The close packed hexagonal structure of titanium is not conducive to high deformation at room temperature such as is required for squeeze riveting. Economical use of titanium riveting is predicated on driving at room temperature. A detailed study of the relationship of heat treatment procedures in conjunction with rivet manufacturing was conducted. The result has been that a rivet is now available that can be squeezed as successfully as the high strength aluminum rivets. Figure 4-5 shows a comparison of the driving capability of Ti 6Al-4V rivets as originally produced and those as currently being used.

More than 500, 1/4-inch diameter rivets have been squeezed without a failure. A limited number of 3/8-inch rivets have been successfully installed. The installation of larger diameters, using this method, are being evaluated.

More than 150, lap shear joint specimens of the type shown in Fig. 4-6, fastened with annealed Ti 6Al-4V rivets, have been fatigue tested. The effects on joint fatigue life of heading force, hole size, and exposure to stress and temperature are shown in Figs. 4-7, 4-8, and 4-9. Curves in Fig. 4-8 indicate that reasonable hole tolerances can be used.

A gun driven rivet system was developed for those areas not requiring the high squeeze installation procedures. This system uses dry film lubricated rivets that are installed in interference fit holes.

Installation is accomplished as follows:

a. The rivet is driven into the hole.

b. The projecting end of the rivet is resistance heated by a contact electrode during a timed heat cycle.

c. The rivet is upset by a standard rivet gun using the electrode as the bucking bar. Activation of air pressure to the rivet gun is solenoid controlled to prevent driving the rivet before proper heading temperature has been reached and current is cut off.

4.1.4.2 A286 and Monel Rivets

A286 rivets are used for applications requiring installation by gun driving at room temperature. Standard shop rivet guns and bucking bars are used to install A286 rivets in sizes through 1/4-inch diameter. The A286 rivets are similar to NAS 1198 and NAS 1200 except for improved dimensional tolerances and closer controls on strength and corrosion resistance. For improved fatigue performance, A286 rivets may be installed with the same squeeze process developed for Ti 6Al-4V rivets.

More than 450 lap shear joint specimens of the type shown in Fig. 4-6, fastened with A286 rivets, have been fatigue tested to evaluate configuration and installation variables. Figures 4-10 through 4-14 show the effects on joint fatigue life of heading force, hole size, exposure to stress and temperature, gun driving, and hole condition.

Monel rivets are used in areas where the strength of A286 or titanium is not required.

4.1.5 Blind Fasteners

Materials selected for use in blind rivets are A286 and Monel. Nominal sizes 1/8-, 5/32-, and 3/16-inch diameter are used in wire drawing and bulbed Cherrylock configurations. A286 blind rivets have a 95,000 psi minimum shear strength, and Monel blind rivets have a 50,000 psi minimum shear strength. Where the ratio of the total sheet stackup to the hole diameter (T/D) is less than one, only the bulbed Cherrylock configuration is used.

Table 4-C shows representative shear and tensile data for 3/16-inch diameter A286 blind rivets (NAS 1399 style) tested at room and elevated temperature before and after exposure at 550°F.

A286 blind bolts having a minimum shear strength of 95,000 psi are used in sizes 1/4 through 1/2 inch diameter. Table 4-D shows representative shear and tensile data for 1/4-inch diameter A286 blind bolts (MS 90353 style) tested at room and elevated temperature before and after exposure at 550°F.

Fastener manufacturers are currently developing titanium blind rivets and blind bolts which will be used as they become available.

4.1.6 Panel Fasteners

High strength A286 panel fasteners are used in structural applications where panels must be removed frequently. These fasteners were chosen because of their strength, material compatibility,

Example of the very limited headability of the first 1/4 in. diameter Ti 6Al-4V rivets. The head is barely formed when squeezed to 1[illegible],000 [illegible] and was cracked diagonally across the head.

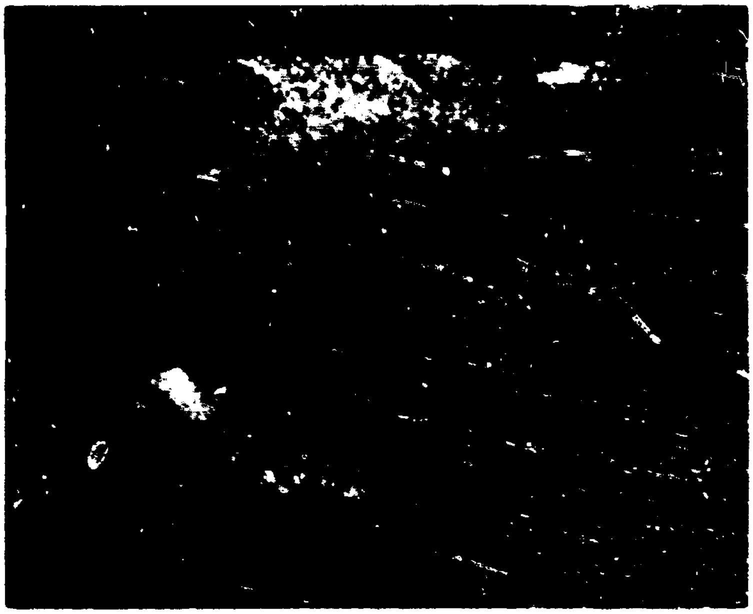
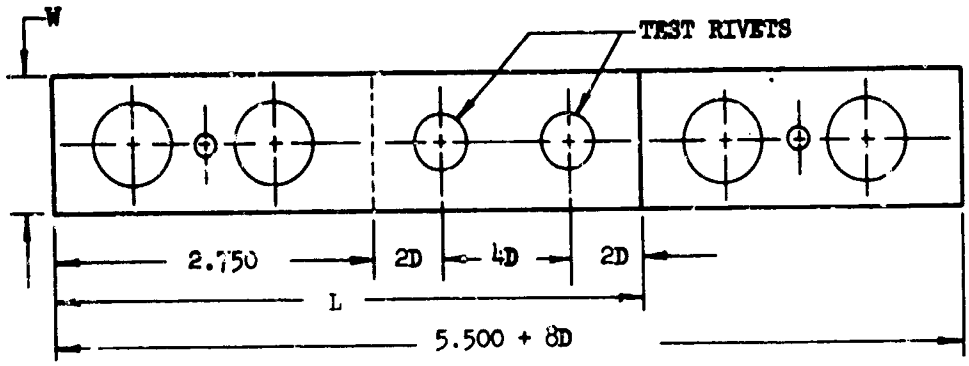
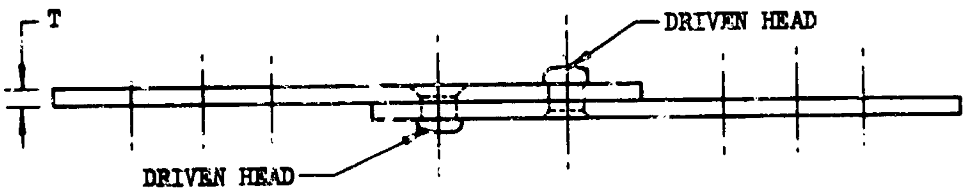


Illustration of improved headability of current Ti-6Al-4V rivets headed with flat dies. The 1/4 in. diameter rivets were squeezed to 3[illegible],000 lbs and the head is approximately 1.[illegible] times the shank diameter.

Figure 4-5. Headability Comparison Showing Heat Treatment Improvement





D	0.125	0.188	0.250
W	0.500	0.750	1.000
T	0.045	0.070	0.090
L	3.750	4.250	4.750

D = Nominal Fastener Diameter
All Dimensions in Inches

Figure 4-6. Joint Fatigue Test Specimen

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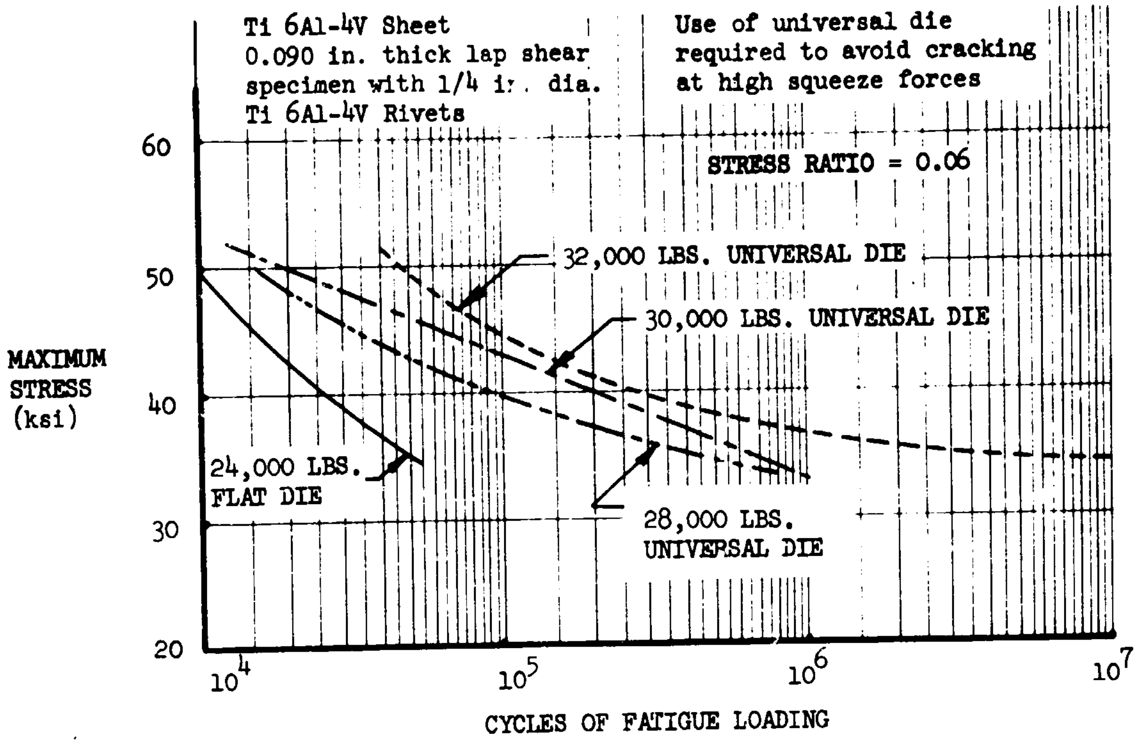

