FOREWORD

The final Technical Engineering Report covering all work performed under Contract AF 33(616)-6346 from 31 March 1959 to 31 March 1962 is divided into four volumes, as follows:

Volume 1 - Summary of mechanical and physical property data collected, including creep and fatigue.

Volume 2a - Details of data collection program. Test techniques and results for tension, compression, bearing, shear, crippling, joints, and physical properties.

Volume 2b - Test techniques and results for creep and fatigue.

Volume 3 - Tables of data collected.

This work was primarily conducted by the Structural Research Department, Engineering Research Laboratory of Lockheed-Georgia Company, a Division of Lockheed Aircraft Corporation. The contract was initiated under Project No. 7381, "Materials Application," Task No. 738103, "Data Collection and Correlation." It was monitored by the Metals and Ceramics Laboratory, Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Captain R. G. Henning and Mr. A. W. Brisbane were the project engineers.

Lockheed-Georgia Company supervision was provided by Mr. D. G. Cumro, Structural Research Department Engineer.

ABSTRACT

Mechanical and physical property data, necessary to fulfill the requirements of Phase II of the Department of Defense Titanium Alloy Sheet Rolling Program, were obtained for selected solution treated and aged titanium alloys in sheet form.

Four alloys were investigated: B120VCA (Ti-13V-11Cr-3Al), Ti-6Al-4V, Ti-2.5Al-16V and Ti-4Al-3Mo-1V. They were supplied by the producers in the heat treated condition from three or more heats and three thicknesses of each alloy. Static mechanical property data for tension, compression, bearing, shear and crippling; creep and rupture data for tension, compression, bearing and shear; and axial-load fatigue data were obtained at room and elevated temperatures. Fastener and weld joint data from -320°F to 80°F and physical properties from -420°F to 1200°F were obtained.

Volume 1 summarizes mechanical and physical properties in a form consistent with those given in MIL-HDBK-5.

This technical documentary report has been reviewed and is approved.

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I - INTRODUCTION

In the mid 1950's, the Department of Defense organized an integrated program to accelerate the development of high strength titanium alloy sheet for use in design of advanced aircraft and missile systems. This program, the Titanium Alloy Sheet Rolling Program, was coordinated and administered by the Bureau of Aeronautics, Department of the Navy. The Materials Adviory Board of the National Academy of Sciences was requested to establish a panel to act in an advisory capacity to the Bureau of Aeronautics, and did so with individuals selected from research organizations and academic institutions, from the titanium producing industry and from various aircraft companies. Liaison representatives were provided to the Panel by the various governmental agencies concerned with titanium alloy development. The first meeting of Materials Advisory Board Titanium Alloy Sheet Rolling Panel was held on June 5 and 6, 1956 in Washington, D. C. At this meeting a three phase program was outlined. Phases I and III were concerned with Manufacturing Development and Material Evaluation, respectively. Phase II, with which the present work is concerned, was defined as Design Data Accumulation and was directed toward the development of mechanical property data applicable to design uses for the heat treated titanium alloys. The initiation of work on Phase II was delayed in order for manufacturing development to progress sufficiently to establish consistent processing techniques which would make sheet material, having uniform properties, available for testing. Work commenced on Phase II of the DOD TASRP on 31 March 1959.

General

The program for collection of design data summarized in this report was divided into four basic phases as follows:

1. Phase I, "Static Properties" - room and elevated temperature data for short-time tension, compression, bearing, shear and crippling; effect of long-time temperature exposure on tensile properties.

2. Phase II, "Creep-Rupture Properties" - creep and rupture properties for tension and bearing; creep properties for compression; and rupture properties for shear.

3. Phase III, "Fatigue Properties" - axial-load tension-tension and tension-compression fatigue data at room and elevated temperatures for various stress ratios and stress concentration factors.

4. Phase IV, "Physical and Joint Properties" - measurement of specific heat, thermal coefficient of expansion and thermal conductivity from -420°F to 1200°F; strength data for mechanical and welded joints from -320°F to 80°F.

Manuscript released by the authors on May 30, 1962 for publication as an ASD Technical Documentary Report.

heats of each alloy and was specified to meet the requirements of quality, interstitial limits and strength established by the Materials Advisory Board. However, some of the required material was unavailable from producer's current supplies and it was necessary to substitute early DOD sheet, commercial sheet and reheat treated sheet. For certain test conditions requiring forming and welding the material was received in the solution treated condition and was subsequently aged by Lockheed. The testing procedures employed in this program followed the recommendations of the MAB Subpanel on Uniform Procedures for Structural Design Data Collection as specified in Reference 1. Members of this subpanel acted in a consulting capacity during the course of data collection.

Volume 1

The final engineering report is presented in four volumes. The scope of this volume, Volume 1, is to analyze and summarize the data collected and present them in a form consistent with that used in MIL-HDBK-5, "Strength of Metal Aircraft Elements" (Reference 2). For that purpose, the format of the following sections utilizes, as nearly as possible, the same terminology, symbols, section numbers and graphical form as MIL-HDBK-5. The designating section numbers employed for each alloy evaluated herein are not in numerical sequence but conform to those proposed in Reference 3 for future inclusions in the Handbook.

Although this work represents many tests, the sample size for a given property was limited by the number of variables. The only grouping of data for this summary was by heats, and a maximum sample size of 30 at room temperature and nine at each elevated temperature was thus obtained. This limitation should be considered in the use of these data as design allowables. A basic statistical treatment, involving an assumed normal distribution and tolerance limits, was employed where practicable from the standpoint of sample size and data scatter. Room-temperature properties reported herein were reduced by this method. It is understood that several other statistical procedures for establishing design allowables which are not biased by sample size have been proposed and recommended. These summary data, when ultimately combined with others, may lend themselves to statistical analysis by an alternate procedure increasing the reliability of the design values for heat treated titanium alloy sheet.

5.1 GENERAL

Design strength properties and related characteristics of some titanium alloys used in aircraft and missile structural fabrication are contained in this report. The strength properties are those commonly used in aircraft and missile structural design, such as tension, compression, bearing and shear. The effects of elevated temperatures are included, as well as data on creep and fatigue.

The properties reported are for solution treated and aged sheet material only, and are based exclusively on tests conducted in pursuance of the objectives of the present program. The material was supplied by the producers in the heat treated condition. Details of thermal treatment, chemical composition and other metallurgical considerations are given in Volume 2a of this report.

5.1.1 Material Properties

5.1.1.1 Mechanical Properties

Design strength properties at room and elevated temperatures, stress-strain relationships and creep data are available for the titanium alloys. The properties are presented for sheet material in three nominal gages of 0.020, 0.063 and 0.125 inch, except where indicated. Longitudinal and transverse properties are given individually with the exception of creep data where transverse values were not measured. Low-temperature mechanical properties are not included; however, some tensile, weld joint and fastener joint data were obtained for temperatures down to -320°F and are summarized in Volume 2a.

Variations in mechanical properties as a function of rate of straining were not investigated. For tension and compression, strain-rate was constant at 0.006 in./in./min. through the 0.2 percent yield offset, and a comparable rate was maintained for bearing and shear. The effect of strain-rate on allowable strength should be considered in the application of titanium alloys.

5.1.1.1.1 Strength Properties. The design strength properties at room temperature are listed at the beginning of the section covering each alloy. The basis, B, for the values tabulated is as follows: test results for each heat of each alloy were combined and the mean and the standard deviation of the sample were determined. Since at least three heats per thickness were tested, a sample size of 30 was available for analysis in most cases. The distribution was assumed to be normal and the method described in Reference 4 for one-sided tolerance limits was utilized so that it could be asserted with 95 percent confidence that 90 percent of the strength values would exceed those tabulated. This procedure was used for tension, compression, bearing and shear strengths (F_{tu}, F_{ty}, F_{cy}, F_{bru}, F_{bry} and F_{su}) and was also used for tensile and compressive moduli (E and E_c).

In establishing curves for percent of room-temperature property versus temperature; the average value for a given elevated-temperature property, based on nine tests in most samples, was ratioed to the average room-temperature value for that property. The percentages obtained, when multiplied by room-temperature design values tabulated at the beginning of each alloy section, ordinarily give elevated-temperature data within a few percent of the minimal value in the elevated-temperature test sample.

All elevated-temperature data reported are for exposure times of 1/2-hour with the exception of those in Tables 5.2.4.0(b) and 5.2.4.0(c) for 6Al-4V; 5.2.5.0(b) and 5.2.5.0(c) for 4Al-3Mo-1V; 5.2.6.0(b) and 5.2.6.0(c) for 2.5Al-16V; and 5.2.9.0(b) and 5.2.9.0(c) for 13V-11Cr-3Al. The effect of long-time temperature exposure on tensile strength is shown in these tables. One group of test panels for each alloy was exposed to a temperature of 600°F for 500 hours. For half of the panels, a constant tensile stress equal to 1/3 the average 600°F ultimate tensile stress was maintained during the exposure period. The remainder of the panels were not loaded during exposure. A second group of panels was processed for the same two load conditions but at a temperature of 900°F for ten hours. Tensile tests on specimens machined from each panel were conducted at room and at exposure temperatures. Average test values were reduced to the design values given in the tables by the following procedure:

$$F_{tu}\ (\text{exposed}) = \frac{\text{UTS (exposed)}}{\text{UTS}} \times F_{tu}$$

$$F_{ty}\ (\text{exposed}) = \frac{\text{TYS (exposed)}}{\text{TYS}} \times F_{ty}$$

where:

F_{tu} and F_{ty} – ultimate tensile stress and tensile yield stress "B" values from design property Tables 5.2.4.0(a), 5.2.5.0(a), 5.2.6.0(a), and 5.2.9.0(a)

UTS – average room-temperature ultimate tensile stress

TYS – average room-temperature tensile yield stress

F_{tu} (exposed) – derived ultimate tensile stress reported in exposure tables

F_{ty} (exposed) – derived tensile yield stress reported in exposure tables

UTS (exposed) – average ultimate tensile stress after temperature exposure

TYS (exposed) – average tensile yield stress after temperature exposure

5.1.1.1.2 Ductility. Elongation is not a design allowable but is of some use in the comparison and selection of materials. The scatter in test results, including variations associated with mode and location of failure, was quite large in many cases for the alloys tested in the present program. Since statistical analysis of the type employed herein was impracticable, values reported for elongation are average test results. For the heat treated titanium alloys, elongation in 2-inches as a function of temperature is approximately constant from room temperature to 800°F. From 800°F to 1000°F ductility increases rapidly. Average elongation values are summarized for each alloy, heat and thickness in the summary figures of Volume 2a. Percent elongation in 2, 1/4 and 1/8-inch is presented in Volume 3.

5.1.1.1.3 Stress-Strain Relationships. The stress-strain relationships presented, which include elastic, tangent and secant moduli, are typical curves based on average test data. Being typical, these curves will not correspond to yield-stress and modulus-of-elasticity data presented as design allowables. However, the stress-strain relationships are no less useful, since there are well-known methods for using these curves in design by reducing them to a minimum curve or by using Ramberg-Osgood Parameters obtained from the typical curves. Ramberg-Osgood Parameters for compressive stress-strain curves for the titanium alloys are tabulated in Volume 3 of this report.

If discrepancies exist between the modulus or yield stress of the stress-strain curves and the modulus or yield stress of the tables or elevated-temperature-property curves, the latter values should be used.

5.1.1.1.4 Creep. The percentage of room-temperature ultimate tensile stress for time to rupture and time to attain various amounts of creep strain is given in curves presented in each alloy section, where available. The deformation indicated is the result of creep only and does not include loading deformation or thermal expansion. These curves were derived by constructing a "best-fit" line to the creep test data, and ratioing stress values obtained from this line to the average room-temperature ultimate tensile stress.

Larson-Miller plots of the tensile creep data were made utilizing a polynomial function with a least squares fit to the test points. These plots and details of computational procedures are presented in Volume 2b. Compressive creep, bearing creep-rupture, and shear rupture data are included in Volume 2b.

5.1.1.2 Physical Properties

Measurements were made for several of the physical properties of the titanium alloys and are included in each alloy section. A temperature range from -420°F to 1200°F was covered and detail results and experimental techniques are given in Volume 2a.

5.1.2 Titanium Alloy Index

The titanium alloys for which properties are included in this report are as follows:

Section	Alloys
5.2.4	Ti-6Al-4V
5.2.5	Ti-4Al-3Mo-1V
5.2.6	Ti-2.5Al-16V
5.2.9	Ti-13V-11Cr-3Al

5.2 ALLOYS

5.2.4 6Al-4V Titanium Alloy

5.2.4.0 Comments and Properties

Room-temperature mechanical and physical properties are shown in Table 5.2.4.0(a). Effect on tensile properties of long-time exposure to elevated temperature is given in Tables 5.2.4.0(b) and (c). The temper index for 6Al-4V titanium alloy is as follows:

Section	Temper or Condition
5.2.4.1	Solution treated and aged

For the solution treated and aged material reported herein, some variations in processing history were noted. The heat treatments included are:

1715F for 3 min., W. Q. - 950F for 4 hrs., A. C.
1700F for 15 min., W. Q. - 950F for 4 hrs., A. C.
1700F for 3 min., W. Q. - 950F for 4 hrs., A. C.
1700F for 20 min., O. Q. - 900F for 4 hrs., A. C.
1690F for 12 min., W. Q. - 900F for 4 hrs., A. C.
1675F for 20 min., W. Q. - 935F for 4 hrs., A. C.
1675F for 20 min., W. Q. - 900F for 4 hrs., A. C.
1665F for 12 min., W. Q. - 900F for 4 hrs., A. C.

TABLE 5.2.4.0(a) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 6Al-4V TITANIUM ALLOY

Alloy....................	6Al-4V	
Form....................	Sheet	
Condition................	Solution Treated and Aged	
Thickness (in.)...........	0.063	0.125
Basis....................	B	B
Mechanical Properties:		
F_{tu}, ksi		
L....................	166	166
T....................	167	167
F_{ty}, ksi		
L....................	143	147
T....................	149	151
F_{cy}, ksi		
L....................	157	157
T....................	154	163
F_{su}, ksi		
L....................	102	108
T....................	104	109
F_{bru}, ksi (e/D=1.5)		
L....................	242	255
T....................	245	259
F_{bru}, ksi (e/D=2.0)		
L....................	293	300
T....................	304	311
F_{bry}, ksi (e/D=1.5)		
L....................	219	227
T....................	219	225
F_{bry}, ksi (e/D=2.0)		
L....................	243	253
T....................	244	259
e, percent(a)		
L....................	6.2	6.7
T....................	6.7	7.1
E, 10^6 psi		
L....................	15.2	15.6
T....................	15.4	16.2
E_c, 10^6 psi		
L....................	15.2	16.0
T....................	15.9	17.2
Physical Properties:		
ω, lb/in.^{3}................	0.160	
C, Btu/(lb)(F)............	0.128 (at 75°F)	
K, Btu/[(hr)(ft^2)(F)/ft]..	4.3 (at 70°F)	
α, 10^{-6} in./in./F.........	5.3 (100° to 200°F)	

(a) Elongations are average test values.

TABLE 5.2.4.0(b) EFFECT OF 500-HOUR EXPOSURE AT 600°F ON THE TENSILE PROPERTIES OF 6Al-4V TITANIUM ALLOY

Condition..................	Solution Treated and Aged	
Thickness (in.).............	0.063	0.125
Exposed at temperature in the unstressed condition:		
F_{tu}, ksi (at room temp.)		
L.....................	168	167
T.....................	166	167
F_{ty}, ksi (at room temp.)		
L.....................	144	152
T.....................	148	153
F_{tu}, ksi (at 600°F)		
L.....................	124	123
T.....................	129	127
F_{ty}, ksi (at 600°)		
L.....................	95	100
T.....................	105	106
Exposed at temperature while stressed to 1/3 average 600°F ultimate tensile stress:		
F_{tu}, ksi (at room temp.)		
L.....................	166	167
T.....................	168	168
F_{ty}, ksi (at room temp.)		
L.....................	144	152
T.....................	149	154
F_{tu}, ksi (at 600°F)		
L.....................	123	123
T.....................	128	128
F_{ty}, ksi (at 600°F)		
L.....................	93	102
T.....................	101	106

TABLE 5.2.4.0(c) EFFECT OF 10-HOUR EXPOSURE AT 900°F ON THE TENSILE PROPERTIES OF 6Al-4V TITANIUM ALLOY

Condition	Solution Treated and Aged	
Thickness (in.)	0.063	0.125
Exposed at temperature in the unstressed condition:		
F_{tu}, ksi (at room temp.)		
L	166	164
T	167	166
F_{ty}, ksi (at room temp.)		
L	148	151
T	152	155
F_{tu}, ksi (at 900°F)		
L	106	108
T	112	111
F_{ty}, ksi (at 900°F)		
L	80	79
T	89	82
Exposed at temperature while stressed to 1/3 average 900°F ultimate tensile stress:		
F_{tu}, ksi (at room temp.)		
L	167	165
T	166	164
F_{ty}, ksi (at room temp.)		
L	144	149
T	150	150
F_{tu}, ksi (at 900°F)		
L	106	107
T	112	110
F_{ty}, ksi (at 900°F)		
L	78	76
T	85	88

5.2.4.1 Solution Treated and Aged Condition

Room and elevated temperature data for this condition are presented in Figures 5.2.4.1.1(a) through 5.2.4.1.6(d).

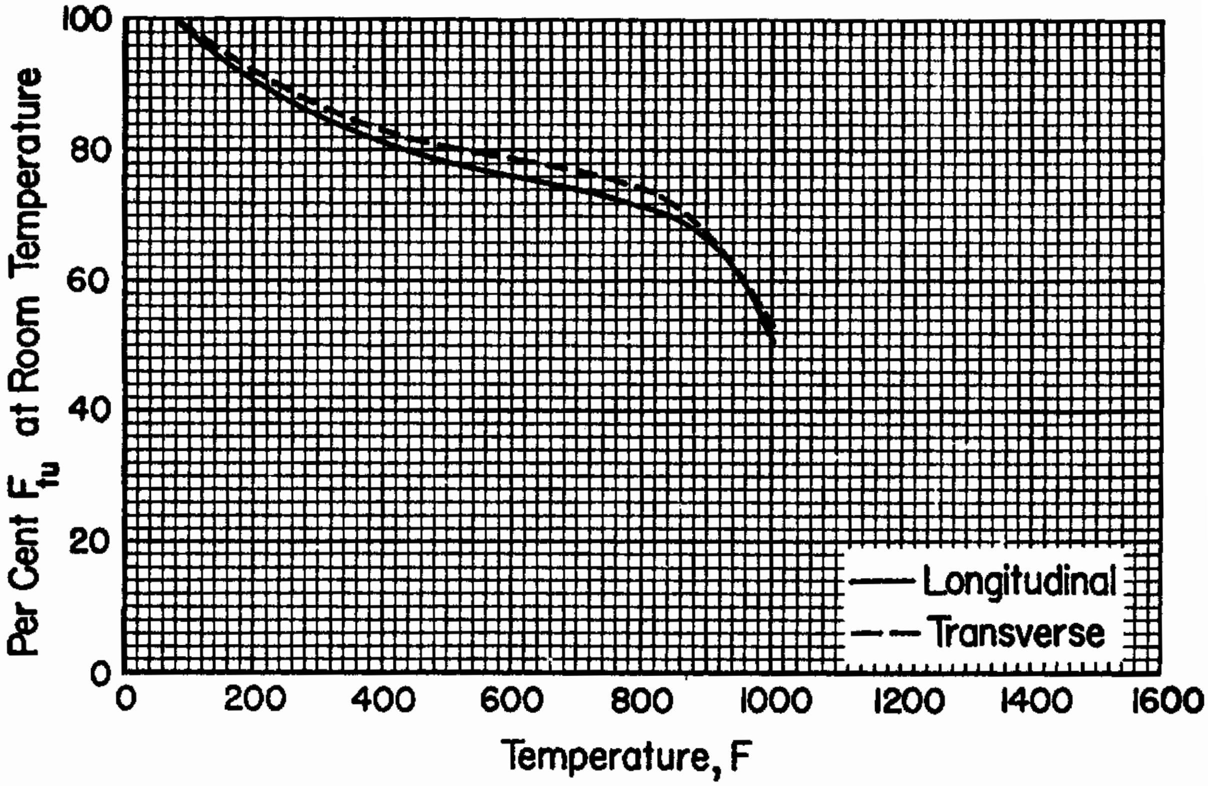

FIGURE 5.2.4.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

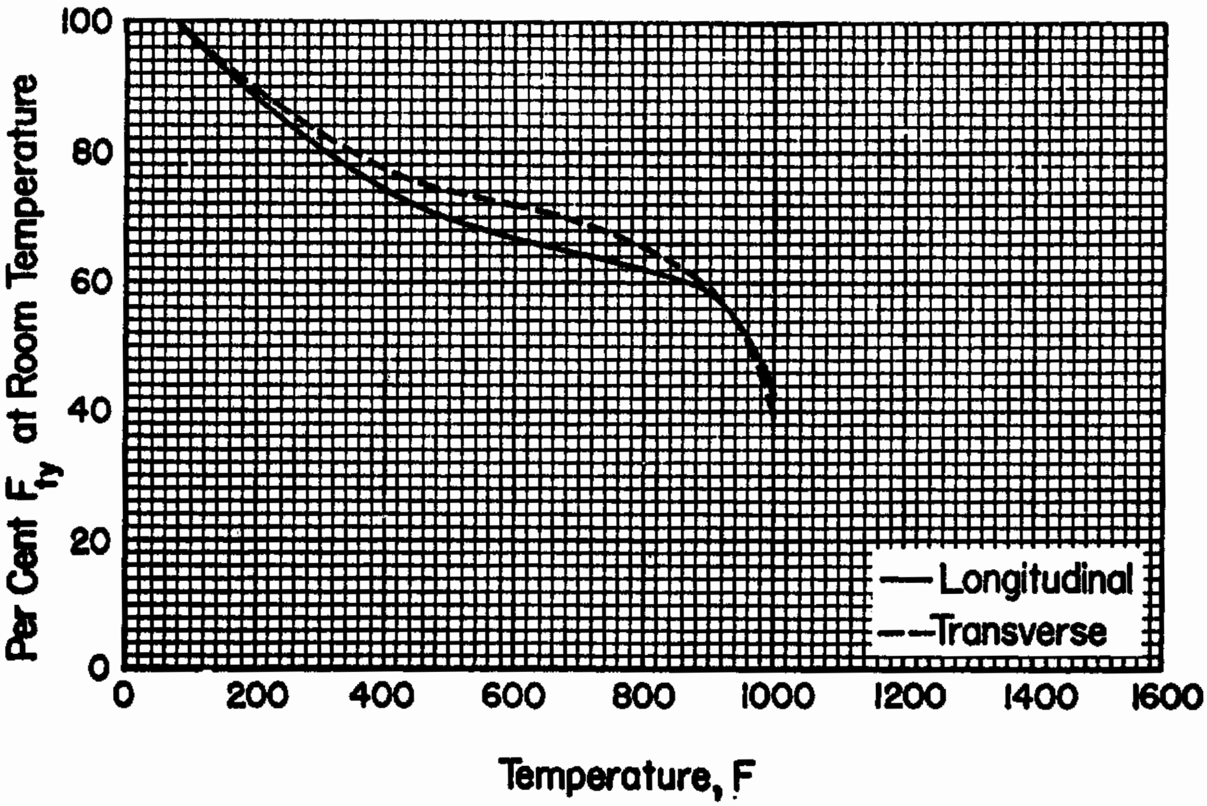

FIGURE 5.2.4.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

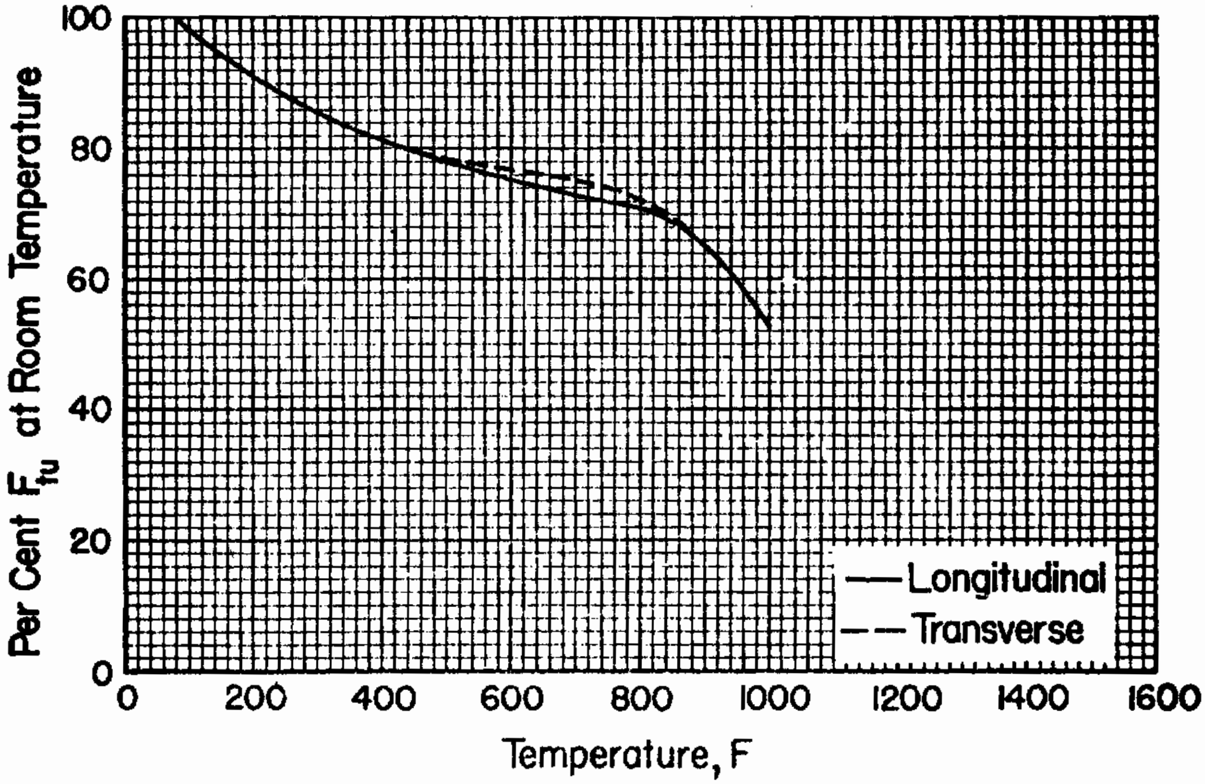

FIGURE 5.2.4.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

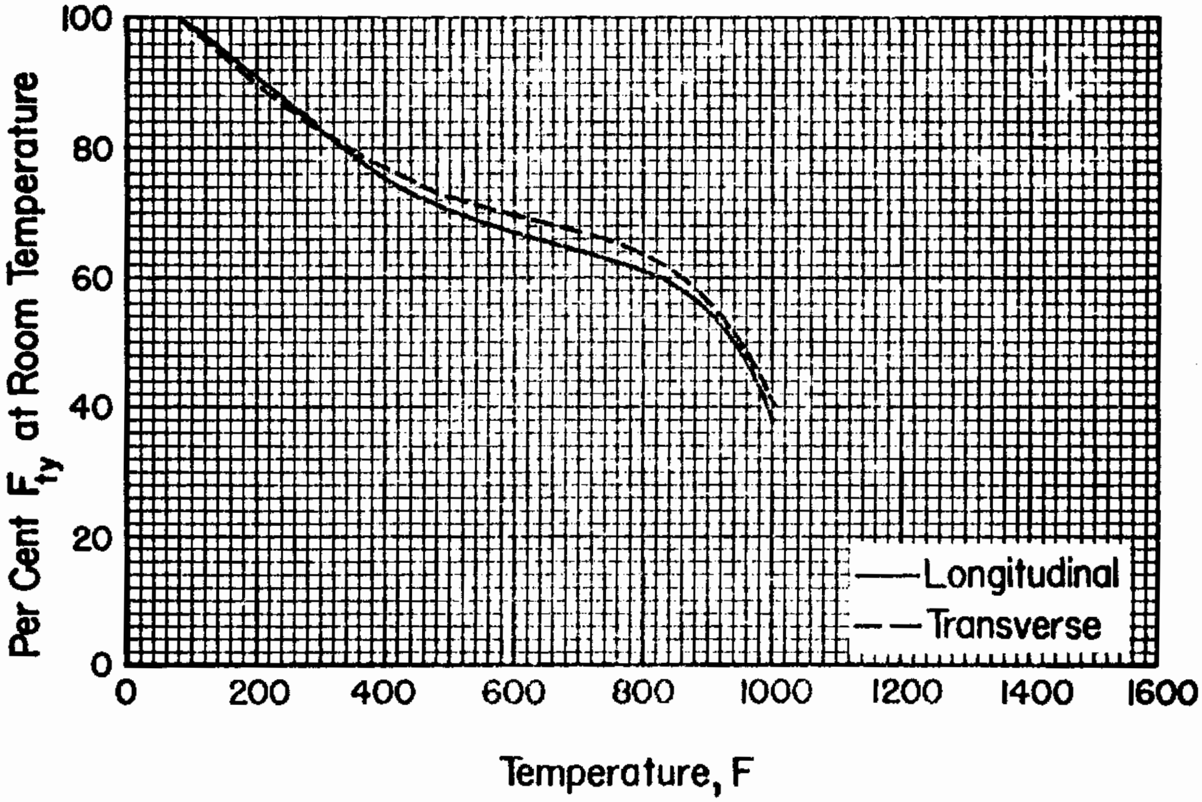

FIGURE 5.2.4.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

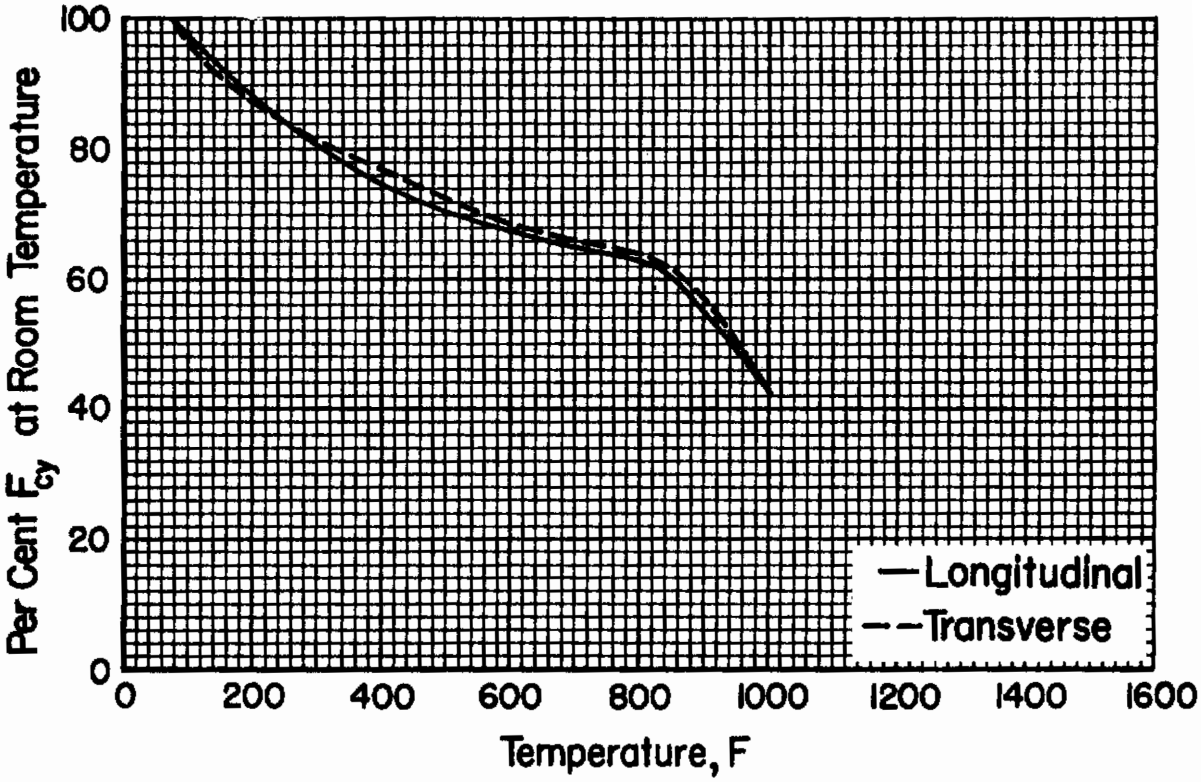

FIGURE 5.2.4.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

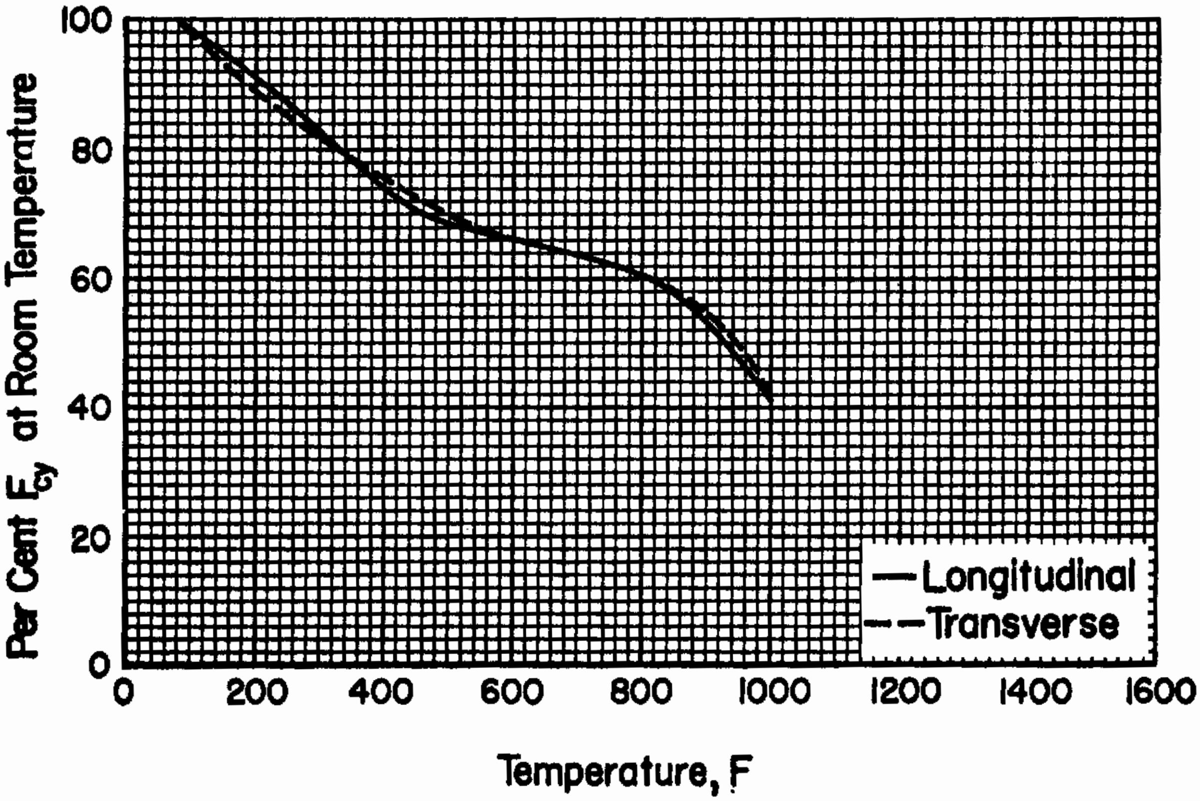

FIGURE 5.2.4.1.2(b). Effect of temperature on the compressive yield strength (F_{cy}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

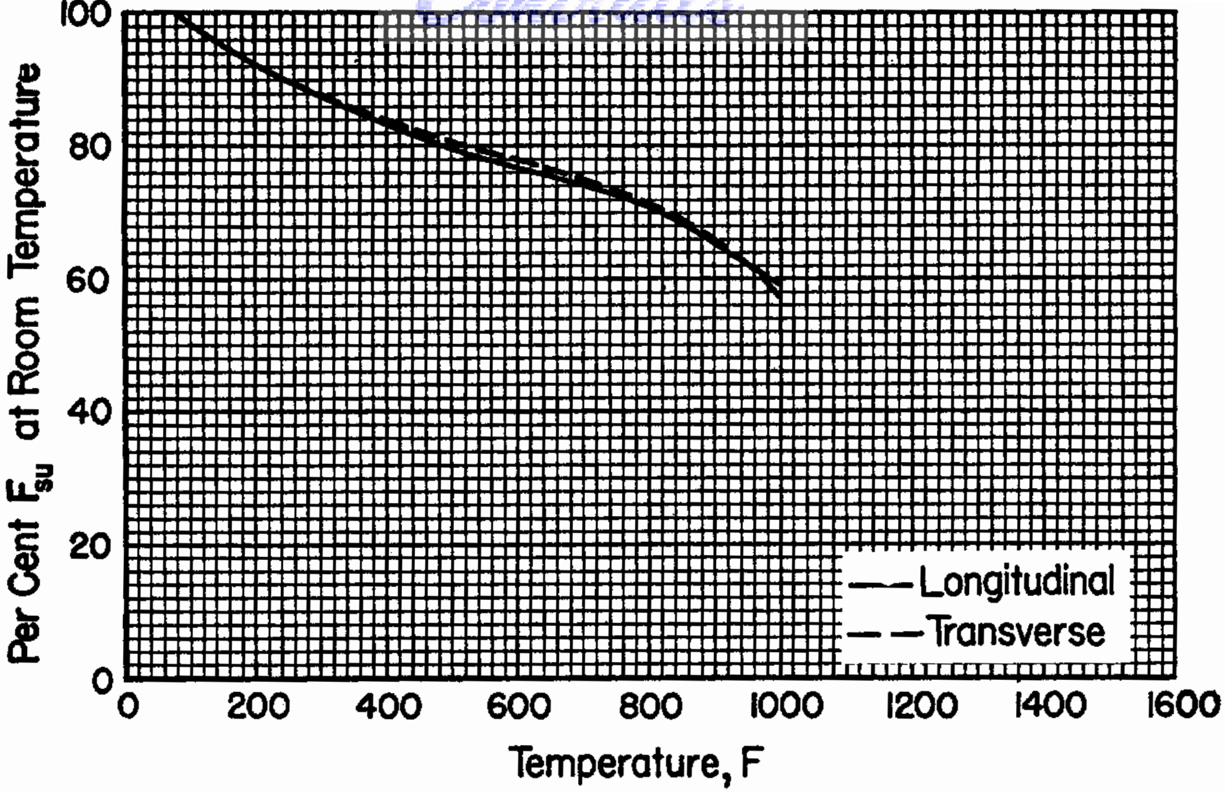

FIGURE 5.2.4.1.2(c). Effect of temperature on the ultimate shear strength (F_{su}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

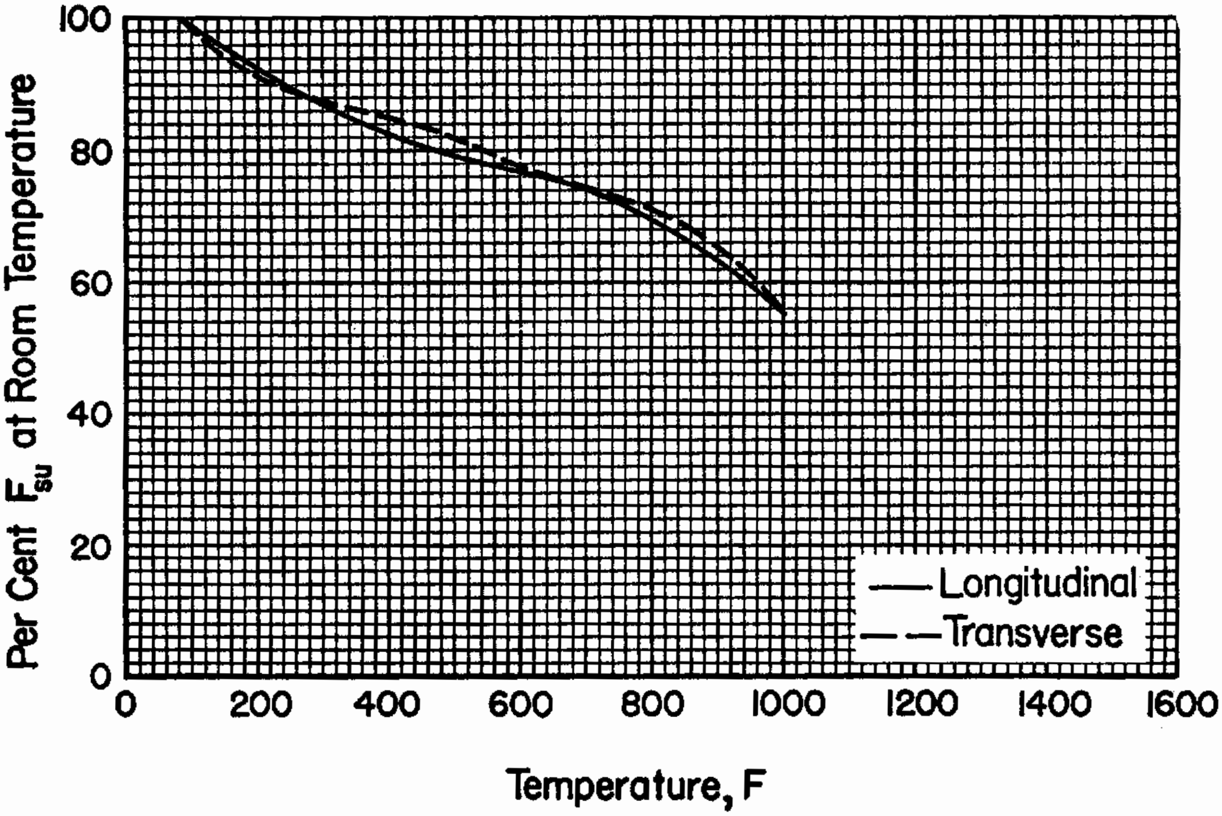

FIGURE 5.2.4.1.2(d). Effect of temperature on the ultimate shear strength (F_{su}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

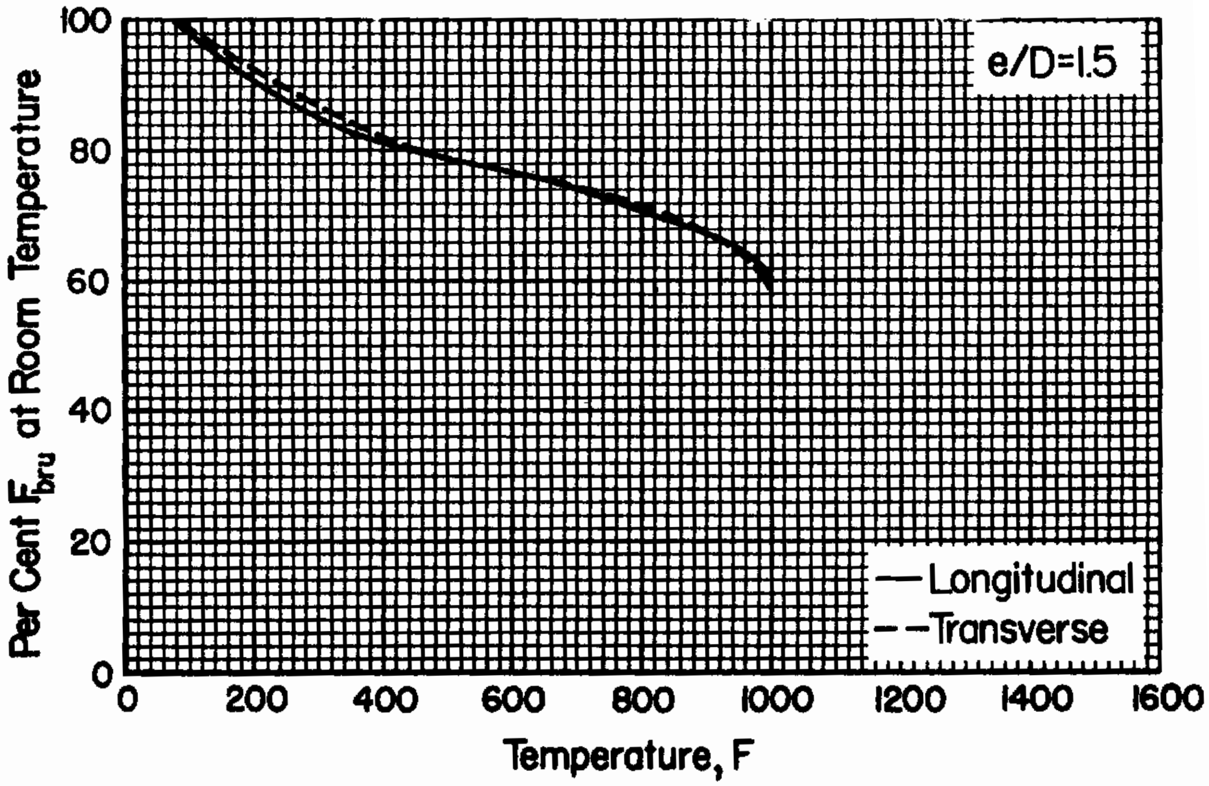

FIGURE 5.2.4.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

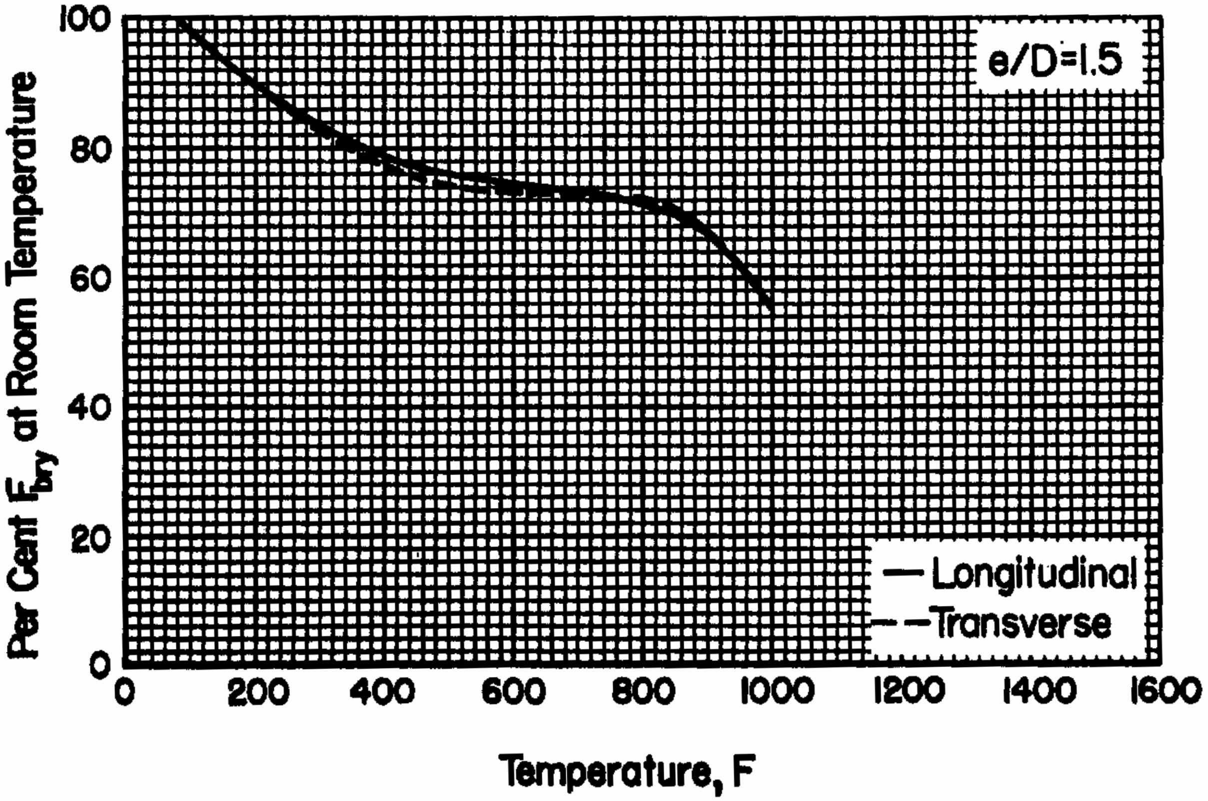

FIGURE 5.2.4.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

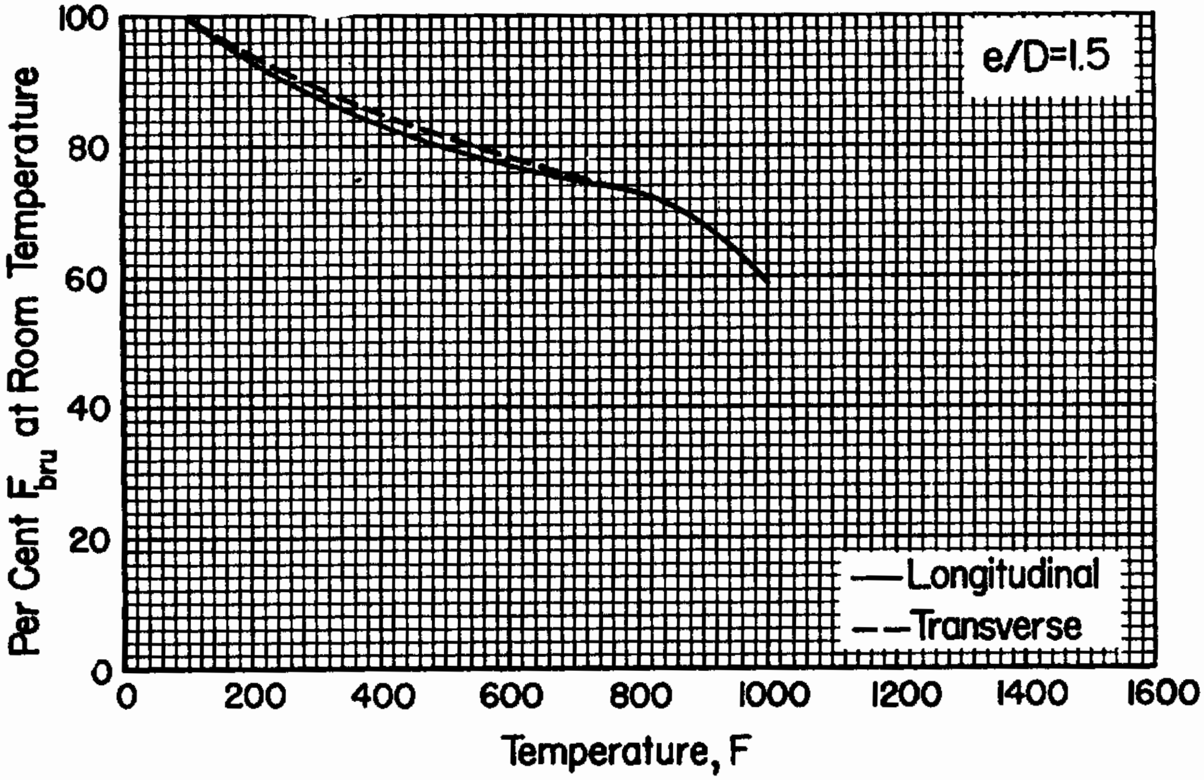

FIGURE 5.2.4.1.3(c). Effect of temperature on the ultimate bearing strength (F_{bru}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

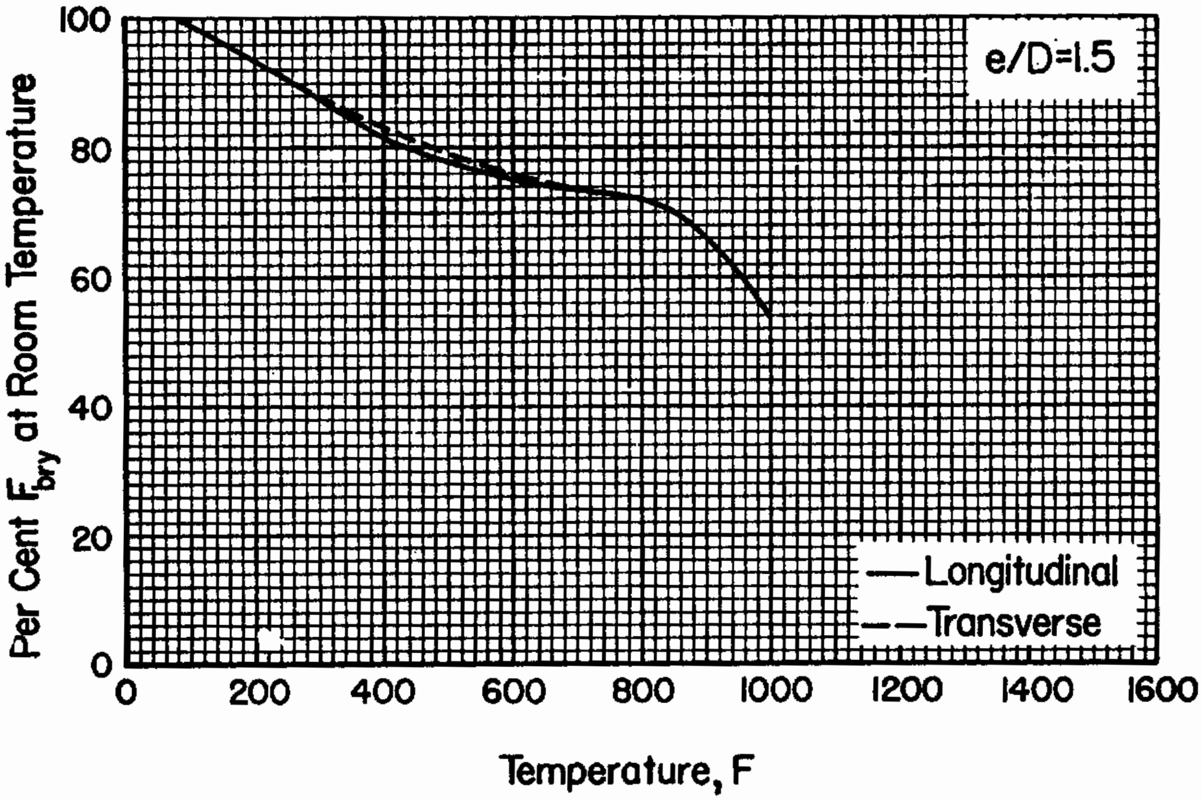

FIGURE 5.2.4.1.3(d). Effect of temperature on the bearing yield strength (F_{bry}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

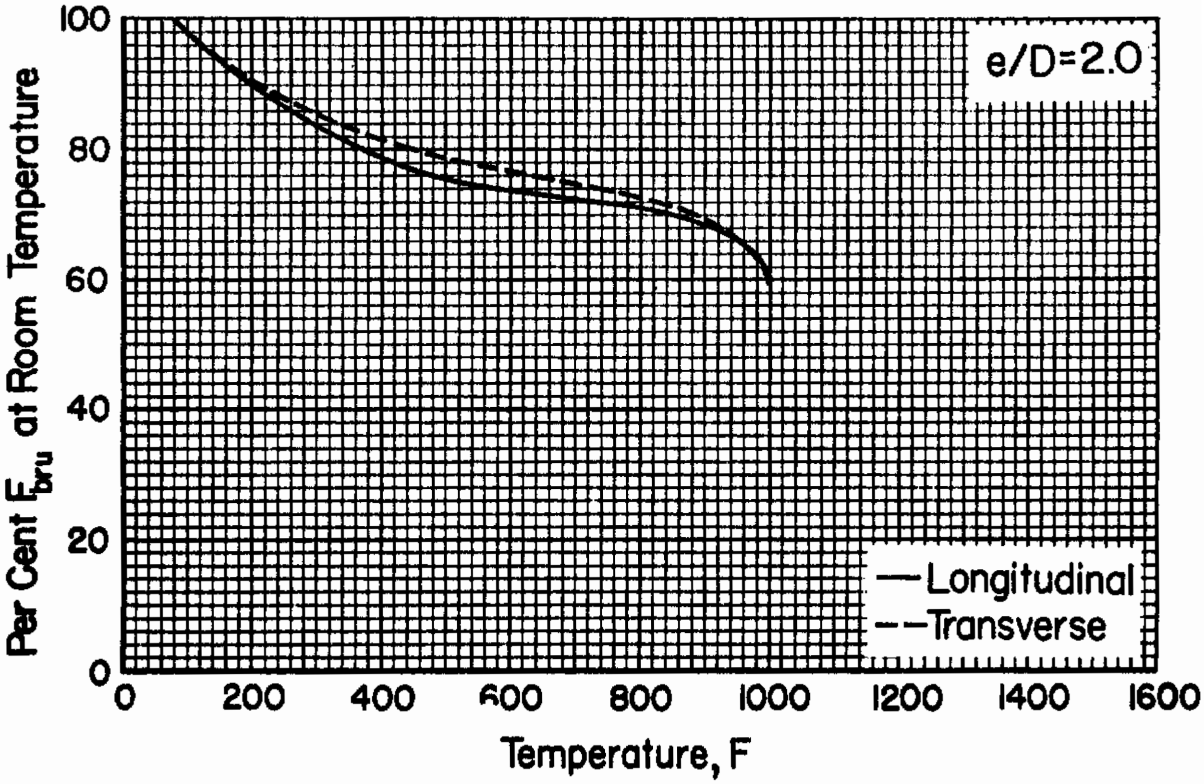

FIGURE 5.2.4.1.3(e). Effect of temperature on the ultimate bearing strength (F_{bru}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

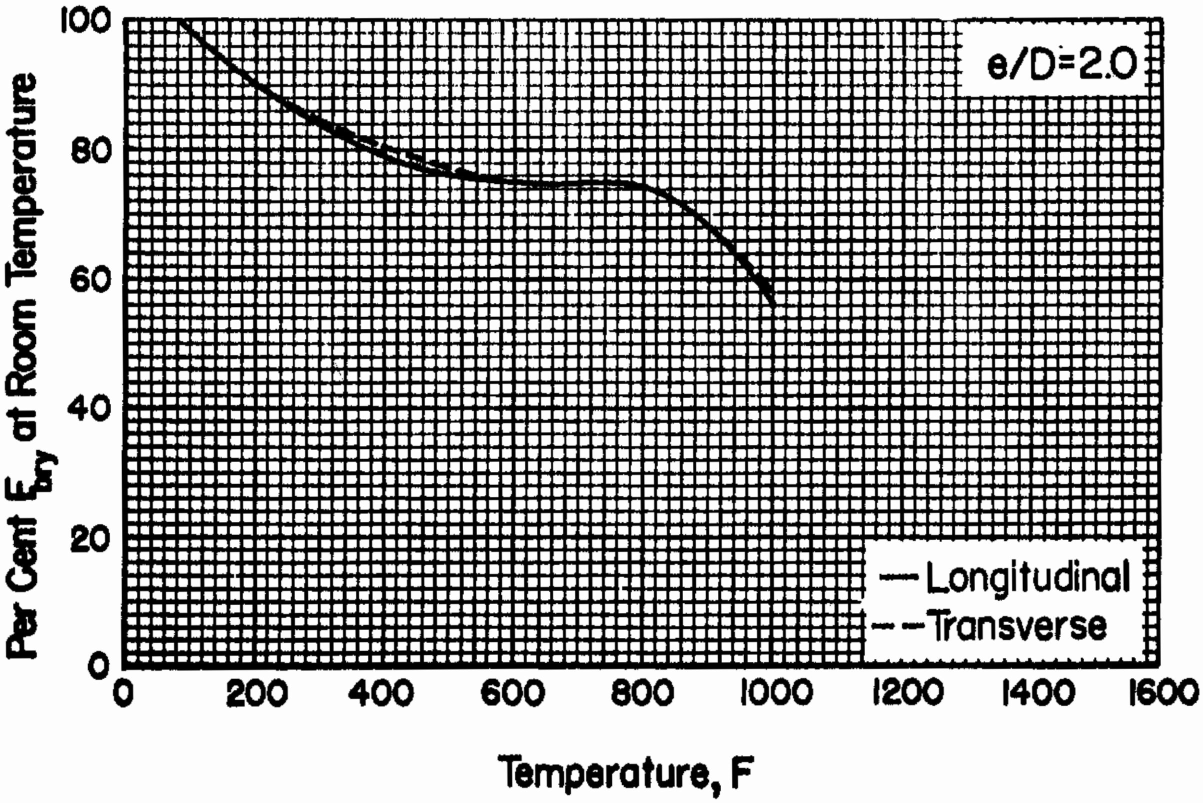

FIGURE 5.2.4.1.3(f). Effect of temperature on the bearing yield strength (F_{bry}) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

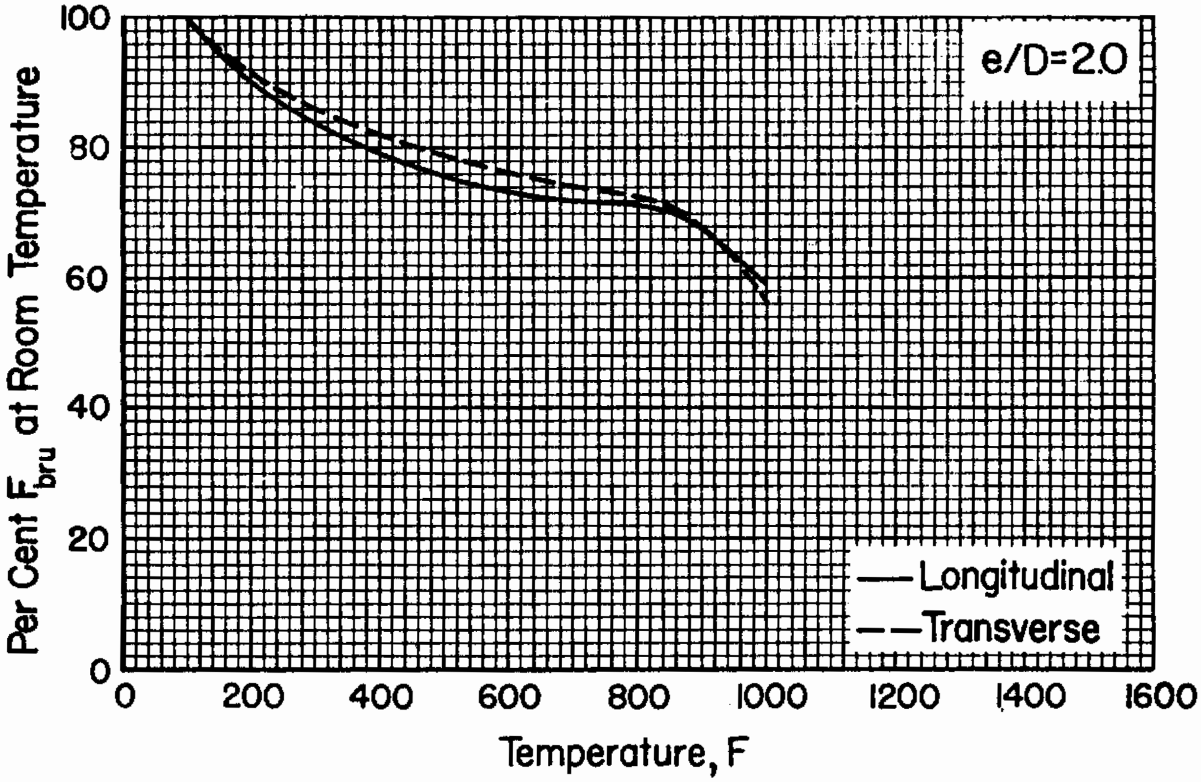

FIGURE 5.2.4.1.3(g). Effect of temperature on the ultimate bearing strength (F_{bru}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

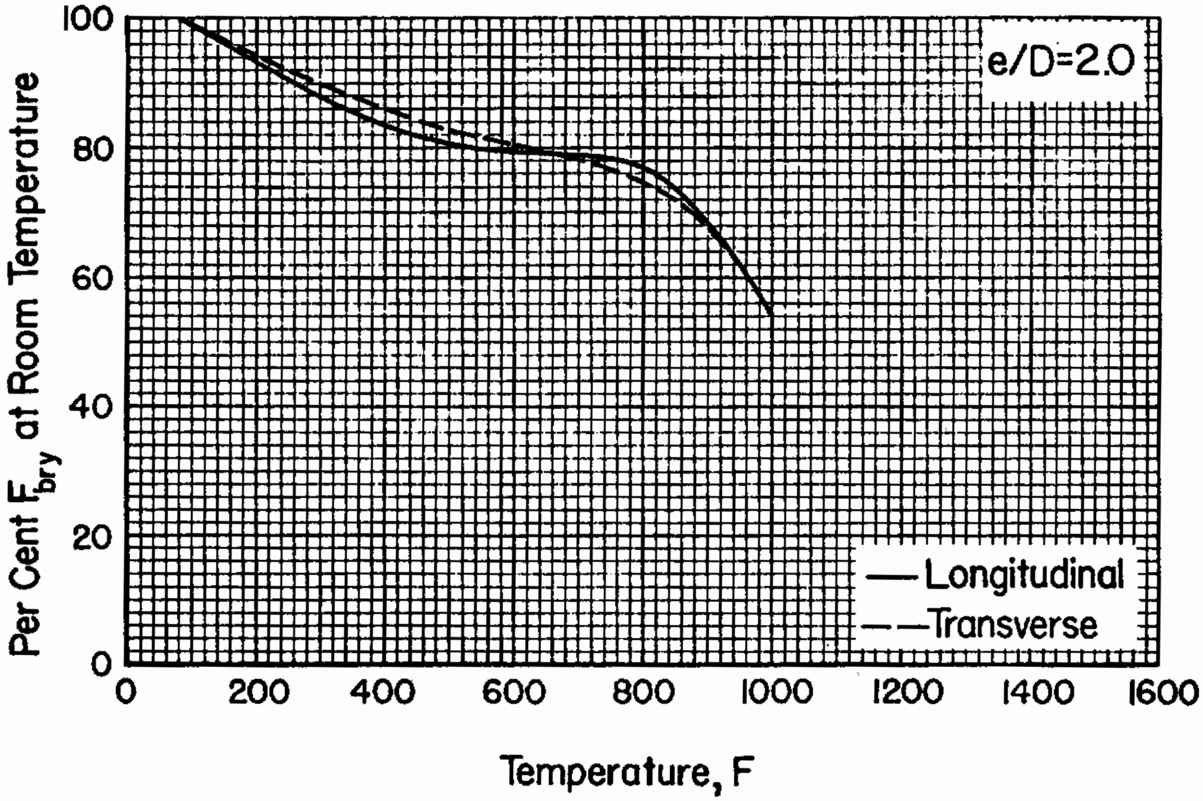

FIGURE 5.2.4.1.3(h). Effect of temperature on the bearing yield strength (F_{bry}) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

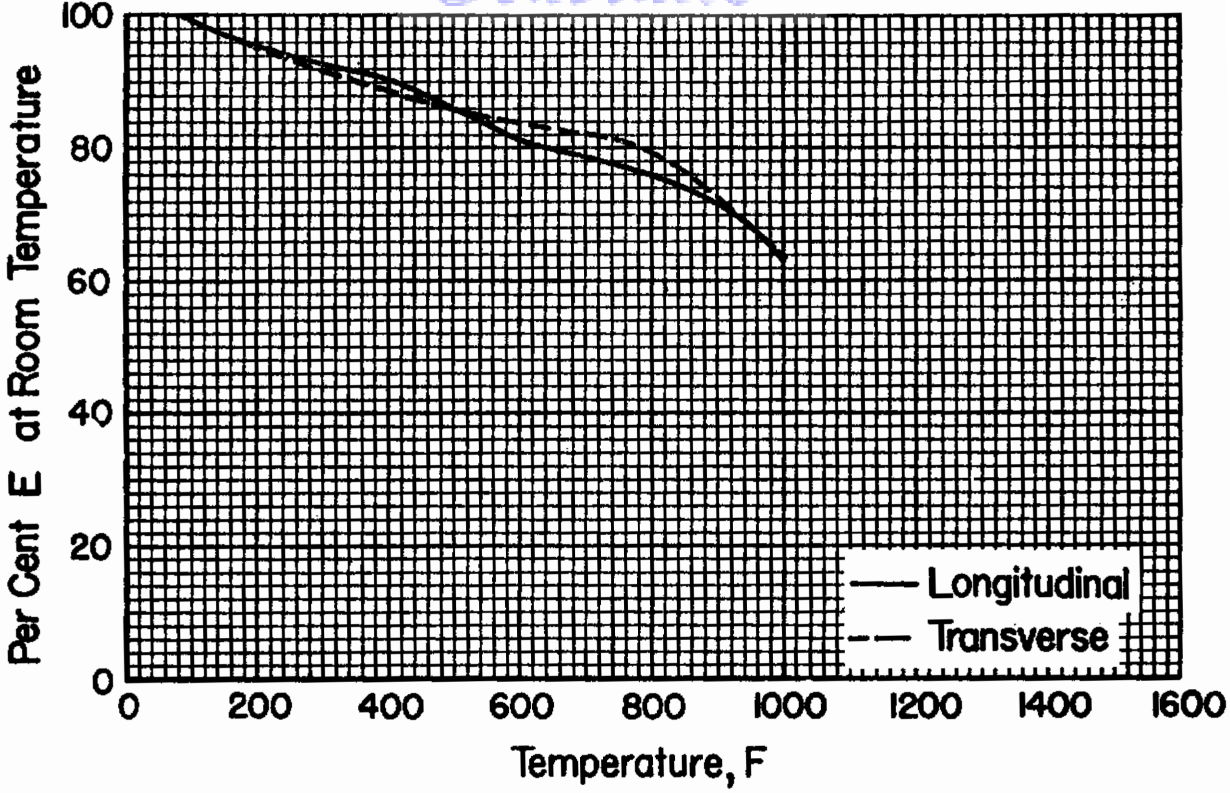

FIGURE 5.2.4.1.4(a). Effect of temperature on the tensile modulus (E) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

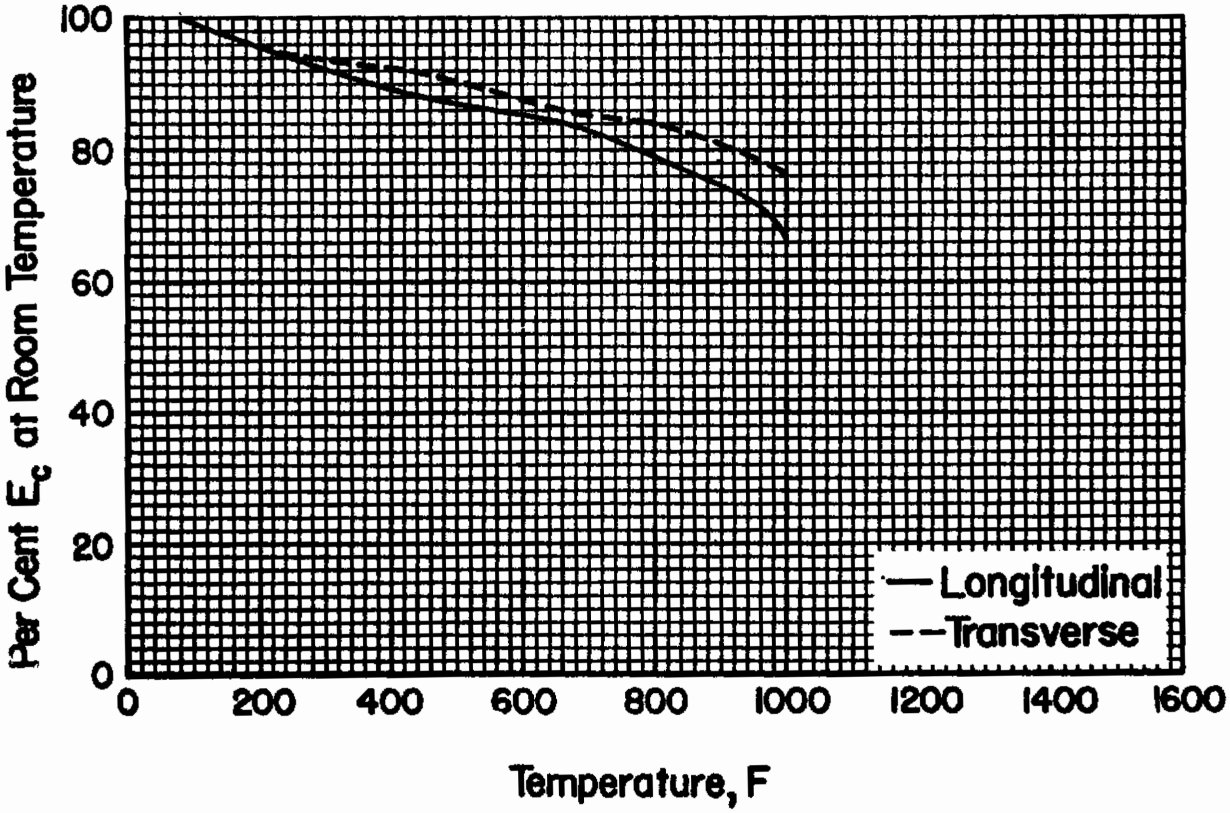

FIGURE 5.2.4.1.4(b). Effect of temperature on the compressive modulus (E_c) of 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

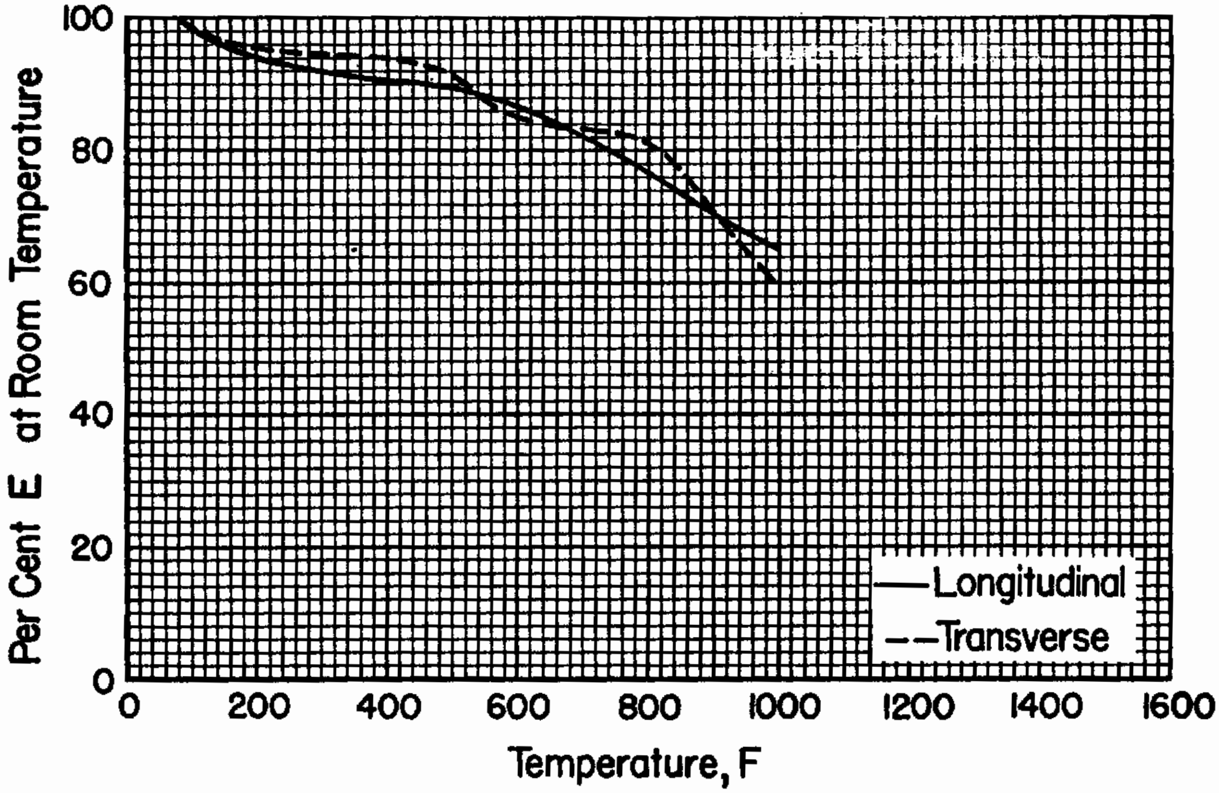

FIGURE 5.2.4.1.4(c). Effect of temperature on the tensile modulus (E) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

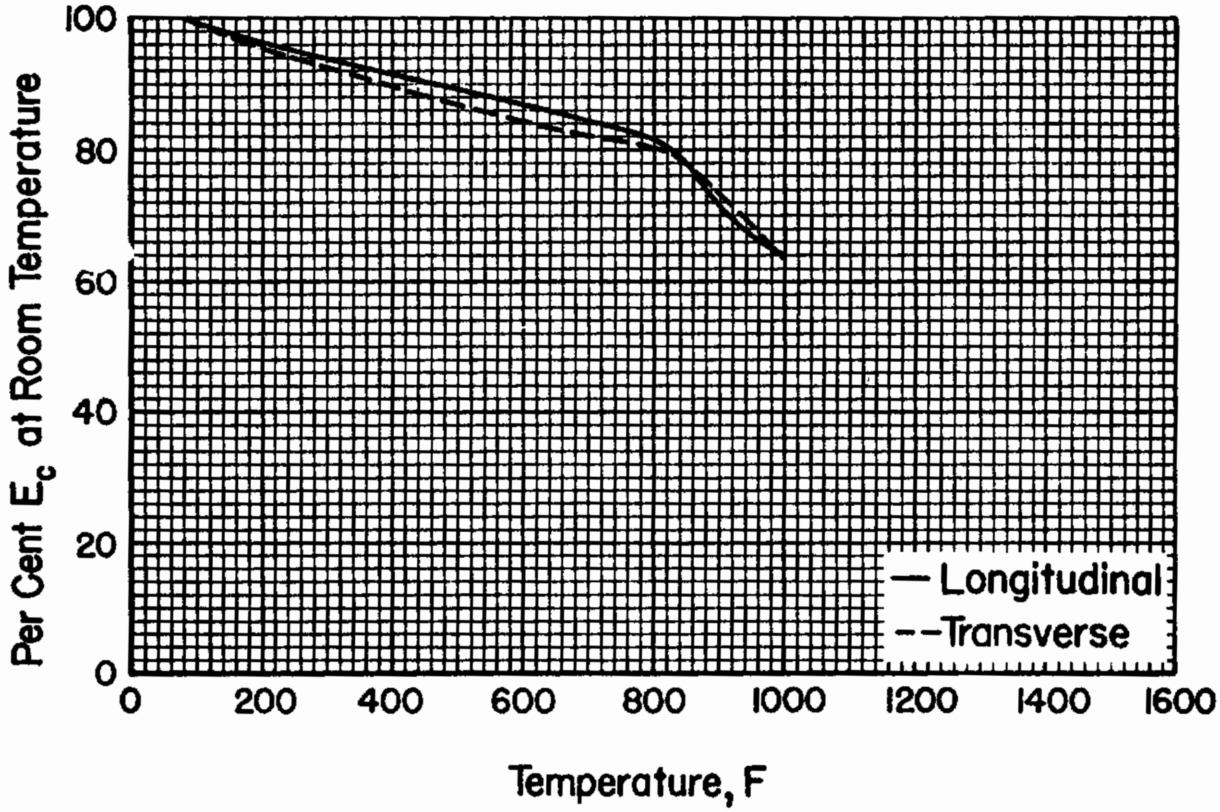

FIGURE 5.2.4.1.4(d). Effect of temperature on the compressive modulus (E_c) of 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

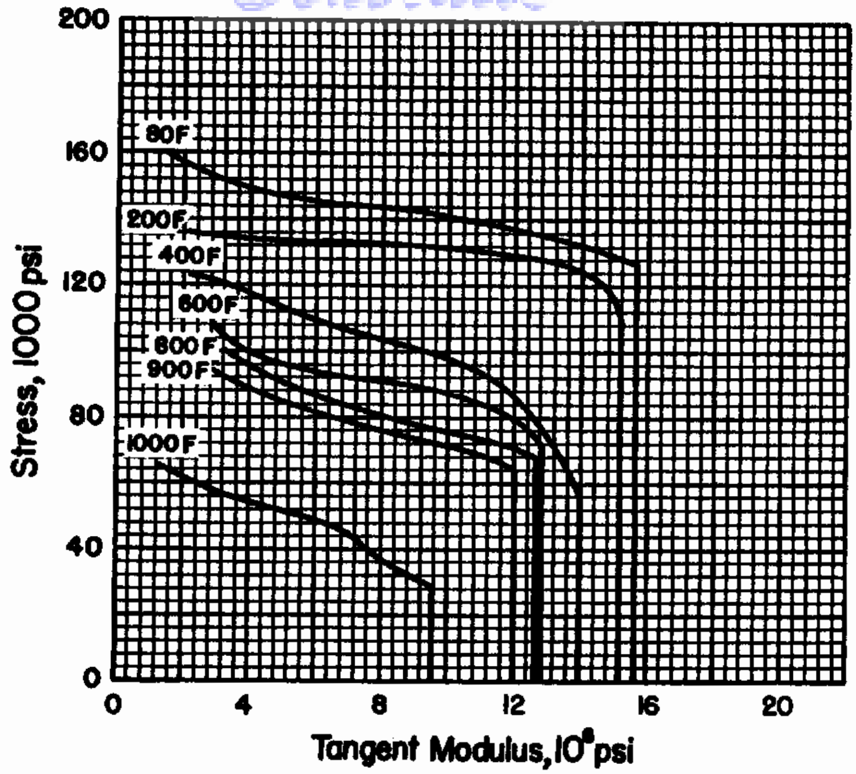

FIGURE 5.2.4.1.4(e). Typical longitudinal tensile tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

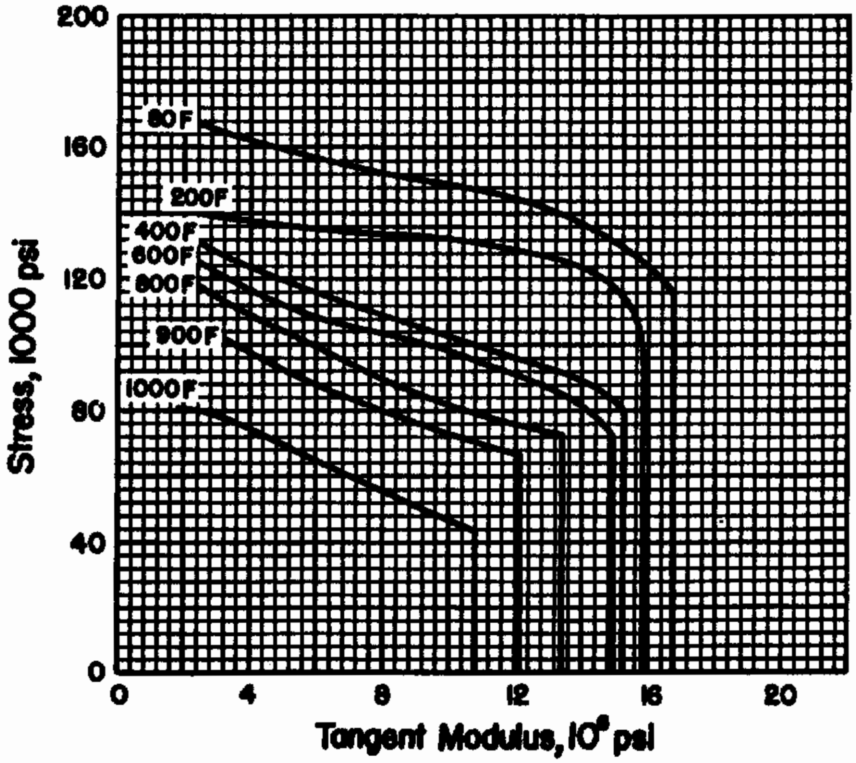

FIGURE 5.2.4.1.4(f). Typical transverse tensile tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

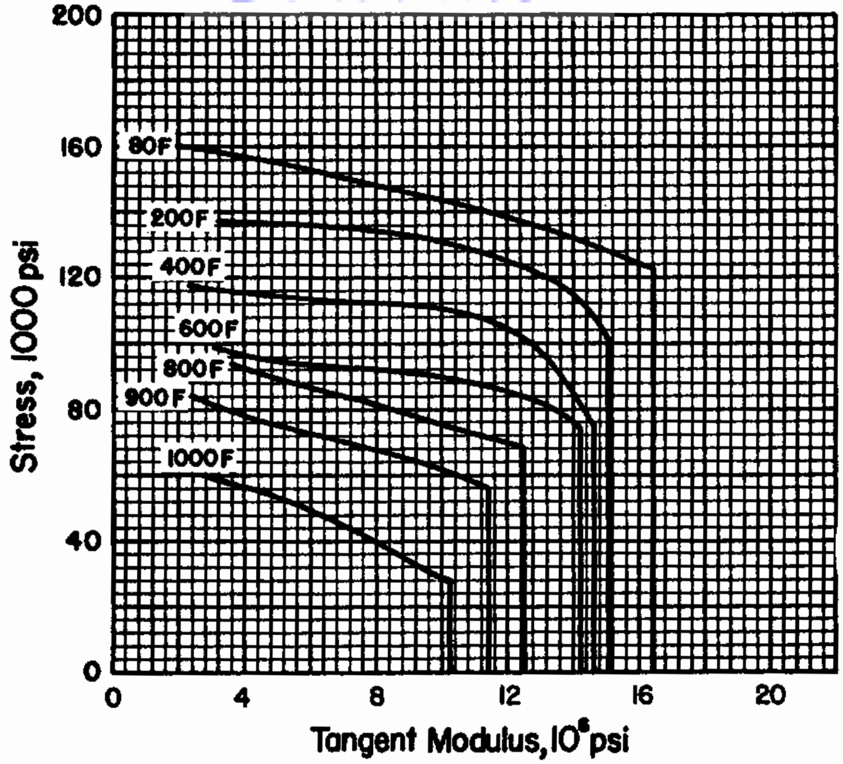

FIGURE 5.2.4.1.4(g). Typical longitudinal tensile tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

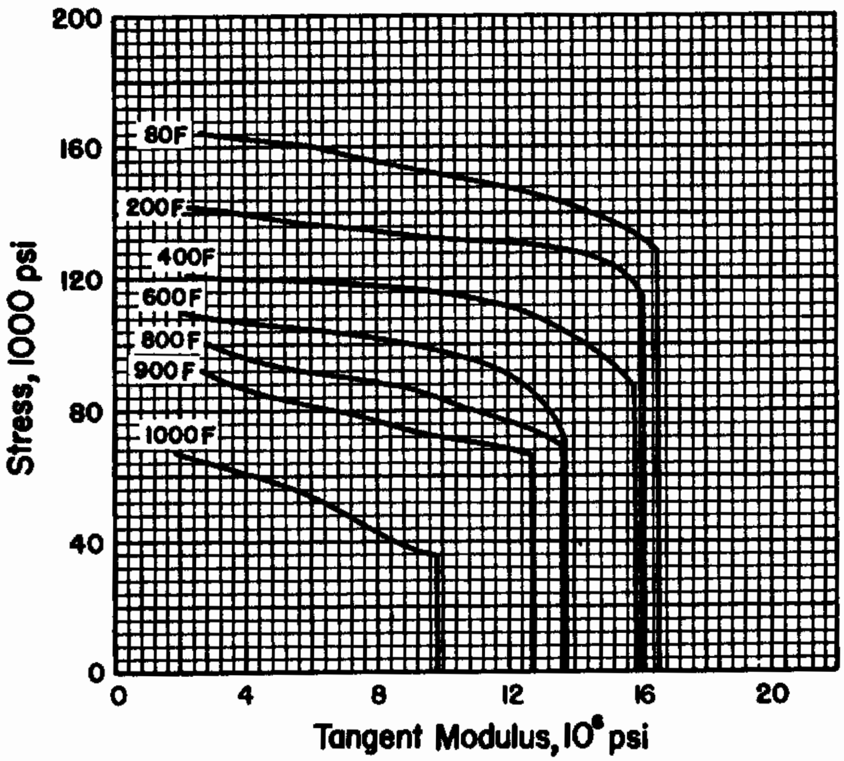

FIGURE 5.2.4.1.4(h). Typical transverse tensile tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

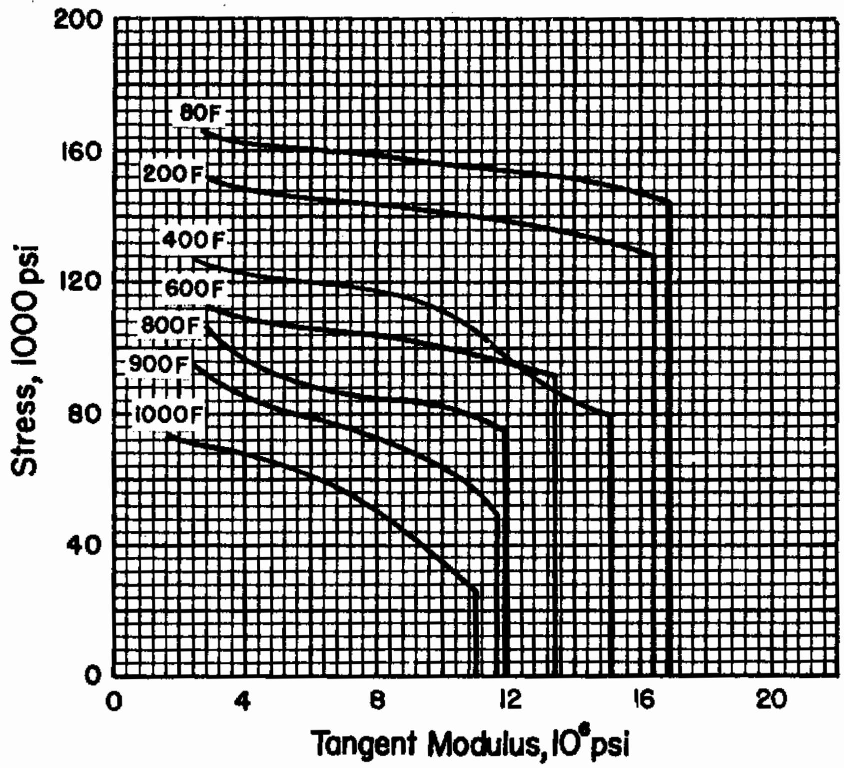

FIGURE 5.2.4.1.4(i). Typical longitudinal compressive tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

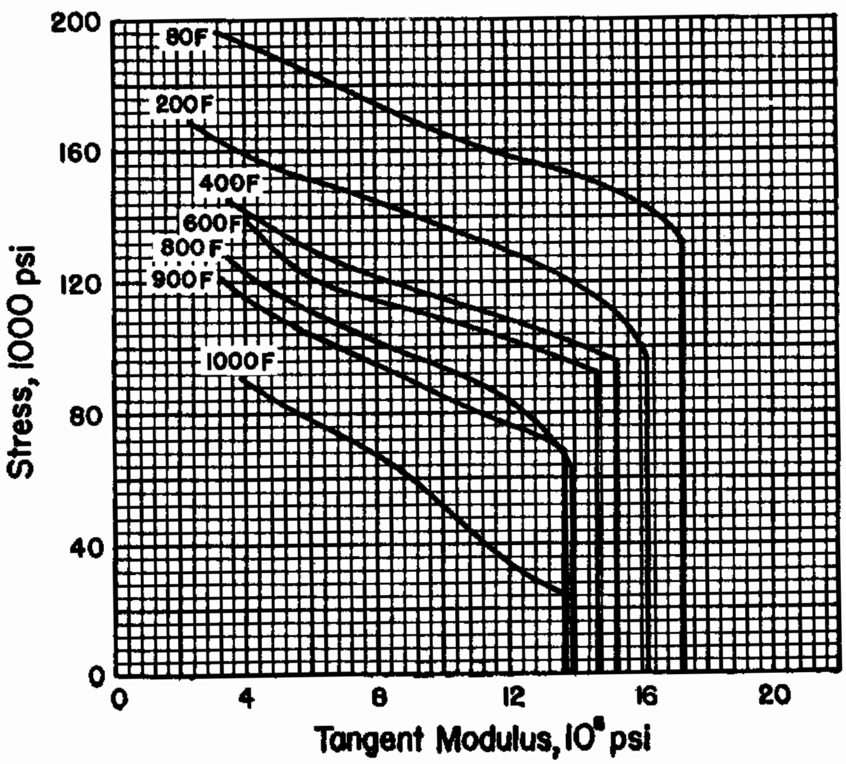

FIGURE 5.2.4.1.4(j). Typical transverse compressive tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

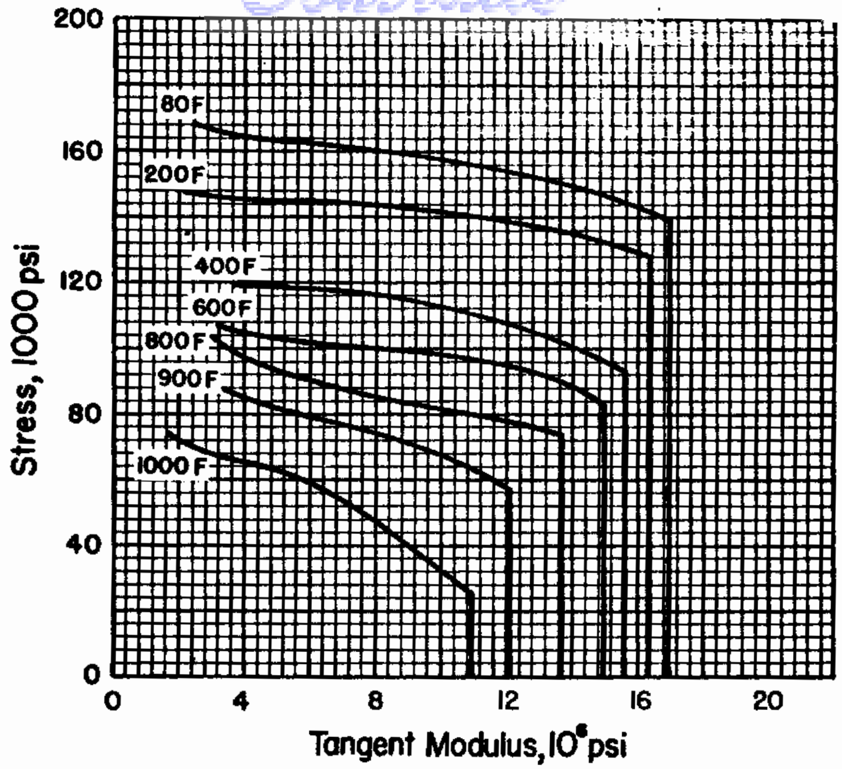

FIGURE 5.2.4.1.4(k). Typical longitudinal compressive tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

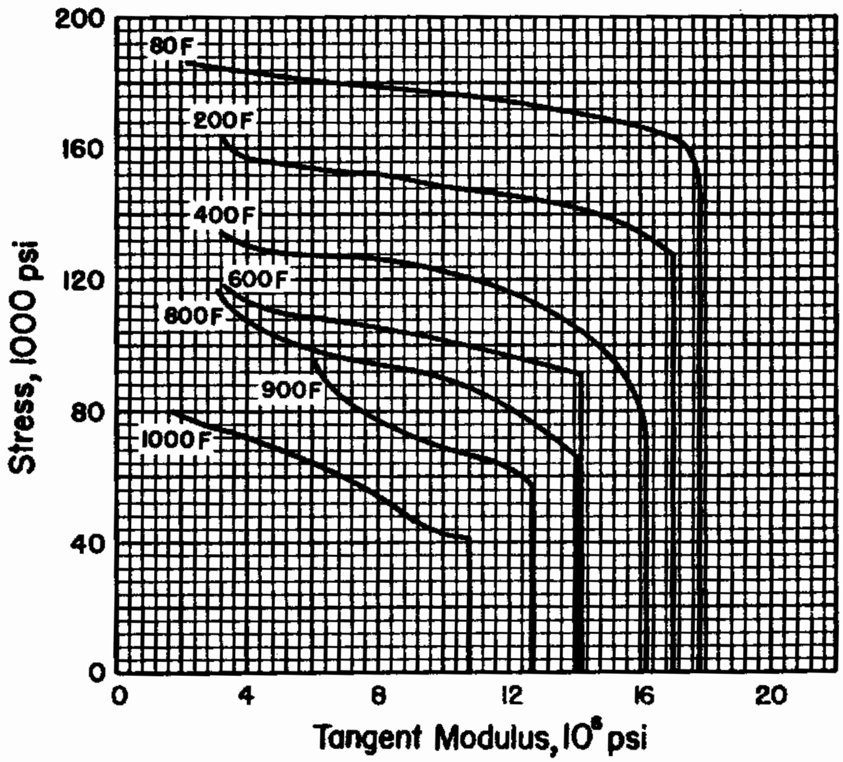

FIGURE 5.2.4.1.4(l). Typical transverse compressive tangent-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

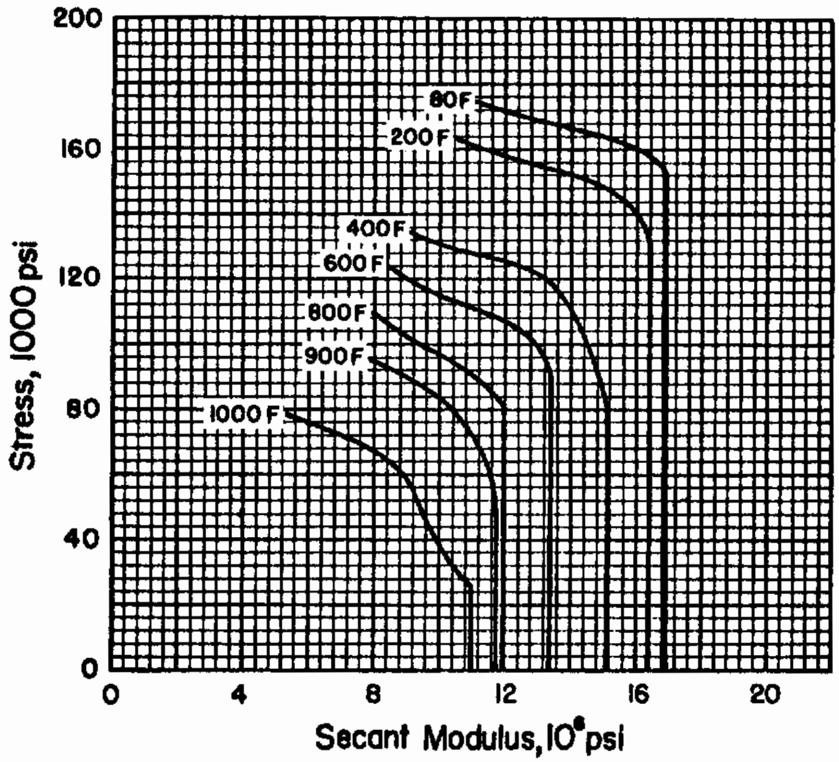

FIGURE 5.2.4.1.4(m). Typical longitudinal compressive secant-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

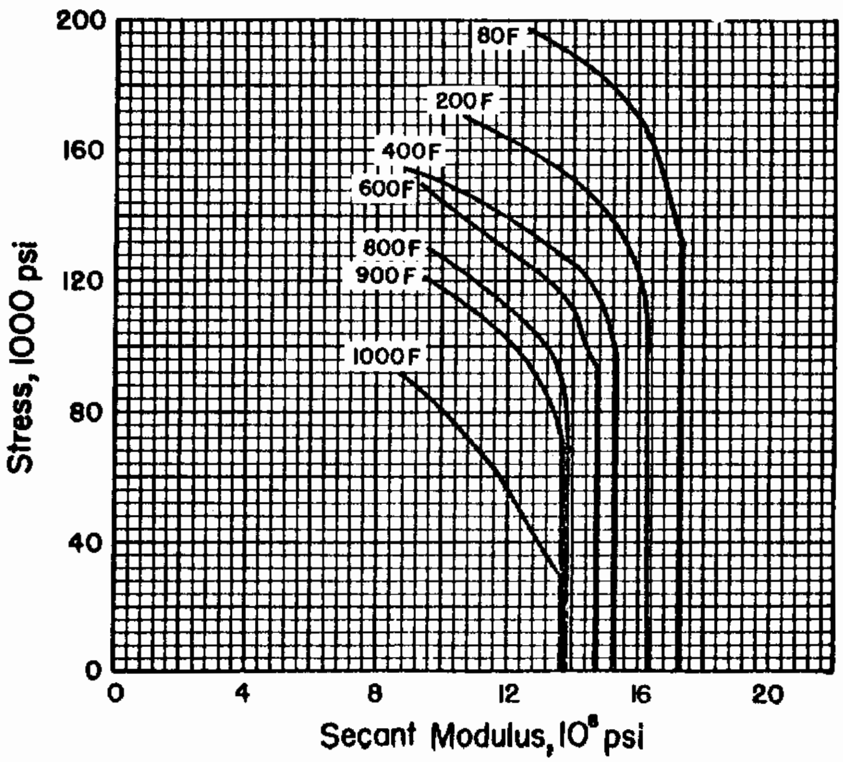

FIGURE 5.2.4.1.4(n). Typical transverse compressive secant-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

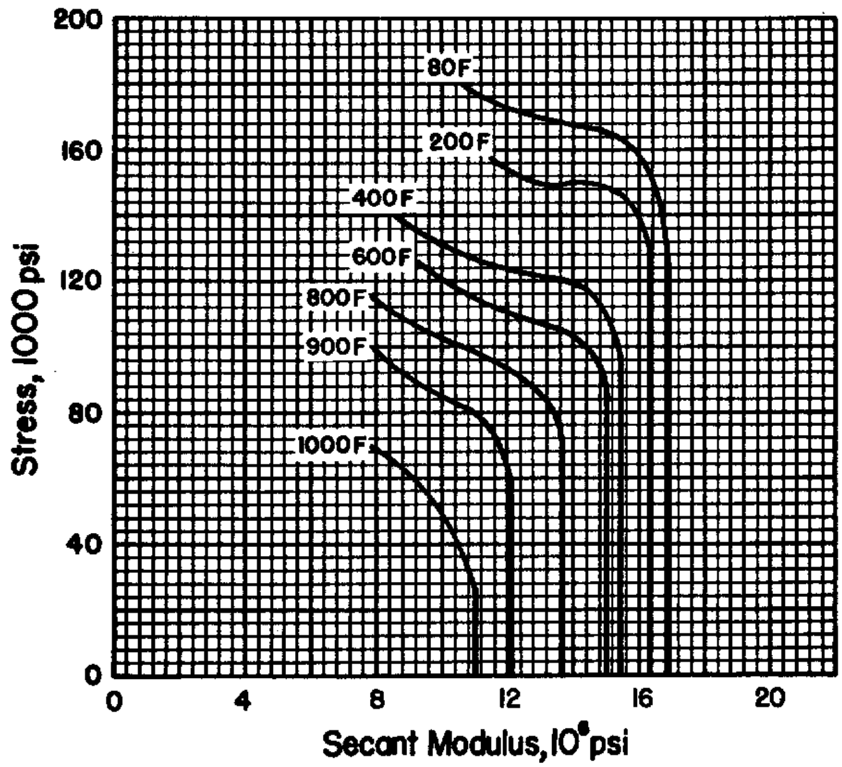

FIGURE 5.2.4.1.4(o). Typical longitudinal compressive secant-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

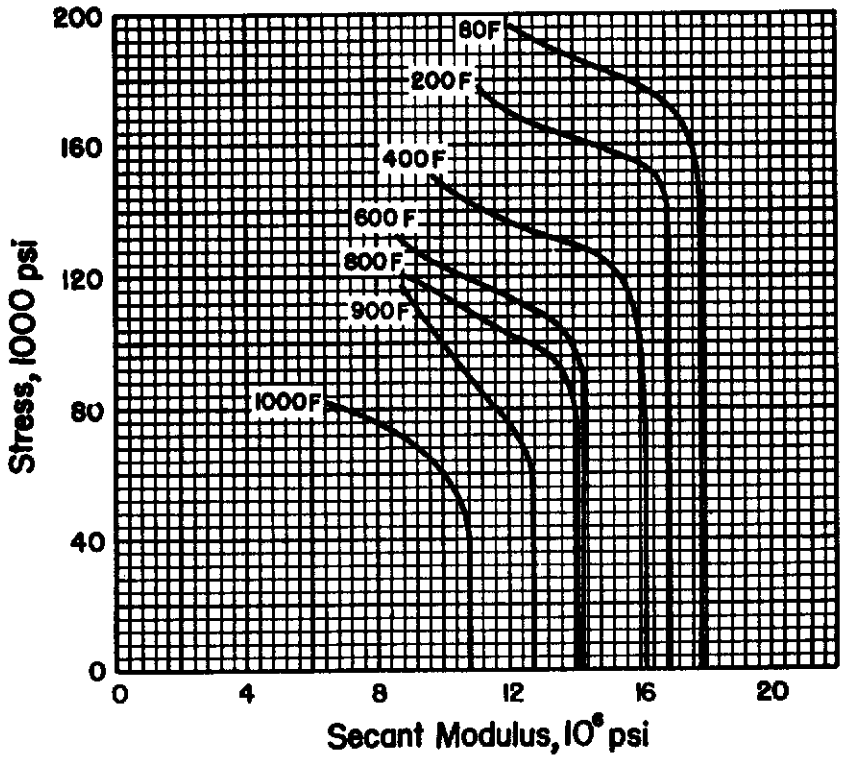

FIGURE 5.2.4.1.4(p). Typical transverse compressive secant-modulus curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

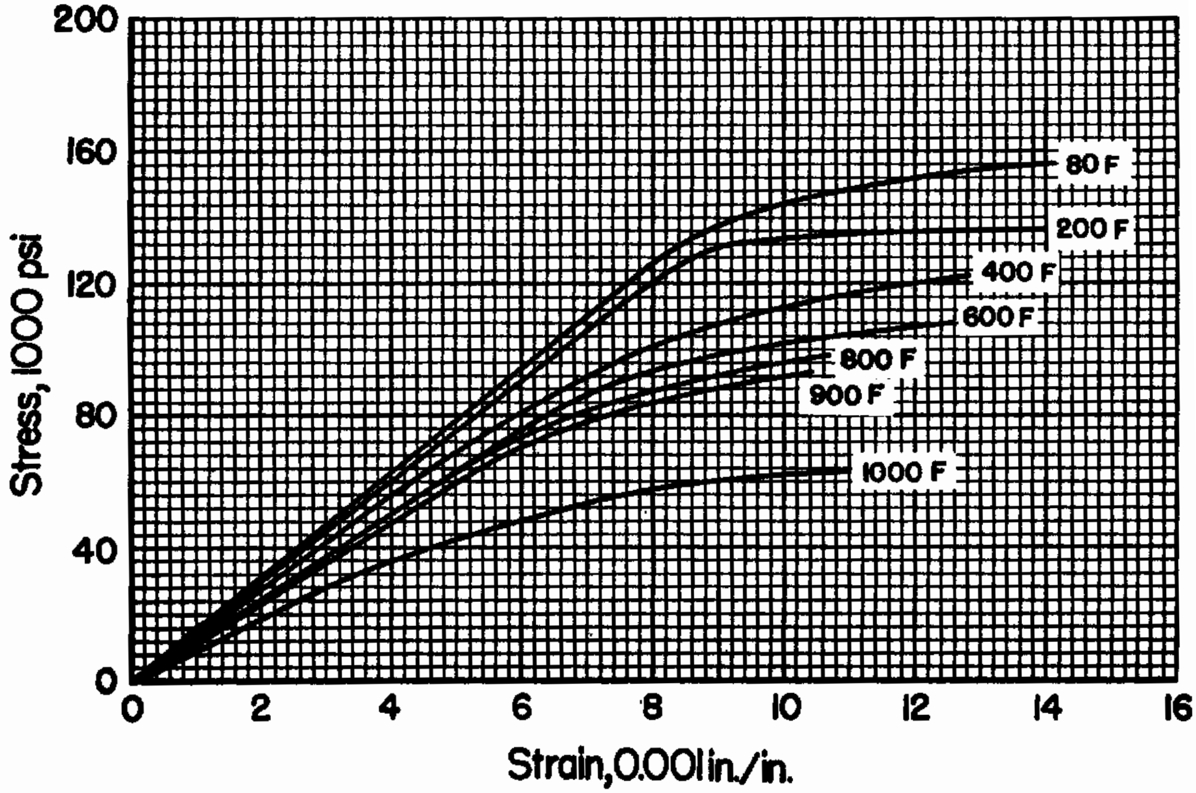

FIGURE 5.2.4.1.5(a). Typical longitudinal tensile stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick thick).