Figure 4-7. Heading Force Study, Ti-6Al-4V Rivets

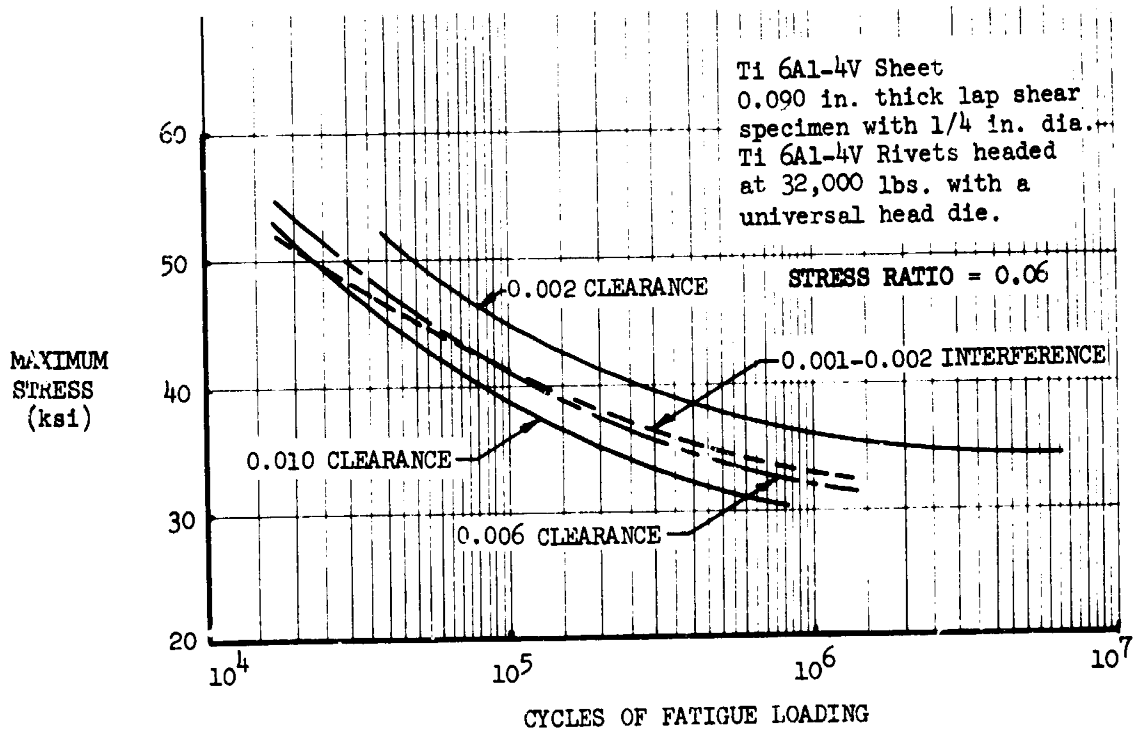

Figure 4-8. Hole Size Study, Ti-6Al-4V Rivets

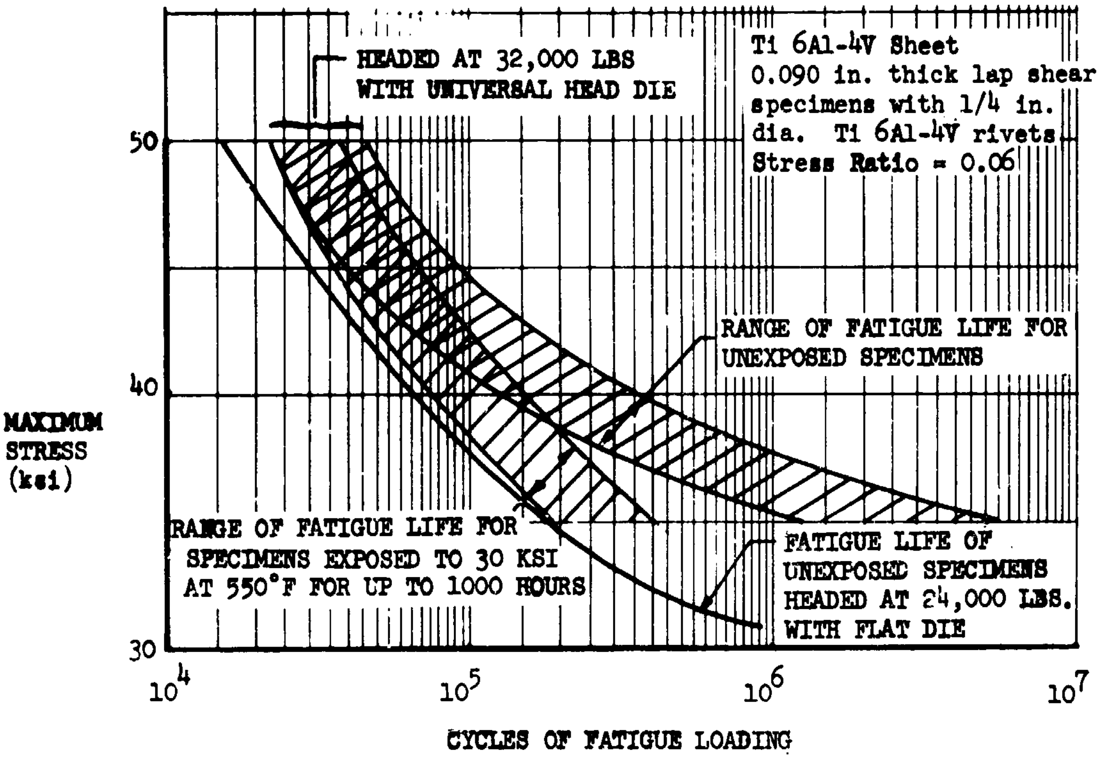

Figure 4-9. Exposure Study, Ti-6Al-4V Rivets

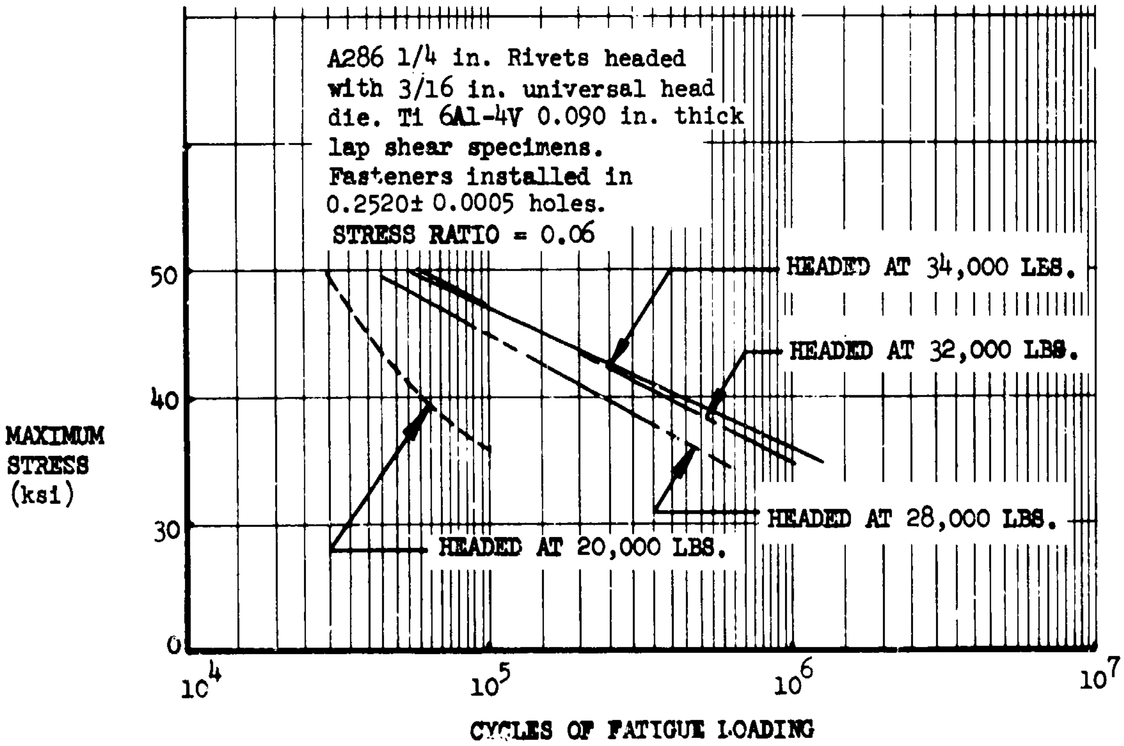

Figure 4-10. Heading Force Study, A286 Rivets

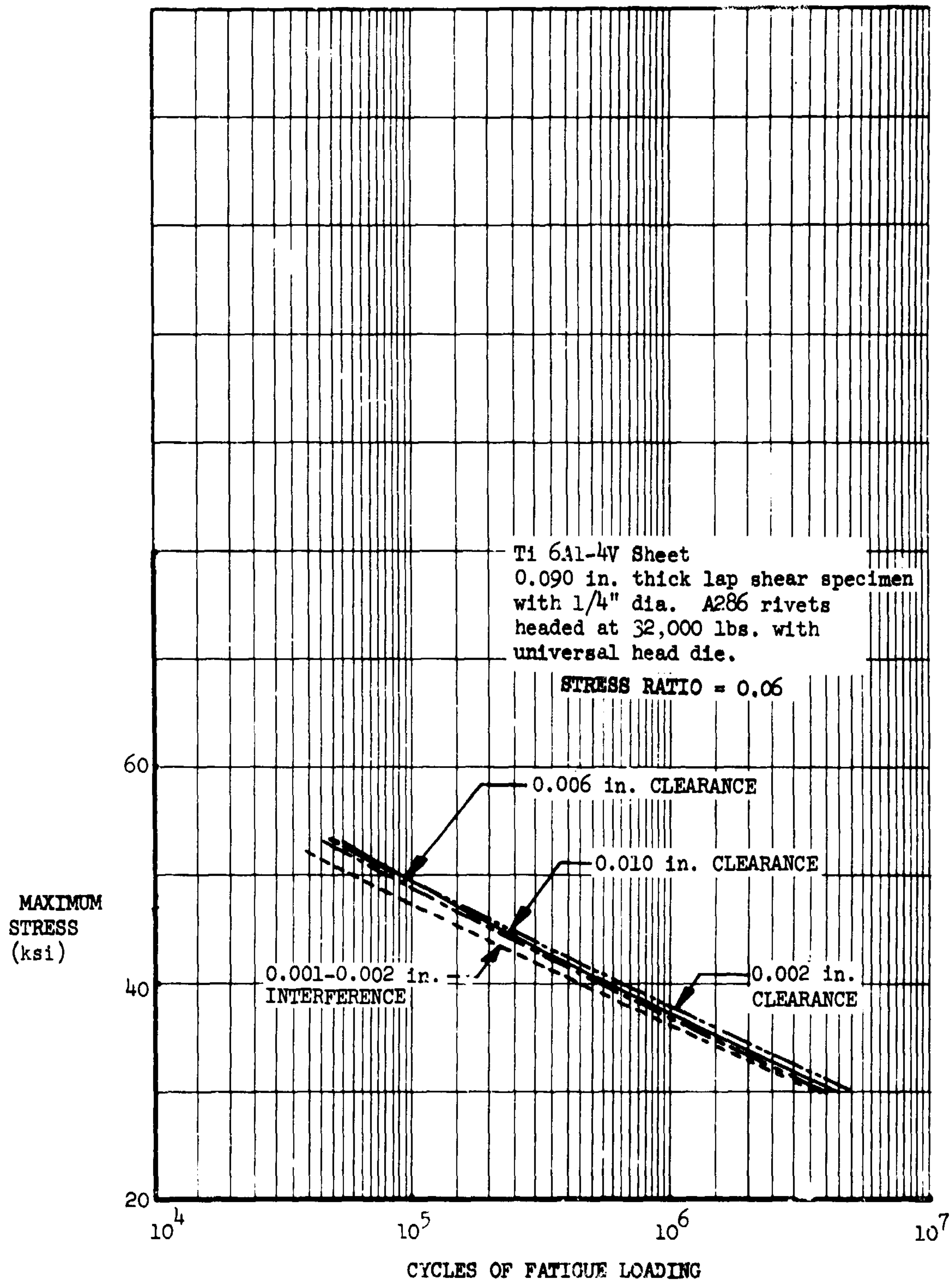

Figure 4-11. Hole size Study, A286 Rivets

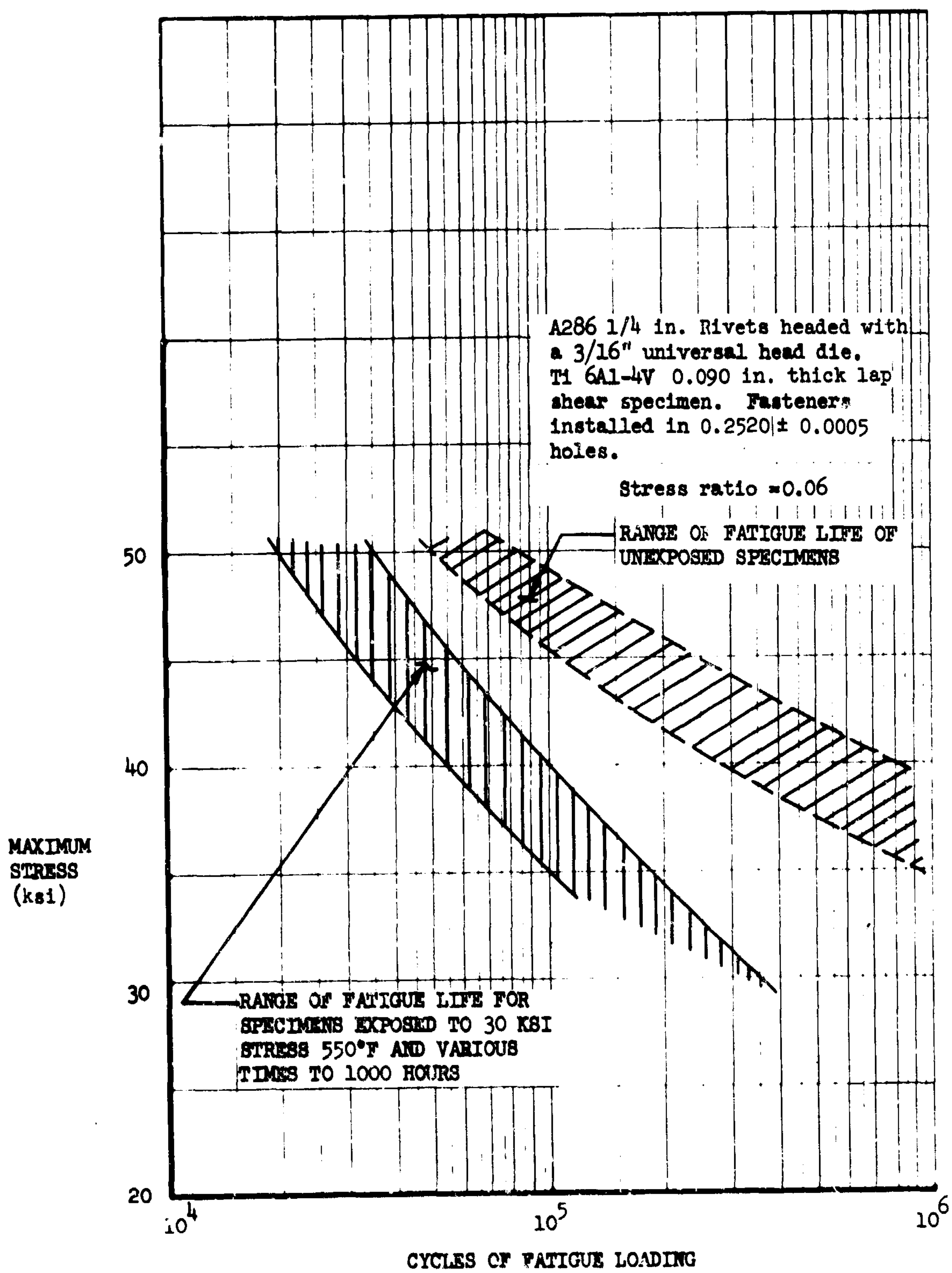

Figure 4-12. Exposure Study, A286 Rivets

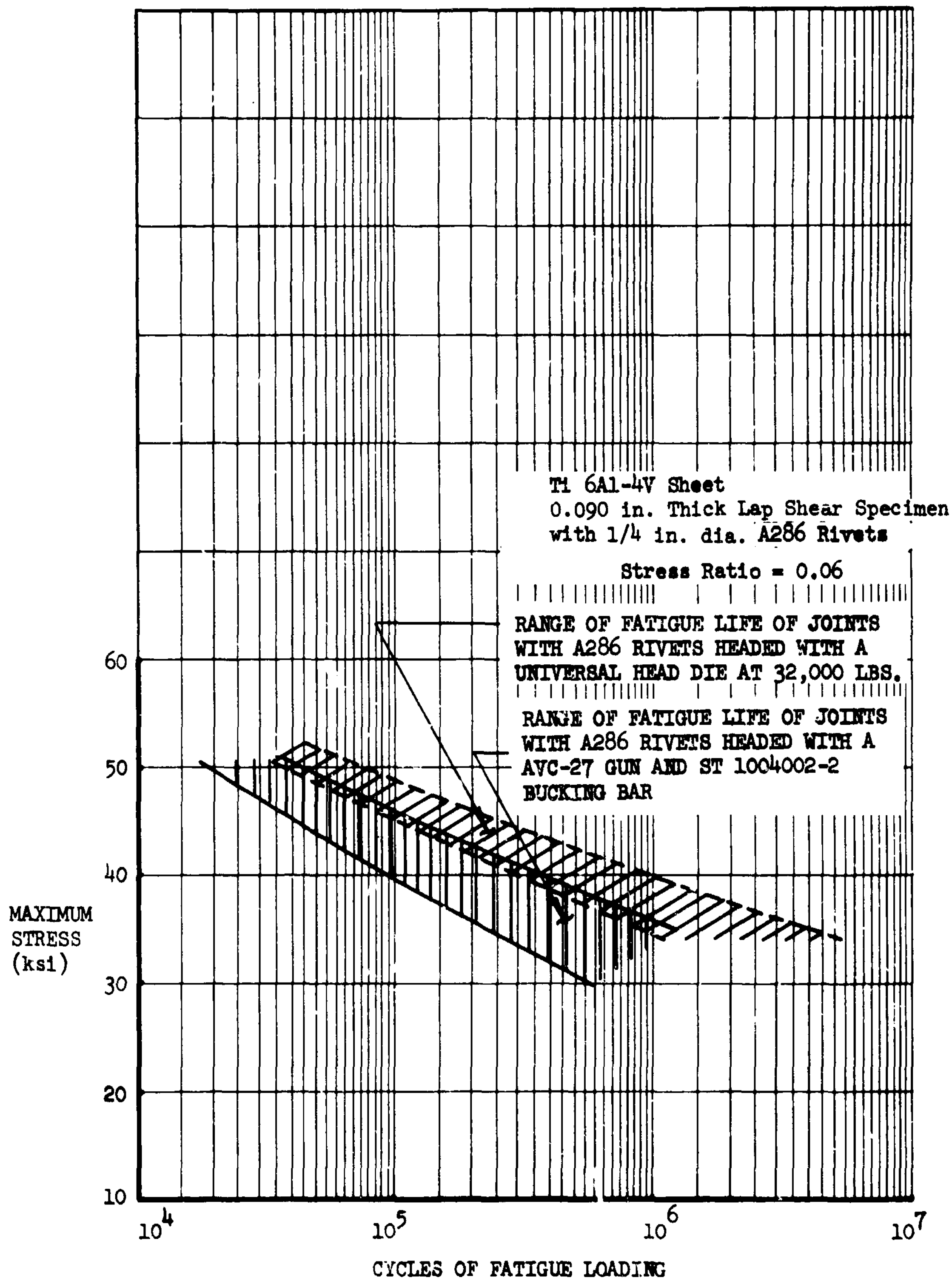

Figure 4-13. Heading Method Study, A286 Rivets

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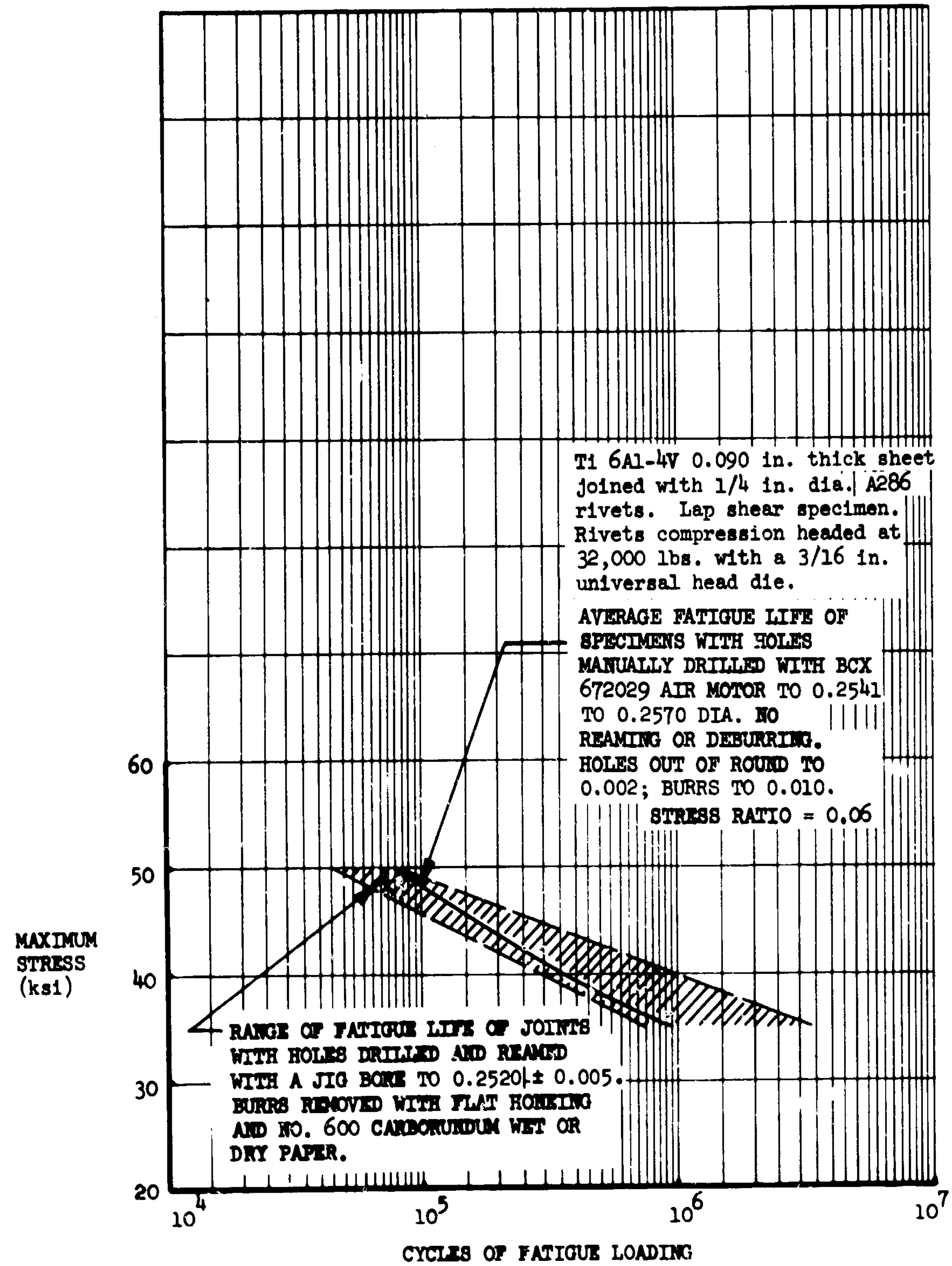

Figure 4-14. Manually and Precision Drilled Hole Study, A286 Rivets

Table 4-C. Room and Elevated Temperature Strengths of A286 Blind Rivets

Nominal Diameter (Inches)	Test Condition	Ultimate Double Shear Strength (lb)
0.187	Room Temperature Test No Exposure	5,840 5,820 6,120
	Room Temperature Test after 1,000 Hours at 550°F	6,200 6,100 6.175
	550°F Test After 1,000 Hours at 550° F	5,500 5,500 5,400
		Ultimate Tensile Strength (lb)
0.187	Room Temperature Test No Exposure	1,690 1,755 1,865
	Room Temperature Test after 1,000 Hours at 550°F	2,050 2,075 2,385
	550°F Test After 1,000 Hours at 550° F	1,950 1,990 2,390

and availability. Room temperature shear and tensile strength values are shown below.

These panel fasteners meet or exceed the strength requirements of Military Specification MIL-F-22978.

Camloc 4002 series quarter turn panel fasteners are used where high strength fasteners are not required. These panel fasteners meet the strength requirements of Military Specification MIL-F-5591, are suitable for use to 700°F, and have proved satisfactory in commercial airplanes.