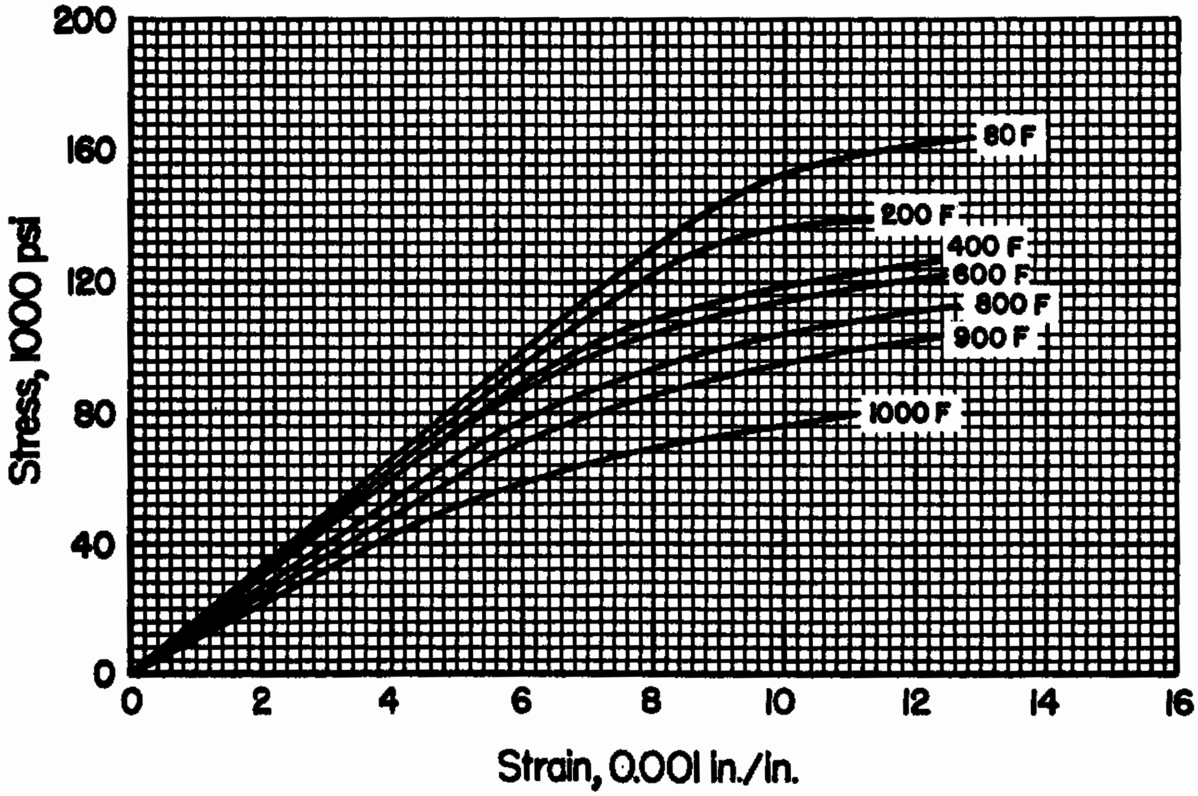

FIGURE 5.2.4.1.5(b). Typical transverse tensile stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

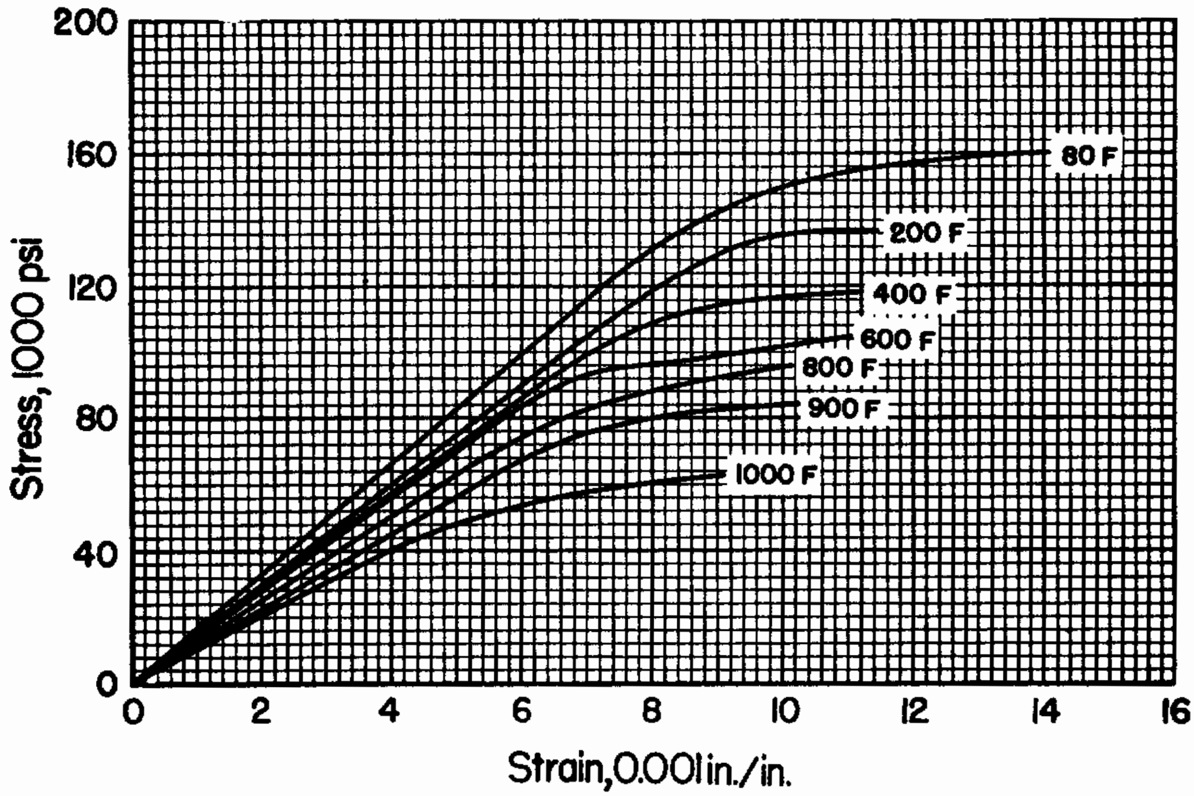

FIGURE 5.2.4.1.5(c). Typical longitudinal tensile stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

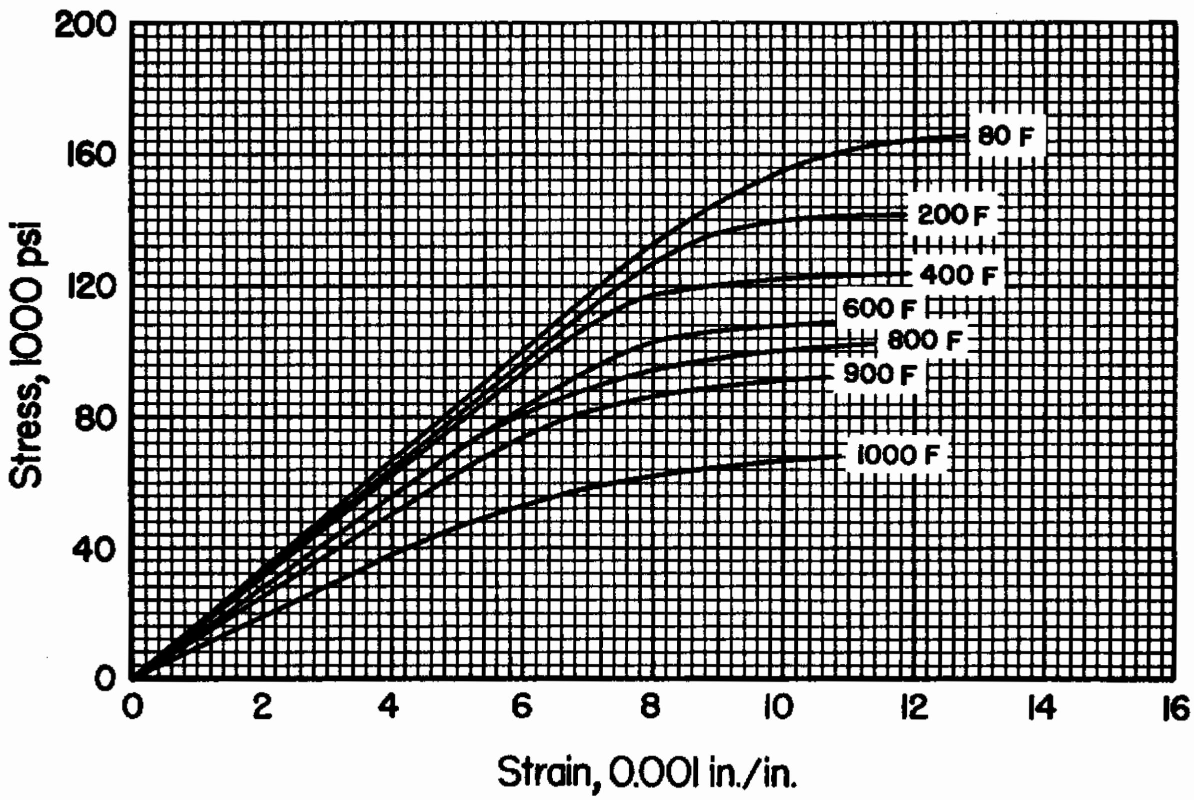

FIGURE 5.2.4.1.5(d). Typical transverse tensile stress-strain curves for 6Al-4V solution treated and aged alloy titanium alloy (0.125 inch thick sheet).

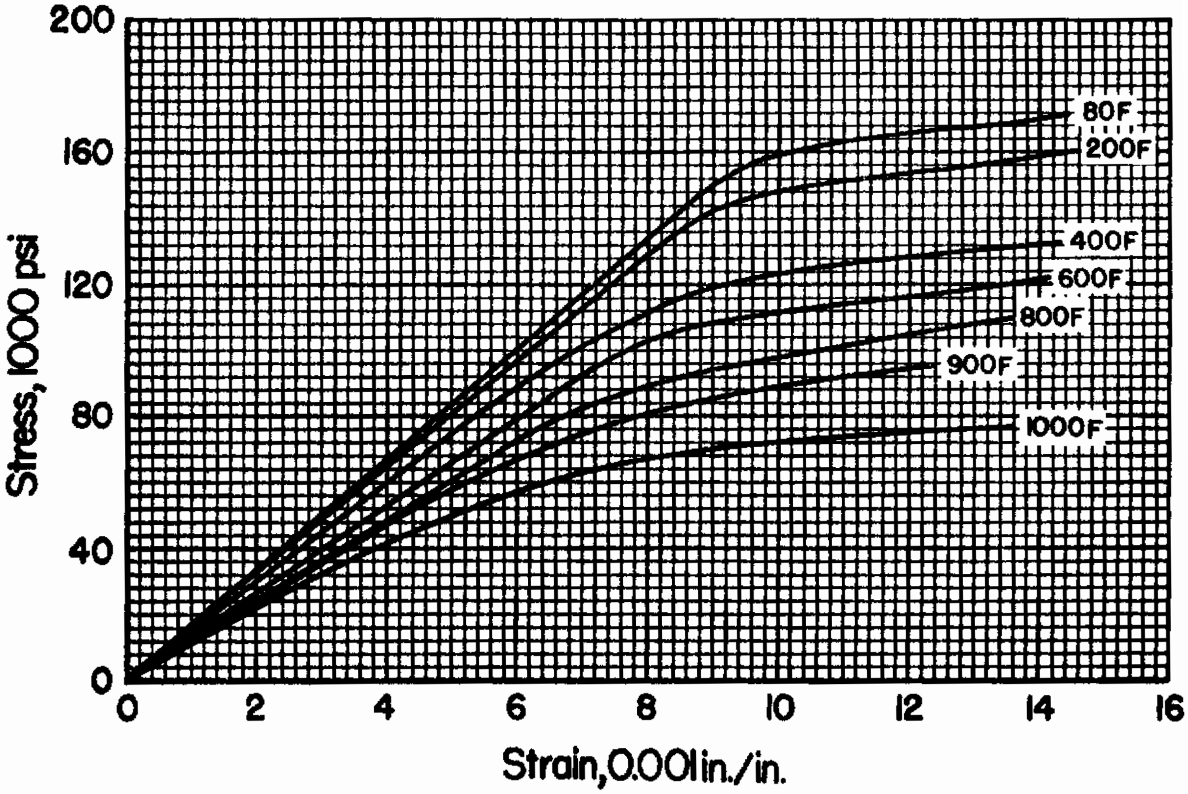

FIGURE 5.2.4.1.5(e). Typical longitudinal compressive stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

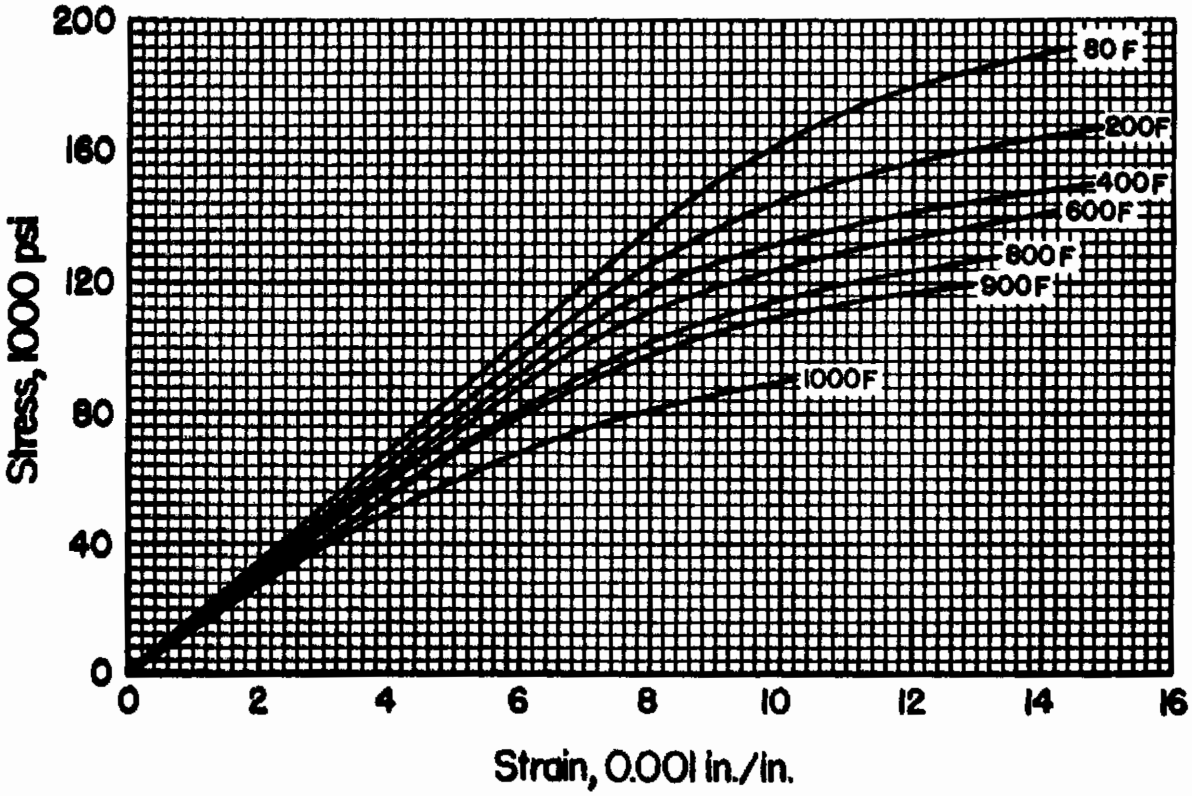

FIGURE 5.2.4.1.5(f). Typical transverse compressive stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet).

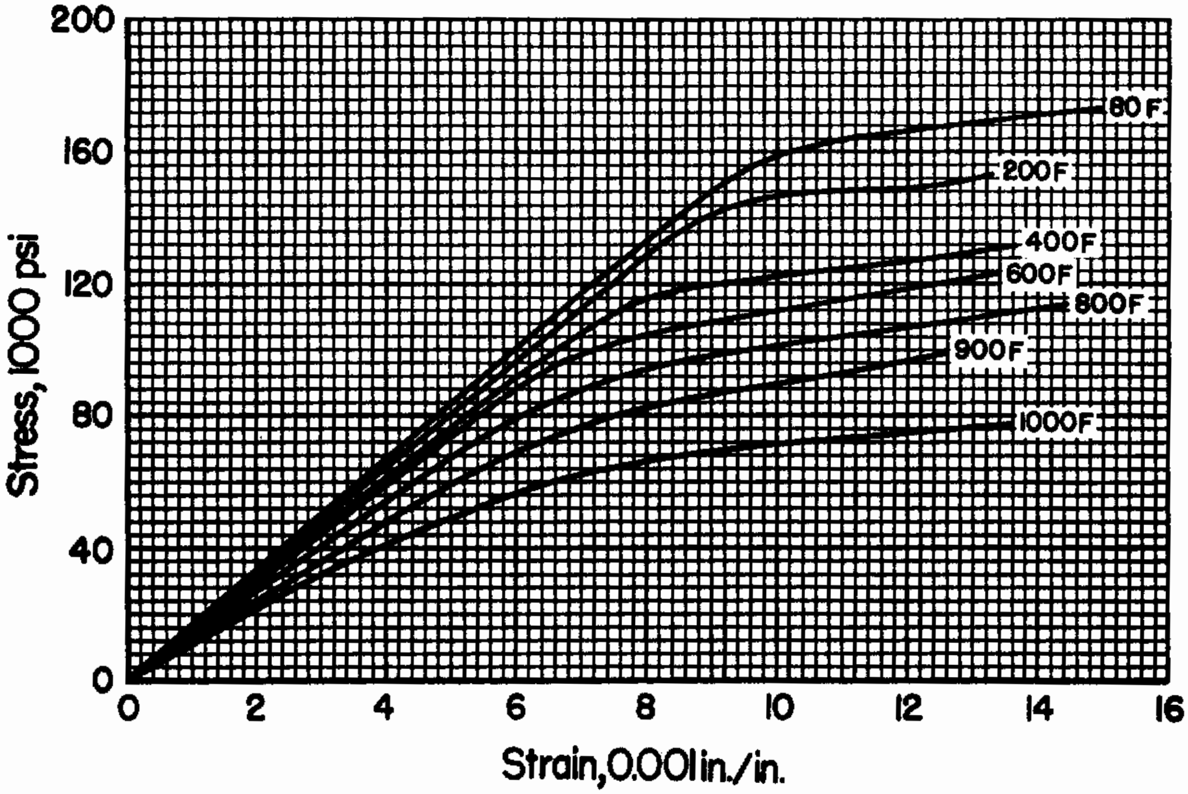

FIGURE 5.2.4.1.5(g). Typical longitudinal compressive stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

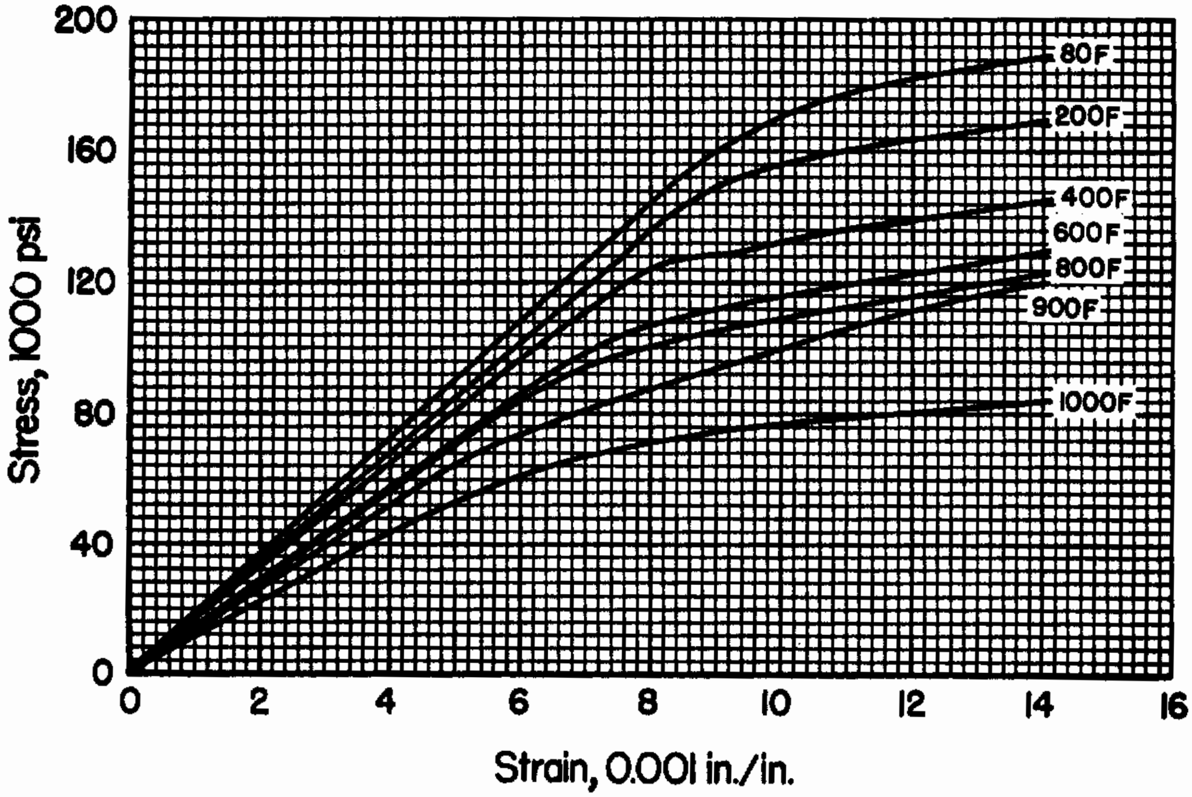

FIGURE 5.2.4.1.5(h). Typical transverse compressive stress-strain curves for 6Al-4V solution treated and aged titanium alloy (0.125 inch thick sheet).

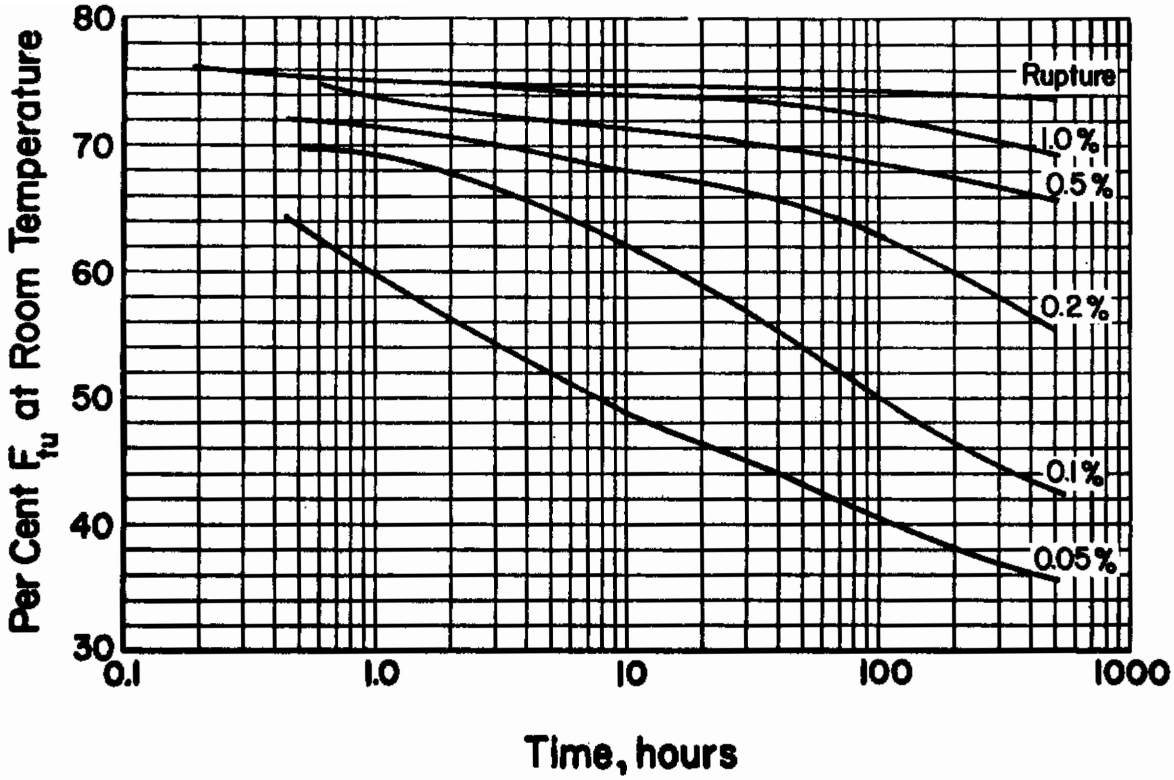

FIGURE 5.2.4.1.6(a). Creep and rupture data for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet) at 600°F.

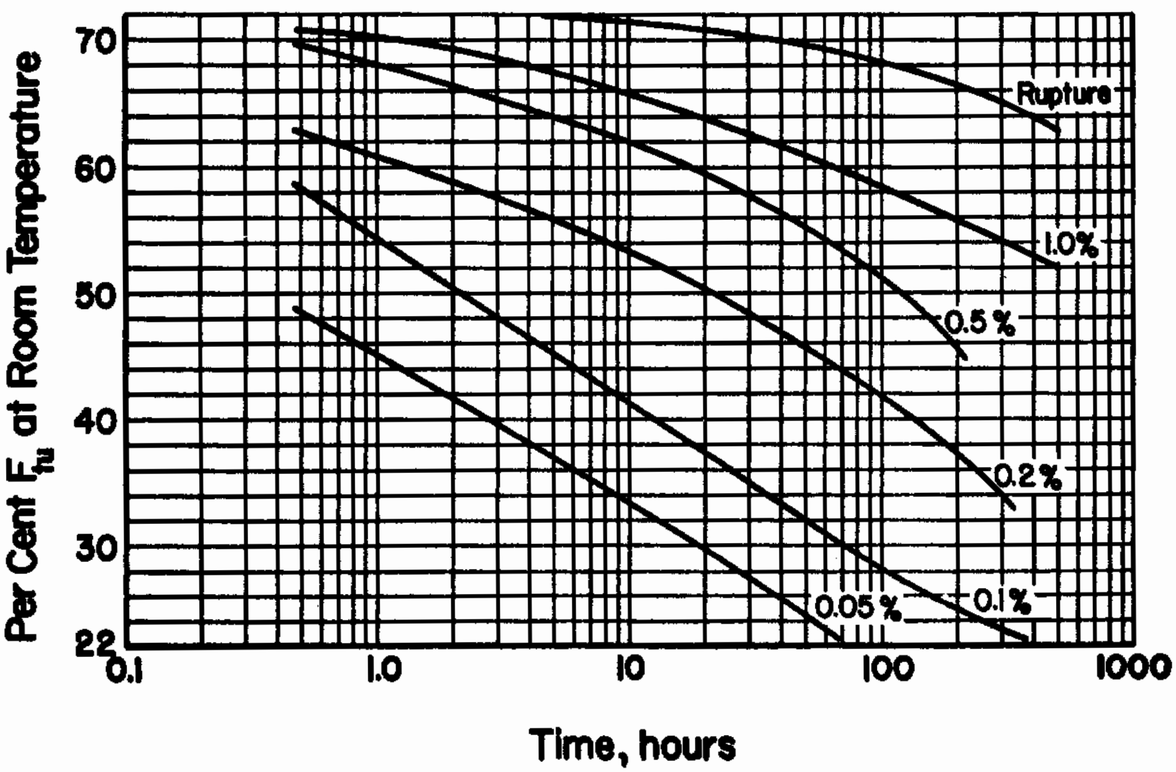

FIGURE 5.2.4.1.6(b). Creep and rupture data for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet) at 700°F.

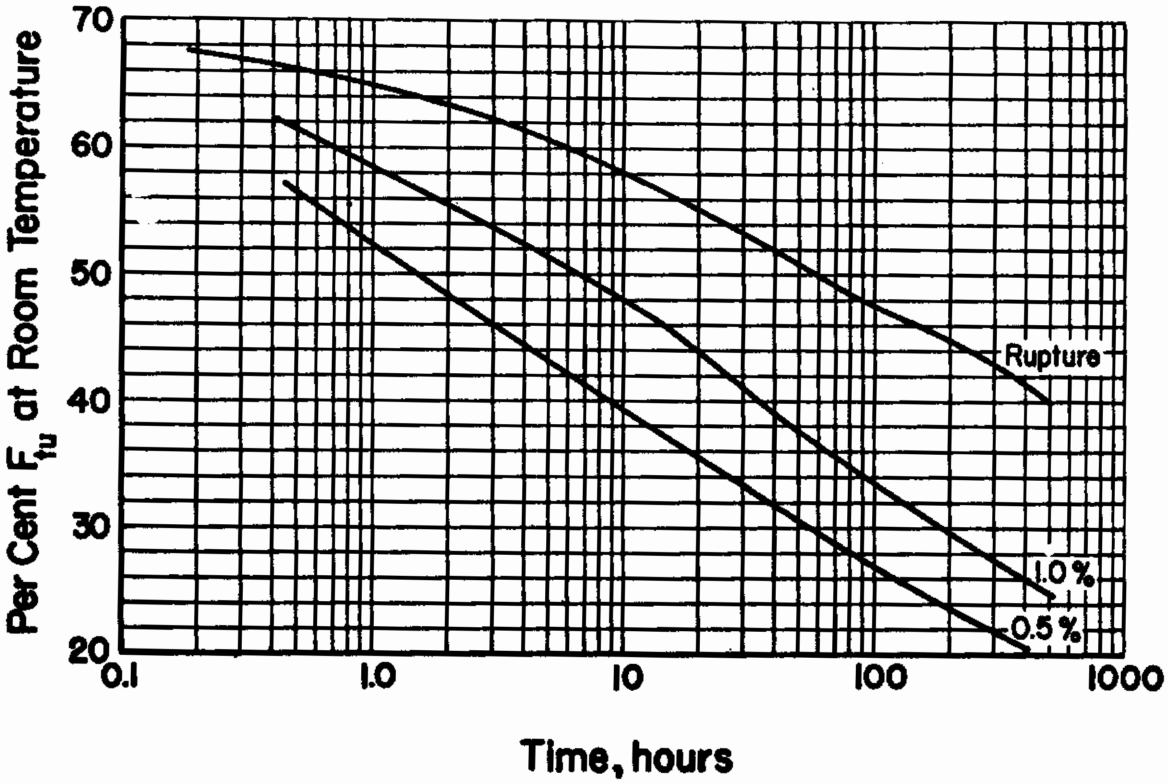

FIGURE 5.2.4.1.6(c). Creep and rupture data for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet) at 800°F.

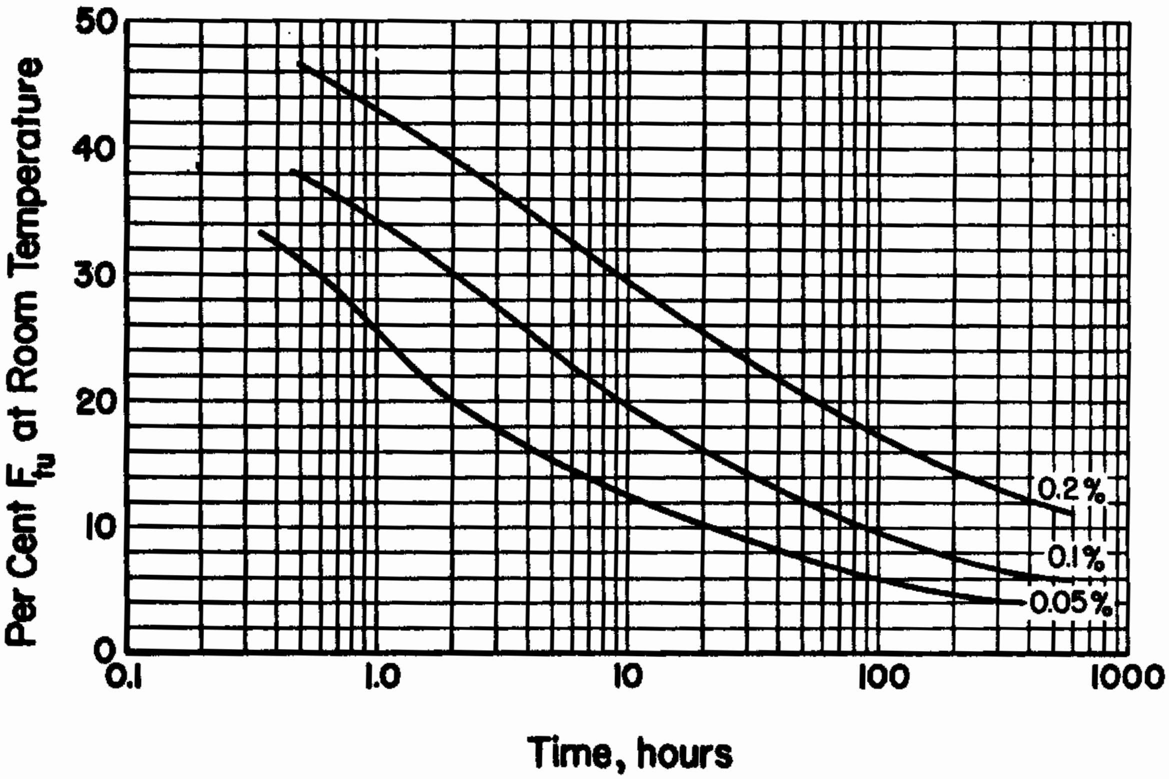

FIGURE 5.2.4.1.6(d). Creep and rupture data for 6Al-4V solution treated and aged titanium alloy (0.063 inch thick sheet) at 800°F.

5.2.5 4Al-3Mo-1V Titanium Alloy

5.2.5.0 Comments and Properties

Room-temperature mechanical and physical properties are shown in Table 5.2.5.0(a). Effect on tensile properties of long-time exposure to elevated temperature is given in Tables 5.2.5.0(b) and (c). The temper index for 4Al-3Mo-1V titanium alloy is as follows:

Section	Temper or Condition
5.2.5.1	Solution treated and aged

For the solution treated and aged material reported herein, the processing history was:

1650F to 1655F for 15 to 30 min. - 925F for 12 hrs.

TABLE 5.2.5.0(a) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 4Al-3Mo-1V TITANIUM ALLOY

Alloy	4Al-3Mo-1V		
Form	Sheet		
Condition	Solution Treated and Aged		
Thickness (in.)	0.020	0.063	0.125
Basis	B	B	B
Mechanical Properties:			
F_{tu}, ksi			
L	189	184	183
T	193	186	187
F_{ty}, ksi			
L	168	154	146
T	172	164	162
F_{cy}, ksi			
L	..	159	154
T	..	170	184
F_{su}, ksi			
L	110	98	108
T	111	104	112
F_{bru}, ksi (e/D=1.5)			
L	256	246	250
T	260	261	274
F_{bru}, ksi (e/D=2.0)			
L	295	301	306
T	287	328	324
F_{bry}, ksi (e/D=1.5)			
L	236	225	227
T	236	232	236
F_{bry}, ksi (e/D=2.0)			
L	231	252	266
T	241	279	279
e, percent (a)			
L	4.4	6.2	6.0
T	4.2	6.6	7.7
E, 10^6 psi			
L	15.9	15.1	15.2
T	15.9	15.8	16.7
E_c, 10^6 psi			
L	..	16.0	15.9
T	..	16.5	17.3
Physical Properties:			
ω, lb/in.^{3}	0.163		
C, Btu/(lb)(F)	0.126 (at 75°F)		
K, Btu/[(hr)(ft^2)(F)/ft]	4.8 (at 70°F)		
α, 10^{-6} in./in./F	5.1 (100°F to 200°F)		

(a) Elongations are average test values.

TABLE 5.2.5.0(b) EFFECT OF 500-HOUR EXPOSURE AT 600°F ON THE TENSILE PROPERTIES OF 4Al-3Mo-1V TITANIUM ALLOY

Condition................	Solution Treated and Aged		
Thickness (in.)..........	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L..................	196	186	187
T..................	196	184	187
F_{ty}, ksi (at room temp.)			
L..................	178	155	155
T..................	176	162	166
F_{tu}, ksi (at 600°F)			
L..................	148	142	140
T..................	150	142	145
F_{ty}, ksi (at 600°F)			
L..................	111	113	100
T..................	116	119	111
Exposed at temperature while stressed to 1/3 average 600°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L..................	196	186	188
T..................	196	186	188
F_{ty}, ksi (at room temp.)			
L..................	177	169	152
T..................	176	163	162
F_{tu}, ksi (at 600°F)			
L..................	146	148	140
T..................	145	151	144
F_{ty}, ksi (at 600°F)			
L..................	112	97	99
T..................	119	108	111

TABLE 5.2.5.0(c) EFFECT OF 10-HOUR EXPOSURE AT 900°F ON THE TENSILE PROPERTIES OF 4Al-3Mo-1V TITANIUM ALLOY

Condition.................	Solution Treated and Aged		
Thickness (in.)...........	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L...................	195	187	182
T...................	193	186	184
F_{ty}, ksi (at room temp.)			
L...................	174	159	151
T...................	172	165	162
F_{tu}, ksi (at 900°F)			
L...................	125	115	116
T...................	125	116	121
F_{ty}, ksi (at 900°F)			
L...................	89	82	77
T...................	89	86	84
Exposed at temperature while stressed to 1/3 average 900°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L...................	195	186	184
T...................	190	184	187
F_{ty}, ksi (at room temp.)			
L...................	172	155	144
T...................	174	160	161
F_{tu}, ksi (at 900°F)			
L...................	123	117	114
T...................	125	117	122
F_{ty}, ksi (at 900°F)			
L...................	85	76	74
T...................	90	83	83

5.2.5.1 Solution Treated and Aged Condition

Room and elevated temperature data for this condition are presented in Figures 5.2.5.1.1(a) through 5.2.5.1.6(d).

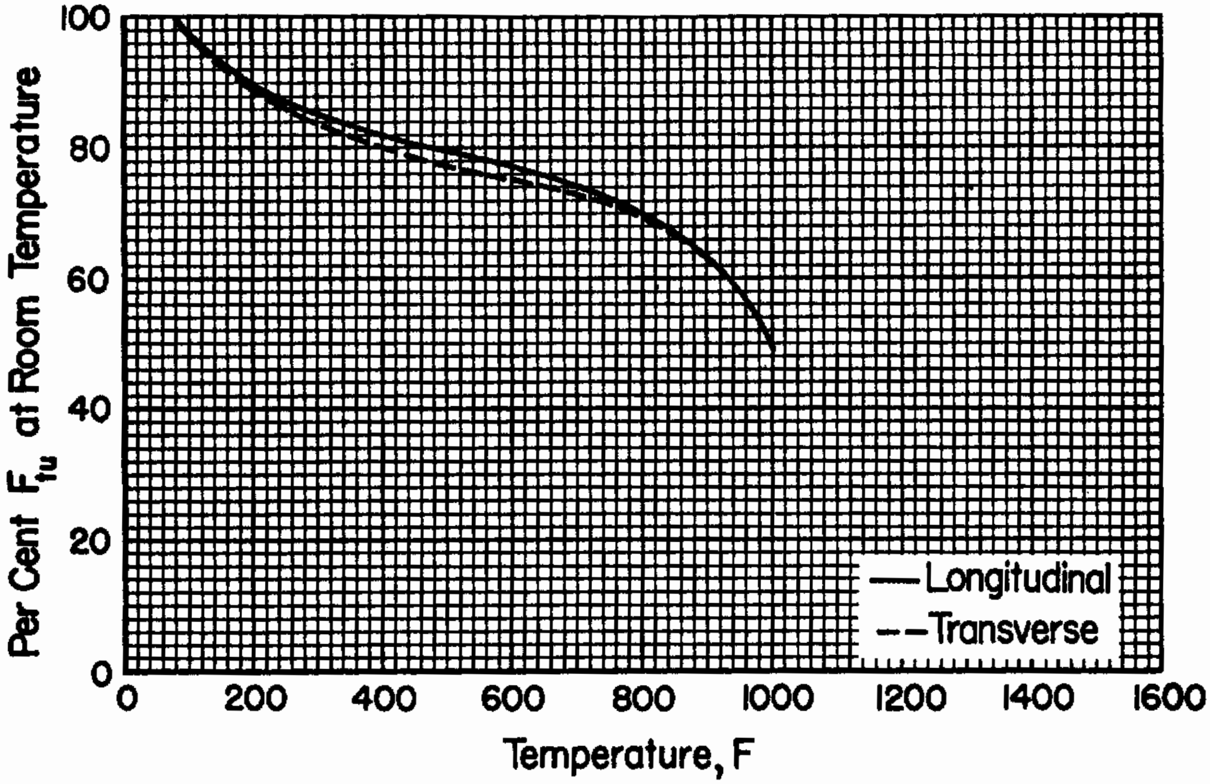

FIGURE 5.2.5.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

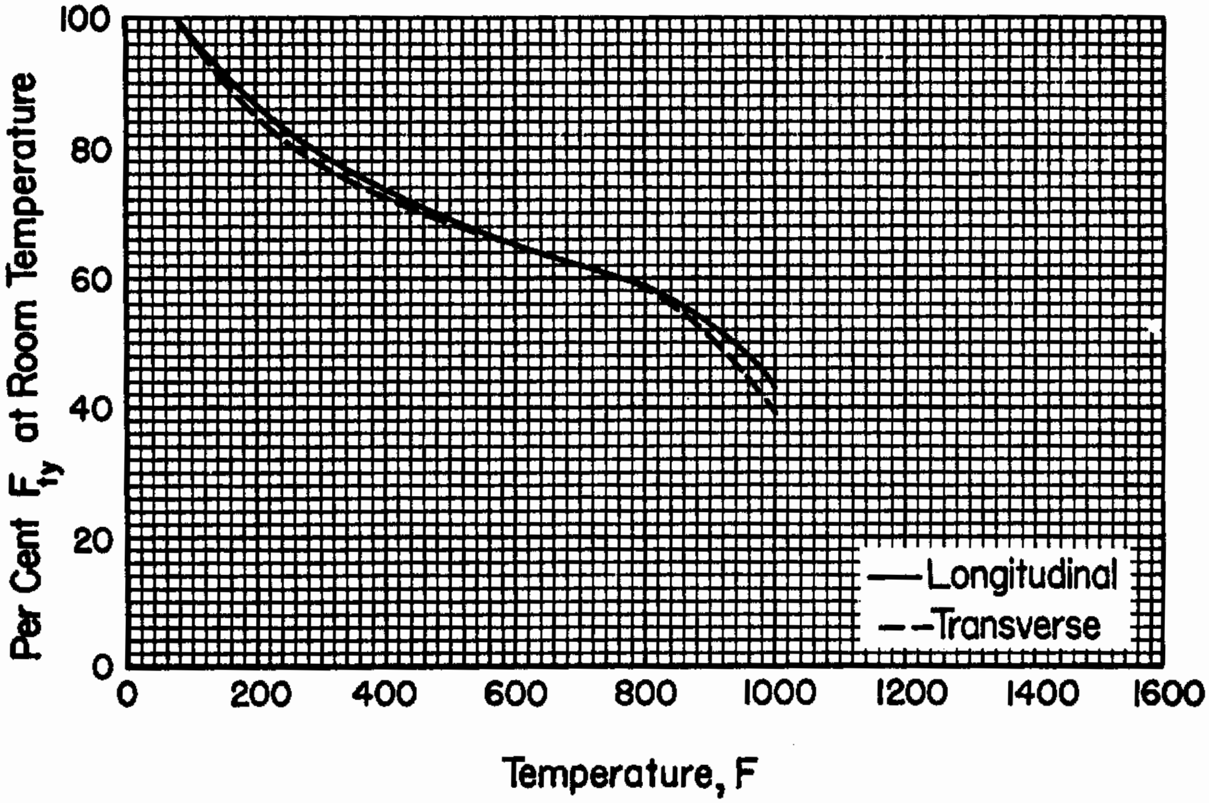

FIGURE 5.2.5.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

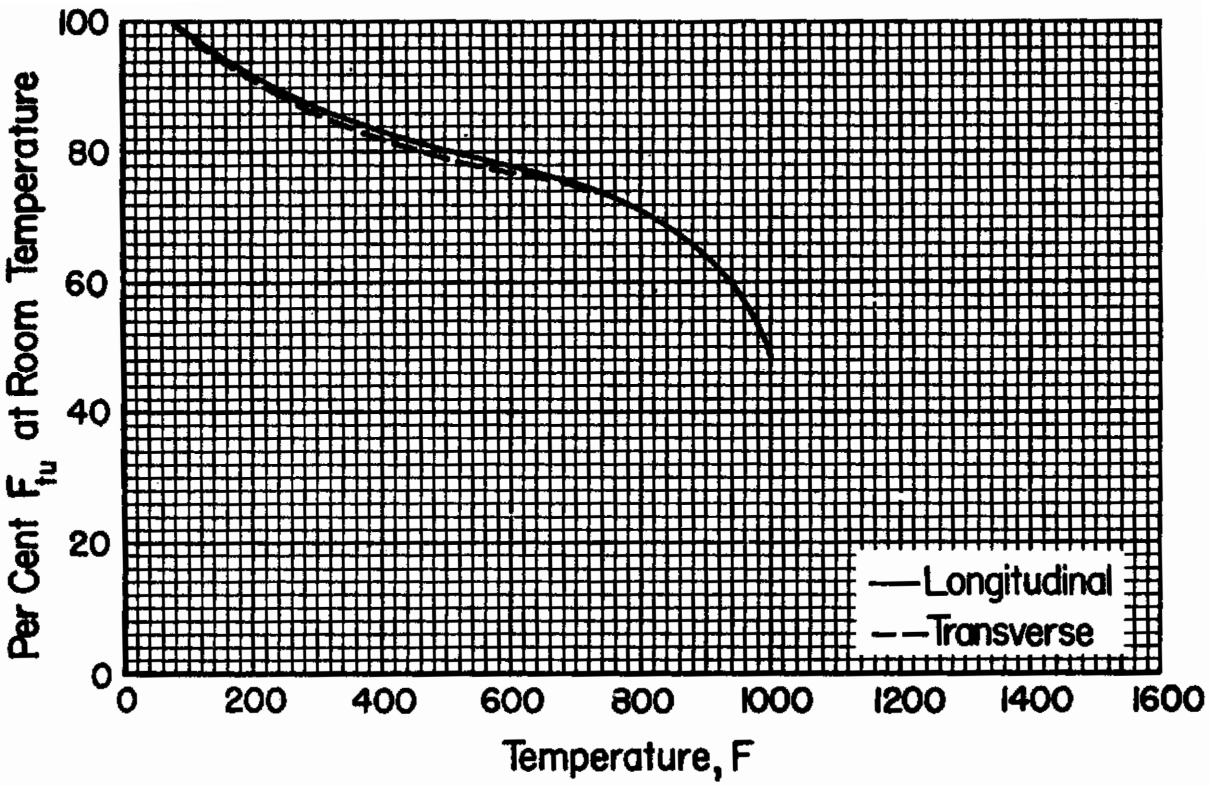

FIGURE 5.2.5.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

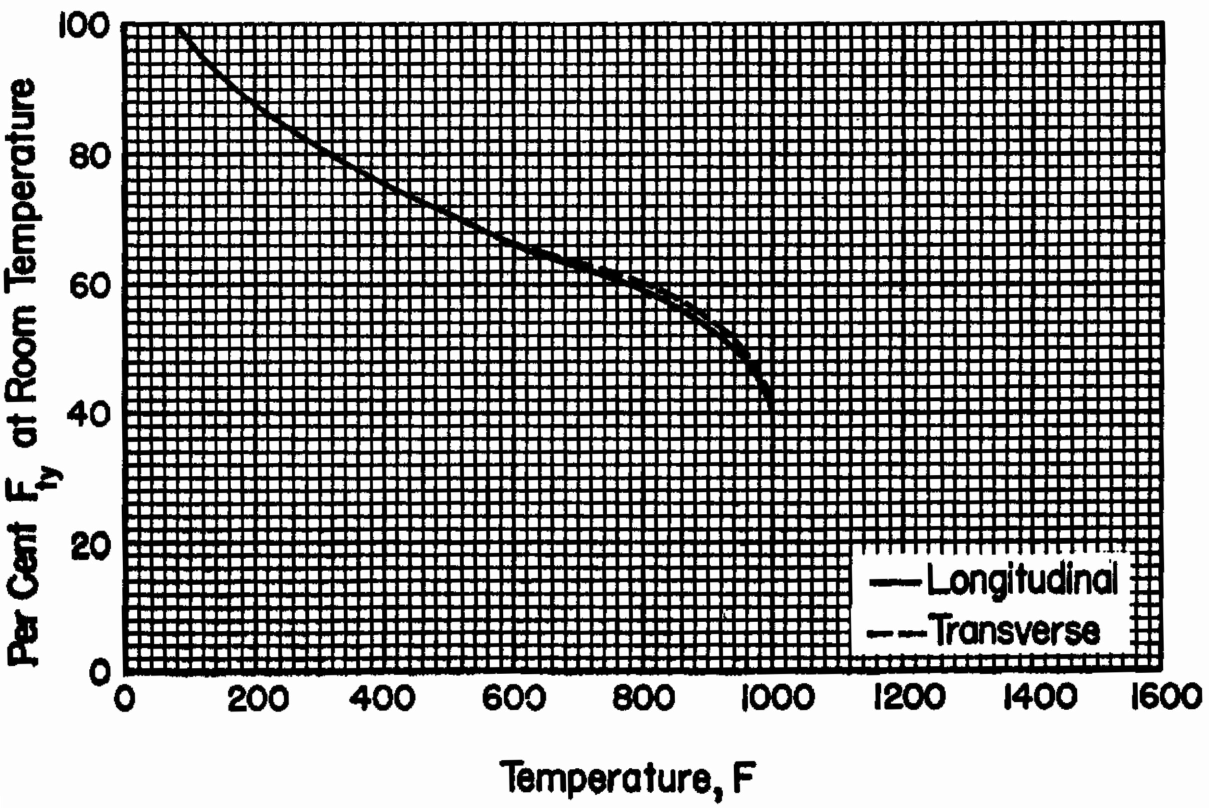

FIGURE 5.2.5.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

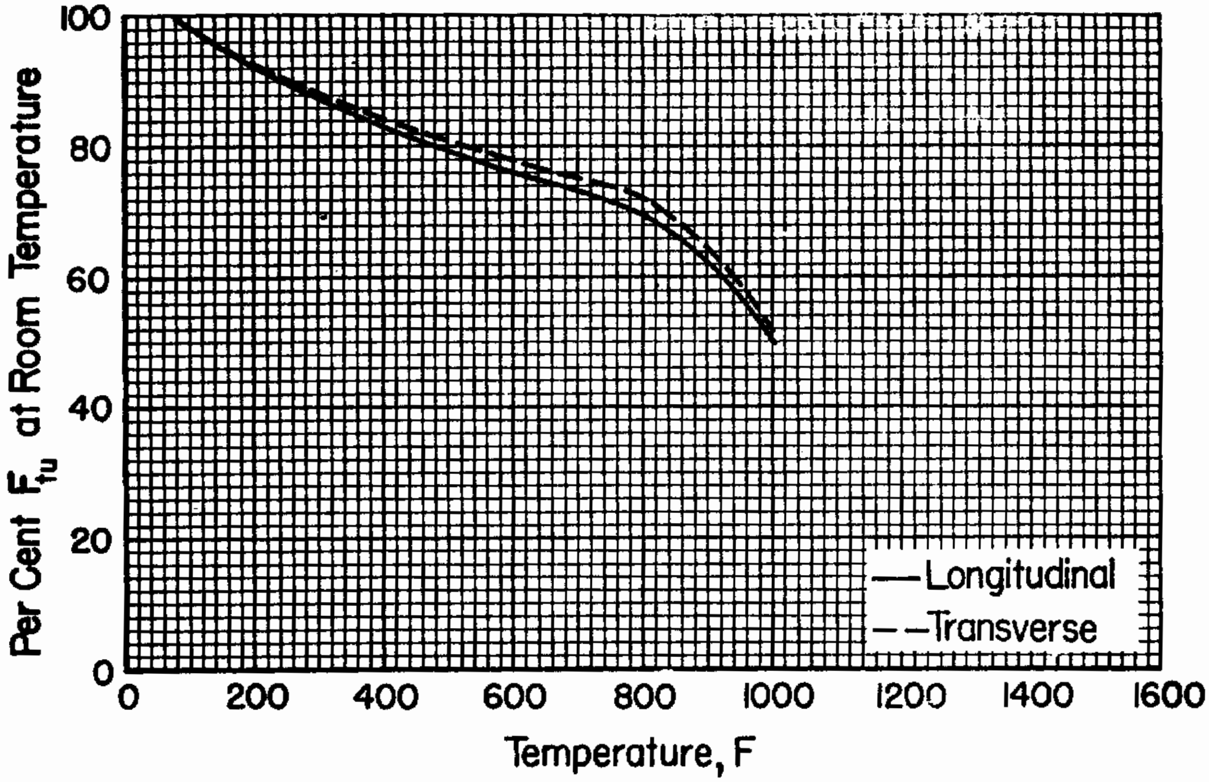

FIGURE 5.2.5.1.1(e). Effect of temperature on the ultimate tensile strength (F_{tu}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

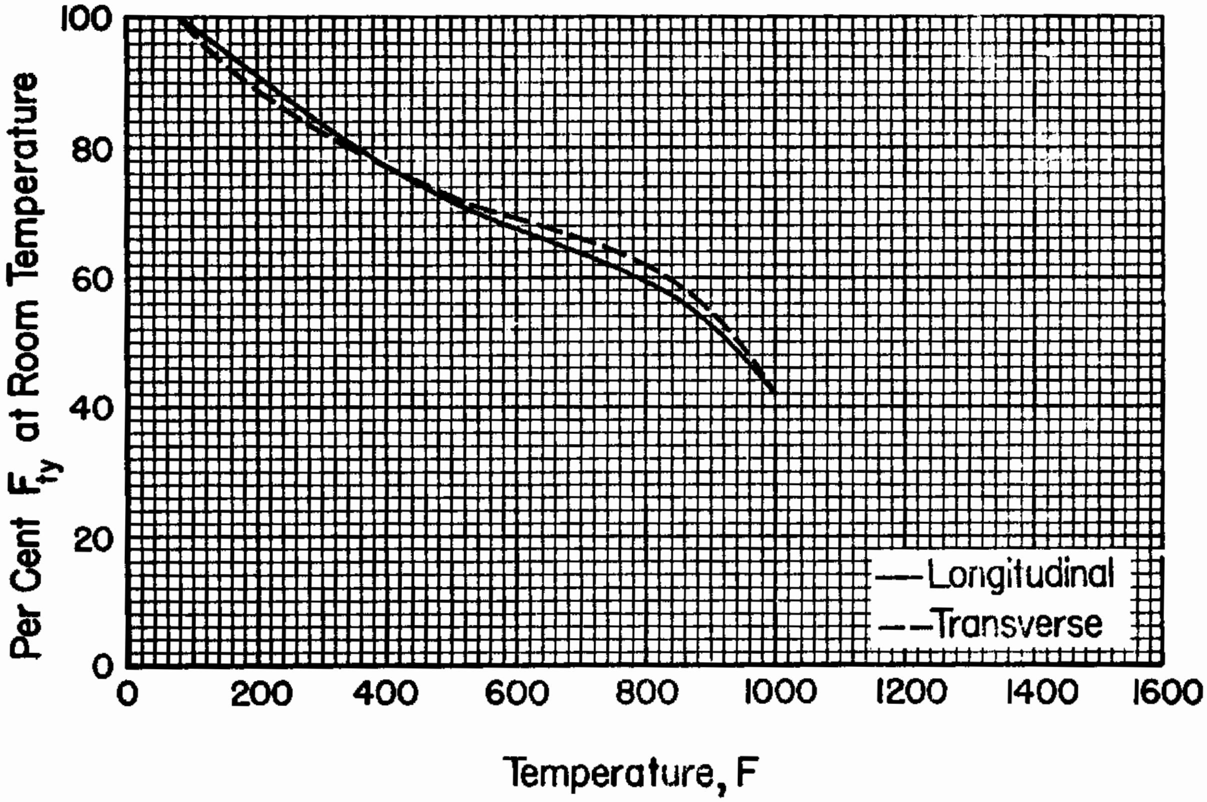

FIGURE 5.2.5.1.1(f). Effect of temperature on the tensile yield strength (F_{ty}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

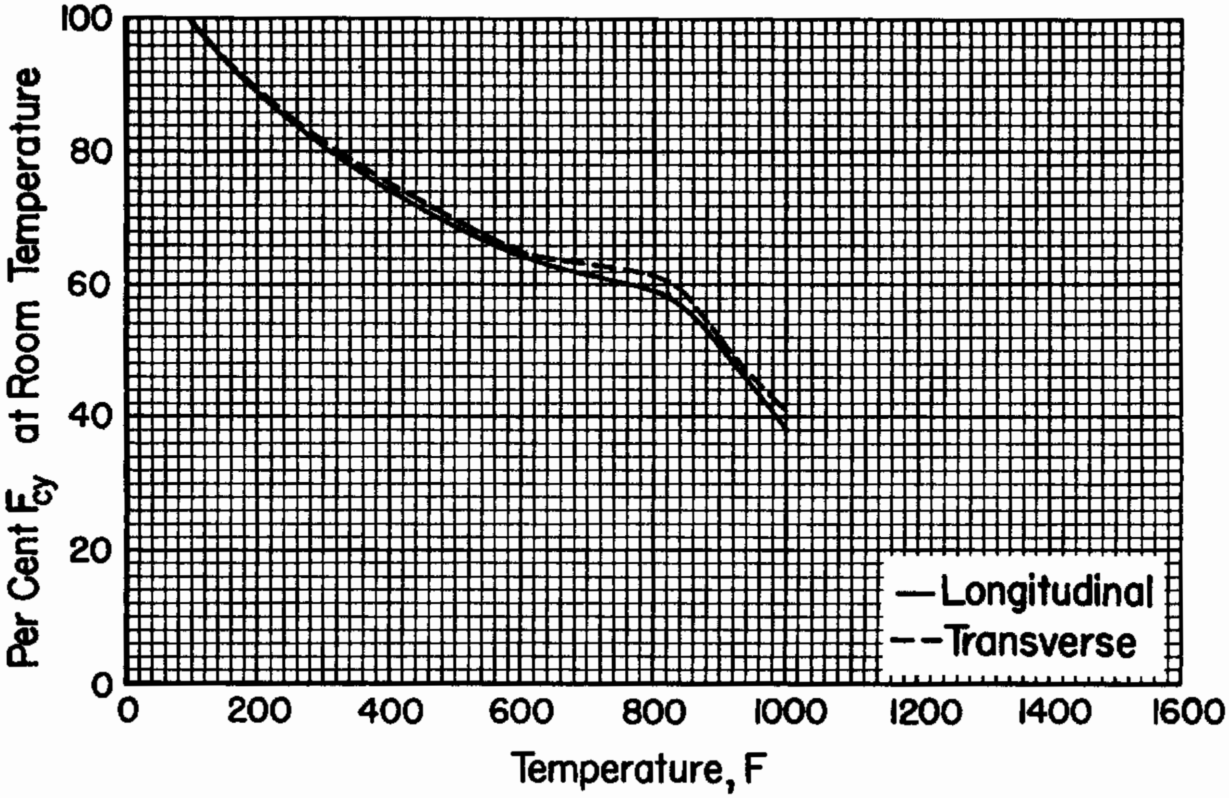

FIGURE 5.2.5.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

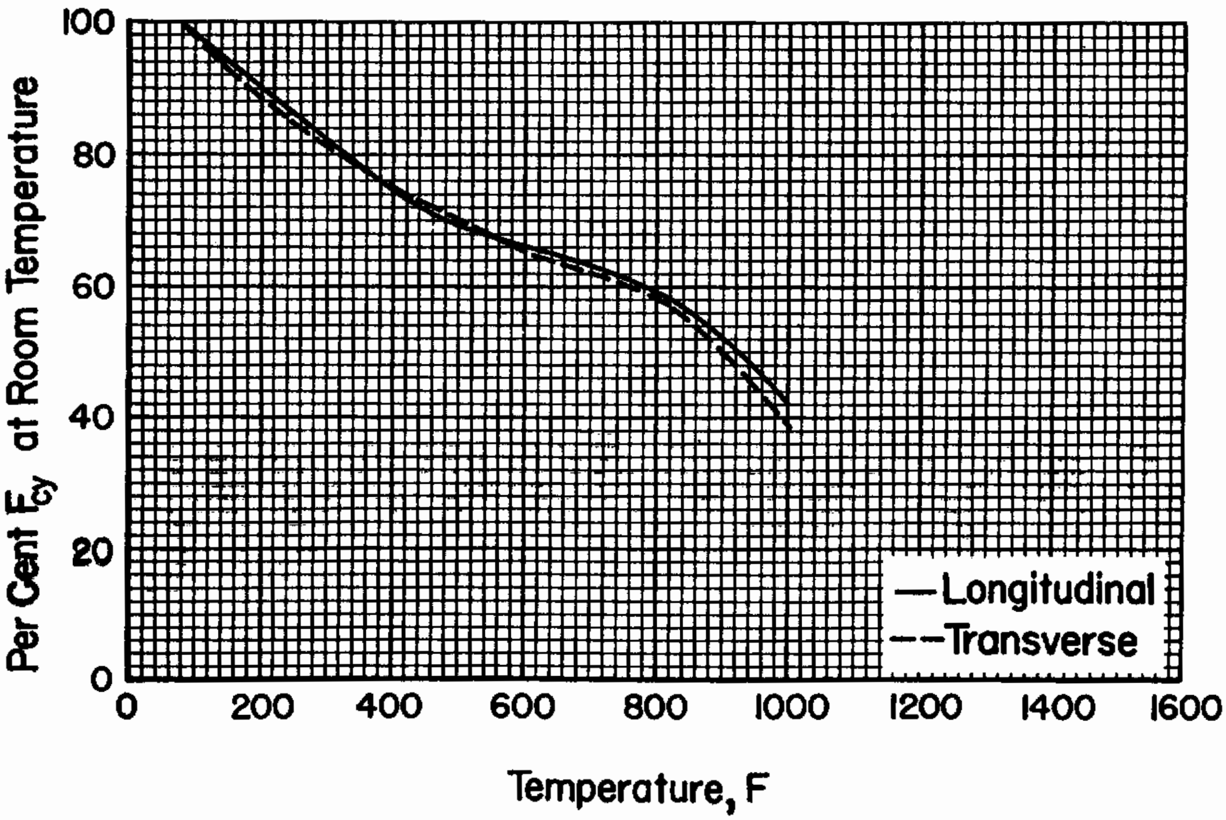

FIGURE 5.2.5.1.2(b). Effect of temperature on the compressive yield strength (F_{cy}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

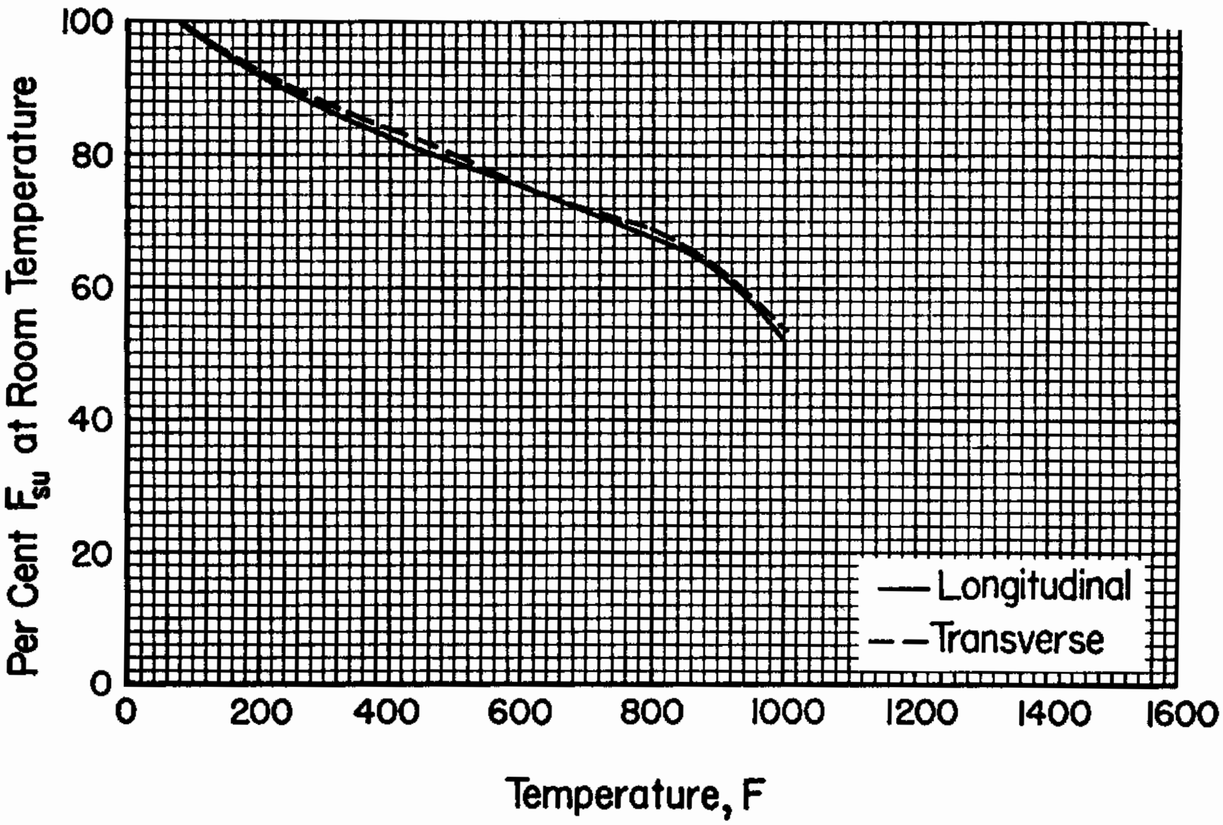

FIGURE 5.2.5.1.2(c). Effect of temperature on the ultimate shear strength (F_{su}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

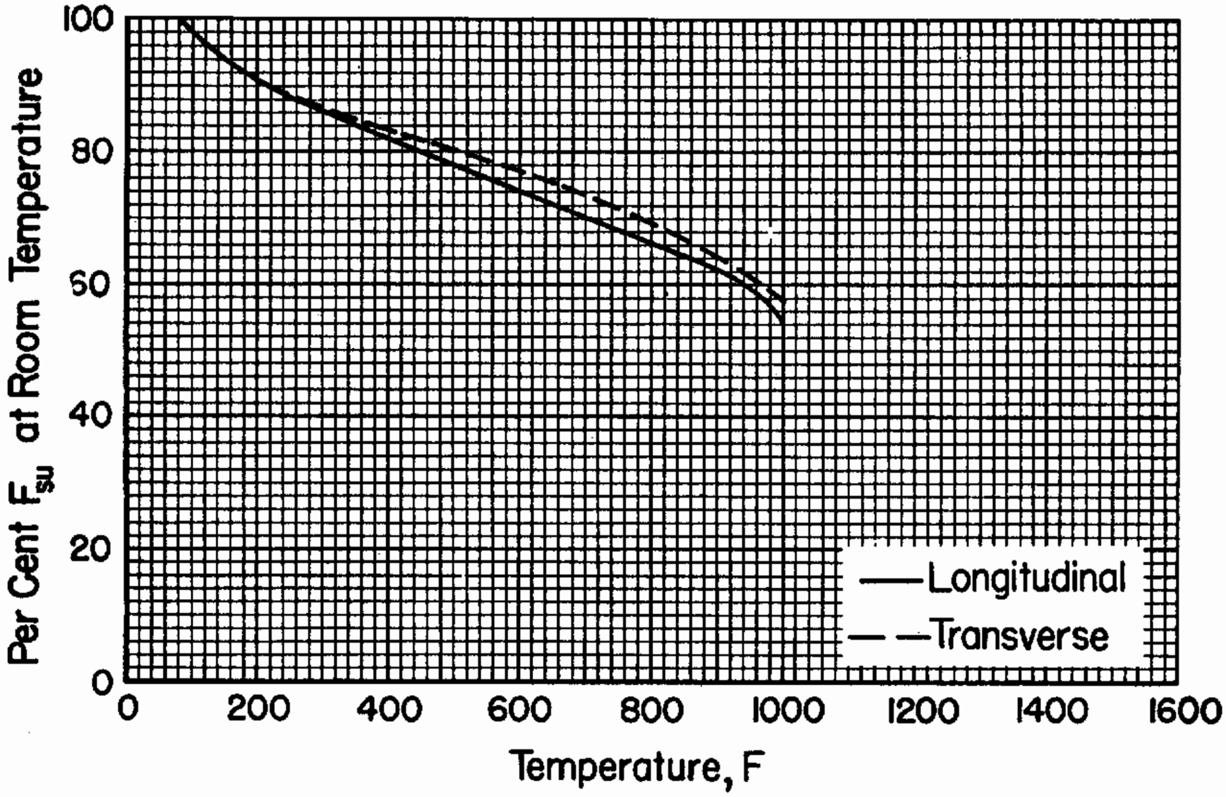

FIGURE 5.2.5.1.2(d). Effect of temperature on the ultimate shear strength (F_{su}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

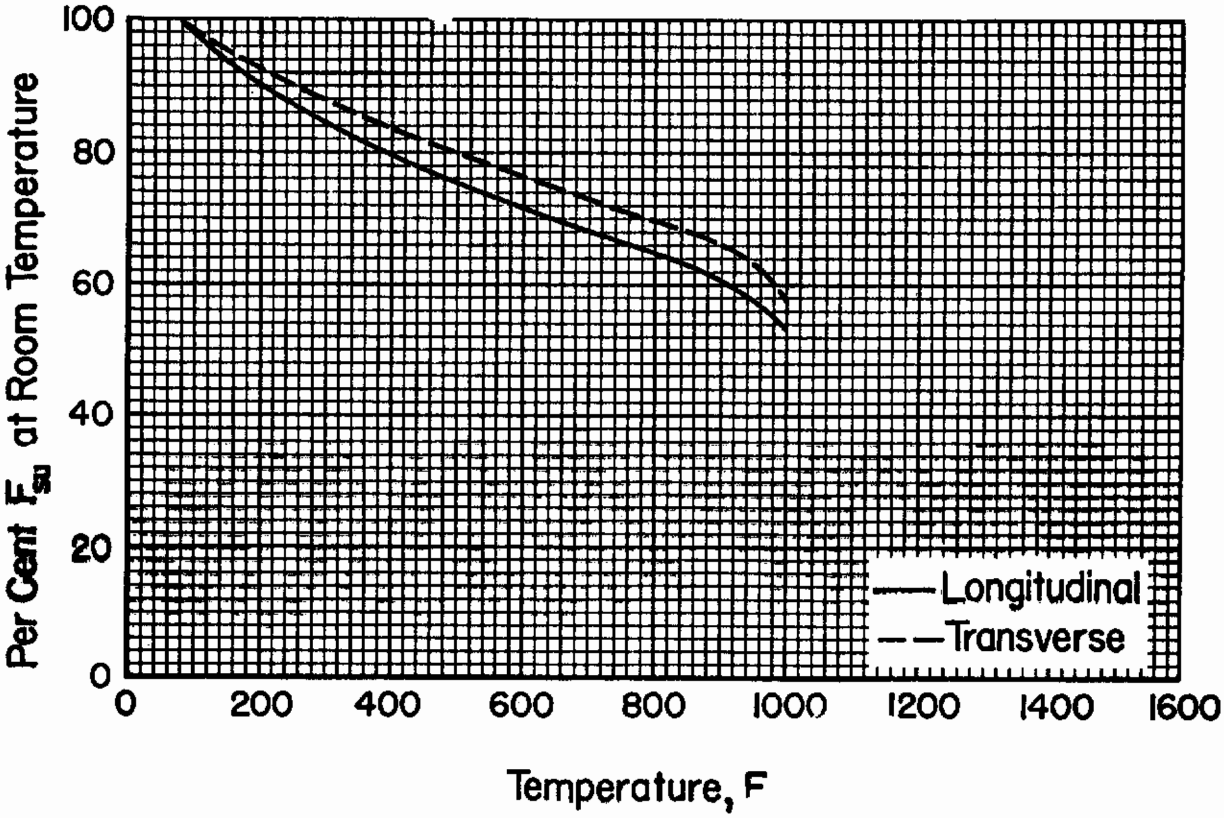

FIGURE 5.2.5.1.2(e). Effect of temperature on the ultimate shear strength (F_{su}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

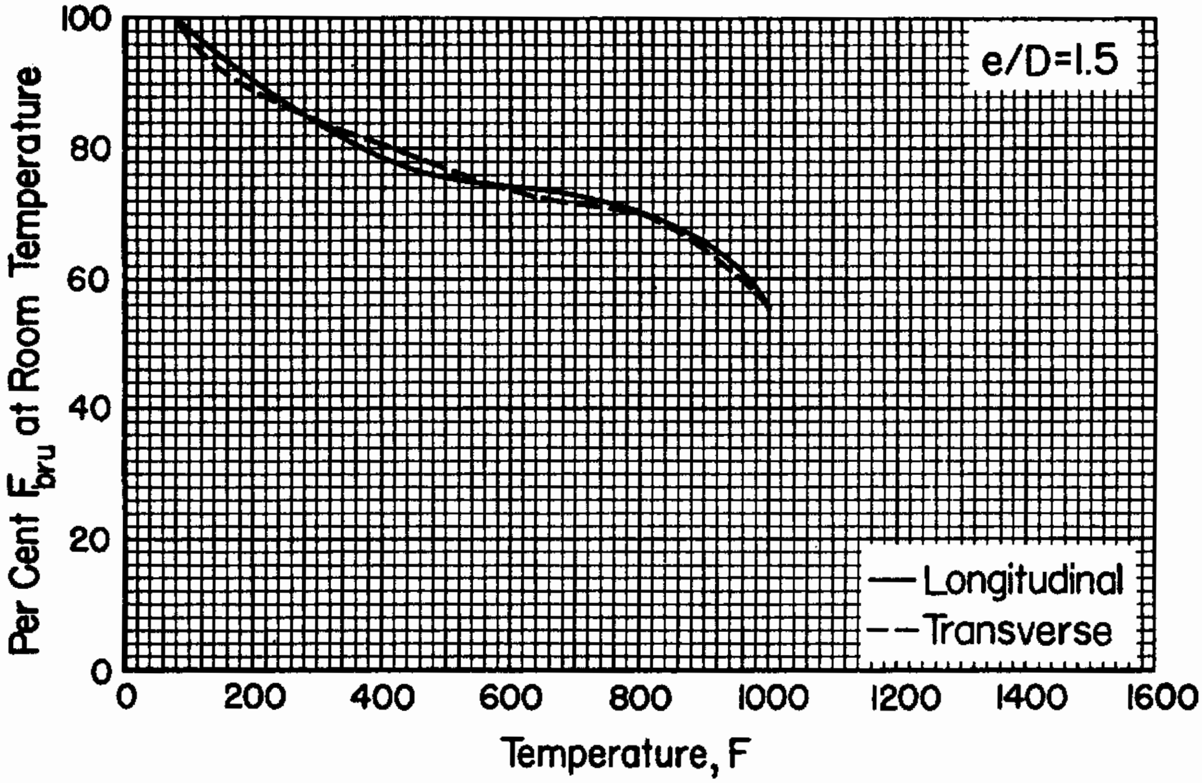

FIGURE 5.2.5.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

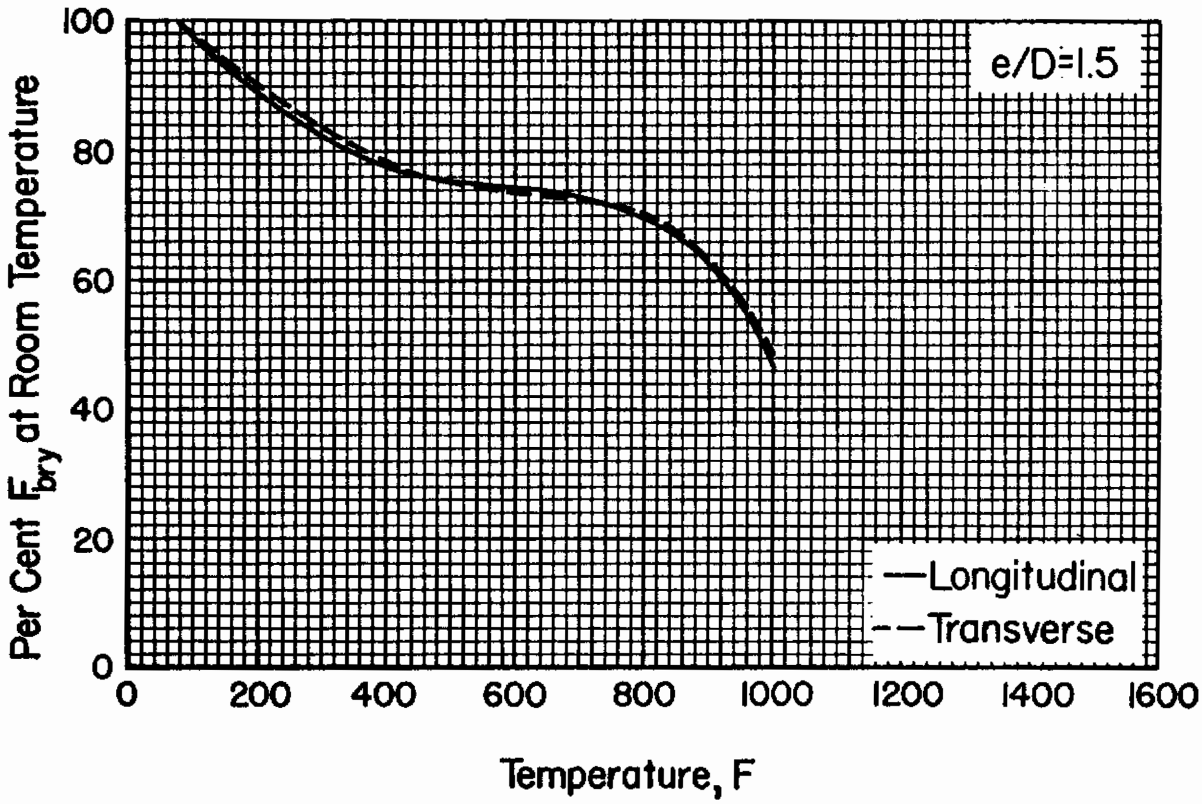

FIGURE 5.2.5.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

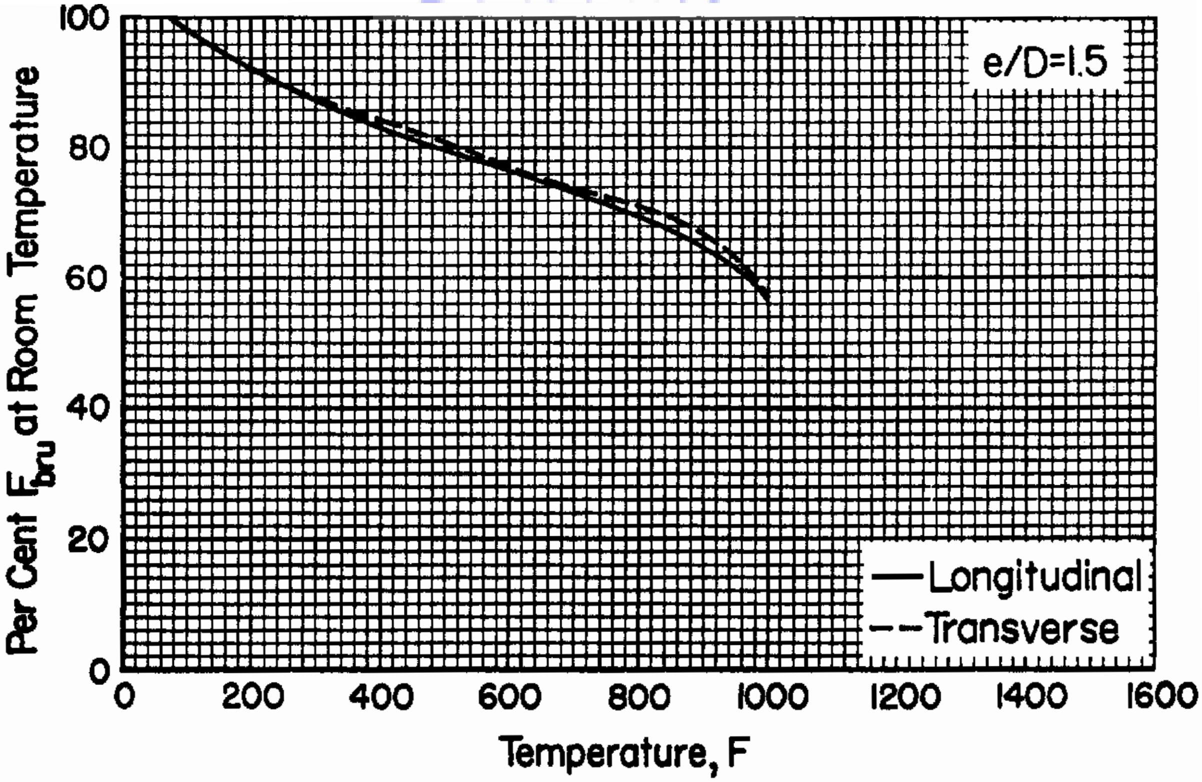

FIGURE 5.2.5.1.3(c). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

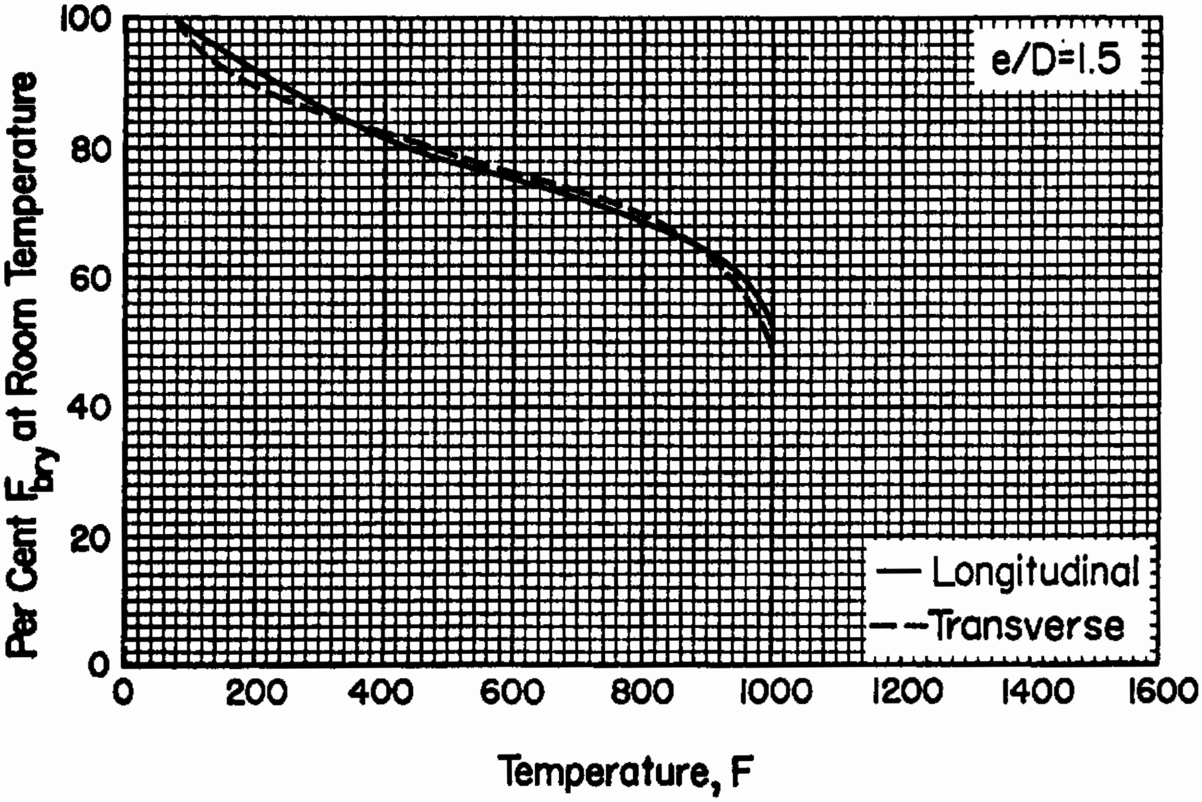

FIGURE 5.2.5.1.3(d). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

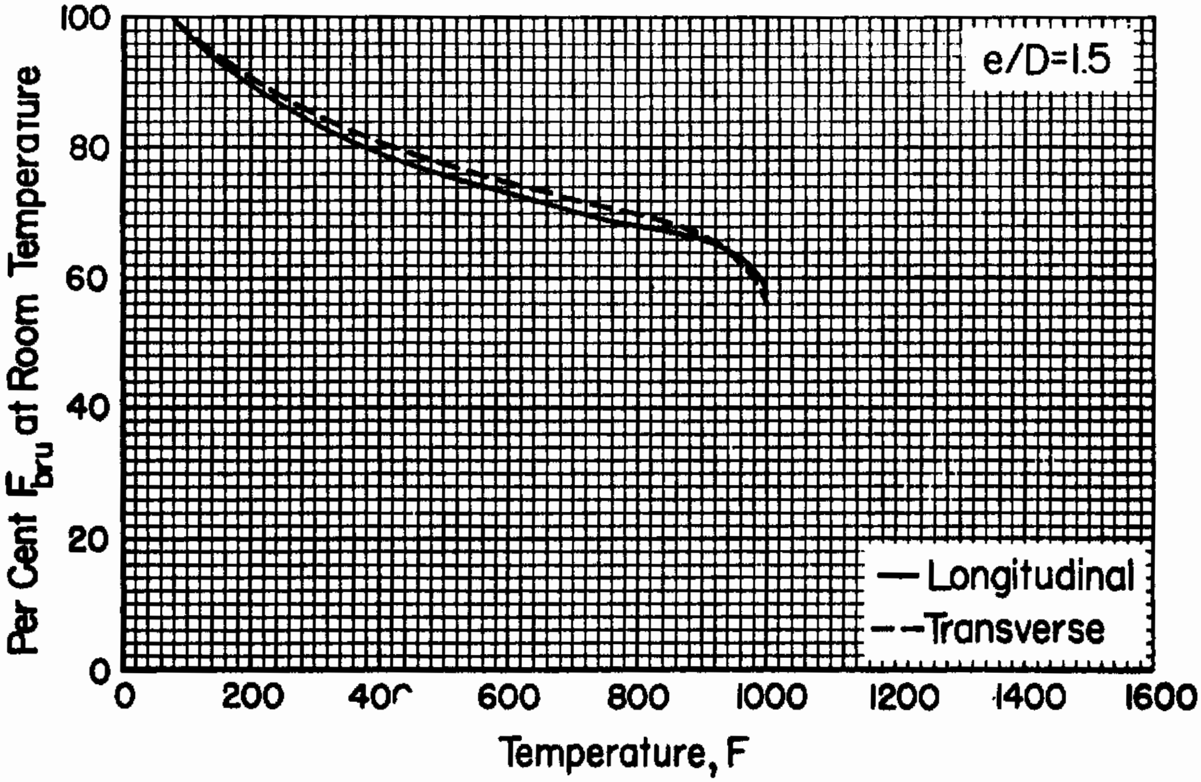

FIGURE 5.2.5.1.3(e). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

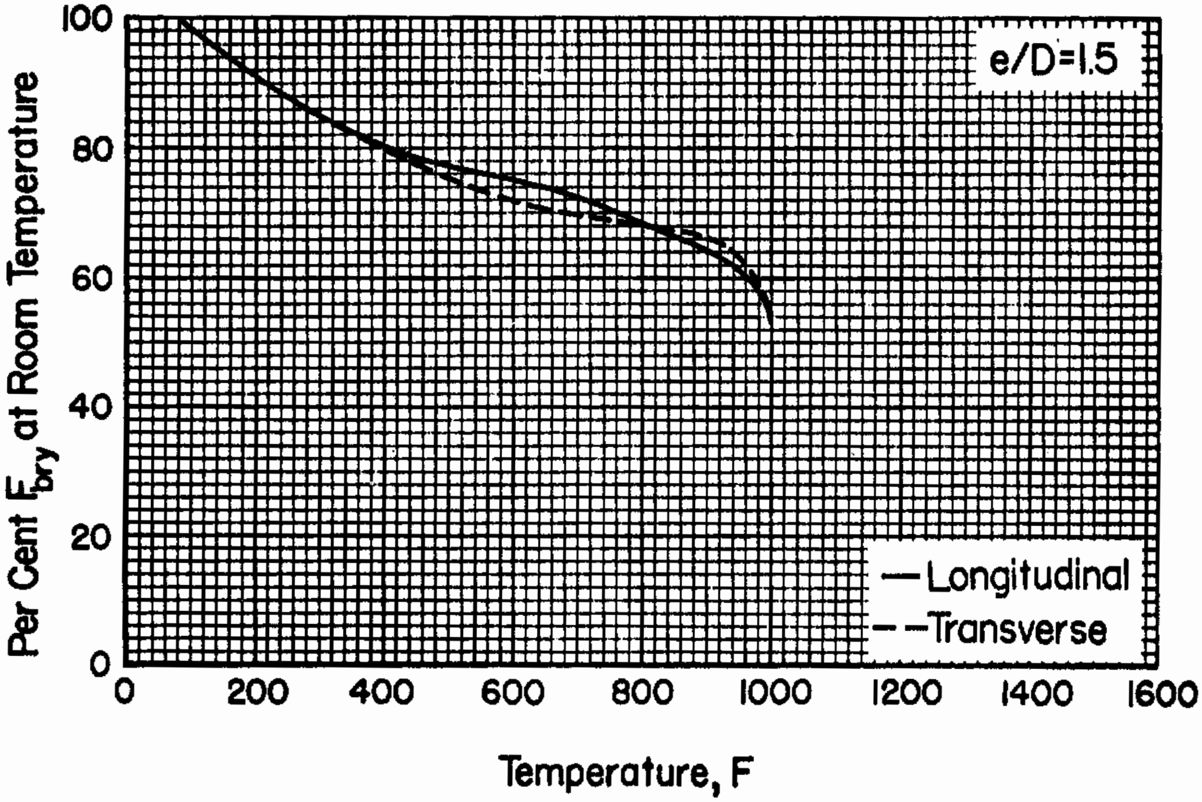

FIGURE 5.2.5.1.3(f). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

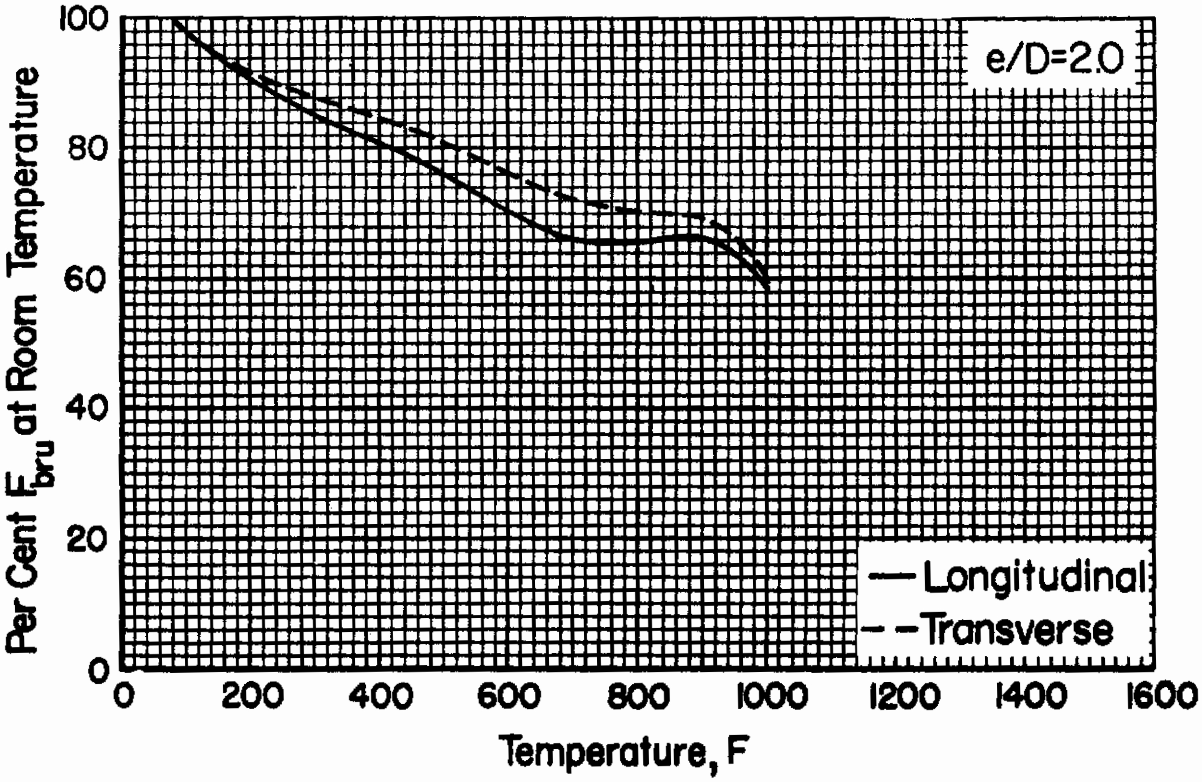

FIGURE 5.2.5.1.3(g). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

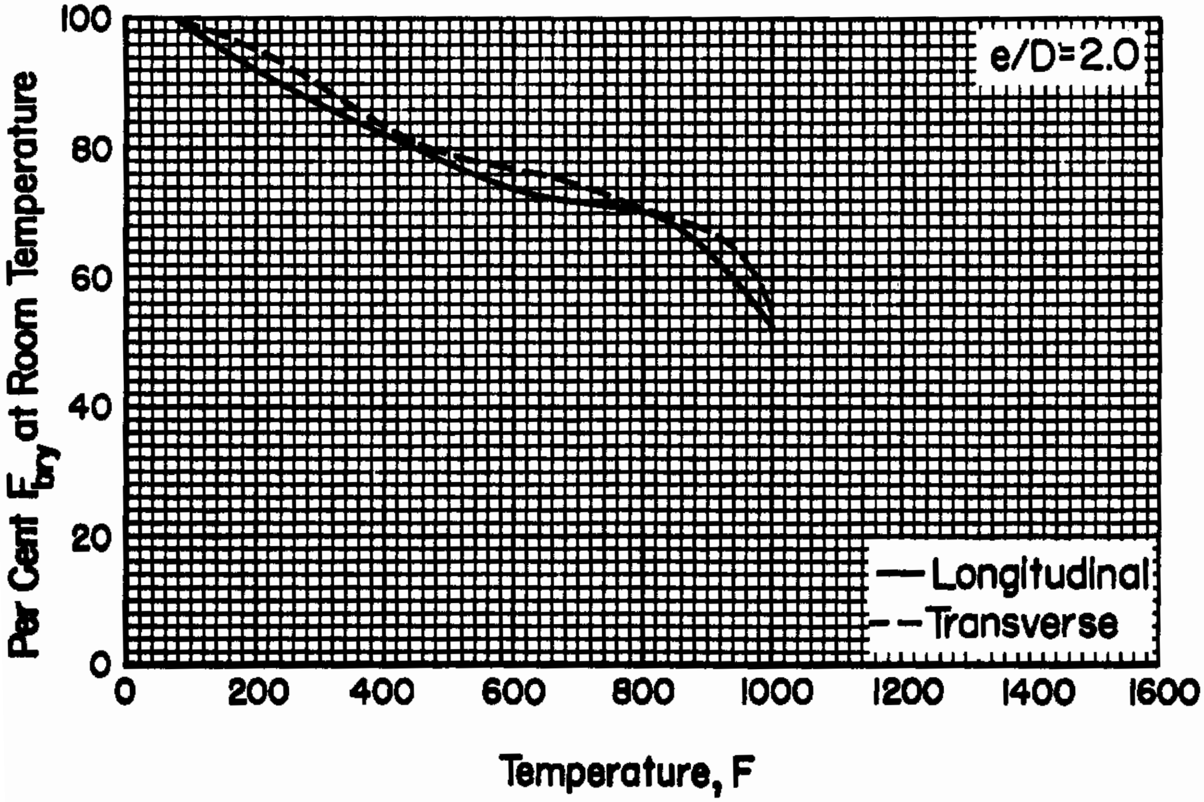

FIGURE 5.2.5.1.3(h). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

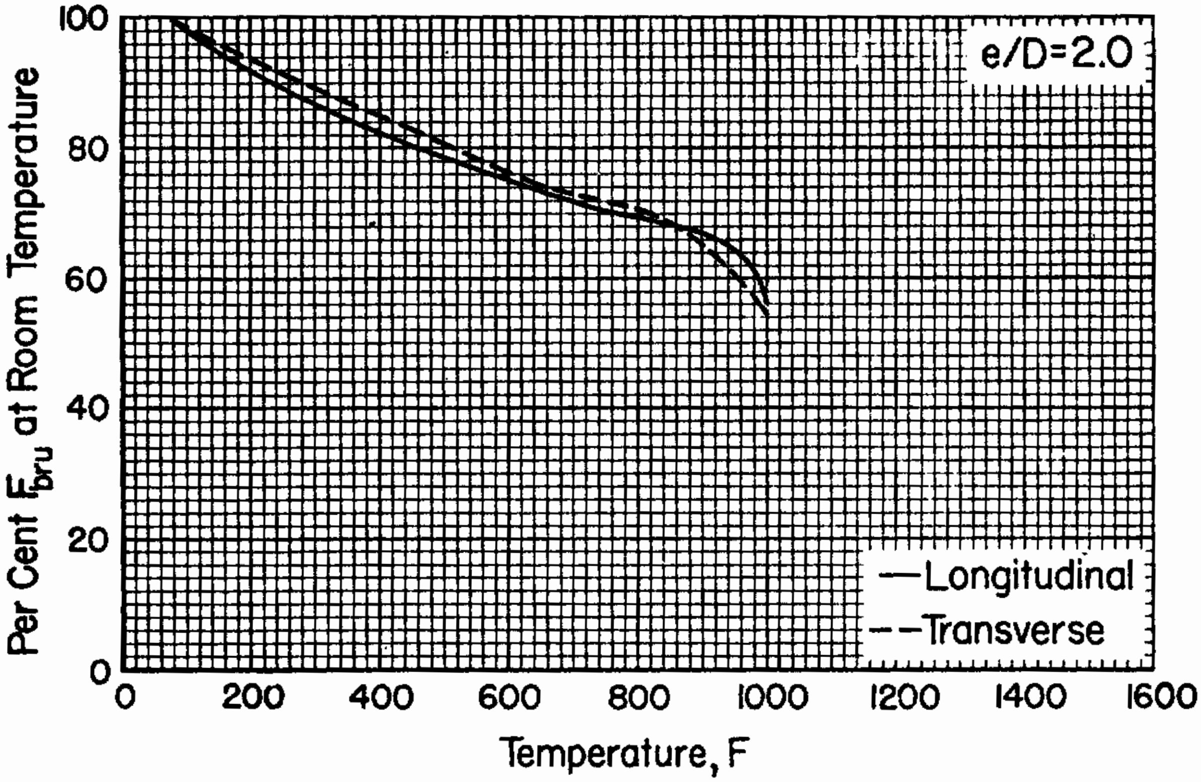

FIGURE 5.2.5.1.3(i). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

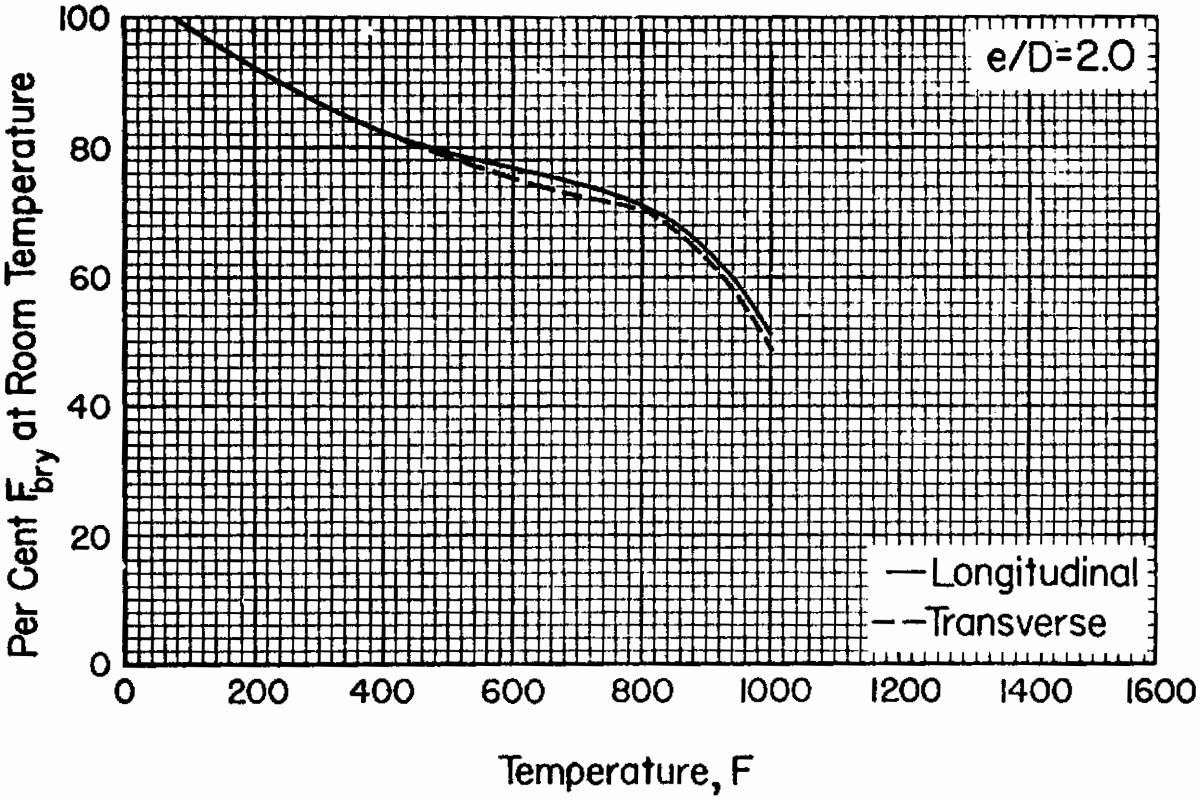

FIGURE 5.2.5.1.3(j). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

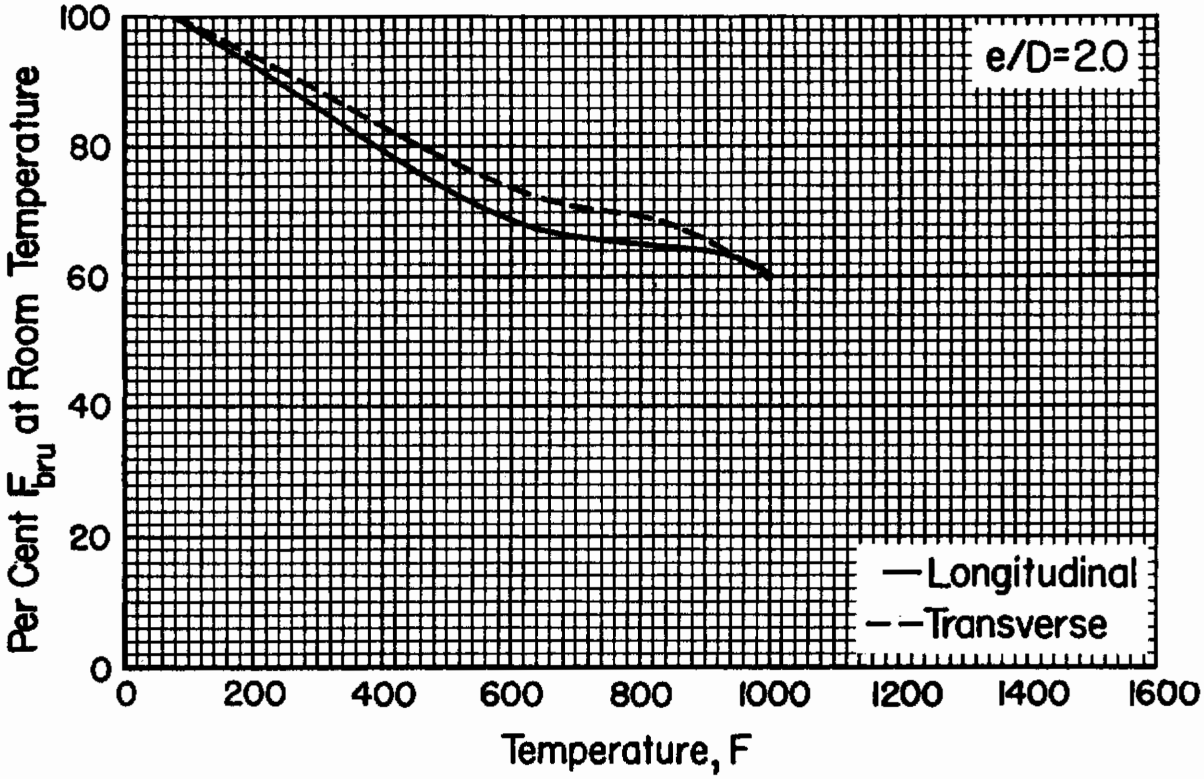

FIGURE 5.2.5.1.3(k). Effect of temperature on the ultimate bearing strength (F_{bru}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