	Fastener Diameter		
Strength Values	1/4-Inch	5/16-Inch	3/8-Inch
Ultimate Single Shear (Pounds)	2,100	3,200	5,800
Ultimate Tensile Load (Pounds)	1,800	2,200	3,300

Table 4-D. Room and Elevated Temperature Strengths of A286 Blind Bolts

Nominal Diameter (Inches)	Test Conditions	Ultimate Double Shear Strength (Pounds)
0.25	Room Temperature No Exposure	10,120 10,020 10,420
	Room Temperature Test After 1000 Hours at 550°F	10,425 10,475 10,500
	500°F Test After 1000 Hours at 550°F	9,000 8,740 8,780
		Ultimate Tensile Strength (lb)
0.25	Room Temperature No Exposure	3,435 3,200 3,375
	Room Temperature Test After 1000 Hours at 550°F	4,280 4,825 2,765
	500°F Test After 1000 Hours at 550°F	3,730 3,795 3,750

4.1.7 Hole Preparation, Fasteners

4.1.7.1 Drilling
Tools, which provide integral cutting edges to produce all configuration requirements of the hole, are used wherever positive power feed drilling equipment can be used and precision holes are required. These tools produce a finished hole in one pass rather than the three pass process of drilling, reaming, and countersinking. Further, they provide maximum assurance of quality and consistency of drilled precision holes, as well as reduced fabrication time.

4.1.7.2 Punching
The process for producing class II holes by punching is controlled by company specification. This process has produced 0.25 inch diameter punched holes in annealed Ti 6Al-4V in thicknesses from 0.040 to 0.140 inches. Process development included a study of the following:

a. Die Clearance — 0.001 to 0.015 inches

b. Punch Point Shape — 20 degree chisel to flat

c. Punch Pressure — 3,000 lbs. for 0.040 in. thickness to 11,000 lbs. for 0.140 in. thickness.

The best quality holes were produced with a flat point punch with 0.001 inch die clearance. These conditions produced holes with a diameter tolerance of ± 0.002 inches, a surface roughness of less than 50 RHR without delamination.

4.1.7.3 Dimpling

Hot ram coin dimpling is used in those cases where skin gages are too thin to permit countersinking. Dimpling processes, controlled by company specification, produce good quality dimples in Ti 6Al-4V without cracks or orange peel. These processes are used to produce dimples for fasteners in sheet thicknesses from 0.020 to 0.060 inches.

4.1.7.4 Cold Working

A cold working process controlled by company specification is used to improve hole quality for improved fatigue life. The process uses portable tooling, improves hole roundness and finish, and does not require cleaning afterwards. Cold working is done by installing a split sleeve in the hole and pulling a tapered mandrel through the sleeve (see Fig. 4-15).

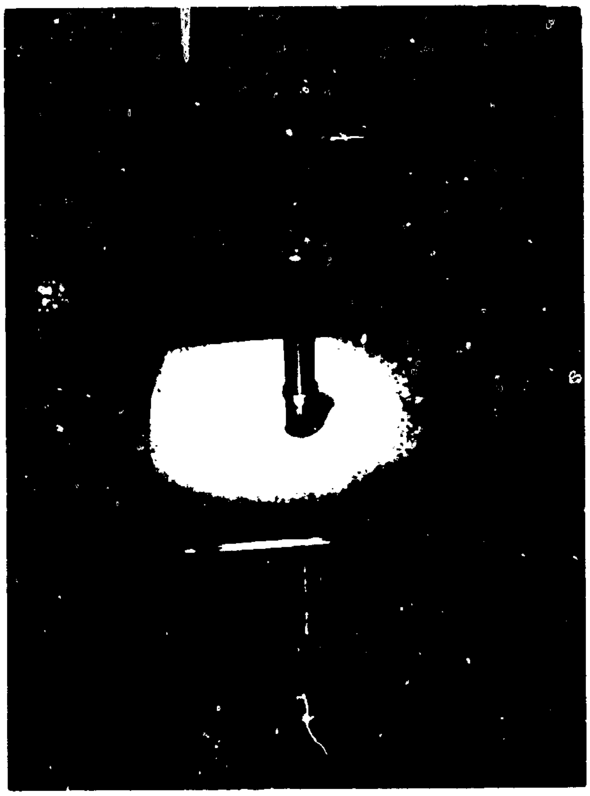

Figure 4-15. Installation Setup for Cold Working Fastener Holes

The maximum interference obtainable is determined by the strength and size of the mandrel and the capacity of the pneumatic puller. A 0.25 in. hole in 0.090-in. thick Ti 6Al-4V requires pulling load of 700 lb at 0.008-in. interference and 1200 lb at 0.010-in. interference. Improvement in hole roundness by cold working is shown in Fig. 4-16.

4.2 BEARINGS

4.2.1 Rolling Element Bearings

Ball, roller, and needle bearings are used for applications which require low frictional torque or high rotating speed. These bearings are used in fairlead, control pulley, bell crank, control rod, torque tube, and track roller applications.

Environmental factors which affect bearing materials and design selection are temperature extremes, corrosive environment, altitude, and presence of extraneous fluid media (such as hydraulic fluids, cleaning fluids, fuel, or water). Operational requirements which affect the bearing material and design selection are magnitude and direction of applied load, allowable envelope size, maximum allowable torque, and rate and types of motion (rotating or oscillatory).

The specific combination of bearing and seal materials, lubricant, exposed surface finishes, and bearing design configuration are determined for each individual application.

To aid in bearing design and material selection, the data sheet shown in Fig. 4-17 will be completed for each bearing application. After reviewing the data sheets, bearing and lubrication specialists provide the specific design and material recommendation. The materials and design are selected to provide maximum bearing service life prior to relubrication or replacement.

4.2.1.1 Material Selection

For antifriction bearings operating in the -65 to 300°F temperature range, the following materials are used:

Bearing Races and Rolling Elements	AISI 52100 vacuum degassed steel stabilized for 300°F operation
Retainer	C 1008 low carbon steel
Exposed Bearing Surfaces	Nickel plated 0.003 inches thick
Rod End Body	17-4PH corrosion resistant steel

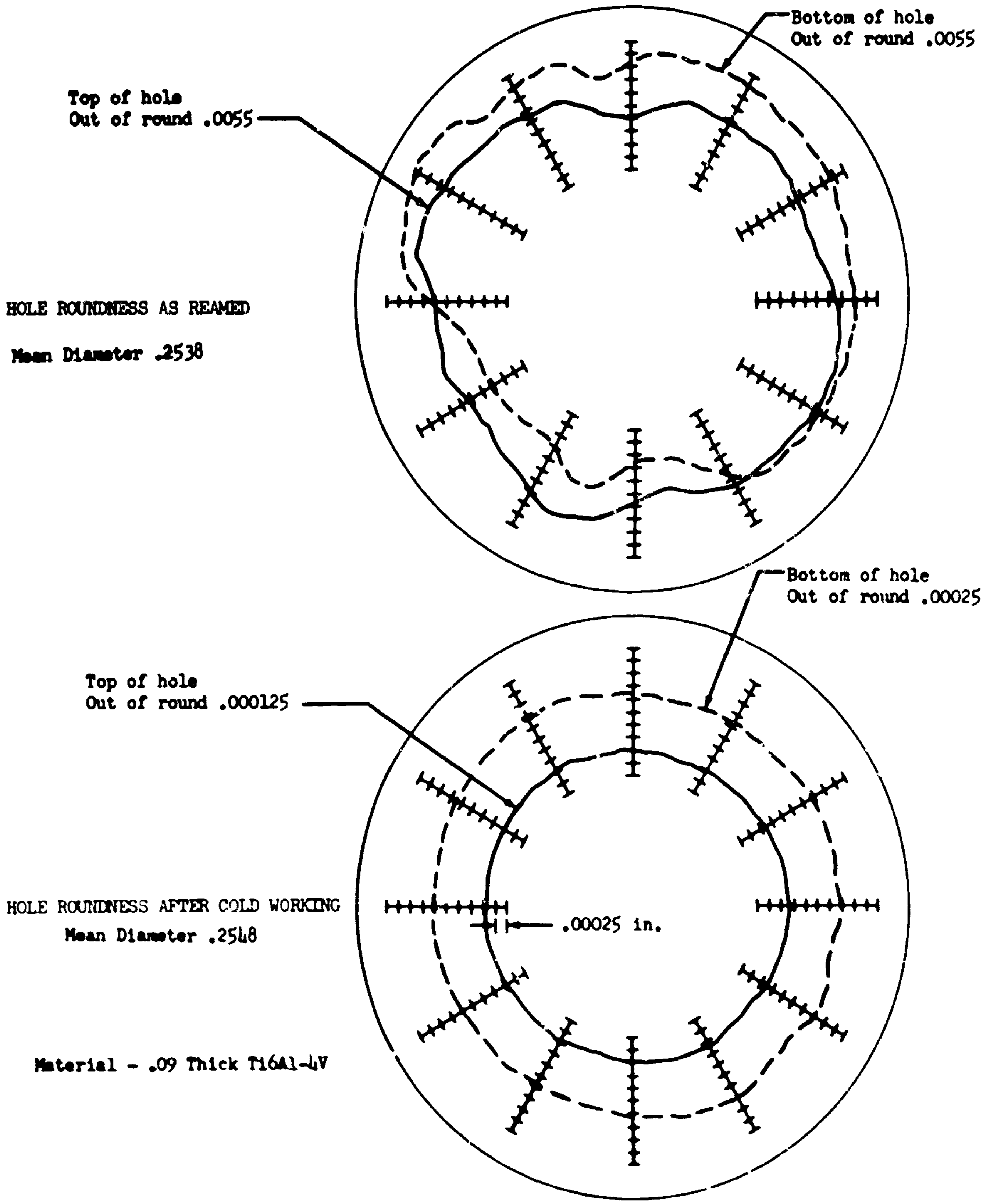

Figure 4-16. Influence of Cold Working on Hole Roundness

B2707 ANTI-FRICTION BEARING DATA SHEET

Date 8-3-66

Design Group CONTROLS Mechanism or Installation ENGINE THRUST CONTROL Sheet No. 1

Designer WINTERER Phone 5-7858 Ref. Layout or Assy. No. C-61

BEARING NO.: AN 201KPBA MFR & NUMBER FAFNIR KPBA

BEARING DIMENSIONS: Bore .5000 O.D. 1.1250 Width .375

APPLICATION: (Describe) SUPPORT OF ENGINE THRUST DRUM ON COUNTERSHAFT BENEATH CONTROL STAND Qty Required Per Assy. 4

BEARING DESCRIPTION:

A. TYPE (Circle): (Ball) Needle Roller

B. MATERIAL: Inner Race SAE 52100 Outer Race SAE 52100 Rolling Elements MIL-B-7949
Cage NONE Seals or Shields FAFNIR PLYA-SEAL

C. SURFACE TREATMENT Inner Race I.D. NONE Outer Race O.D. CLAD PLATE

DESIGN CONDITIONS

A. LOADING:

1. Static
   - (a) Maximum static limit load 120 LB (THRUST) lbs 1200 (RADIAL) lbs
   - (b) "Equivalent" load (for combined loading) "E" 1480 lbs
   - (c) Static capacity or allowable static load "P" 3910 lbs
2. Dynamic
   - (a) Normal operating load - Calculated or estimated 20 (THRUST) lbs 200 (RADIAL) lbs
   - (b) "Equivalent" normal operating load (For combined loading) 246 lbs
   - (c) Dynamic capacity of bearing for life required 2870/1.7 = 1700 lbs

Allowable Torque (Max) ____ Max Load at Max Temp 1200 LB Max Load at Min Temp 1200 LB

Maximum Allowable Bearing Looseness at Max Temp ____ (RADIAL) ____ (AXIAL) at Min Temp ____ (RADIAL) ____ (AXIAL)

B. LIFE:

1. Required Operational Life — (REVOLUTIONS) (HOURS) or 12,500 (CYCLES)
2. Calculated Life at normal or "equiv." operating load ____ (REVOLUTIONS) or 1×10^6 PLUS (CYCLES) ____ (HOURS)