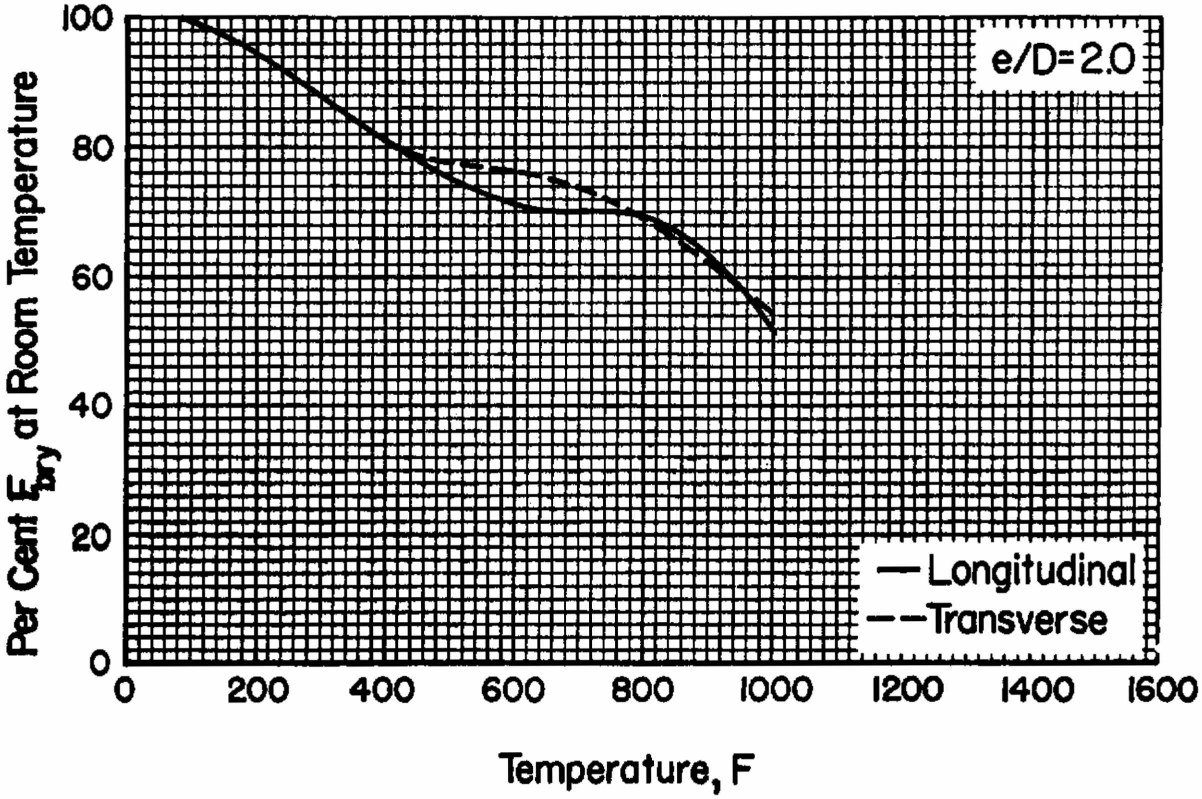

FIGURE 5.2.5.1.3(l). Effect of temperature on the bearing yield strength (F_{bry}) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

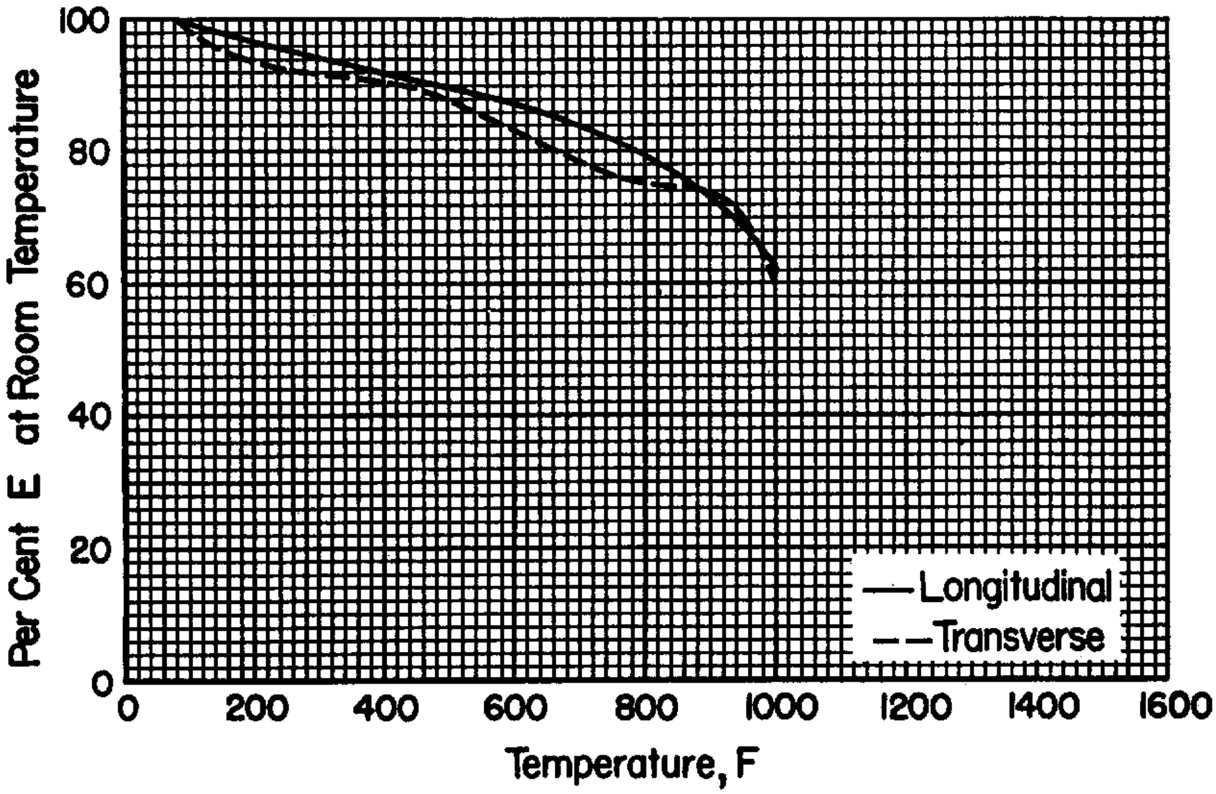

FIGURE 5.2.5.1.4(a). Effect of temperature on the tensile modulus (E) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

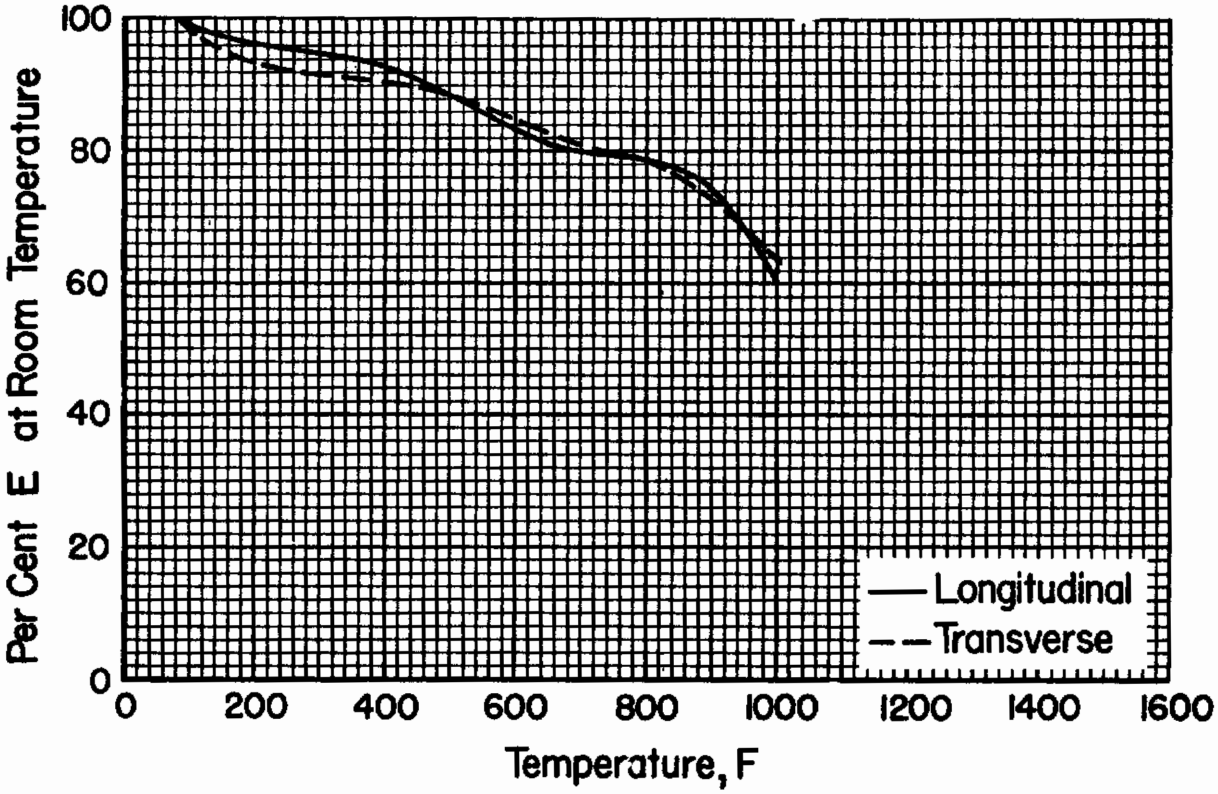

FIGURE 5.2.5.1.4(b). Effect of temperature on the tensile modulus (E) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

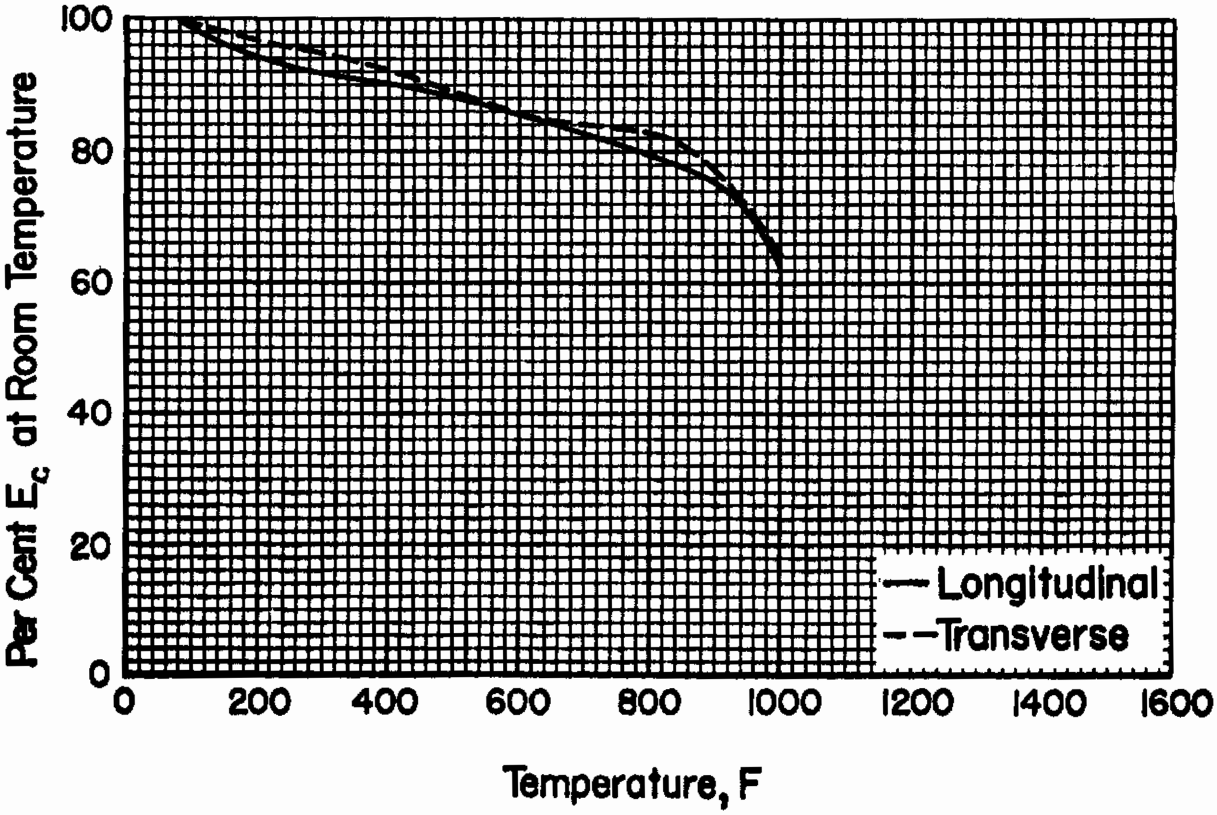

FIGURE 5.2.5.1.4(c). Effect of temperature on the compressive modulus (E_c) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

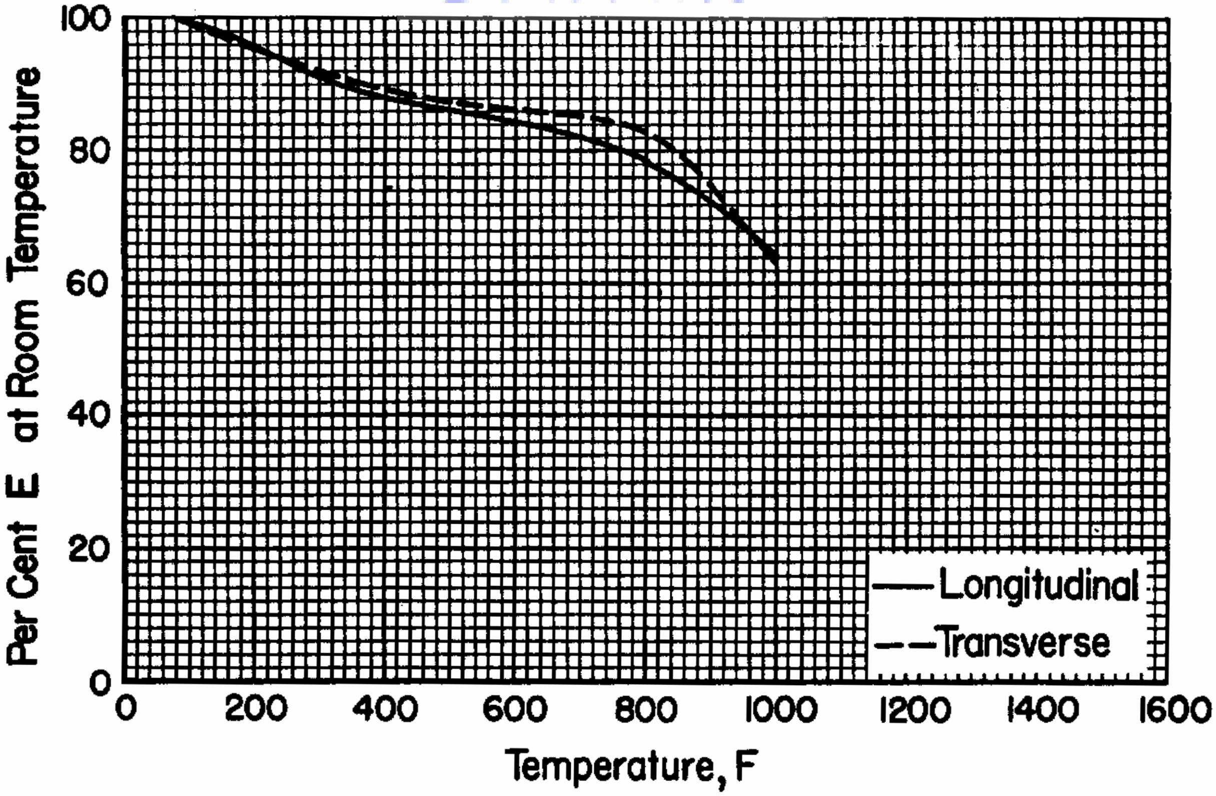

FIGURE 5.2.5.1.4(d). Effect of temperature on the tensile modulus (E) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

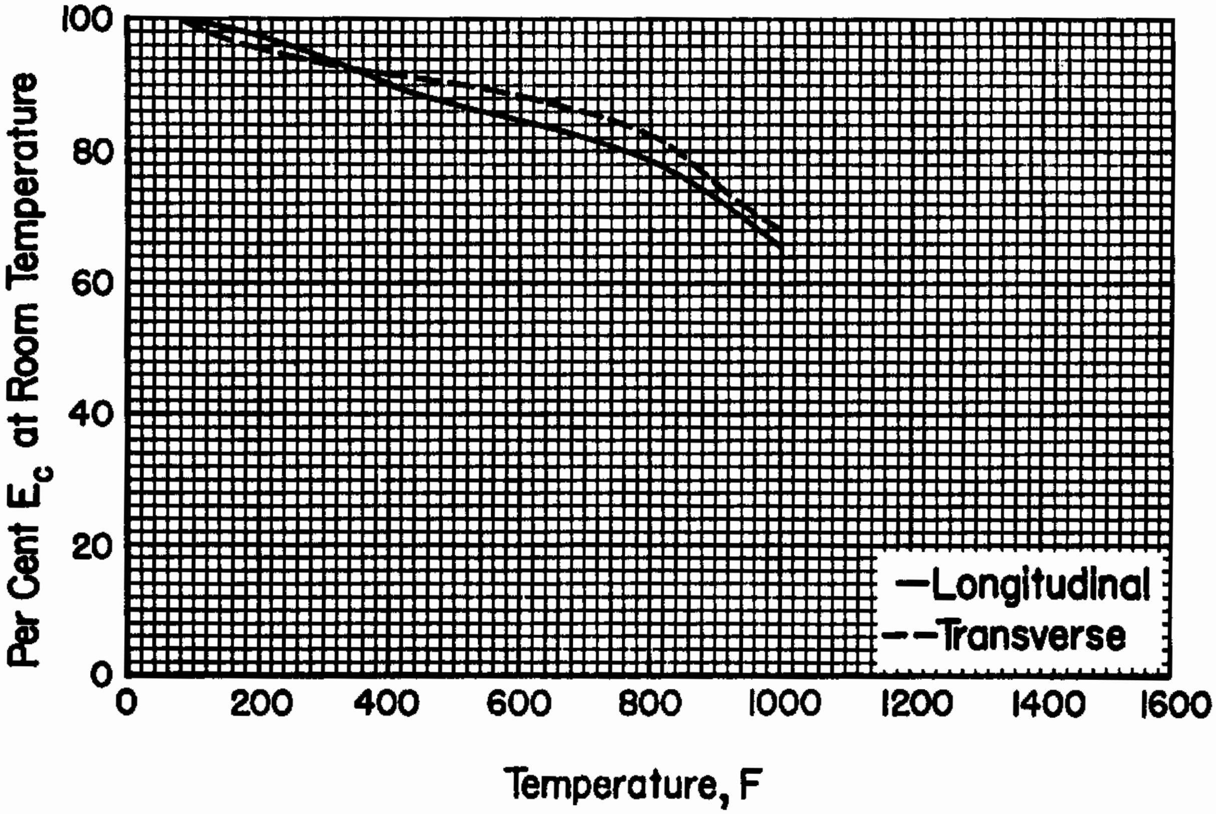

FIGURE 5.2.5.1.4(e). Effect of temperature on the compressive modulus (E_c) of 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

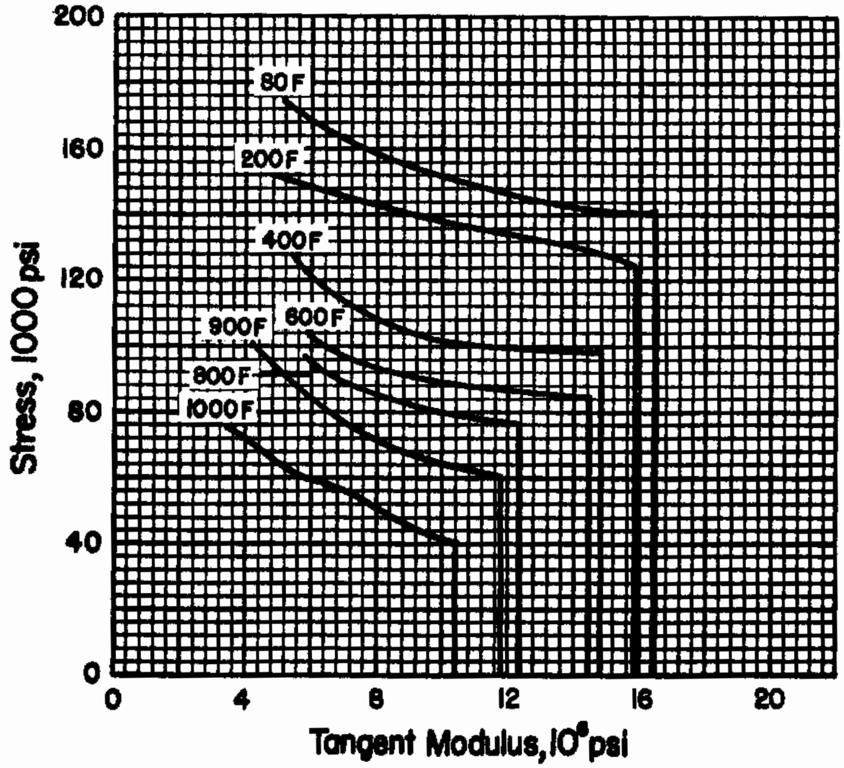

FIGURE 5.2.5.1.4(f). Typical longitudinal tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

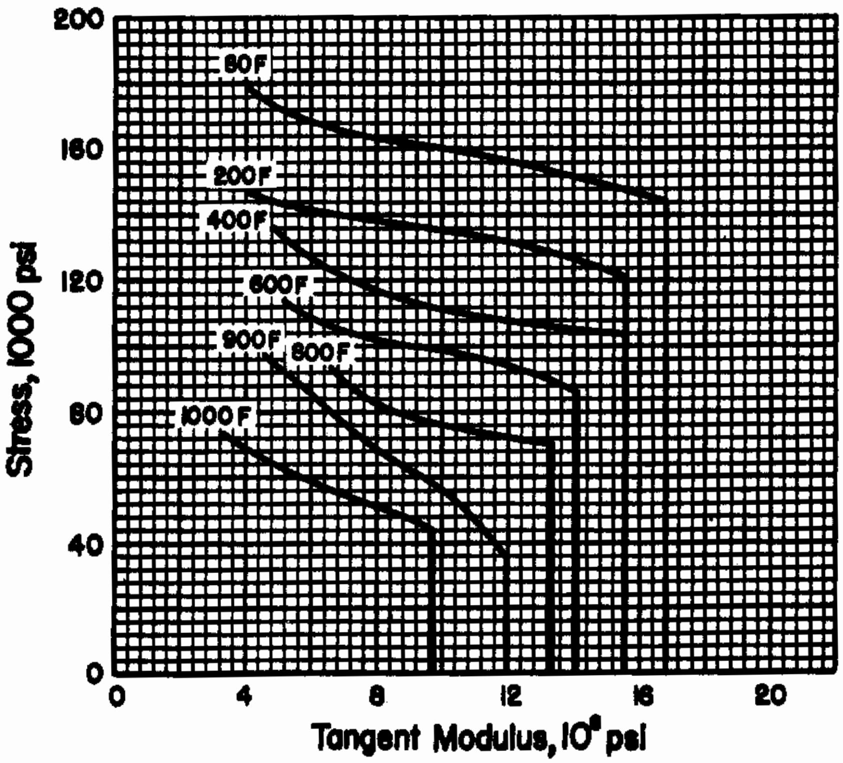

FIGURE 5.2.5.1.4(g). Typical transverse tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

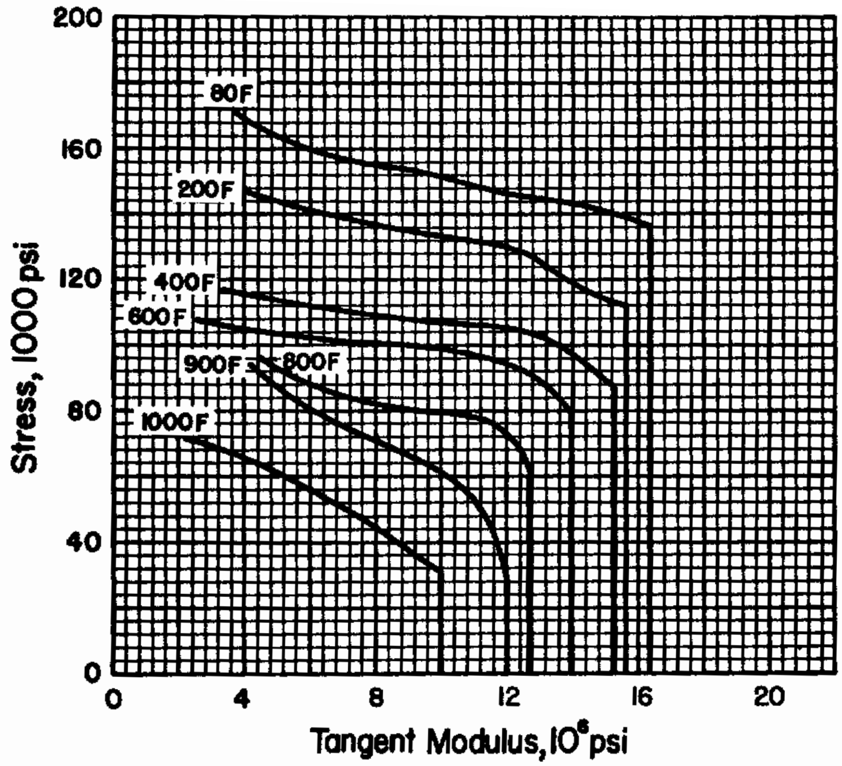

FIGURE 5.2.5.1.4(h). Typical longitudinal tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

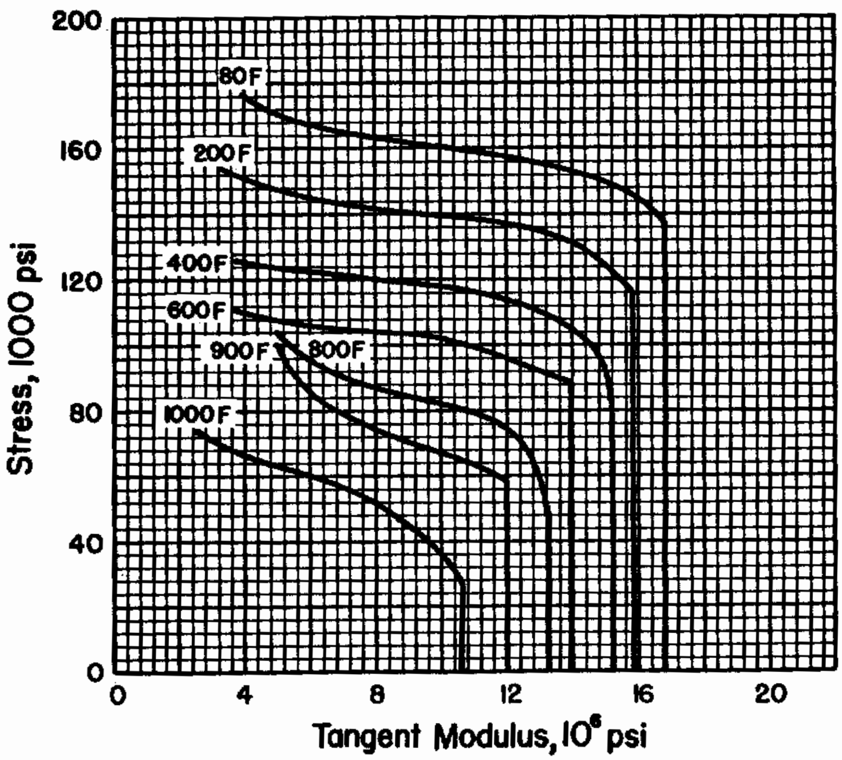

FIGURE 5.2.5.1.4(i). Typical transverse tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

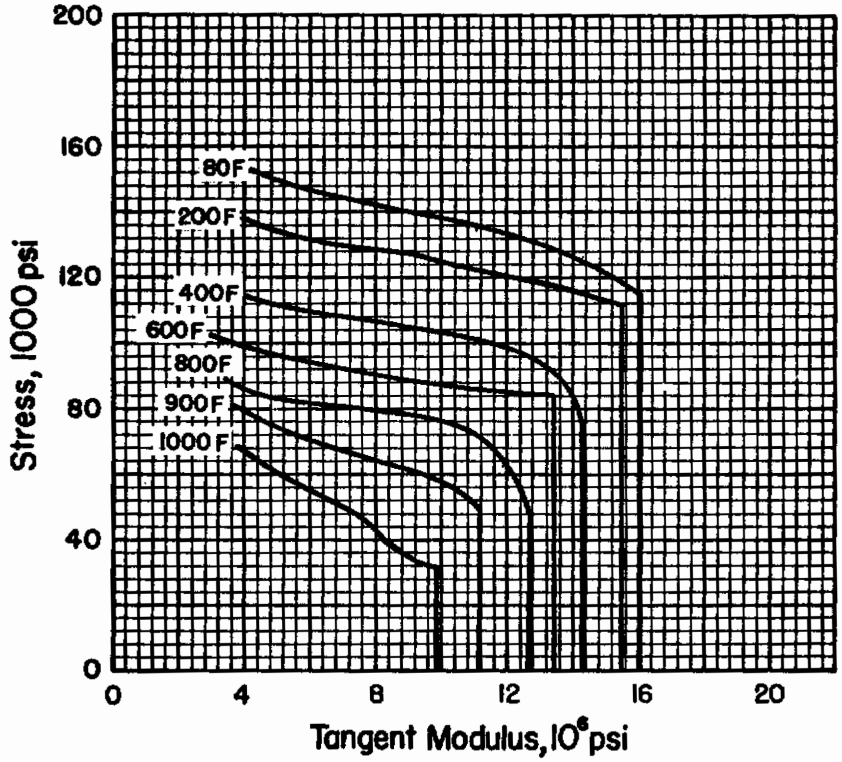

FIGURE 5.2.5.1.4(j). Typical longitudinal tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

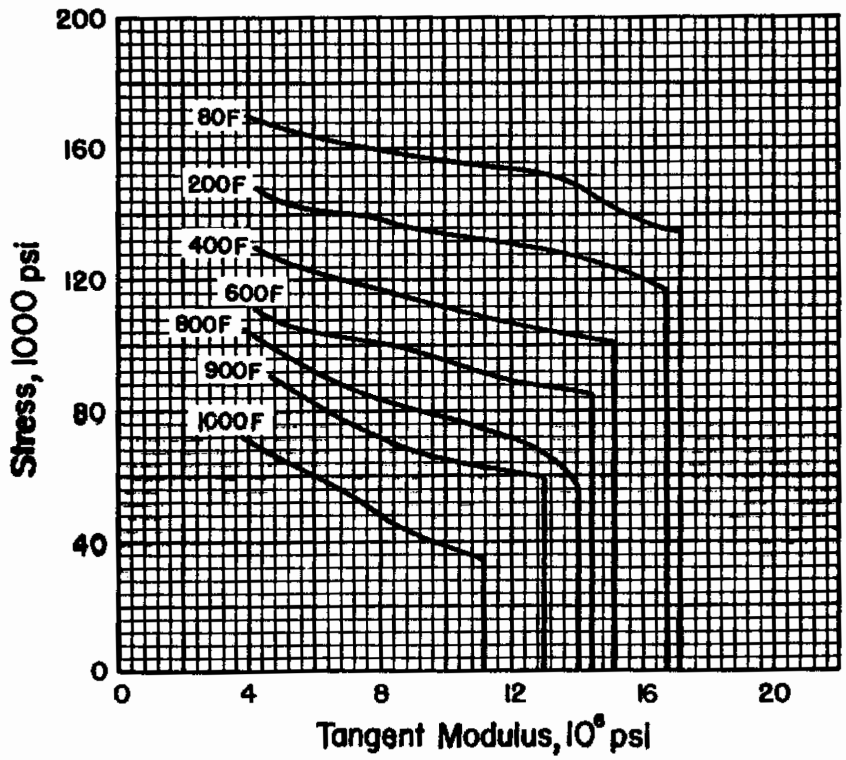

FIGURE 5.2.5.1.4(k). Typical transverse tensile tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

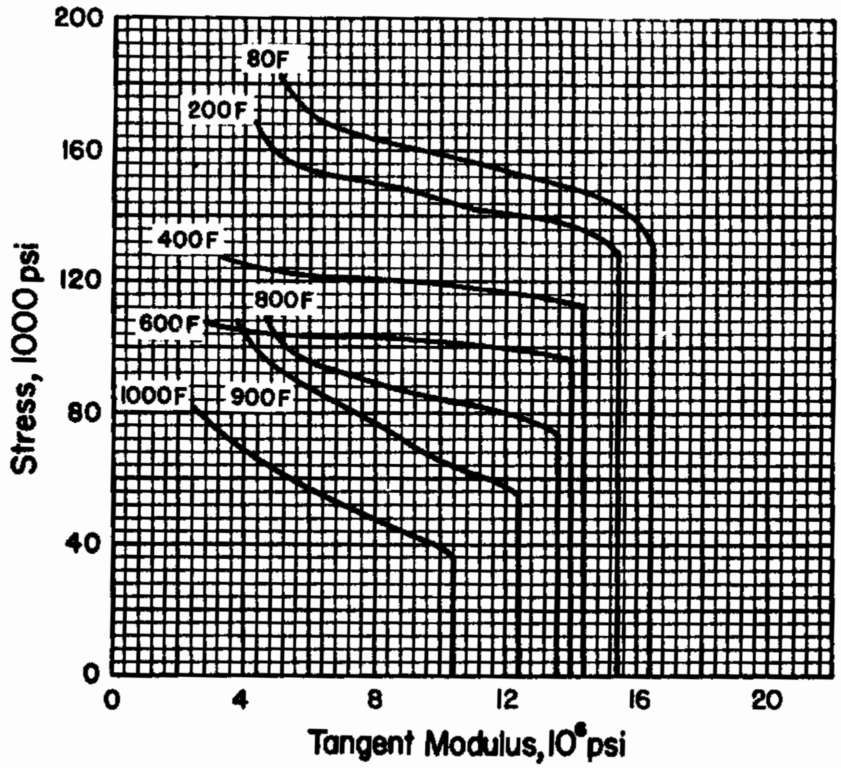

FIGURE 5.2.5.1.4(l). Typical longitudinal compressive tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

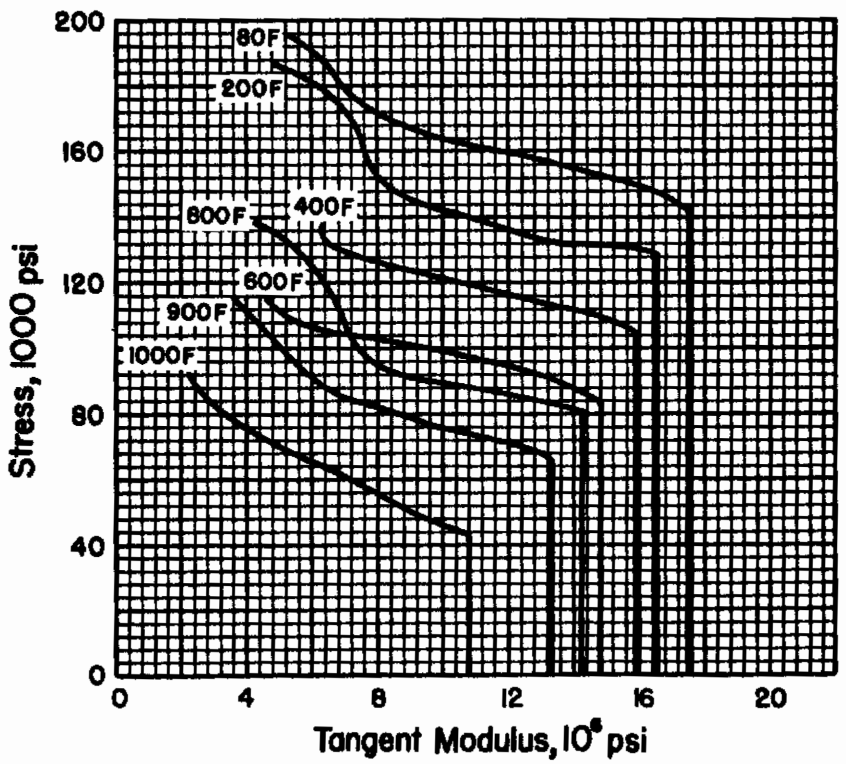

FIGURE 5.2.5.1.4(m). Typical transverse compressive tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

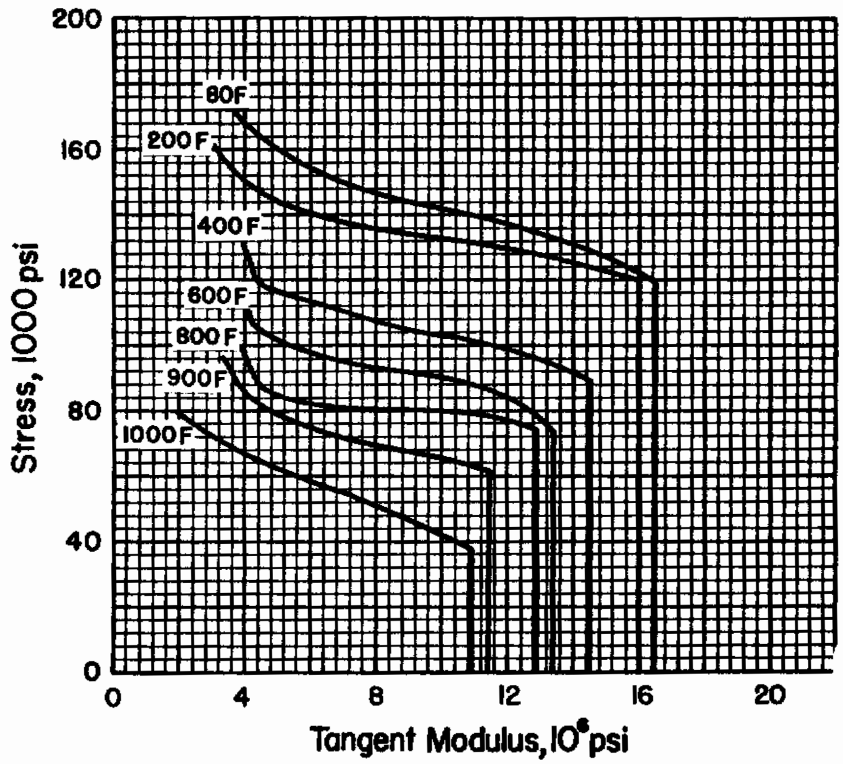

FIGURE 5.2.5.1.4(n). Typical longitudinal compressive tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

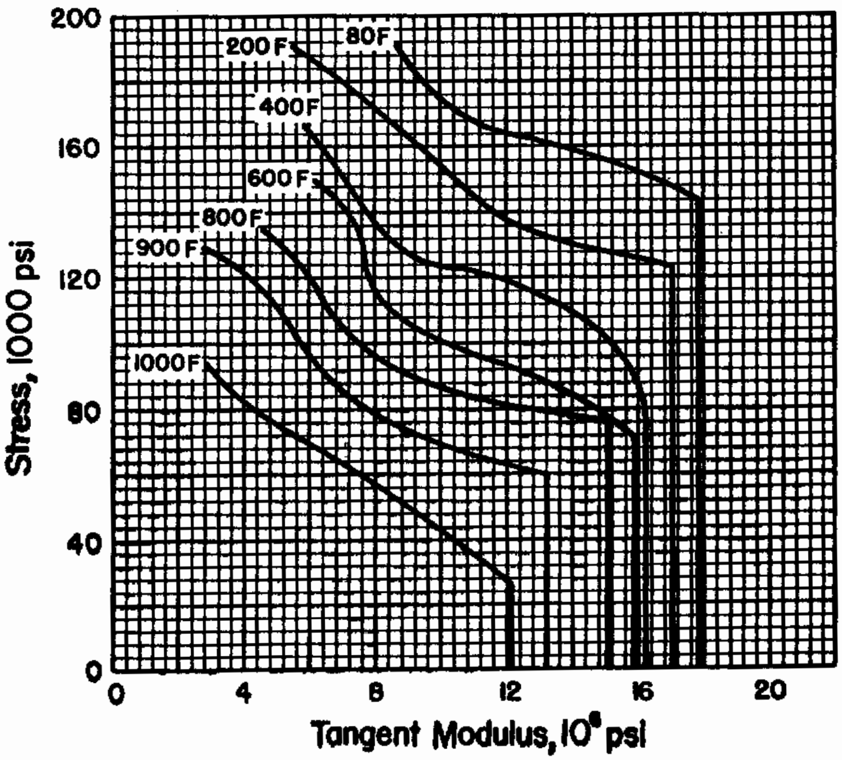

FIGURE 5.2.5.1.4(o). Typical transverse compressive tangent-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

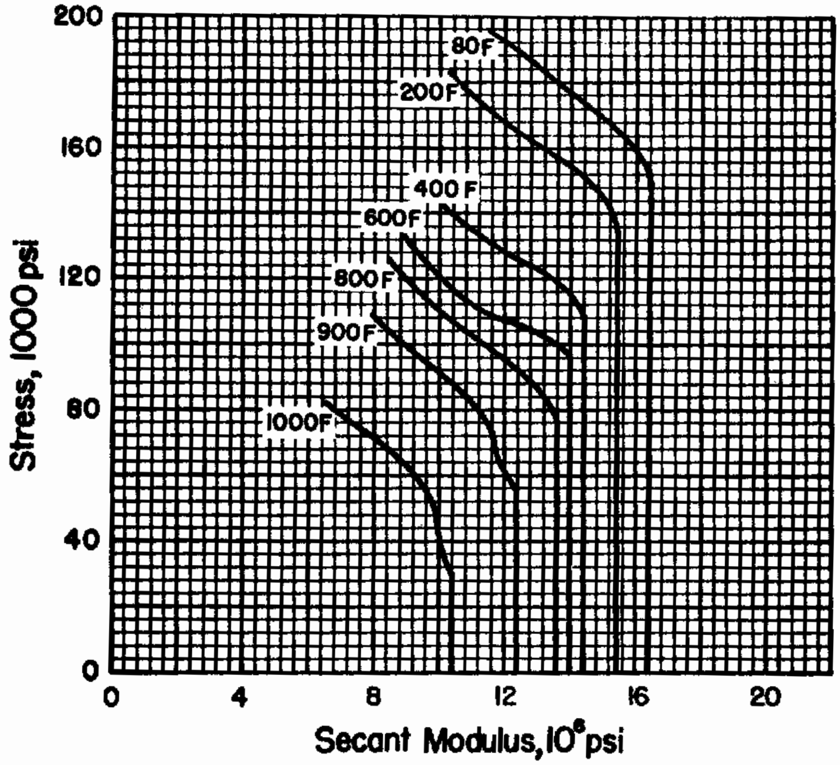

FIGURE 5.2.5.1.4(p). Typical longitudinal compressive secant-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

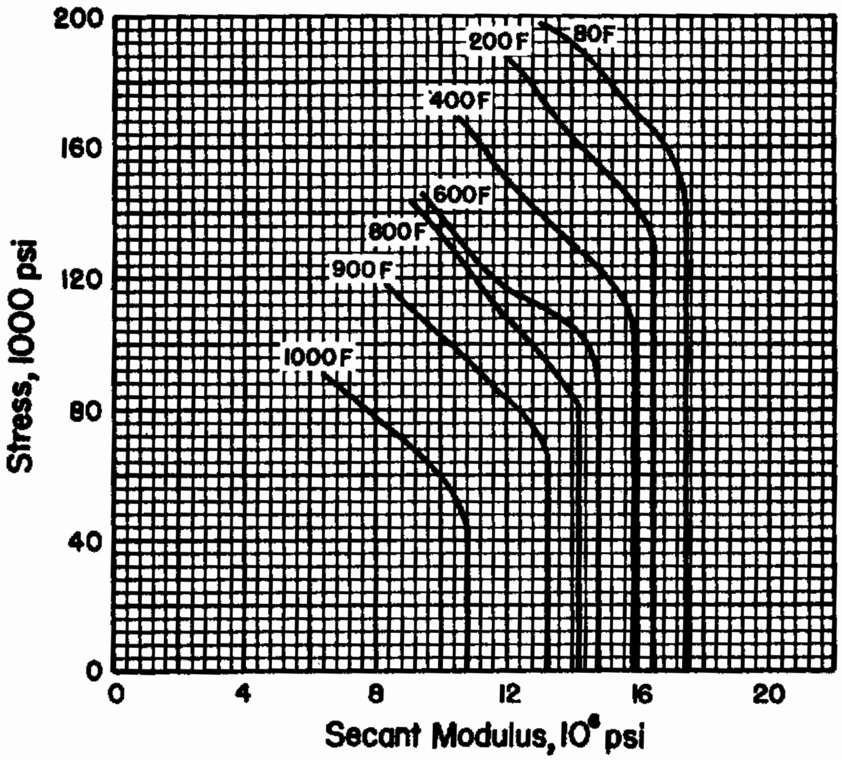

FIGURE 5.2.5.1.4(q). Typical transverse compressive secant-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

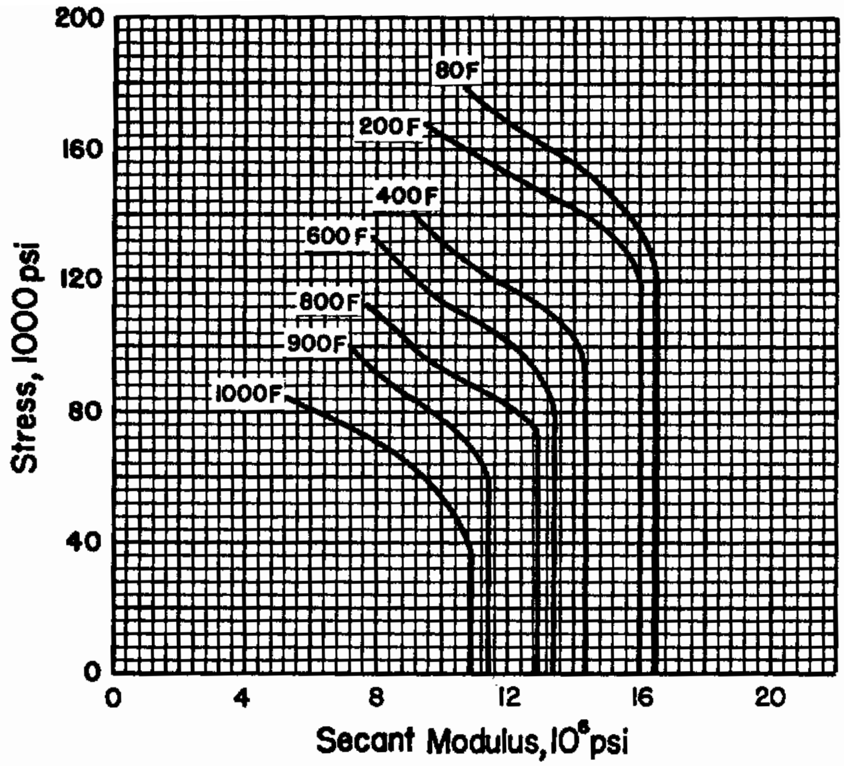

FIGURE 5.2.5.1.4(r). Typical longitudinal compressive secant-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

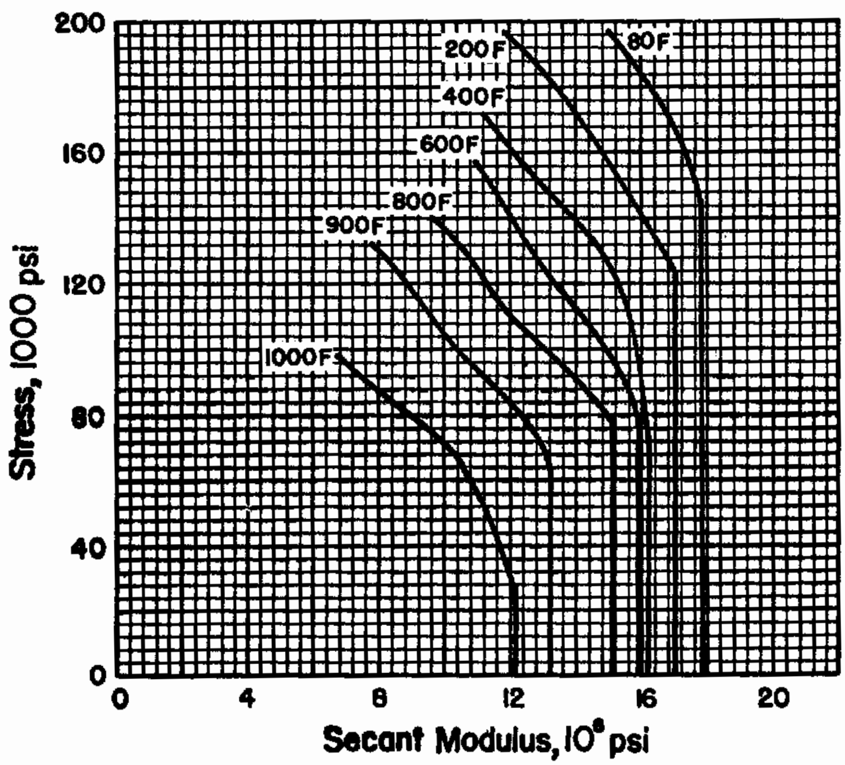

FIGURE 5.2.5.1.4(s). Typical transverse compressive secant-modulus curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

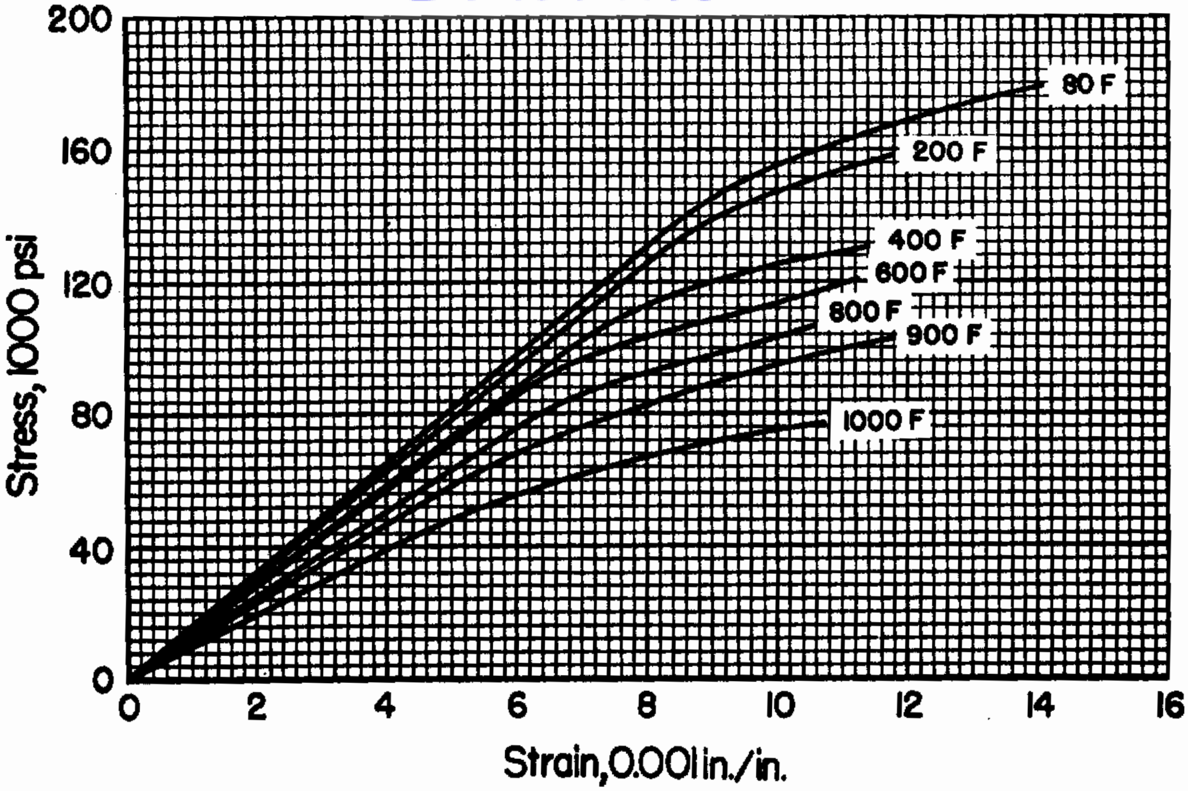

FIGURE 5.2.5.1.5(a). Typical longitudinal tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

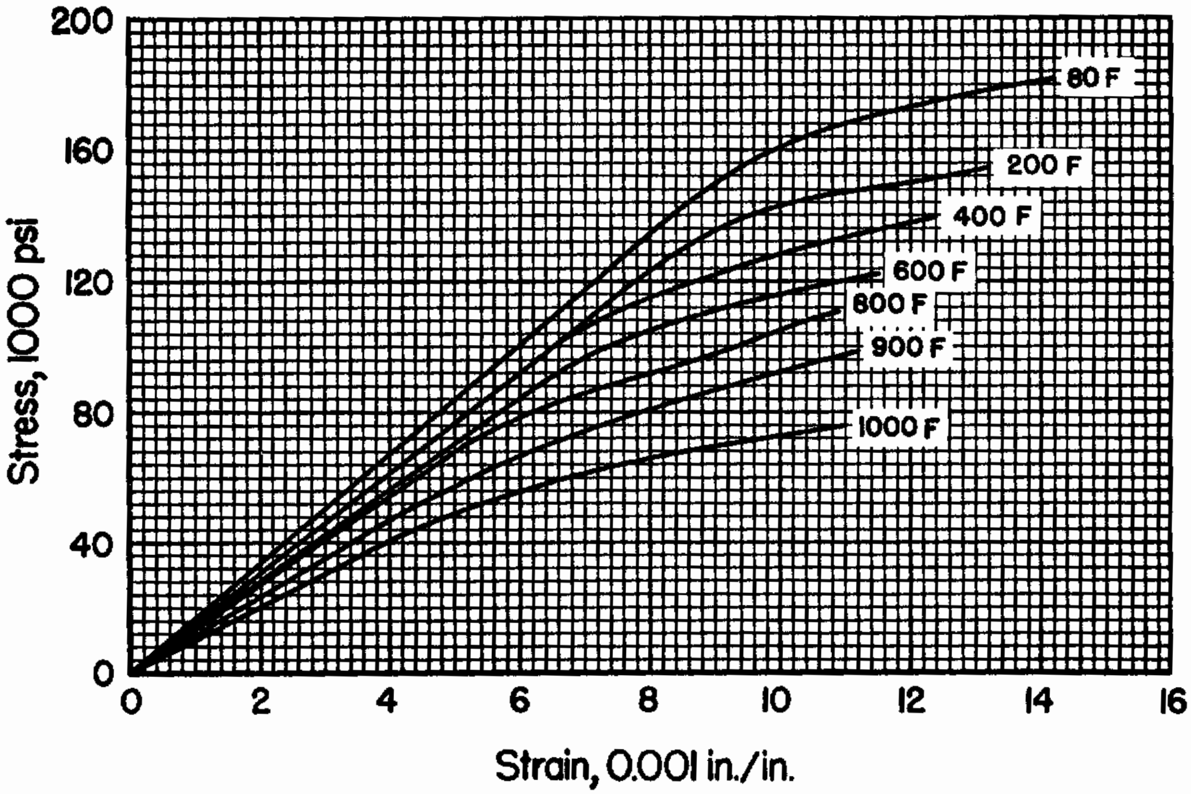

FIGURE 5.2.5.1.5(b). Typical transverse tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.020 inch thick sheet).

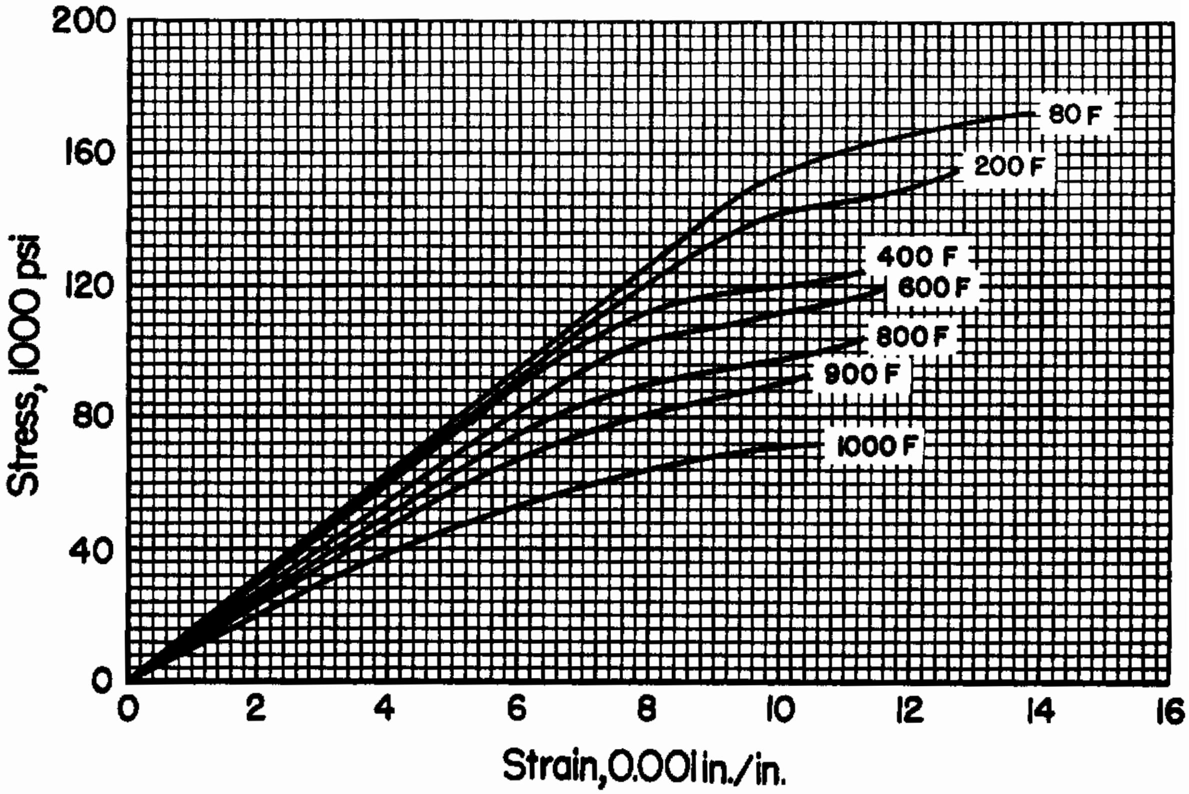

FIGURE 5.2.5.1.5(c). Typical longitudinal tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

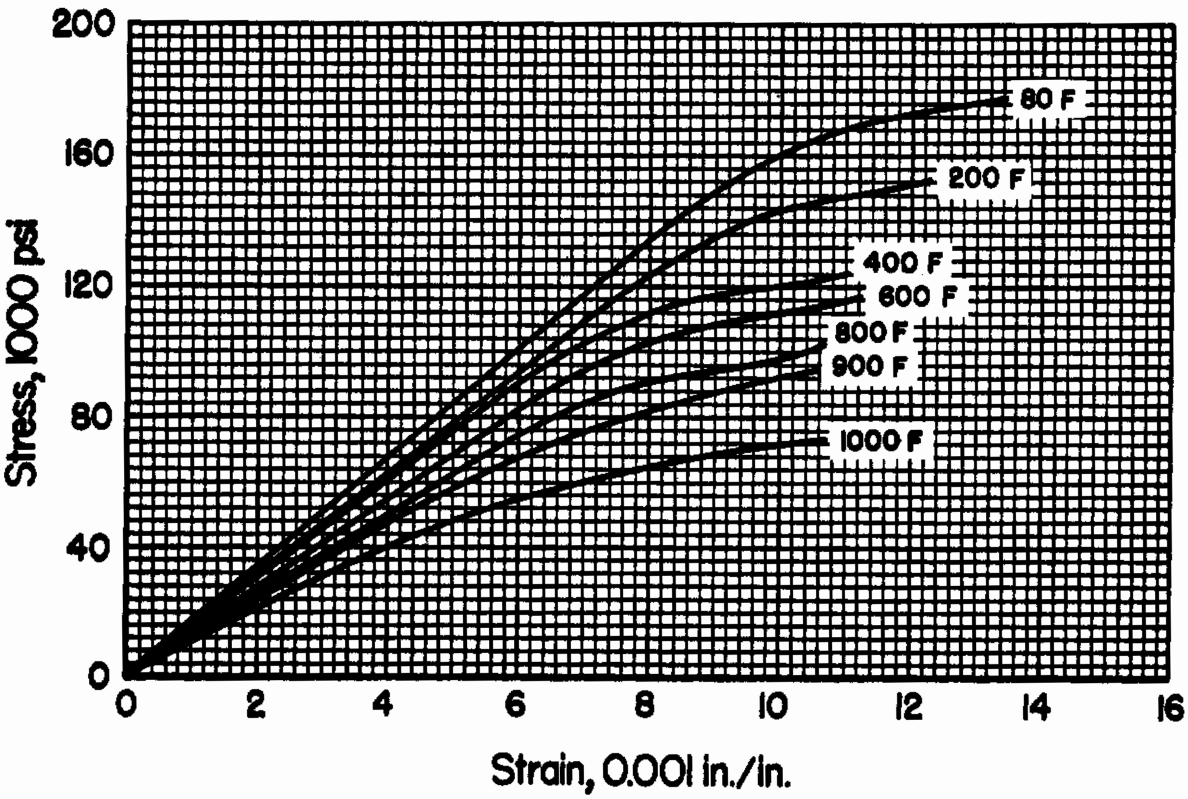

FIGURE 5.2.5.1.5 (d). Typical transverse tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

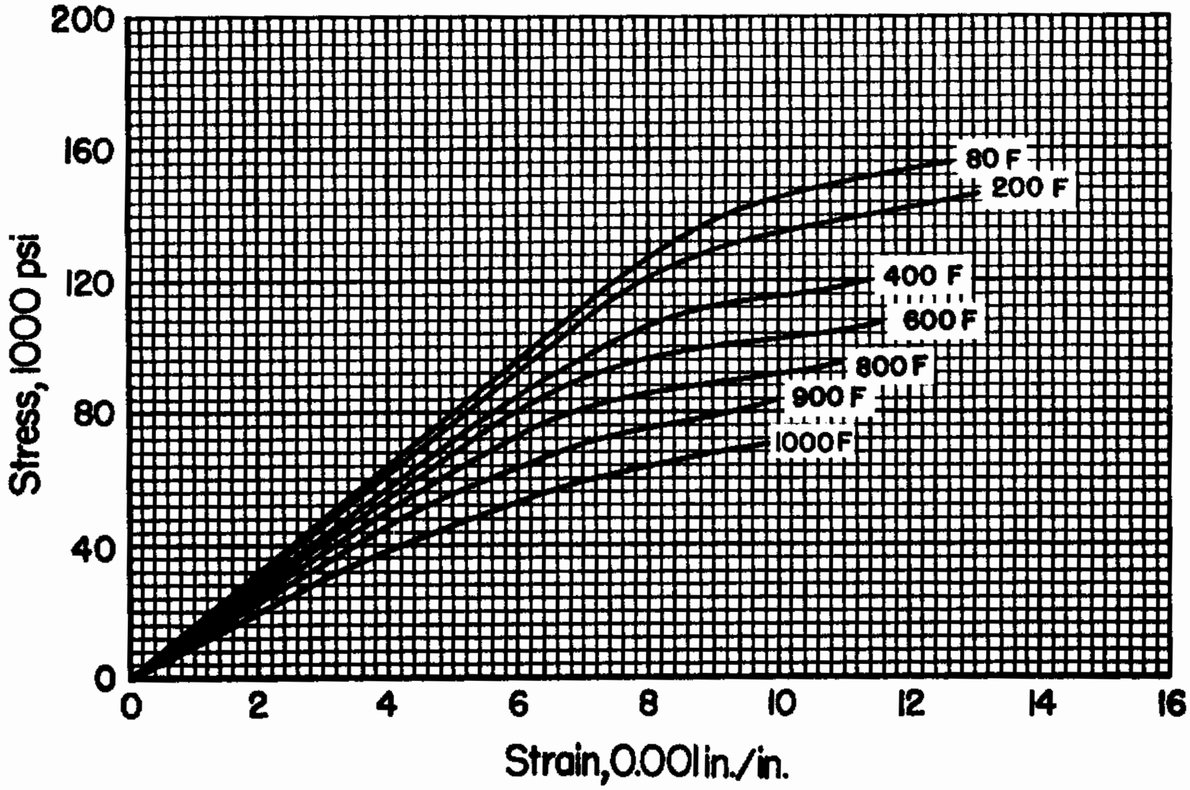

FIGURE 5.2.5.1.5(e). Typical longitudinal tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

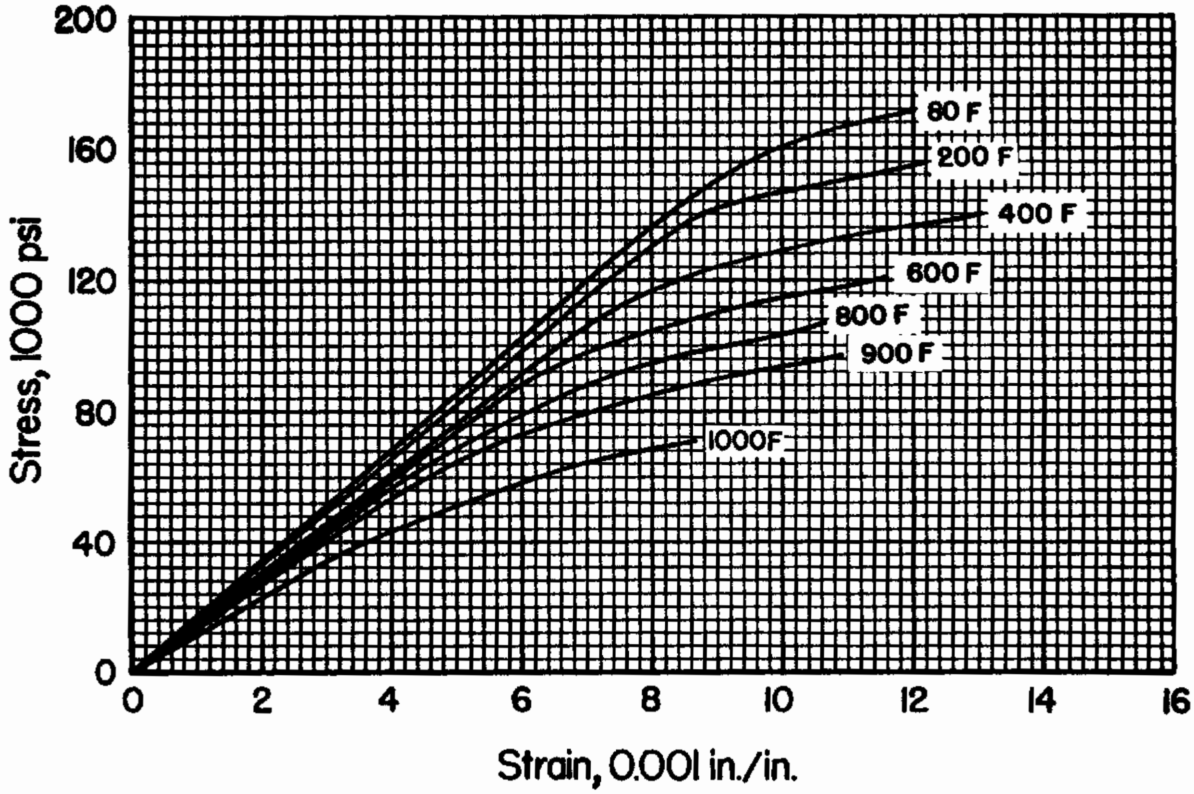

FIGURE 5.2.5.1.5(f). Typical transverse tensile stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

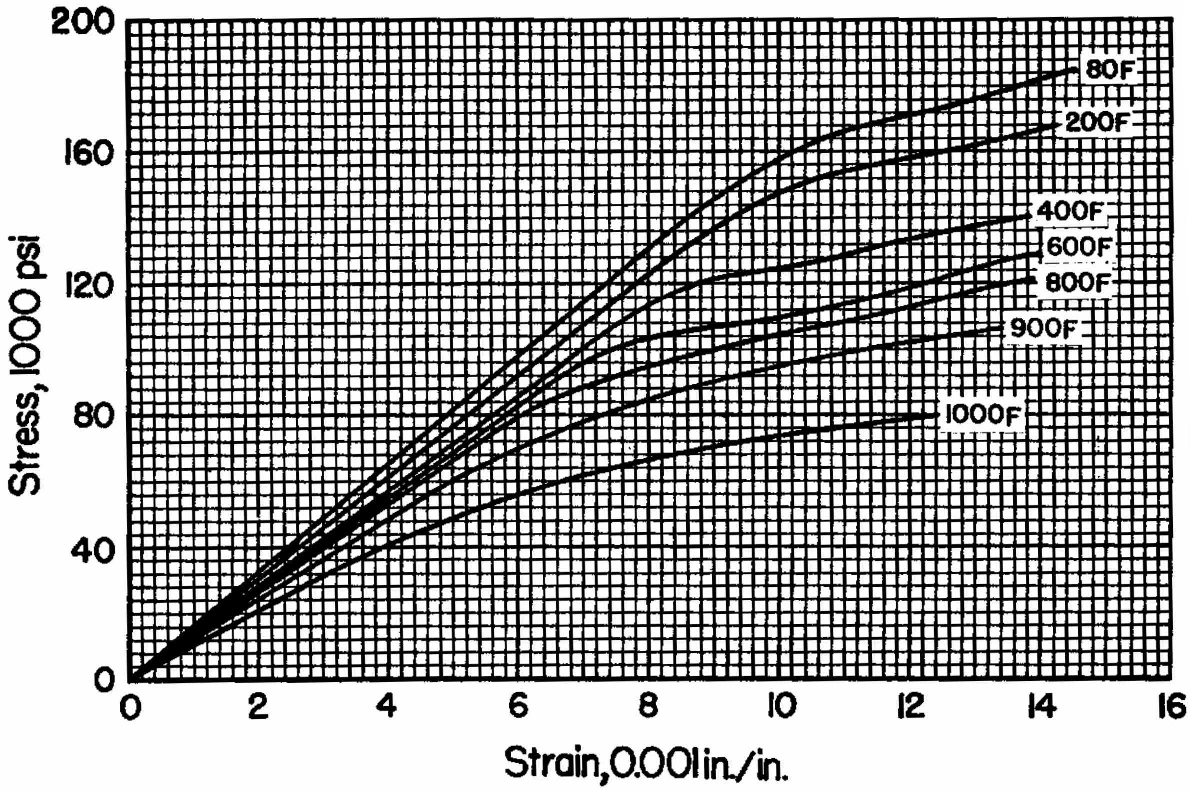

FIGURE 5.2.5.1.5(g). Typical longitudinal compressive stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

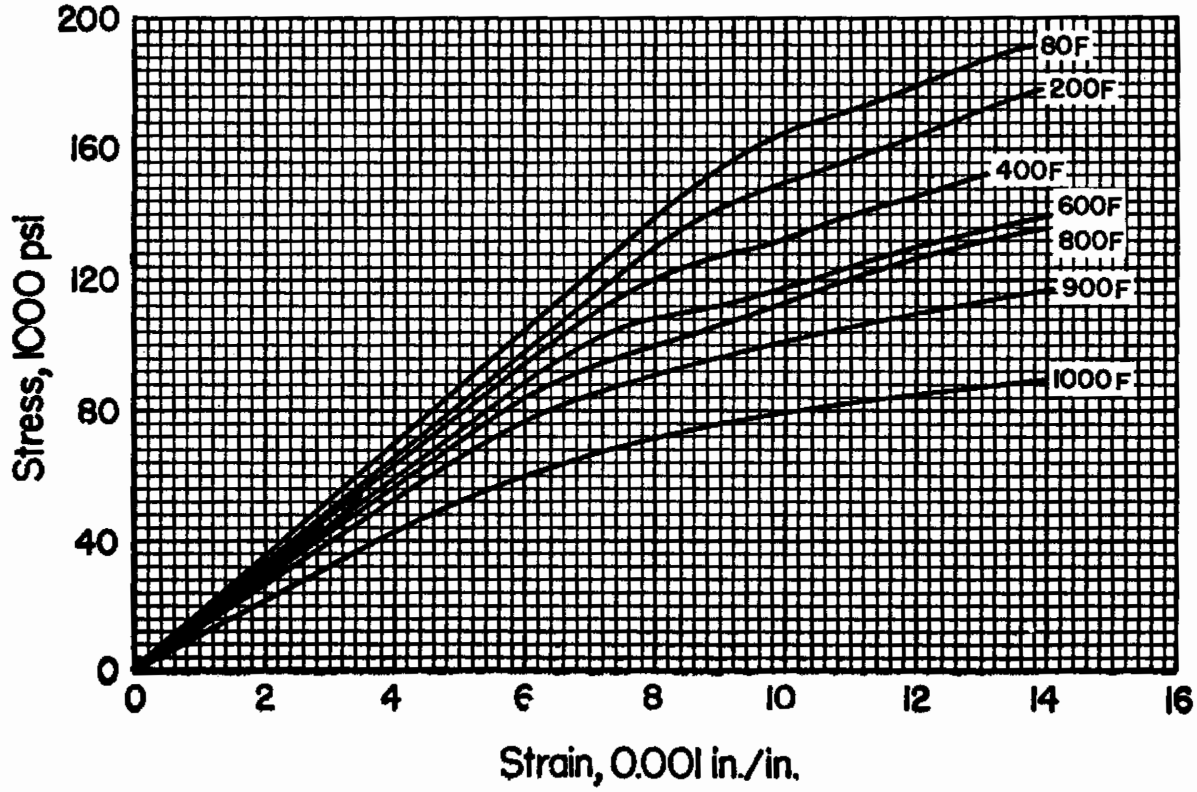

FIGURE 5.2.5.1.5(h). Typical transverse compressive stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet).

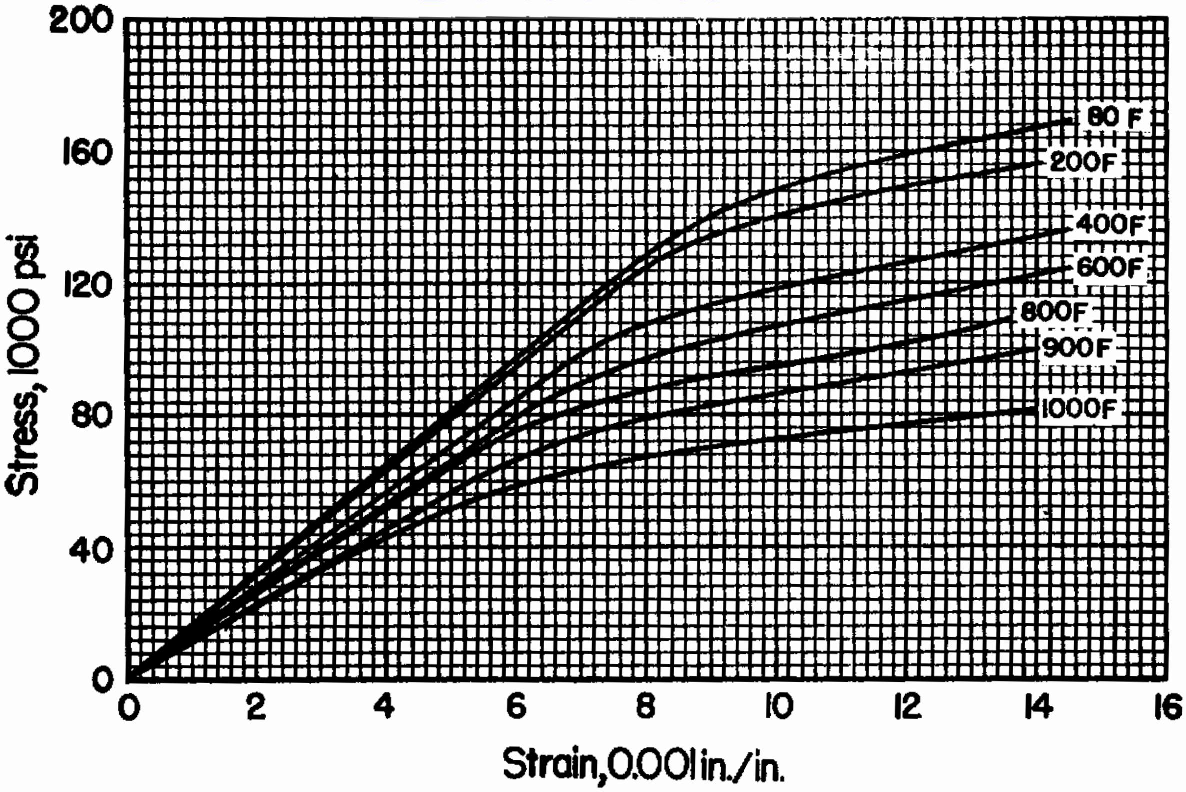

FIGURE 5.2.5.1.5(i). Typical longitudinal compressive stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

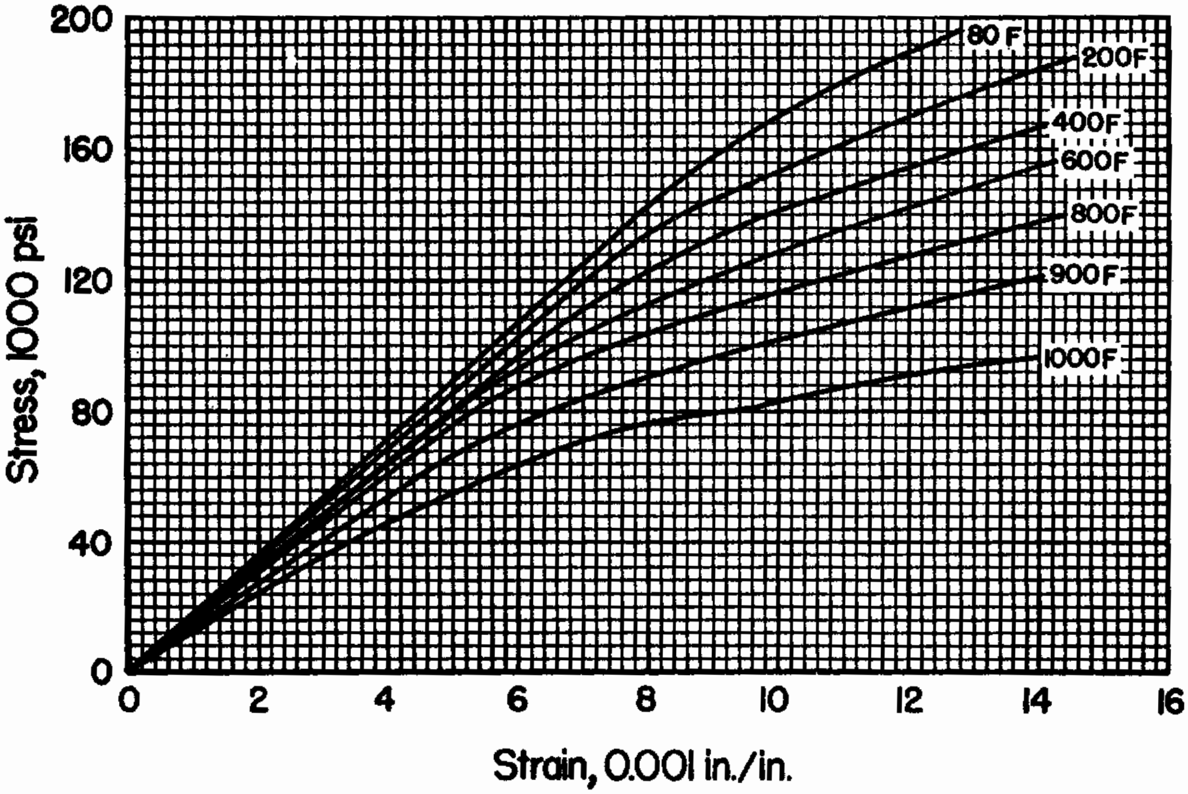

FIGURE 5.2.5.1.5(j). Typical transverse compressive stress-strain curves for 4Al-3Mo-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

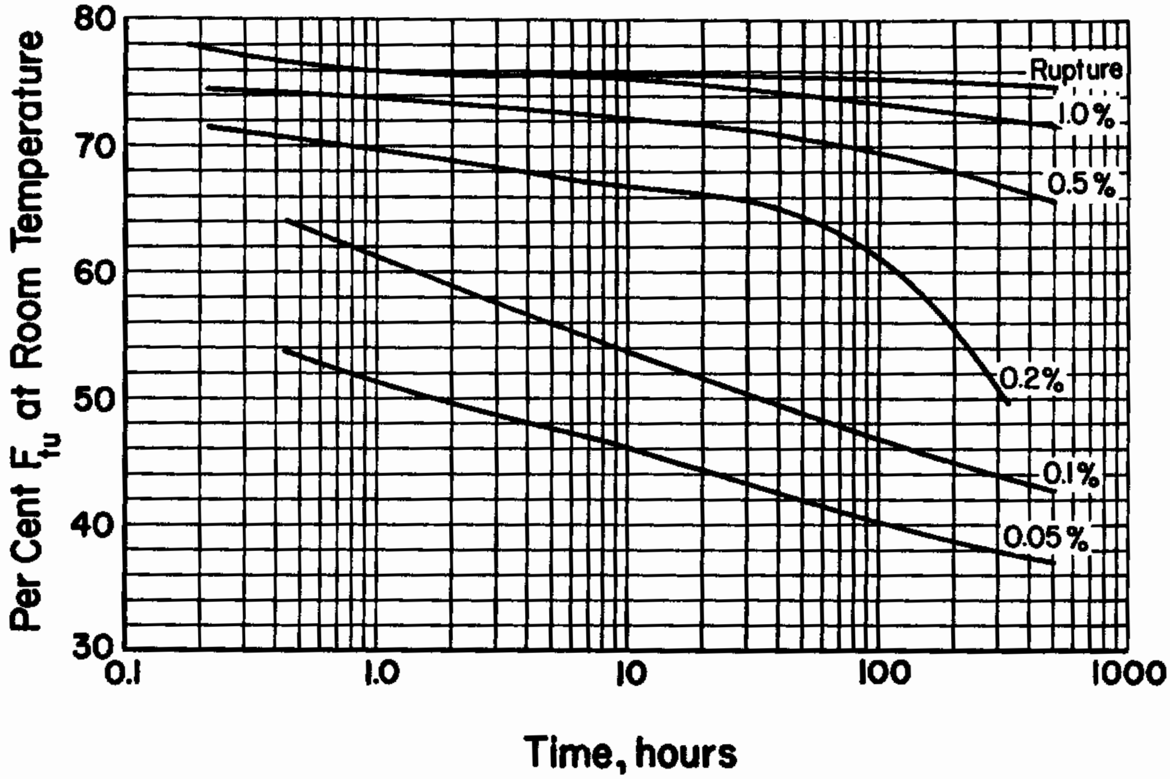

FIGURE 5.2.5.1.6(a). Creep and rupture data for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet) at 600°F.

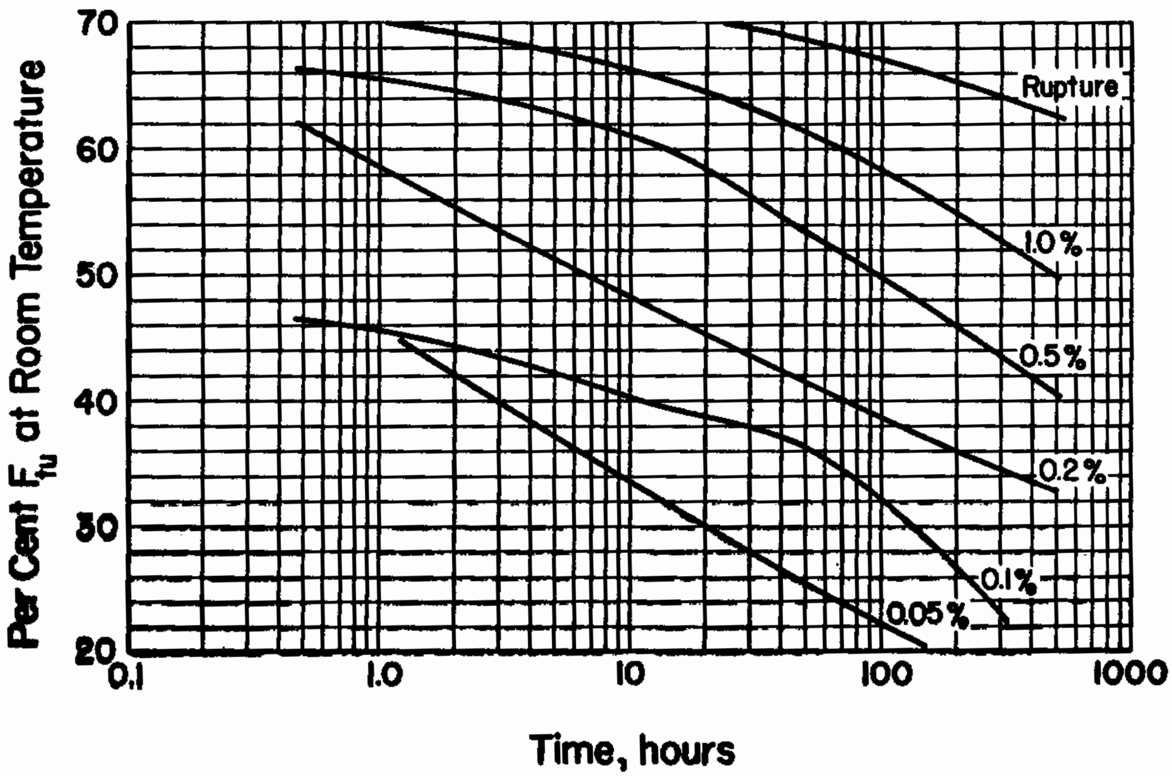

FIGURE 5.2.5.1.6(b). Creep and rupture data for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet) at 700°F.

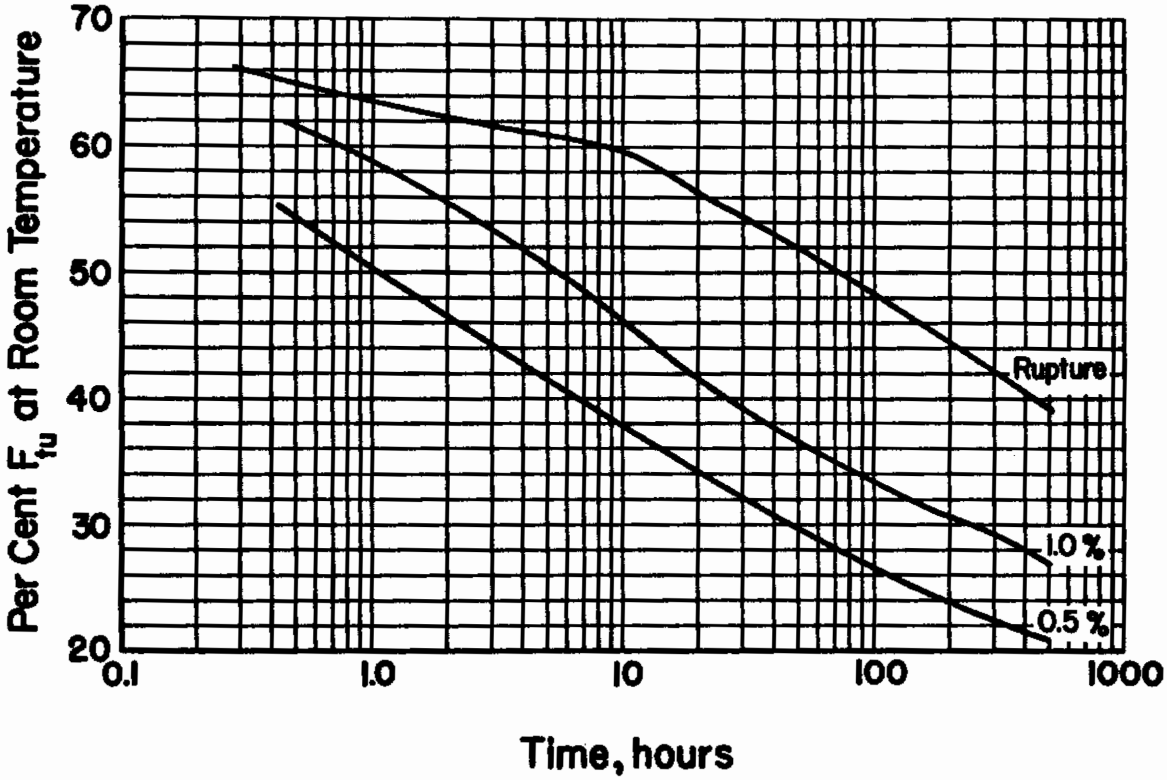

FIGURE 5.2.5.1.6(c). Creep and rupture data for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet) at 800°F.

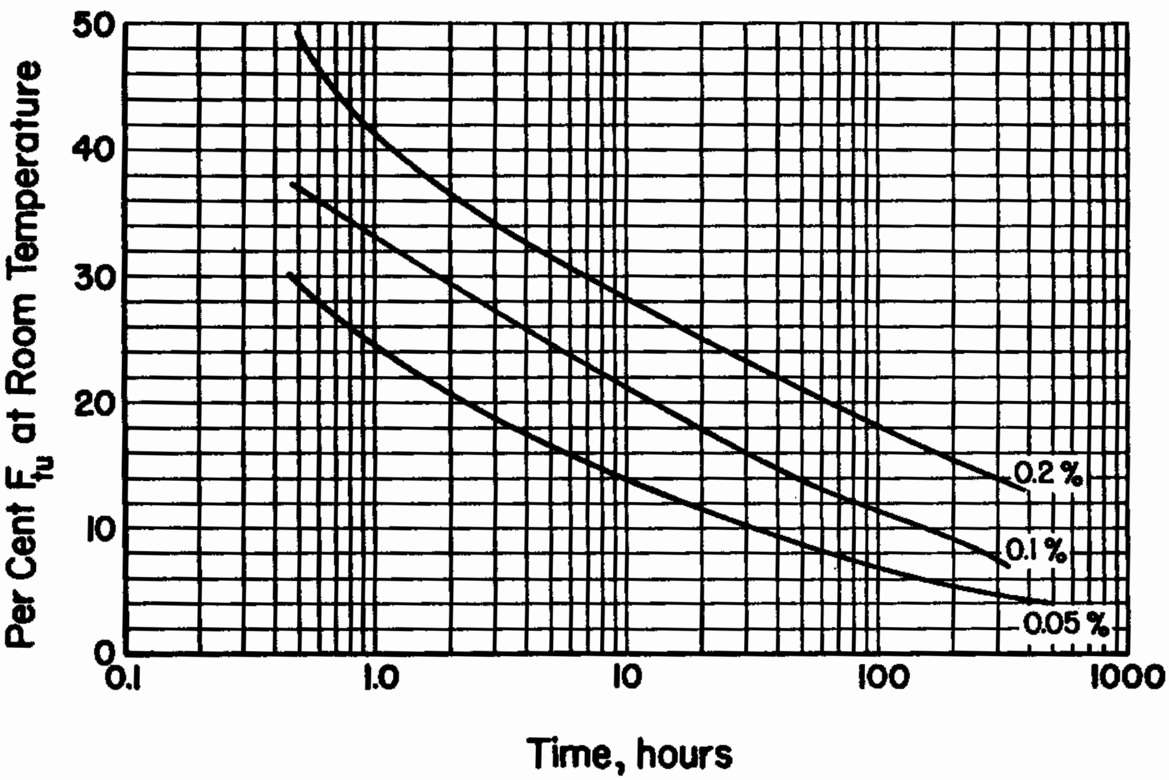

FIGURE 5.2.5.1.6(d). Creep and rupture data for 4Al-3Mo-1V solution treated and aged titanium alloy (0.063 inch thick sheet) at 800°F.

5.2.6 2.5Al-16V Titanium Alloy

5.2.6.0 Comments and Properties

Room-temperature mechanical and physical properties are shown in Table 5.2.6.0(a). Effect on tensile properties of long-time exposure to elevated temperature is given in Tables 5.2.6.0(b) and (c). The temper index for 2.5Al-16V titanium alloy is as follows:

Section	Temper or Condition
5.2.6.1	Solution treated and aged

For solution treated and aged material reported herein, some variations in processing history were noted. The heat treatments included are:

1410F for 30 min. - 990F for 4 hrs.
1410F for 25 min. - 990F for 4 hrs.
1410F for 30 min. - 975F for 6 hrs.
1410F for 30 min. - 975F for 4 hrs.
1400F for 20 min. - 990F for 6 hrs.
1400F for 20 min. - 990F for 4 hrs.
1400F for 25 min. - 975F for 6 hrs.
1400F for 15 min. - 975F for 6 hrs.
1390F for 15 min. - 975F for 6 hrs.
1380F for 30 min. - 990F for 4 hrs.

TABLE 5.2.6.0(a) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 2.5Al-16V TITANIUM ALLOY

Alloy	2.5Al-16V		
Form	Sheet		
Condition	Solution Treated and Aged		
Thickness (in.)	0.020	0.063	0.125
Basis	B	B	B
Mechanical Properties:			
F_{tu}, ksi			
L	170	161	168
T	168	164	168
F_{ty}, ksi			
L	158	145	156
T	157	150	156
F_{cy}, ksi			
L	..	151	162
T	..	156	167
F_{su}, ksi			
L	104	102	106
T	102	100	105
F_{bru}, ksi (e/D=1.5)			
L	222	234	235
T	215	234	233
F_{bru}, ksi (e/D=2.0)			
L	252	282	283
T	250	283	274
F_{bry}, ksi (e/D=1.5)			
L	203	208	211
T	210	208	214
F_{bry}, ksi (e/D=2.0)			
L	226	231	248
T	227	231	246
e, percent(a)			
L	3.7	6.2	6.9
T	3.8	5.4	6.3
E, 10^6 psi			
L	14.4	13.9	13.8
T	14.0	14.2	14.0
E_c, 10^6 psi			
L	..	14.1	14.8
T	..	14.1	15.0
Physical Properties:			
ω, lb/in.^{3}	0.168		
C, Btu/(lb)(F)	0.126 (at 75°F)		
K, Btu/[(hr)(ft^2)(F)/ft]	5.0 (at 70°F)		
α, 10^{-6} in./in./F	5.0 (100° to 200°F		

(a) Elongations are average test values.

TABLE 5.2.6.0(b) EFFECT OF 500-HOUR EXPOSURE AT 600°F ON THE TENSILE PROPERTIES OF 2.5Al-16V TITANIUM ALLOY

Condition.................	Solution Treated and Aged		
Thickness (in.)...........	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L....................	177	174	180
T....................	178	178	179
F_{ty}, ksi (at room temp.)			
L....................	161	159	164
T....................	164	166	167
F_{tu}, ksi (at 600°F)			
L....................	144	139	146
T....................	144	143	148
F_{ty}, ksi (at 600°F)			
L....................	125	121	128
T....................	126	125	130
Exposed at temperature while stressed to 1/3 average 600°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L....................	182	179	182
T....................	182	182	183
F_{ty}, ksi (at room temp.)			
L....................	168	165	171
T....................	168	169	170
F_{tu}, ksi (at 600°F)			
L....................	147	142	152
T....................	144	140	151
F_{ty}, ksi (at 600°F)			
L....................	128	123	136
T....................	126	127	133

TABLE 5.2.6.0(c) EFFECT OF 10-HOUR EXPOSURE AT 900°F ON THE TENSILE PROPERTIES OF 2.5Al-16V TITANIUM ALLOY

Condition	Solution Treated and Aged		
Thickness (in.)	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L	174	167	171
T	173	171	175
F_{ty}, ksi (at room temp.)			
L	162	154	159
T	162	159	163
F_{tu}, ksi (at 900°F)			
L	112	100	102
T	112	102	106
F_{ty}, ksi (at 900°F)			
L	72	70	70
T	72	77	75
Exposed at temperature while stressed to 1/3 average 900°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L	174	160	173
T	172	163	178
F_{ty}, ksi (at room temp.)			
L	164	150	165
T	164	156	168
F_{tu}, ksi (at 900°F)			
L	107	98	102
T	107	102	110
F_{ty}, ksi (at 900°F)			
L	78	71	77
T	78	77	71

5.2.6.1 Solution Treated and Aged Condition

Room and elevated temperature data for this condition are presented in Figures 5.2.6.1.1(a) through 5.2.6.1.6 (c).

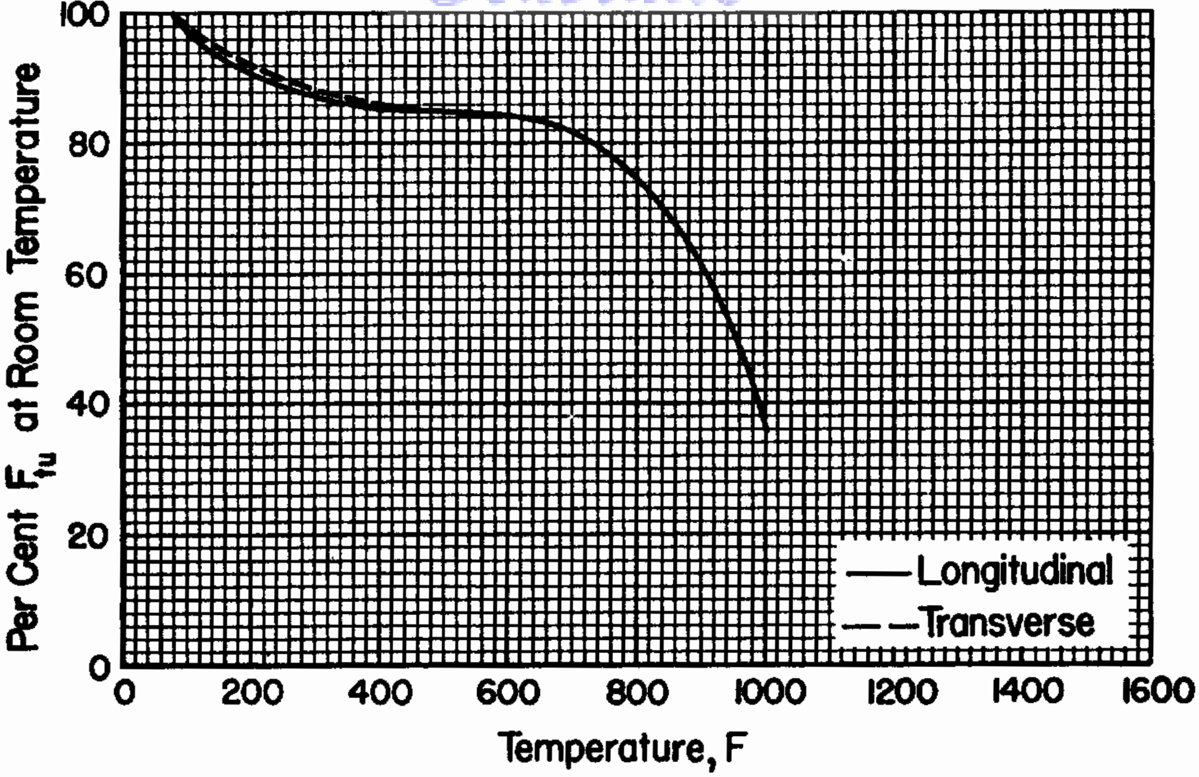

FIGURE 5.2.6.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

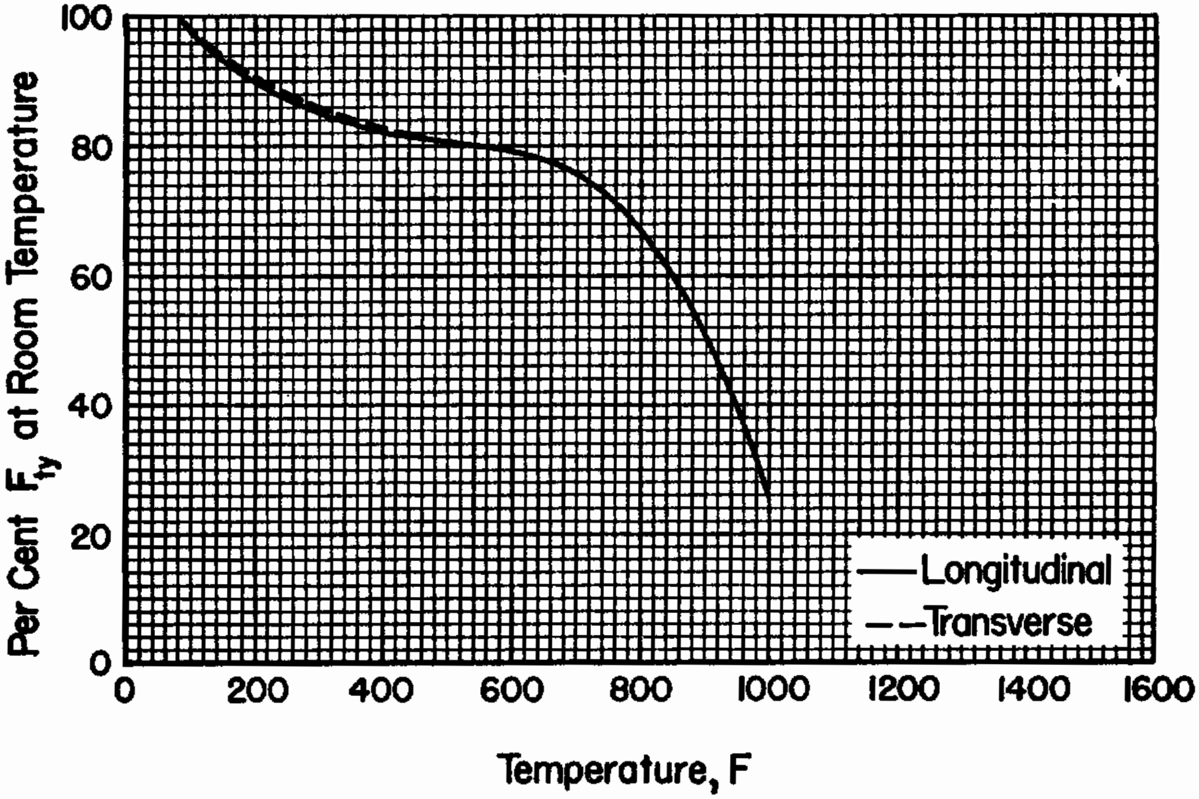

FIGURE 5.2.6.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

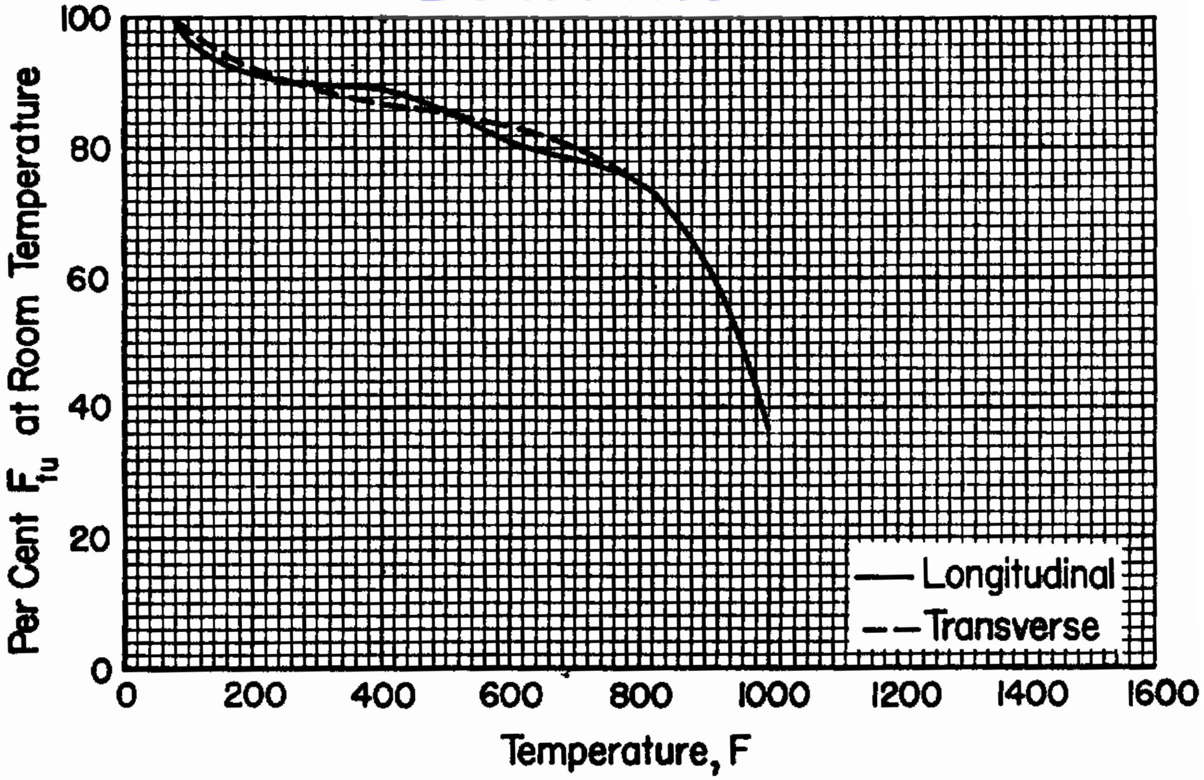

FIGURE 5.2.6.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

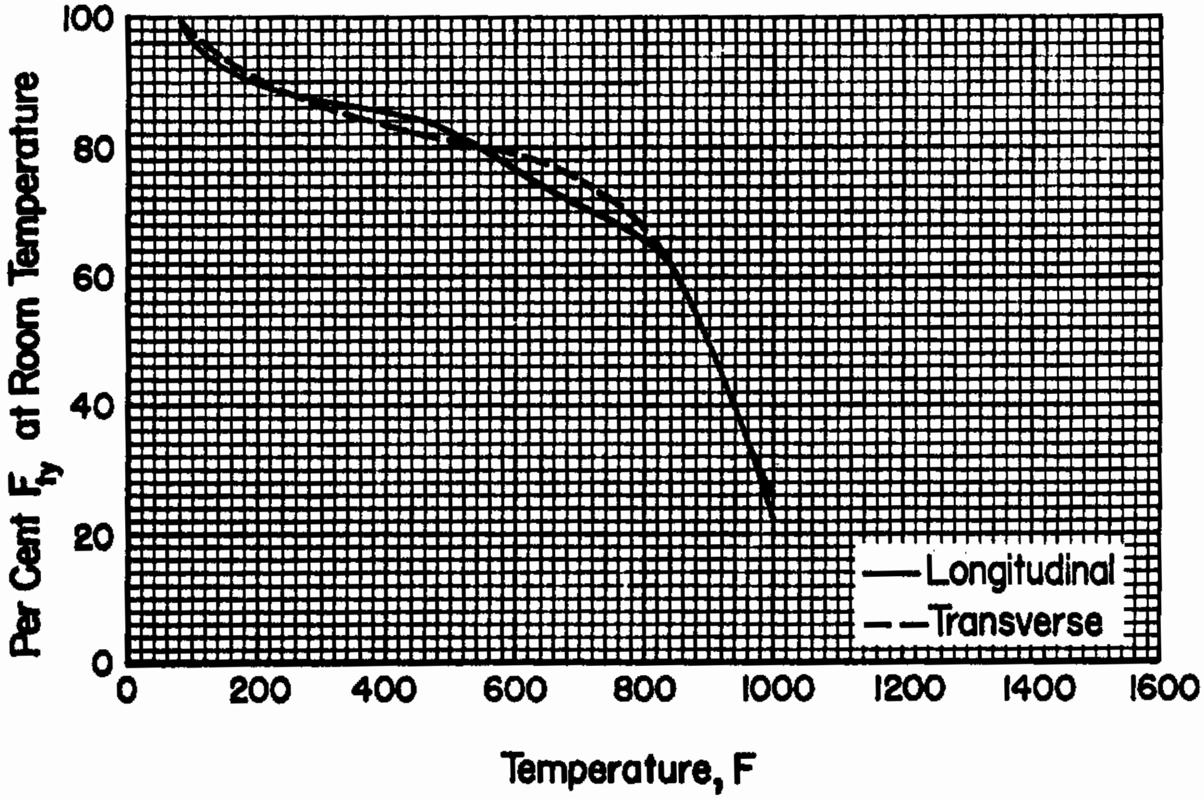

FIGURE 5.2.6.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

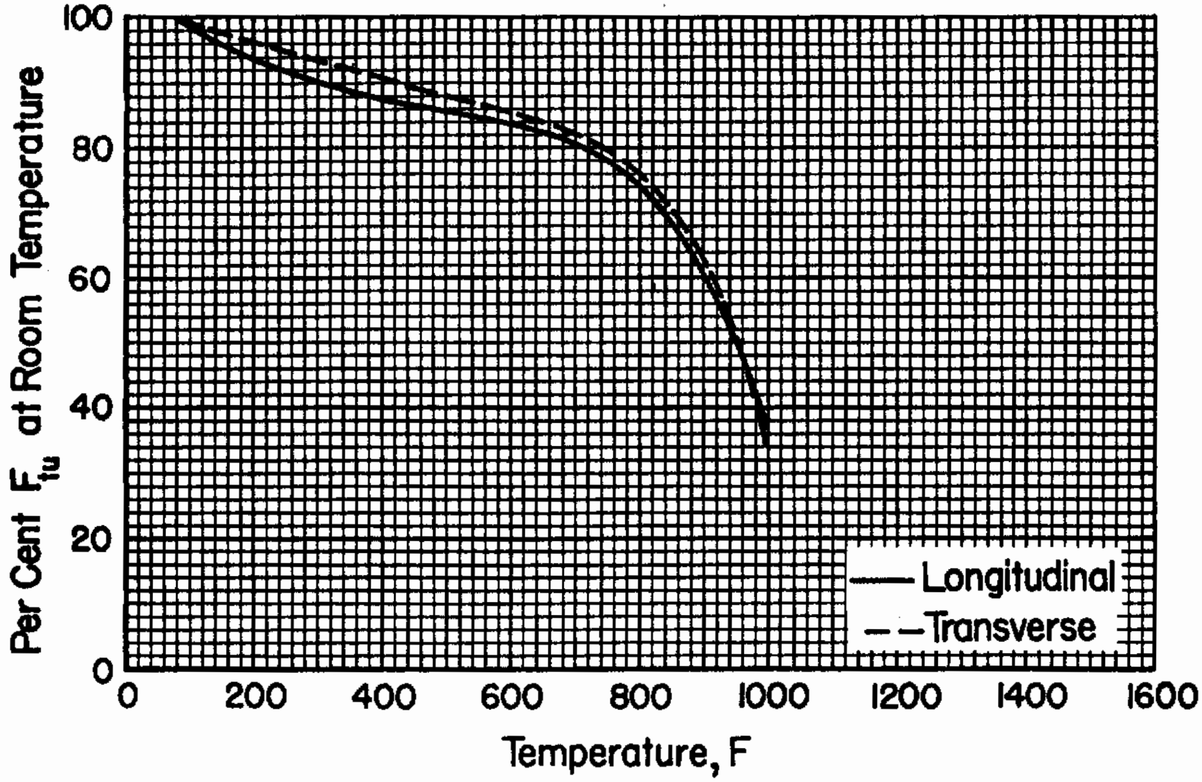

FIGURE 5.2.6.1.1(e). Effect of temperature on the ultimate tensile strength (F_{tu}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

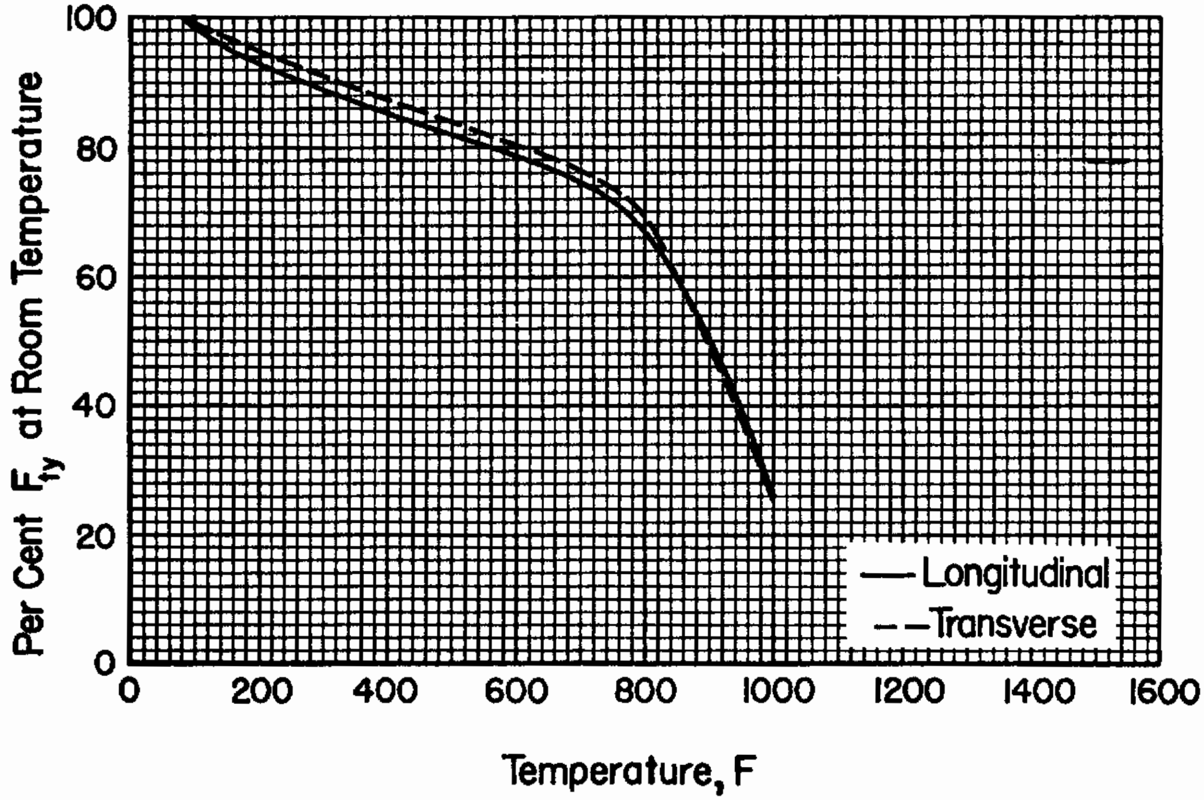

FIGURE 5.2.6.1.1(f). Effect of temperature on the tensile yield strength (F_{ty}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

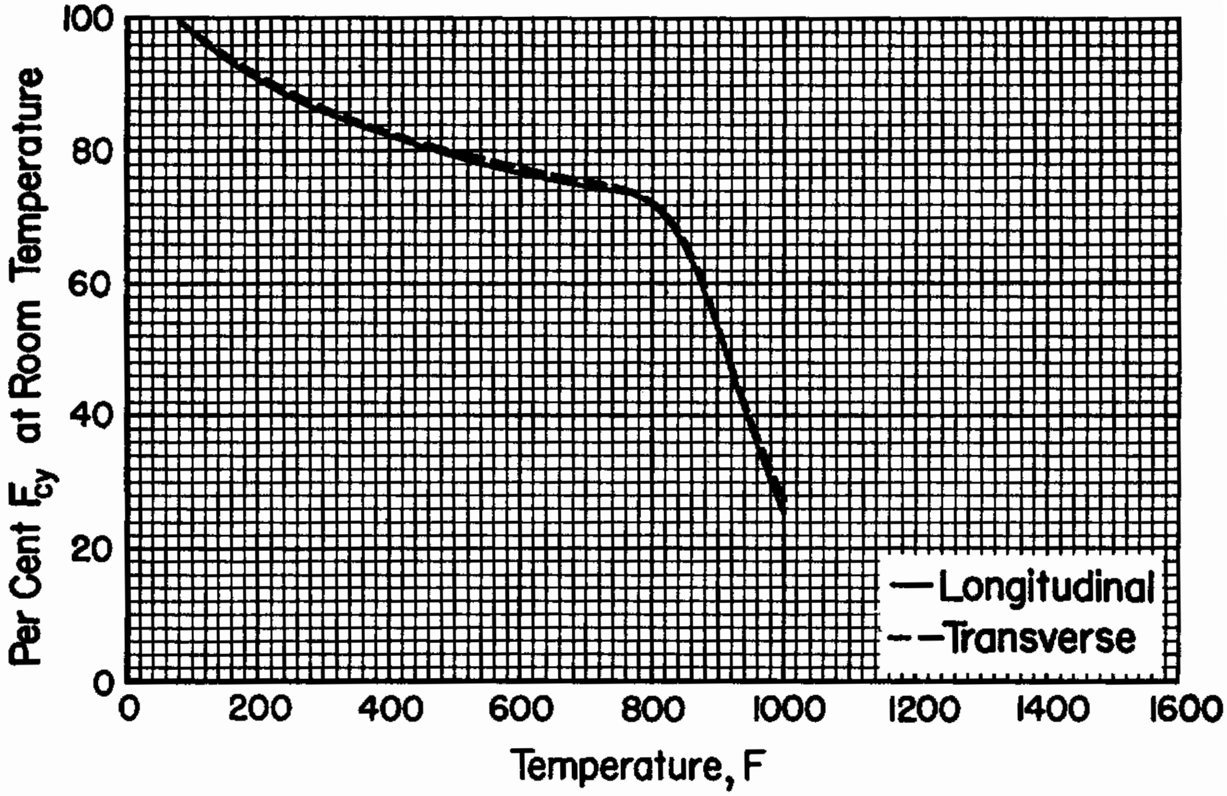

FIGURE 5.2.6.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

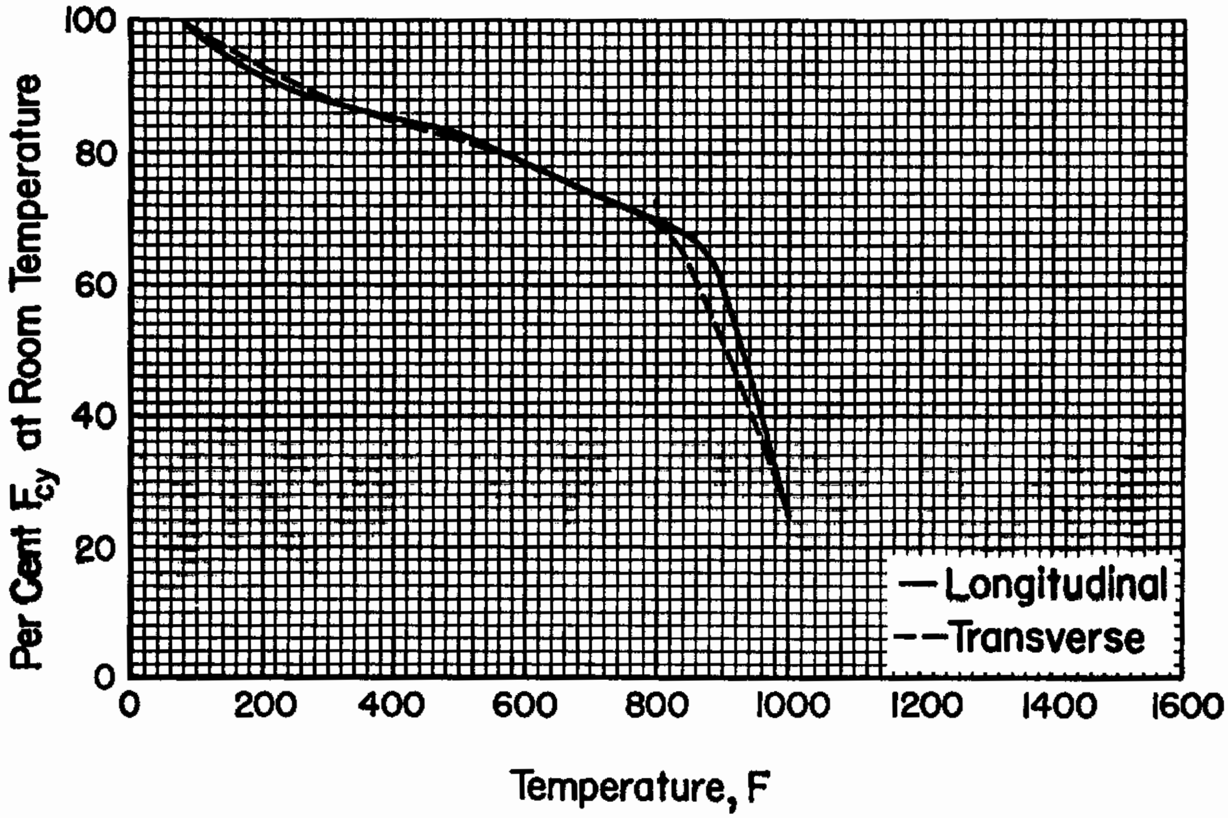

FIGURE 5.2.6.1.2(b). Effect of temperature on the compressive yield strength (F_{cy}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

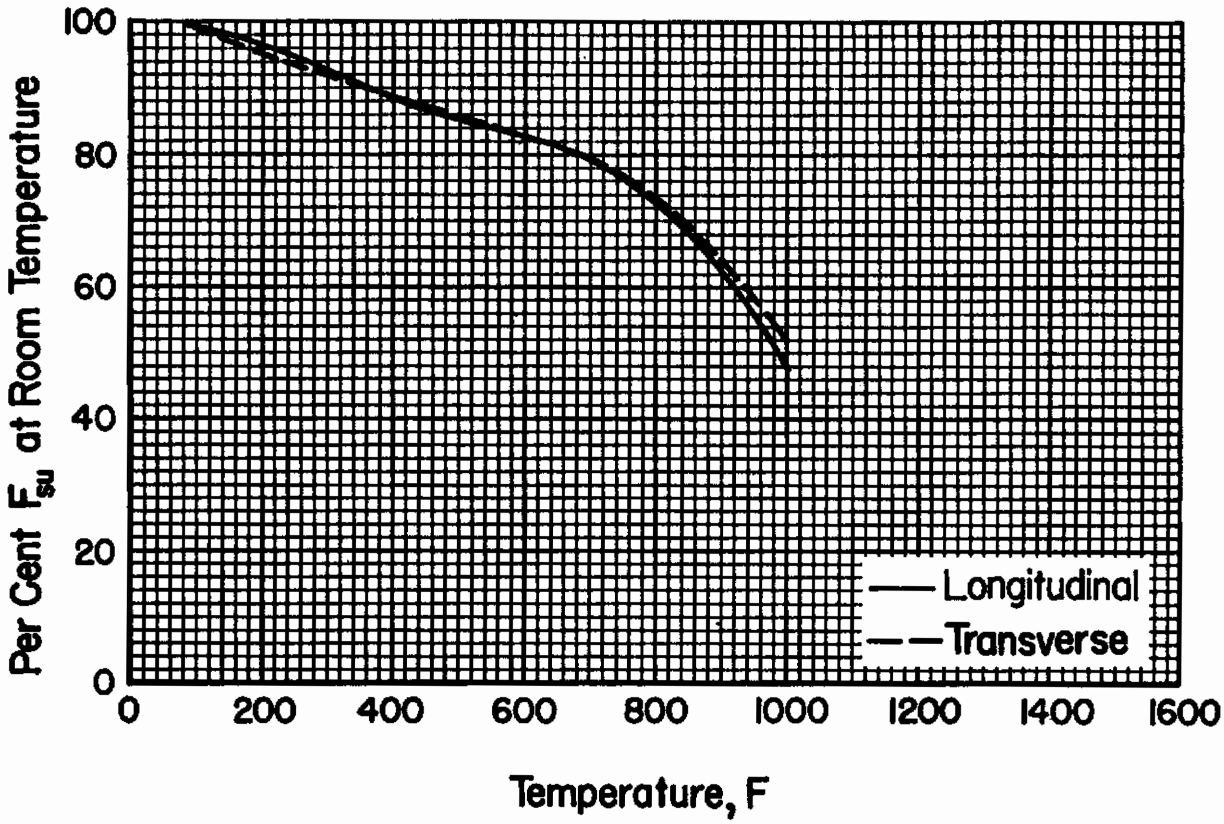

FIGURE 5.2.6.1.2(c). Effect of temperature on the ultimate shear strength (F_{su}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

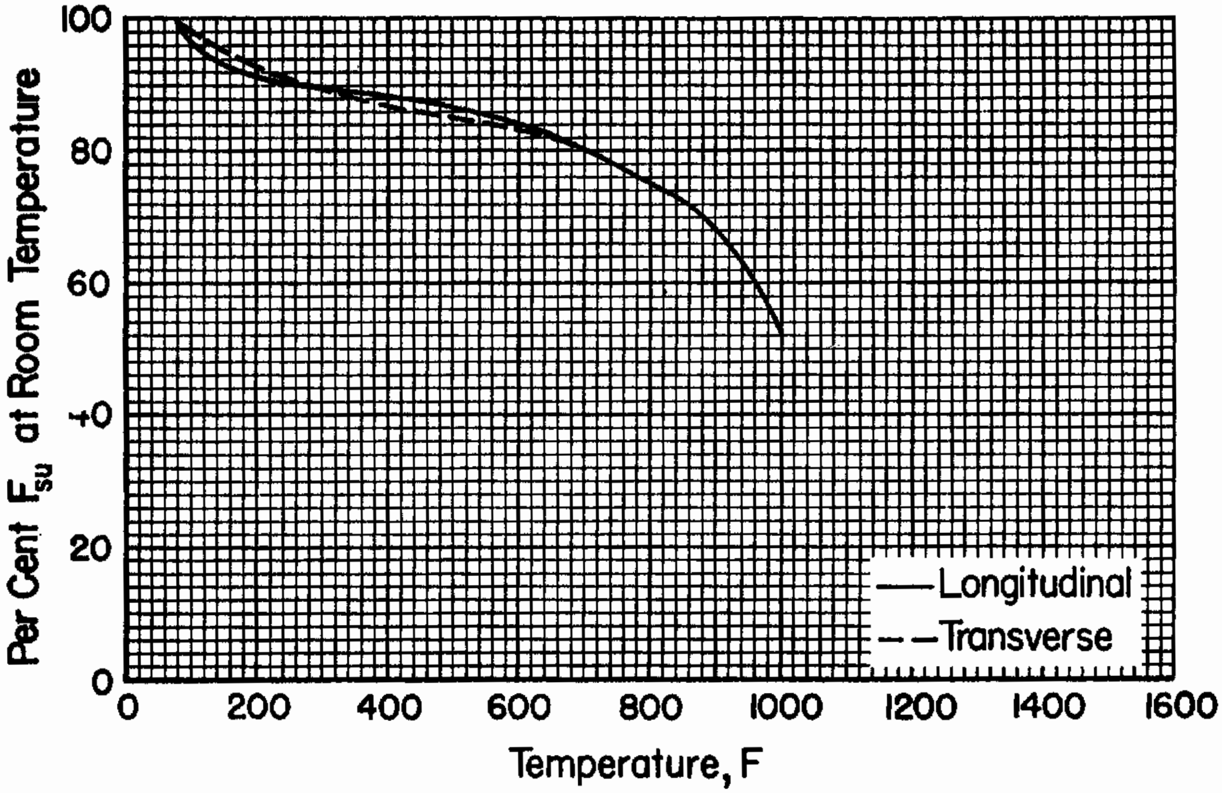

FIGURE 5.2.6.1.2(d). Effect of temperature on the ultimate shear strength (F_{su}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

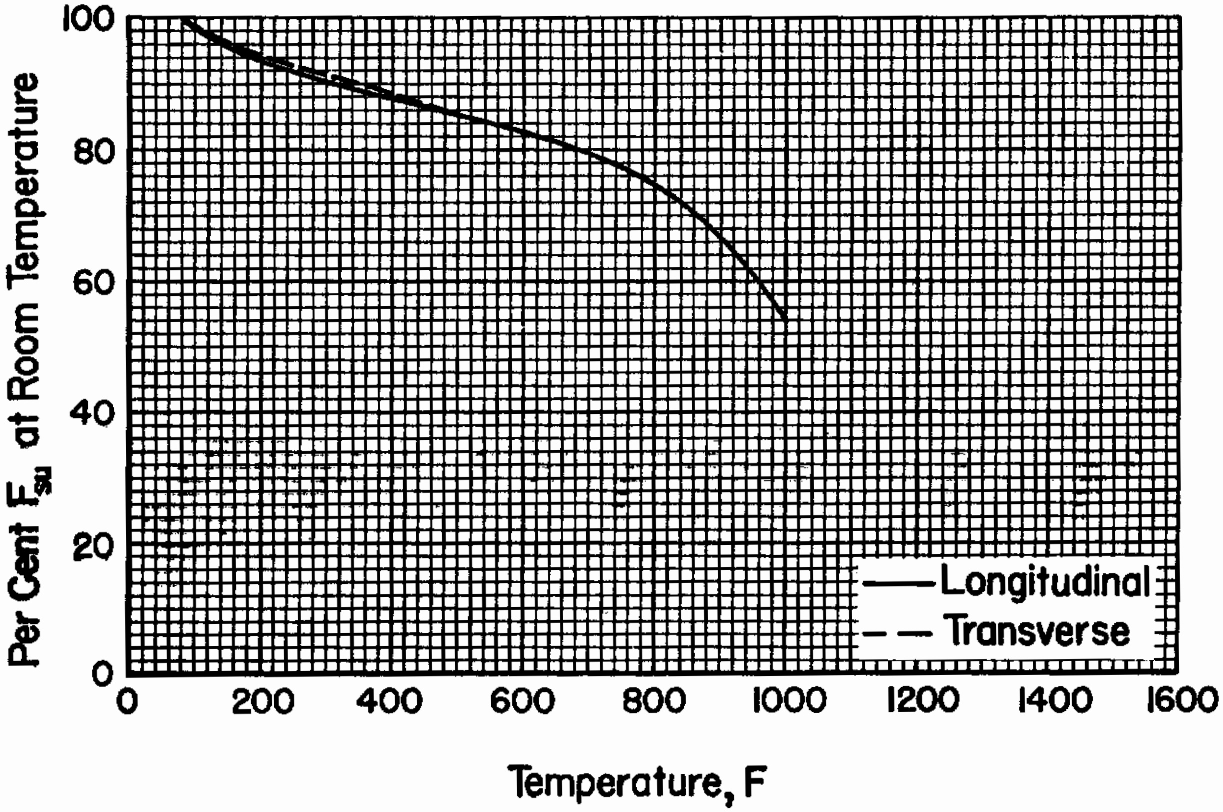

FIGURE 5.2.6.1.2(e). Effect of temperature on the ultimate shear strength (F_{su}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

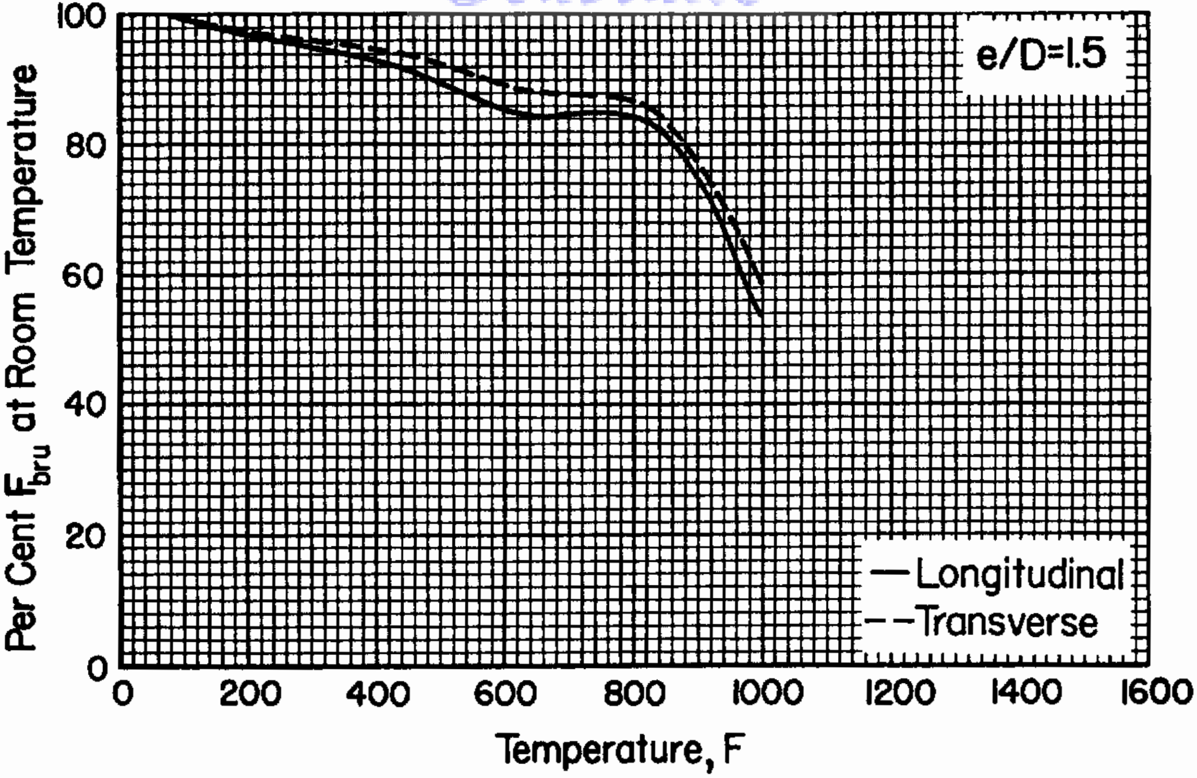

FIGURE 5.2.6.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

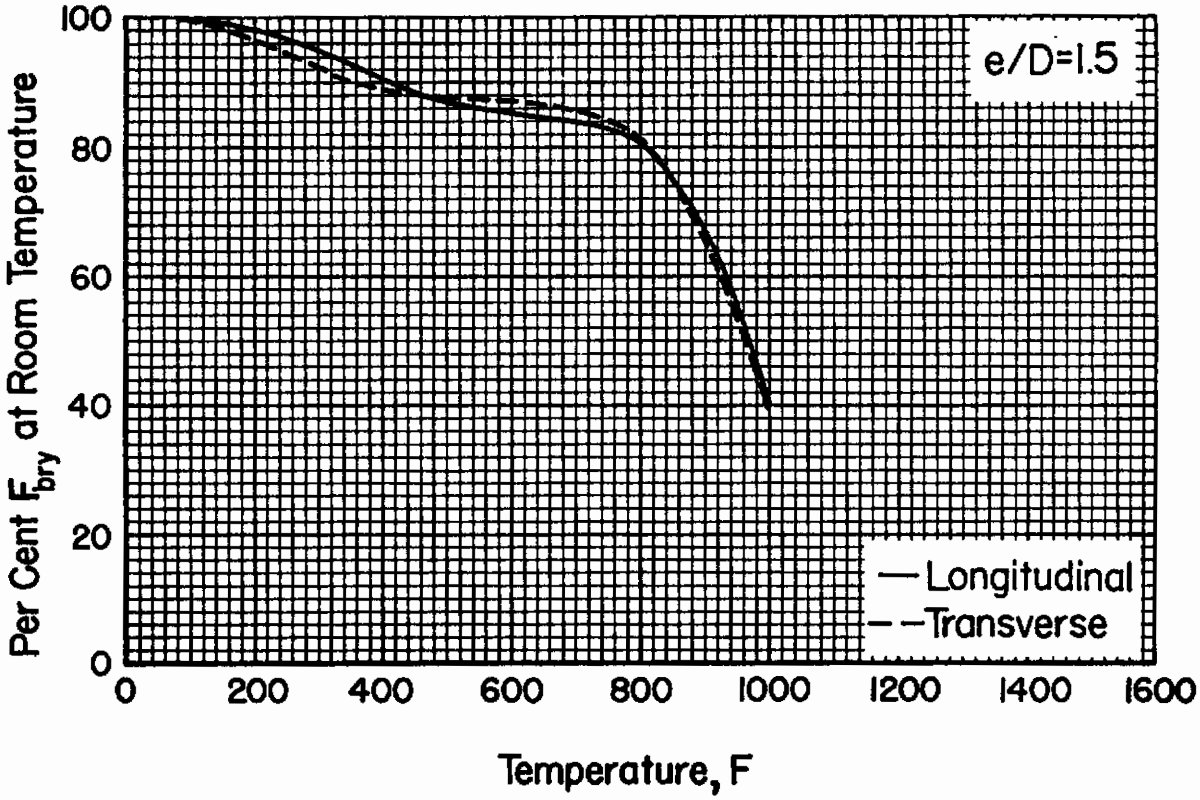

FIGURE 5.2.6.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

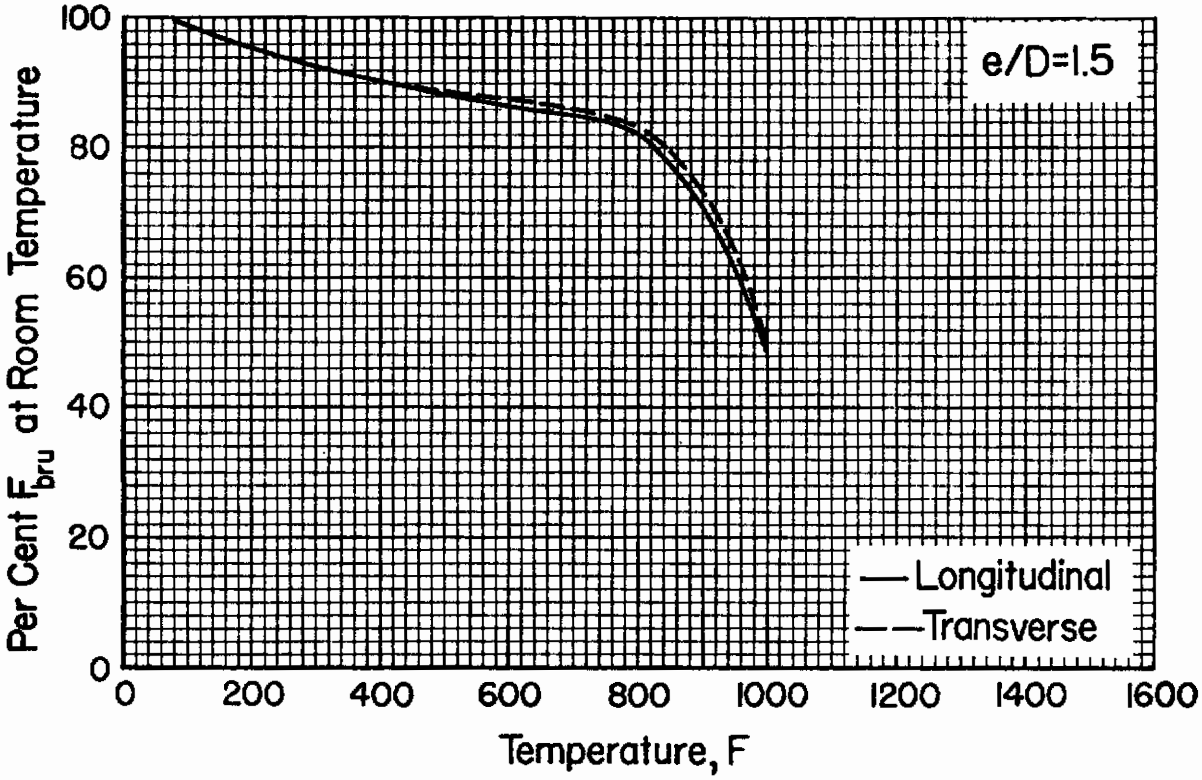

FIGURE 5.2.6.1.3(c). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

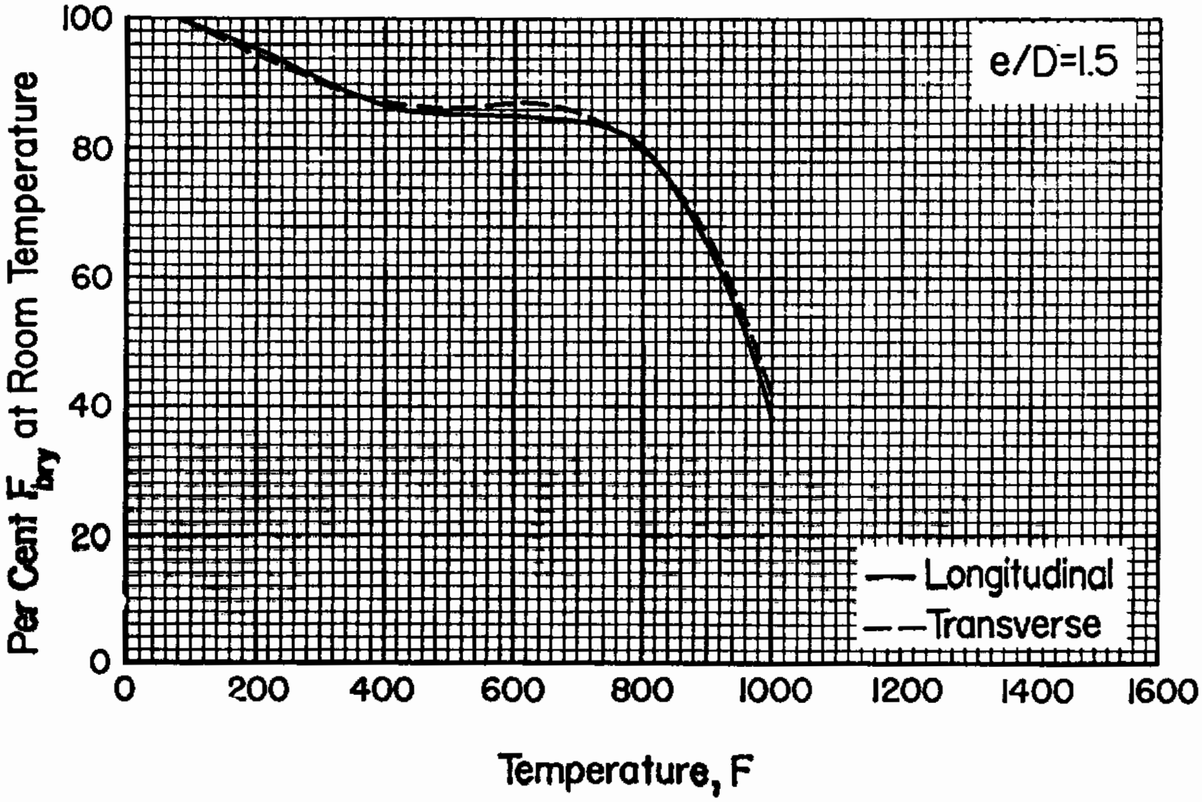

FIGURE 5.2.6.1.3(d). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

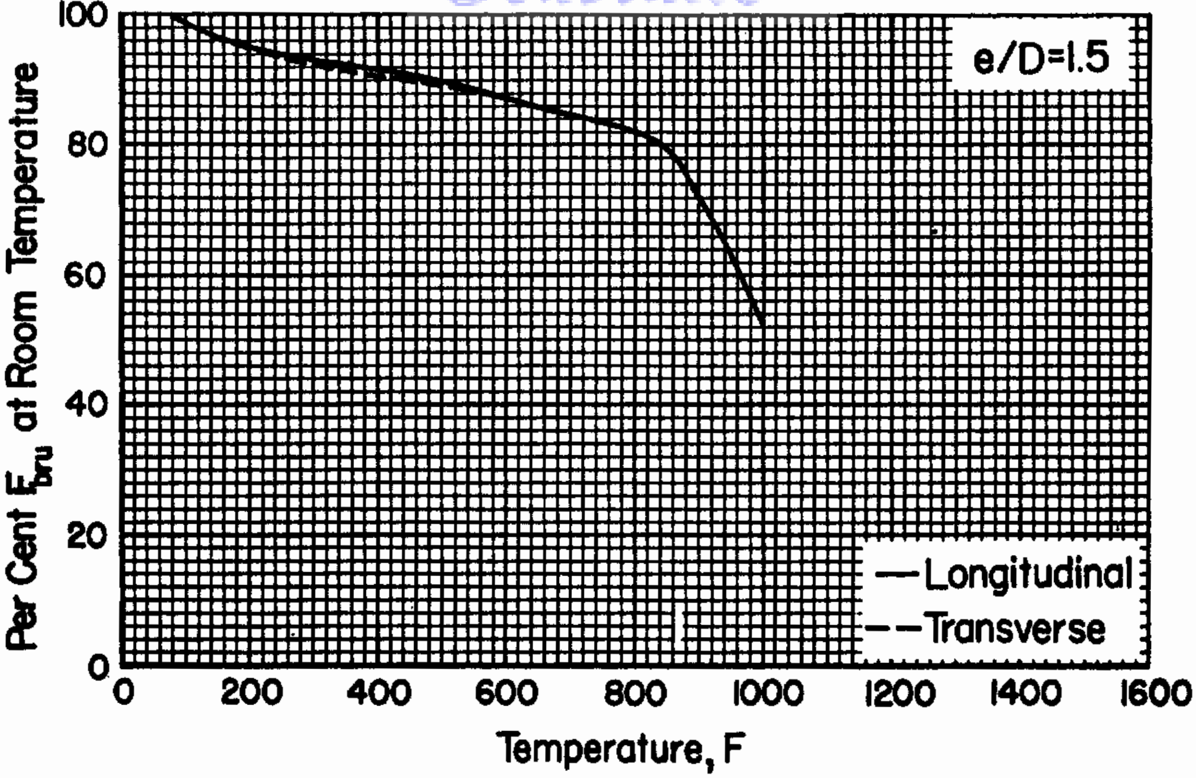

FIGURE 5.2.6.1.3(e). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

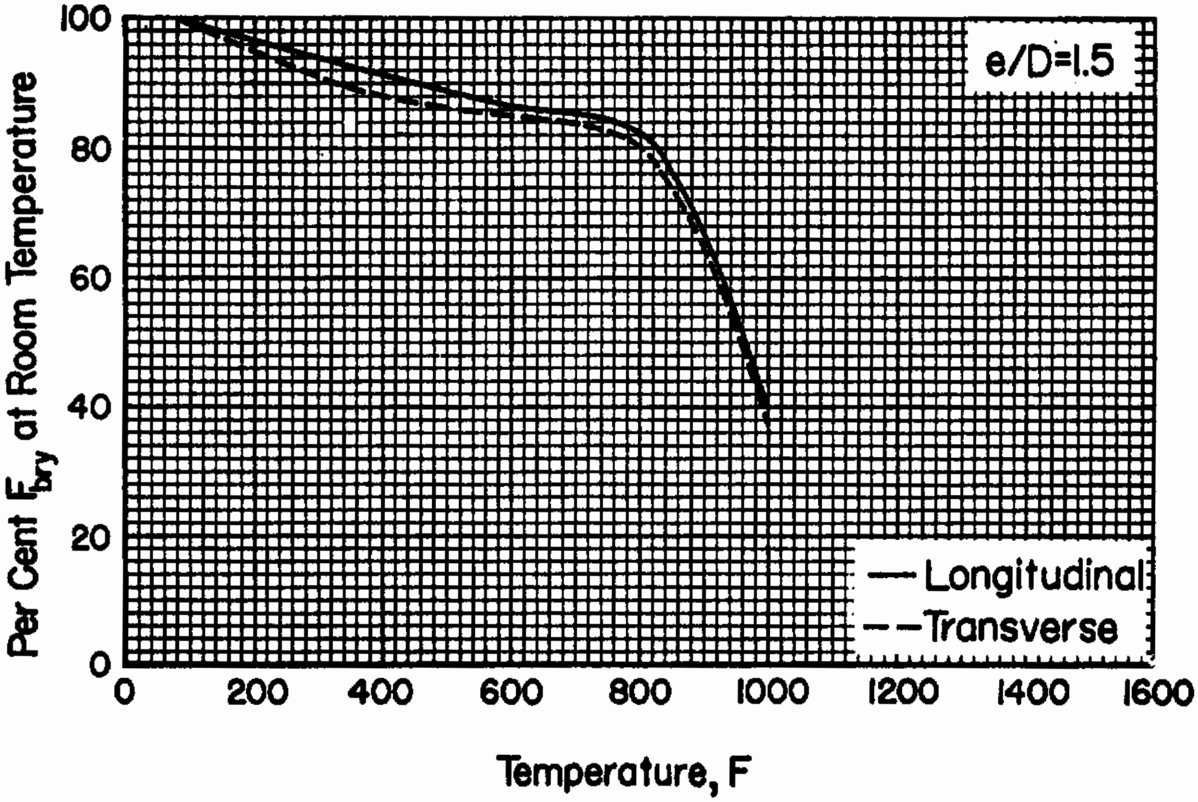

FIGURE 5.2.6.1.3(f). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

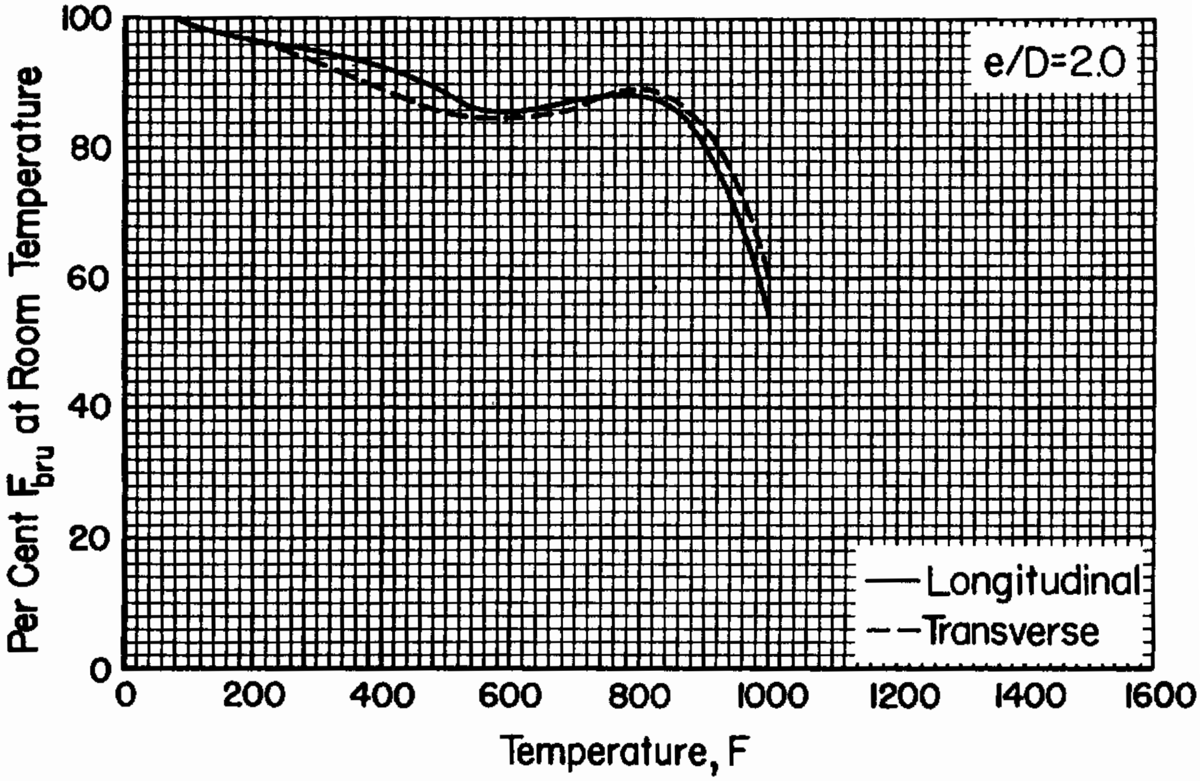

FIGURE 5.2.6.1.3(g). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

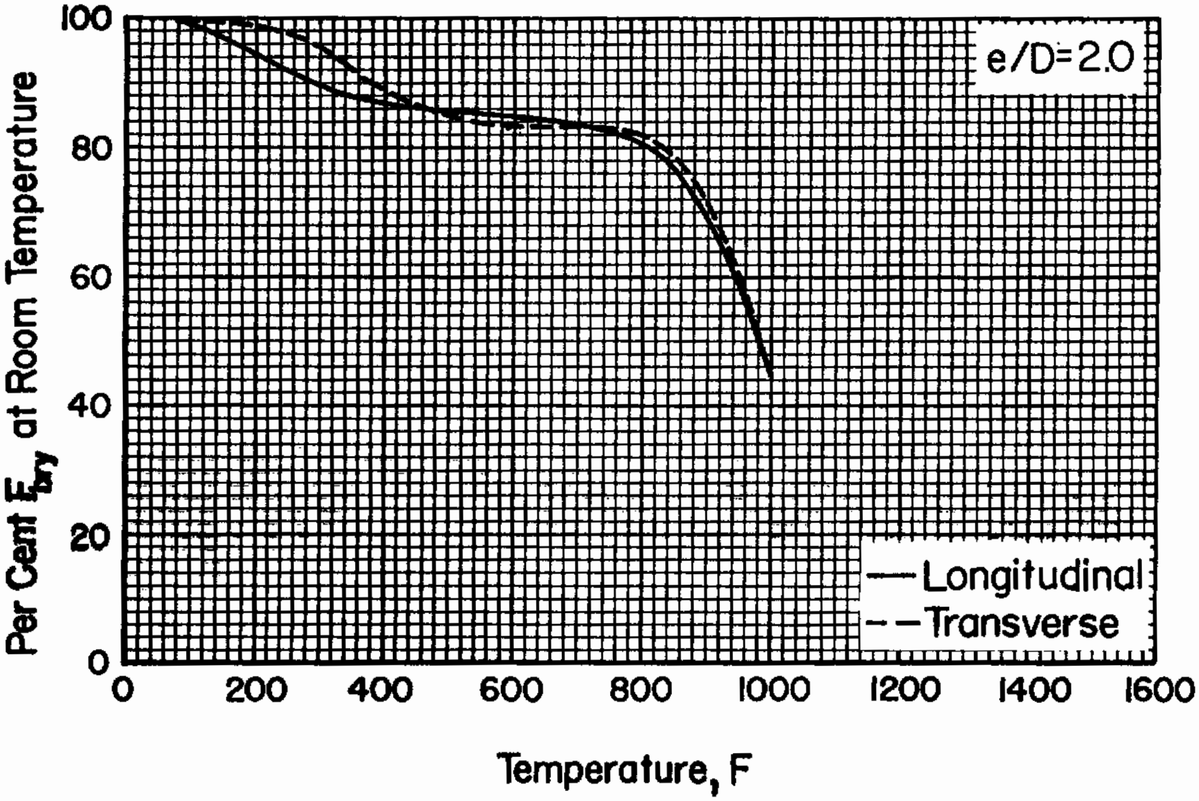

FIGURE 5.2.6.1.3(h). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

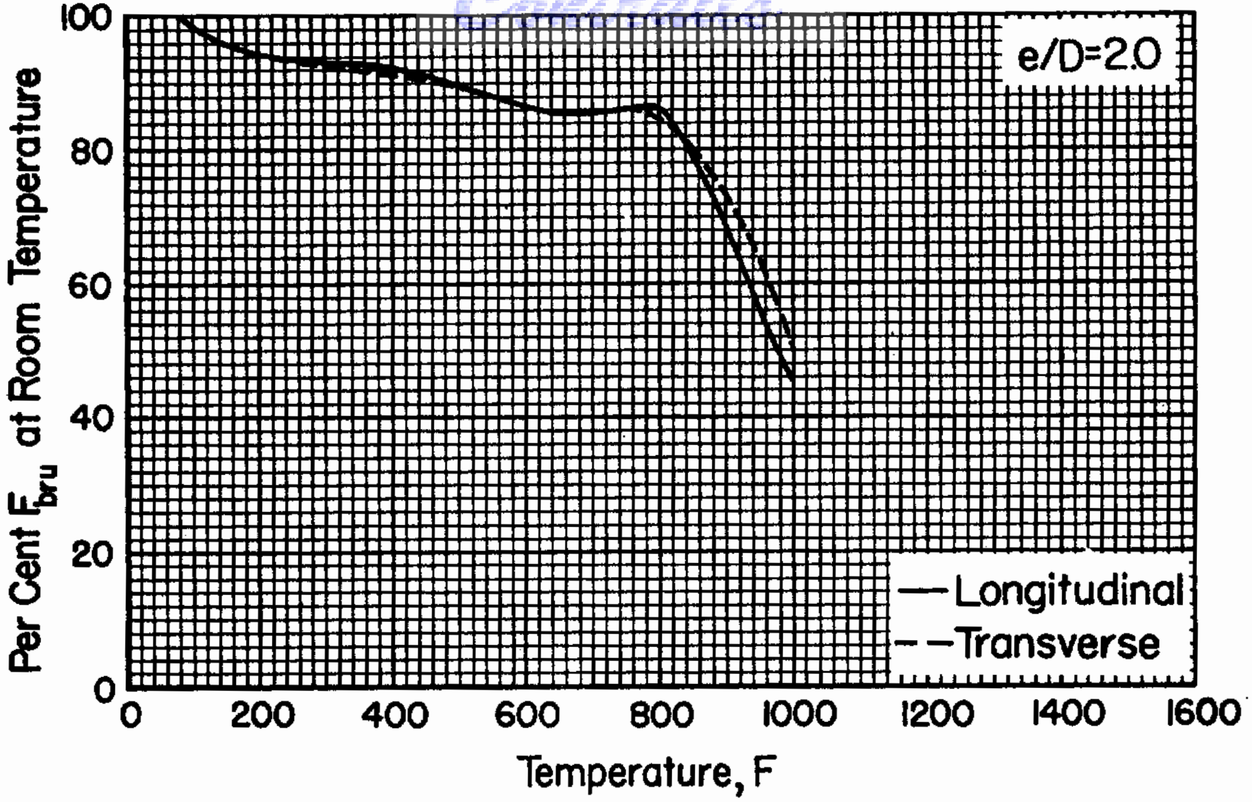

FIGURE 5.2.6.1.3(i). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

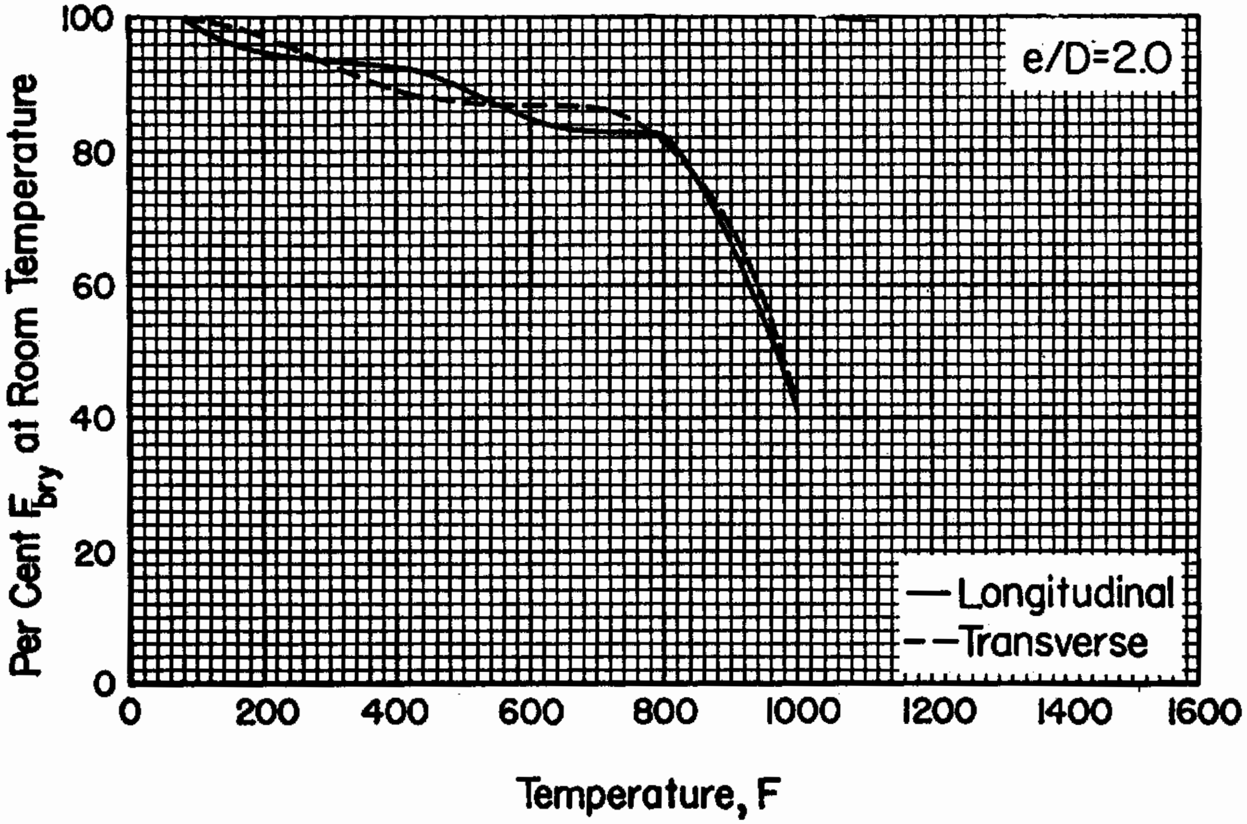

FIGURE 5.2.6.1.3(j). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

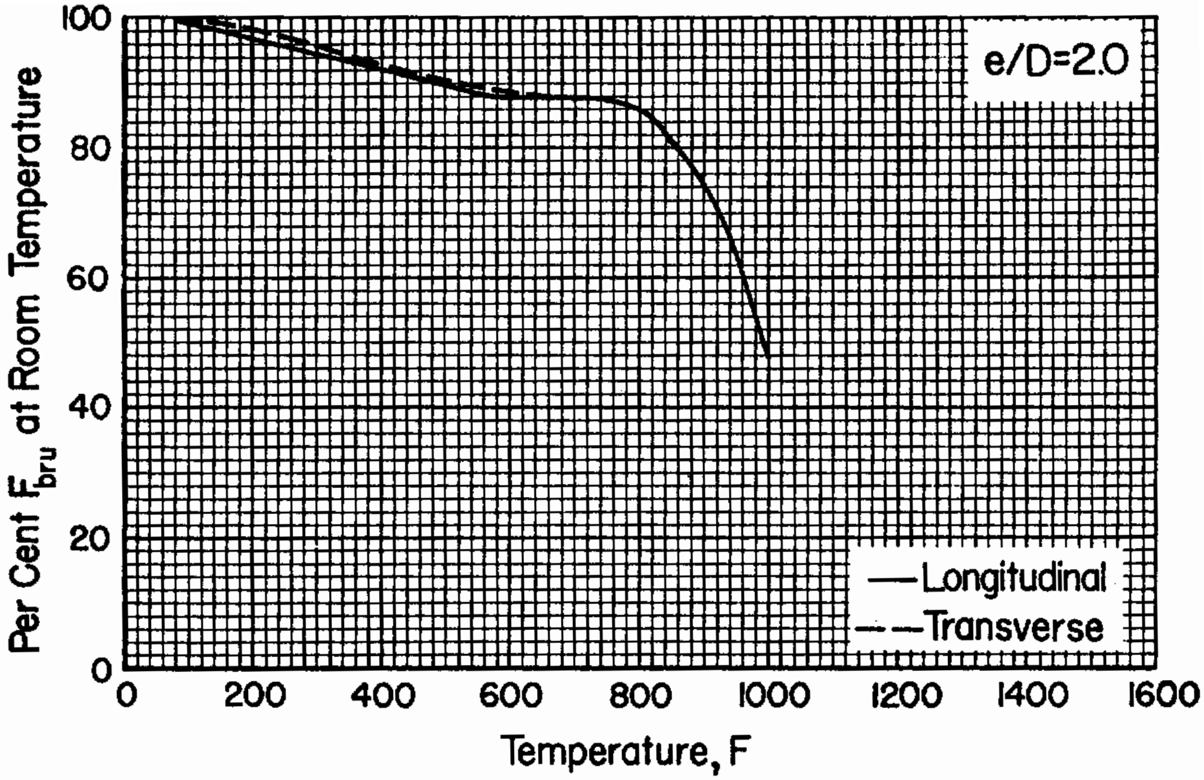

FIGURE 5.2.6.1.3(k). Effect of temperature on the ultimate bearing strength (F_{bru}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

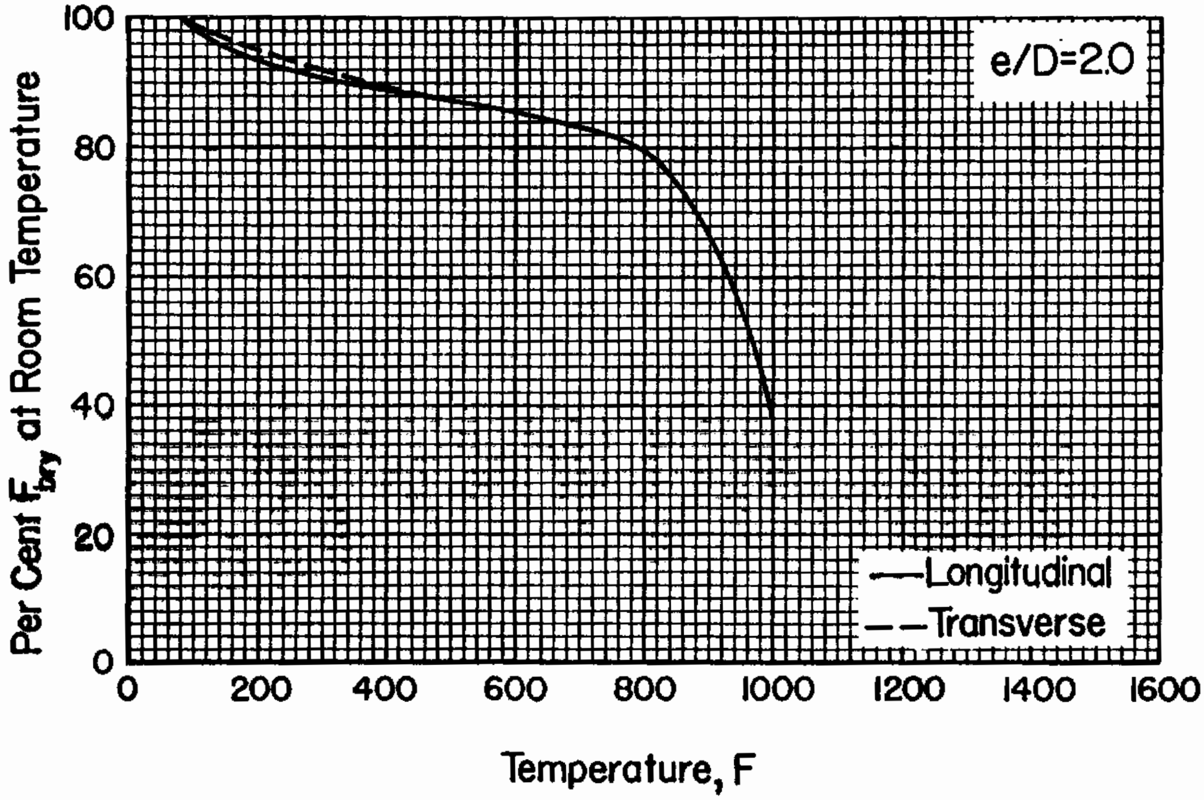

FIGURE 5.2.6.1.3(l). Effect of temperature on the bearing yield strength (F_{bry}) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

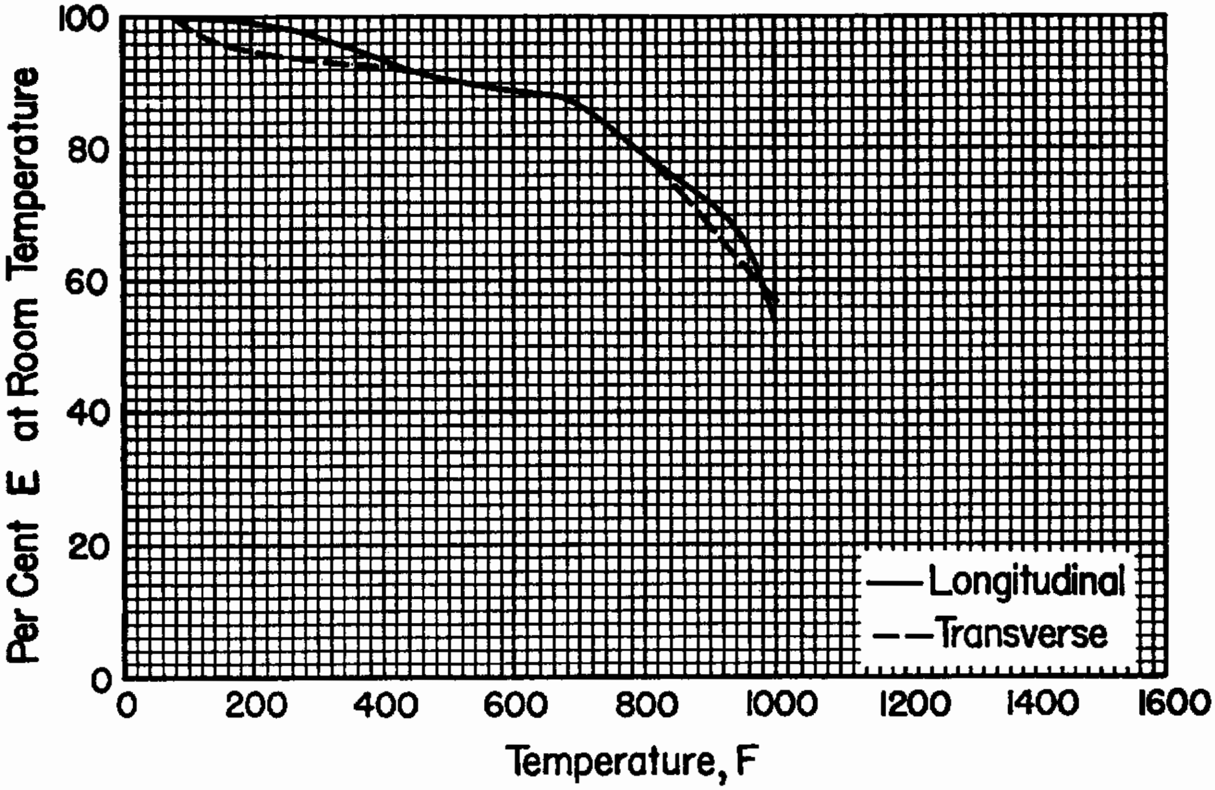

FIGURE 5.2.6.1.4(a). Effect of temperature on the tensile modulus (E) of 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

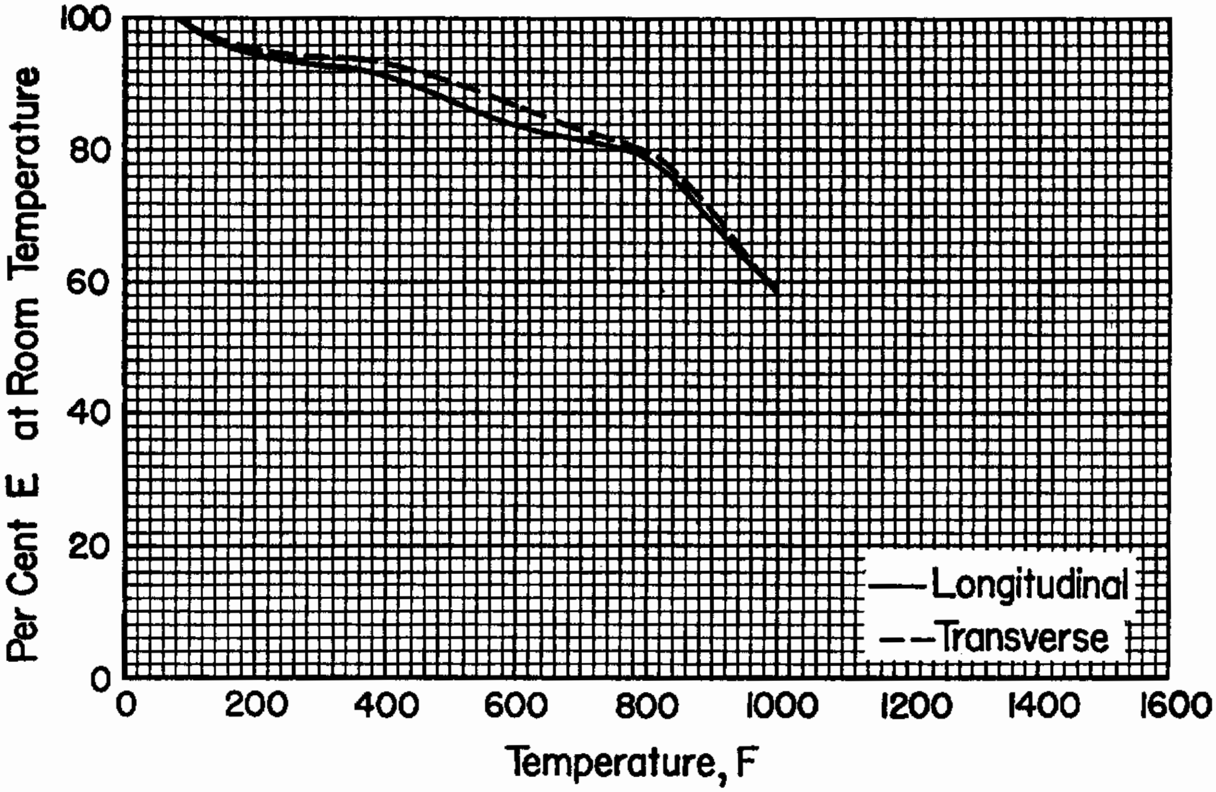

FIGURE 5.2.6.1.4(b). Effect of temperature on the tensile modulus (E) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

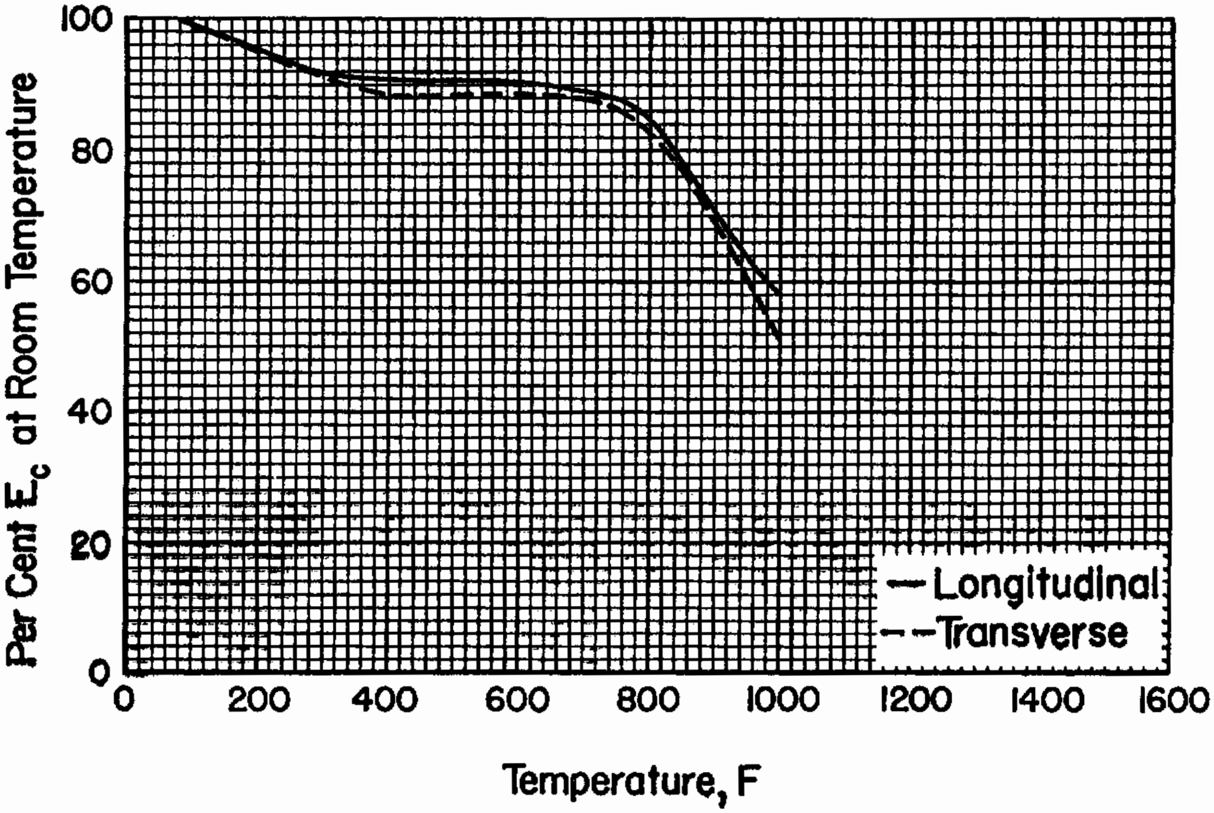

FIGURE 5.2.6.1.4(c). Effect of temperature on the compressive modulus (E_c) of 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

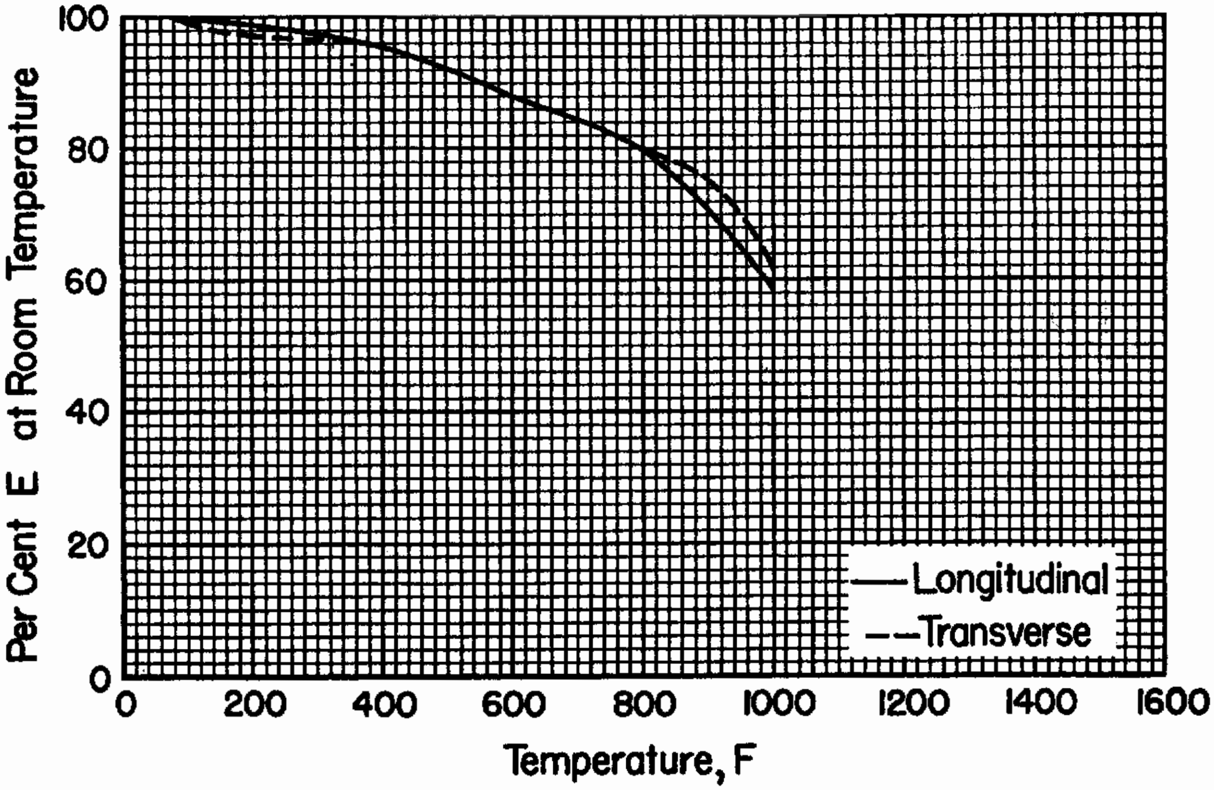

FIGURE 5.2.6.1.4(d). Effect of temperature on the tensile modulus (E) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

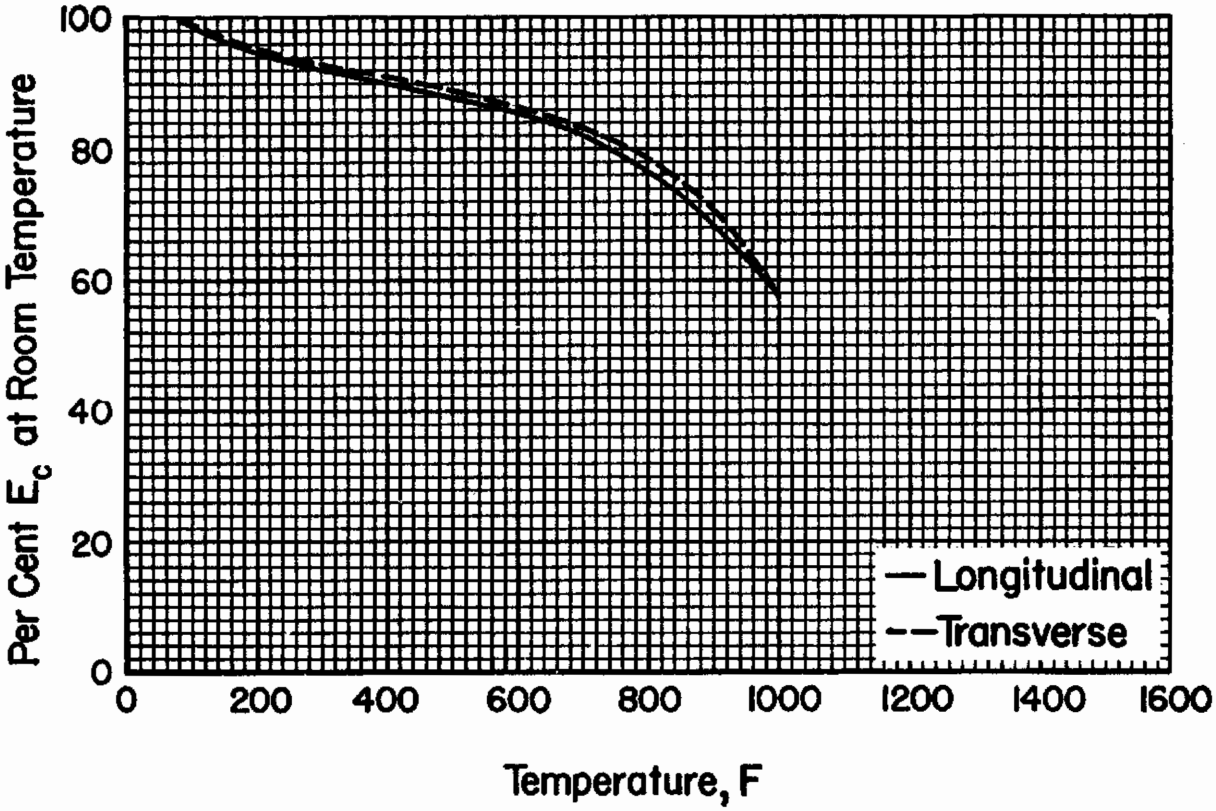

FIGURE 5.2.6.1.4(e). Effect of temperature on the compressive modulus (E_c) of 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

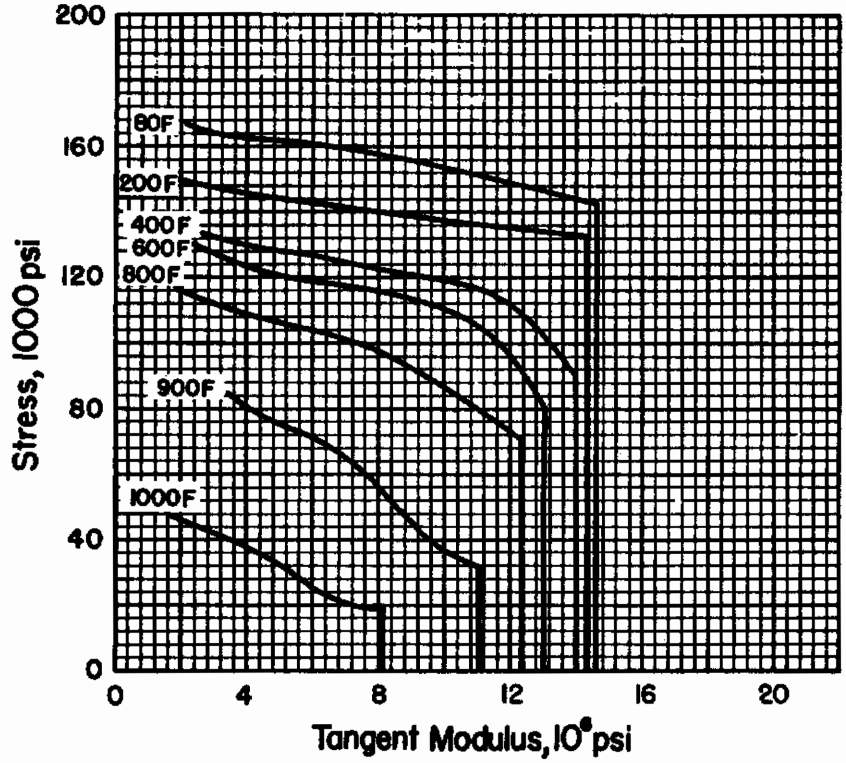

FIGURE 5.2.6.1.4(f). Typical longitudinal tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

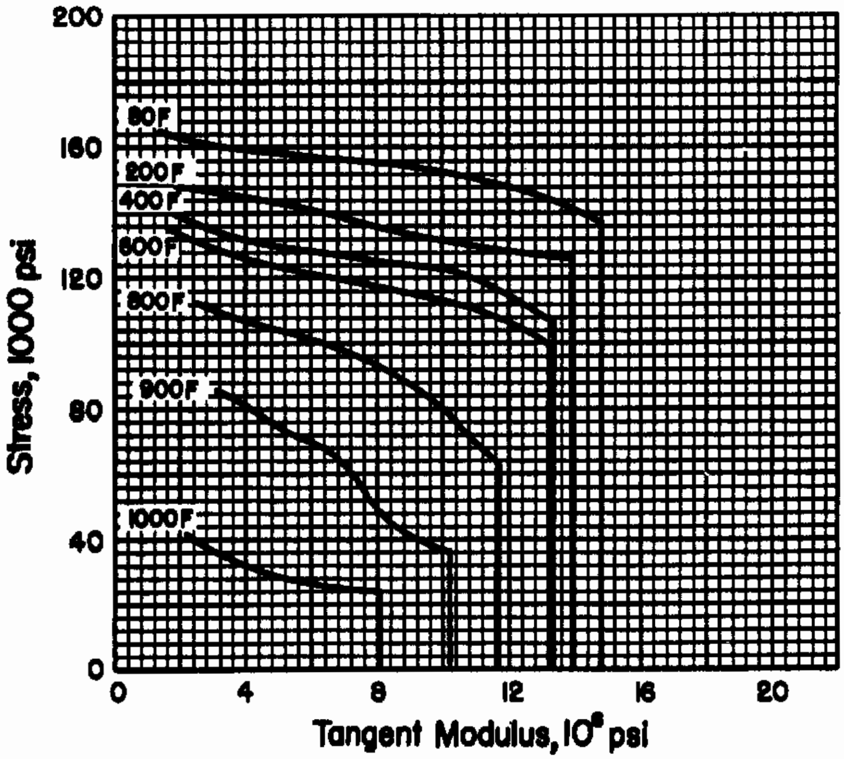

FIGURE 5.2.6.1.4(g). Typical transverse tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

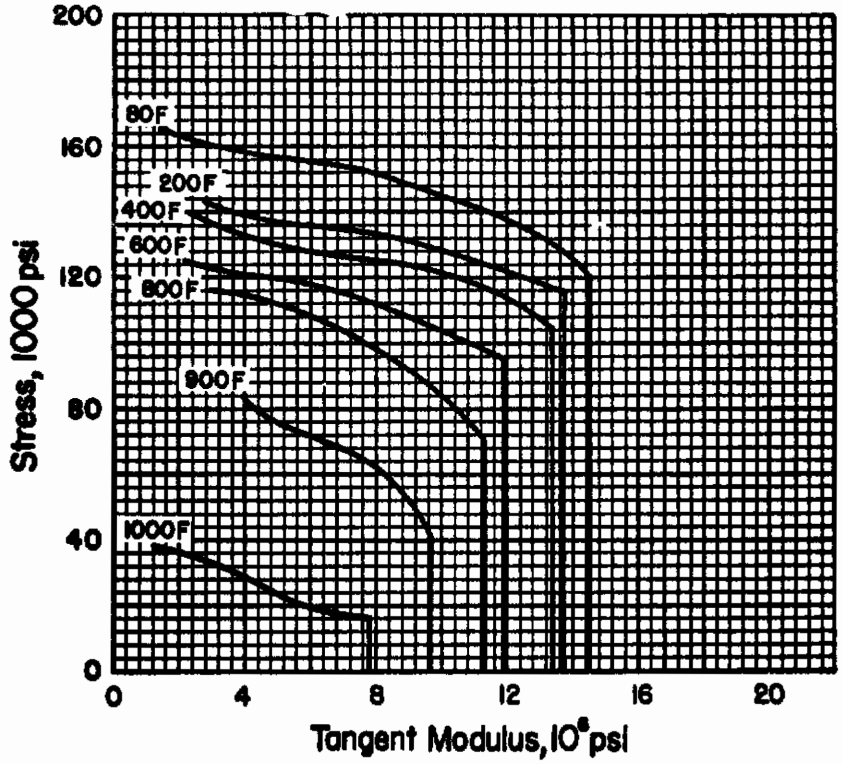

FIGURE 5.2.6.1.4(h). Typical longitudinal tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