C. OPERATION:

1. Speed — (RPM) or 90°/SEC (CYCLES/MIN) No. of degrees per cycle 90°
2. Continuous — Intermittent ✓ (Check) Rotation ✓ IR ____ Or (Check)
3. Temp. Profile -65°F - +160°F (TIME-TEMPERATURE RELATIONSHIP PER FLIGHT) (TOTAL HRS./FLIGHT)
4. Vibration Envelope TO BE DETERMINED Frequency (cps) TO BE DETERMINED

D. INSTALLATION:

1. Housing Material MAG Housing fit-up: Loose ____ Tight ____ Press ____
2. Retention in Housing ____ (CLAMP-UP) ✓ (STAKED) ____ (BONDED) ____ (FLOATING) ____ (OTHER)

E. LUBRICATION:

1. Grease Packed - Spec. No. MIL-G-23827 Oil Bath - Type Oil: NO
2. Provision for relubrication without removal ____ (YES) ✓ (NO) Will bearing operate dry? NO

F. ADDITIONAL COMMENTS:

Materials Tech. Unit Review Comments:

Figure 4-17. Anti-friction Bearing Data Sheet

Bearing Seals	Glass fiber reinforced Teflon or annealed Teflon
Lubricant	MIL-G-25760

For antifriction bearings operating in the -65 to 450°F temperature range, the following materials are used:

Bearing Races and Rolling Elements	AISI 440-C or 440-C modified (14Cr-4Mo) vacuum degassed steel stabilized for 450°F operation
Retainer	AISI 305 or 430 stainless steel or Beryllium Copper
Exposed Bearing Surface Finish	None required
Rod End Body	17-4PH
Bearing Seals	Glass fiber reinforced Teflon or annealed Teflon
Lubricant	Selected from those listed in Par. 3.7.1

4.2.1.2 Design Configurations

a. Control Bearings

Airplane control applications utilize control and fairlead pulleys, bell cranks, and rod end bearings. These bearings are required to support light to medium loads under oscillating motion at low torque levels.

Both full complement and retainer bearings are used. Bearings with a retainer are used for applications which require minimum torque.

Various design types are used to compensate for misalignment resulting from installation tolerances or structural deflection. These types are:

- single or double-row self aligning ball bearings.
- single or double-row concave roller bearings.

For most applications the bearings are prelubricated with grease and sealed. For some applications, where grease lubrication is not practical, a solid lubricant compact material is used in the retainer.

b. Torque Tube Bearings

Torque tube applications require bearings to support medium loads at speeds from 200 to 500 revolutions per minute.

The following design types are used as required.

- Single row ball bearing
- External self aligning ball bearing
- Internal self aligning double row roller bearing

c. Track Roller Bearings

Needle bearings are used in control surface track applications where support of heavy loads at slow rotational speeds is required. The bearings are sealed and the outer races are contour controlled to provide maximum bearing to track contact area. In lightly loaded track applications, ball bearing track rollers may be used.

Important factors affecting track roller bearing and track performance are the track material hardness and wear resistance. The track material selected is 9 Ni-4Co-.30C at 220 KSI minimum ultimate tensile strength. Further discussion of this material is in Par. 2.2.1.

4.2.1.3 Developmental Test Evaluation

An extensive test program is being conducted to determine the cumulative environmental effects on hardness, dimensional stability, and oxidation and corrosion resistance of the bearing materials. Seal and lubricant performance is also being evaluated. Tests are being performed at temperatures from -65° to 450°F and atmospheric pressures encountered at B-2707 cruise altitude. Additional bearing development programs, sponsored by The Boeing Company, are being conducted by three aircraft bearing companies.

Phase I will evaluate lubricant performance and phase II testing will develop bearing load life data using the best lubricant selected in phase I.

a. Ball Bearing Tests

The Fafnir Bearing Company is testing 9307 size ball bearings with 440-C races and balls. Test conditions are as follows:

Ambient Temperature	450°F
Applied Load	2,000 pounds

Oscillation Angle	±45 degrees
Oscillation Rate	5 cycles per minute

b. Concave Roller Bearing Tests
Rex Chainbelt Incorporated (Shafer Bearing Division) is evaluating concave roller bearing performance at 450°F. Test bearings are double row roller bearings with 440-C races and rollers and Armalon (Teflon impregnated fiber glass) seals. A photograph of the test machine is shown in Fig. 4-18.

c. Track Roller Bearing Tests
The Torrington Company will be testing track roller bearings at 400°F. The bearings have 440-C races and rollers and Teflon seals. The bearing size and test conditions are as follows:

Bearing Size	0.875 inches bore, 2 inches O.D.
Applied Load	8,000 pounds
Track Stroke	6.25 and 30 in.

A photograph of the test machine is shown in Fig. 4-19.

d. Company Test Programs
Antifriction control bearings are tested in the machine shown in Fig. 4-20 to determine load life and torque data for preparation of design allowables.

A test machine is being designed to test track roller bearings. This machine will be used to develop load life and torque data for preparation of track roller design allowables. In addition to the above testing, work is being conducted to evaluate the use of a Boeing developed lubricant compact material in retainers. Lubricant compact materials are described in Sec. 3.7.2.

4.2.2 Sliding Surface Bearings
Plain journal bearings, plain spherical bearings, and sliding track bearings are included in this category. These bearings are used in preference to rolling element bearings when loads are high, bearing surface speed is low, space for the bearing is limited, and torque requirements are not critical. These bearings are used in actuator head and rod end, control surface hinge, landing gear door hinge and trunnion, engine mount, engine throttle linkage, and track applications. Sliding surface bearings offer maximum load capacity in a minimum envelope and are used in all powered systems.

4.2.2.1 Material Selection
The limiting materials in achieving long bearing life are those at the sliding surface interface and not necessarily the backup materials which can be made of heat and corrosion resisting metals. The metal, coating, plating, or lubricant at the interface is the key material. Test data show that several material combinations are available for long life bearings. These combinations are as follows:

a. Materials such as 17-4PH or NM-100 stainless steel sliding against Vitro Lube 1220 dry film lubricant coating on 17-4PH steel are used to 700°F. The long life of this combination is made possible by the use of Vitro Lube 1220. Of the more than twenty potential high temperature dry films evaluated at The Boeing Company, Vitro Lube 1220 exhibited longer wear life by a ratio of 4 to 1 over the second best material. Tests conducted on Vitro Lube at 10,000 psi and 450°F yielded an average wear life of 83,000 cycles. This life was in very close agreement with the life data published by North American Aviation in their paper, The Development and Testing of a New Ceramic-Bonded Dry Film Lubricant, by M. A. Hagan and F. J. Williams (Ref. 56). For additional information see Sec. 3.7.3.

b. Materials such as 17-4PH or NM-100 stainless steel running against a high temperature solid lubricant compact retained in a metal holder are used up to 700°F. The compact material of this combination was developed by The Boeing Company. Several compositions of this compact have been evaluated and results to date demonstrate its feasibility for use from -65° to 700°F and for loads to 10,000 psi. Development toward improving this compact material is being conducted under Air Force Contract AF 33(615)-3981, Airframe Bearings for Advanced Vehicles (Ref. 57). For load life data, physical properties, mechanical properties, and friction and wear data see Sec. 3.7.2.

c. Materials such as 440-C or 17-4PH steel running against a Teflon glass fabric adhesive bonded with Epon 957 are used up to 400°F. This combination has shown superior performance to bearings bonded with other adhesives. Work on this program began in 1962 when it was determined that a rolling element bearing of a reasonable size would not meet the requirements of the wing pivot bearing. Teflon glass fabric adhesive