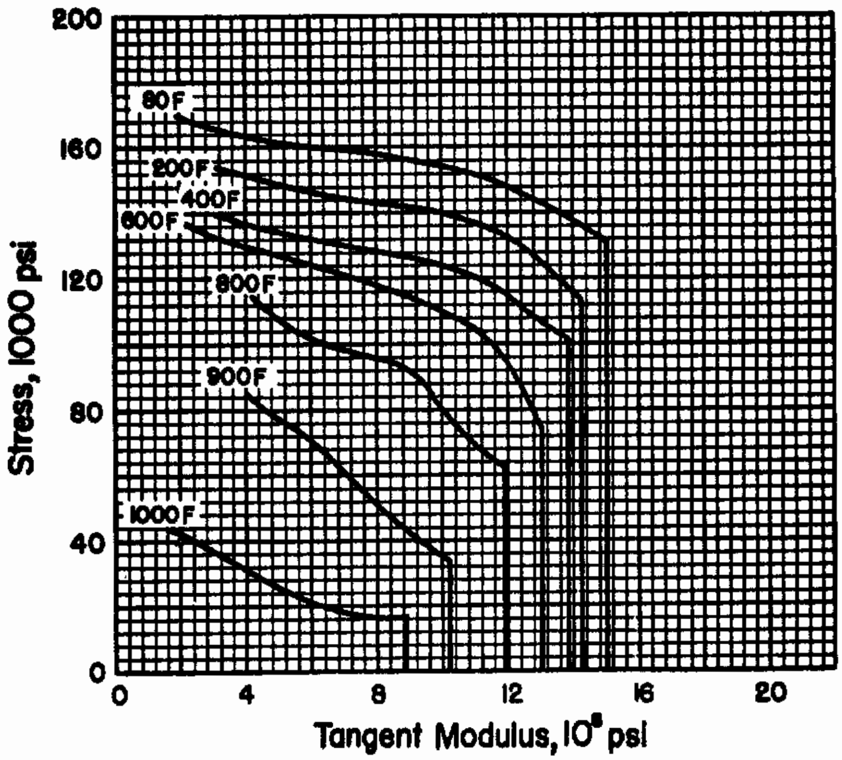

FIGURE 5.2.6.1.4(i). Typical transverse tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

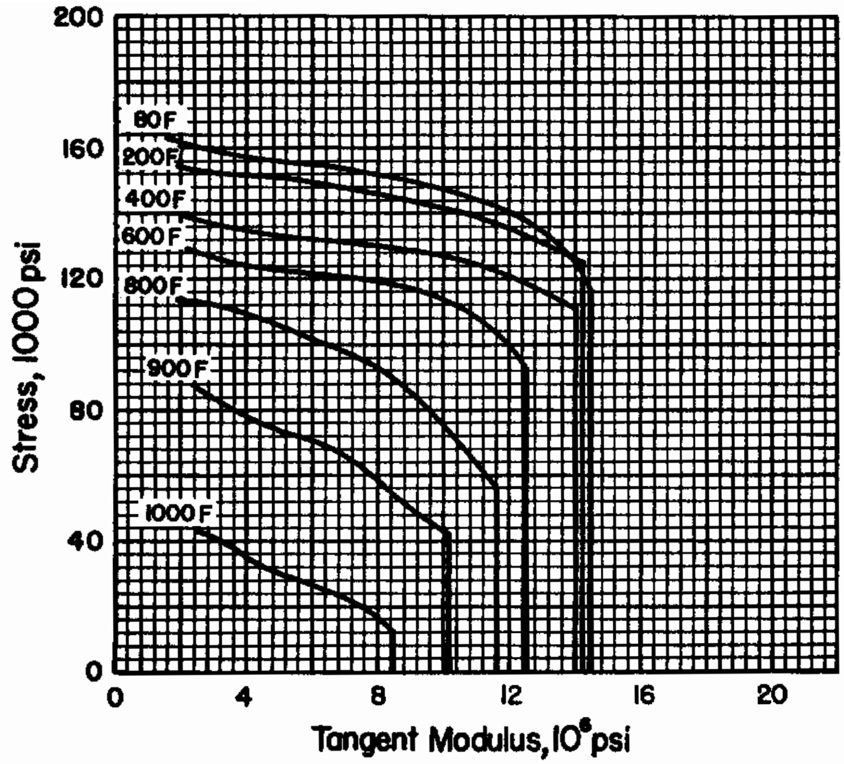

FIGURE 5.2.6.1.4(j). Typical longitudinal tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

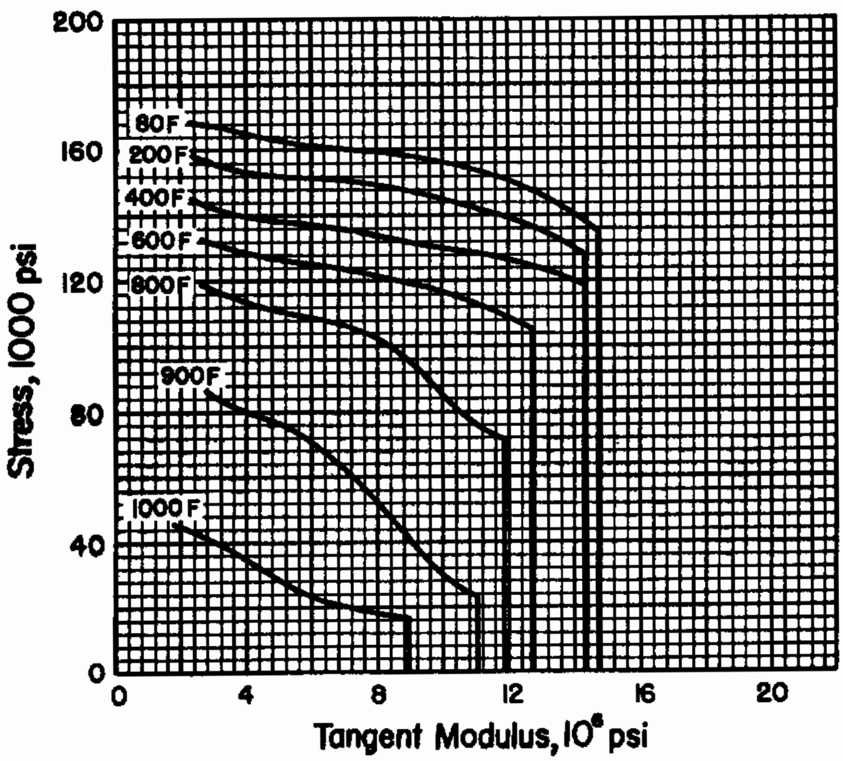

FIGURE 5.2.6.1.4(k). Typical transverse tensile tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

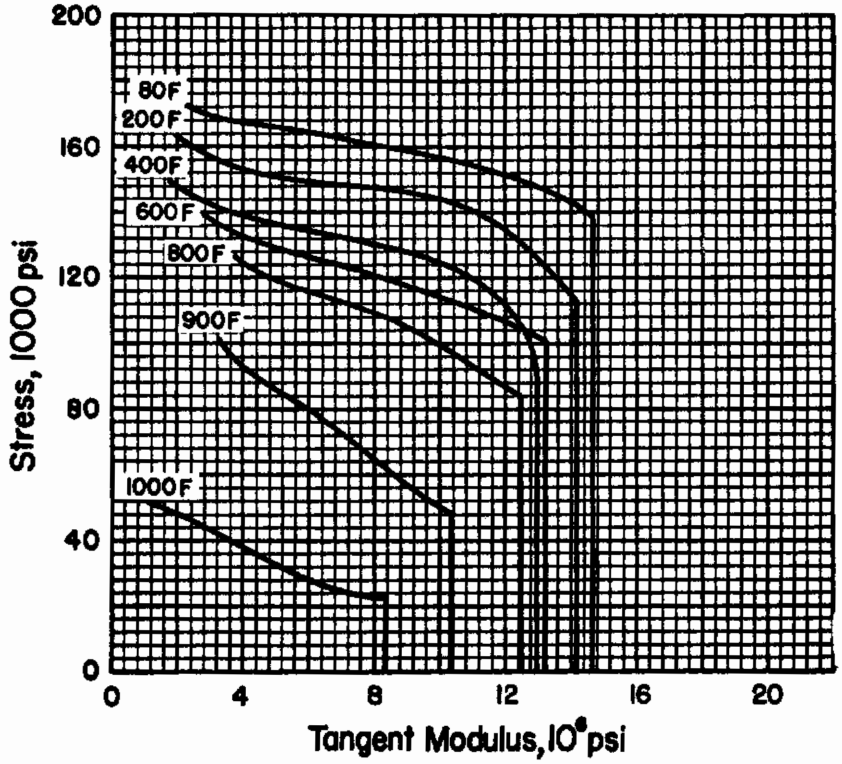

FIGURE 5.2.6.1.4(l). Typical longitudinal compressive tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

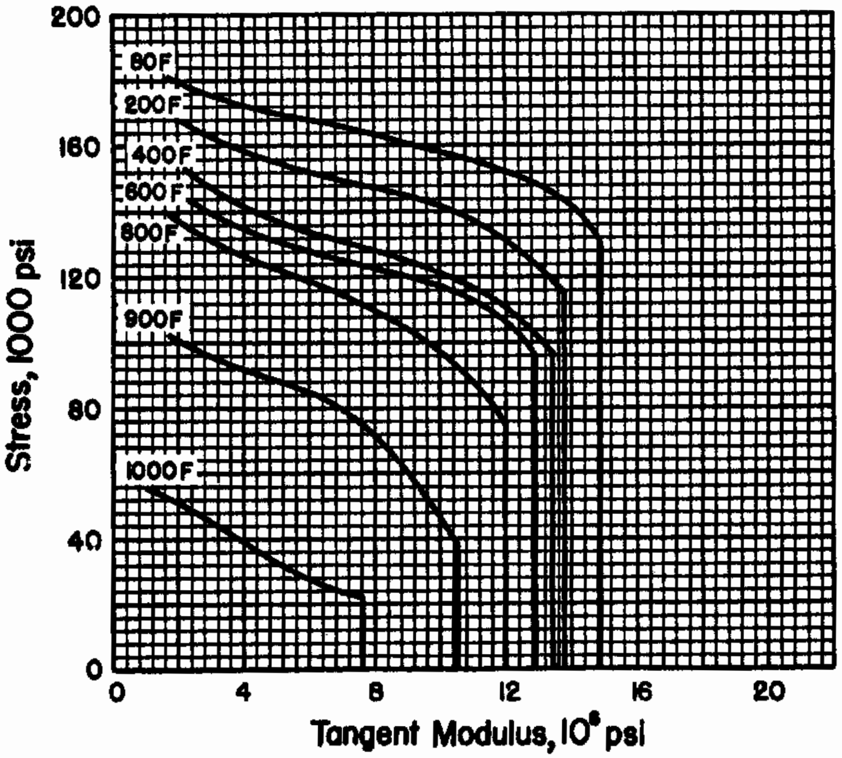

FIGURE 5.2.6.1.4(m). Typical transverse compressive tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

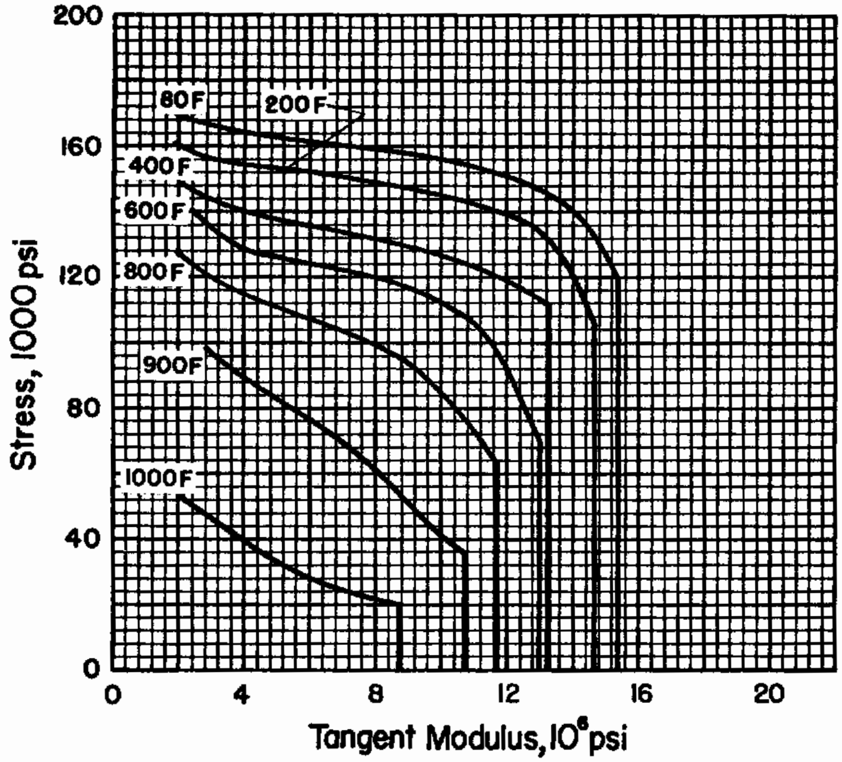

FIGURE 5.2.6.1.4(n). Typical longitudinal compressive tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

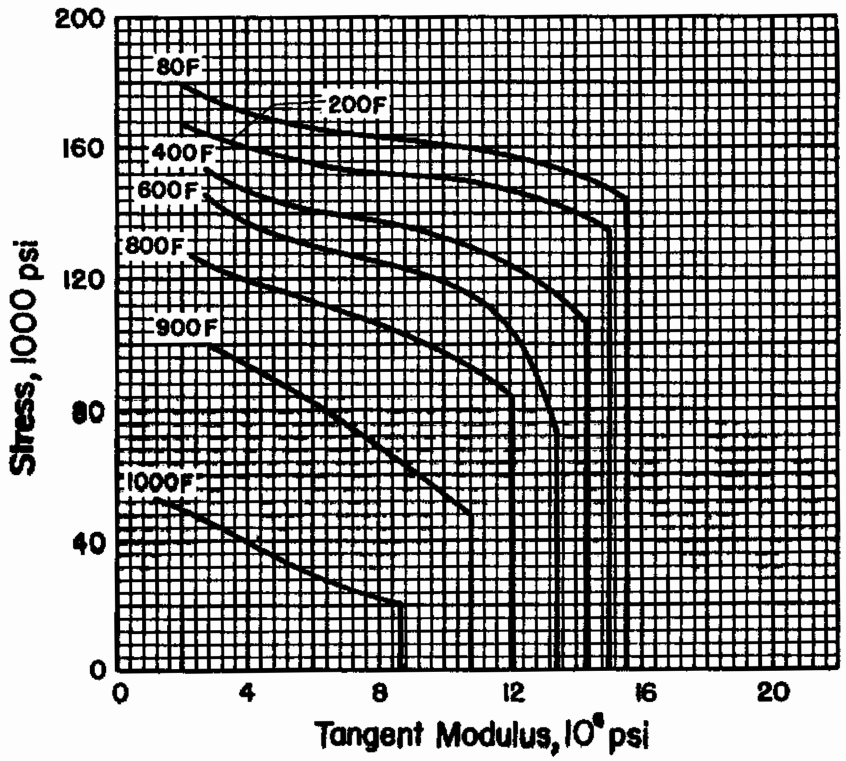

FIGURE 5.2.6.1.4(o). Typical transverse compressive tangent-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

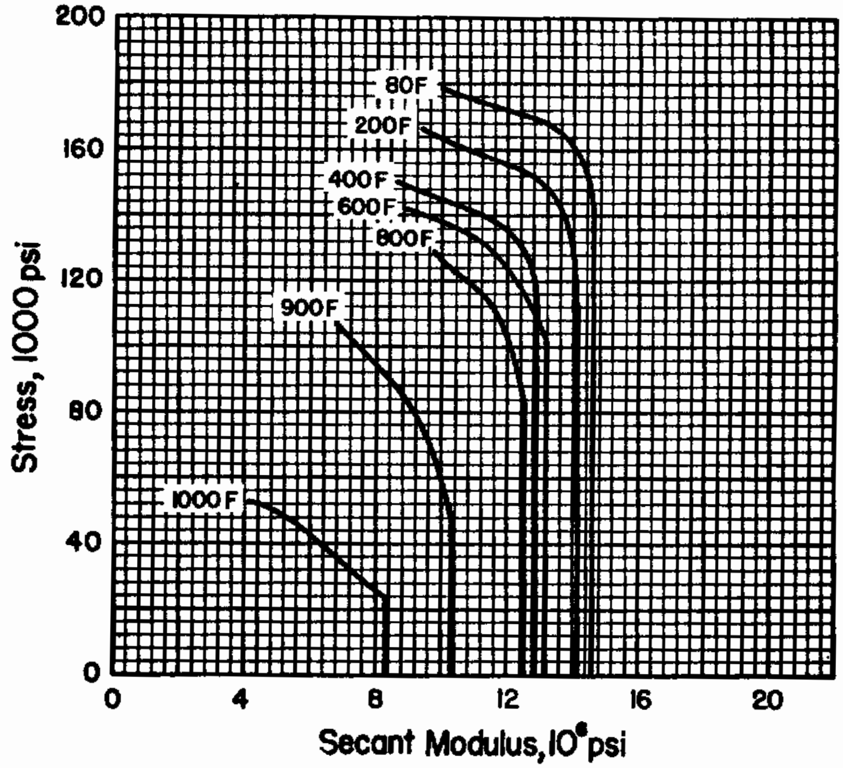

FIGURE 5.2.6.1.4(p). Typical longitudinal compressive secant-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

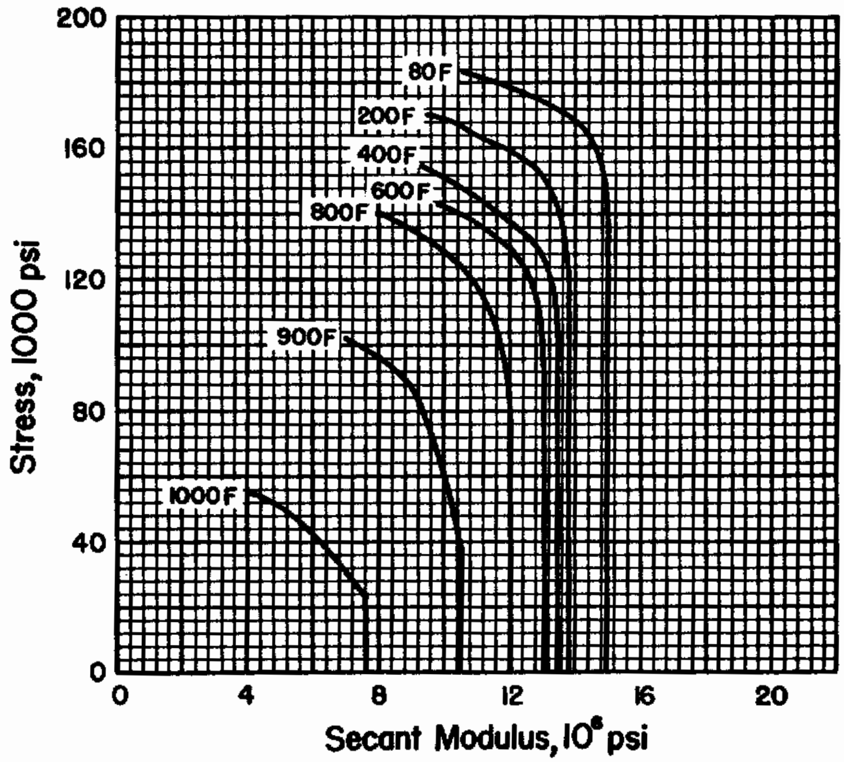

FIGURE 5.2.6.1.4(q). Typical transverse compressive secant-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

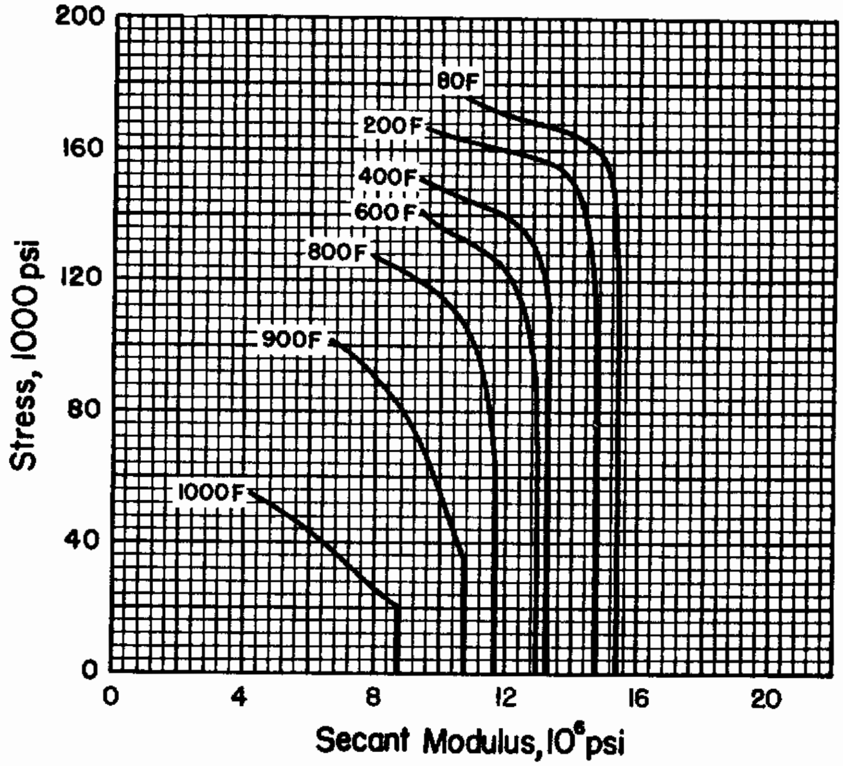

FIGURE 5.2.6.1.4(r). Typical longitudinal compressive secant-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

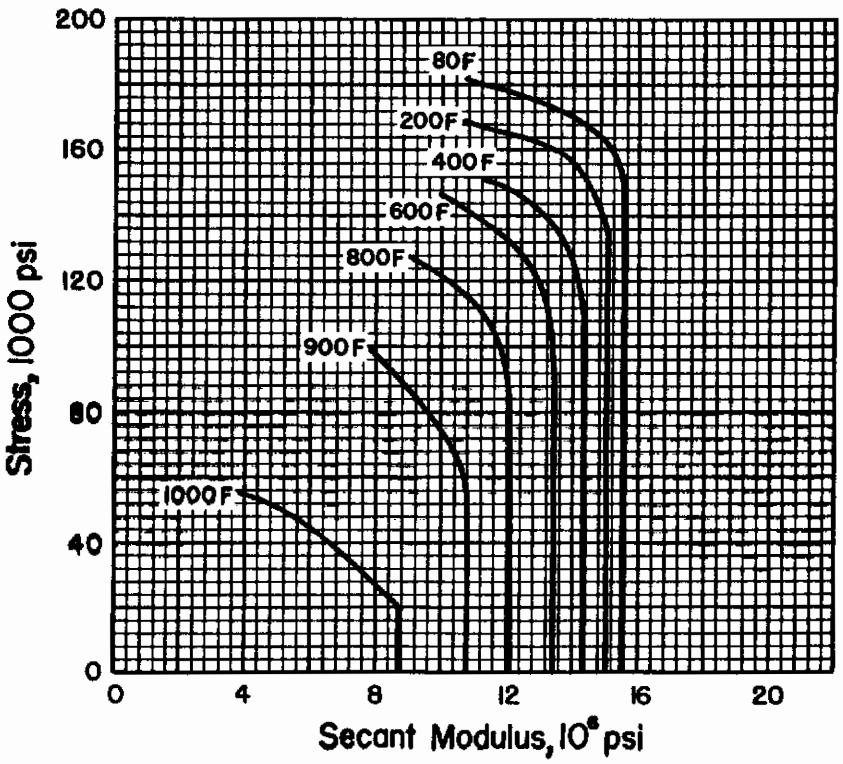

FIGURE 5.2.6.1.4(s). Typical transverse compressive secant-modulus curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

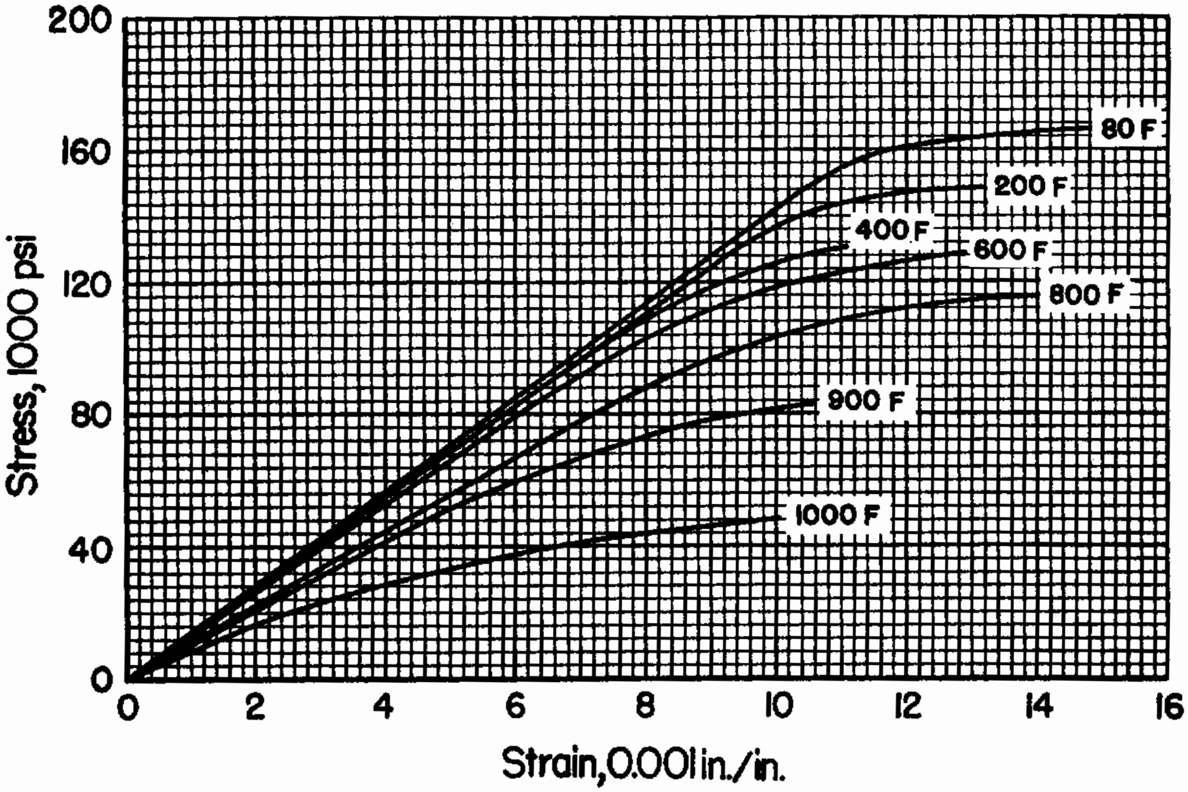

FIGURE 5.2.6.1.5(a). Typical longitudinal tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

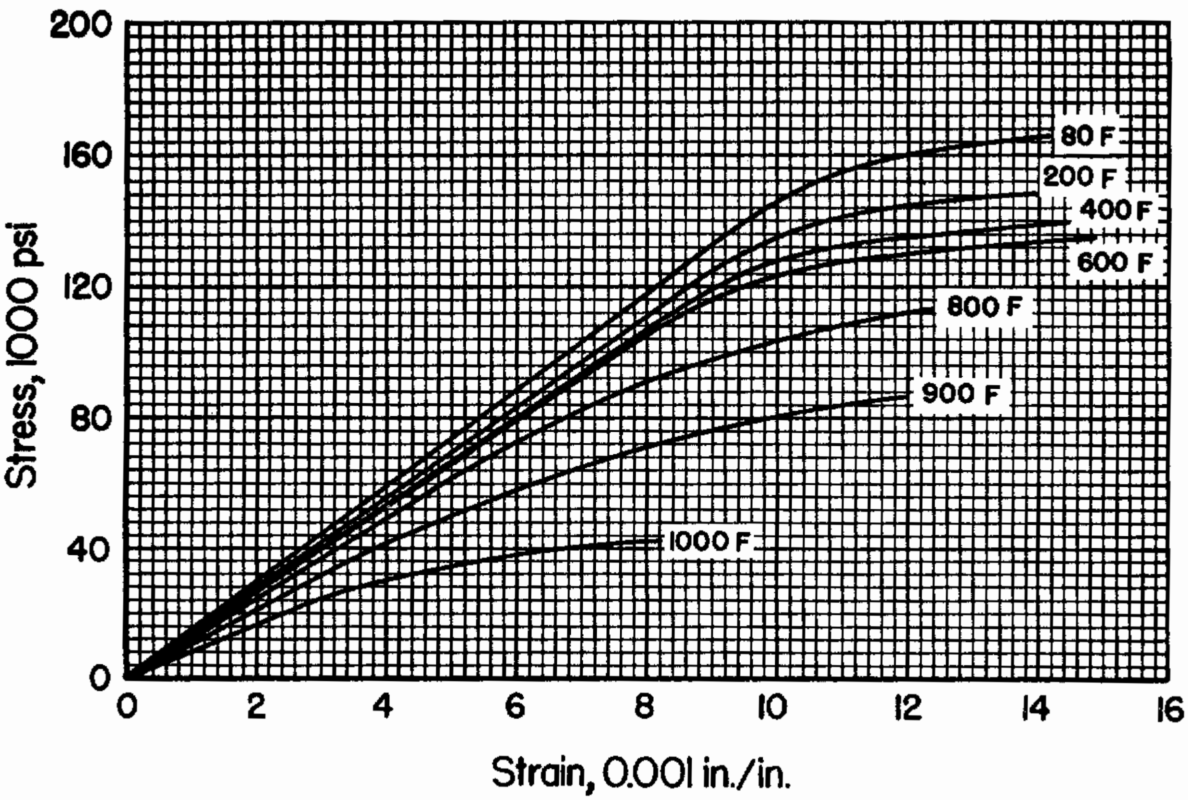

FIGURE 5.2.6.1.5(b). Typical transverse tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.020 inch thick sheet).

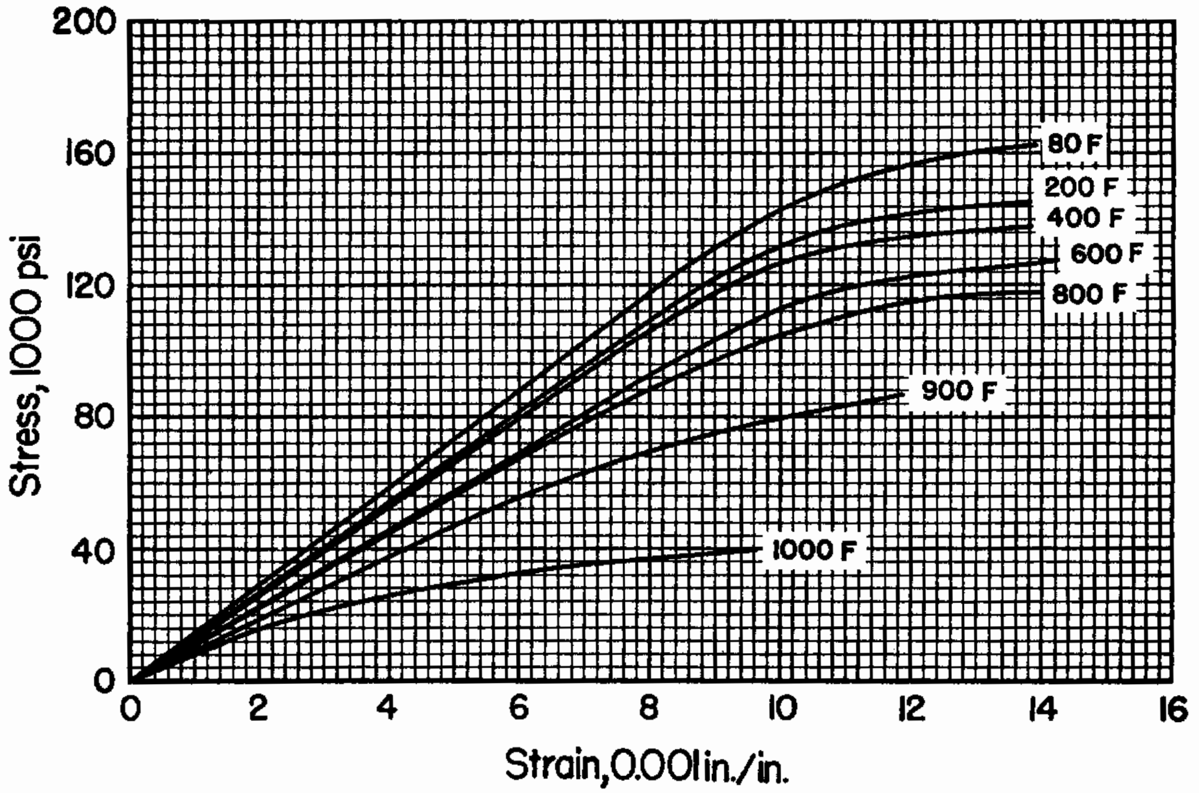

FIGURE 5.2.6.1.5(c). Typical longitudinal tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

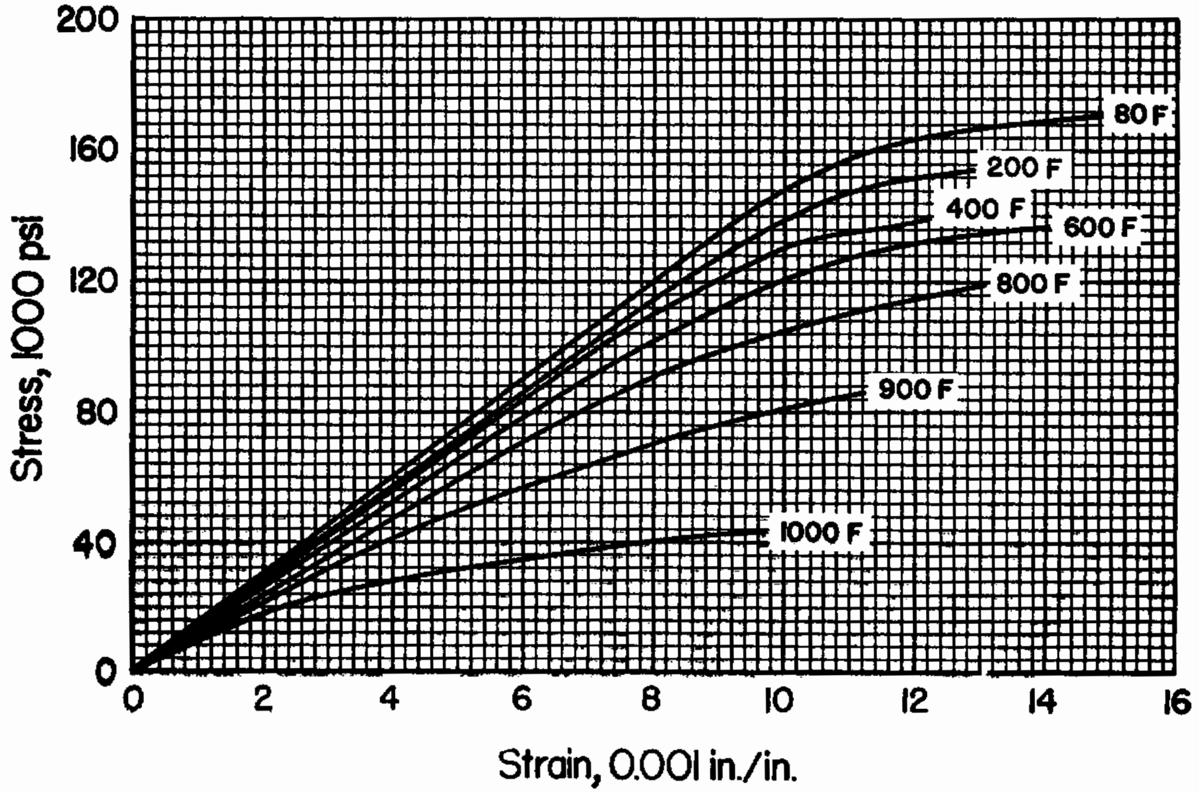

FIGURE 5.2.6.1.5(d). Typical transverse tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

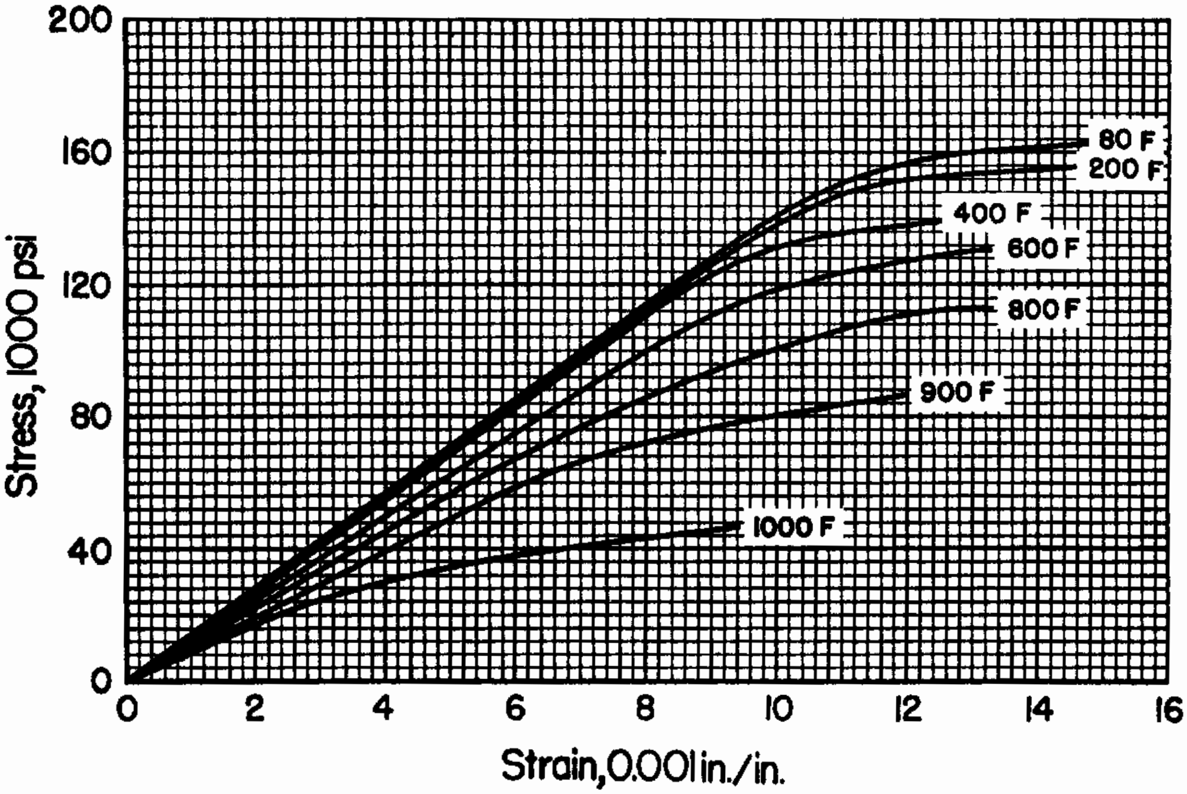

FIGURE 5.2.6.1.5(e). Typical longitudinal tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

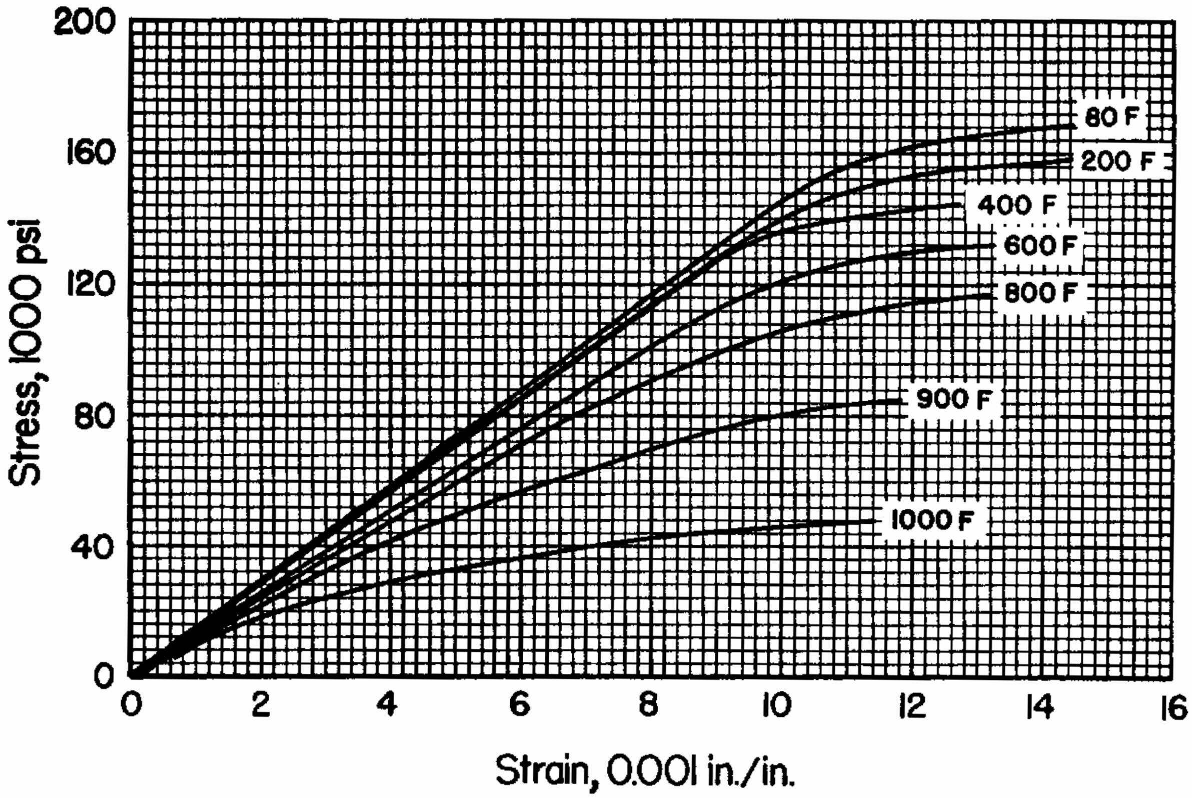

FIGURE 5.2.6.1.5(f). Typical transverse tensile stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

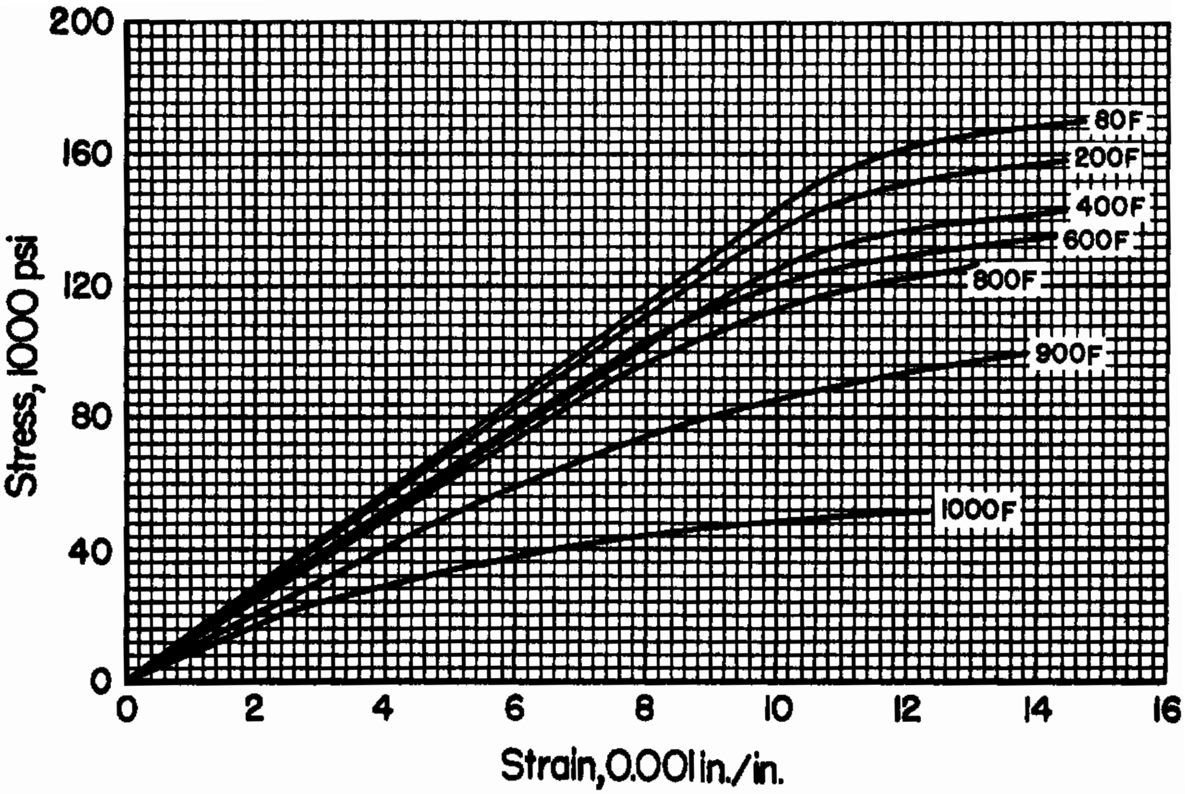

FIGURE 5.2.6.1.5(g). Typical longitudinal compressive stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

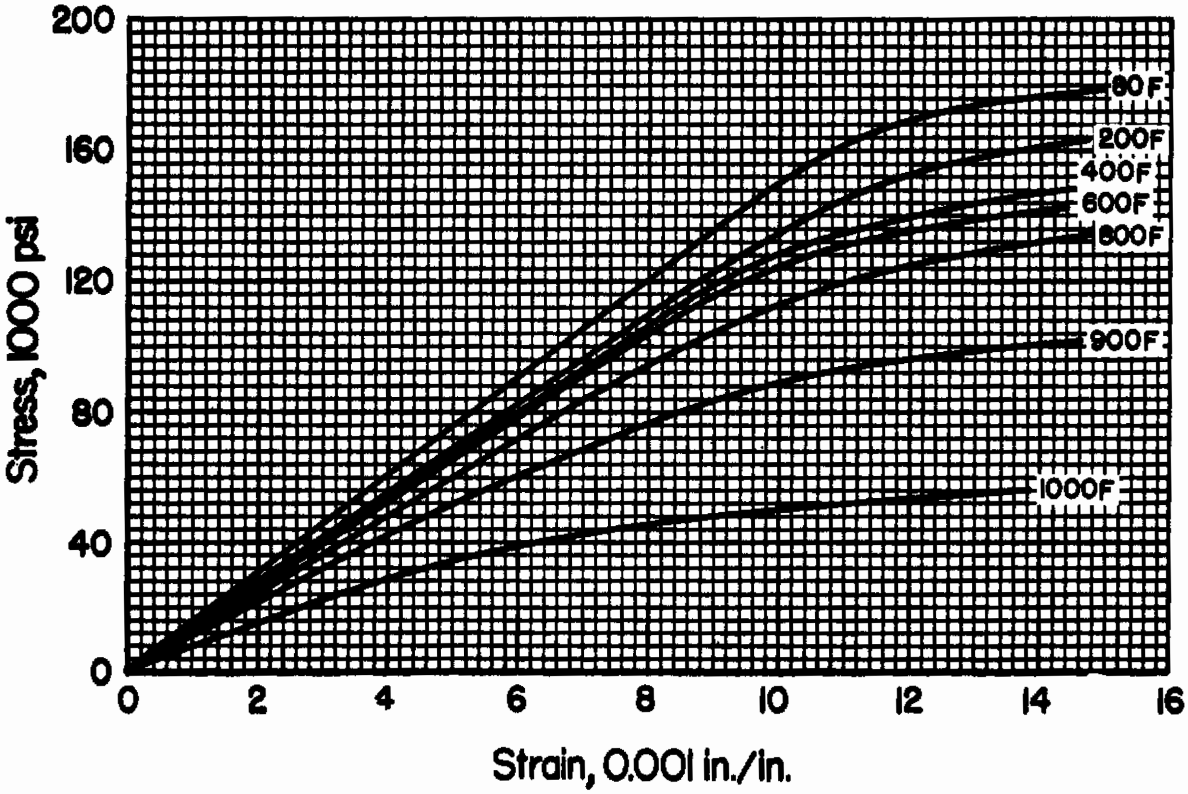

FIGURE 5.2.6.1.5(h). Typical transverse compressive stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet).

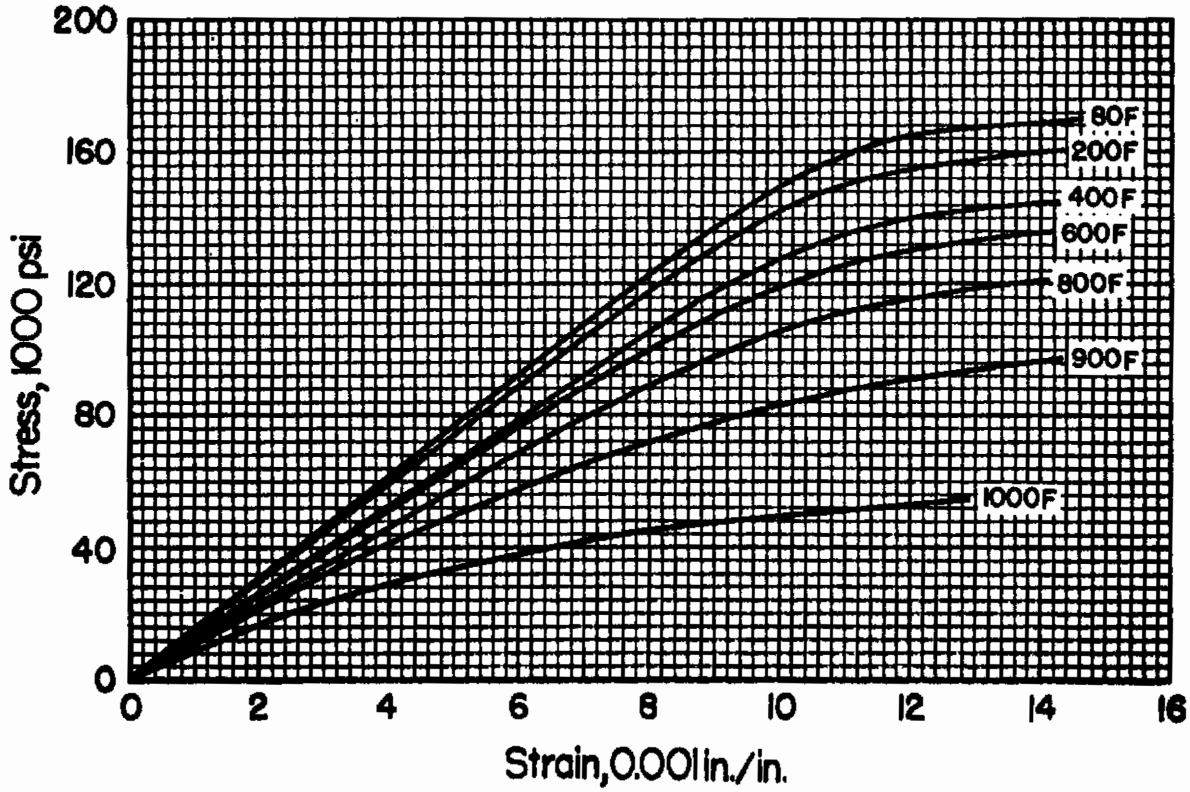

FIGURE 5.2.6.1.5(i). Typical longitudinal compressive stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

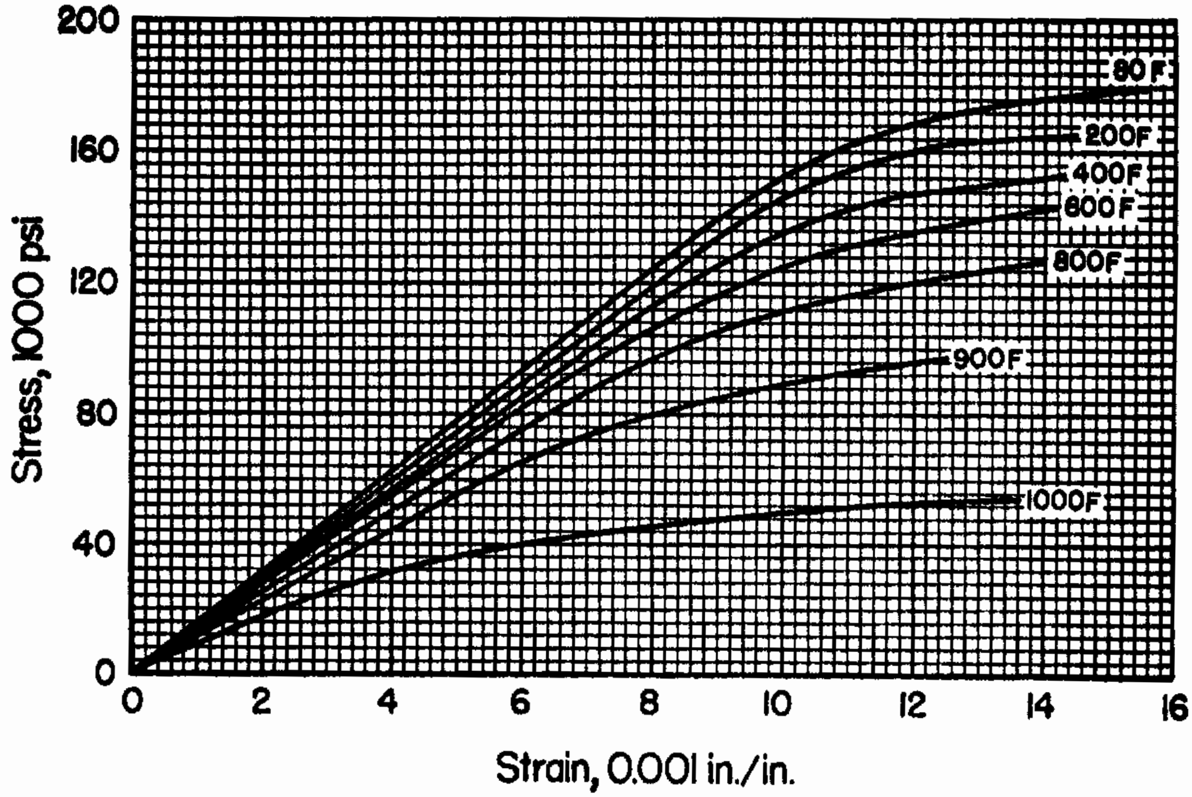

FIGURE 5.2.6.1.5(j). Typical transverse compressive stress-strain curves for 2.5Al-16V solution treated and aged titanium alloy (0.125 inch thick sheet).

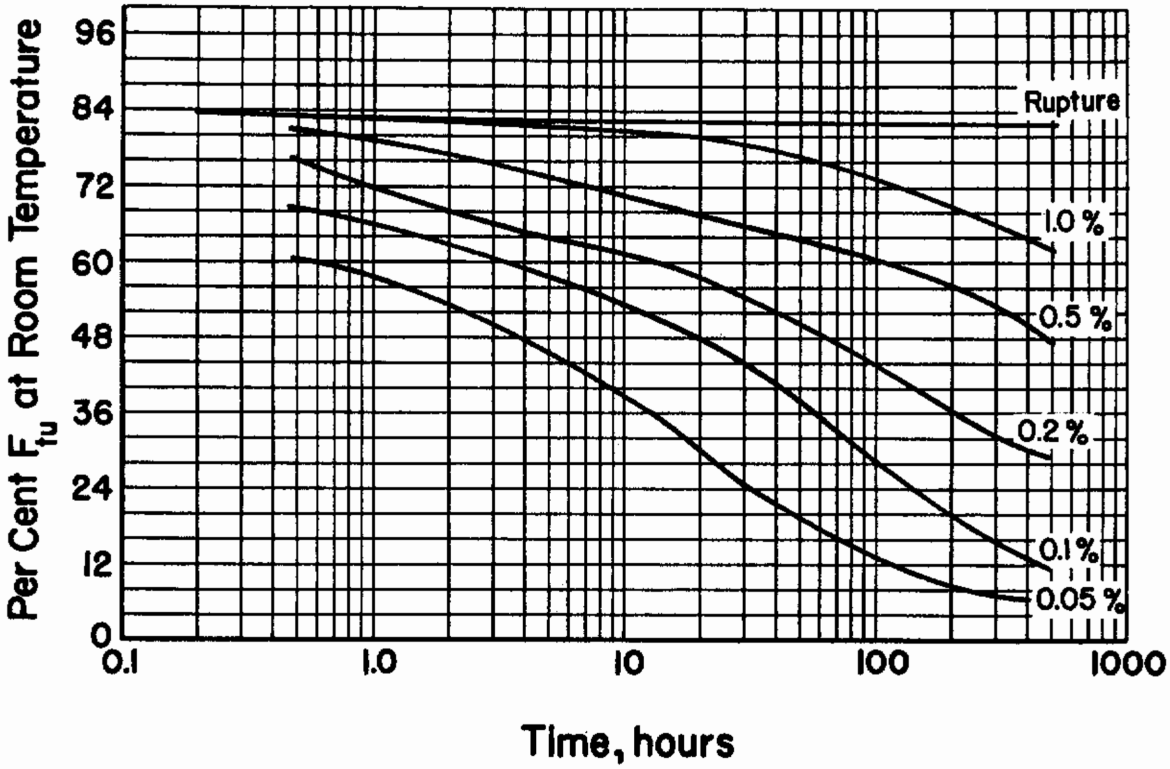

FIGURE 5.2.6.1.6(a). Creep and rupture data for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet) at 600°F.

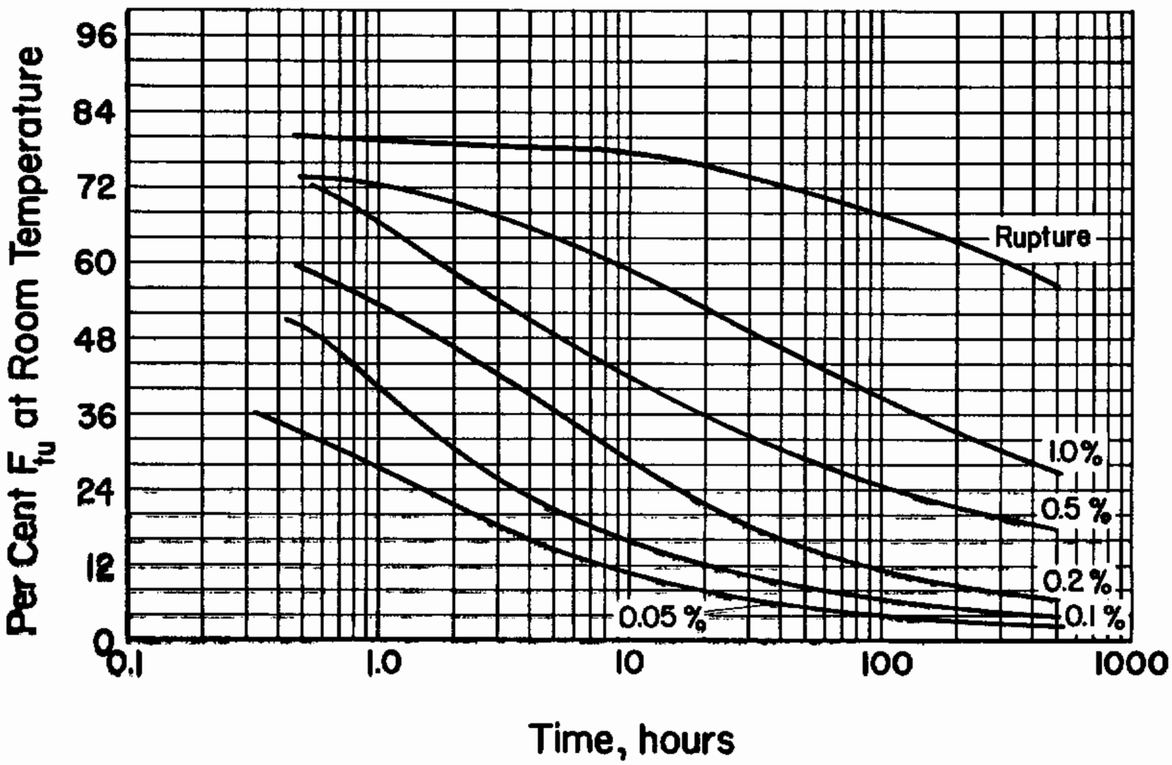

FIGURE 5.2.6.1.6(b). Creep and rupture data for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet) at 700°F.

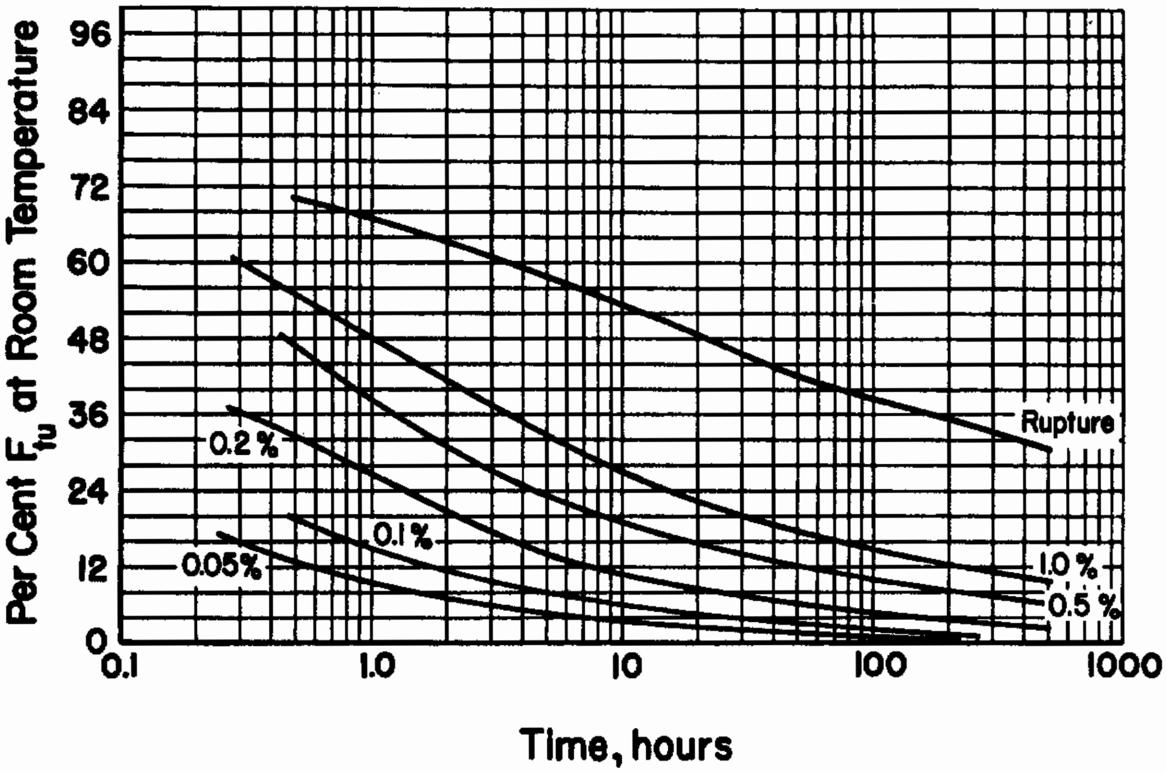

FIGURE 5.2.6.1.6(c). Creep and rupture data for 2.5Al-16V solution treated and aged titanium alloy (0.063 inch thick sheet) at 800°F.

5.2.9 13V-11Cr-3Al Titanium Alloy

5.2.9.0 Comments and Properties

Room-temperature mechanical and physical properties are shown in Table 5.2.9.0(a). Effect on tensile properties of long-time exposure to elevated temperature is given in Tables 5.2.9.0(b) and (c). The temper index for 13V-11Cr-3Al titanium alloy is as follows:

Section	Temper or Condition
5.2.9.1	Solution treated and aged

For solution treated and aged material reported herein, some variations in processing history were noted. The heat treatments included are:

1450F for 30 min., A. C. - 900F for 36 hrs., 1000F for 10 min., A. C.
1450F for 30 min., A. C. - 900F for 90 hrs.
1450F for 30 min., A. C. - 900F for 72 hrs.
1450F for 20 min., A. C. - 900F for 72 hrs.
1450F for 20 min., A. C. - 900F for 60 hrs.

TABLE 5.2.9.0(a) DESIGN MECHANICAL AND PHYSICAL PROPERTIES OF 13V-11Cr-3Al TITANIUM ALLOY

Alloy....................	13V-11Cr-1V		
Form....................	Sheet		
Condition...............	Solution Treated and Aged		
Thickness (in.)..........	0.020	0.063	0.125
Basis...................	B	B	B
Mechanical Properties:			
F_{tu}, ksi			
L..................	167	175	173
T..................	175	178	179
F_{ty}, ksi			
L..................	161	161	157
T..................	163	164	164
F_{cy}, ksi			
L..................	..	165	159
T..................	..	166	169
F_{su}, ksi			
L..................	108	108	108
T..................	110	113	106
F_{bru}, ksi (e/D=1.5)			
L..................	253	257	262
T..................	252	263	267
F_{bru}, ksi (e/D=2.0)			
L..................	315	329	337
T..................	313	335	335
F_{bry}, ksi (e/D=1.5)			
L..................	224	226	225
T..................	225	221	233
F_{bry}, ksi (e/D=2.0)			
L..................	247	251	260
T..................	244	252	265
e, percent(a)			
L..................	2.5	5.7	6.5
T..................	2.4	4.8	5.0
E, 10^6 psi			
L..................	14.8	14.6	14.8
T..................	15.6	15.1	15.3
E_c, 10^6 psi			
L..................	..	15.2	15.3
T..................	..	15.7	15.8
Physical Properties:			
ω, lb/in.^{3}..............	0.174		
C, Btu/(lb)(F)...........	0.126 (at 75°F)		
K, Btu/[(hr)(ft^2)(F)/ft].	4.6 (at 70°F)		
α, 10^{-6} in./in./F........	5.3 (100° to 200°F		

(a) Elongations are average test values.

TABLE 5.2.9.0(b) EFFECT OF 500-HOUR EXPOSURE AT 600°F ON THE TENSILE PROPERTIES OF 13V-11Cr-3Al TITANIUM ALLOY

Condition	Solution Treated and Aged		
Thickness (in.)	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L	169	189	177
T	169	183	181
F_{ty}, ksi (at room temp.)			
L	156	175	165
T	158	168	166
F_{tu}, ksi (at 600°F)			
L	154	167	164
T	158	161	156
F_{ty}, ksi (at 600°F)			
L	132	141	137
T	133	137	133
Exposed at temperature while stressed to 1/3 average 600°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L	167	177	184
T	165	178	178
F_{ty}, ksi (at room temp.)			
L	164	169	170
T	156	166	162
F_{tu}, ksi (at 600°F)			
L	156	158	165
T	160	157	159
F_{ty}, ksi (at 600°F)			
L	136	136	140
T	135	134	135

TABLE 5.2.9.0(c) EFFECT OF 10-HOUR EXPOSURE AT 900°F ON THE TENSILE PROPERTIES OF 13V-11Cr-3Al TITANIUM ALLOY

Condition....................	Solution Treated and Aged		
Thickness (in.)..............	0.020	0.063	0.125
Exposed at temperature in the unstressed condition:			
F_{tu}, ksi (at room temp.)			
L....................	168	187	181
T....................	165	178	178
F_{ty}, ksi (at room temp.)			
L....................	164	175	165
T....................	159	164	164
F_{tu}, ksi (at 900°F)			
L....................	141	144	140
T....................	156	139	142
F_{ty}, ksi (at 900°F)			
L....................	115	124	118
T....................	120	119	118
Exposed at temperature while stressed to 1/3 average 900°F ultimate tensile stress:			
F_{tu}, ksi (at room temp.)			
L....................	154	191	183
T....................	170	182	180
F_{ty}, ksi (at room temp.)			
L....................	..	178	170
T....................	164	174	169
F_{tu}, ksi (at 900°F)			
L....................	141	146	140
T....................	143	144	143
F_{ty}, ksi (at 900°F)			
L....................	122	125	121
T....................	121	123	122

5.2.9.1 Solution Treated and Aged Condition

Room and elevated temperature data for this condition are presented in Figures 5.2.9.1.1(a) through 5.2.9.1.5(j).

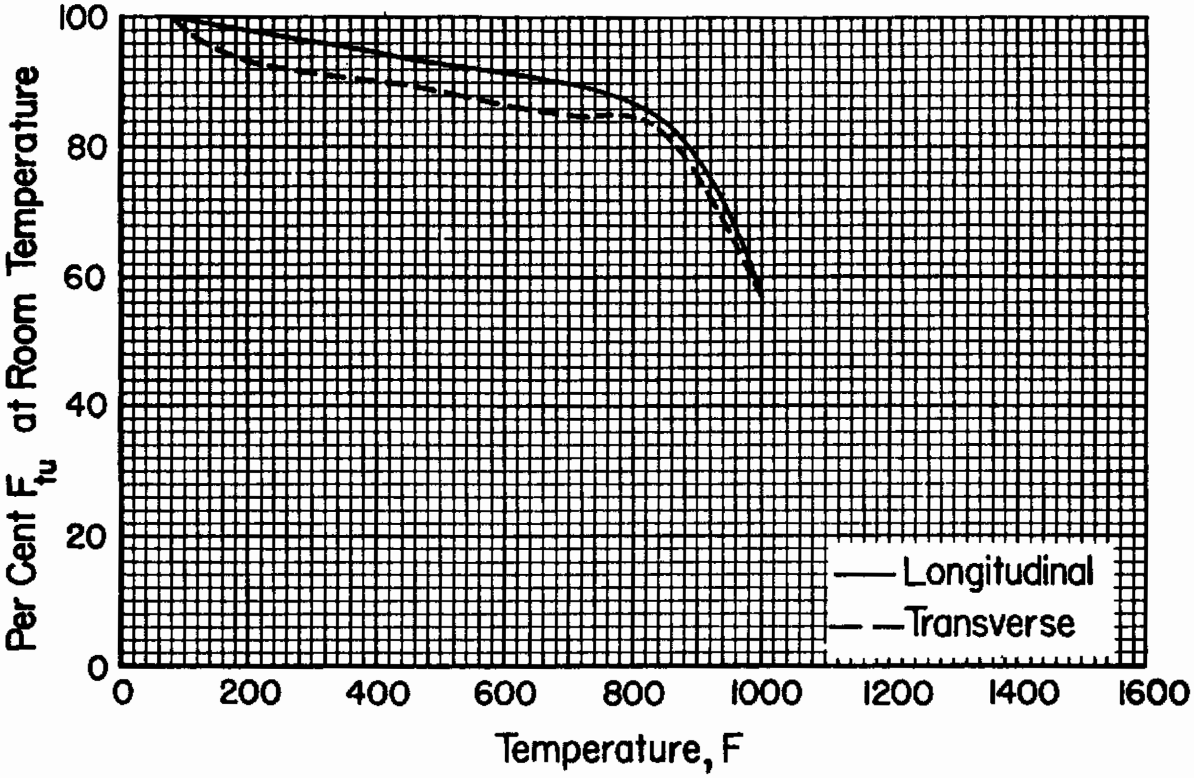

FIGURE 5.2.9.1.1(a). Effect of temperature on the ultimate tensile strength (F_{tu}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

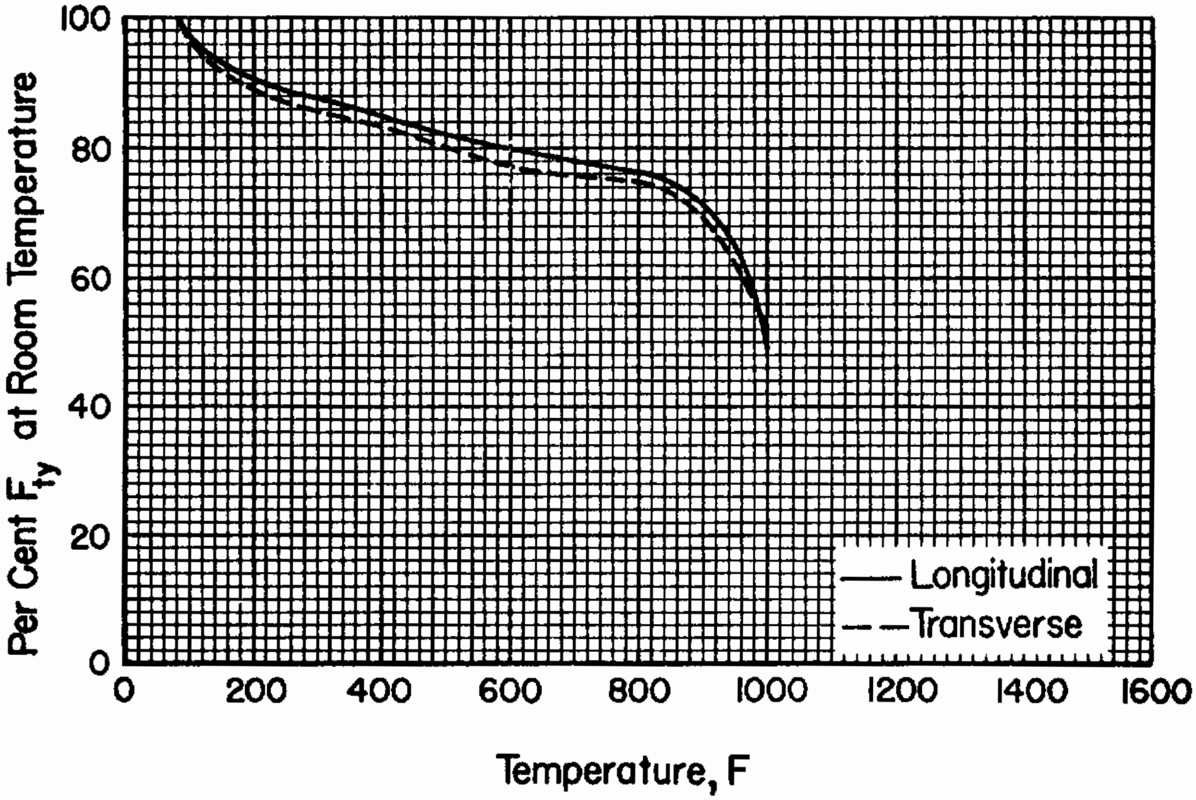

FIGURE 5.2.9.1.1(b). Effect of temperature on the tensile yield strength (F_{ty}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

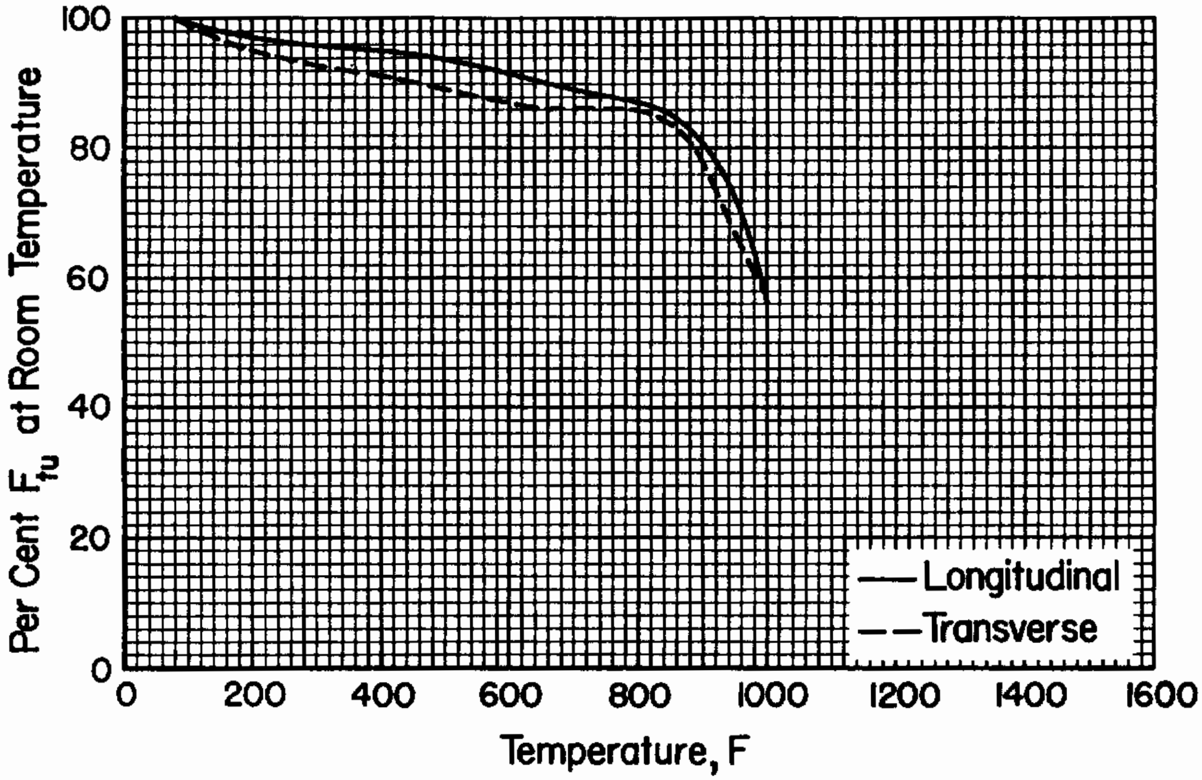

FIGURE 5.2.9.1.1(c). Effect of temperature on the ultimate tensile strength (F_{tu}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

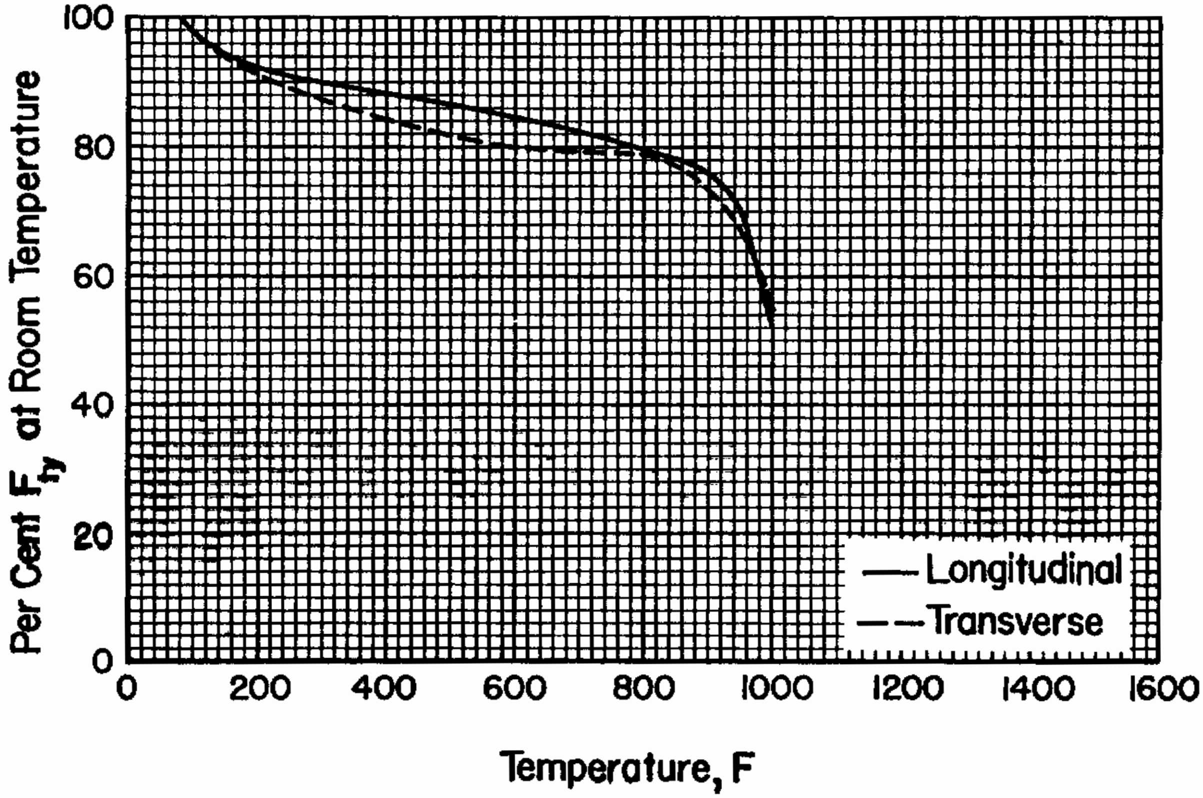

FIGURE 5.2.9.1.1(d). Effect of temperature on the tensile yield strength (F_{ty}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

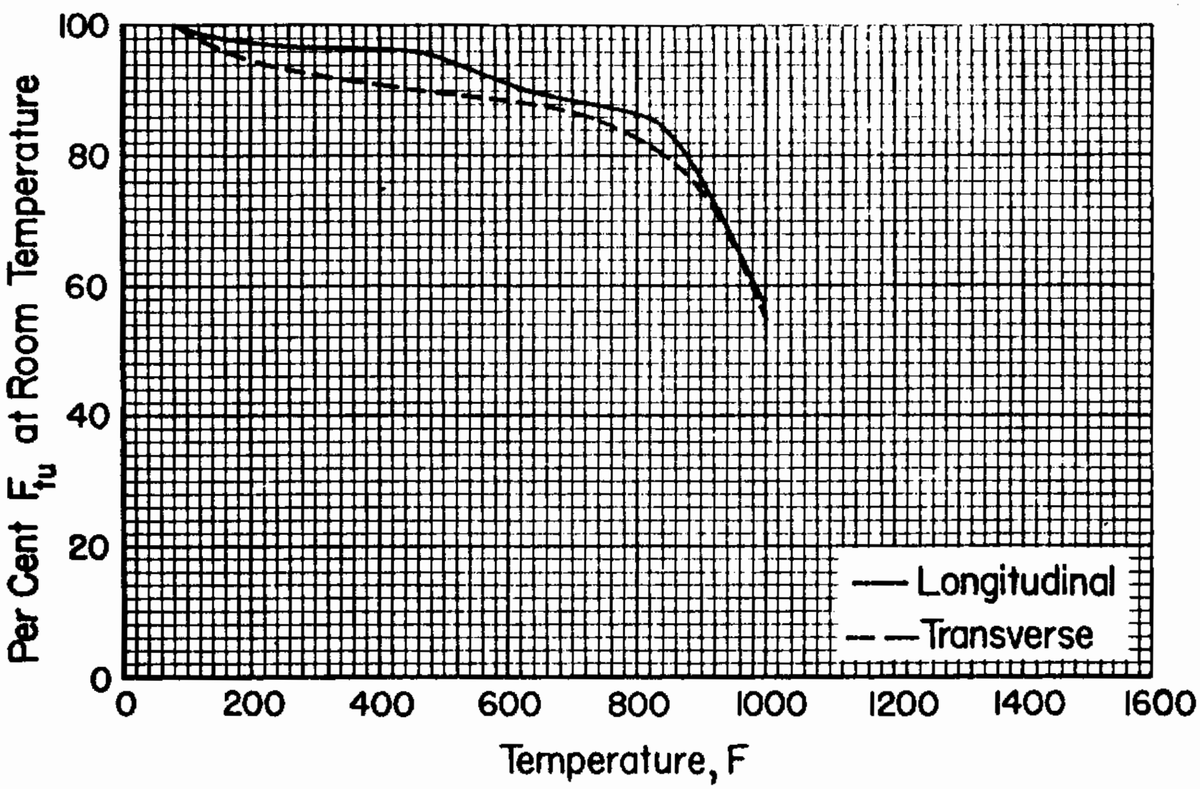

FIGURE 5.2.9.1.1(e). Effect of temperature on the ultimate tensile strength (F_{tu}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

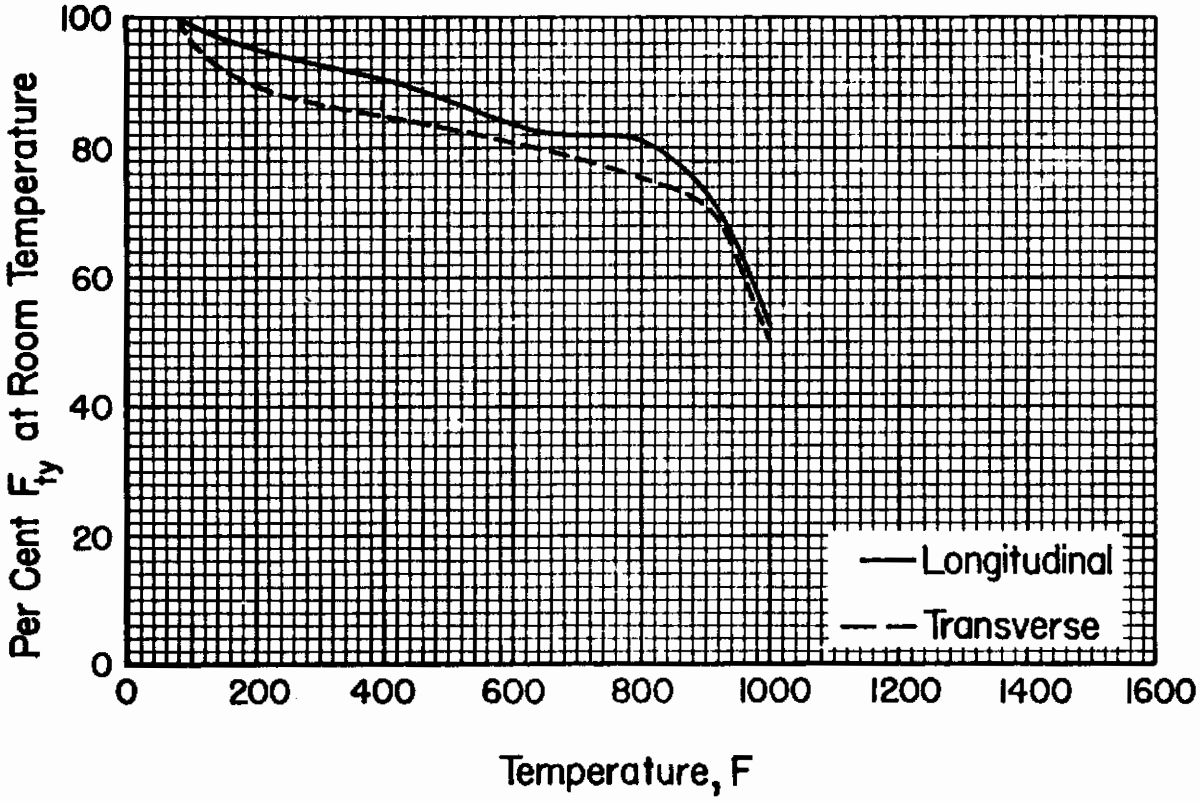

FIGURE 5.2.9.1.1(f). Effect of temperature on the tensile yield strength (F_{ty}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

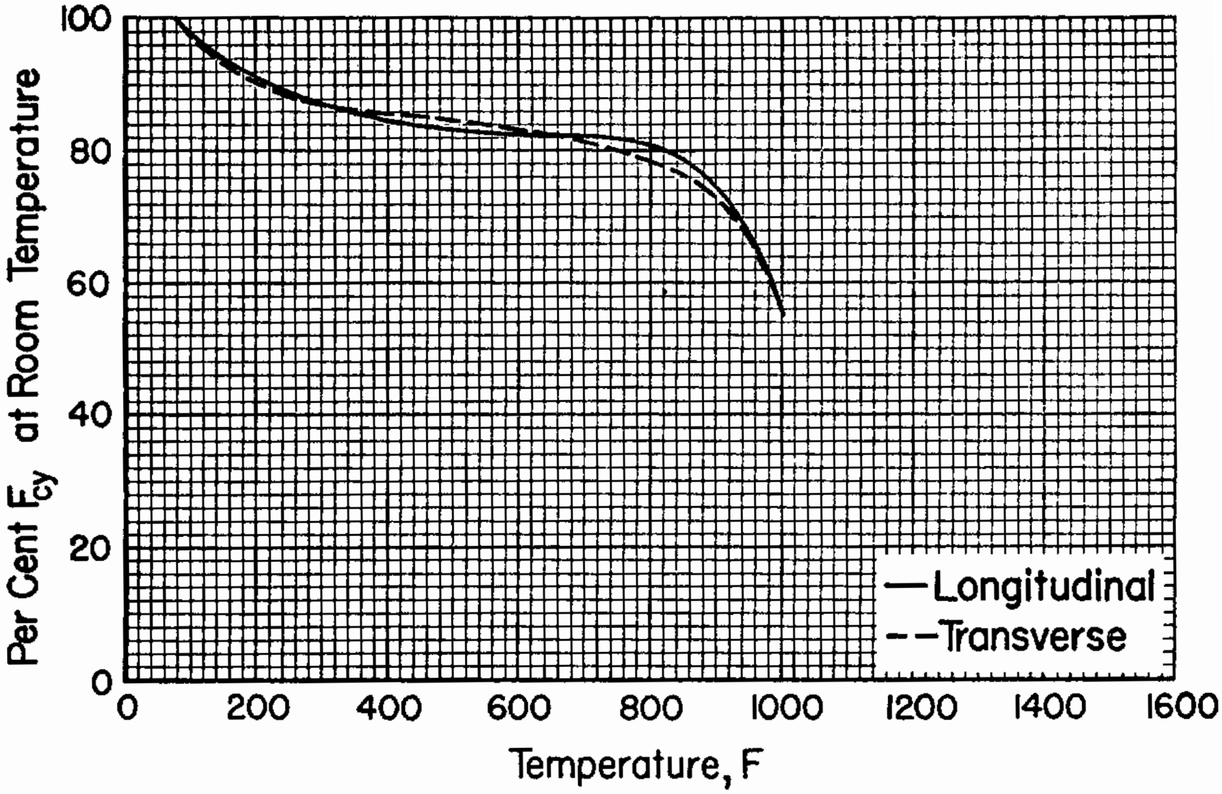

FIGURE 5.2.9.1.2(a). Effect of temperature on the compressive yield strength (F_{cy}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

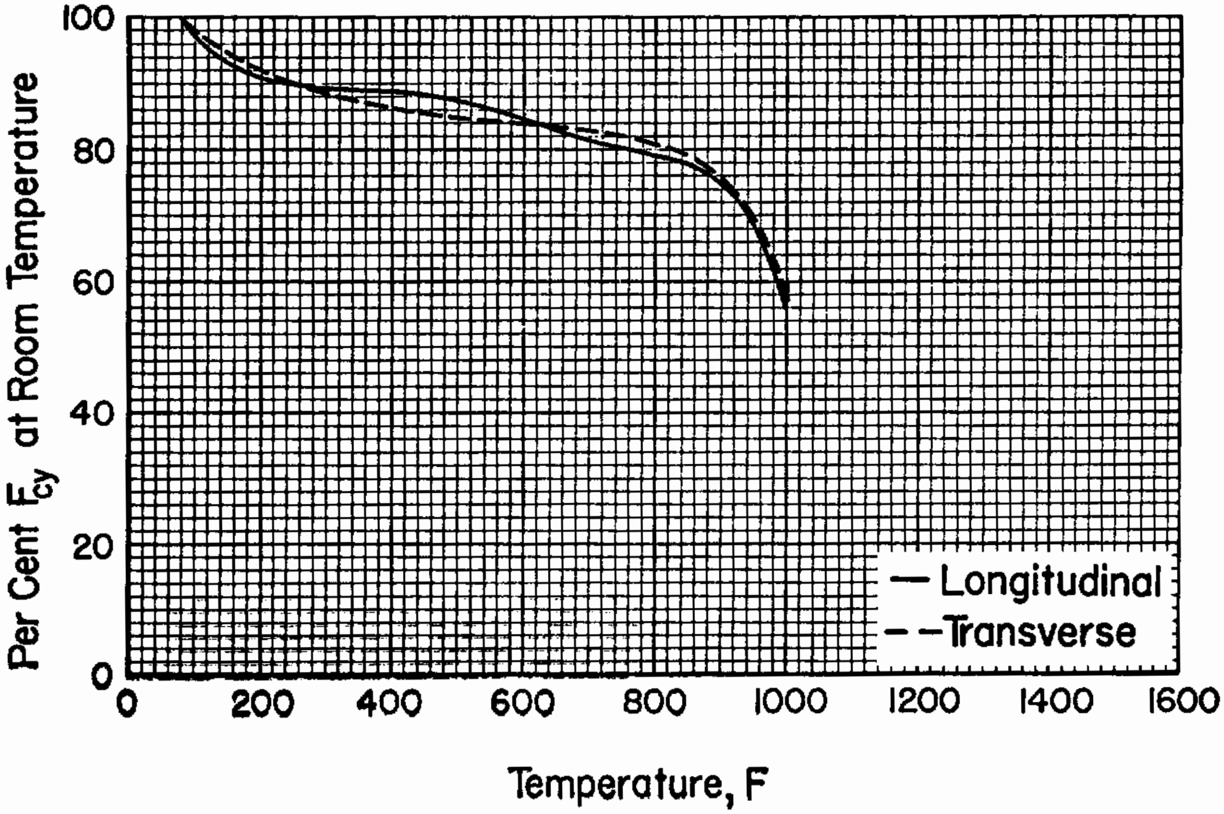

FIGURE 5.2.9.1.2(b). Effect of temperature on the compressive yield strength (F_{cy}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

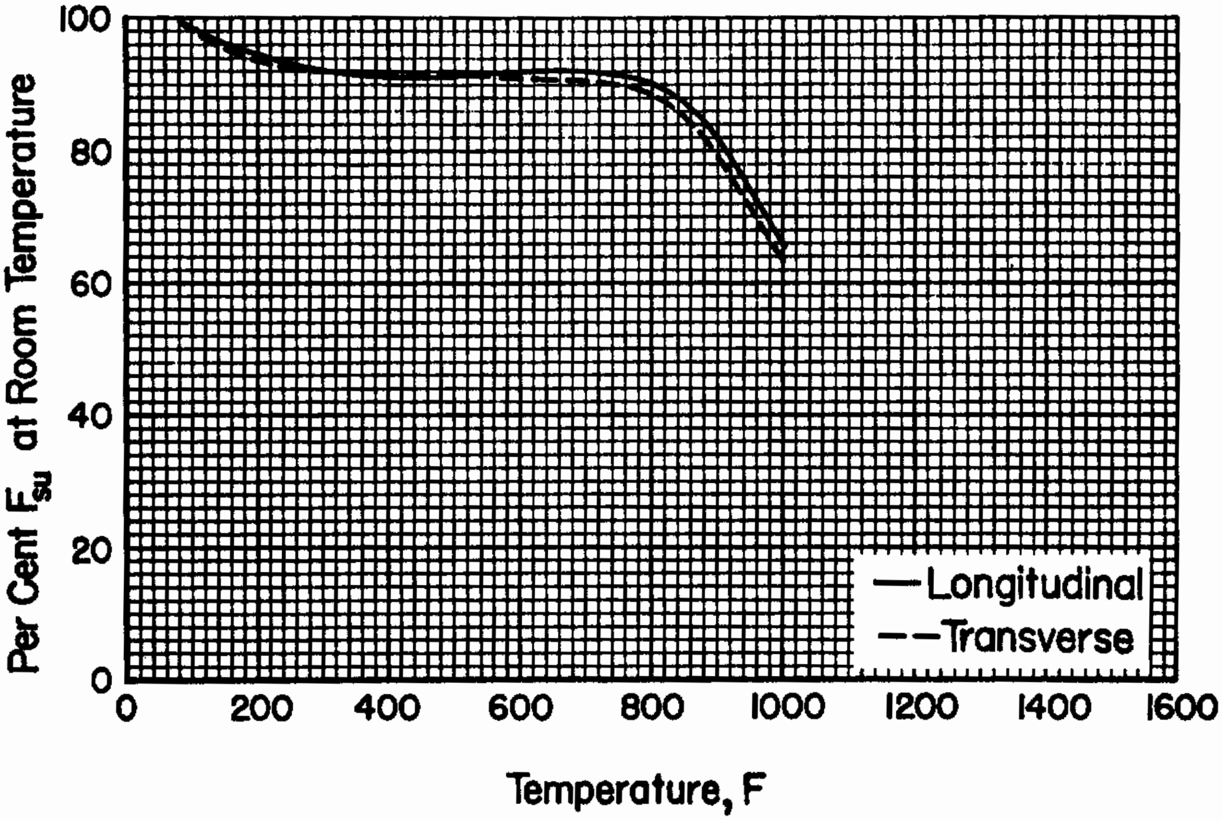

FIGURE 5.2.9.1.2(c). Effect of temperature on the ultimate shear strength (F_{su}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

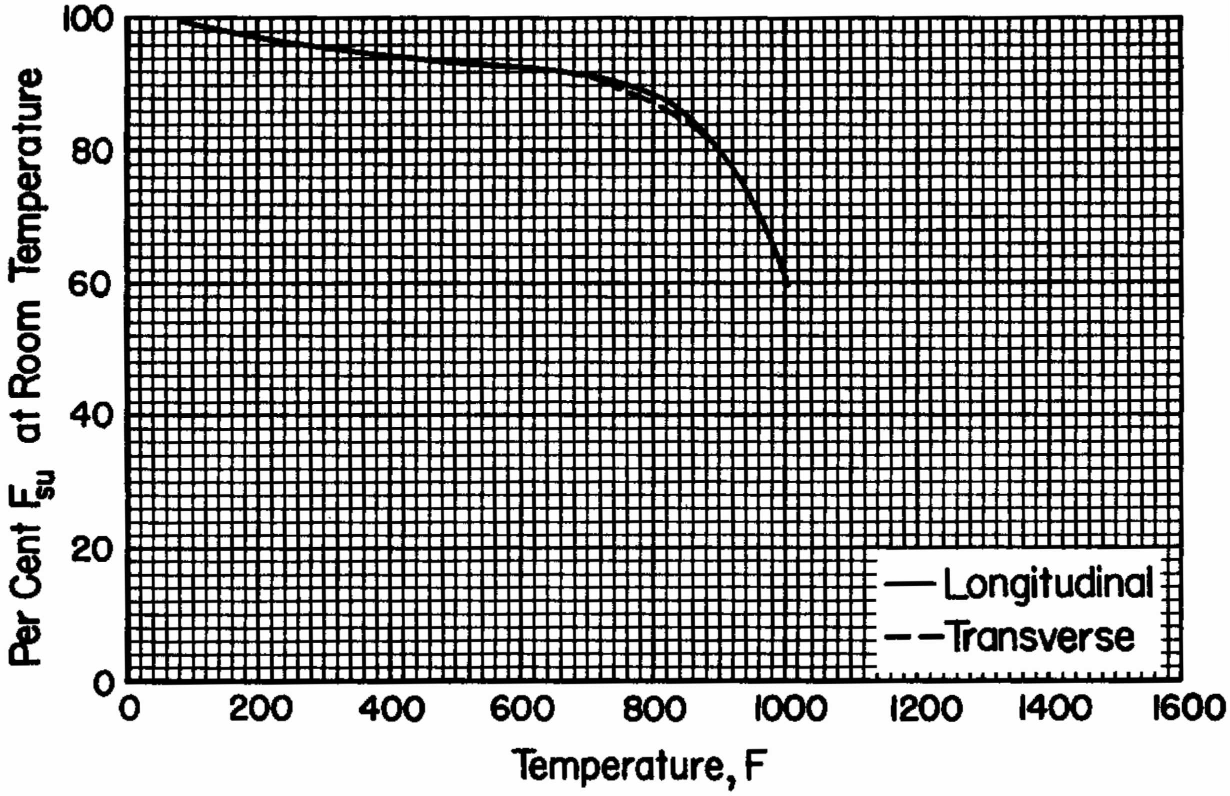

FIGURE 5.2.9.1.2(d). Effect of temperature on the ultimate shear strength (F_{su}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