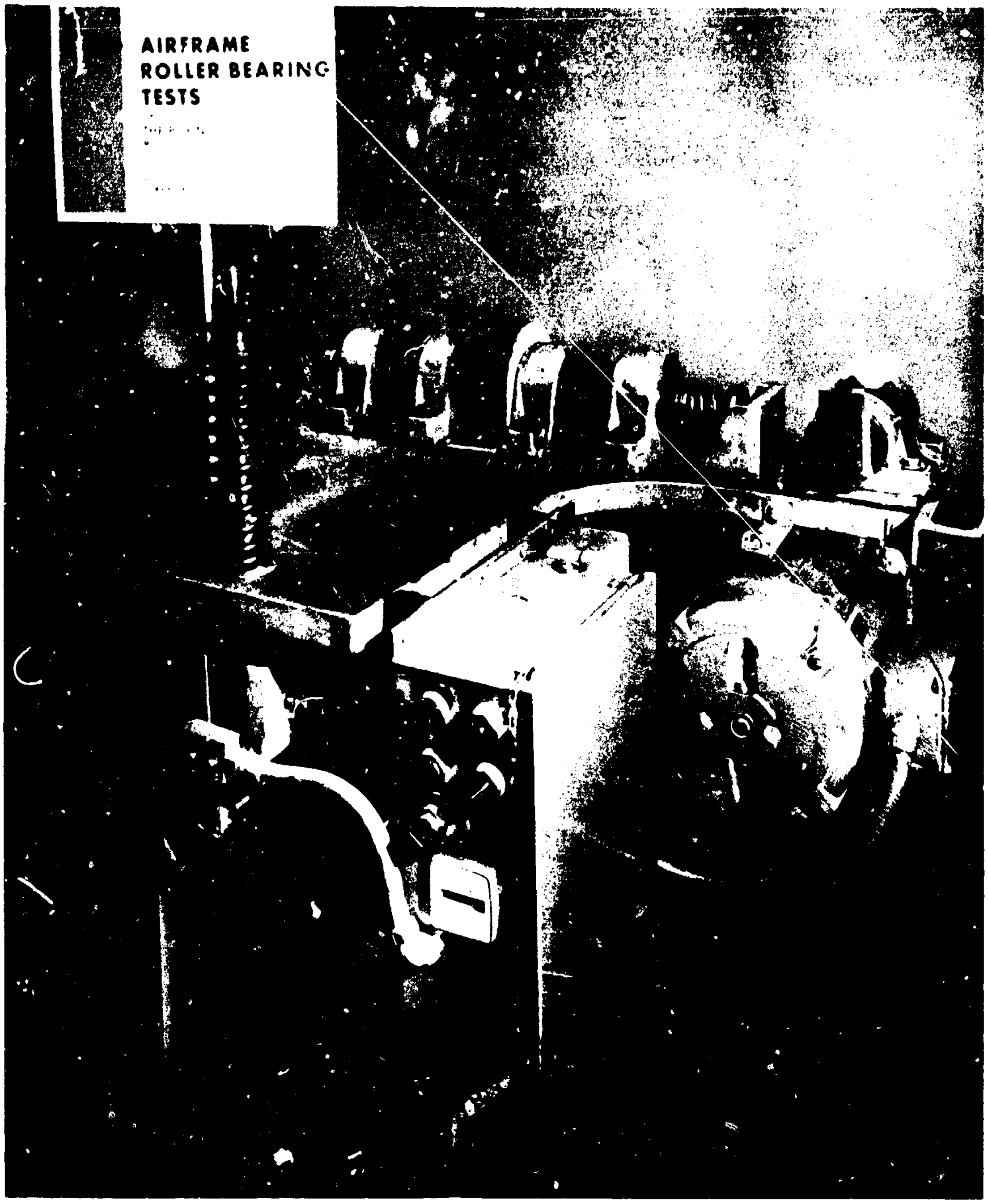

Figure 4-18. Shafer Bearing Test Machine

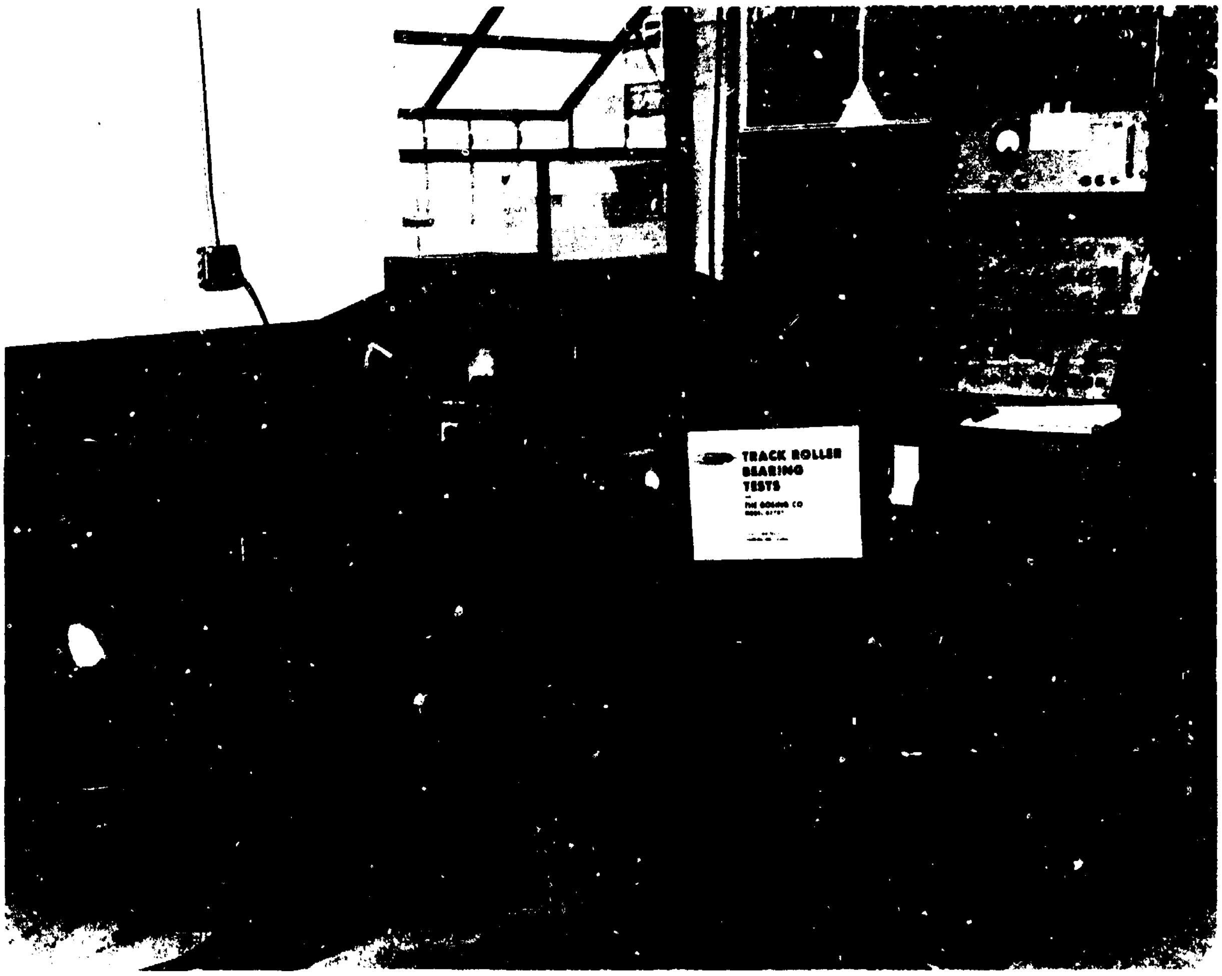

Figure 4-19. Torrington Bearing Test Machine

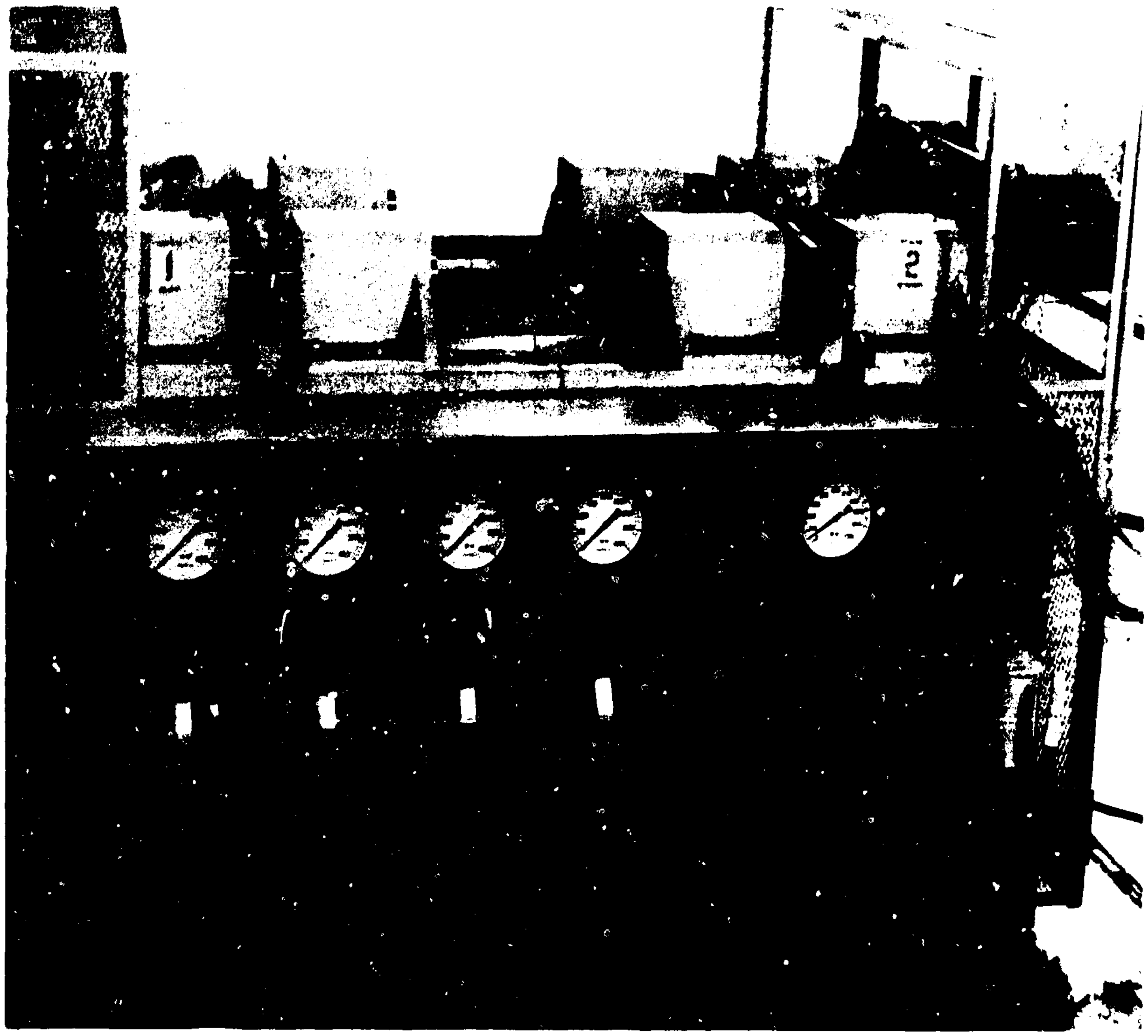

Figure 4-20. Reverse Load, Oscillating Motion, Bearing Test Machine

bonded bearings were evaluated and design data are being obtained from a continuing test program in which a shaft is oscillated in a plain journal bearing. Materials tested include Teflon cotton, Teflon dacron, and Teflon fiberglass fabrics bonded with the adhesives shown in Table 4-E. Testing at temperatures up to 450°F and 20,000 psi show that Teflon fiberglass fabric bonded with Shell Chemical Company's Epon 957 results in longer and more consistent wear life than other combinations tested. This has been substantiated by more than 300 tests on bearings made by The Boeing Company and by bearing manufacturers. A summary of the data is shown in Table 4-F. A photograph of the machine used in these tests is shown in Fig. 4-21. A photograph of equipment used to measure wear by electrical resistance techniques is shown in Fig. 4-22.

The effects of fluid contaminants on bearing life was investigated. A screening test consisted of cycling the bearing to failure after 10 days immersion in the particular fluid which was at 200°F. After exposure to this severe environment new bearings were exposed to an environmental cycle more closely simulating potential airplane environment. This test consisted of immersing the bearing in the fluid at room temperature for 22 hr, removing and drying in air for two hours at 300°F. This cycle was repeated ten times and then the bearing was tested. Results of this environmental testing are shown in Fig. 4-23 and are compared to the minimum bearing life of unexposed bearings.

Valid correlation of the data to results of a test program using a large diameter fabric lined bearing is depicted by the quarter and full scale wing pivot bearing program reported in Document Airframe Design-Part E, V2B2707-9.

d. Wear, temperature, and corrosion resistant metals such as NM-100, AFC-77, and aluminum bronze, are used in conjunction with grease lubrication. Greases such as MIL-G-25760 and the new DuPont PR240AC cover the range from -65° to 450°F. For additional information on greases see Sec. 3.7.1. The materials combination selected depends on the operating temperature, load, contaminating environment, vibration frequency and amplitude, accessibility for relubrication, allowable wear limits, and allowable torque.

Table 4-E. Adhesives Tested in Bearings

Adhesive Designation	Adhesive Type	Manufacturer
A 5900	Phenolic	Reichold Chemical Co.
AF-31	Nitrile-Phenolic	Minnesota Mining & Manufacturing Co.
XB-131	Modified Epoxy	Minnesota Mining & Manufacturing Co.
XC-131	Modified Epoxy	Minnesota Mining & Manufacturing Co.
Epon 957	Modified Epoxy	Shell Chemical Co.
HT 424	Epoxy Phenolic	American Cyanamid, Bloomingdale Dept.
FXM-34B-34	Polyimide with antioxidant	American Cyanamid, Bloomingdale Dept.
FXM-34B-25 (FM-34)	Polyimide with antioxidant and aluminum filler	American Cyanamid, Bloomingdale Dept.

Table 4-F. Bearing Test Results

Adhesive	Test Temp. (°F)	Test Load (PSI)	Prior Heat Soak Temp. (°F)	Prior Heat Soak Time (Hours)	Cycles Wear Life (Avg.)**	Cycles Wear Life Min.	Max.
Epon 957	300	20,000	None	None	600,000	280,000	869,000
	300	20,000	300	1000	250,000	165,000	336,000
	400	20,000	None	None	480,000	299,000	604,000
	400	20,000	400	1000	175,000	94,000	256,000
	450	20,000	None	None	280,000	256,000	300,000
	450	10,000	450	500	180,000	107,000	250,000
	450	10,000	450	1000	90,000	63,000	117,000
XB-131	*300	20,000	None	None	*276,660	268,696	284,623
AF-31	300	20,000	None	None	205,967	752	1,016,586
A 5900	*300	20,000	None	None	*150,728	98,164	203,292
FXM-34B-34	*300	20,000	None	None	*88,909	76,342	101,476
	*300	20,000	300	500	*66,000	65,188	67,187
	*400	20,000	400	500	*98,143	59,351	136,936
	450	10,000	450	1000	96,767	(ONE TEST)	
HT 424	450	10,000	None	None	45,570	7,530	77,300

*2 Tests

**Failure occurs when oscillating shaft wears through approx. 0.014 in. thick Teflon-F/G liner to the metal ring. Tests were performed on a 2.0 in. diameter bearing oscillated through arc of 120 degrees per cycle (± 30 degrees) at rate of 20 cycles per minute.

As an aid in controlling the selection of materials, the information required for each bearing application is recorded on a data sheet similar to the one shown in Fig. 4-17. These data are reviewed by bearing specialists to ensure proper bearing system design.

4.2.2.2 Design Configuration

a. Plain Spherical Bearings

This type of bearing is used in place of plain journal bearings in applications where misalignment is present. Plain spherical bearings are designed for oscillatory motion on the ball bore and self aligning motion on the ball spherical surface. Lubricant materials are applied to both the ball bore and to the race inside diameter. Since the primary motion will occur on the ball bore, lubricants having low wear rates and friction properties are required at this location. Any of the material combinations listed in Par. 4.2 2.1 are suitable for use.

The race is of split construction held together by a sleeve which also retains the bearing in the housing. The inside surface of the race is accurately ground to match the ball spherical surface. This eliminates the poor conformity of race to ball generally found in swaged race bearing, permits precise control of internal clearances, and reduces bearing looseness resulting from applied load and wear. The ball

Figure 4-21. Oscillating Motion Bearing Test Machine

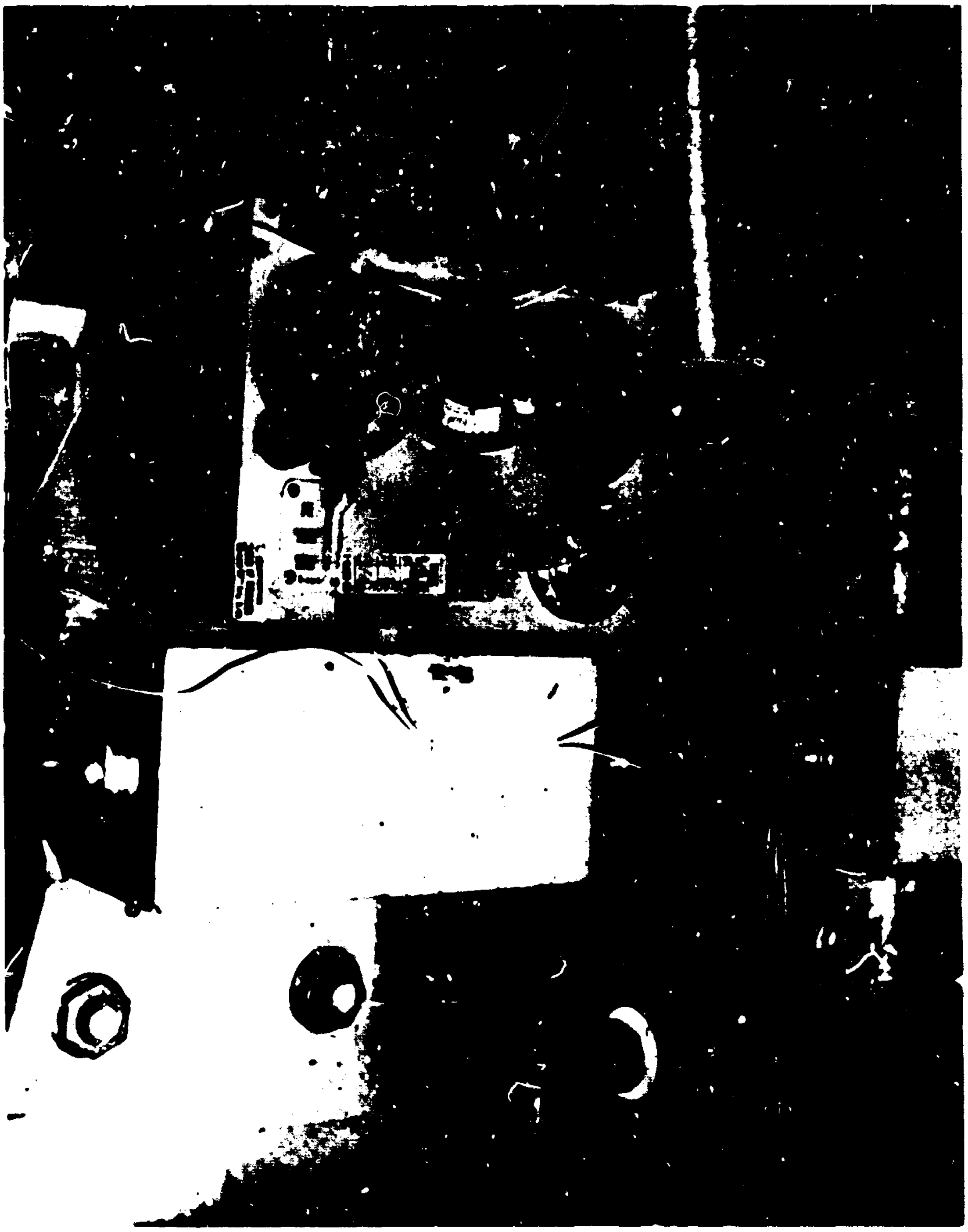

Figure 4-22. Equipment for Wear Measurement by Electrical Resistance Techniques

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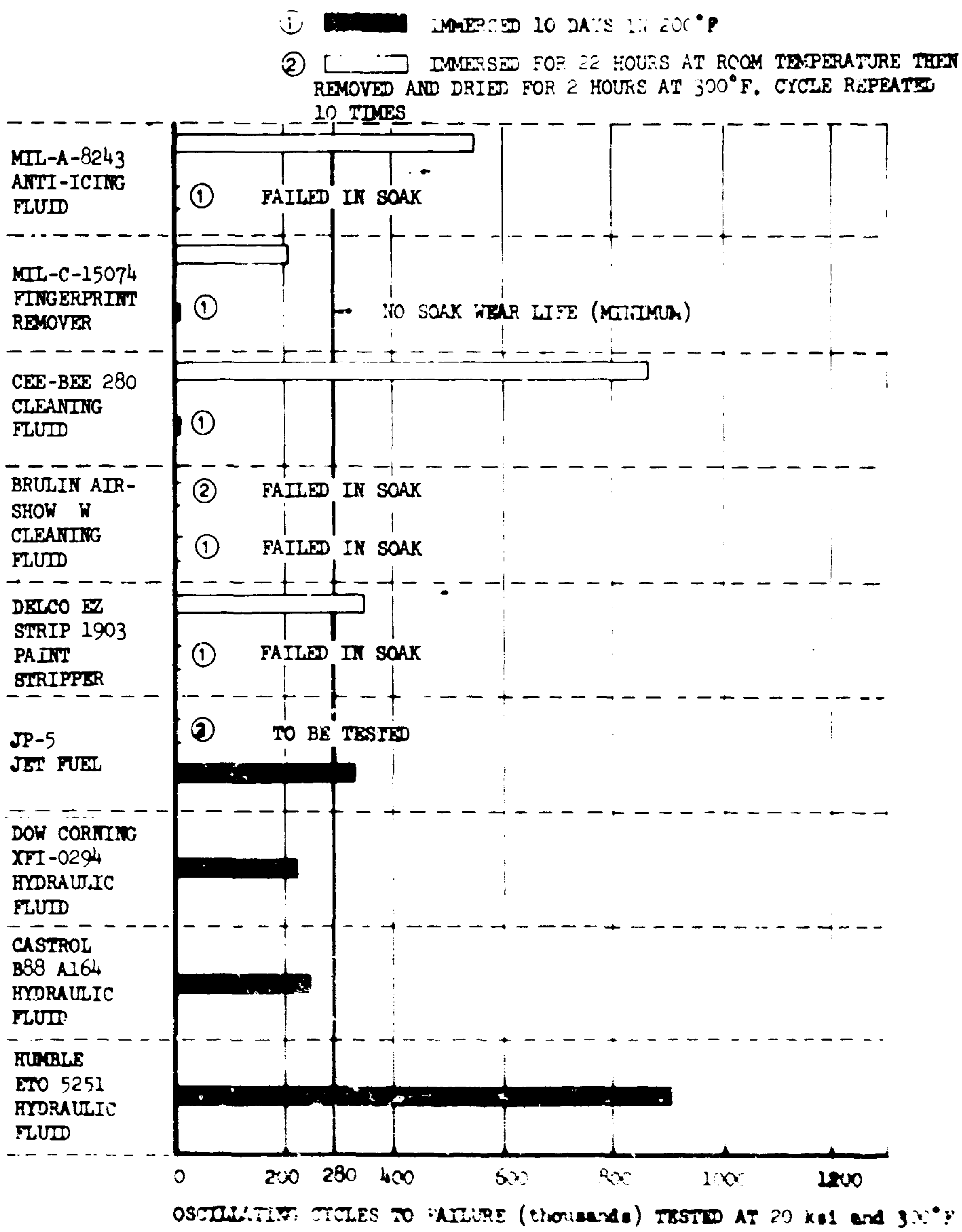

Figure 4-23. Fluid Compatibility Test, Epon 957 Adhesive

bore is bushed to permit positive system clamp up, to prevent bore lubricant damage during pin installation and removal, and to prevent pin damage should the lubricant fail. See Fig. 4-24.

b. **Plain Journal and Sliding Track Bearings**
These bearings utilize the same material lubricant combinations as for the plain spherical bearings.

4.2.2.3 Development Programs
Several development programs have been established to obtain load life curves for sliding surface bearings. These programs are obtaining data on the bearing lubricant material combinations shown in Sec. 4.2.2.1.

Design data on sliding surface bearing material combinations are being obtained in two ways. The first is by reciprocating a coated flat plate under a loaded rider at temperatures to 550°F as shown in Fig. 4-25. The machine used for this testing is shown in Fig. 4-26. The second method is to test plain spherical bearings having the desired metal lubricant combinations on the ball bore and spherical surface. During testing, primary oscillating motion occurs at the interface between the bearing bore and the pin with misalignment occurring on the ball spherical surface. Environmental and operational factors under investigation include applied loads to 40,000 psi, temperatures from 65 to 550°F, altitudes to 65,000 feet, oscillation angles from ± 1 degree to ± 30 degrees, oscillation rates to 60 cycles per minute, relubrication intervals, and contaminating environments. See Fig. 4-20 for a photograph of the test machine.

4.2.2.4 Bearing Retention
Standard mechanical retention methods such as bolted end plates and snap rings are used wherever space and design loads allow. Where space does not allow mechanical retention, the bearings are retained by roller staking or by interference fit. As a positive means of resisting thrust loads, roller staking is used instead of or in addition to interference fit. Bearing retention processes are controlled by a company specification. Bearing outer races are coated with a dry film lubricant to protect Ti 6Al-4V housings during installation and removal of bearings. For interference fit bearings, the bearing outer race or the housing hole is coated to prevent galling and slipping. The application of the coatings is covered by company specifications. Table 4-G shows push out loads for various interference conditions and coatings.

4.3 SYSTEM PARTS
Hydraulic and fuel system fittings and hose assemblies, valves, actuators, tubing support clamps, and metal seals are fabricated from materials compatible with the system operating temperatures, support structure, and other environmental considerations. See D6A10120-1 for further information.