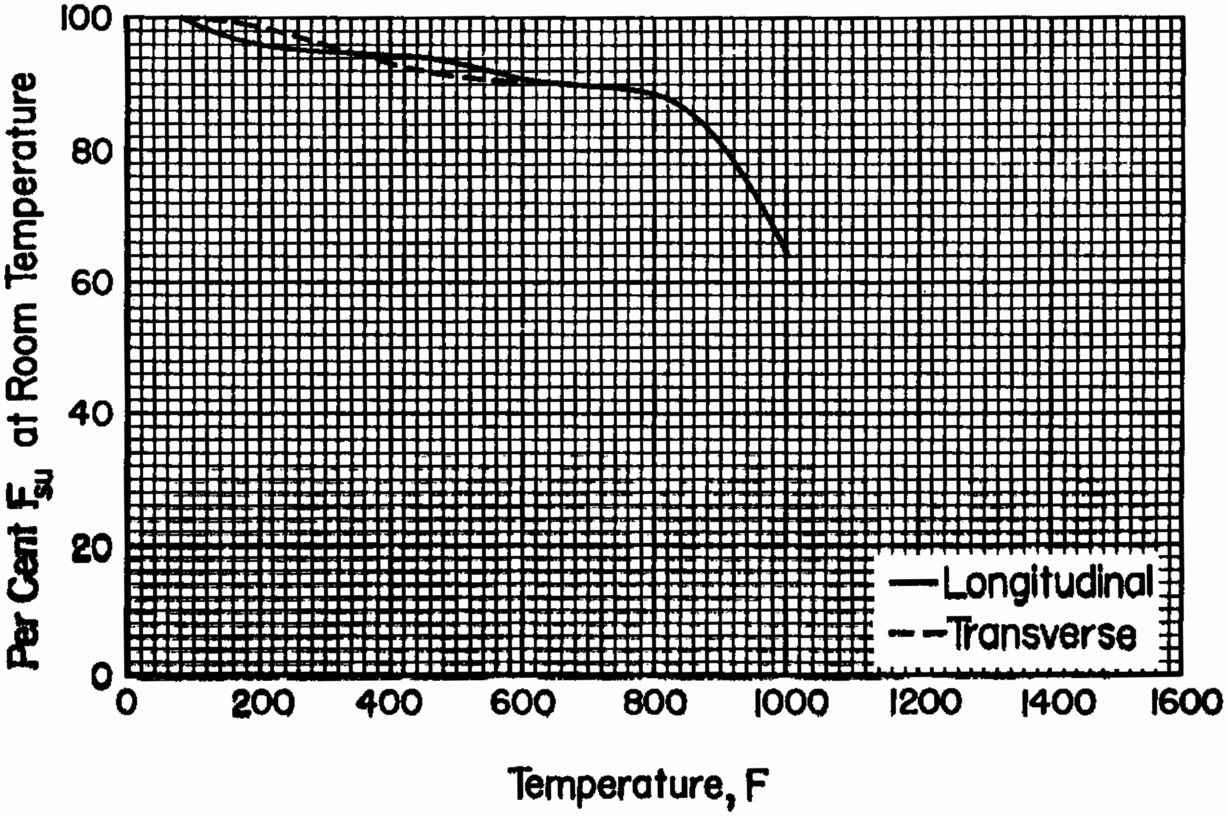

FIGURE 5.2.9.1.2(e). Effect of temperature on the ultimate shear strength (F_{su}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

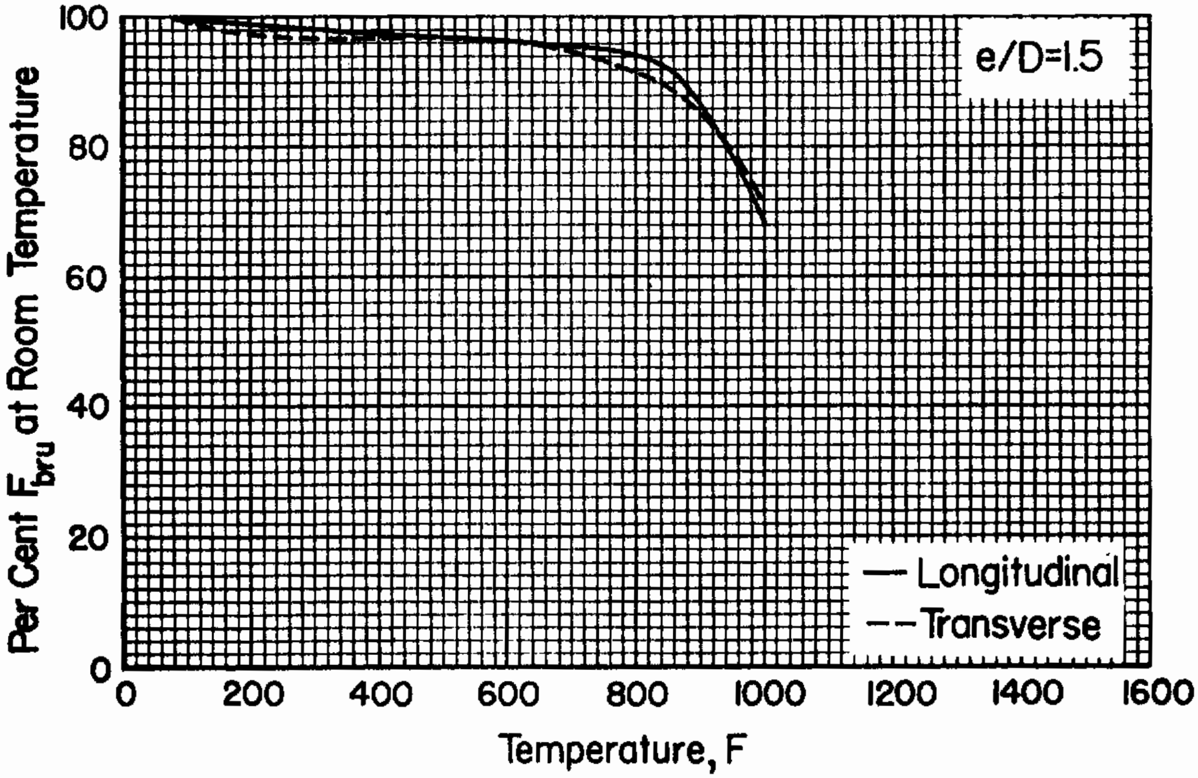

FIGURE 5.2.9.1.3(a). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

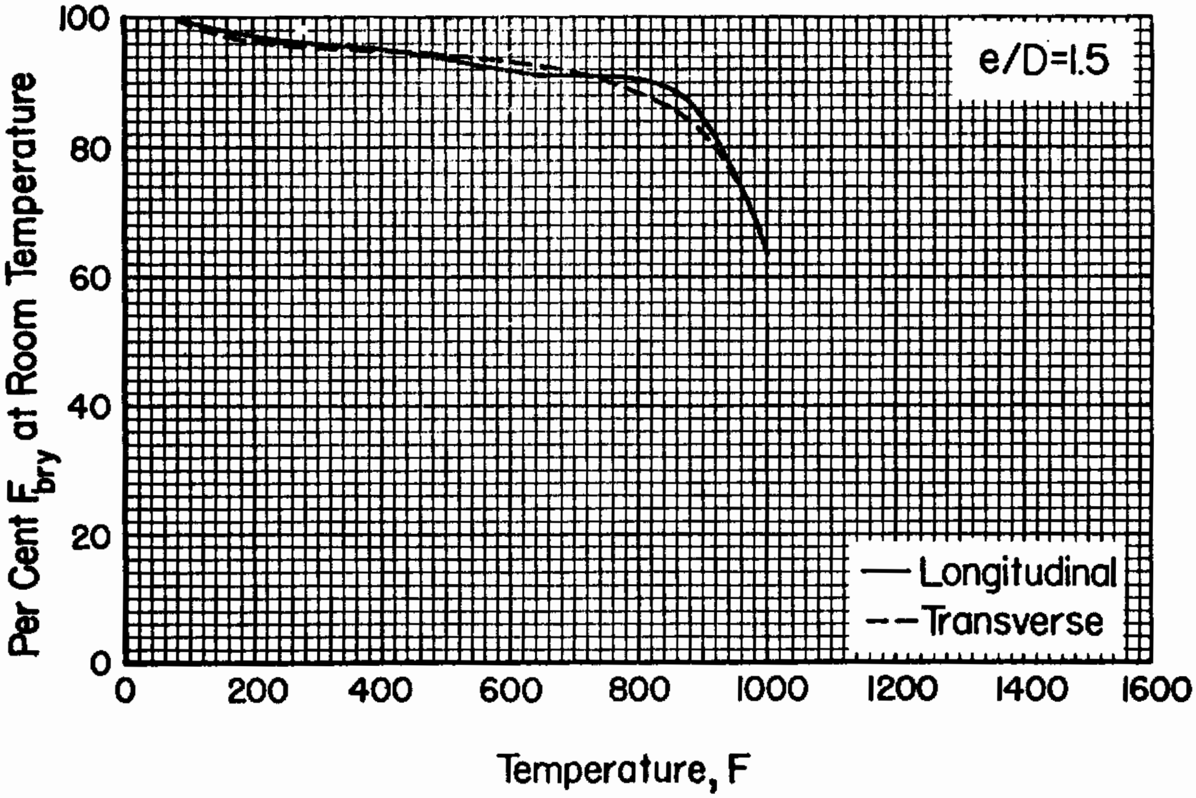

FIGURE 5.2.9.1.3(b). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

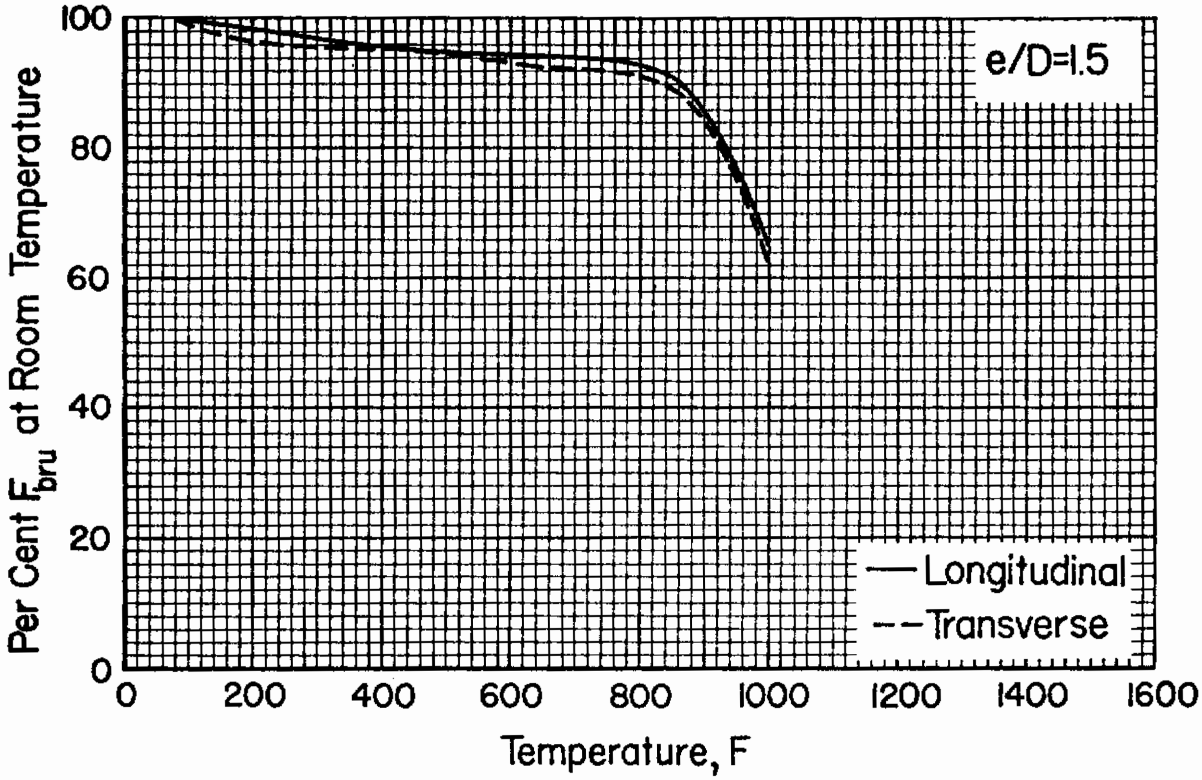

FIGURE 5.2.9.1.3(c). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

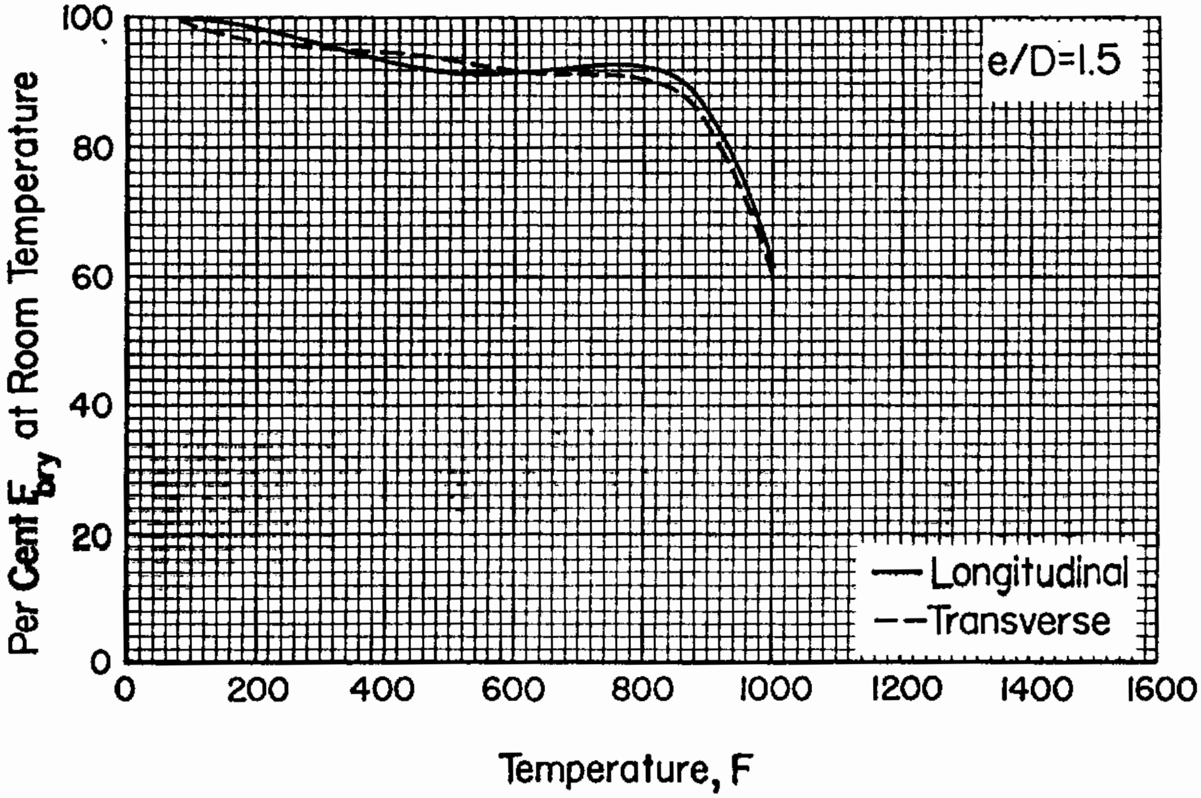

FIGURE 5.2.9.1.3(d). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

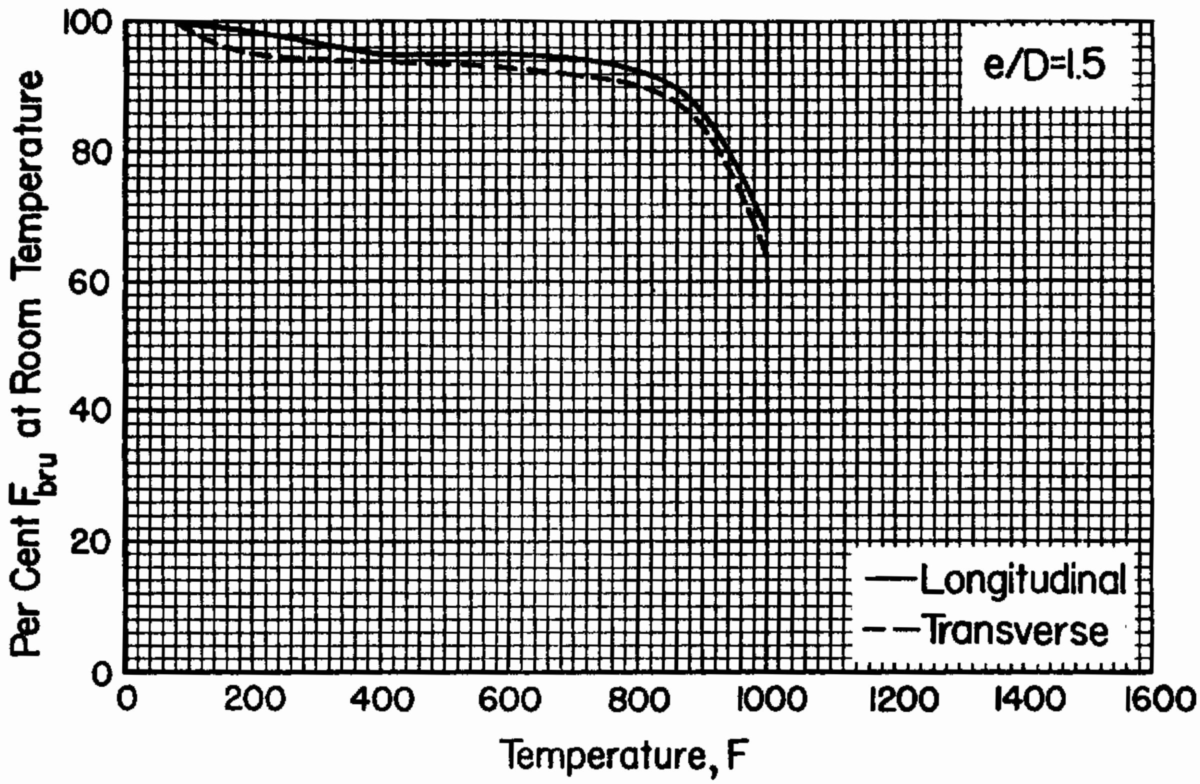

FIGURE 5.2.9.1.3(e). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

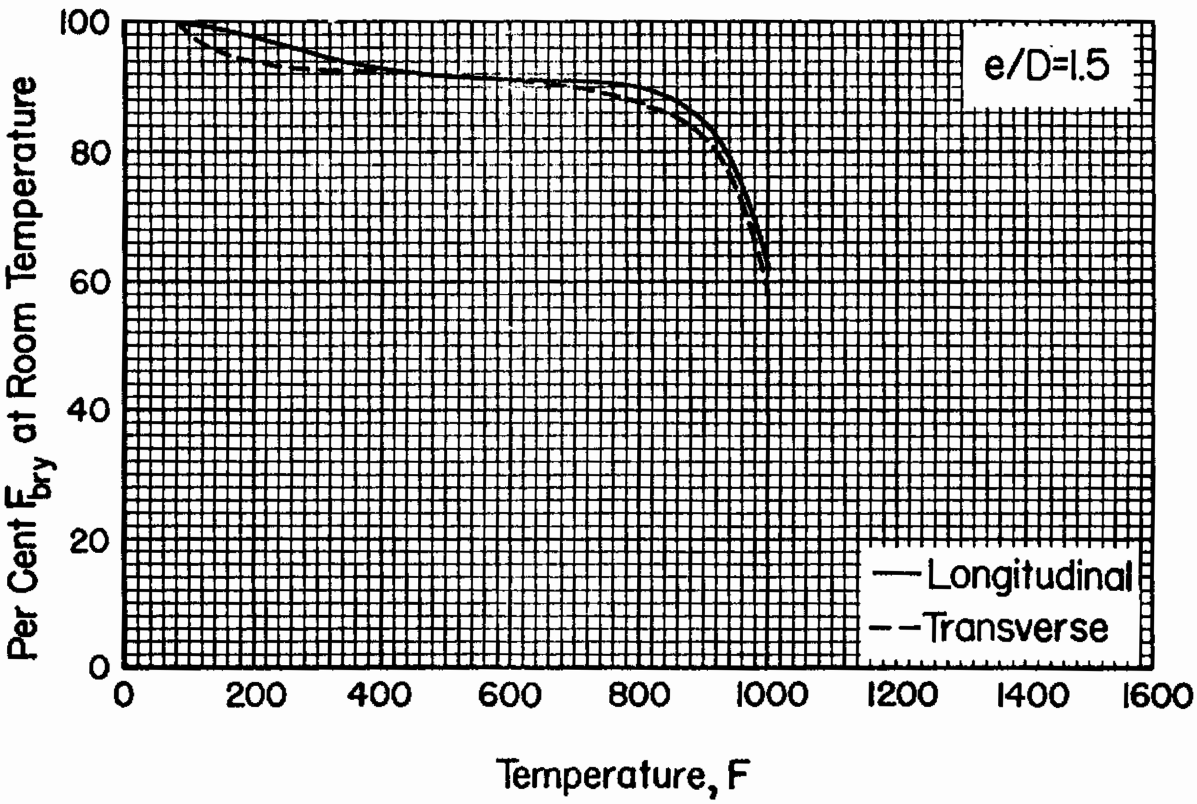

FIGURE 5.2.9.1.3(f). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

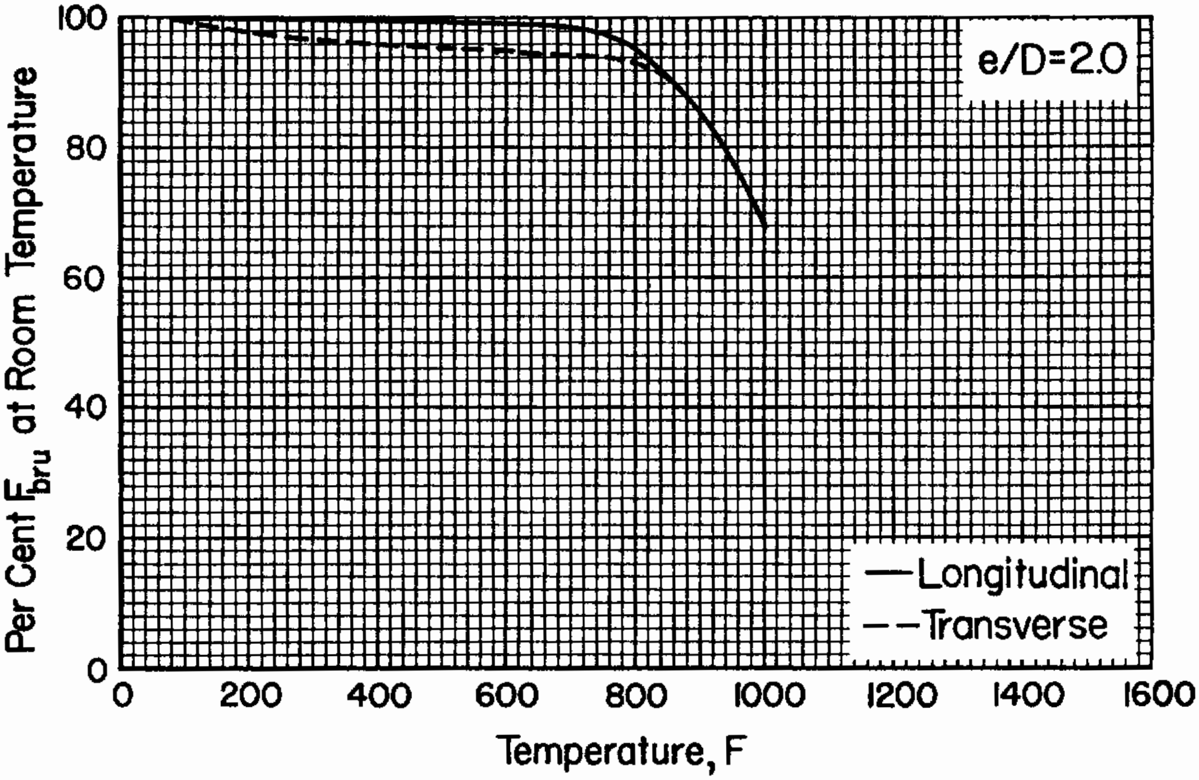

FIGURE 5.2.9.1.3(g). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

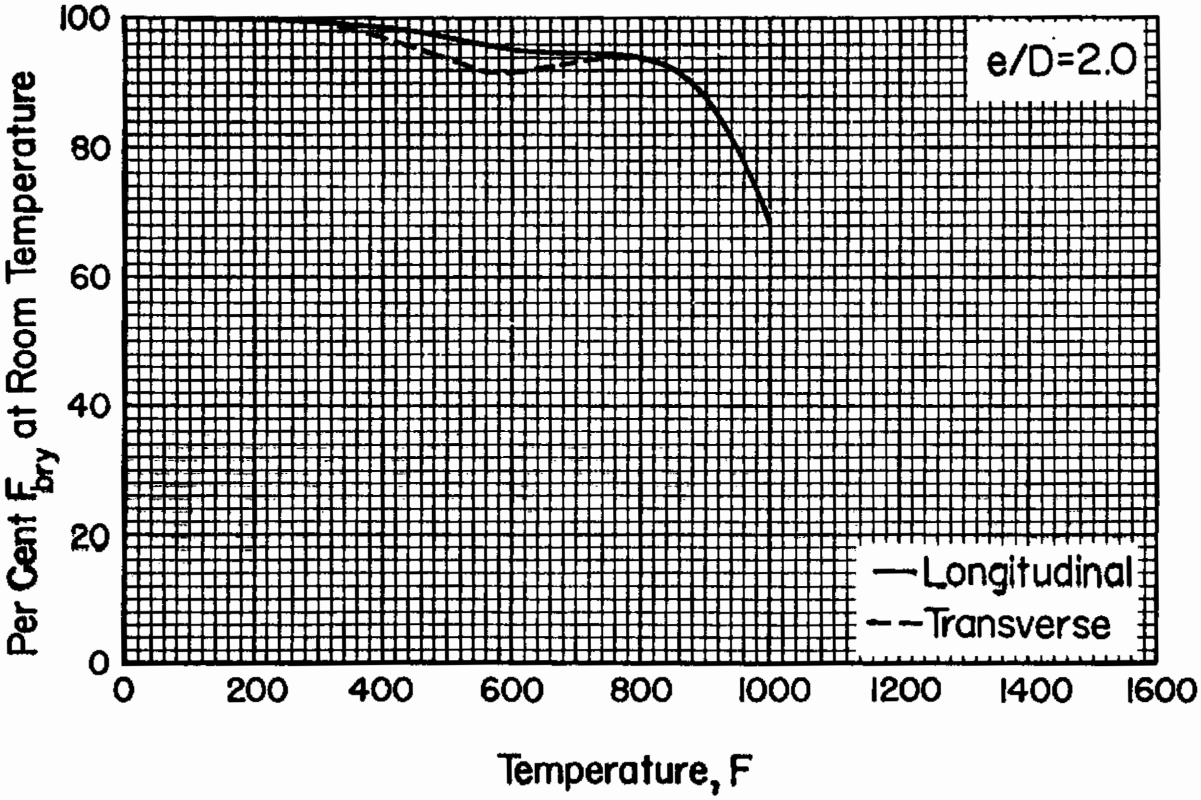

FIGURE 5.2.9.1.3(h). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

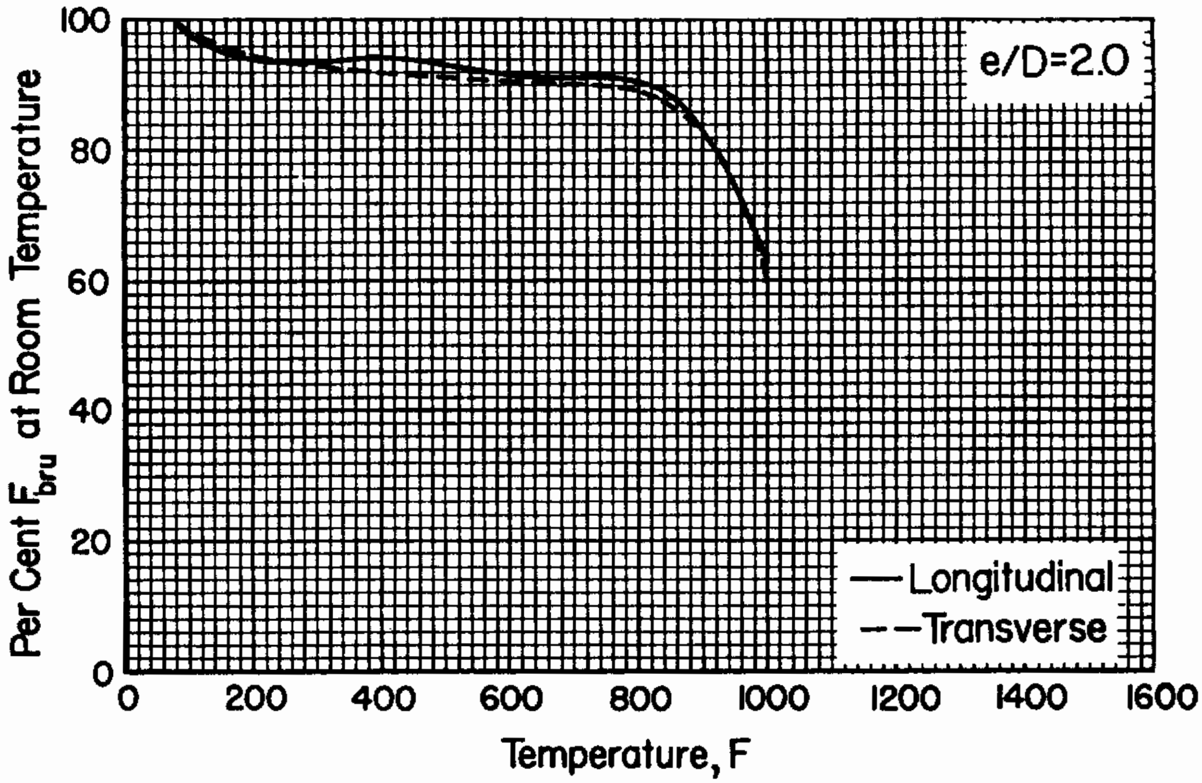

FIGURE 5.2.9.1.3(i). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

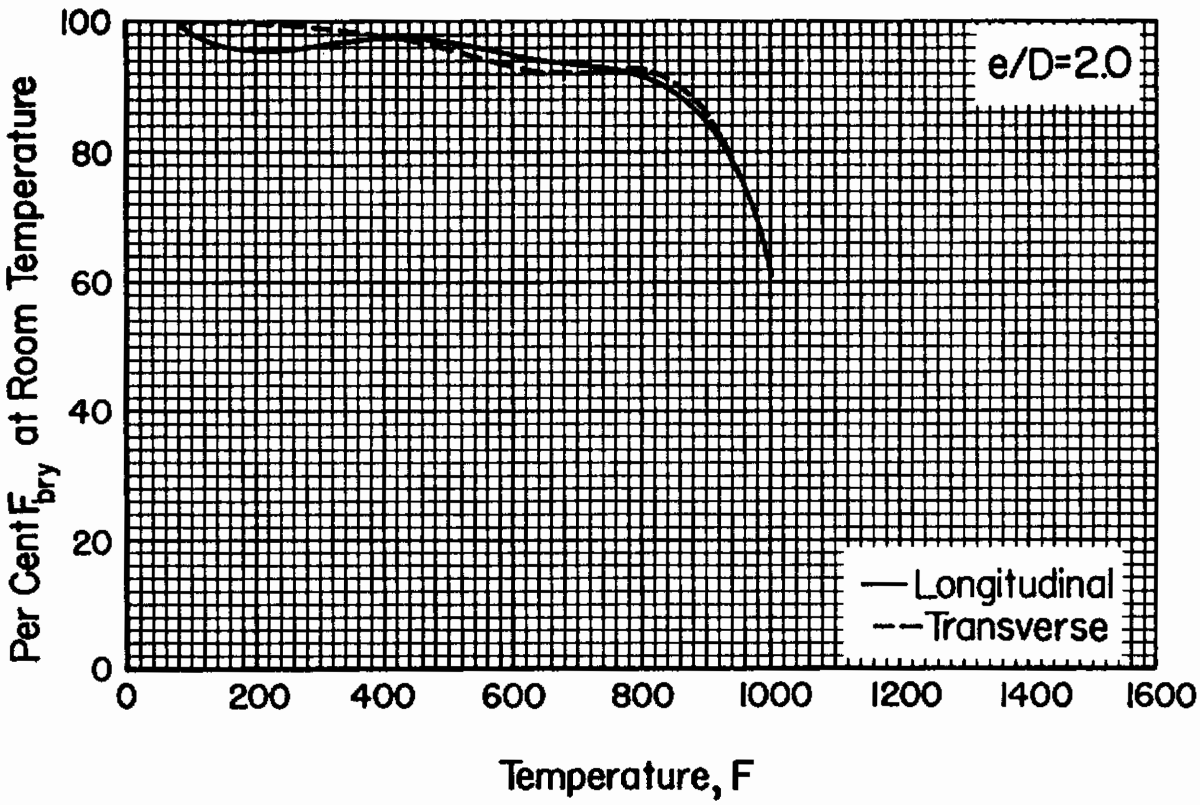

FIGURE 5.2.9.1.3(j). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

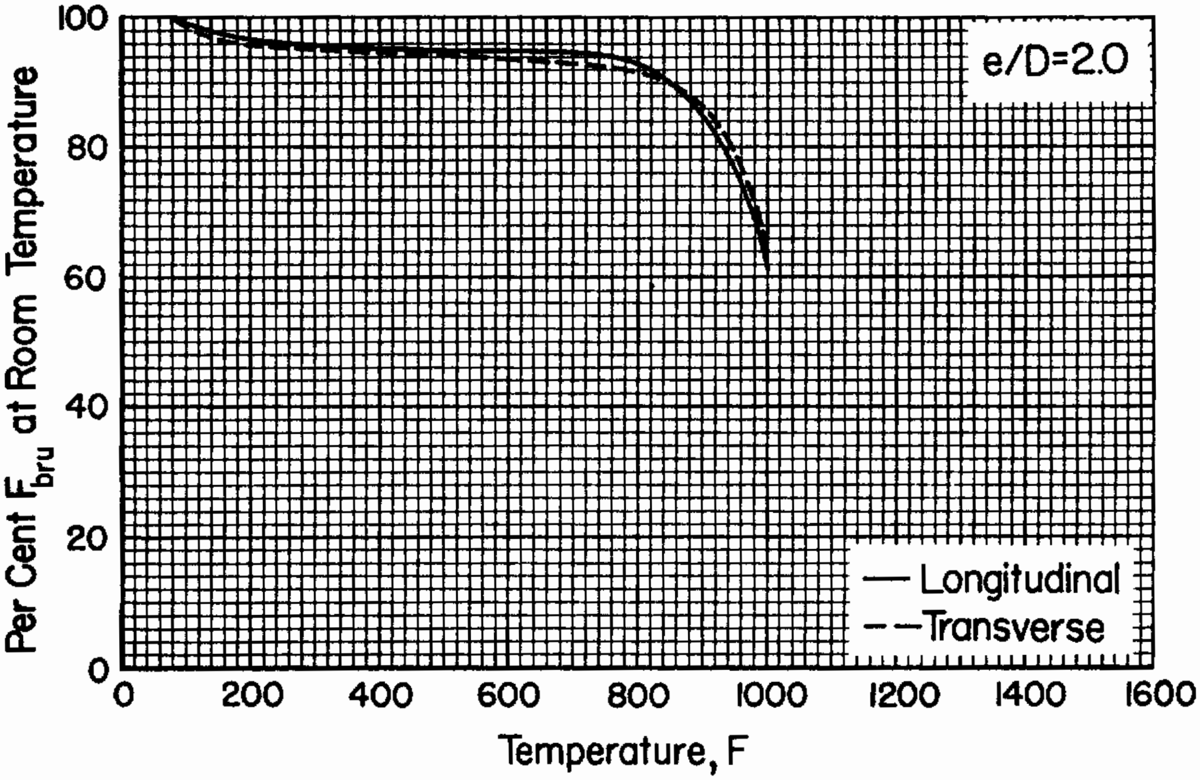

FIGURE 5.2.9.1.3(k). Effect of temperature on the ultimate bearing strength (F_{bru}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

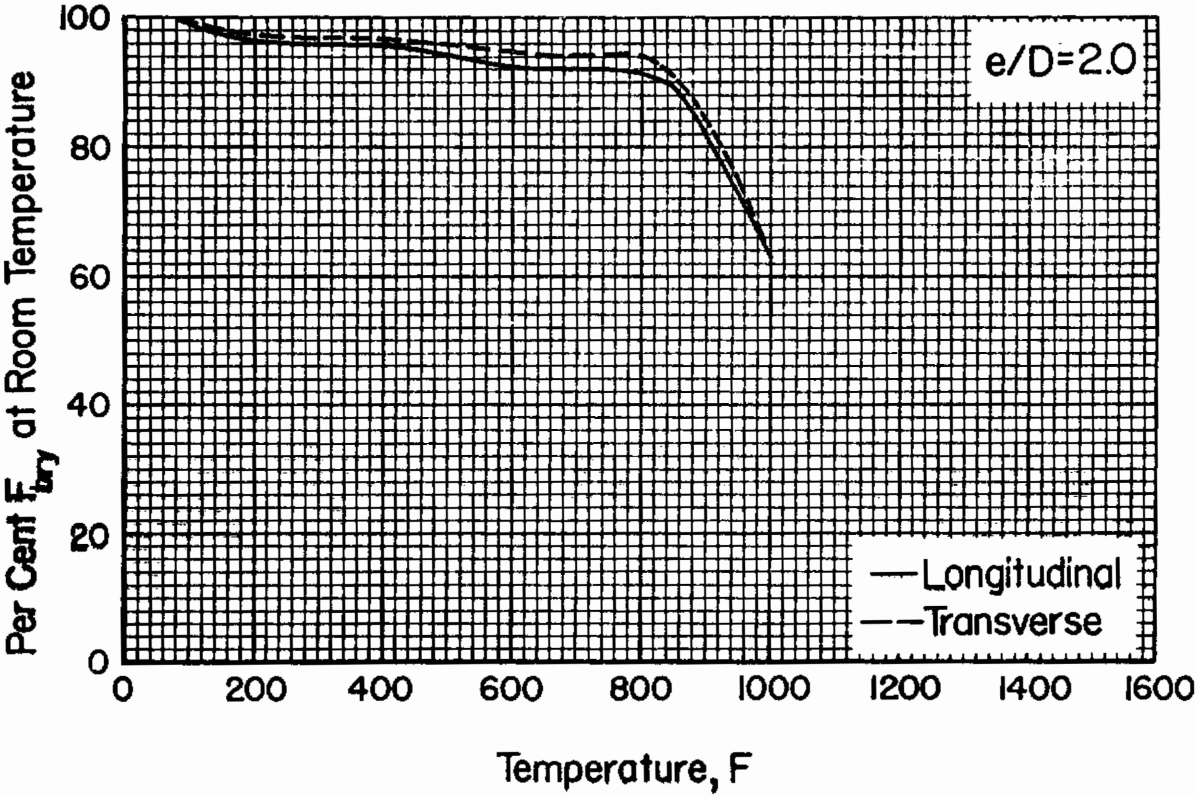

FIGURE 5.2.9.1.3(l). Effect of temperature on the bearing yield strength (F_{bry}) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

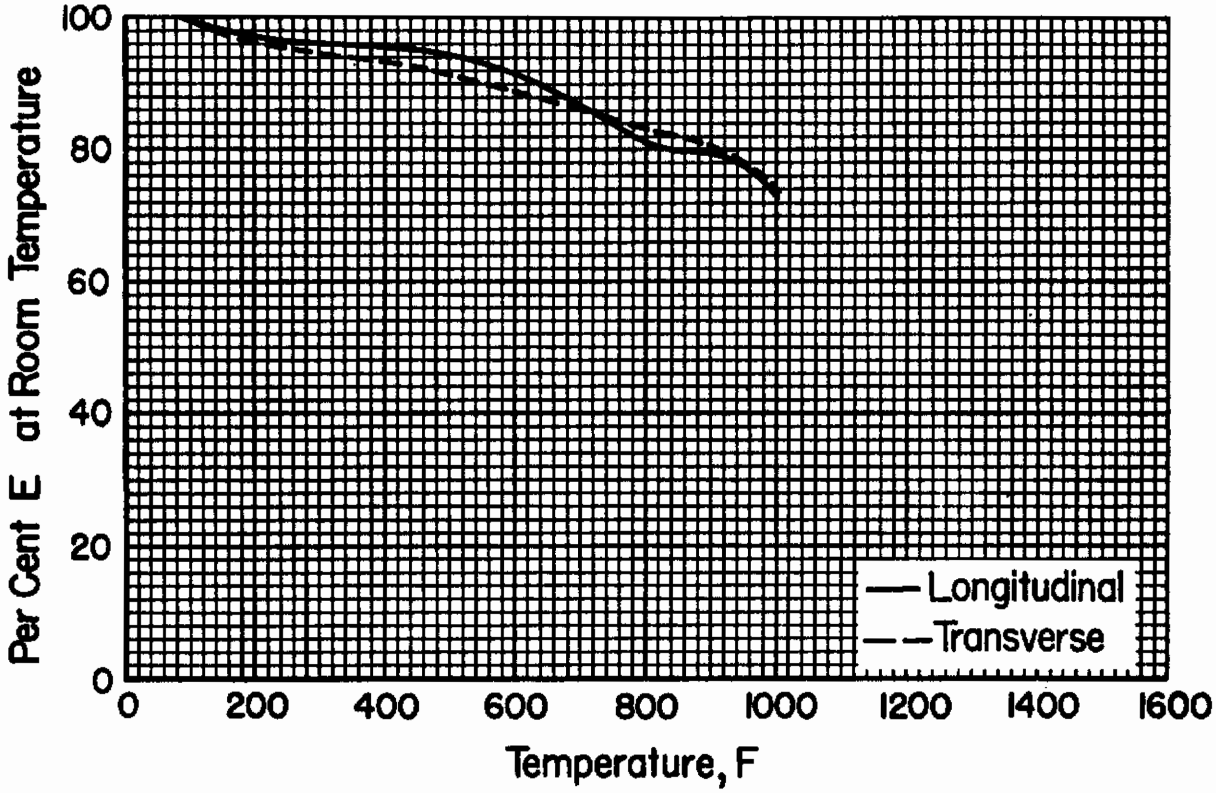

FIGURE 5.2.9.1.4(a). Effect of temperature on the tensile modulus (E) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

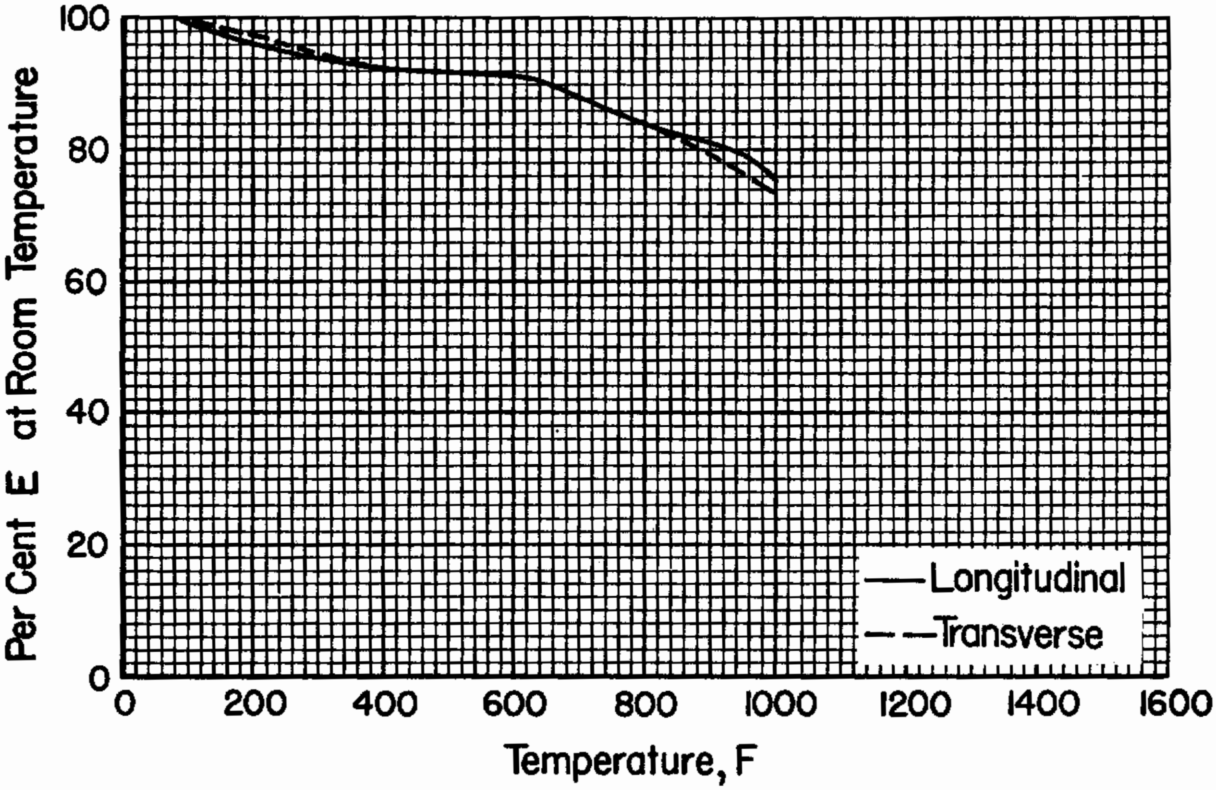

FIGURE 5.2.9.1.4(b). Effect of temperature on the tensile modulus (E) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

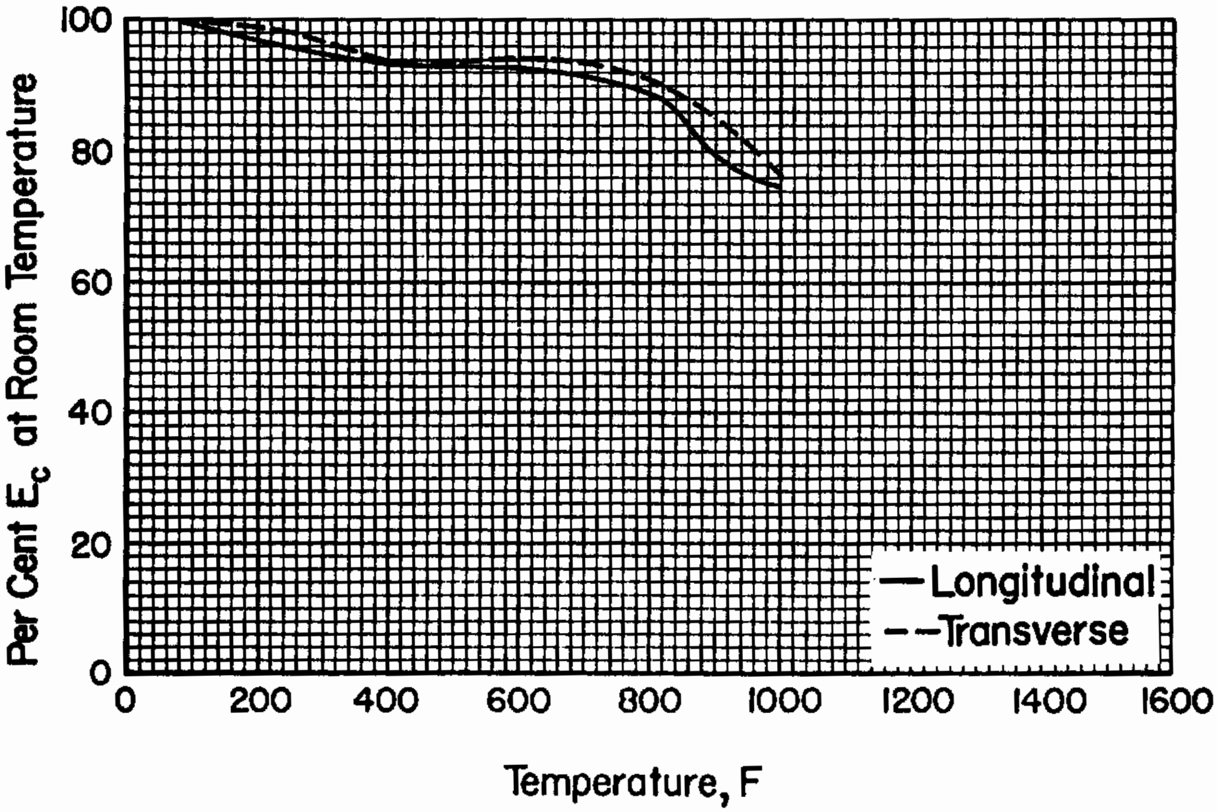

FIGURE 5.2.9.1.4(c). Effect of temperature on the compressive modulus (E_c) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

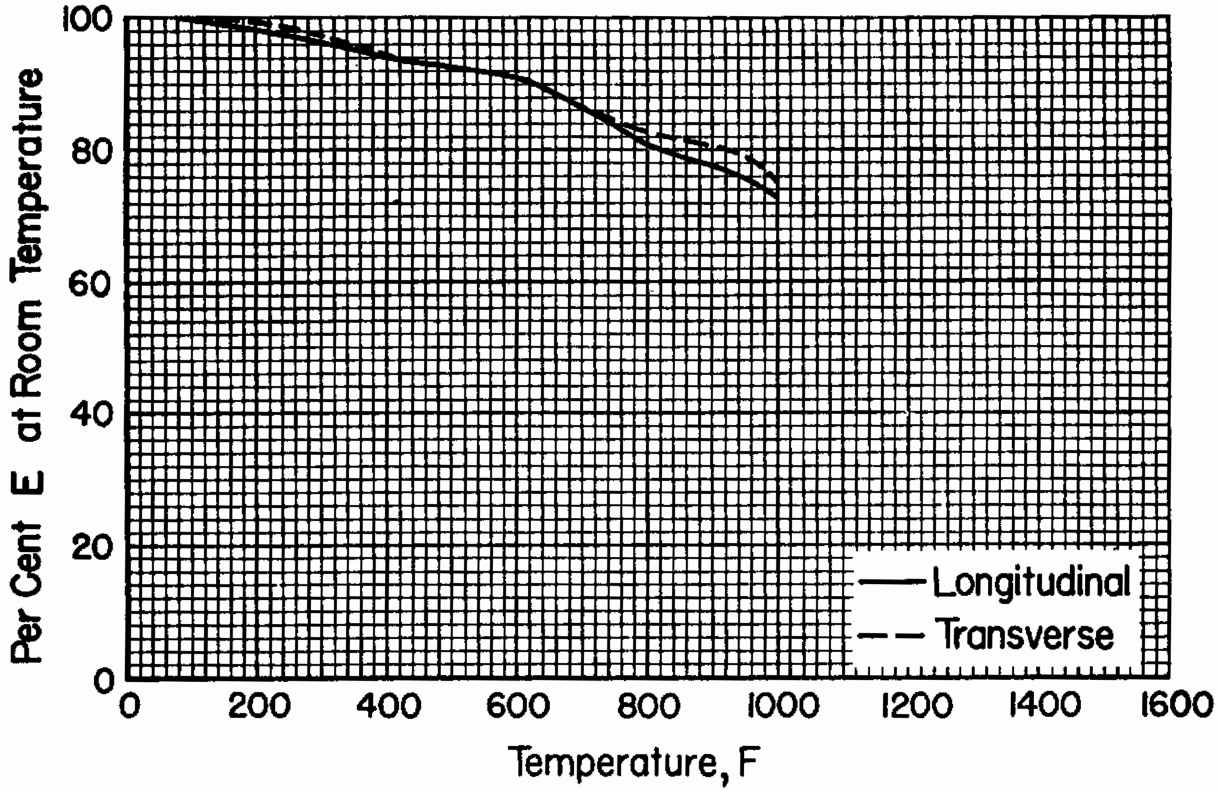

FIGURE 5.2.9.14(d). Effect of temperature on the tensile modulus (E) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

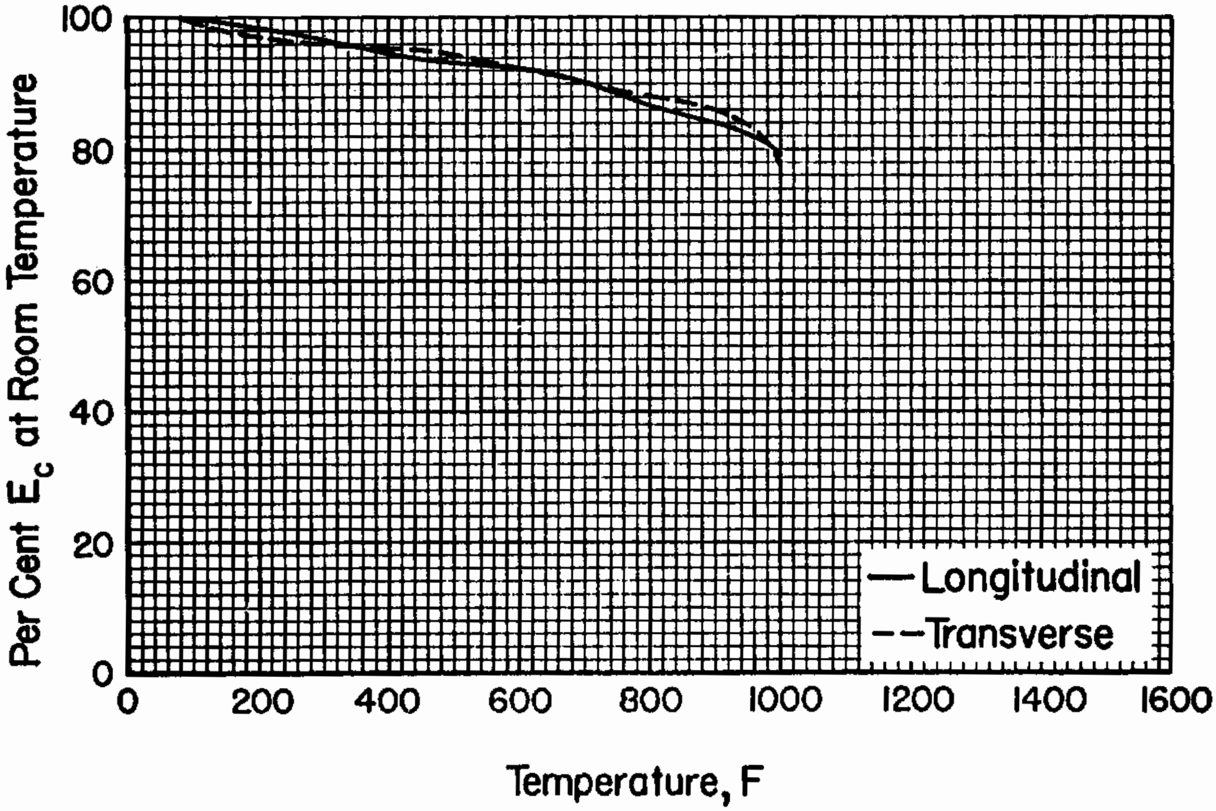

FIGURE 5.2.9.1.4(e). Effect of temperature on the compressive modulus (E_c) of 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

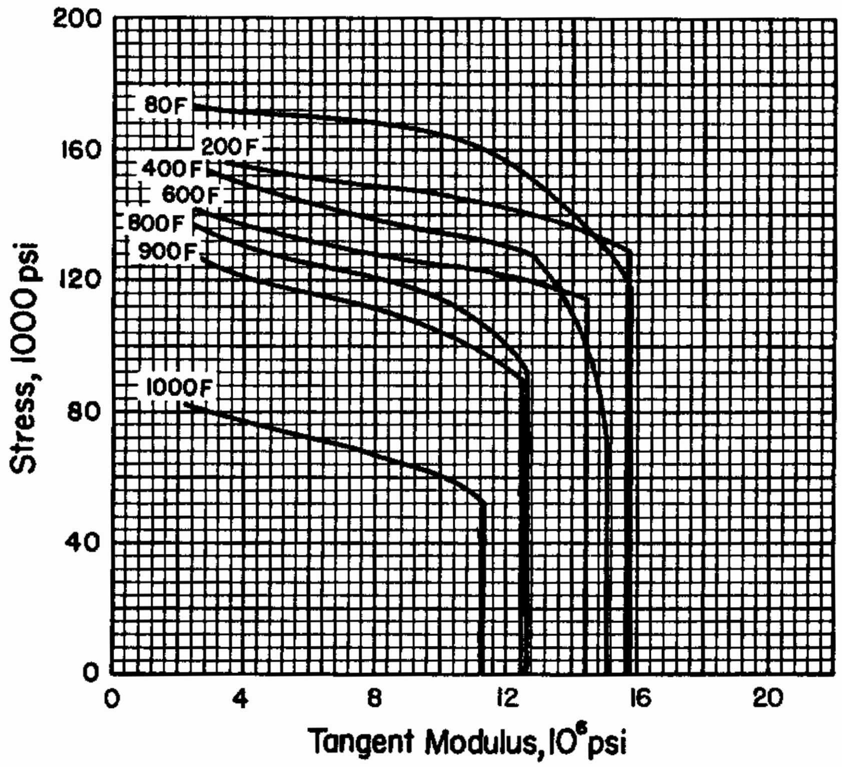

FIGURE 5.2.9.1.4(f). Typical longitudinal tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

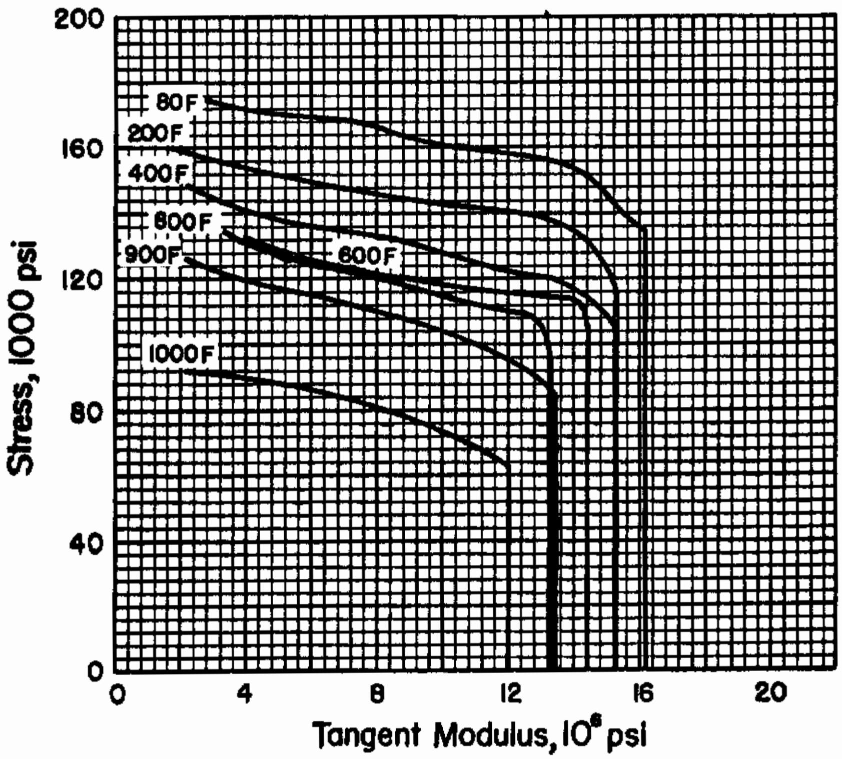

FIGURE 5.2.9.1.4(g). Typical transverse tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

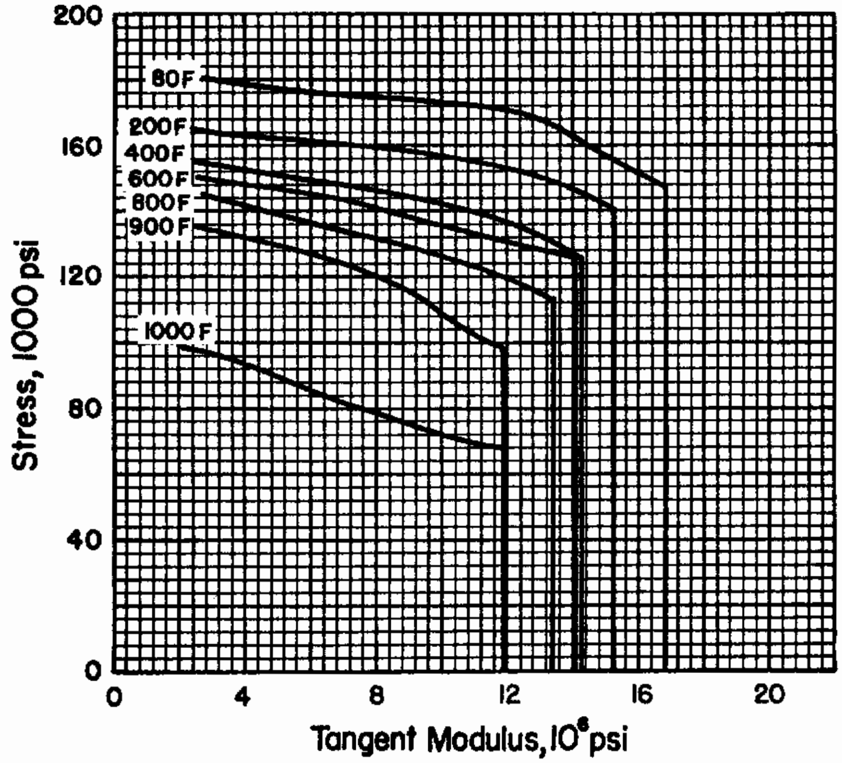

FIGURE 5.2.9.1.4(h). Typical longitudinal tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

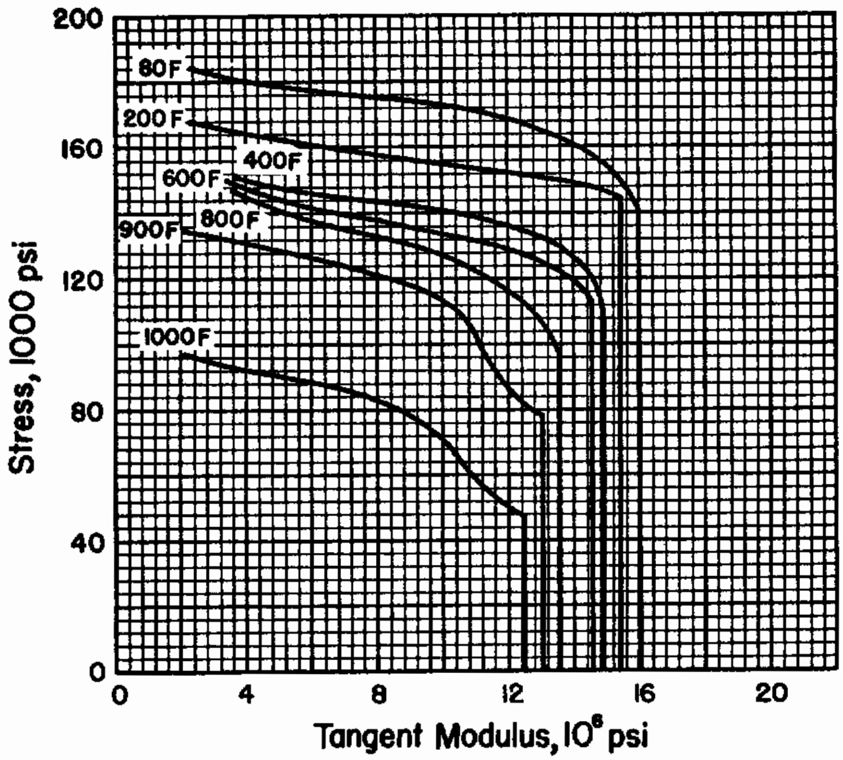

FIGURE 5.2.9.1.4(i). Typical transverse tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

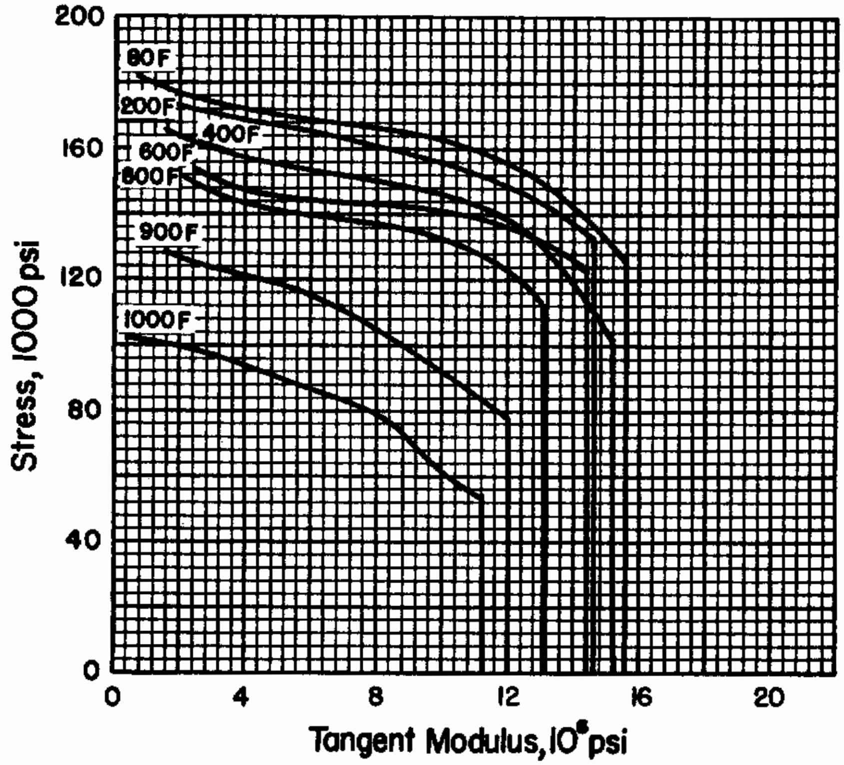

FIGURE 5.2.9.1.4(j). Typical longitudinal tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

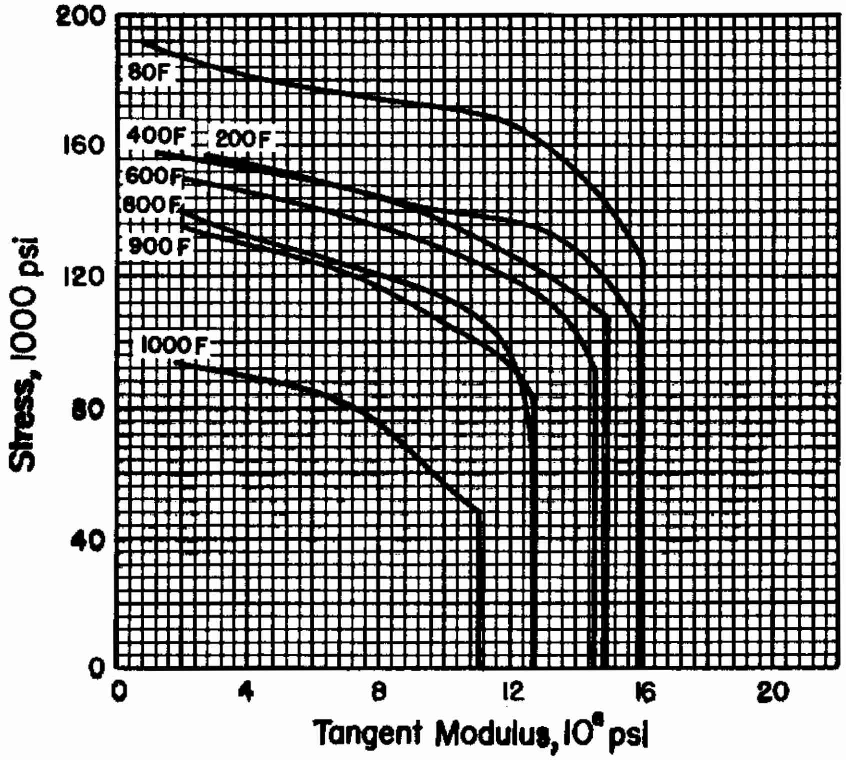

FIGURE 5.2.9.1.4(k). Typical transverse tensile tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

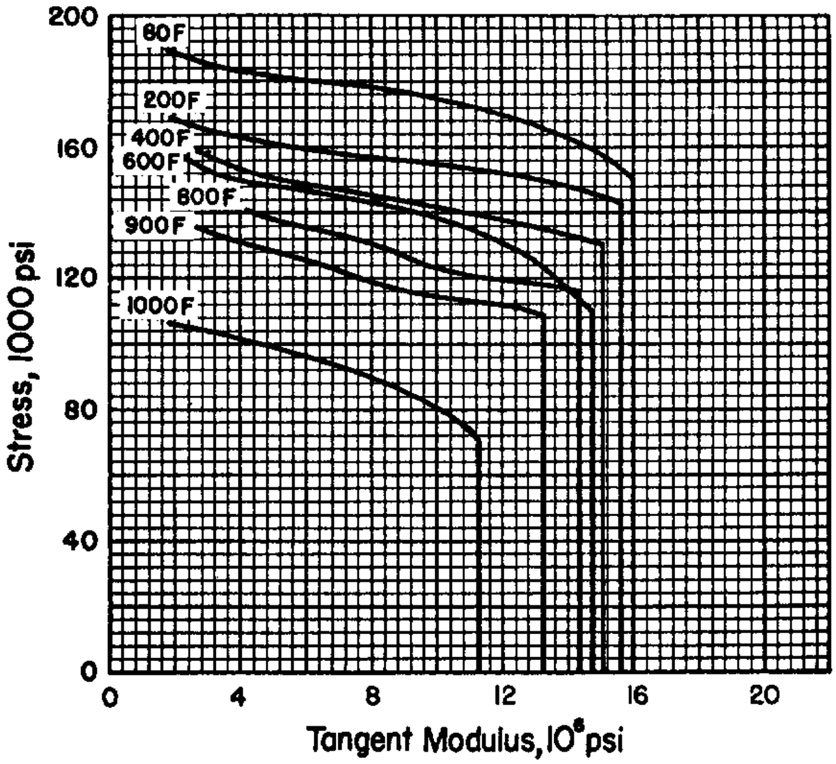

FIGURE 5.2.9.1.4(l). Typical longitudinal compressive tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

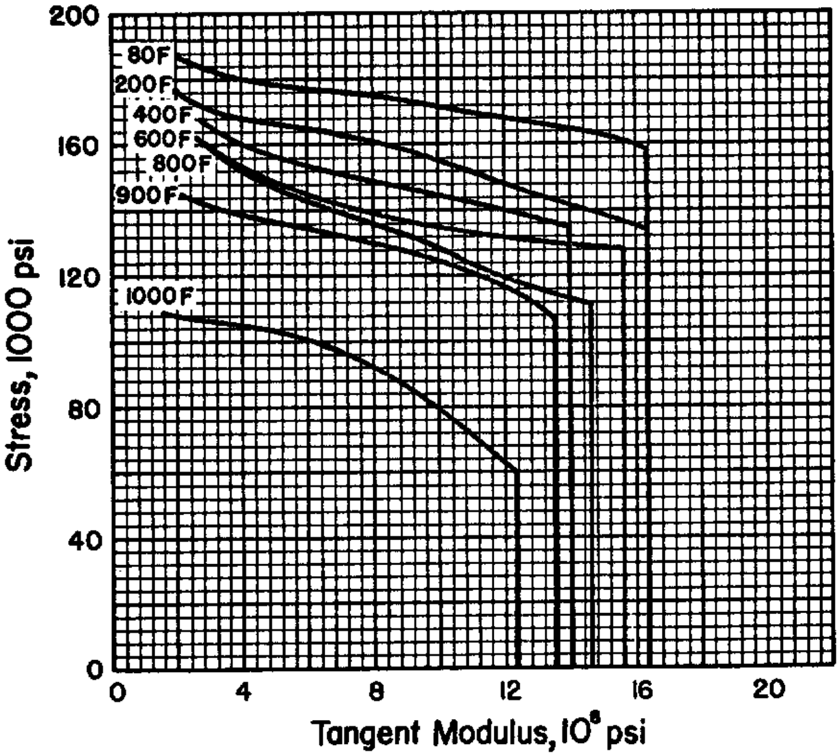

FIGURE 5.2.9.1.4(m). Typical transverse compressive tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

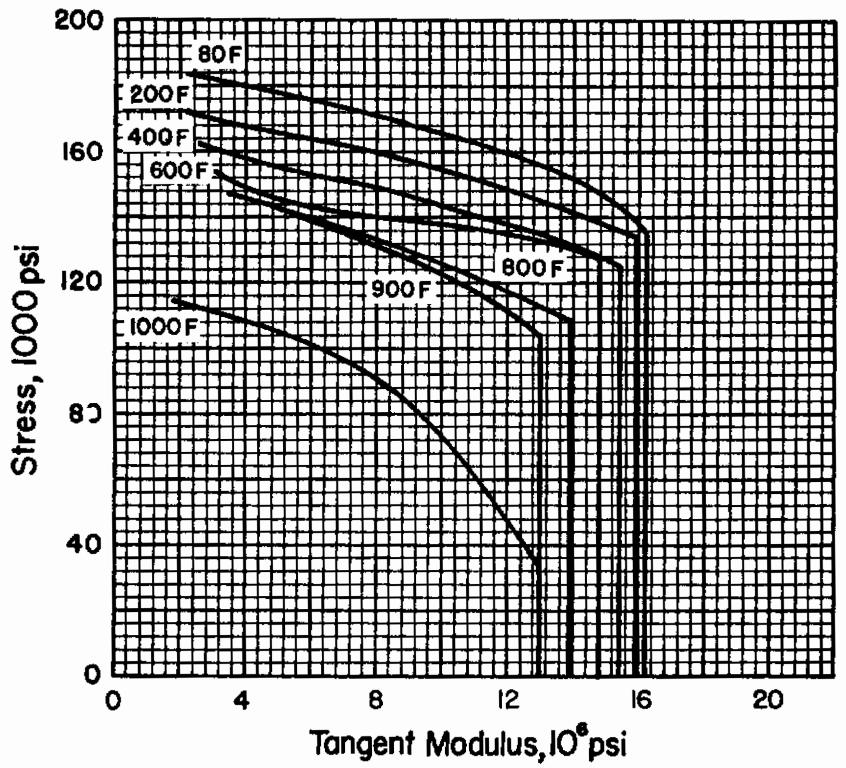

FIGURE 5.2.9.1.4(n). Typical longitudinal compressive tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

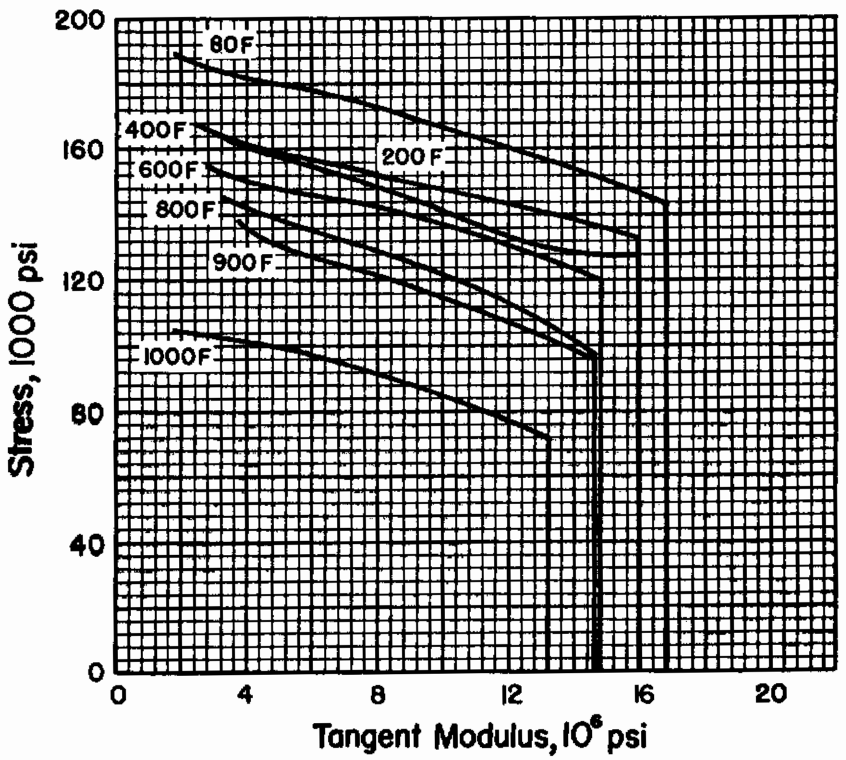

FIGURE 5.2.9.1.4(o). Typical transverse compressive tangent-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

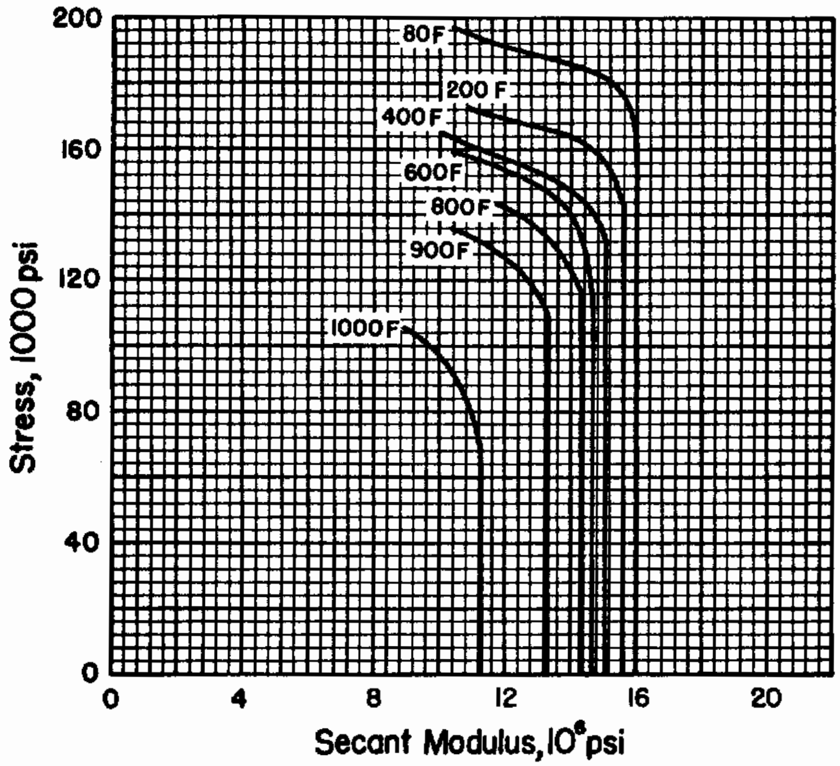

FIGURE 5.2.9.1.4(p). Typical longitudinal compressive secant-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

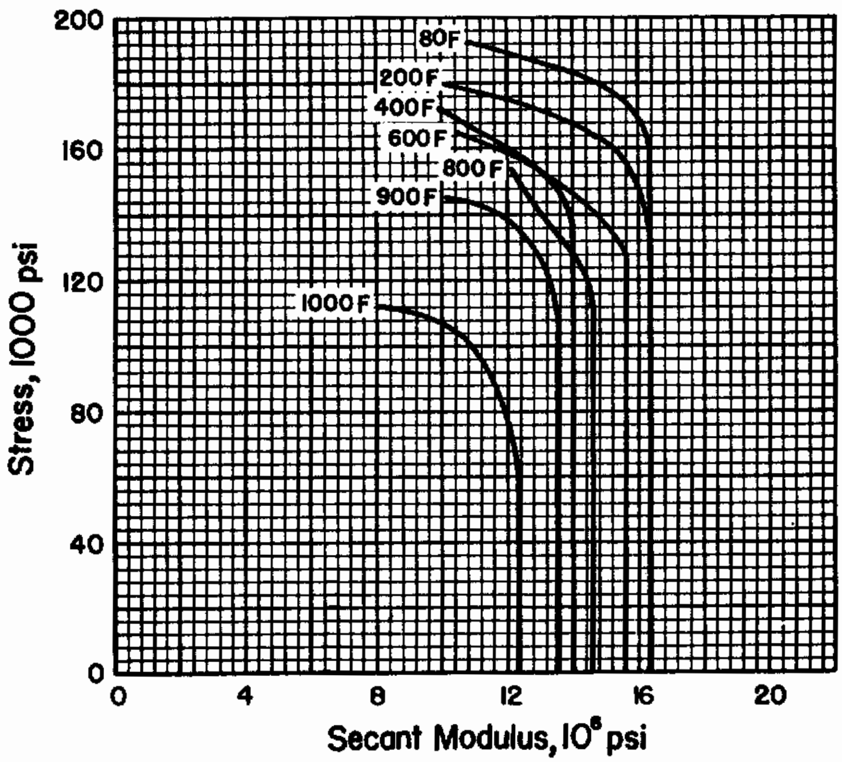

FIGURE 5.2.9.1.4(q). Typical transverse compressive secant-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

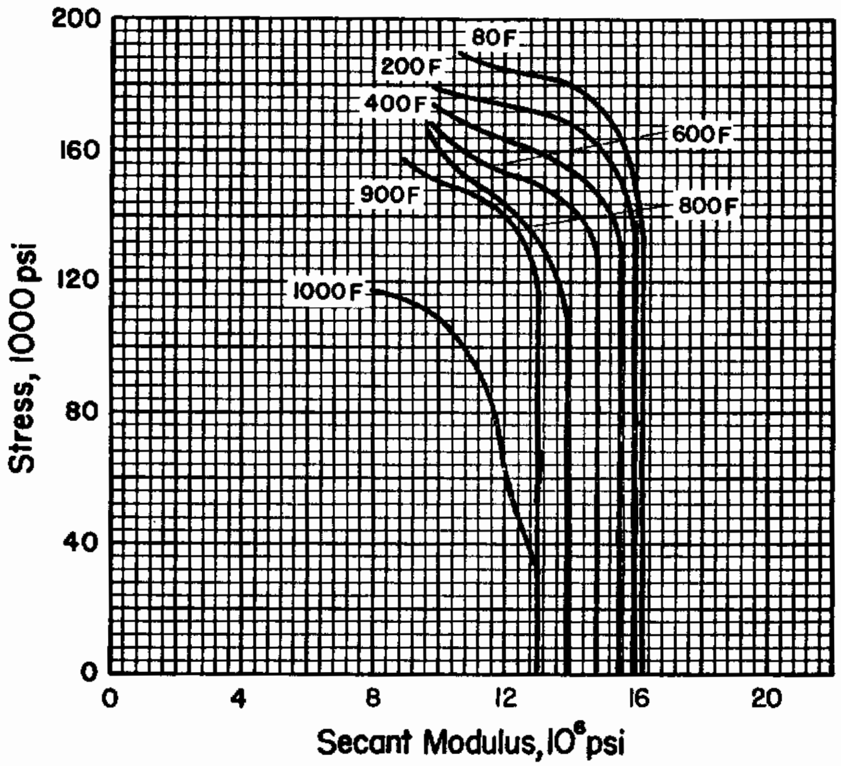

FIGURE 5.2.9.1.4(r). Typical longitudinal compressive secant-modulus curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

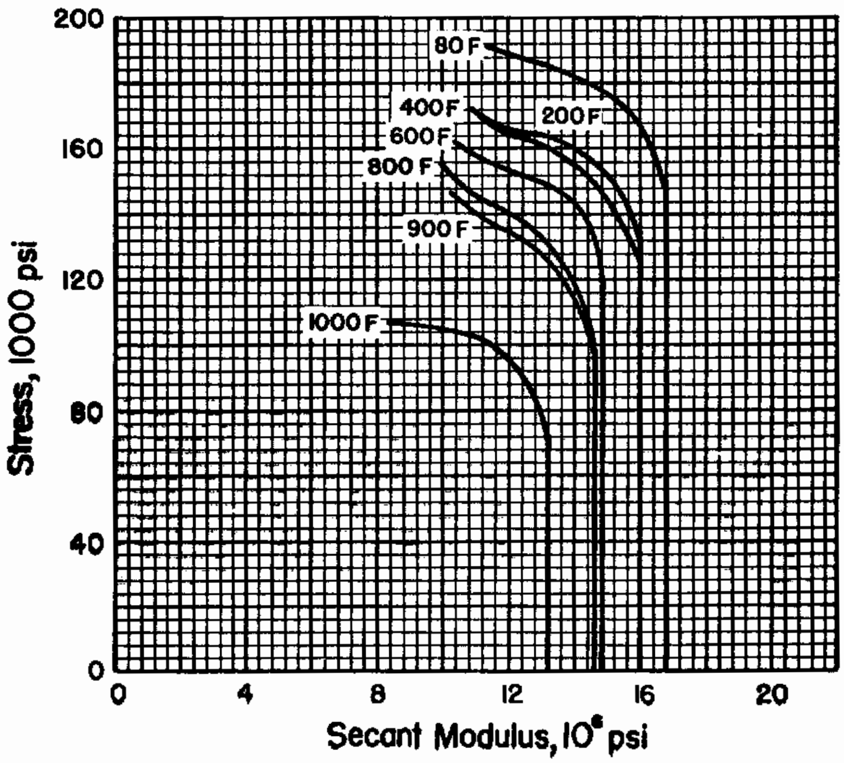

FIGURE 5.2.9.1.4(s). Typical transverse compressive secant-modulus curves for 13V-11Cr-1V solution treated and aged titanium alloy (0.125 inch thick sheet).

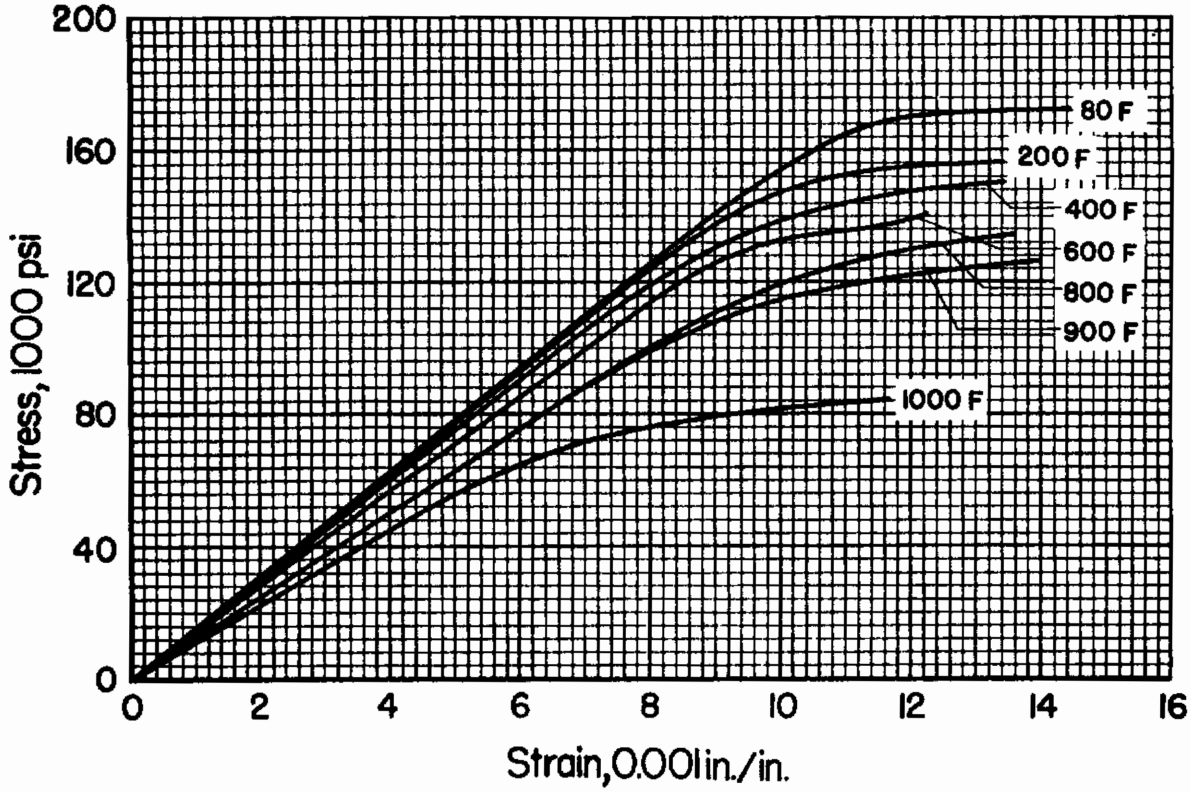

FIGURE 5.2.9.1.5(a). Typical longitudinal tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

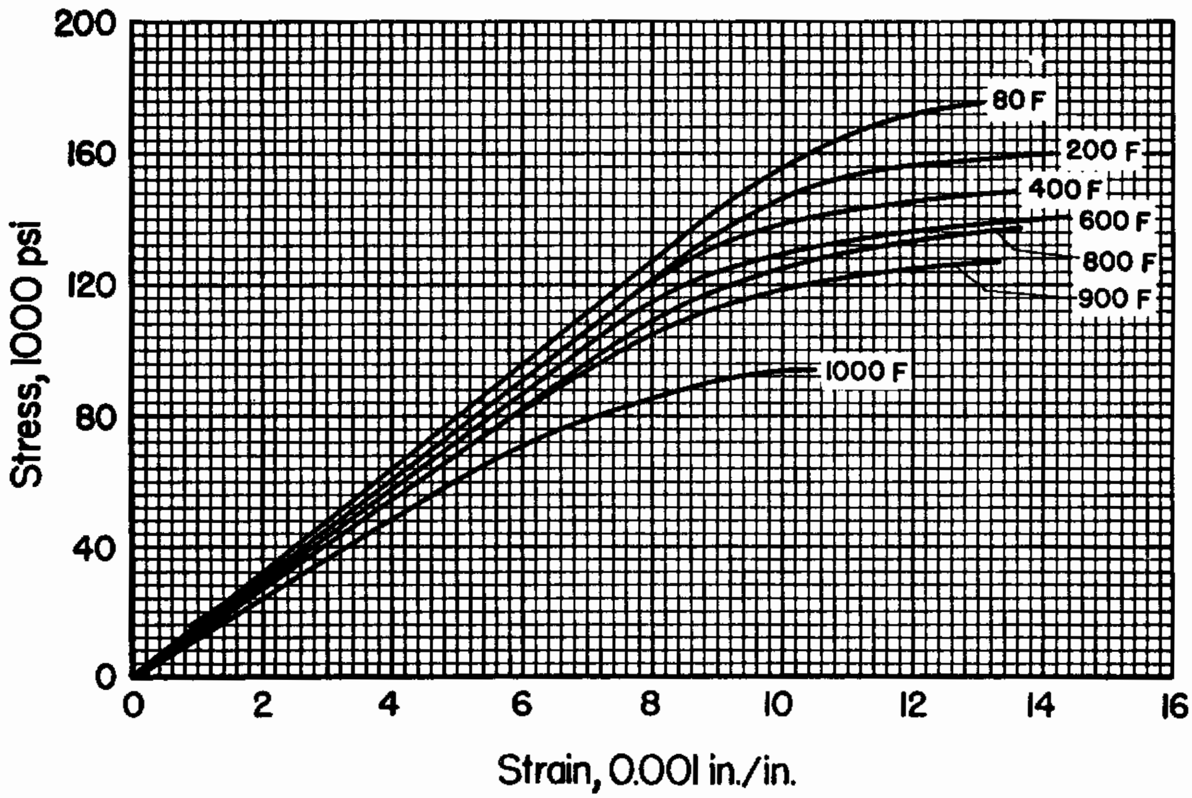

FIGURE 5.2.9.1.5(b). Typical transverse tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.020 inch thick sheet).

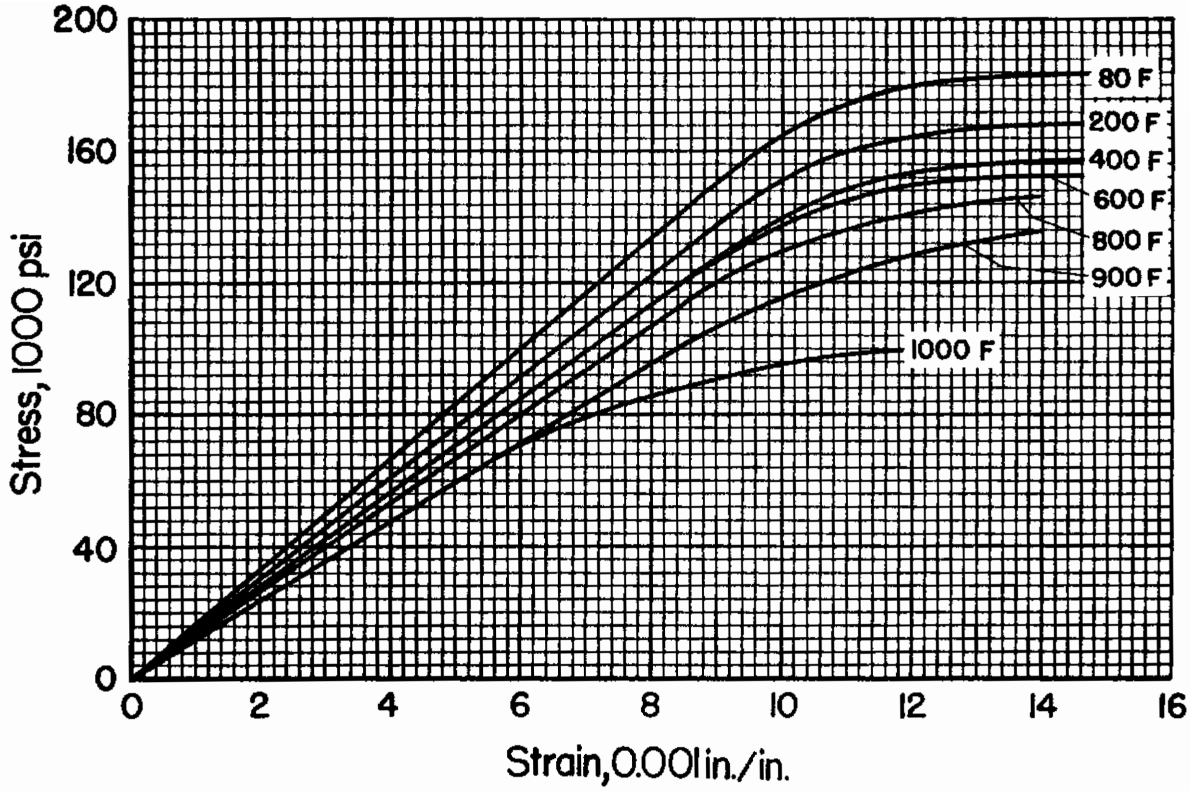

FIGURE 5.2.9.1.5(c). Typical longitudinal tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

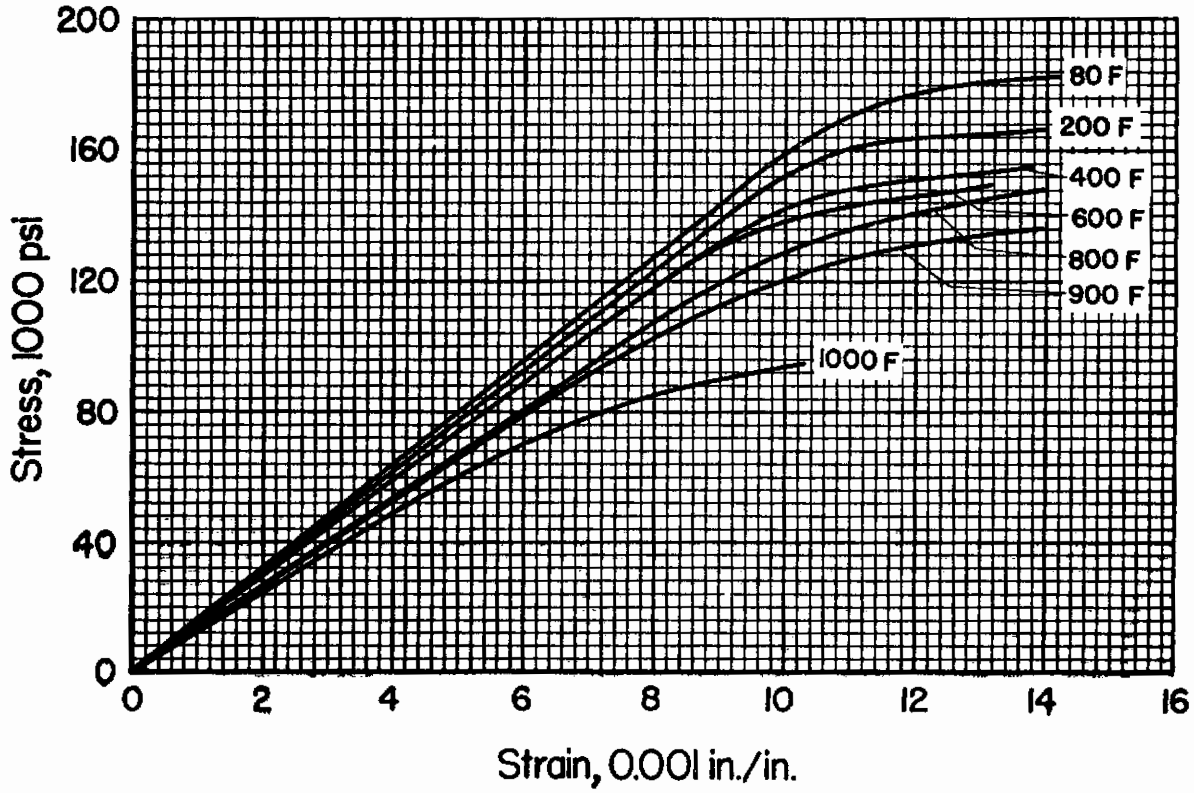

FIGURE 5.2.9.1.5(d). Typical transverse tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

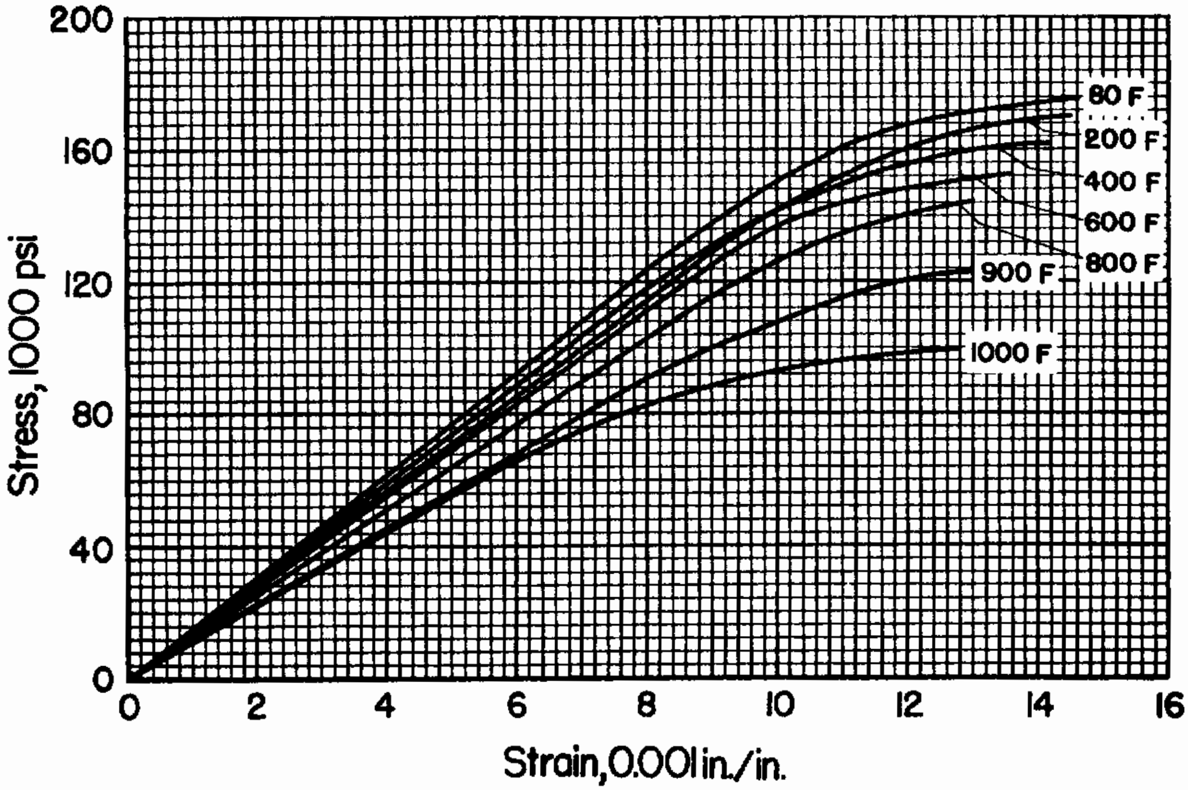

FIGURE 5.2.9.1.5(e). Typical longitudinal tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

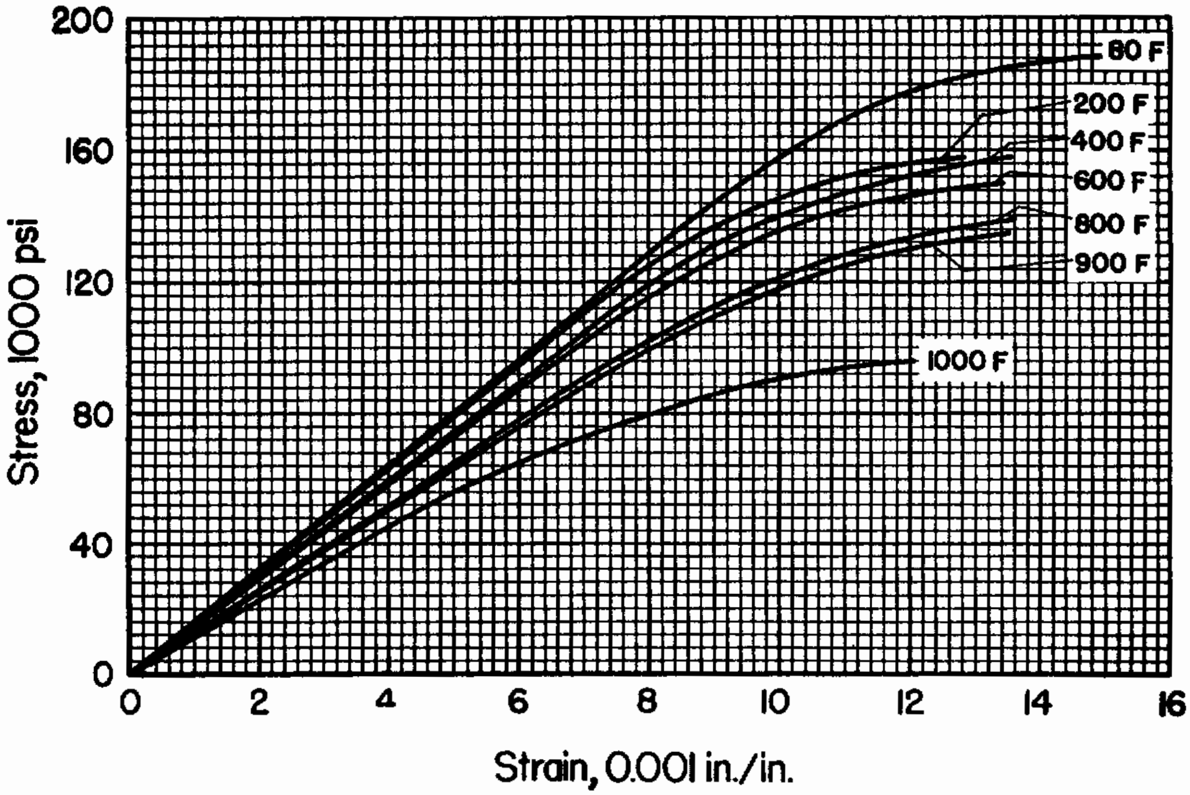

FIGURE 5.2.9.1.5(f). Typical transverse tensile stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick).