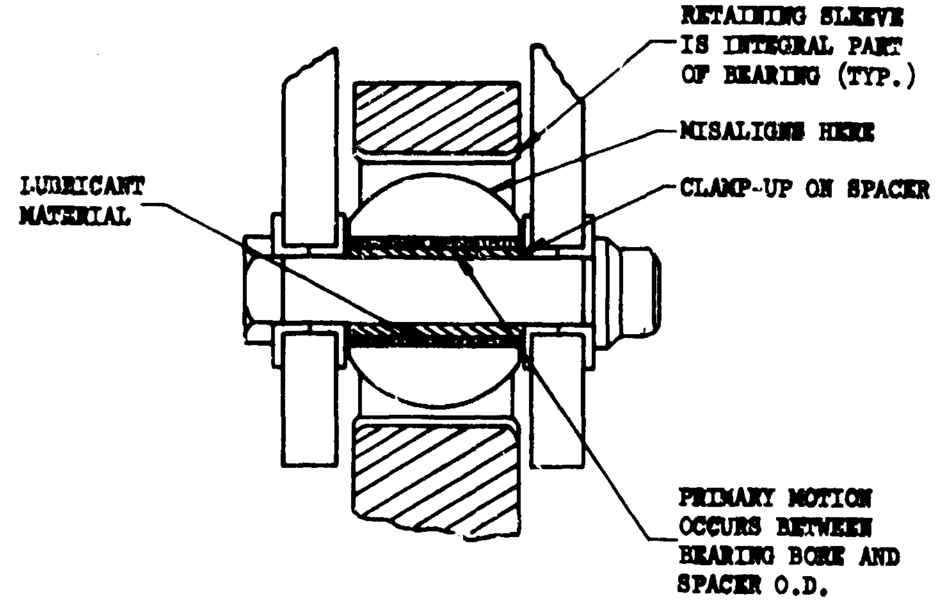

Figure 4-24. Typical Plain Spherical Bearing Installation

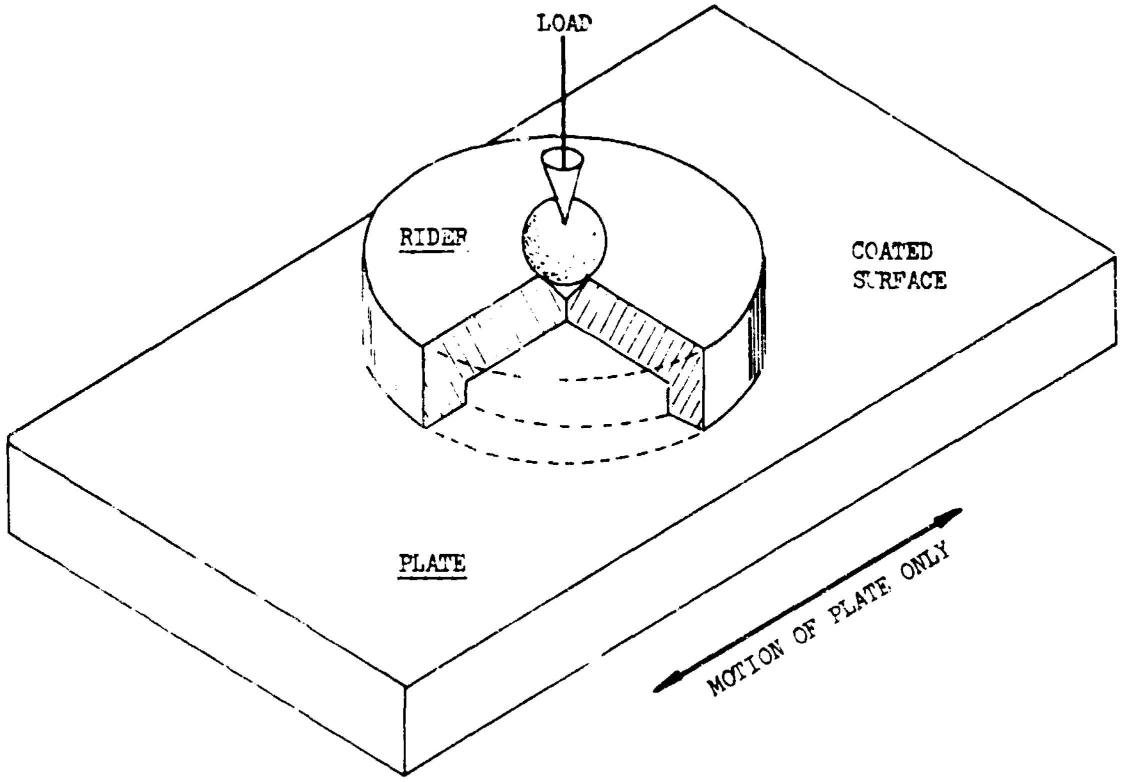

Figure 4-25. Sliding Surface Bearing Material Test Specimens

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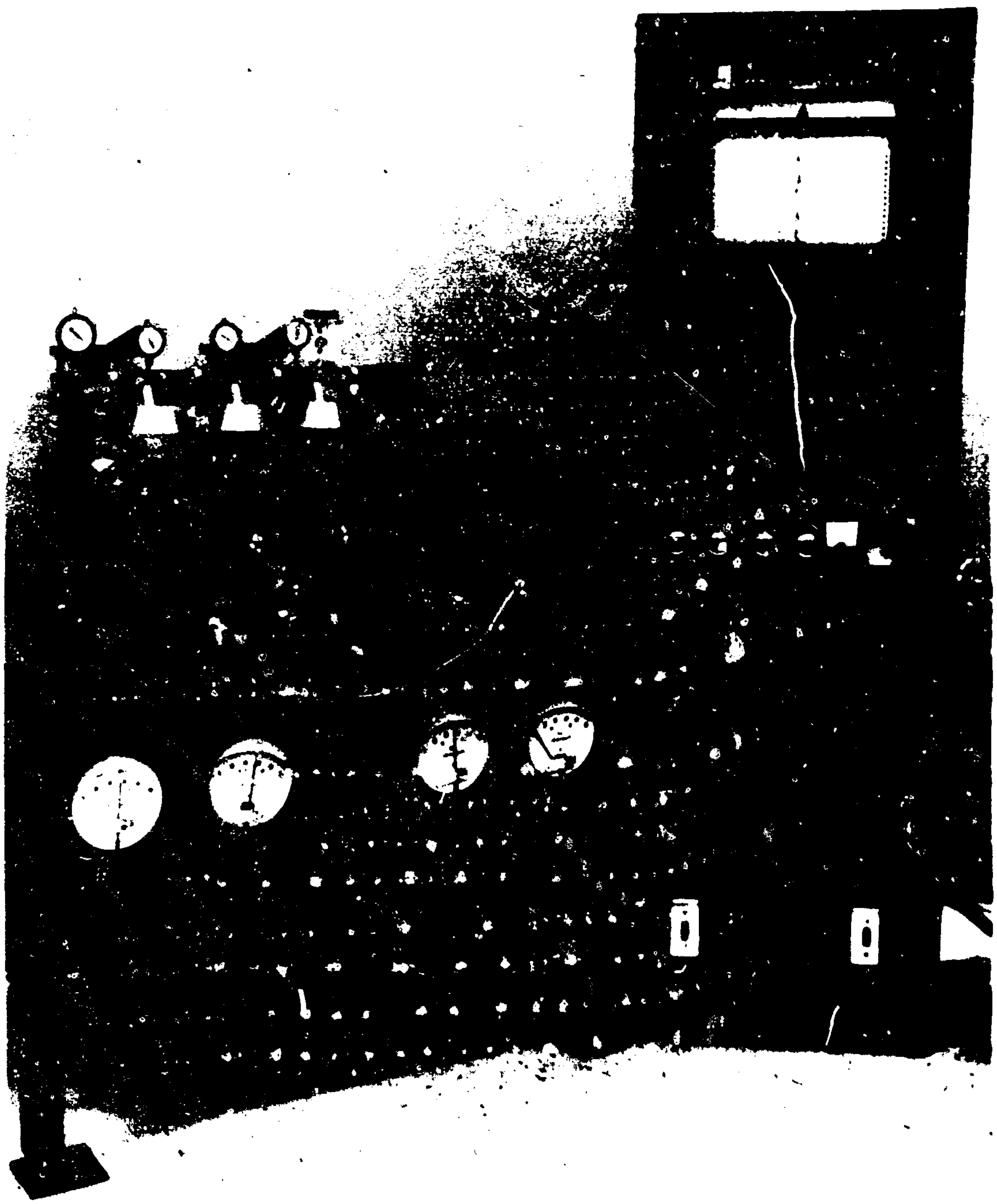

Figure 4-26. Wear and Friction Test Machine

Table 4-G Pushout Loads for Interference Fit Bearings

Coating	Applied To	Pushout Load (lb) At 0. 0005-In Interference	Pushout Load (lb) At 0. 0017-In. Interference
Lubeco 2123	Bearing	1,000	2,600
Titanium Oxide	Bearing or Housing	1,200	3,900
Hard Chrome	Bearing	----	2,900
Watervliet Hard Coating	Housing	1,300	3,600
Uncoated	Housing & Bearing	600	2,300

1 1-in. OD by 0.40 in. wide 17-4PH bearings in Ti 6A1-4V housings

5.0 APPLICABLE DOCUMENTS

5.1 The following documents of the exact issue shown form a part of this document to the extent specified herein. In the event of conflict between documents referred to here and other detailed contents of Sections 2., 3., and 4., the detailed requirements of Sections 2., 3., and 4. take precedence.

FAR 25	Federal Aviation Regulations, Part 25, Air Worthiness Standards, Transport Category Airplanes
MS-33557	Nonstructural Rivets for Blind Attachment, Limitations for Design and Usage
MS-33588A	Nuts and Plate Nuts, Self-Locking, Aircraft Design and Usage Limitations
MS-33633A	Inserts, Screw Threaded, Design and Usage, Limitations for (ASG)
MS-33750	Recess-Hi-Torque, Dimensions of Recess Gage, and Driver for
MIL-A-5090	Adhesives, Heat Resistant, Airframe Structural Metal to Metal
MIL-A-8806	Acoustical Noise Level in Aircraft, General Specification for
MIL-A-9067C	Adhesive Bonding, Process and Inspection Requirements for
MIL-C-5688A	Cable Assemblies, Aircraft, Proof Testing and Prestretching of
MIL-C-6021E (1)	Castings, Classification and Inspection of
MIL-C-6818C	Clamps, Instrument Mountings, Aircraft
MIL-F-007179B	Finishes and Coatings, General Specifications for Protection of Aerospace Weapons Systems, Structures and Parts
MIL-F-22978A	Fastener, Rotary, Quick Operating, High Strength
MIL-F-5991	Fasteners, Panel
MIL-F-7190A	Forgings, Steel, for Aircraft and Special Ordinance Applications
MIL-M-25047B	Marking for Airplanes, Airplane Parts, and Missiles, (Ballistic Missiles Excluded)
MIL-N-25027B (1)	Nut, Self-Locking, 250 Deg. F., 450 Deg. F., and 800 Deg. F., 125 ksi F_{tu}, 60 ksi F_{tu}, 30 ksi F_{tu}
MIL-P-23460A	Pin, Quick Release Positive Locking
MIL-P-9400A (2)	Plastic Laminate Materials and Sandwich Construction, Glass Fiber Base, Low Pressure Aircraft Structural, Process Specification Requirements
MIL-R-5647B	Rivets, Aluminum and Aluminum Alloy

MIL-R-7705A	Radomes, General Specification for
MIL-R-8814 (1)	Rivets, Blind, Non-structural Type
MIL-S-5002A	Surface Treatments and Metallic Coatings for Metal Surfaces of Weapons Systems
MIL-S-7742	Screw Threads, Standard, Optimum Selected Series, General Specification for
MIL-S-7839	Screws, Structural, Aircraft
MIL-S-8802	Sealing Compound, Temperature Resistant Integral Fuel Tanks and Fuel Cells, Cavities, High Adhesion
MIL-S-8879	Screw Threads, Controlled Radius Root with Increased Minor Diameter, General
MIL-T-5842A (1)	Transparent Areas, Anti-Icing, Defrosting and Defogging Systems, General Specification for
MIL-STD-10A	Surface Roughness, Waviness and Lay
MIL-STD-143	Specifications and Standards, Order of Precedence for Selection of
MIL-STD-453	Inspection, Radiographic

Air Force Systems Command Manual 80-1 HIAD

MIL-HDBK-5	Metallic Materials and Elements for Flight Vehicular Structures
NAS 618	Fastener - Recommended Shank, Hole and Head to Shank Fillet Radius Limit for
NAS 621	Fasteners - Titanium Alloy Procurement Specification
NAS 1332	Pin, Quick Release Positive Locking, Single and Double Acting
NAS 1347	Identification of Fasteners
NAS 1400	Rivet - Blind, Self-Plugging, Mechanically Locked Spindle
FTMS No. 141	Paint, Varnish, Lacquer and Related Materials, Methods of Test
FTMS No. 175	Adhesives, Methods of Testing
FTMS No. 406	Plastics, Methods of Testing
FTMS No. 601	Rubber, Sampling and Testing
AFR 400-44	Corrosion Prevention Control Program
ANA Bulletin No. 438	Age Control for Synthetic Rubber Parts

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ILLUSTRATIONS

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TABLES

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