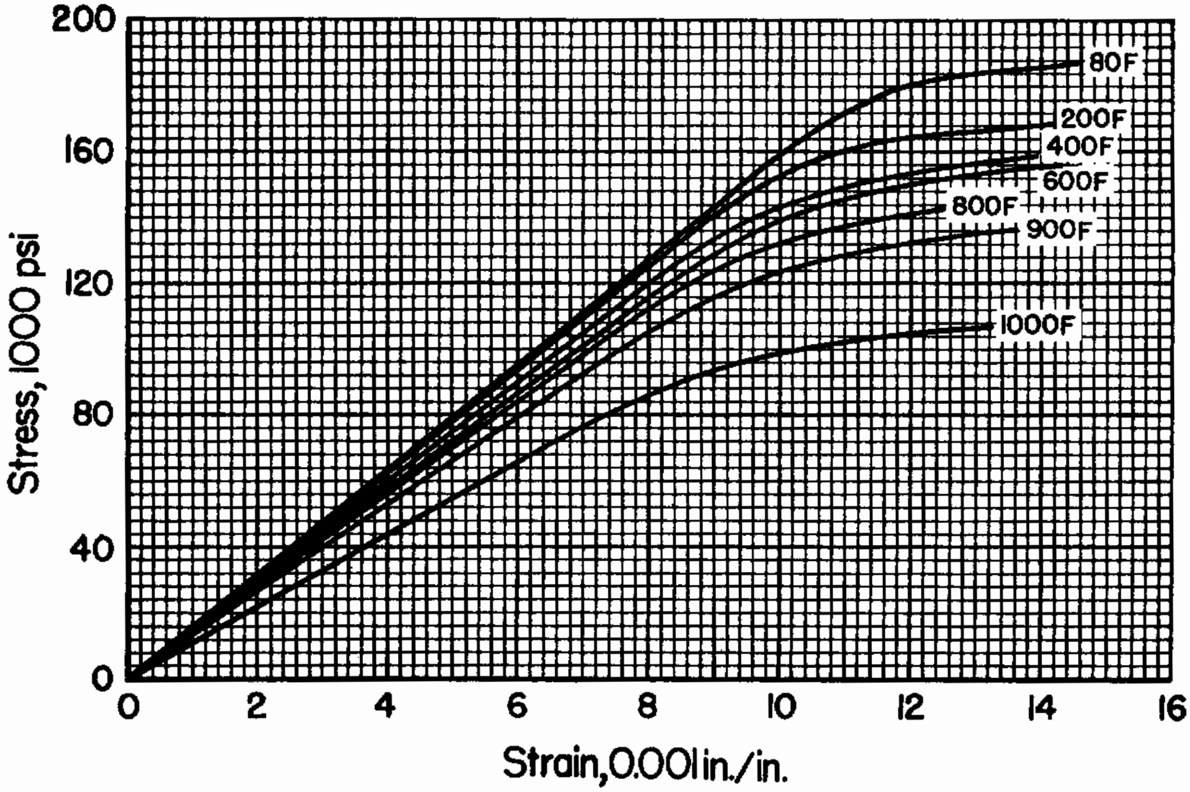

FIGURE 5.2.9.1.5(g). Typical longitudinal compressive stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

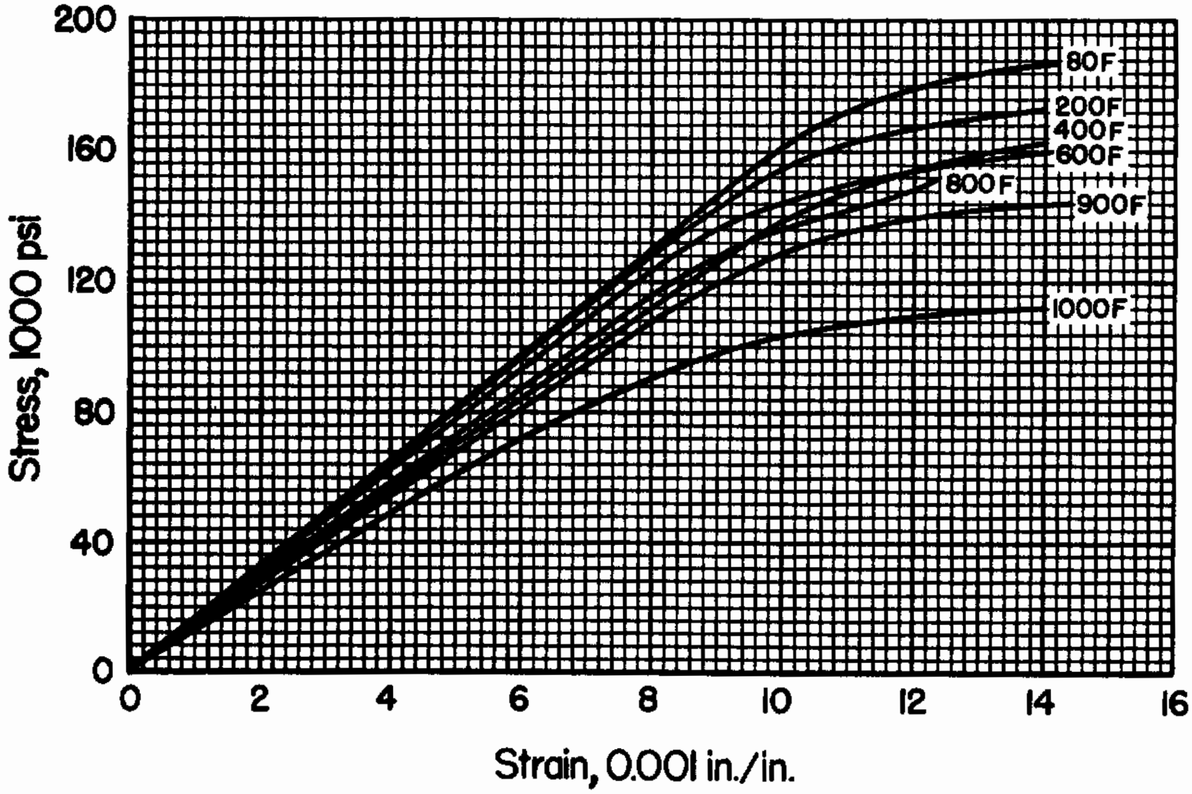

FIGURE 5.2.9.1.5(h). Typical transverse compressive stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.063 inch thick sheet).

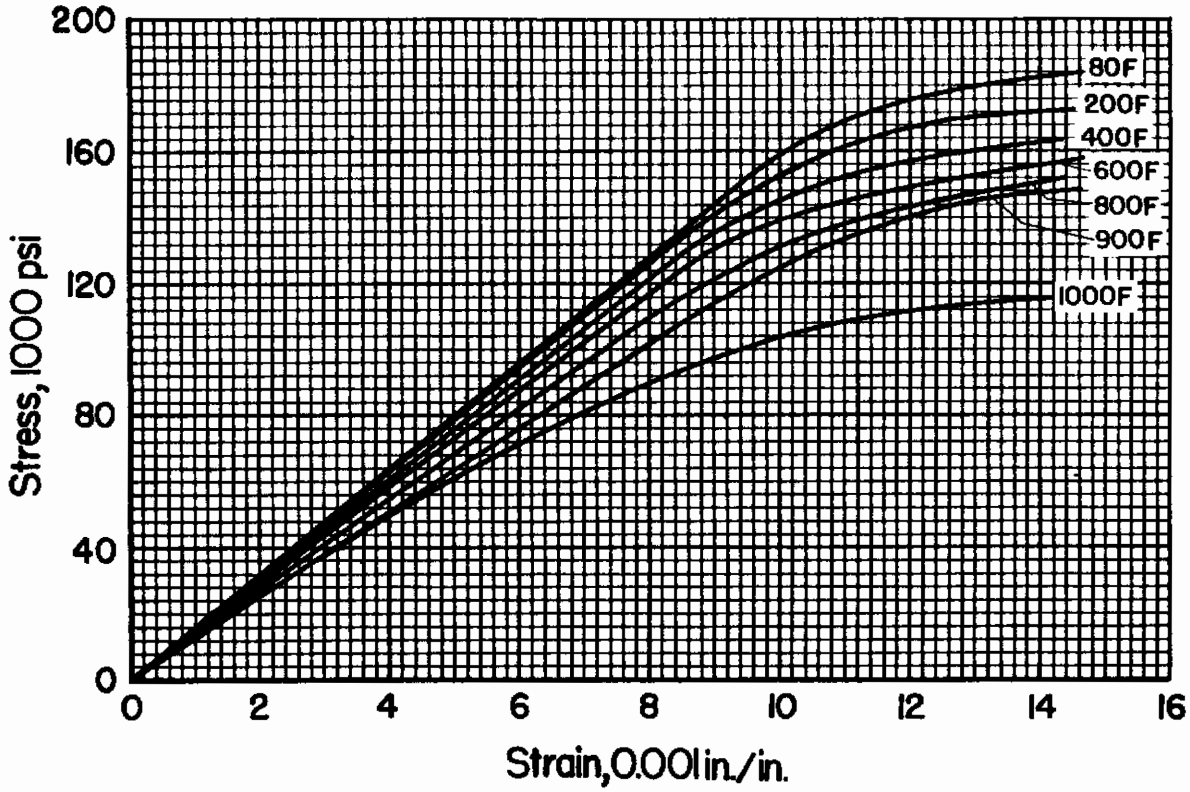

FIGURE 5.2.9.1.5(i). Typical longitudinal compressive stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

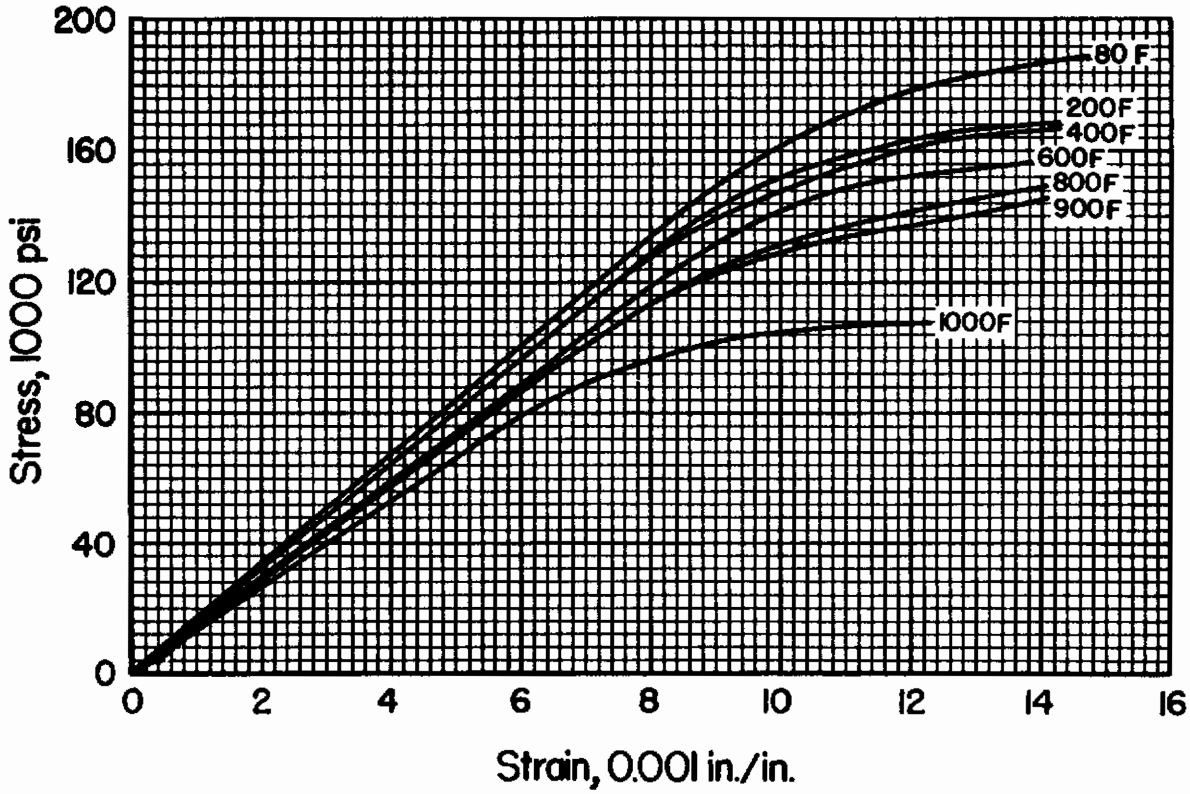

FIGURE 5.2.9.1.5(j). Typical transverse compressive stress-strain curves for 13V-11Cr-3Al solution treated and aged titanium alloy (0.125 inch thick sheet).

5.3 FATIGUE

Axial-load fatigue-strength data for room and elevated temperatures are presented as modified Goodman-type diagrams for solution treated and aged titanium alloys. These curves are for specimens machined from sheet material in the longitudinal grain direction having a theoretical stress concentration of 2.82, as well as for smooth specimens. Stress concentration was obtained by a centrally drilled hole in the test section. Details of experimental technique, complete S-N curves and tabular data are given in Volumes 2b and 3. The S-N curves in Volume 2b were drawn through the average to lower part of the test scatterband and the stress values obtained for each stress ratio ($A = \infty$, 1.0, 0.3 and 0) were used to construct the modified Goodman-type diagrams. Actual test values in these diagrams were plotted on the appropriated line of constant stress ratio and a smooth curve was faired through the four points thus obtained. Up to and including 600°F, the value of $A = 0$ which is plotted on the abscissa for either smooth or notched specimens is the respective value of average ultimate tensile stress. Above 600°F where creep becomes significant within the time spans considered, stress-rupture tests were conducted to obtain $A = 0$ points. Life cycles were converted to total lapsed time using test cycling rates.

5.3.4 Fatigue Properties of 6Al-4V Titanium Alloy

Axial-load fatigue data for smooth and notched specimens at temperatures up to 900°F are given in Figures 5.3.4(a) through 5.3.4(t).

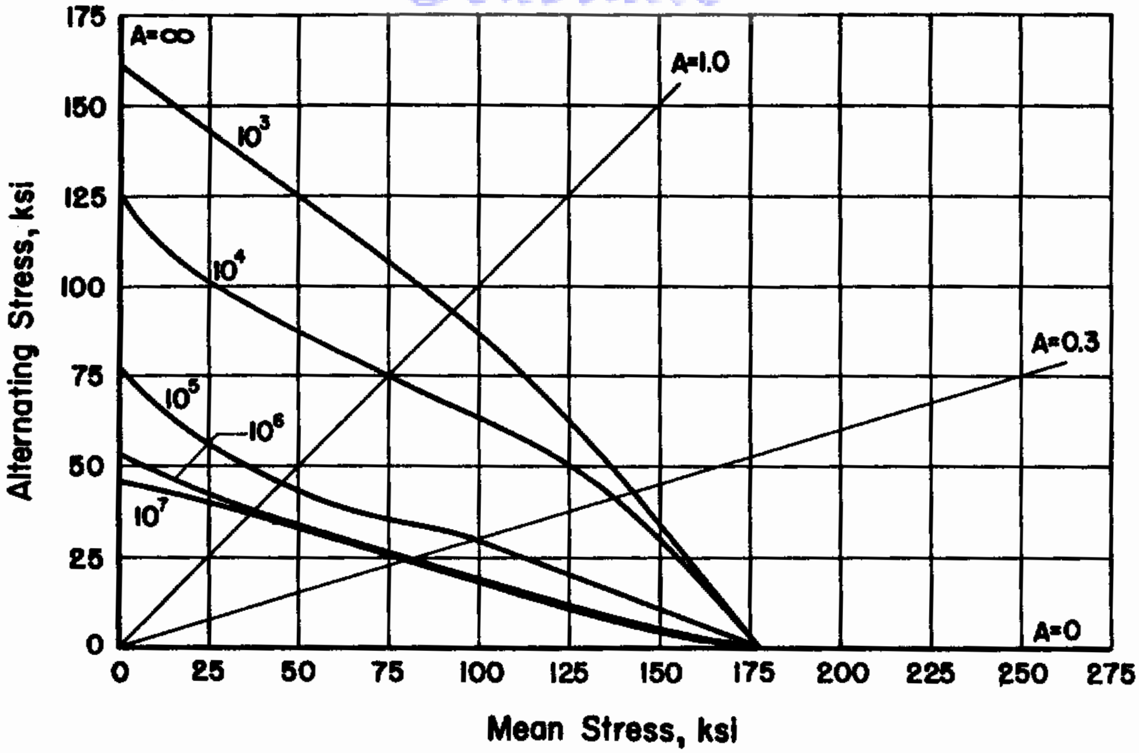

FIGURE 5.3.4(a). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.063 inch thick sheet).

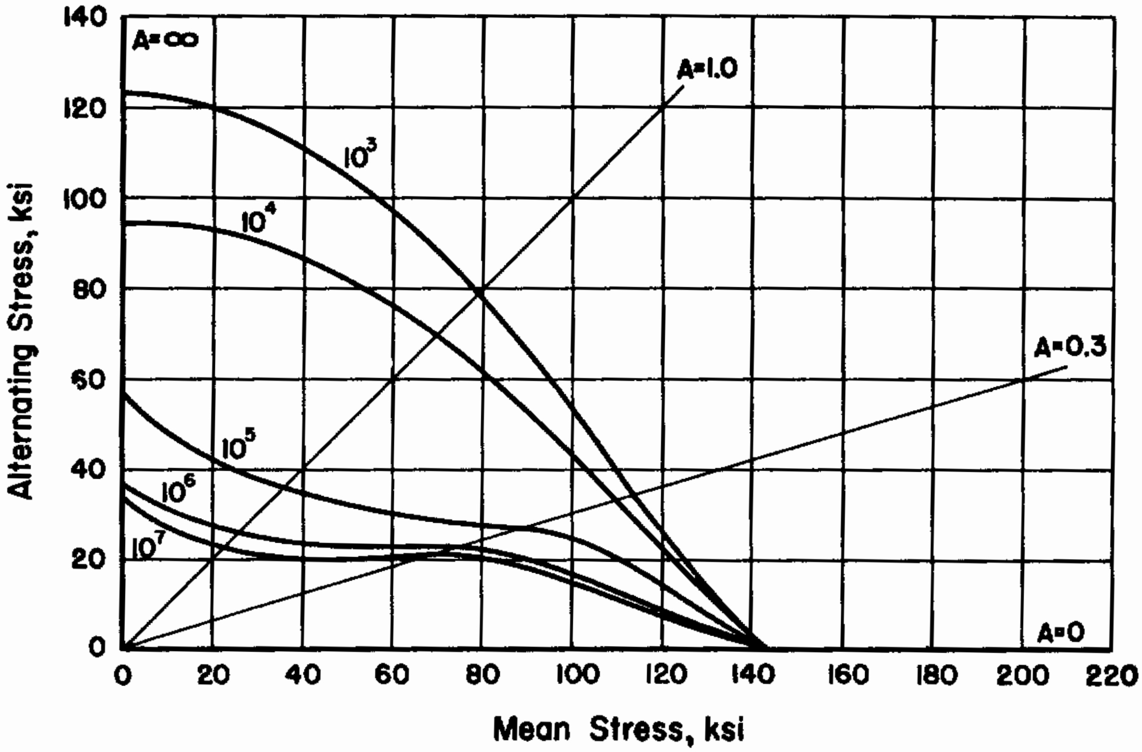

FIGURE 5.3.4(b). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.063 inch thick sheet).

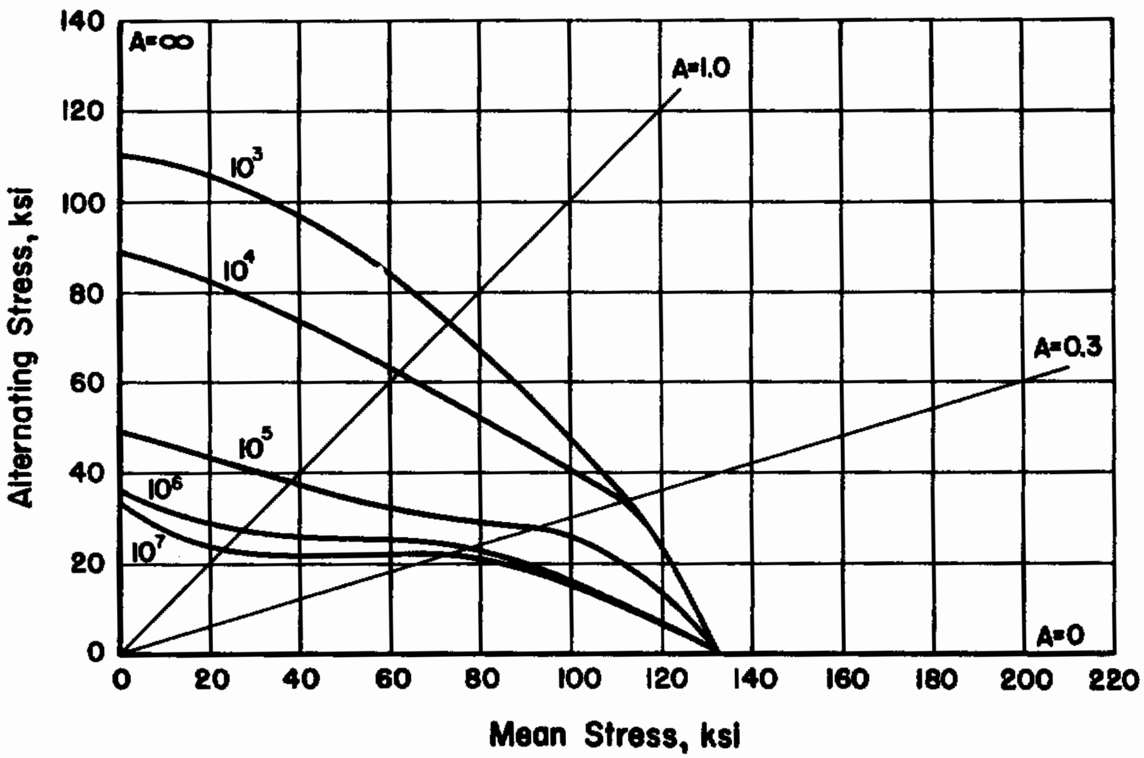

FIGURE 5.3.4(c). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.063 inch thick sheet).

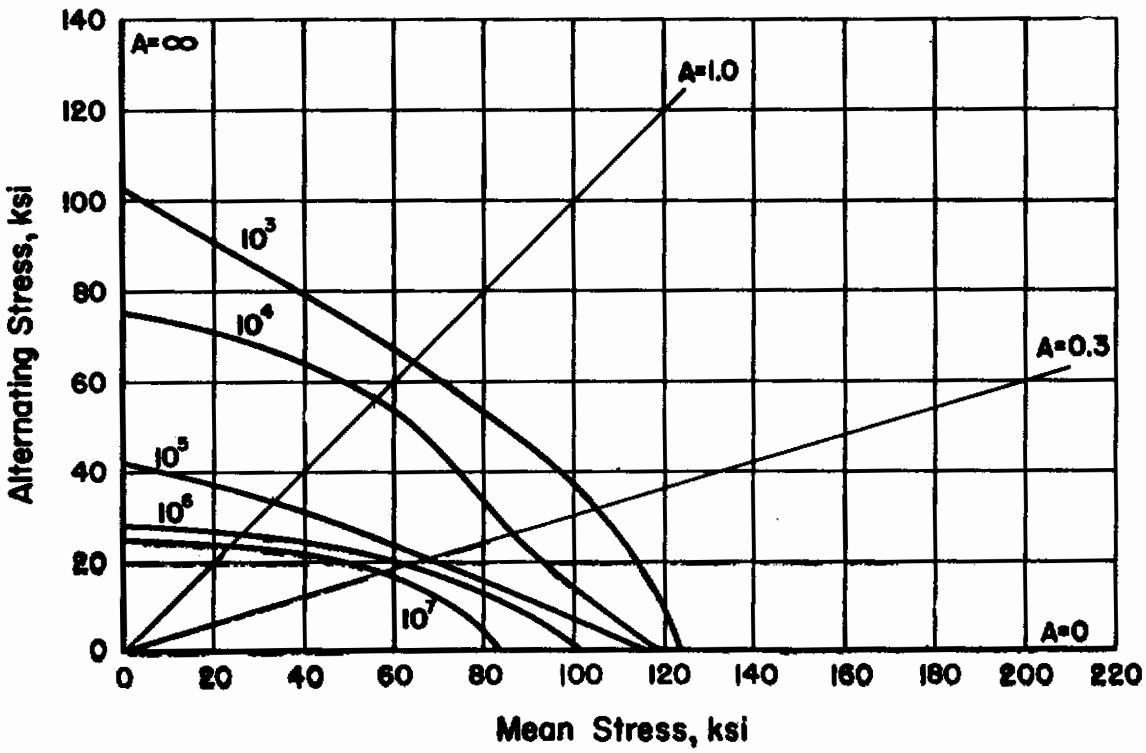

FIGURE 5.3.4(d). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.063 inch thick sheet).

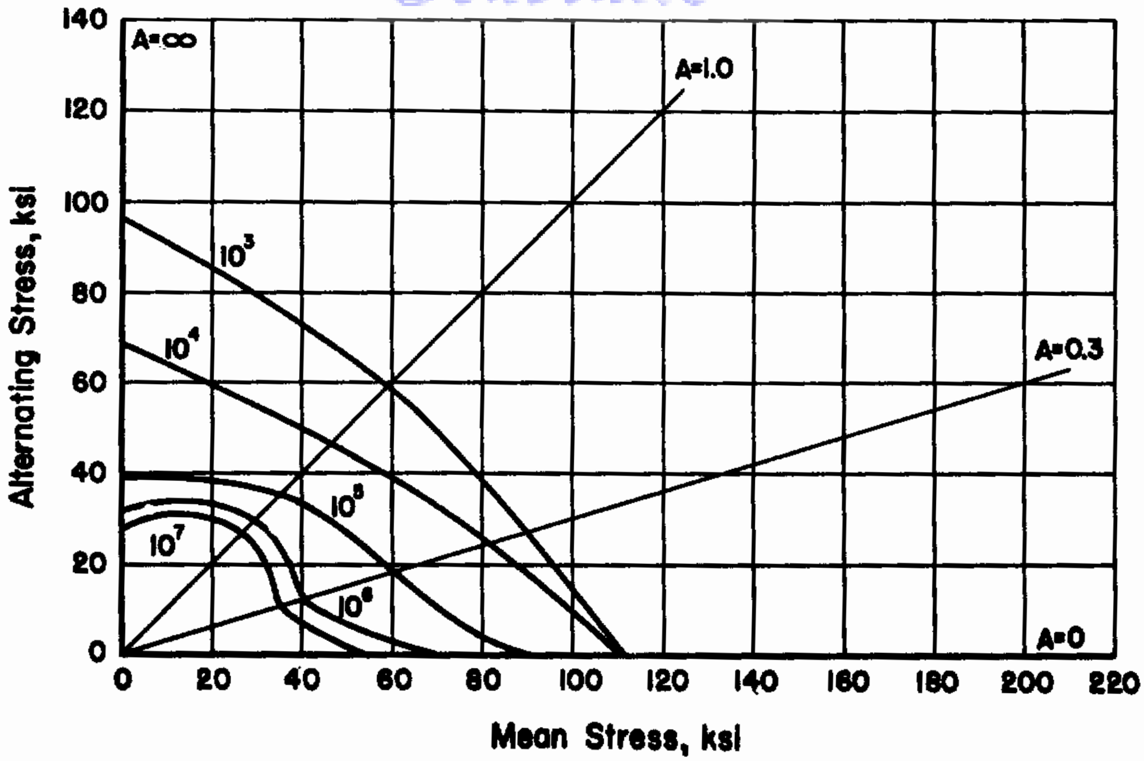

FIGURE 5.3.4(e). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.063 inch thick sheet).

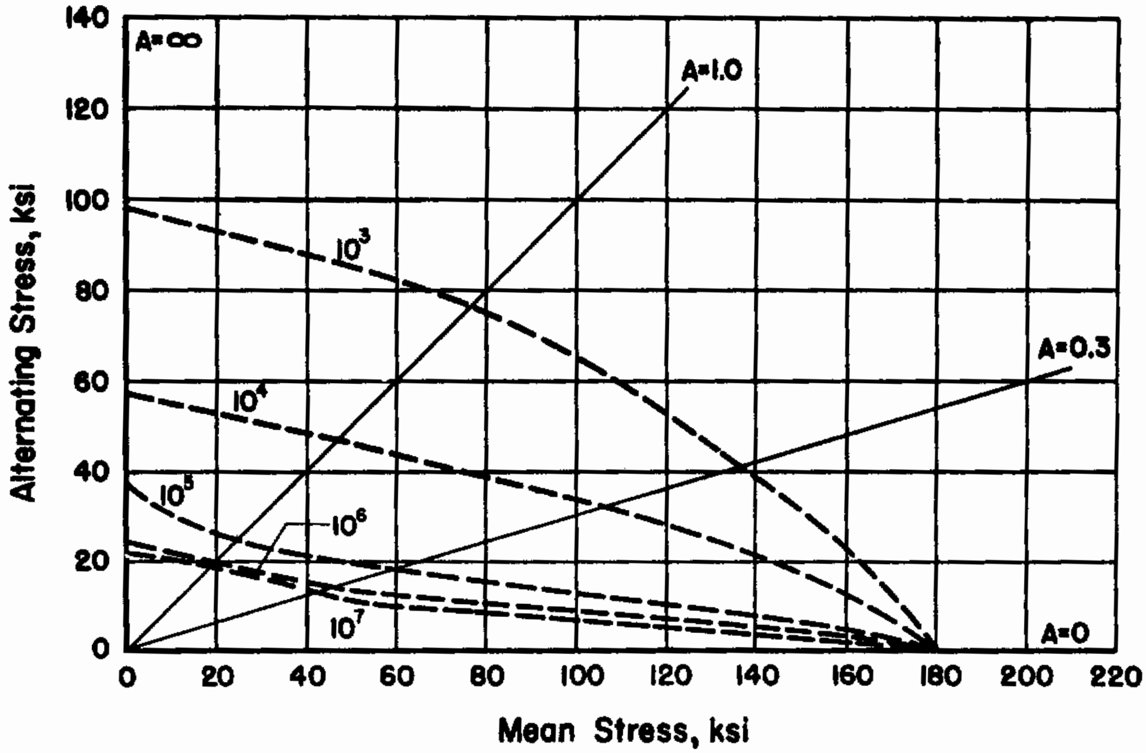

FIGURE 5.3.4(f). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.063 inch thick sheet).

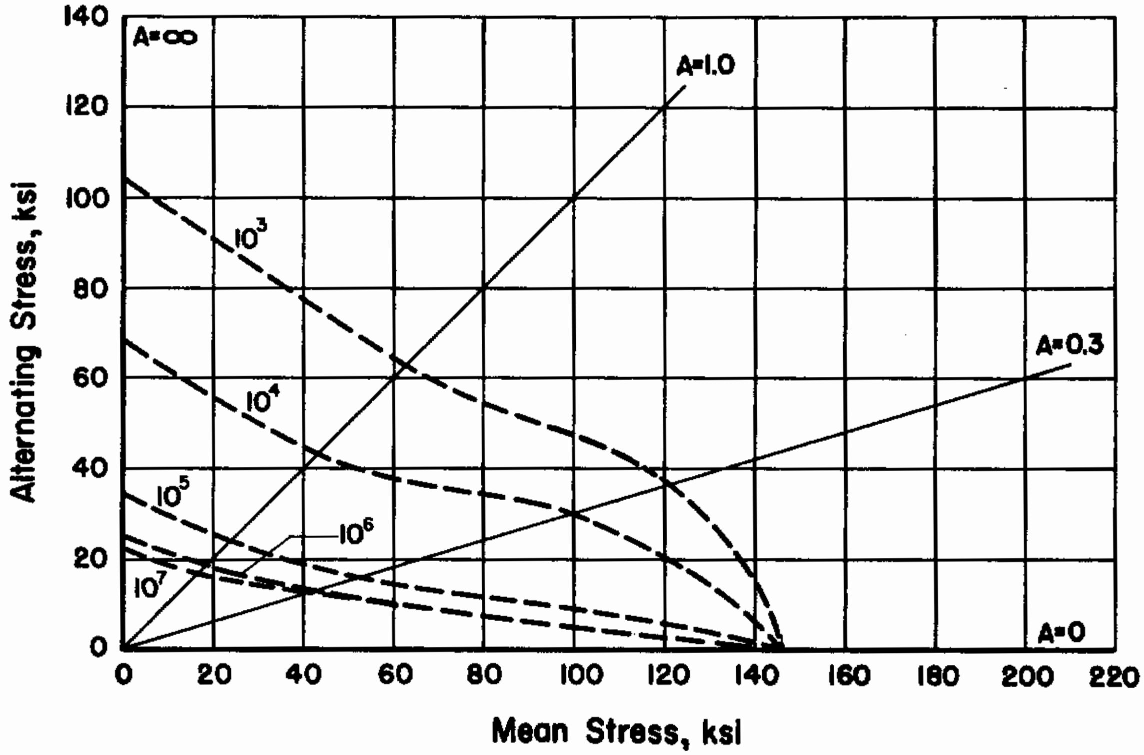

FIGURE 5.3.4(g). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.063 inch thick sheet).

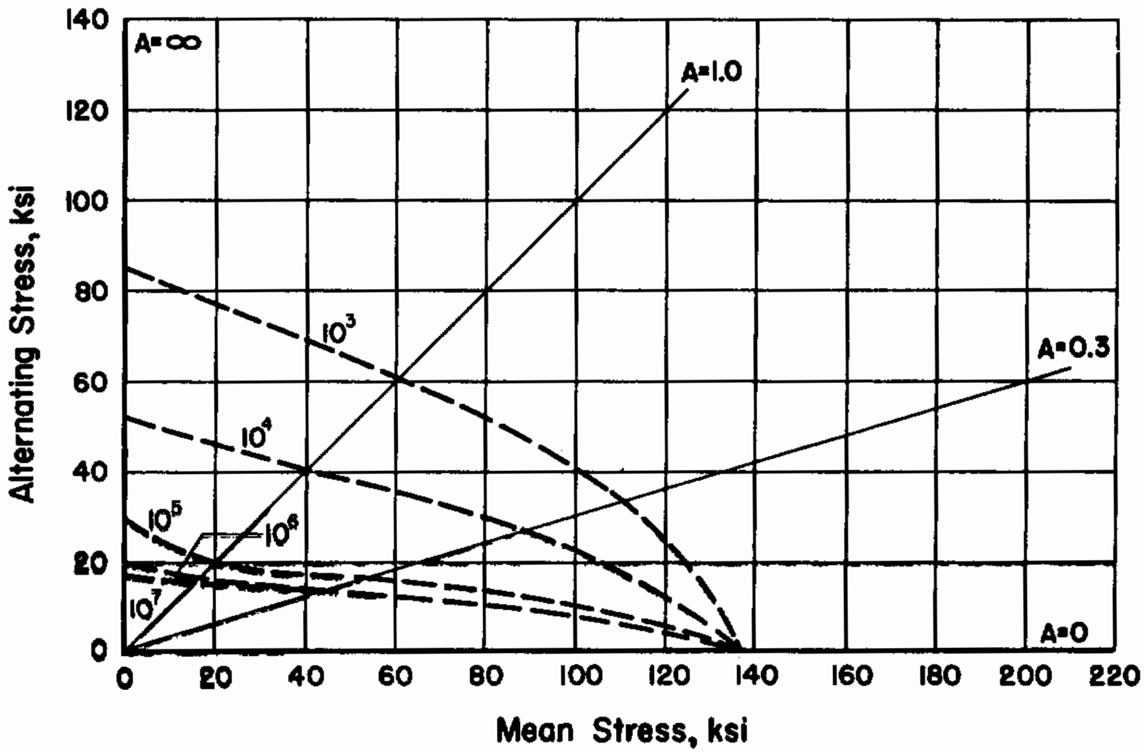

FIGURE 5.3.4(h). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.063 inch thick sheet).

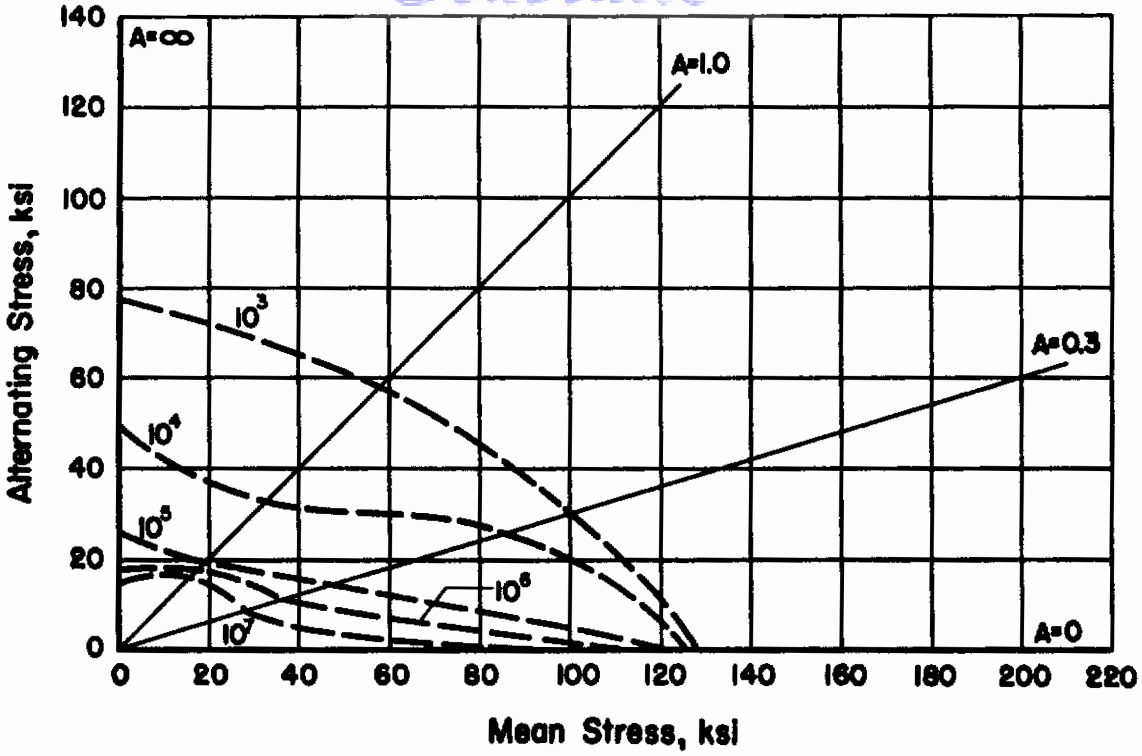

FIGURE 5.3.4(i). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.063 inch thick sheet).

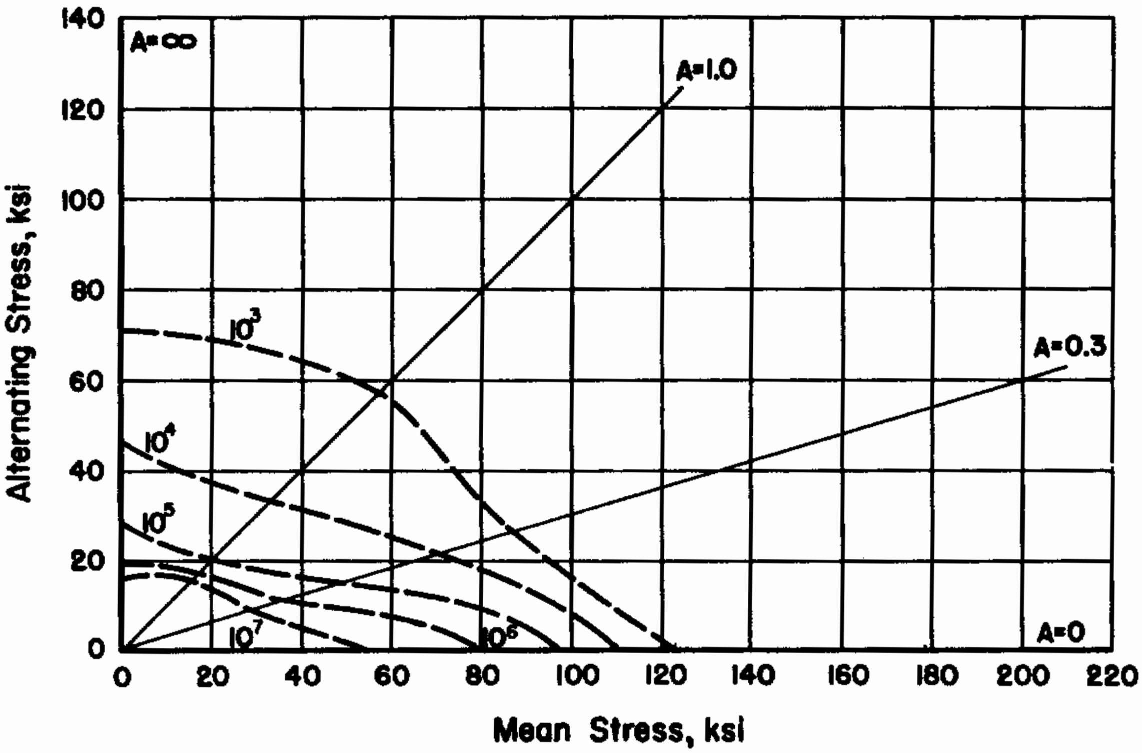

FIGURE 5.3.4(j). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.063 inch thick sheet).

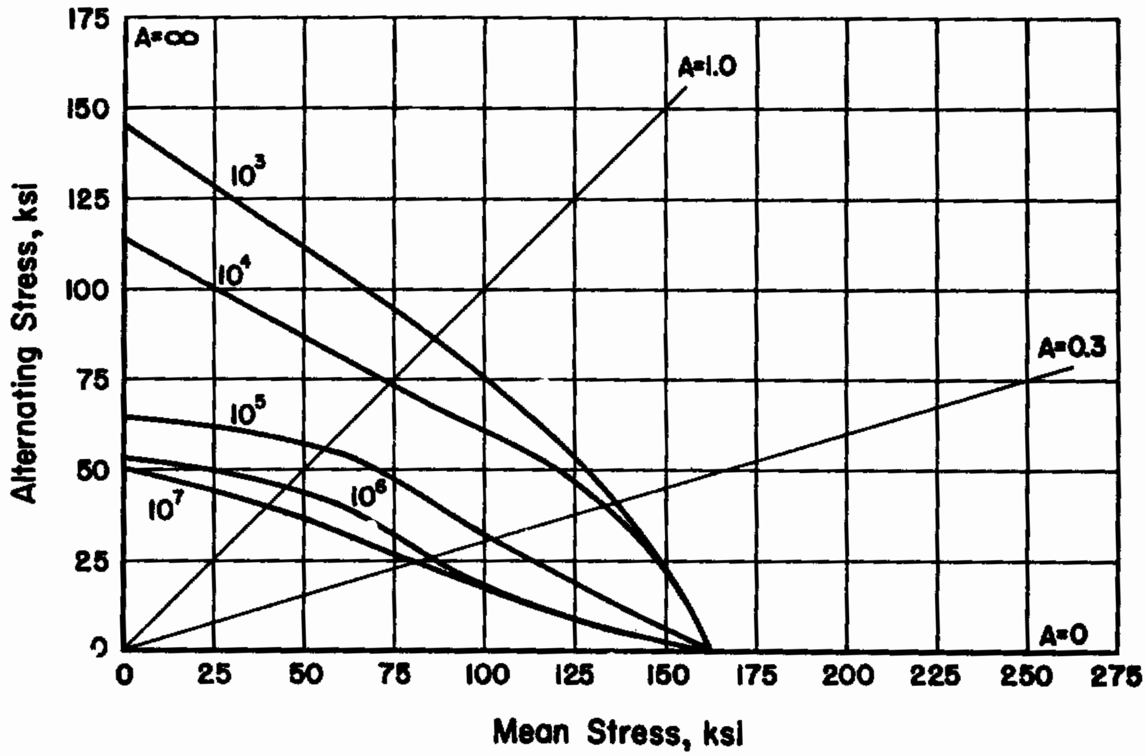

FIGURE 5.3.4(k). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.125 inch thick sheet).

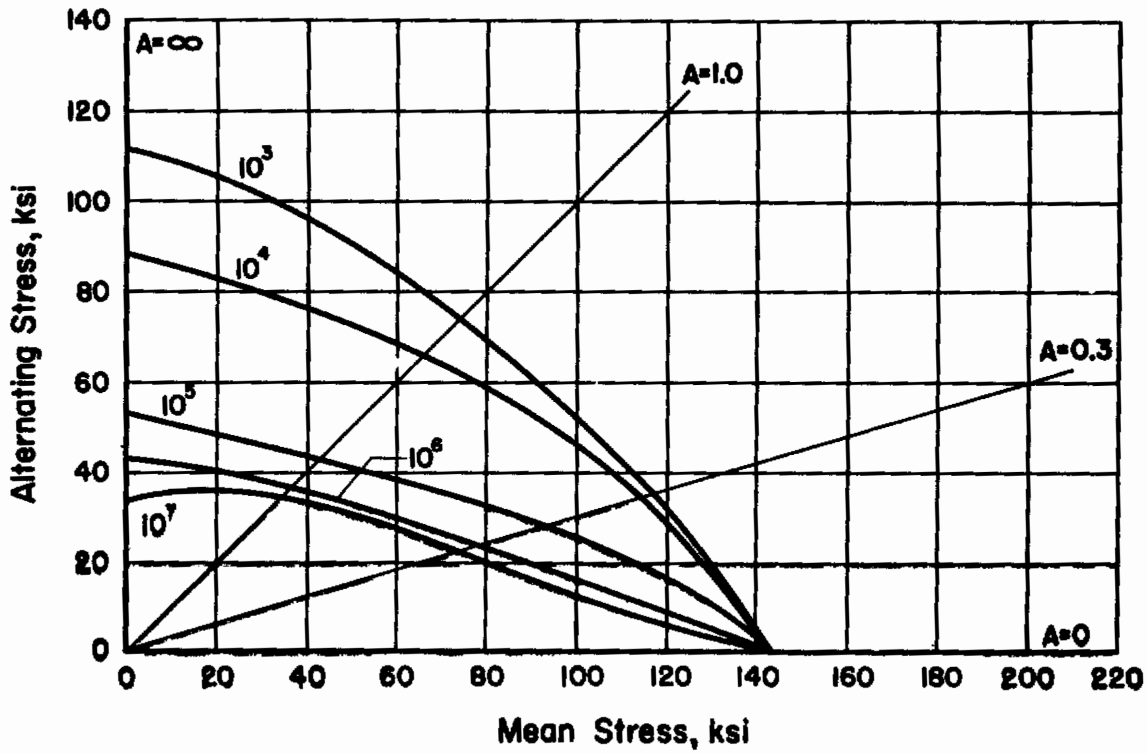

FIGURE 5.3.4(l). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.125 inch thick sheet).

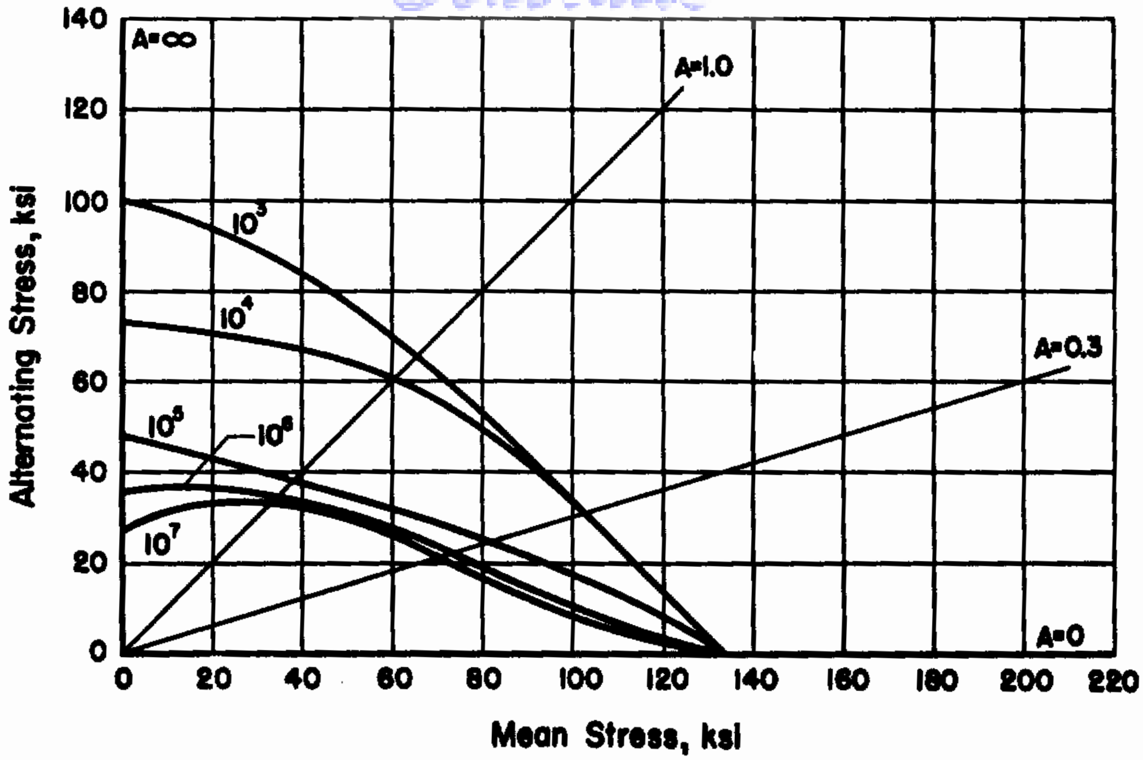

FIGURE 5.3.4(m). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.125 inch thick sheet).

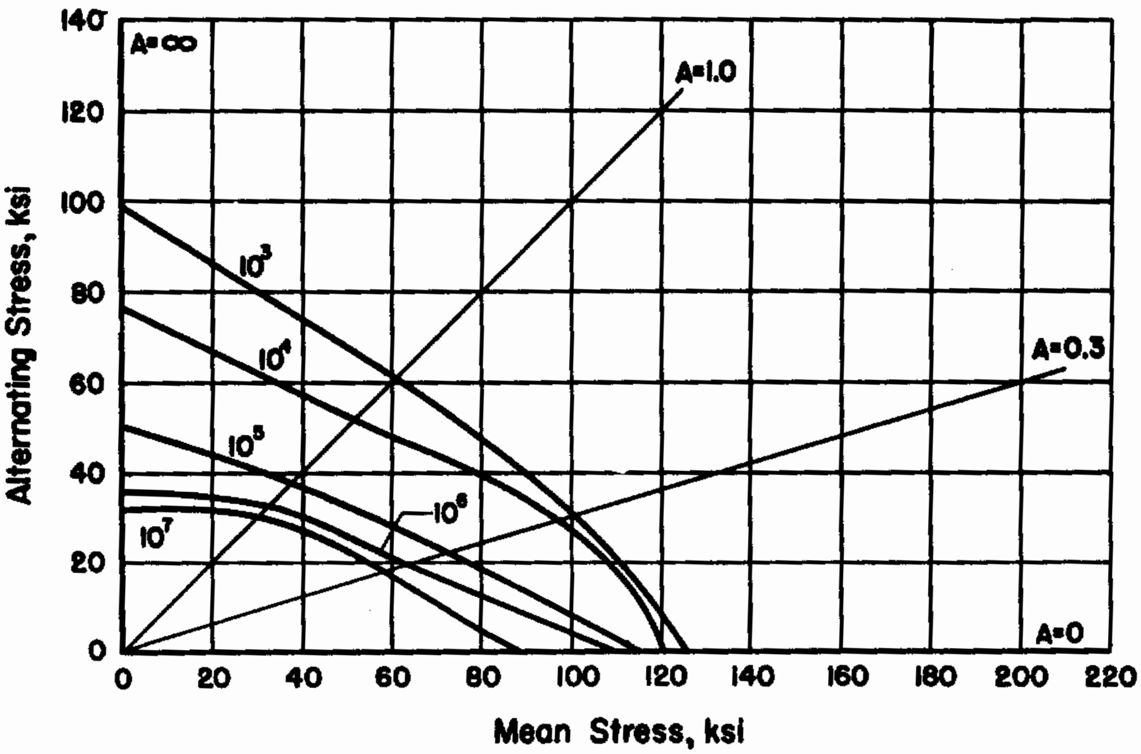

FIGURE 5.3.4(n). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.125 inch thick sheet).

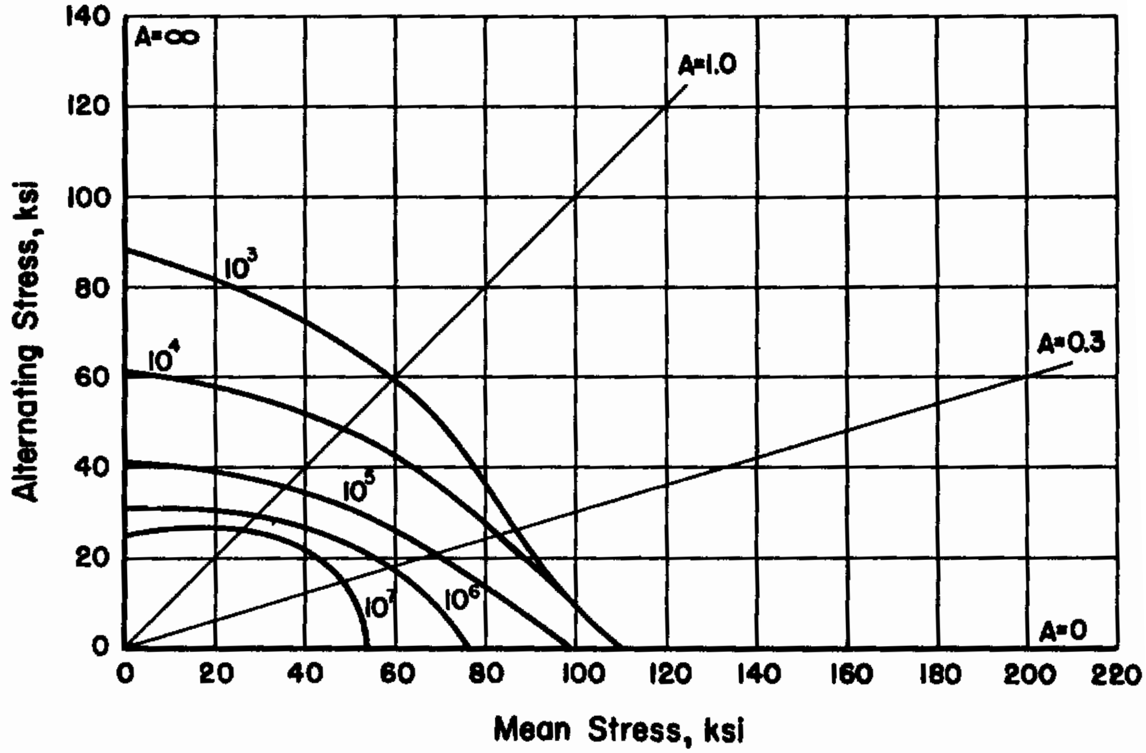

FIGURE 5.3.4(o). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.125 inch thick sheet).

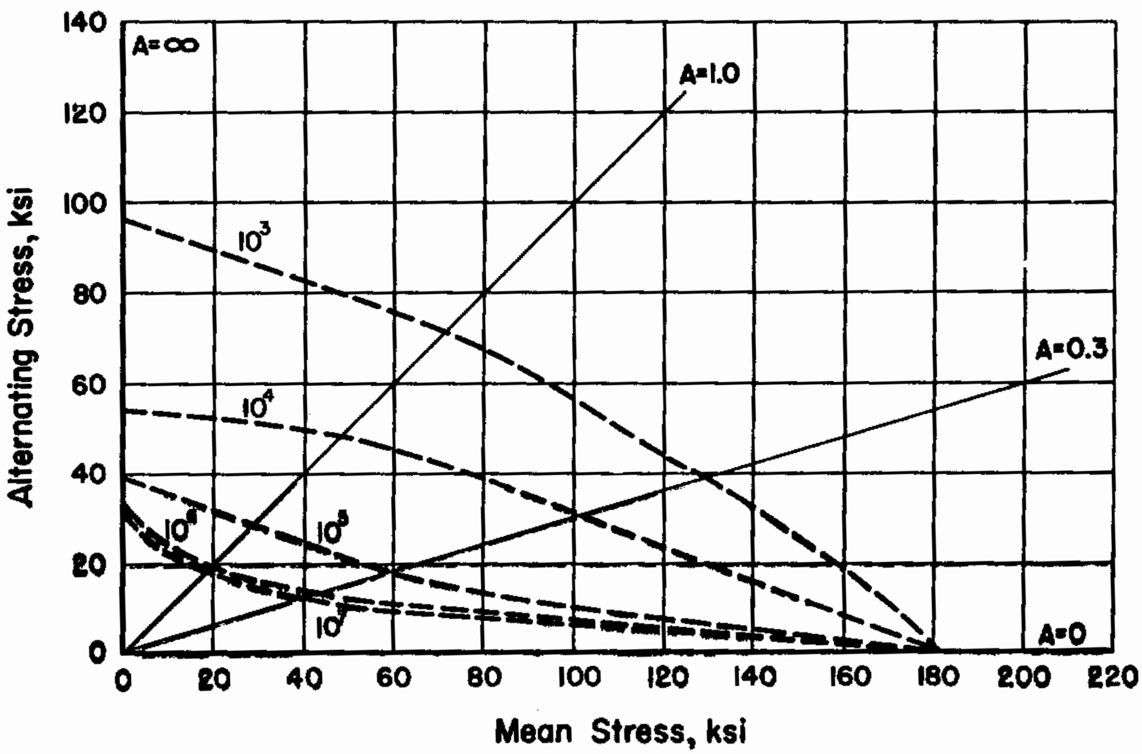

FIGURE 5.3.4(p). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.125 inch thick sheet).

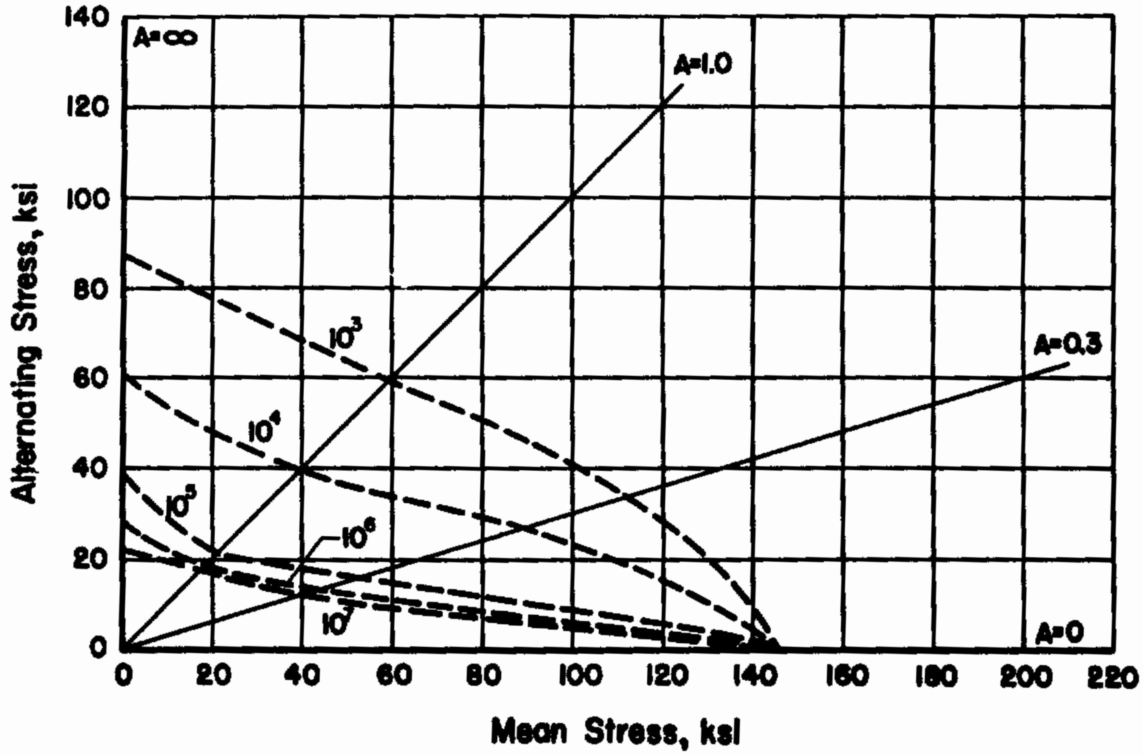

FIGURE 5.3.4(q). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.125 inch thick sheet).

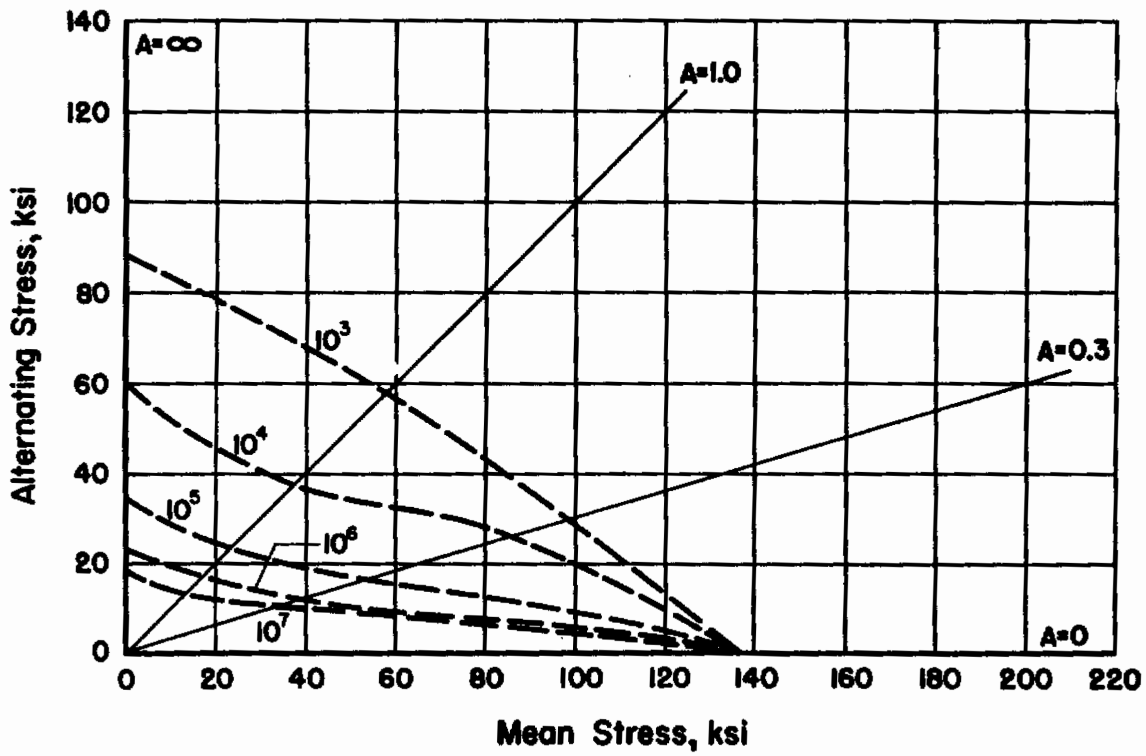

FIGURE 5.3.4(r). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.125 inch thick sheet).

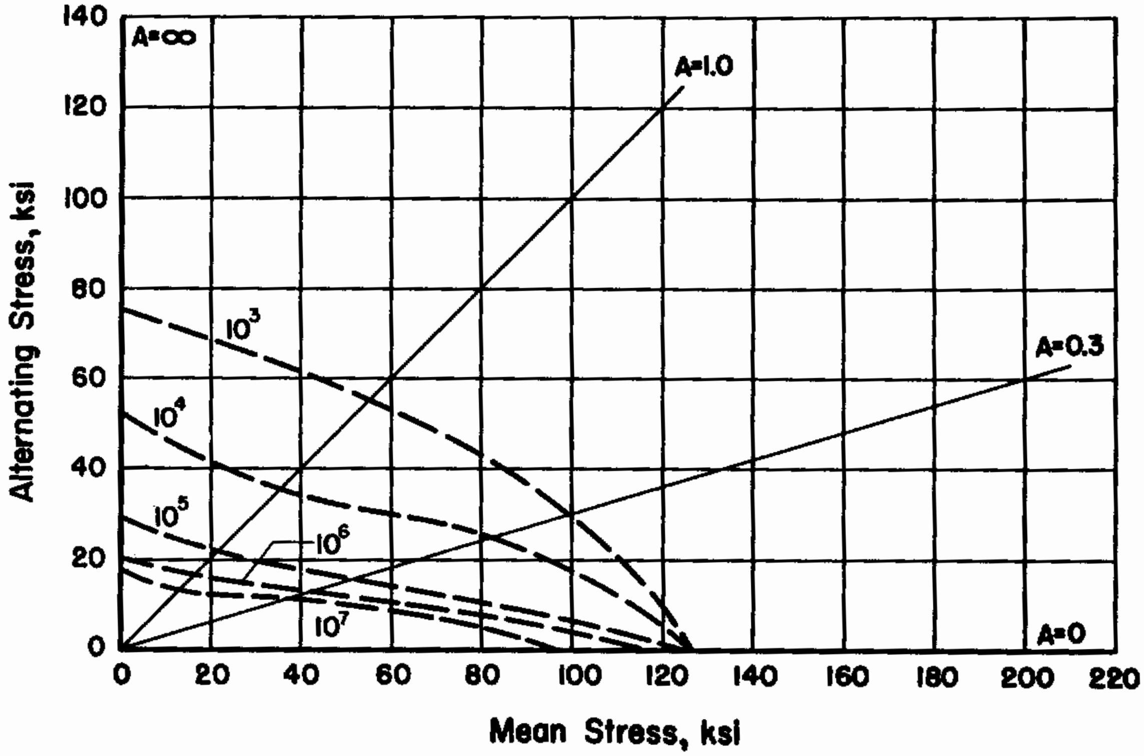

FIGURE 5.3.4(s). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.125 inch thick sheet).

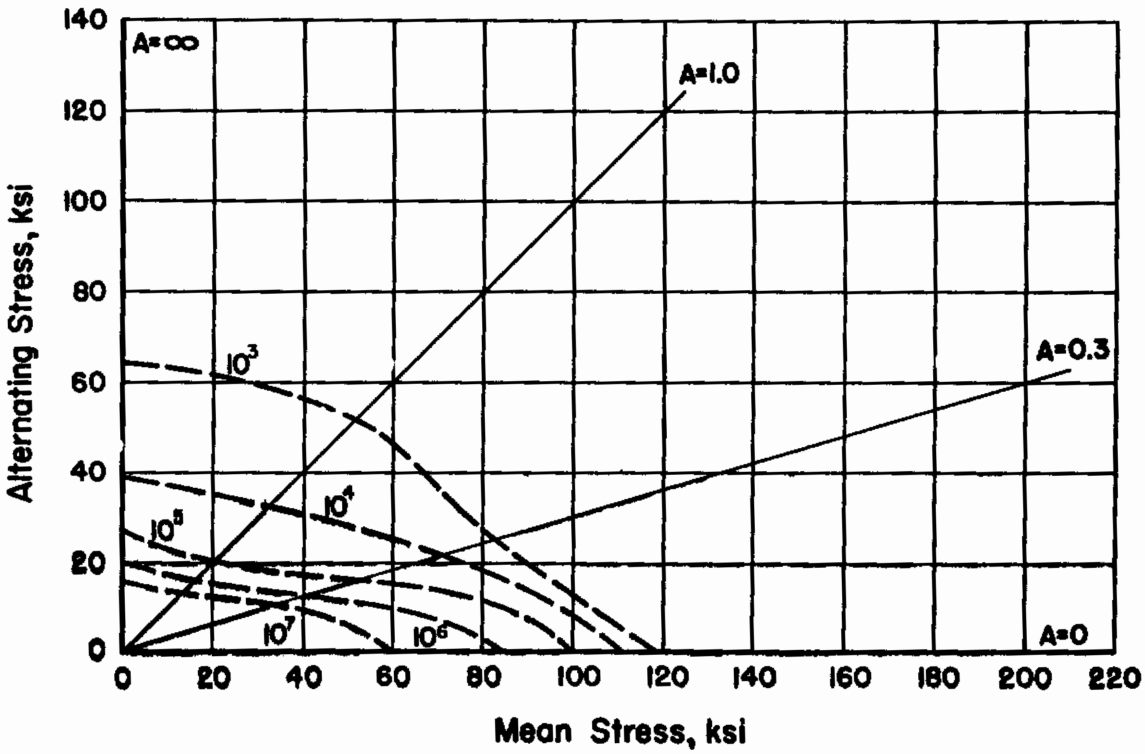

FIGURE 5.3.4(t). Direct stress fatigue properties of 6Al-4V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.125 inch thick sheet).

5.3.5 Fatigue Properties of 4Al-3Mo-IV Titanium Alloy

Axial-load fatigue data for smooth specimens at temperatures up to 900°F are given in Figures 5.3.5(a) through 5.3.5(o). Figures 5.3.5(aa) through 5.3.5(oo) are for specimens having a K_t = 2.82 over the same temperature range.

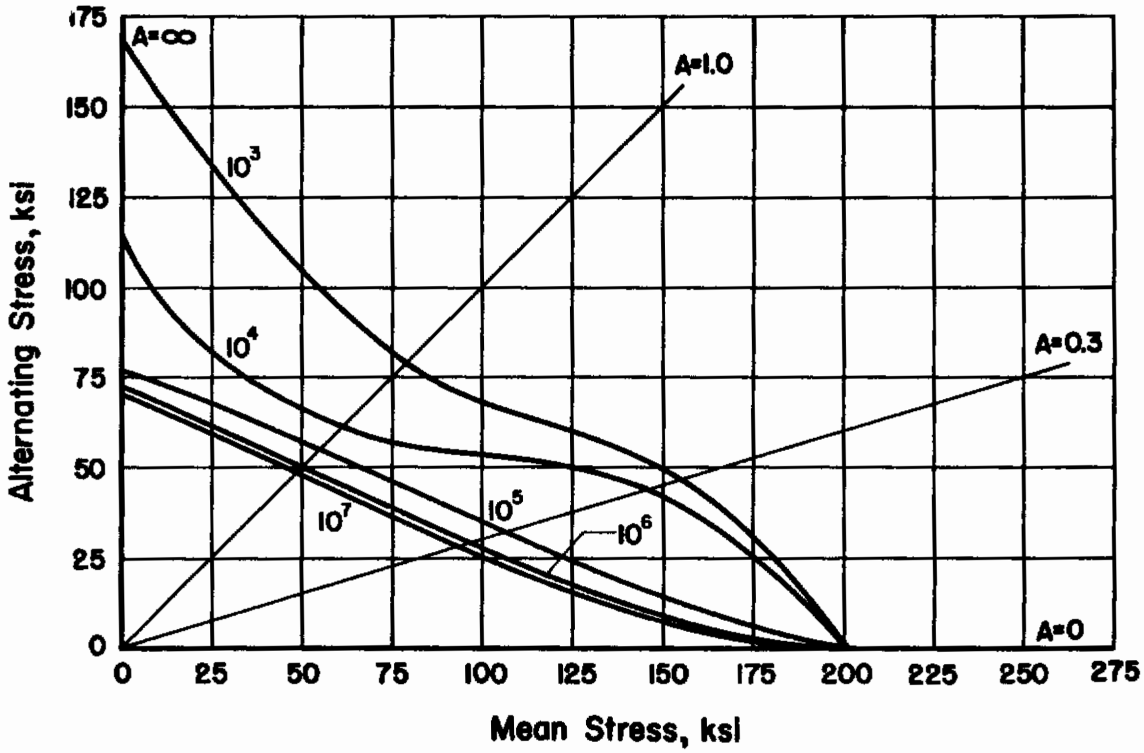

FIGURE 5.3.5(a). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.020 inch thick sheet).

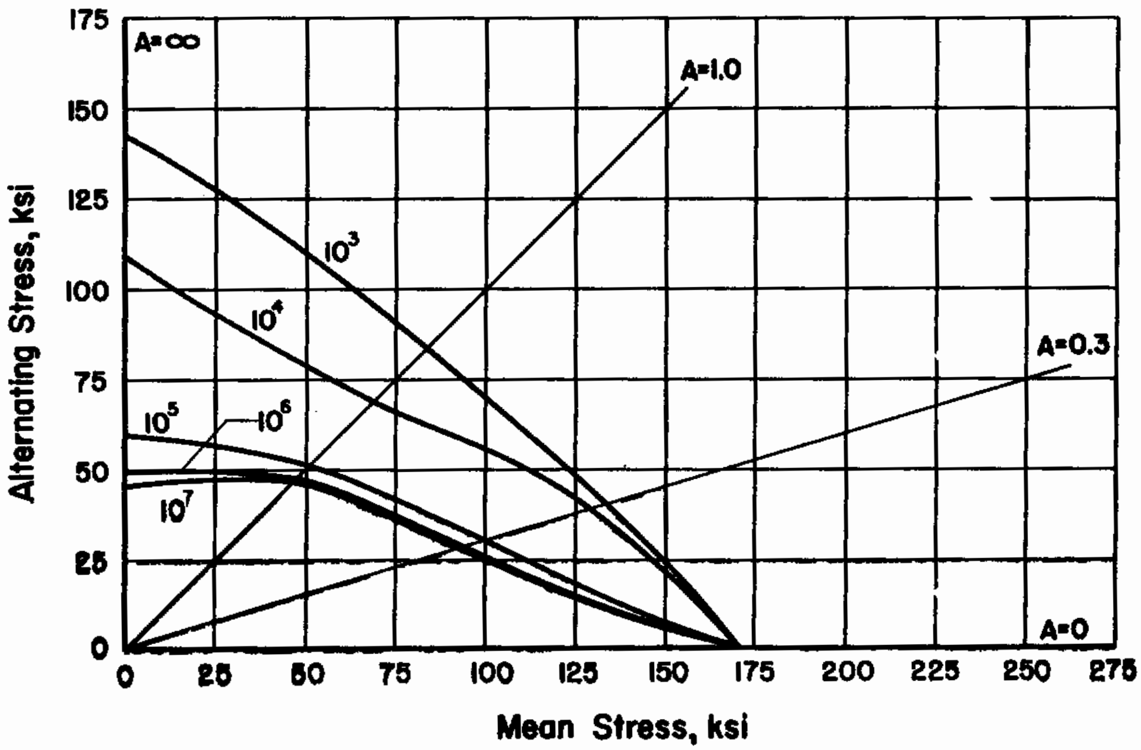

FIGURE 5.3.5(b). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.020 inch thick sheet).

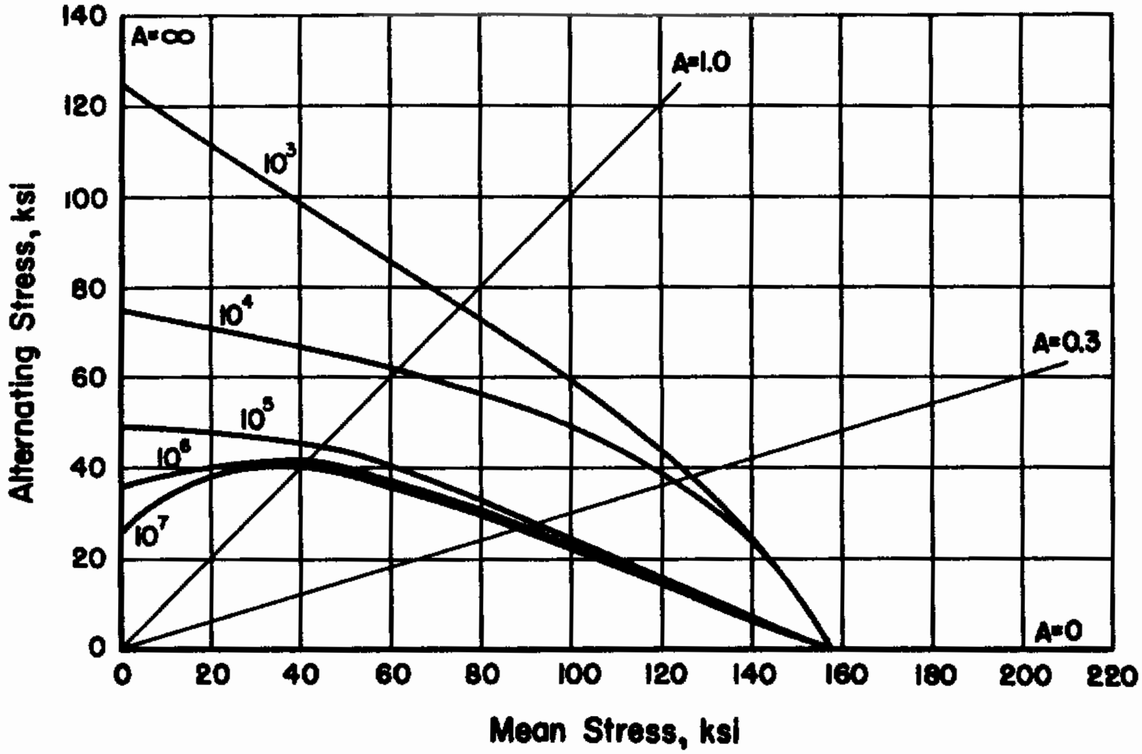

FIGURE 5.3.5(c). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.020 inch thick sheet).

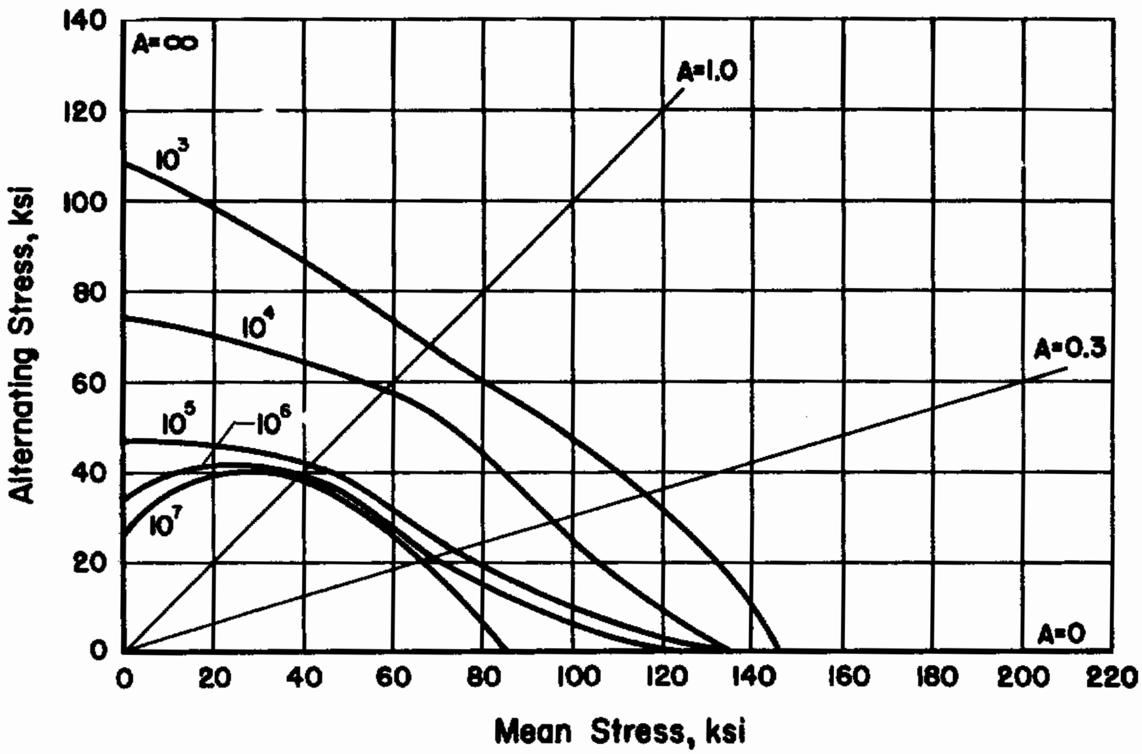

FIGURE 5.3.5(d). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.020 inch thick sheet).

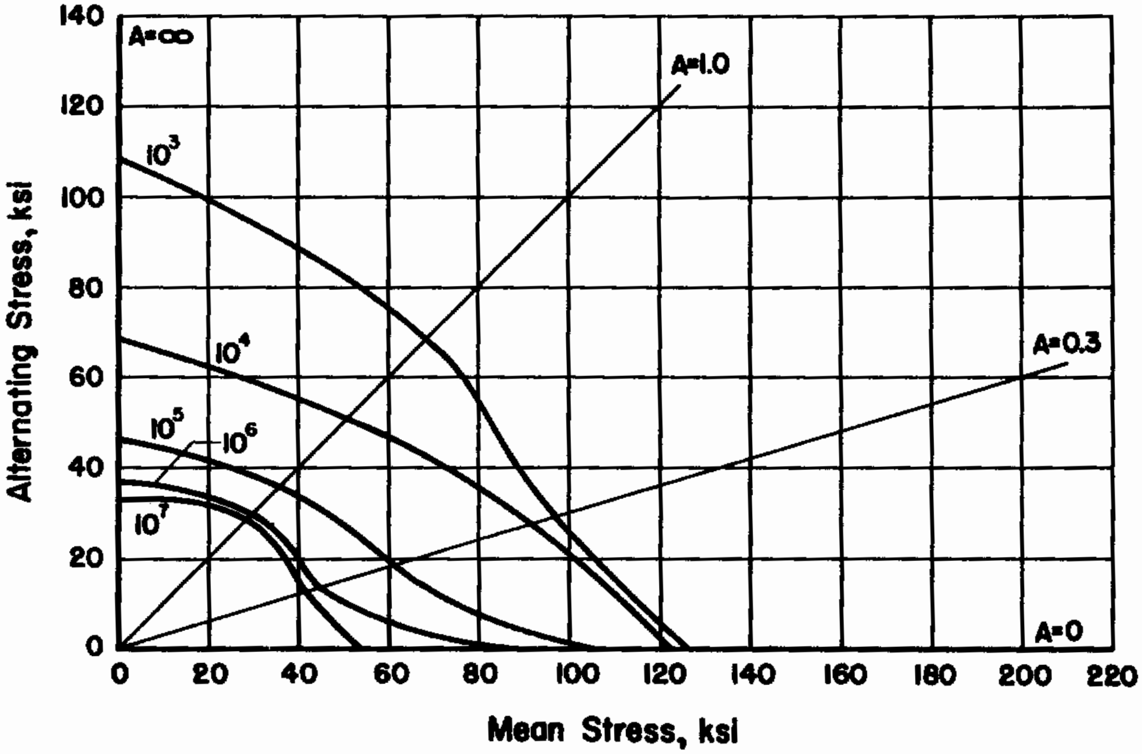

FIGURE 5.3.5(e). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.020 inch thick sheet).

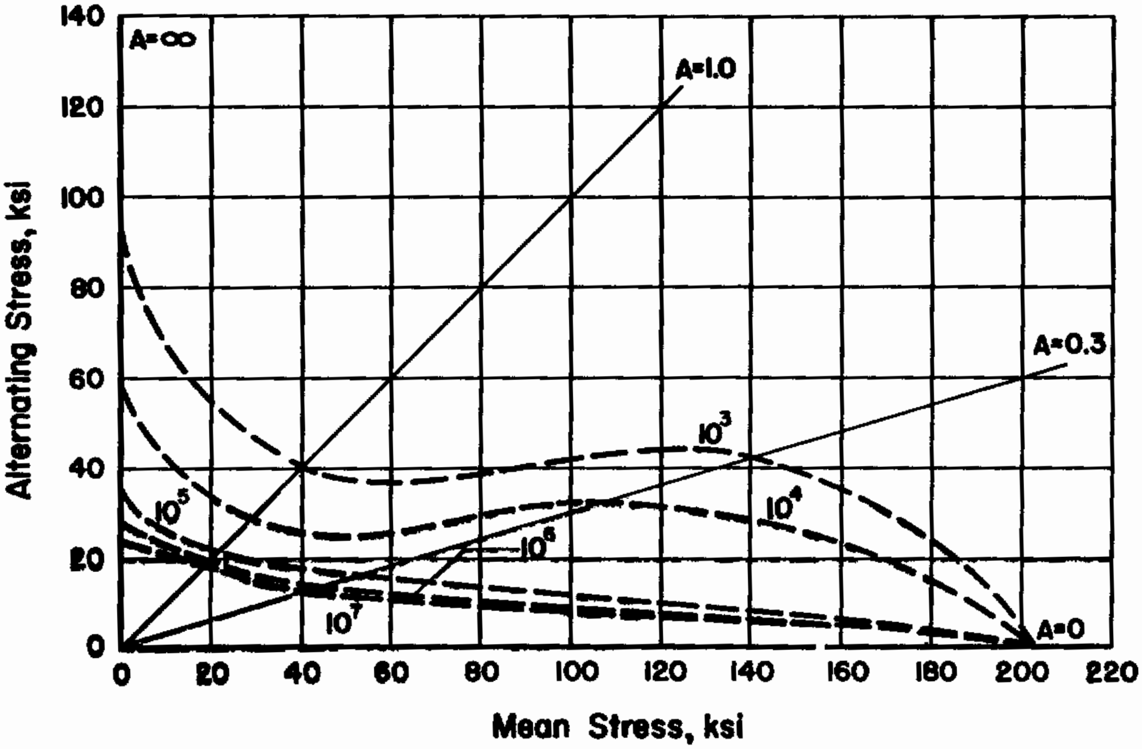

FIGURE 5.3.5(aa). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.020 inch thick sheet).

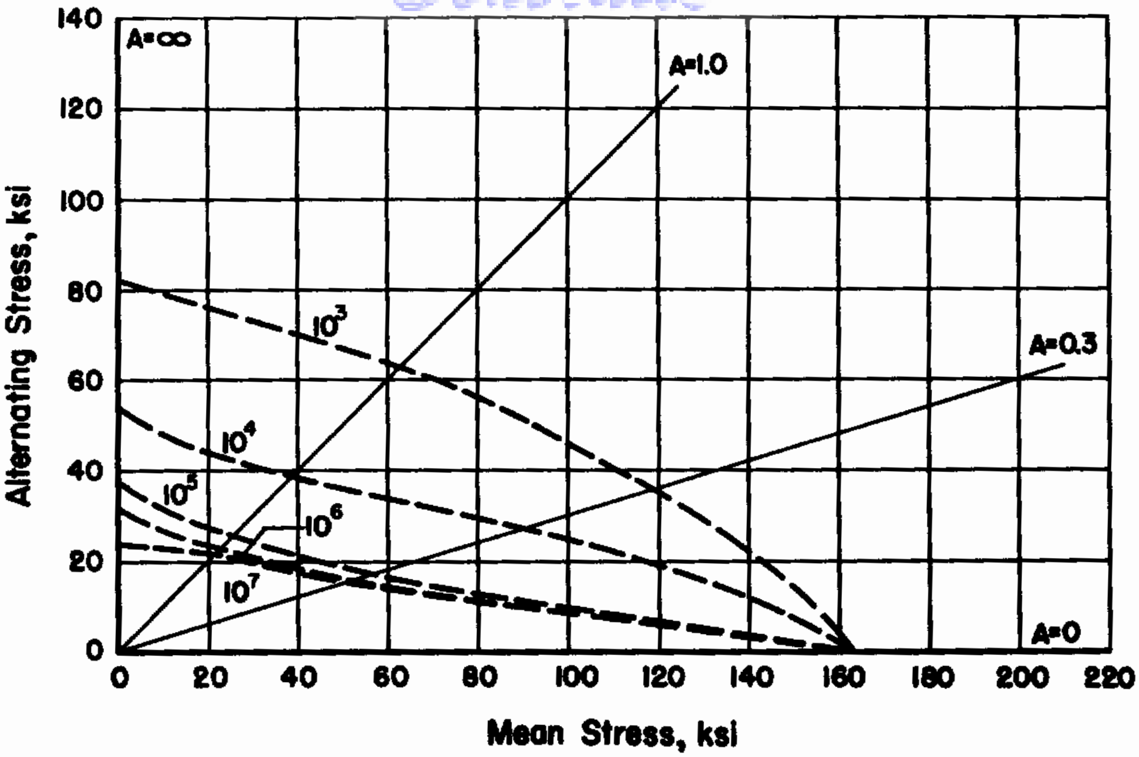

FIGURE 5.3.5(bb). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.020 inch thick sheet).

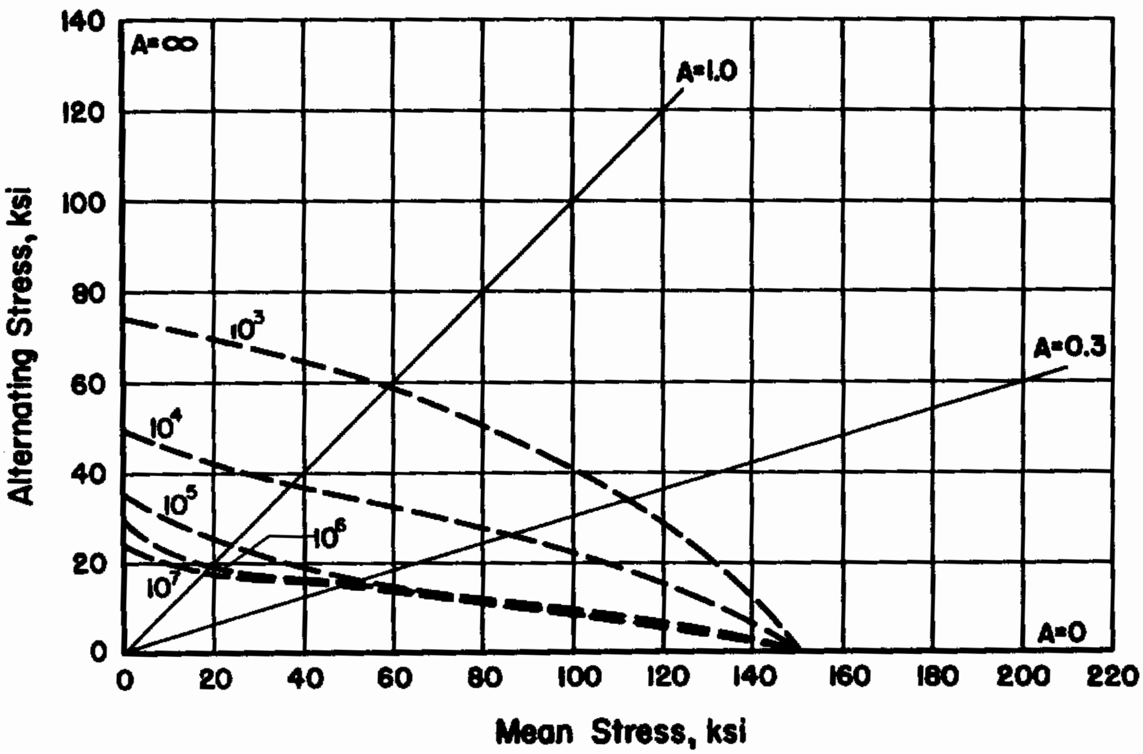

FIGURE 5.3.5(cc). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.020 inch thick sheet).

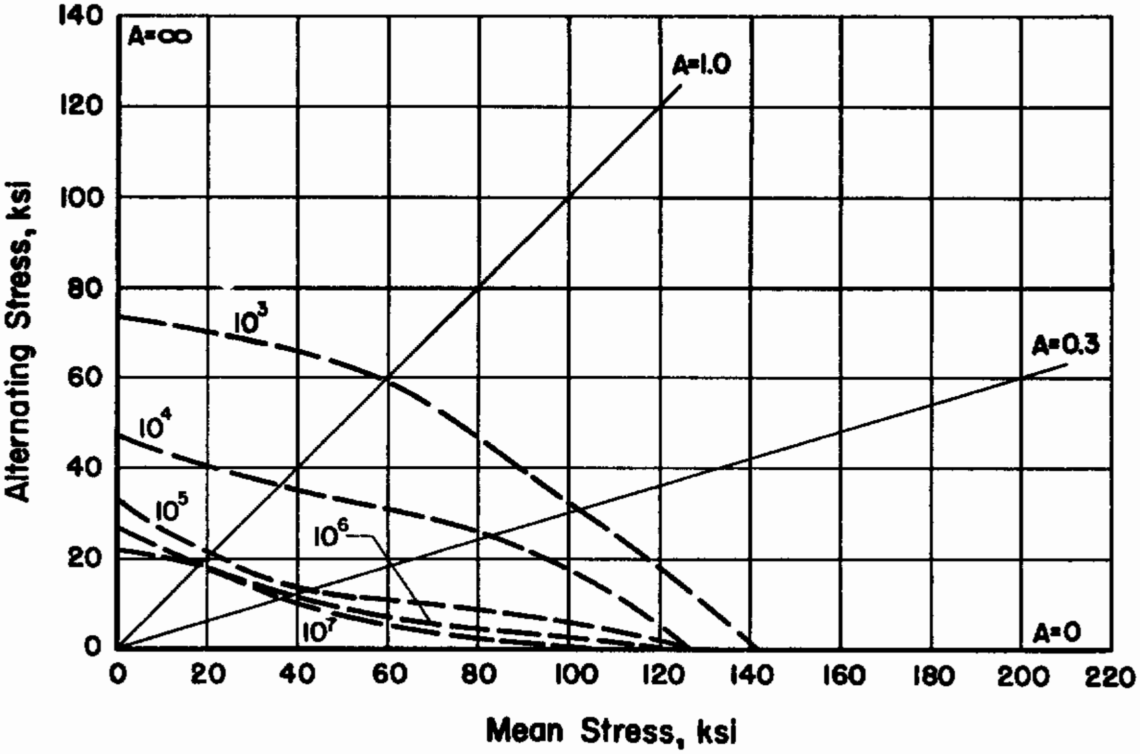

FIGURE 5.3.5(dd). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.020 inch thick sheet).

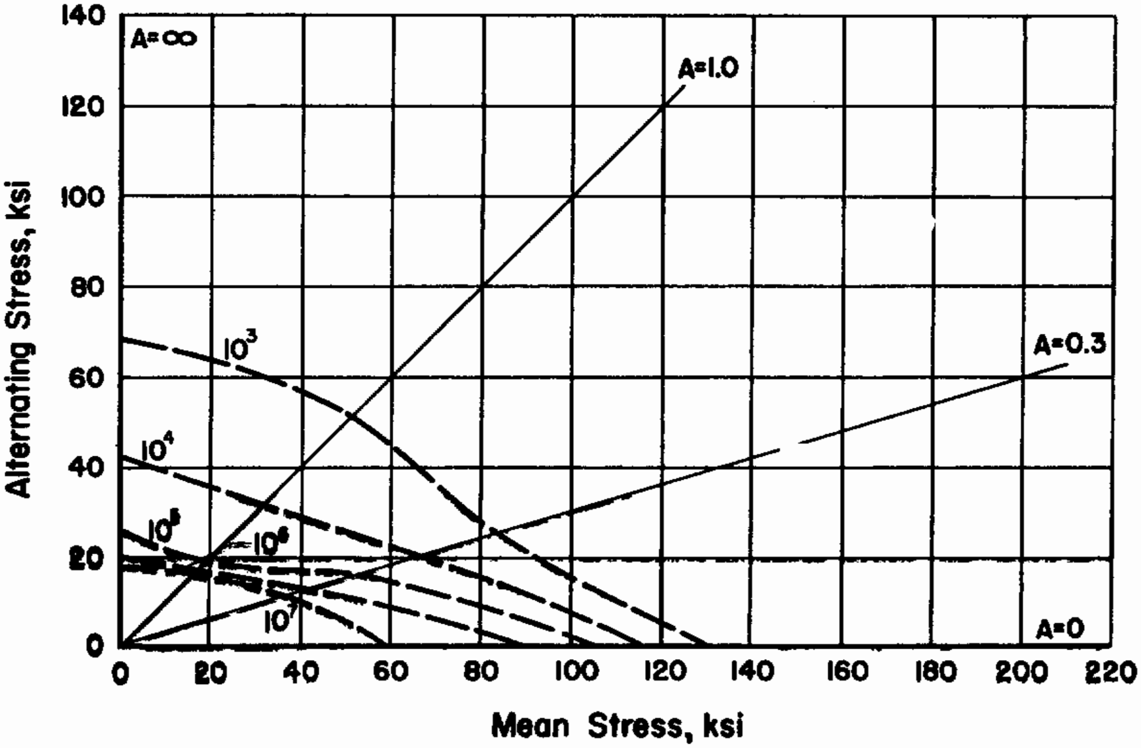

FIGURE 5.3.5(ee). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.020 inch thick sheet).

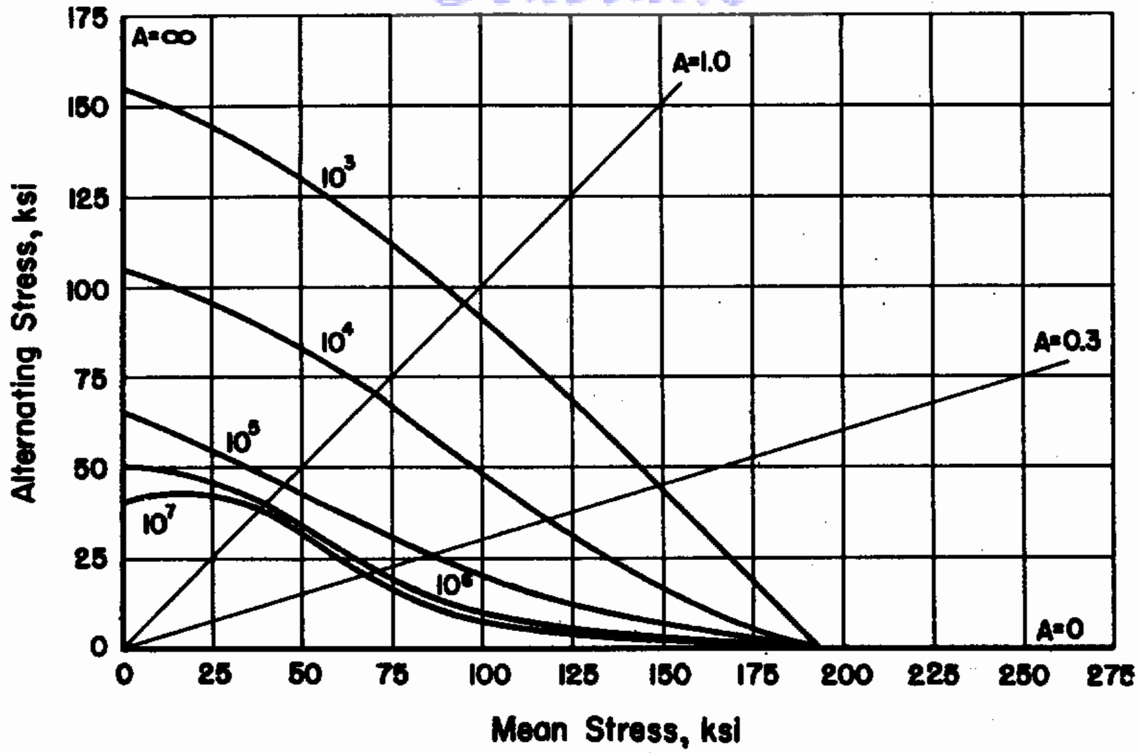

FIGURE 5.3.5(f). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.063 inch thick sheet).

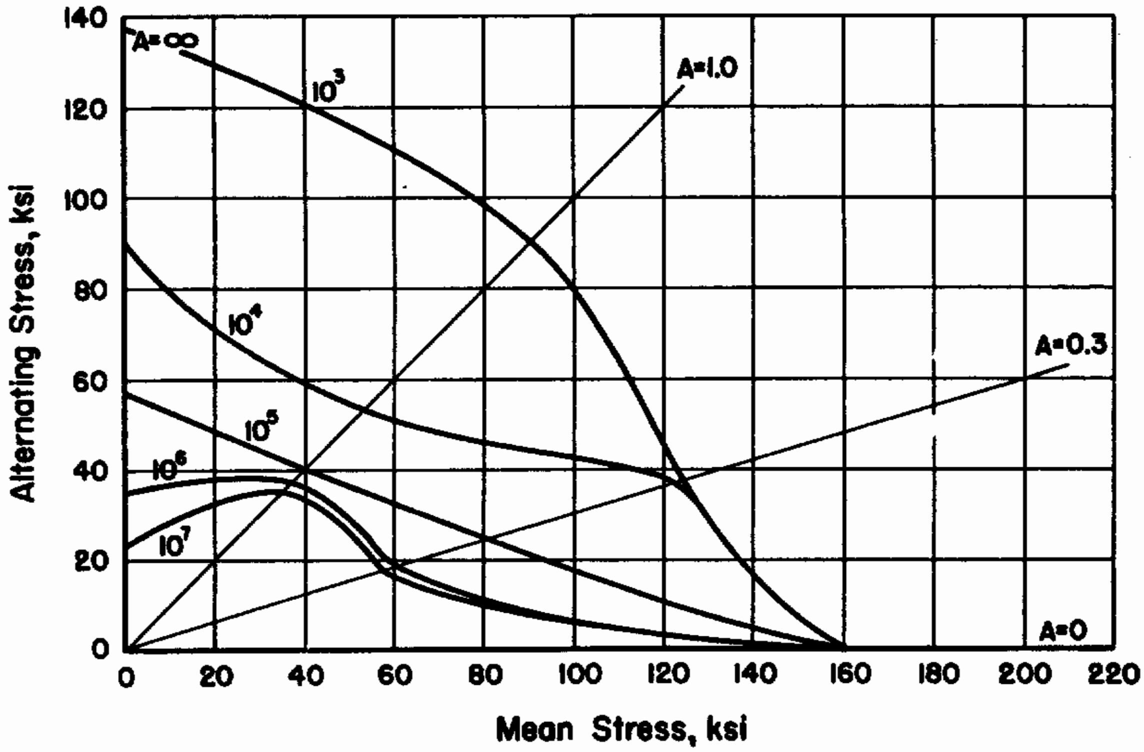

FIGURE 5.3.5(g). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.063 inch thick sheet).

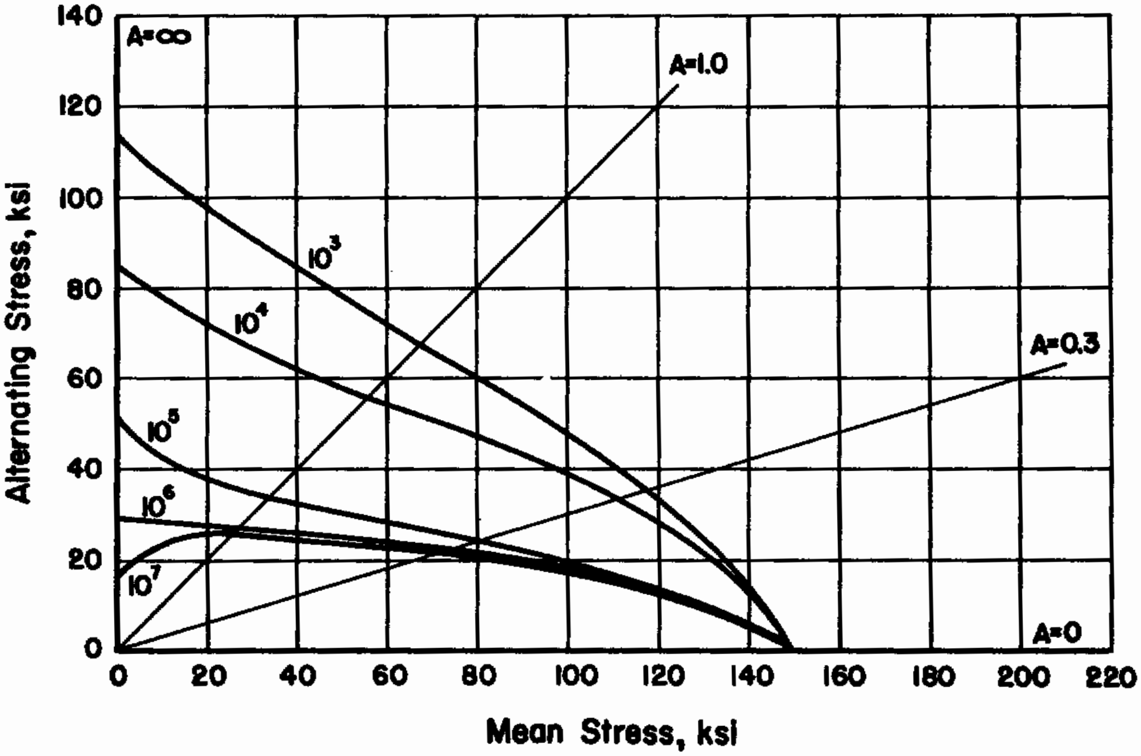

FIGURE 5.3.5(h). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.063 inch thick sheet).

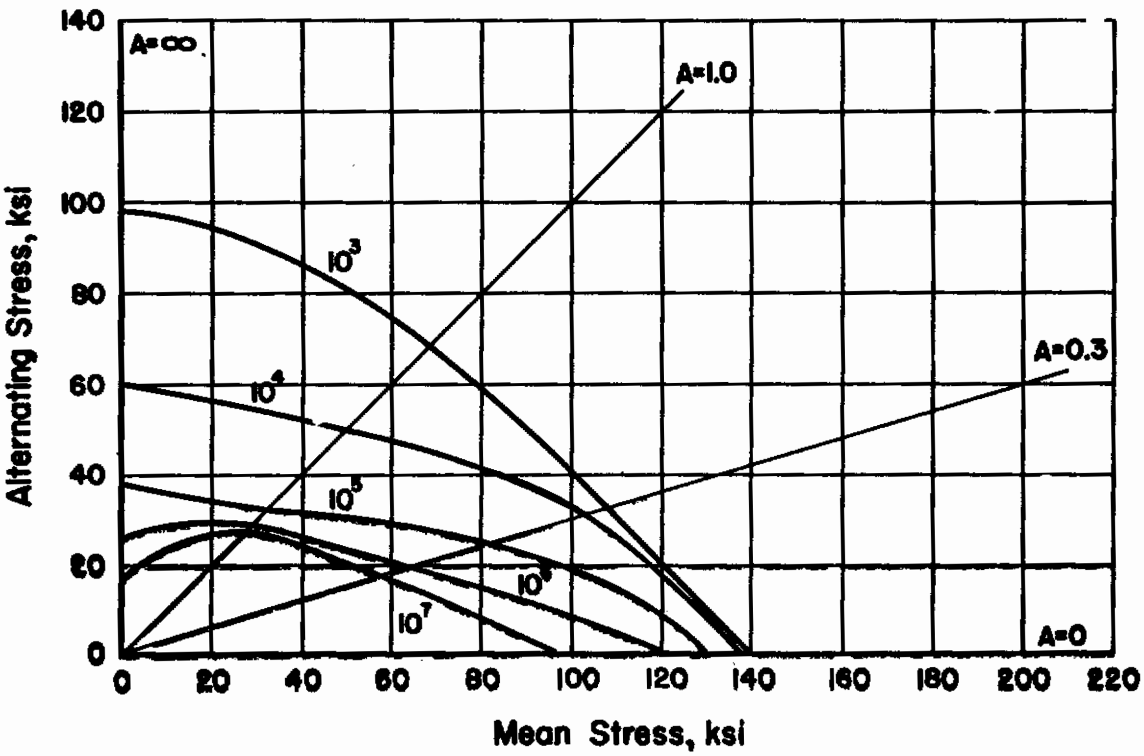

FIGURE 5.3.5(i). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.063 inch thick sheet).

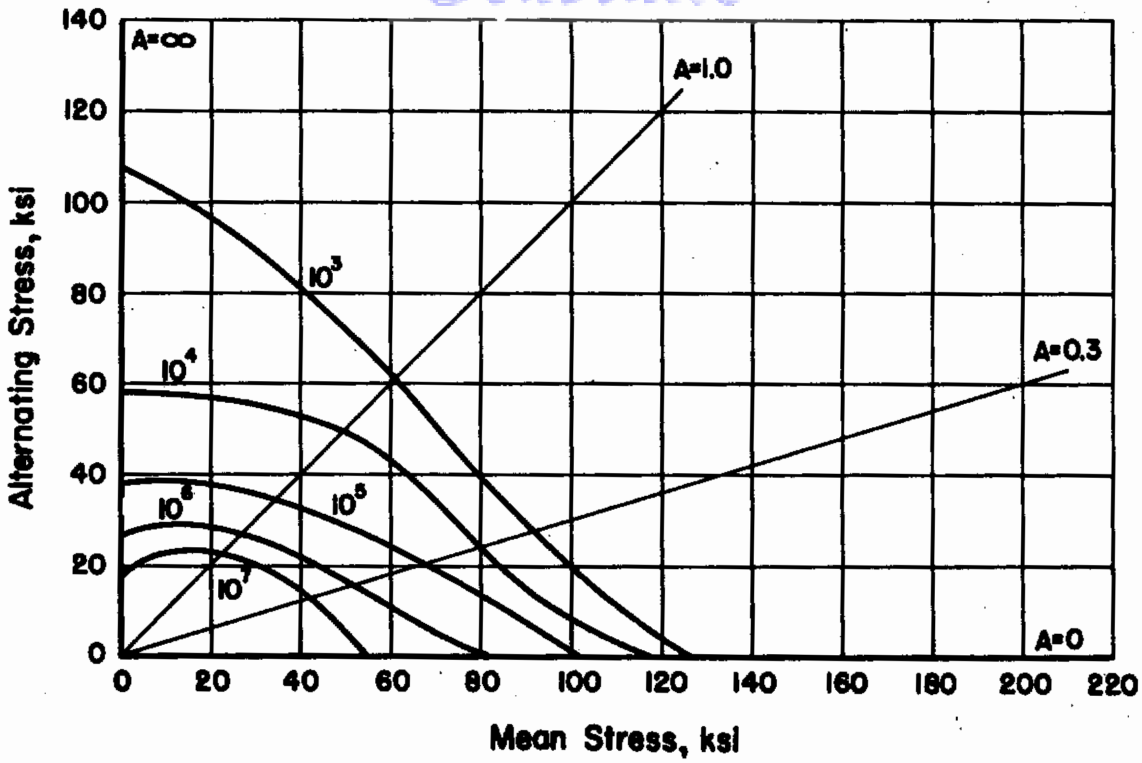

FIGURE 5.3.5(j). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.063 inch thick sheet).

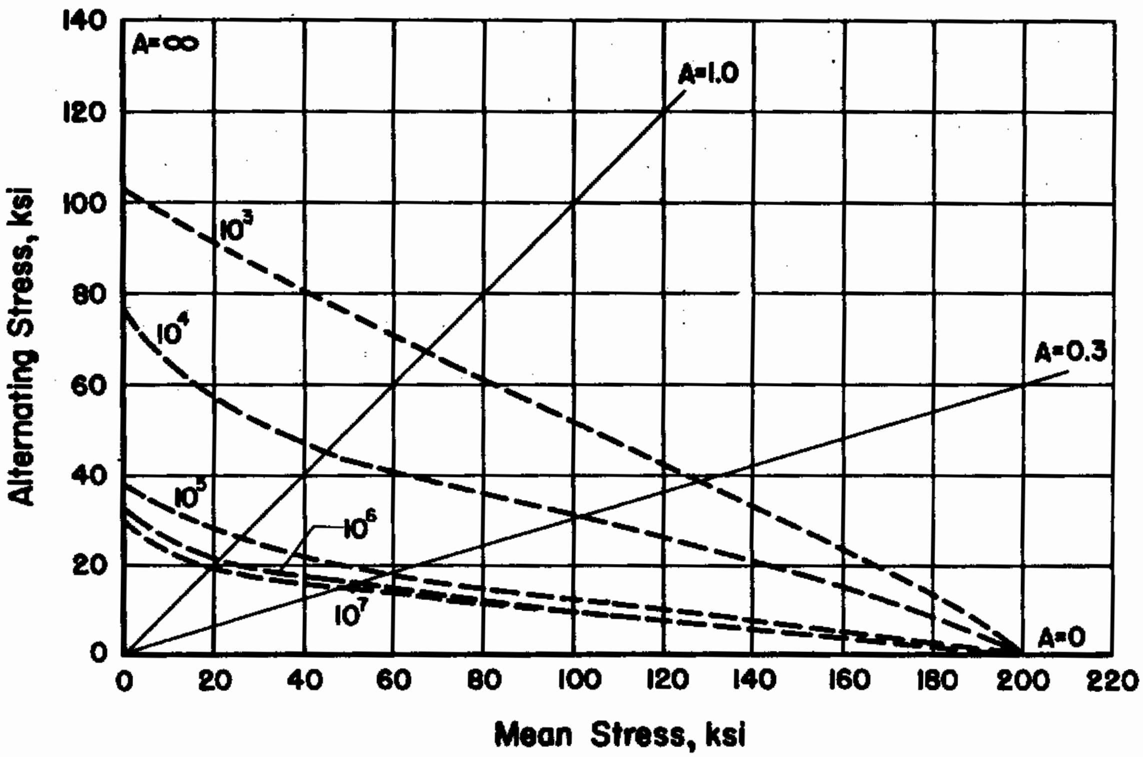

FIGURE 5.3.5(ff). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.063 inch thick sheet).

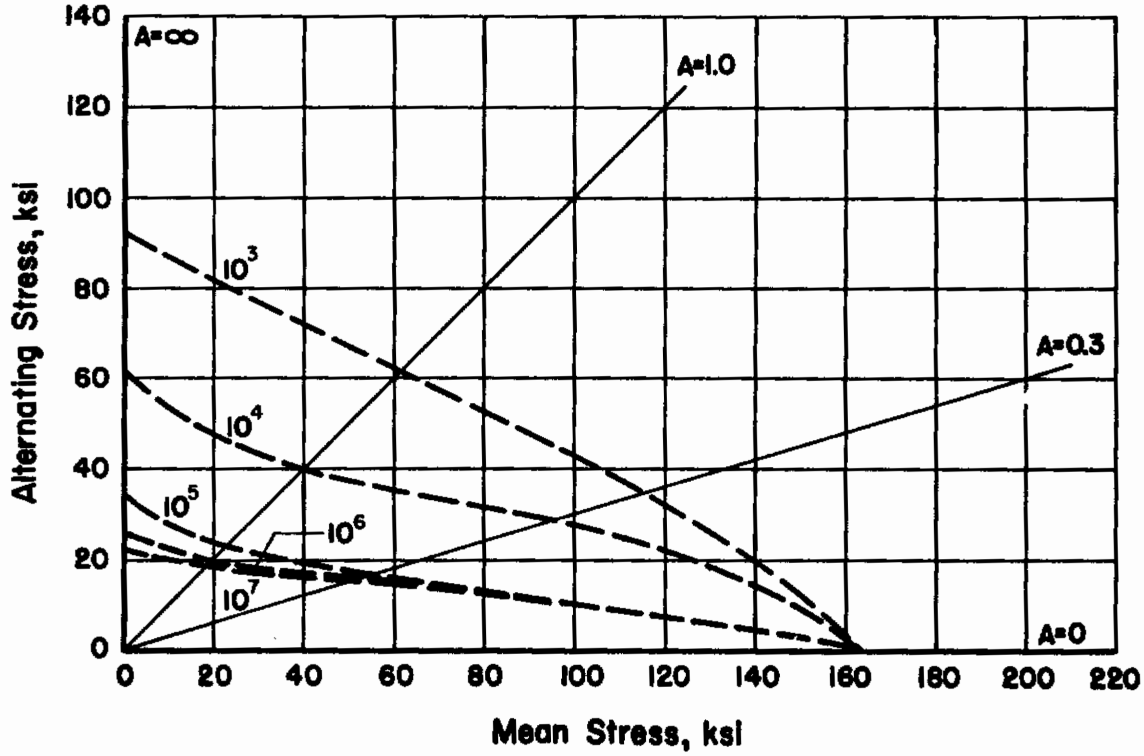

FIGURE 5.3.5(gg). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.063 inch thick sheet).

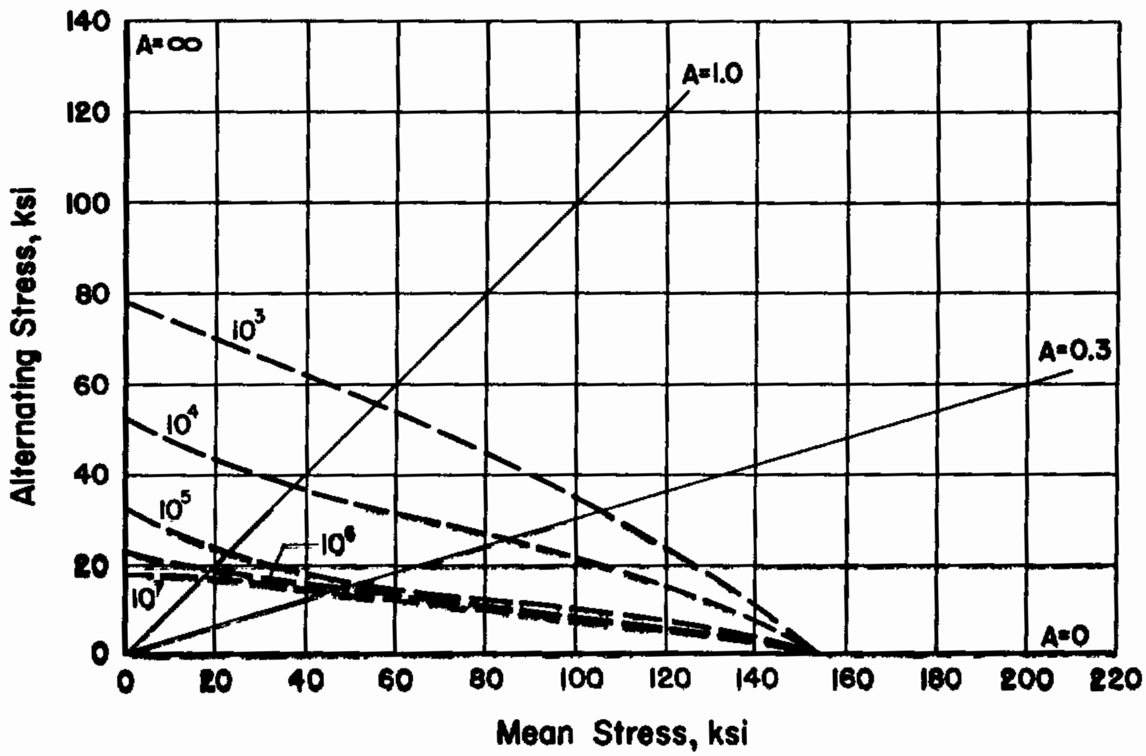

FIGURE 5.3.5(hh). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.063 inch thick sheet).

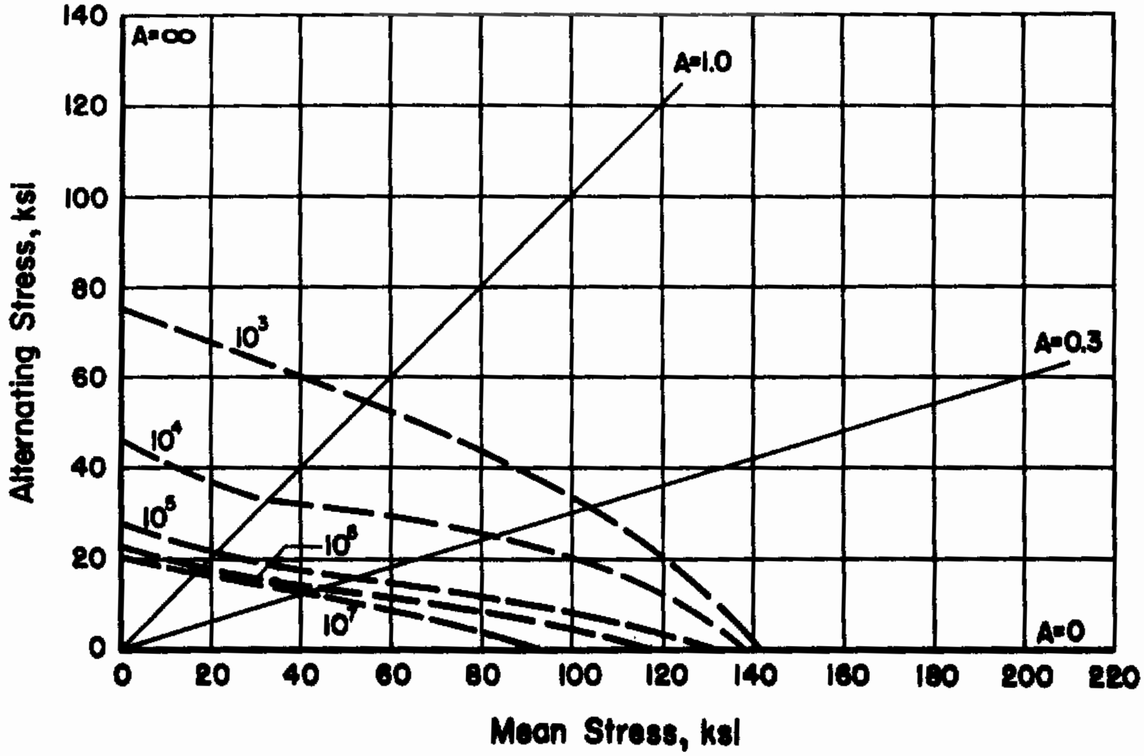

FIGURE 5.3.5(ii). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.063 inch thick sheet).

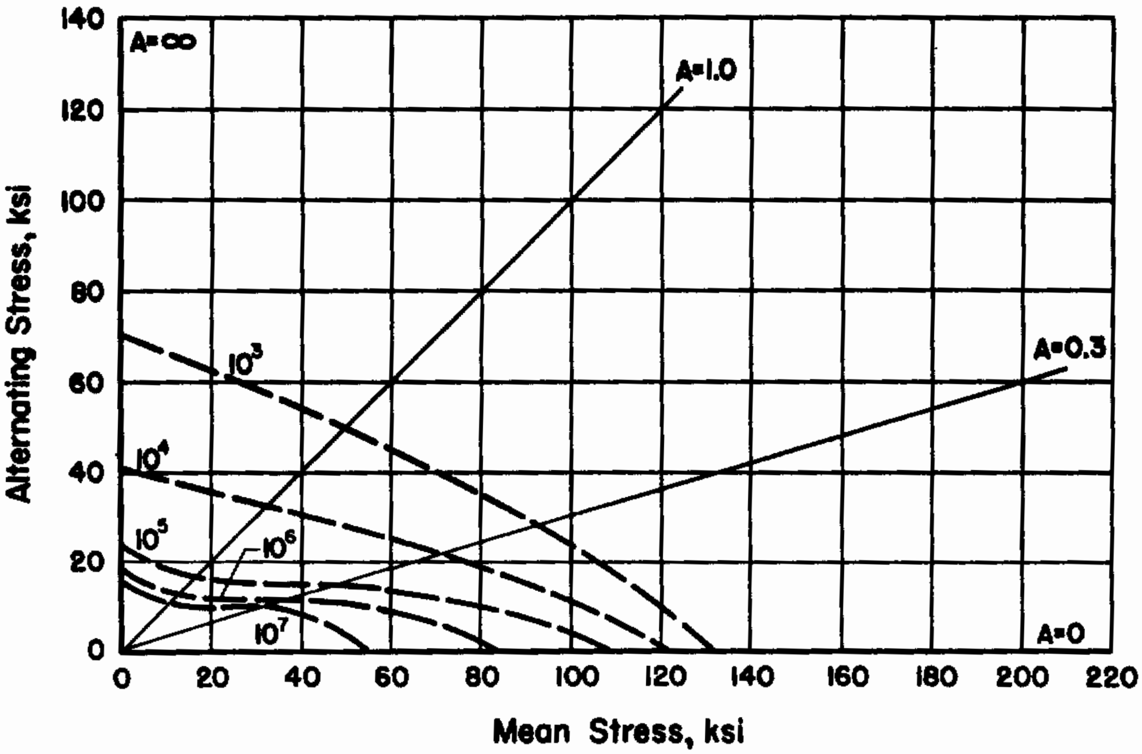

FIGURE 5.3.5(jj). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.063 inch thick sheet).

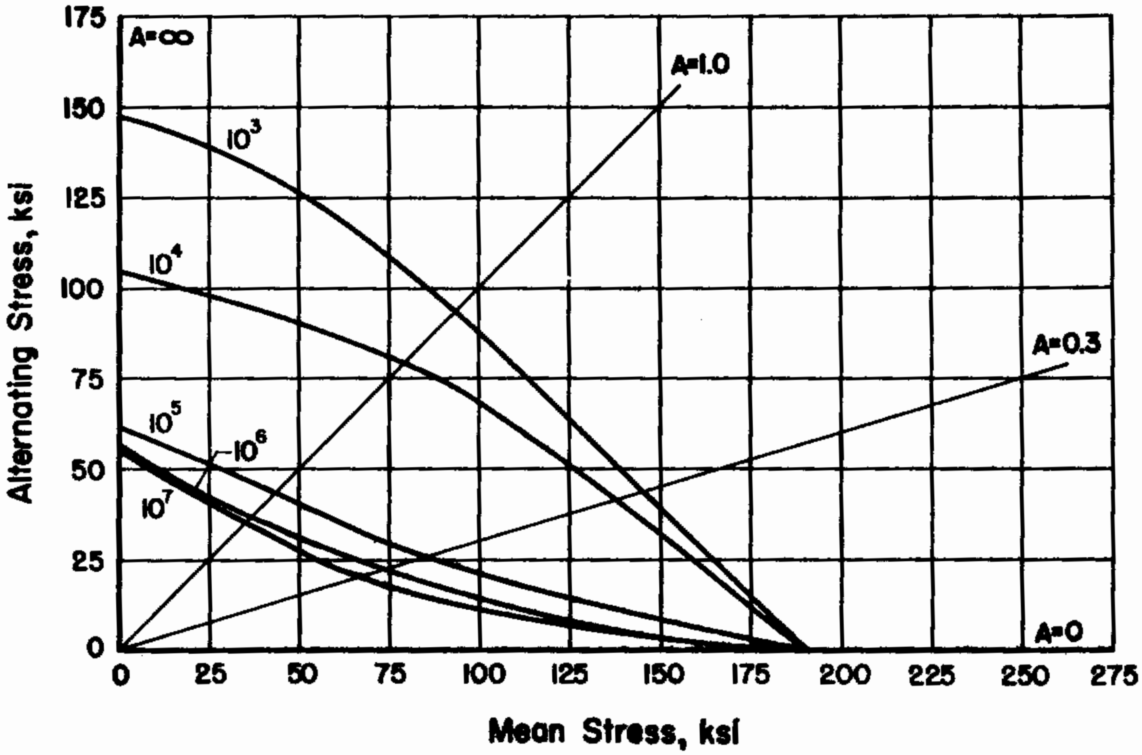

FIGURE 5.3.5(k). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.125 inch thick sheet).

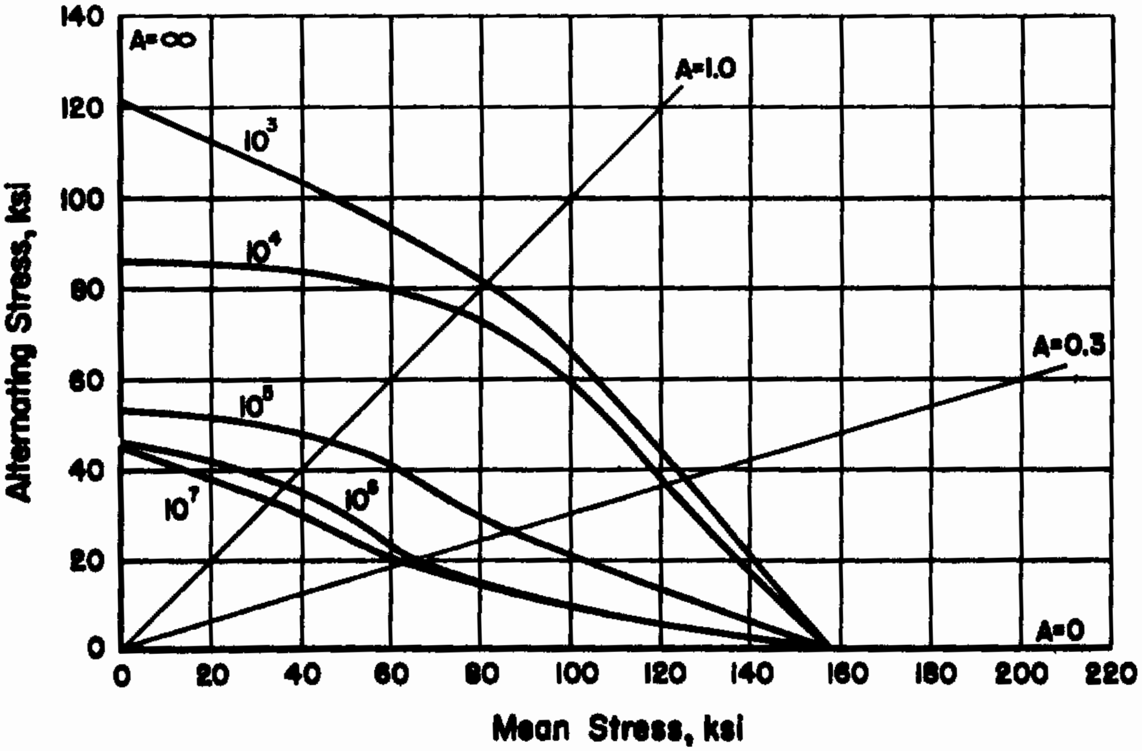

FIGURE 5.3.5(l). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.125 inch thick sheet).

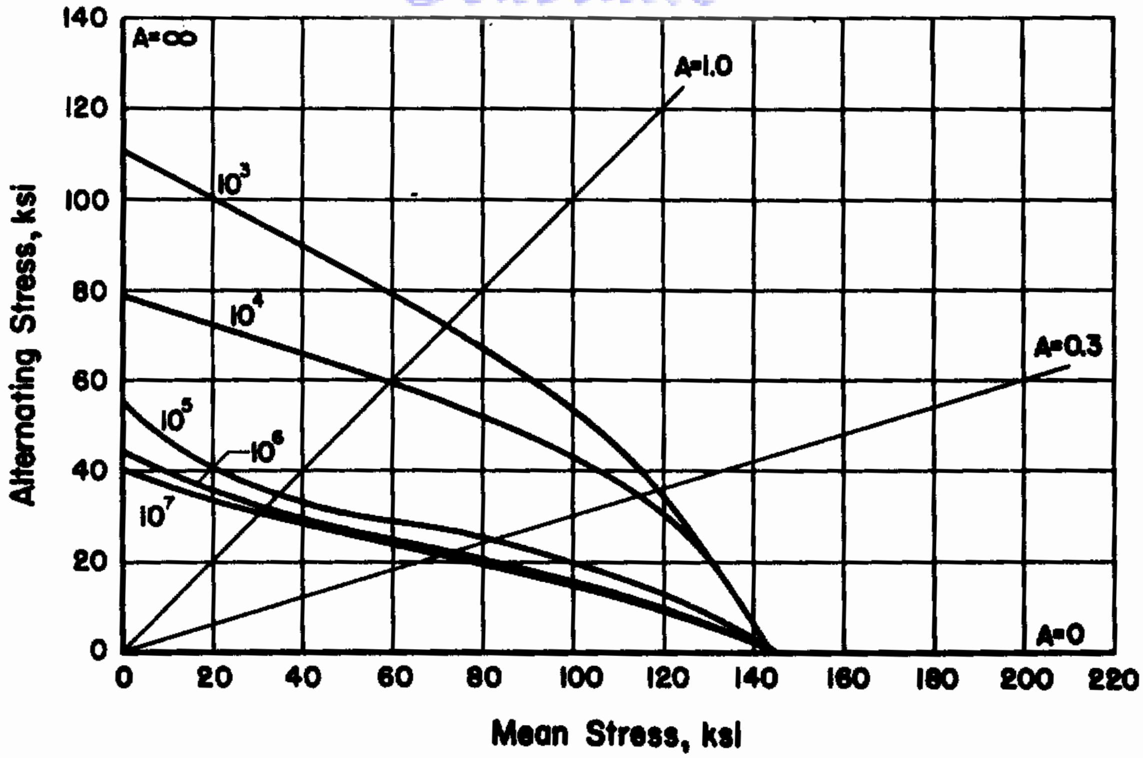

FIGURE 5.3.5(m). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.125 inch thick sheet).

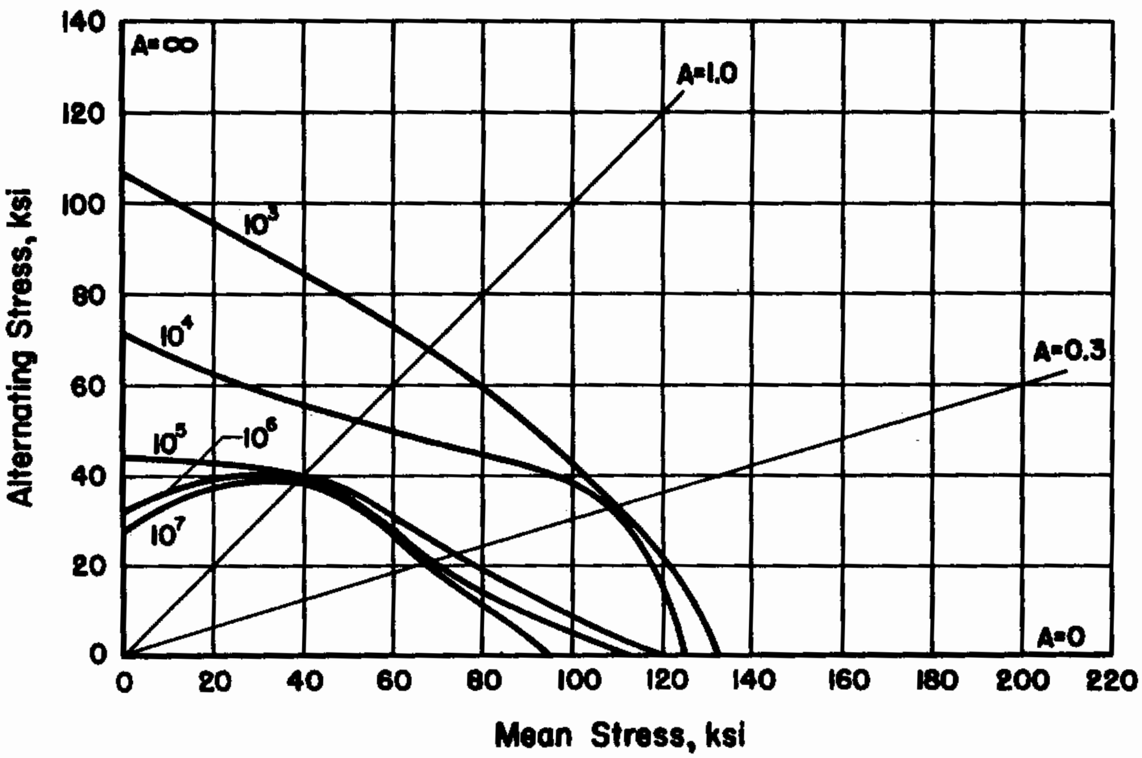

FIGURE 5.3.5(n). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.125 inch thick sheet).

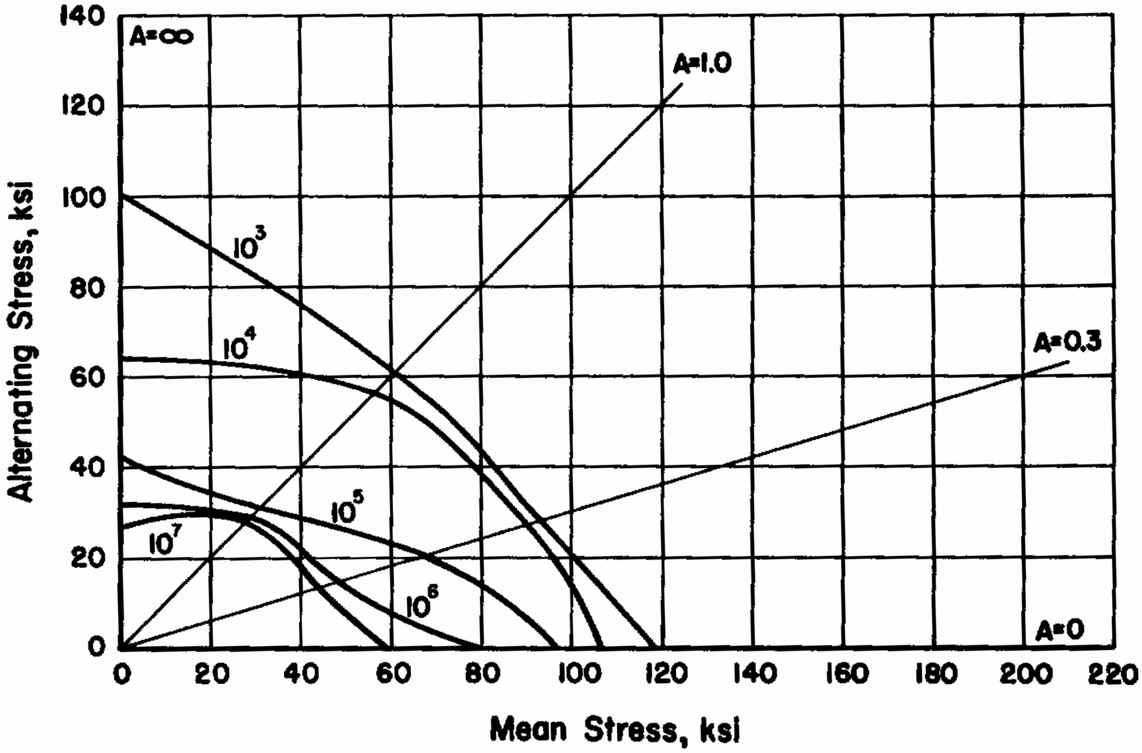

FIGURE 5.3.5(o). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.125 inch thick sheet).

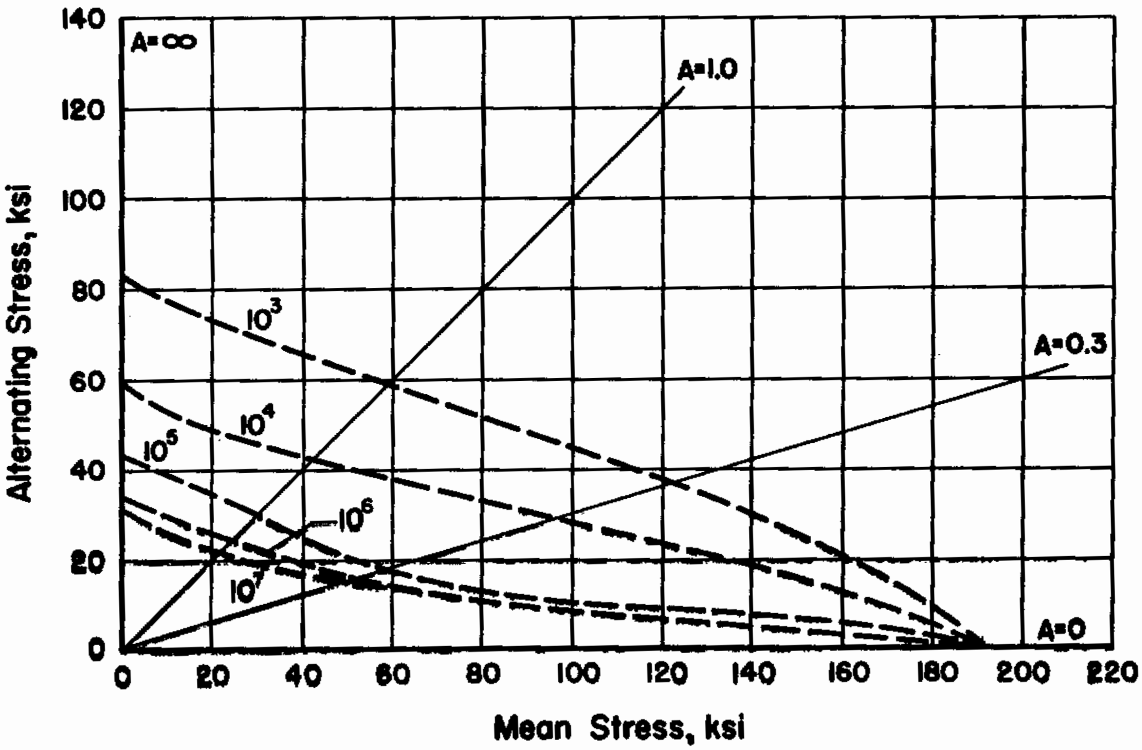

FIGURE 5.3.5(kk). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.125 inch thick sheet).

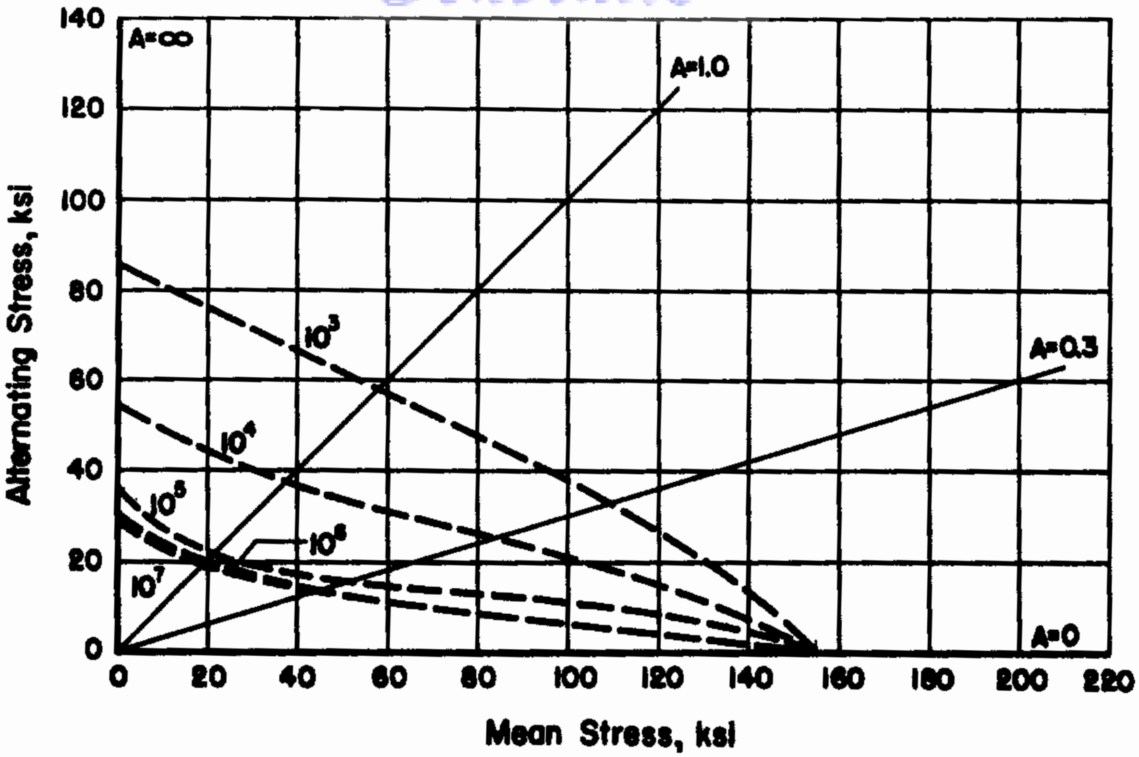

FIGURE 5.3.5(ll). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.125 inch thick sheet).

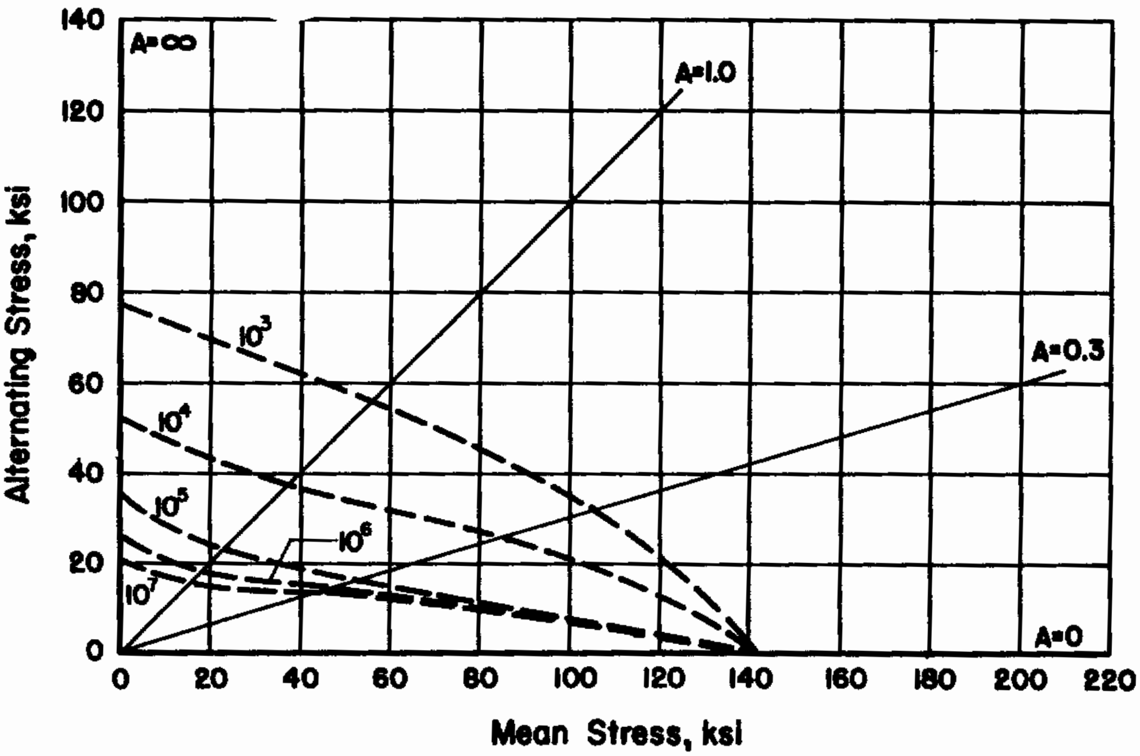

FIGURE 5.3.5(mm). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.125 inch thick sheet).

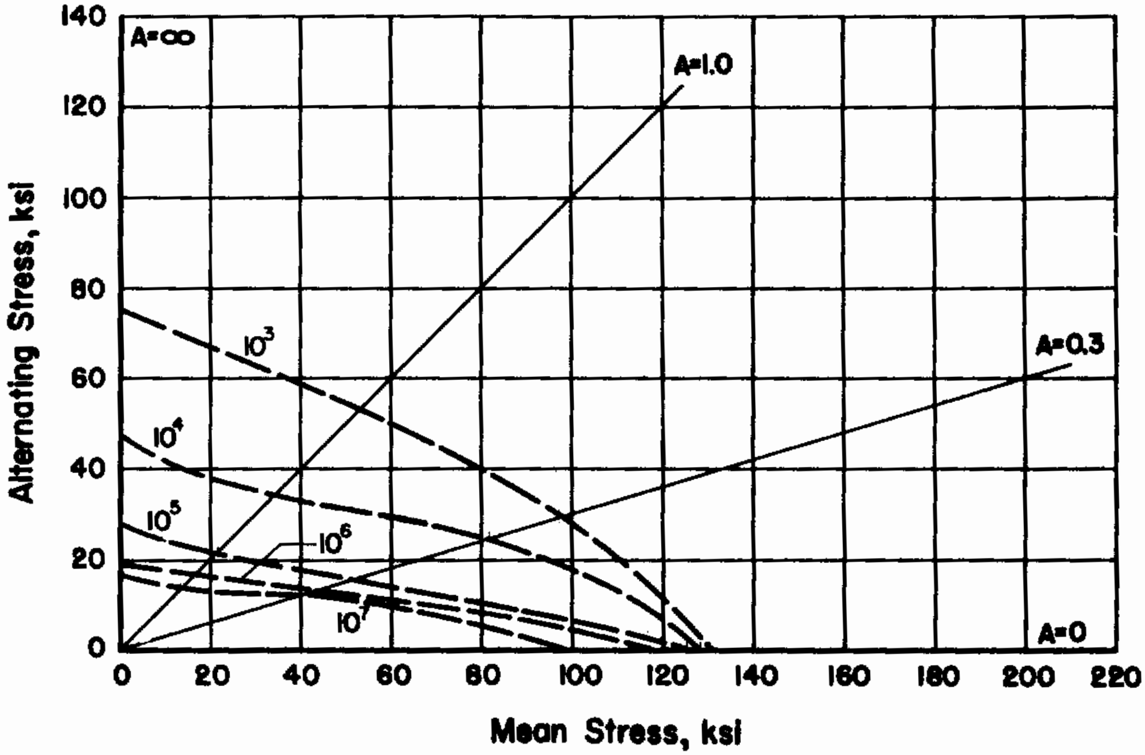

FIGURE 5.3.5(nn). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.125 inch thick sheet).

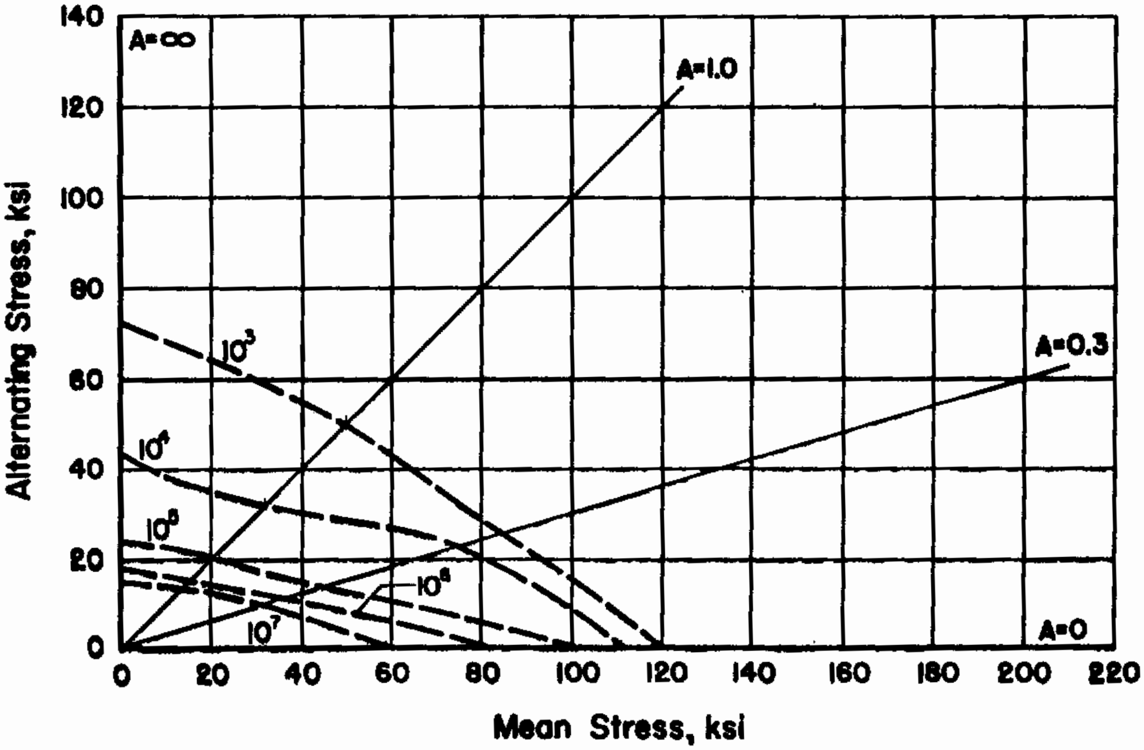

FIGURE 5.3.5(oo). Direct stress fatigue properties of 4Al-3Mo-1V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.125 inch thick sheet).

5.3.6 Fatigue Properties of 2.5Al-16V Titanium Alloy

Axial-load fatigue data for smooth specimens at temperatures up to 900°F are given in Figures 5.3.6(a) through 5.3.6(o). Figures 5.3.6(aa) through 5.3.6(oo) are for specimens having a K_t = 2.82 over the same temperature range.

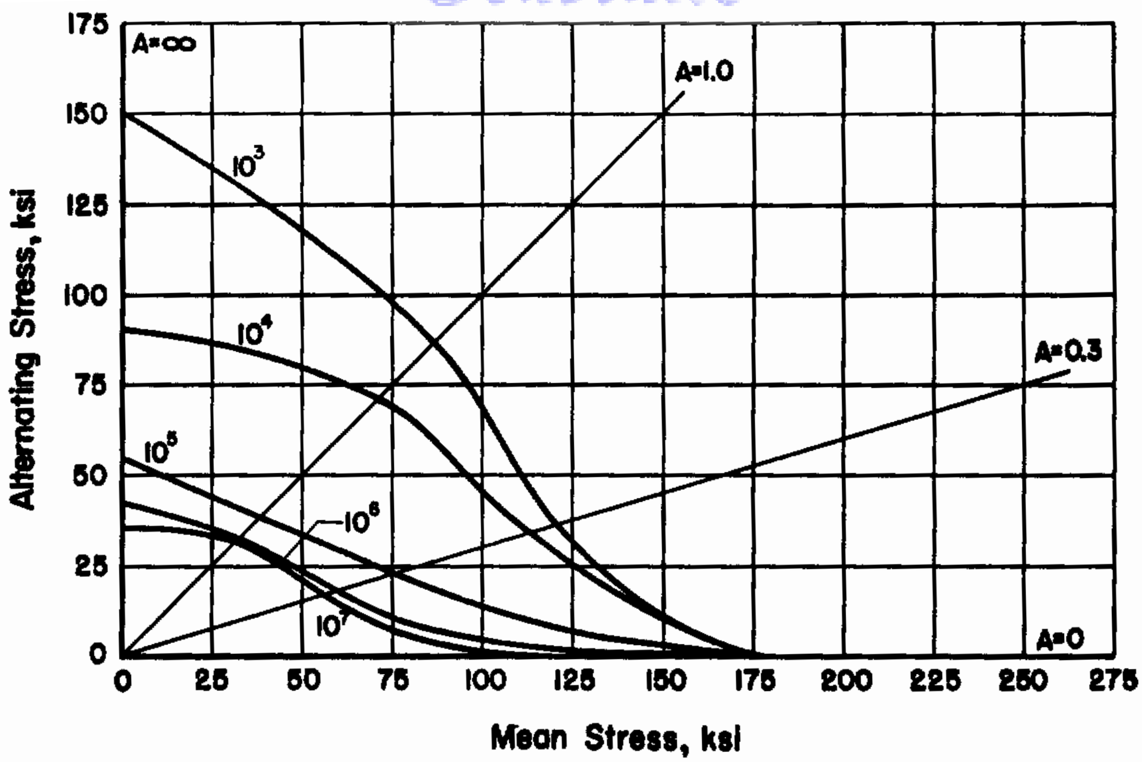

FIGURE 5.3.6(a). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.020 inch thick sheet).

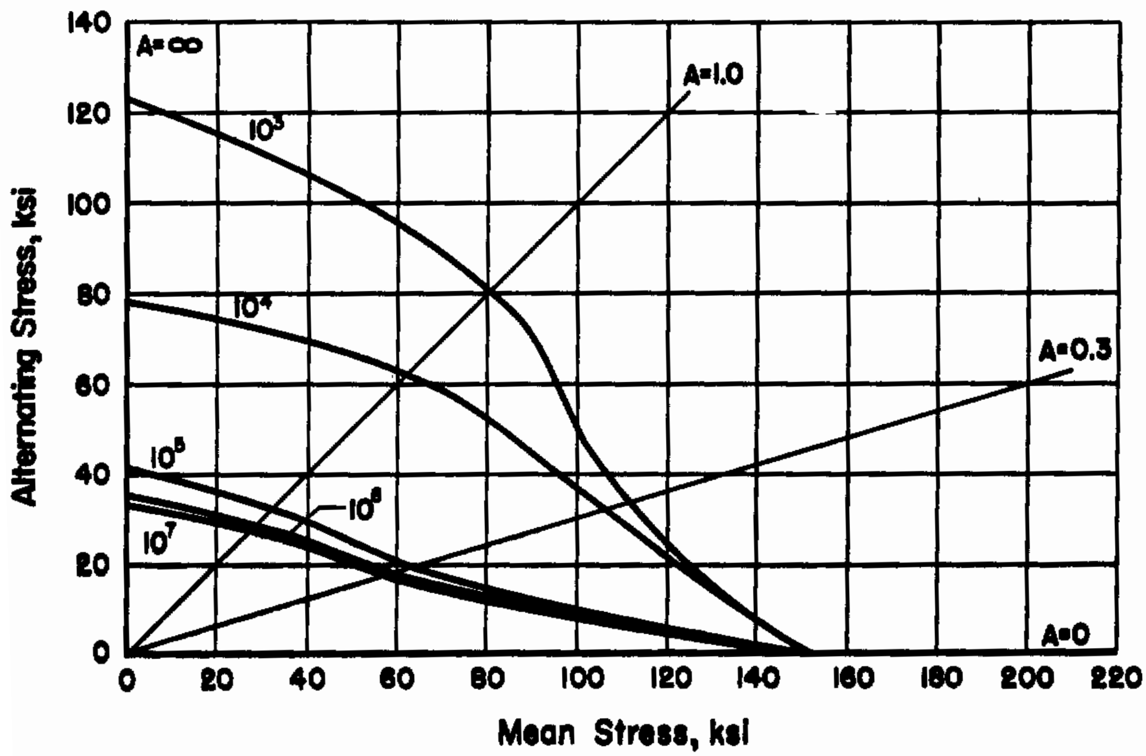

FIGURE 5.3.6(b). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.020 inch thick sheet).

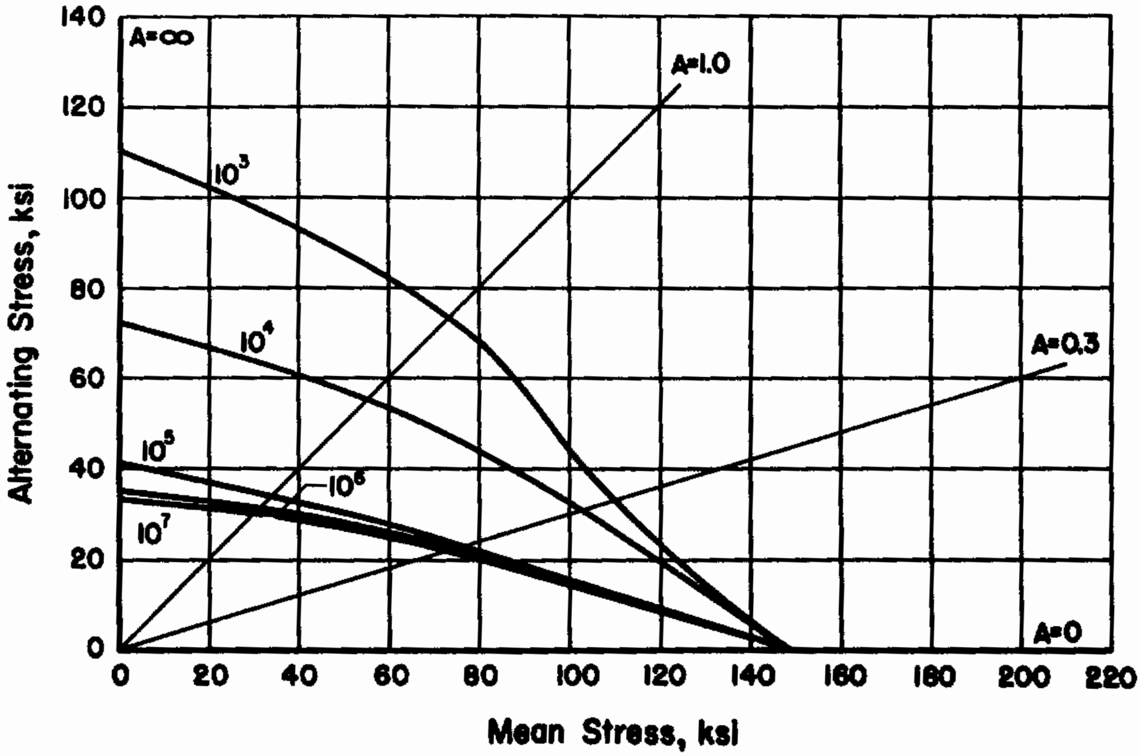

FIGURE 5.3.6(c). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.020 inch thick sheet).

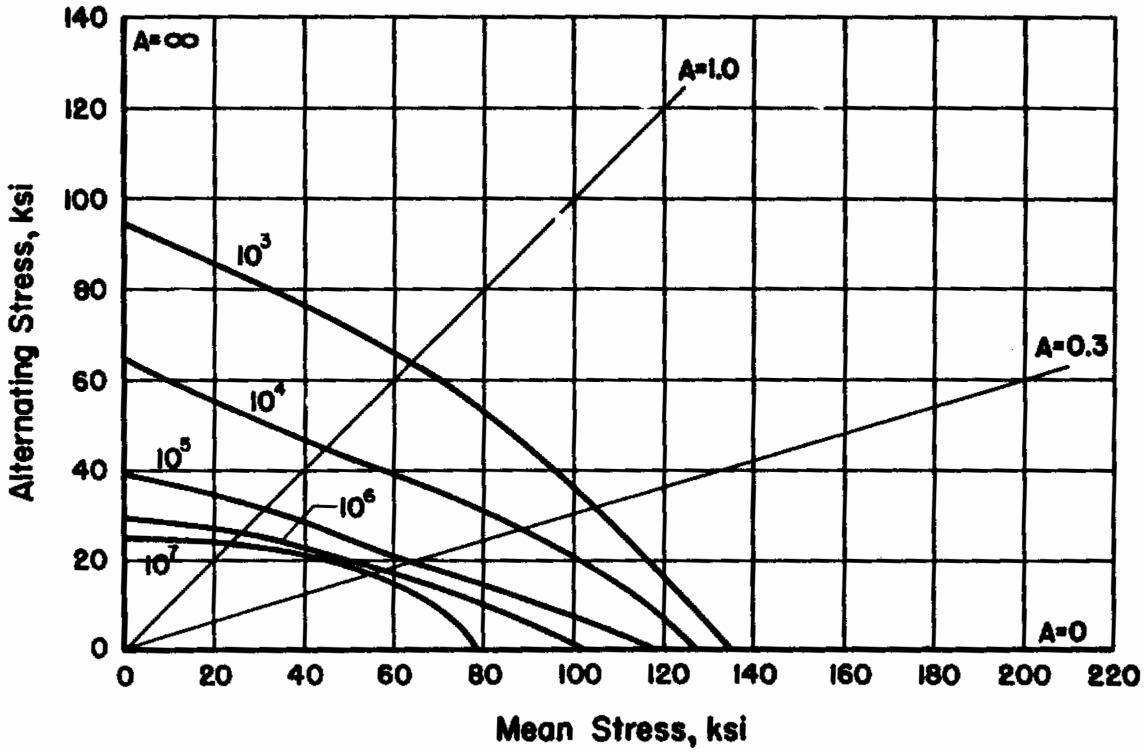

FIGURE 5.3.6(d). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.020 inch thick sheet).

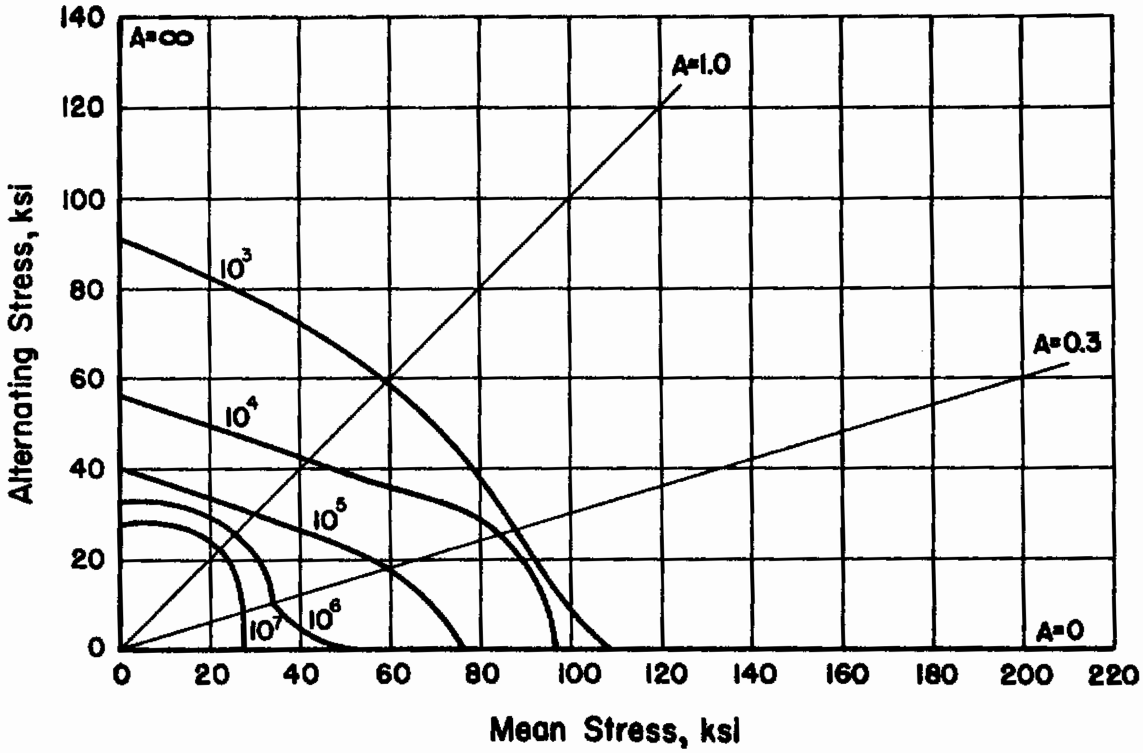

FIGURE 5.3.6(e). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.020 inch thick sheet).

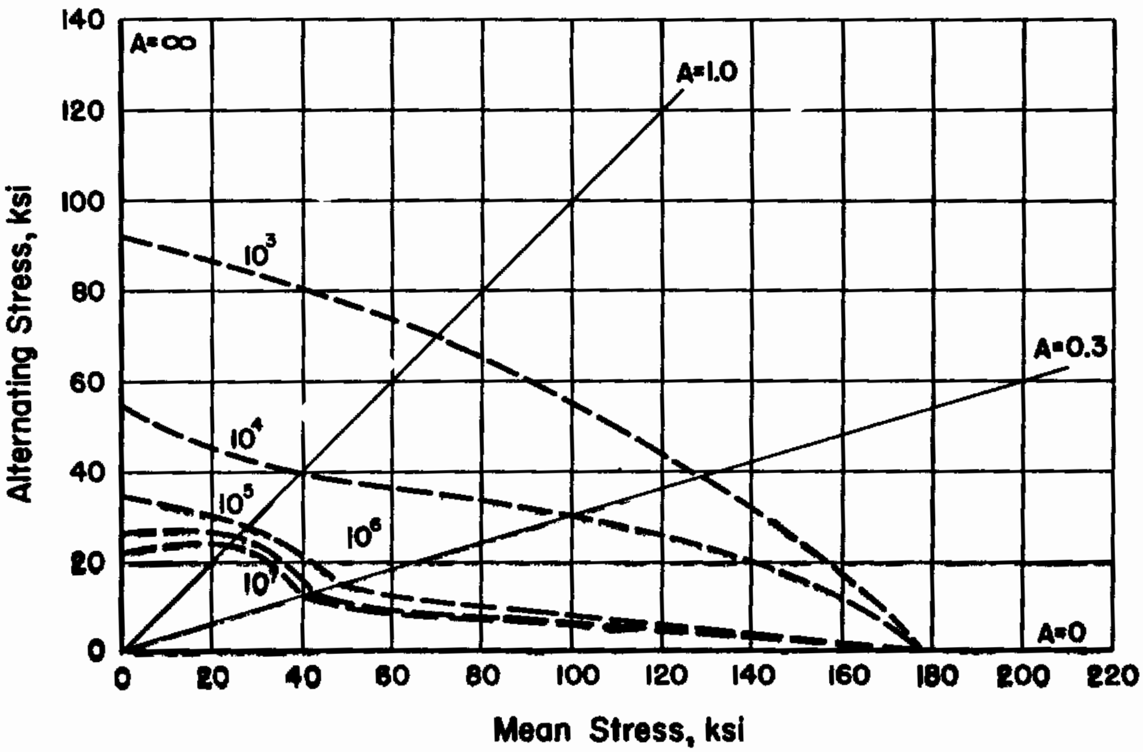

FIGURE 5.3.6(aa). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.020 inch thick sheet).

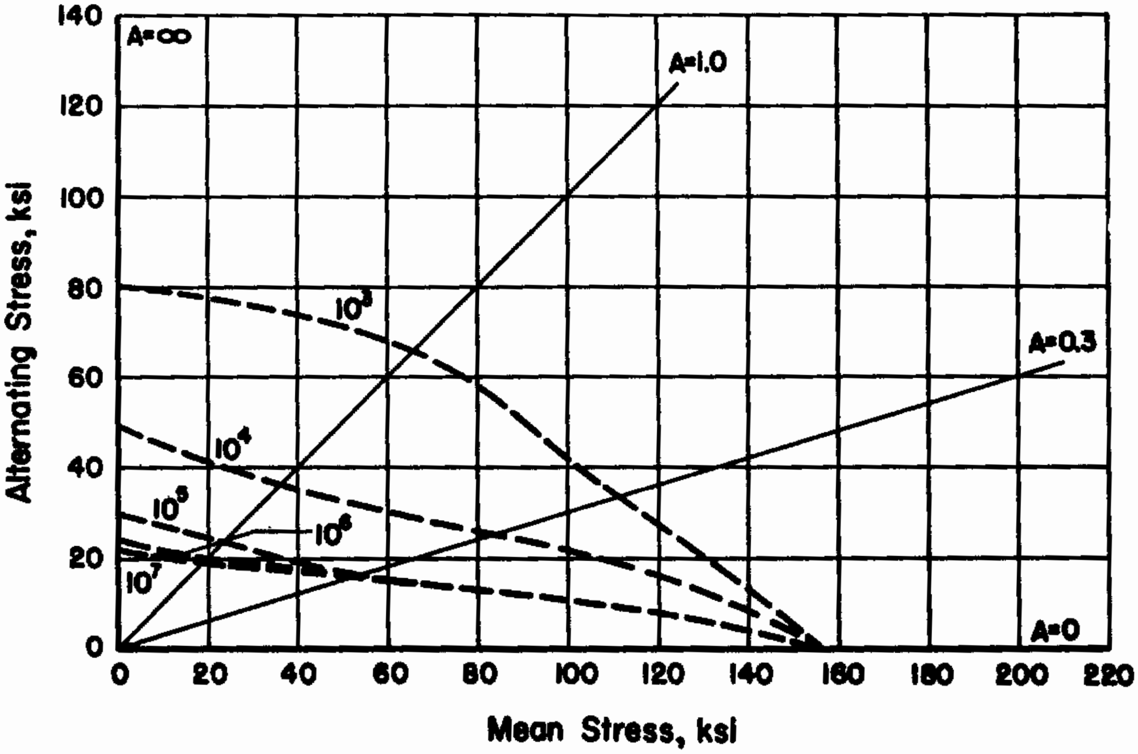

FIGURE 5.3.6(bb). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.020 inch thick sheet).

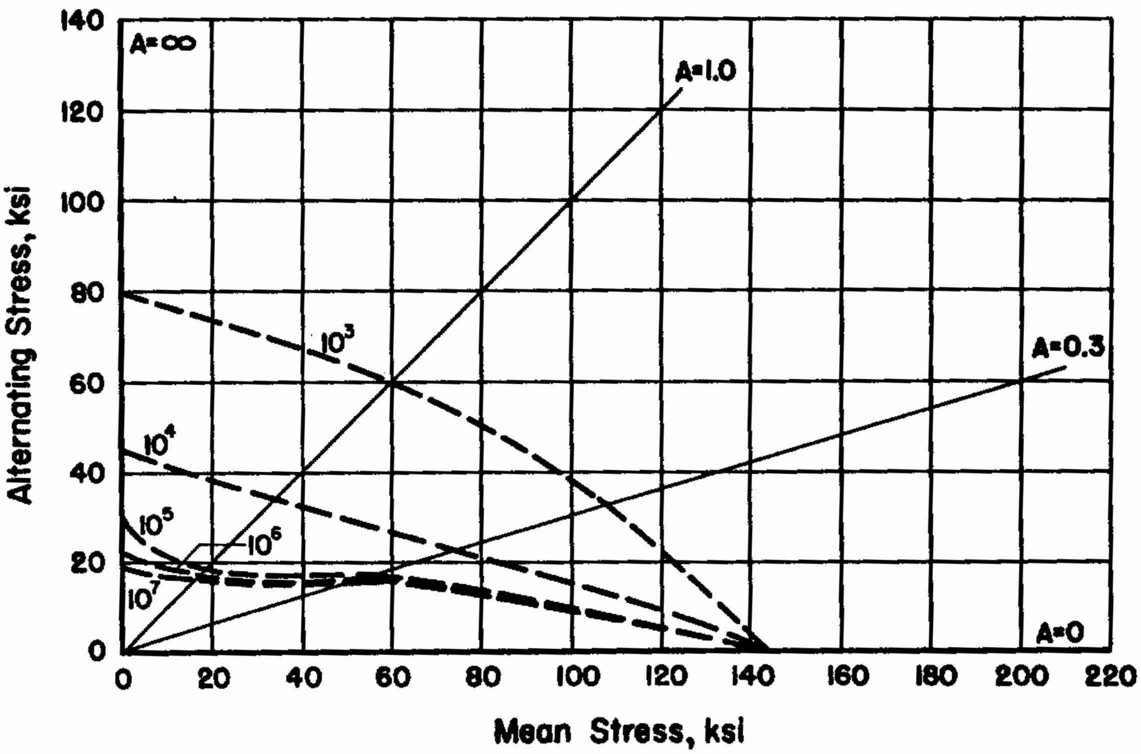

FIGURE 5.3.6(cc). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.020 inch thick sheet).

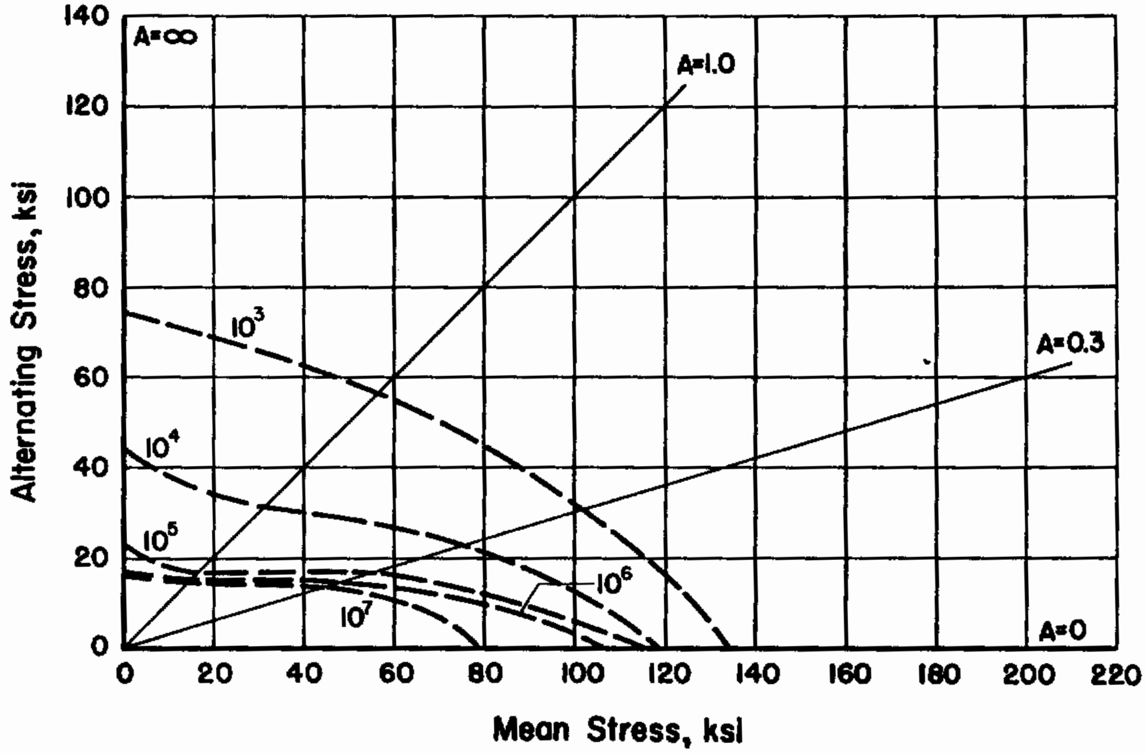

FIGURE 5.3.6(dd). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.020 inch thick sheet).

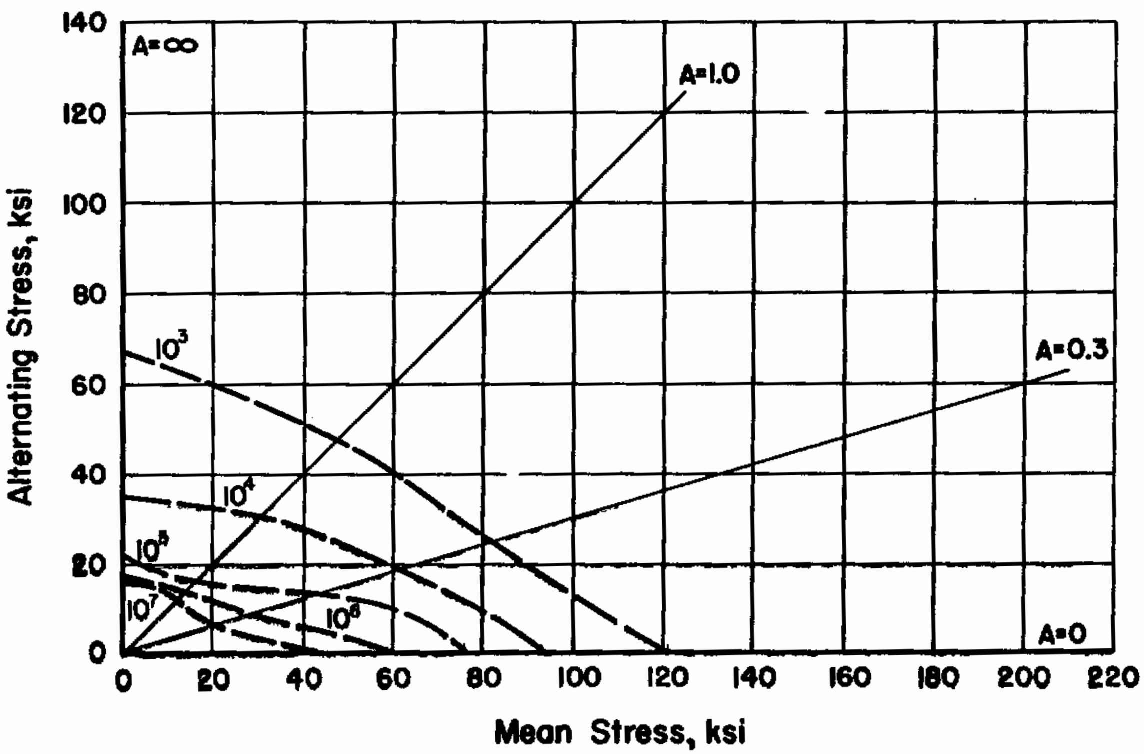

FIGURE 5.3.6(ee). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.020 inch thick sheet).

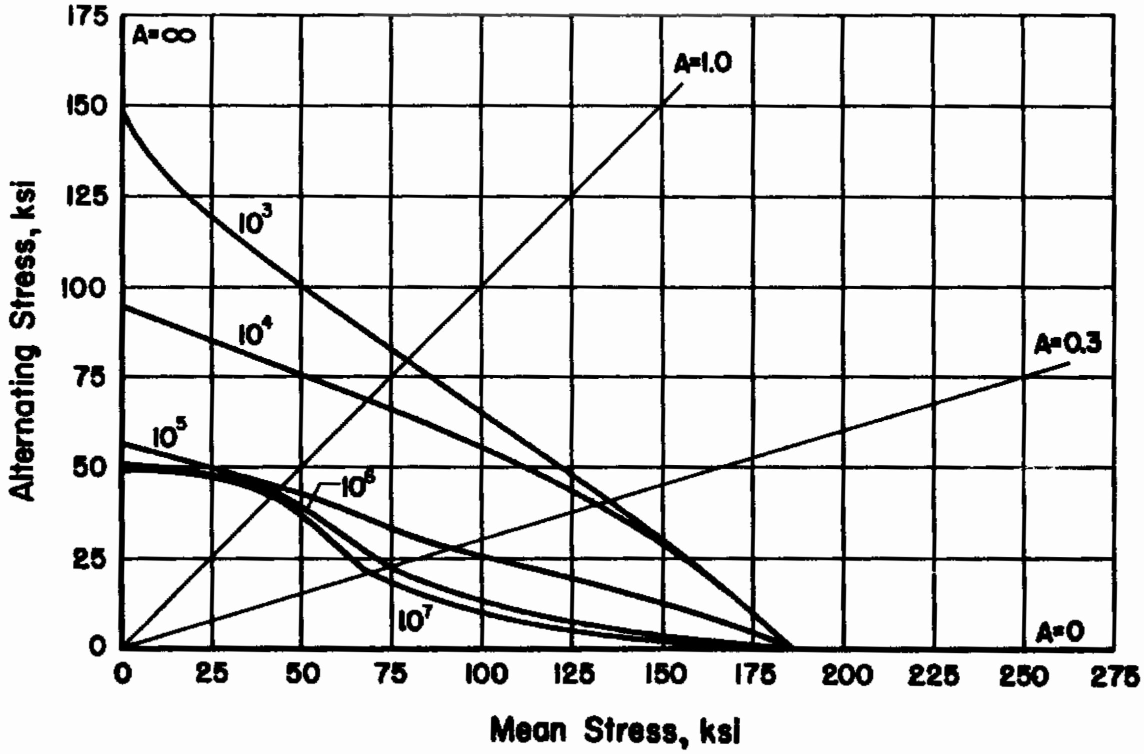

FIGURE 5.3.6(f). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.063 inch thick sheet).

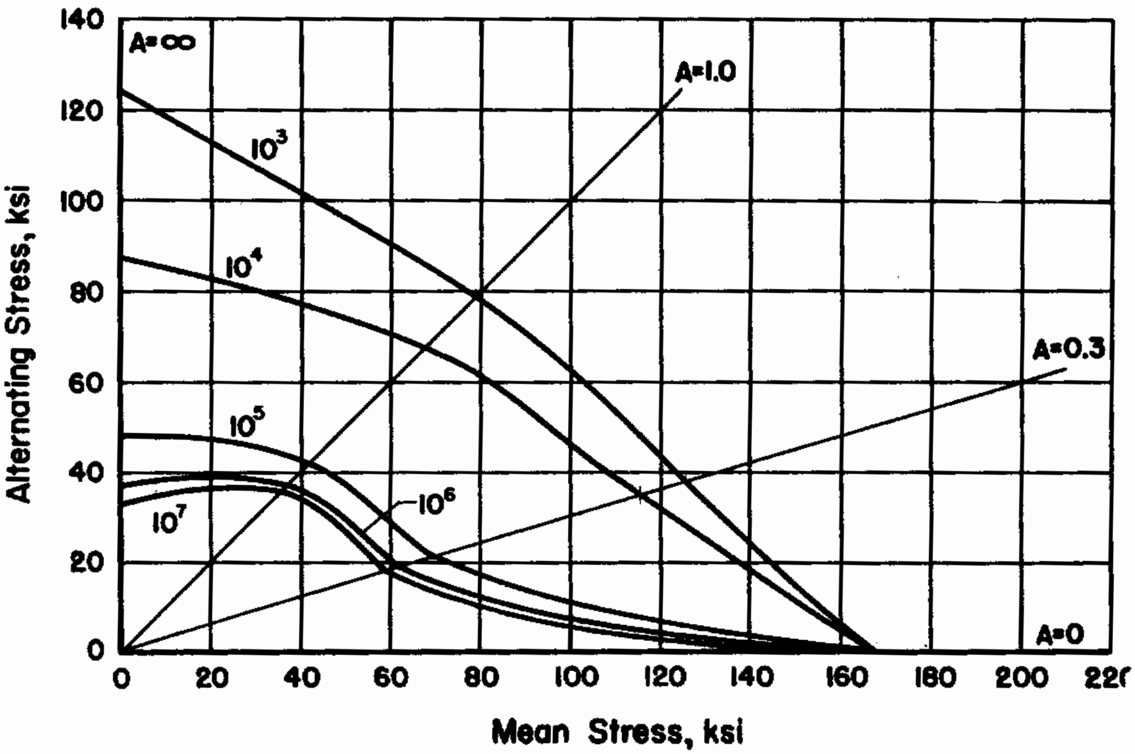

FIGURE 5.3.6(g). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.063 inch thick sheet).

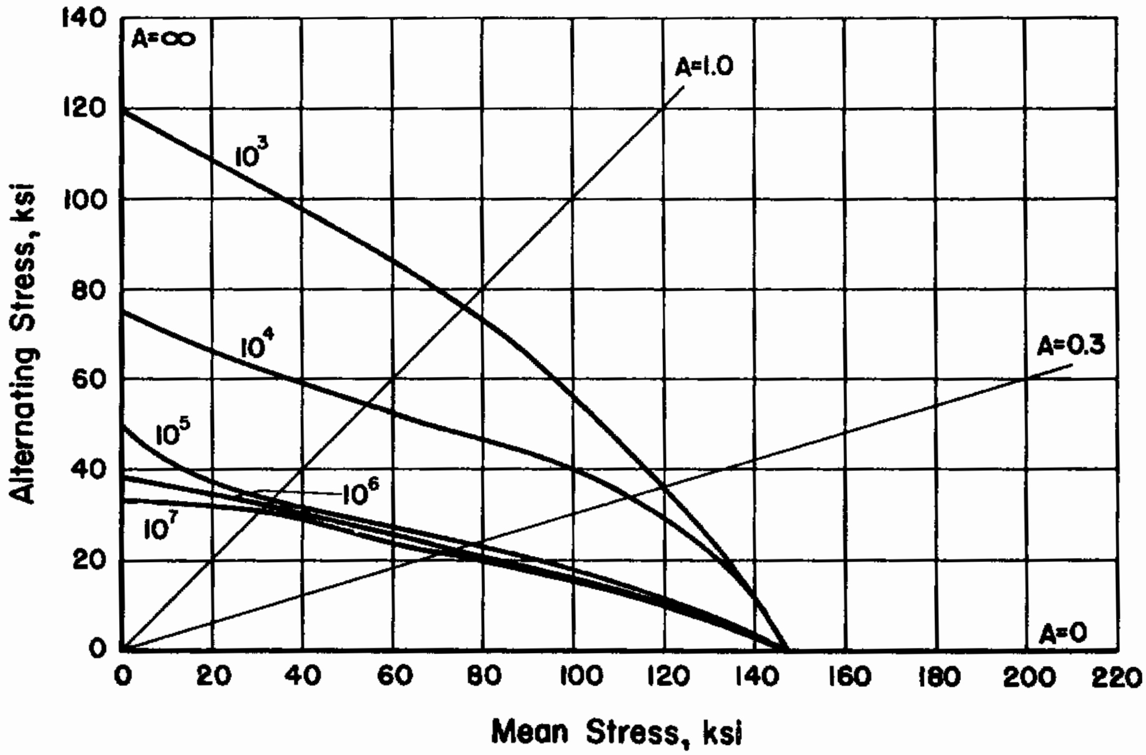

FIGURE 5.3.6(h). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.063 inch thick sheet).

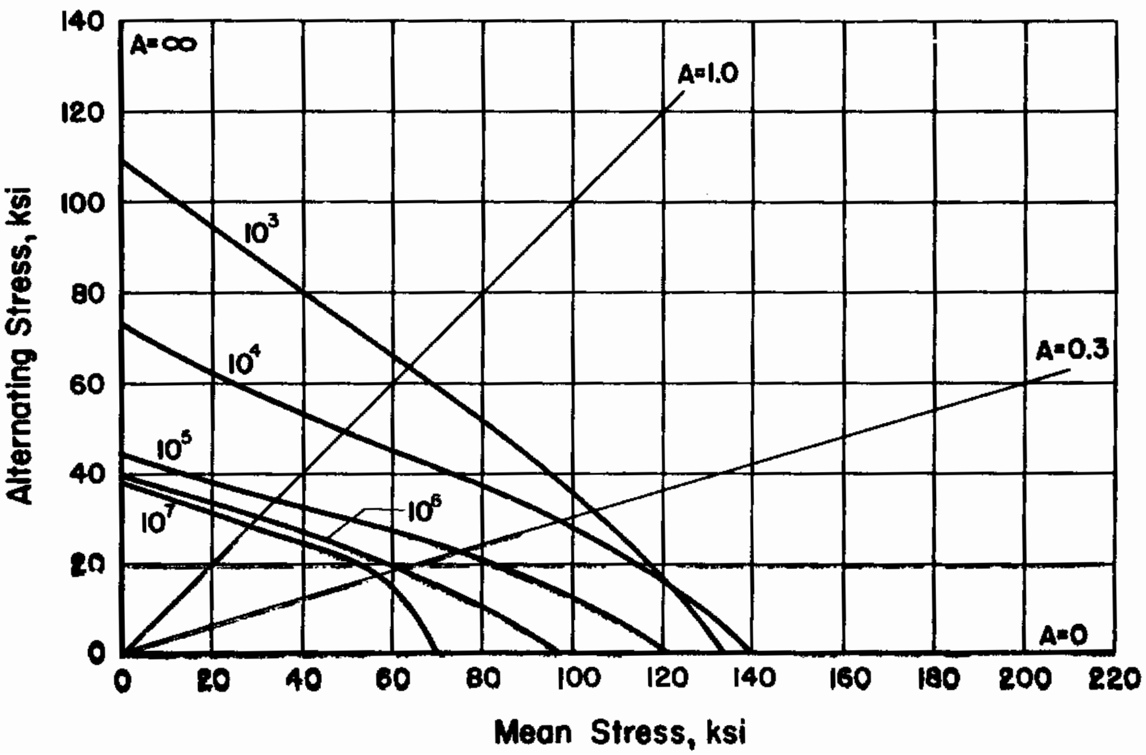

FIGURE 5.3.6(i). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.063 inch thick sheet).

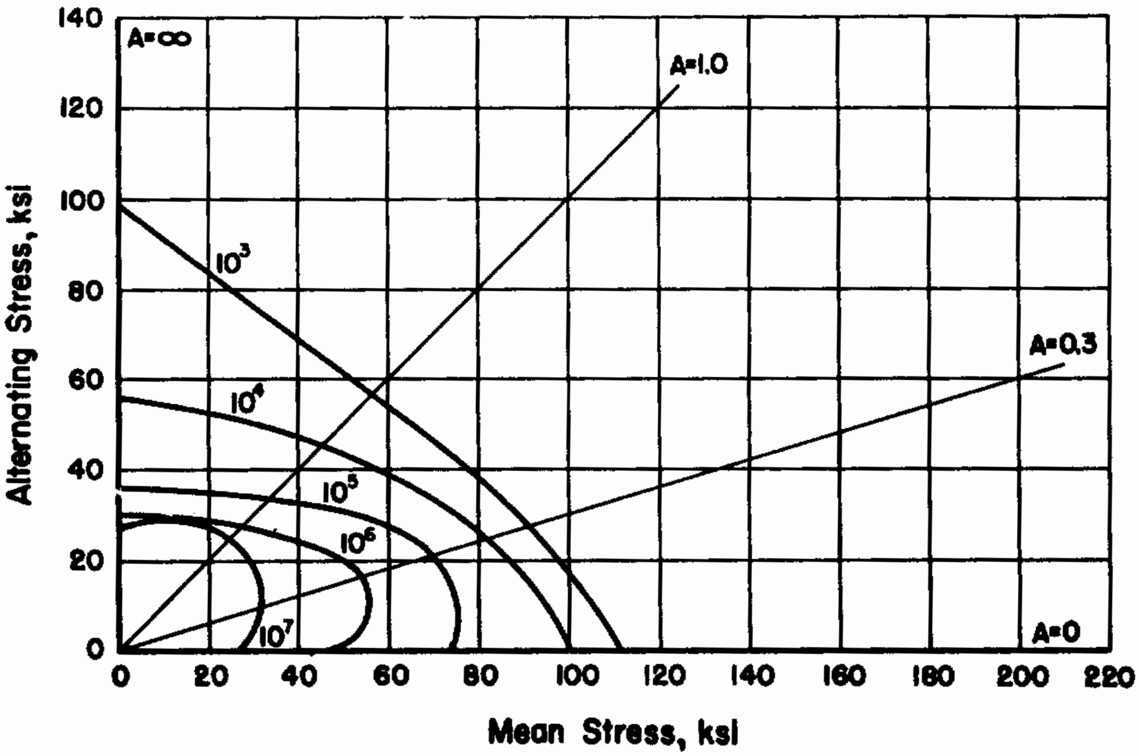

FIGURE 5.3.6(j). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.063 inch thick sheet).

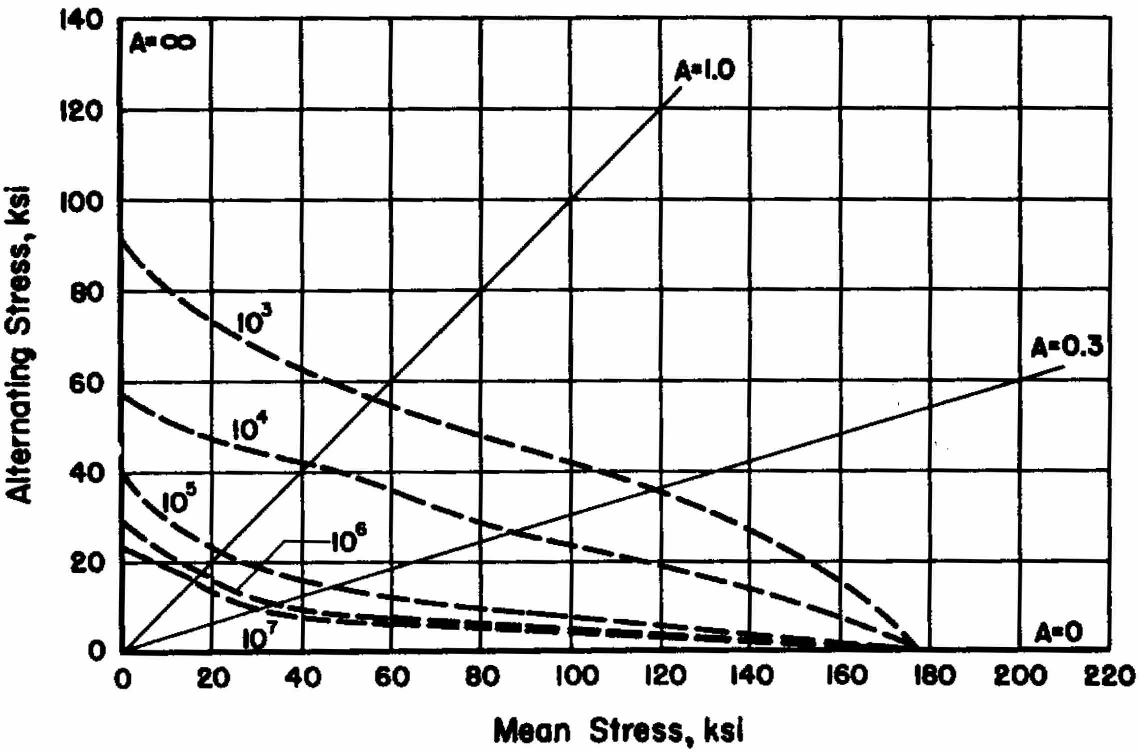

FIGURE 5.3.6(ff). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.063 inch thick sheet).

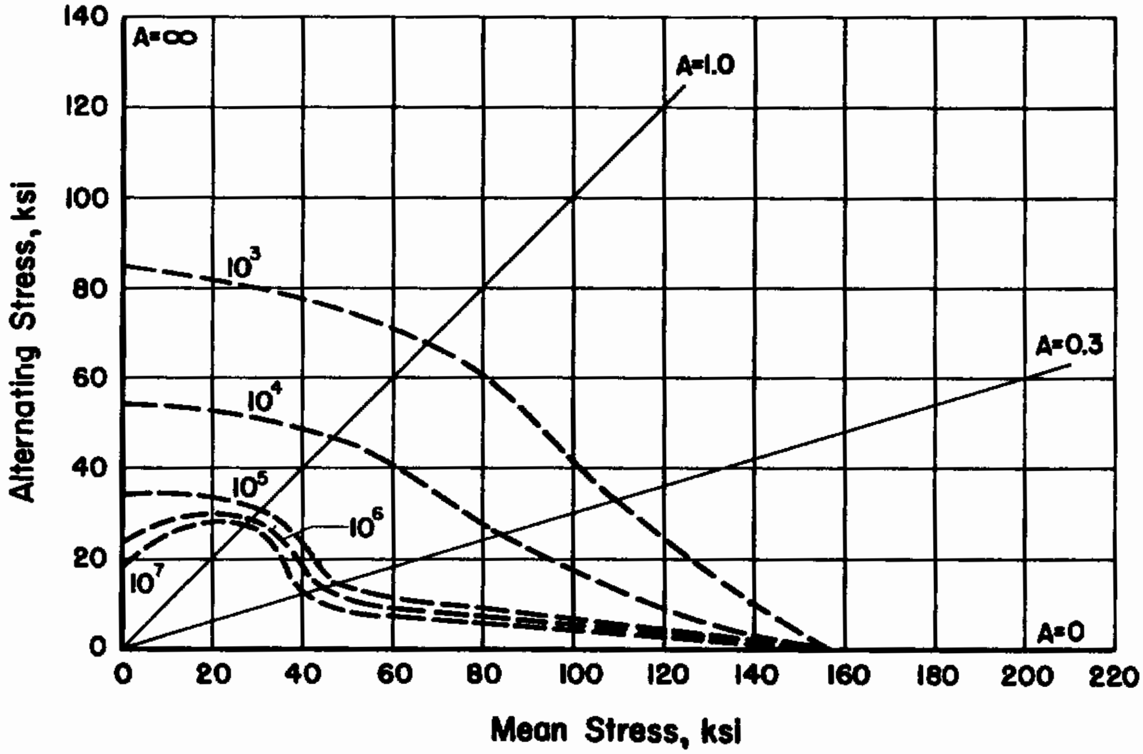

FIGURE 5.3.6(gg). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.063 inch thick sheet).

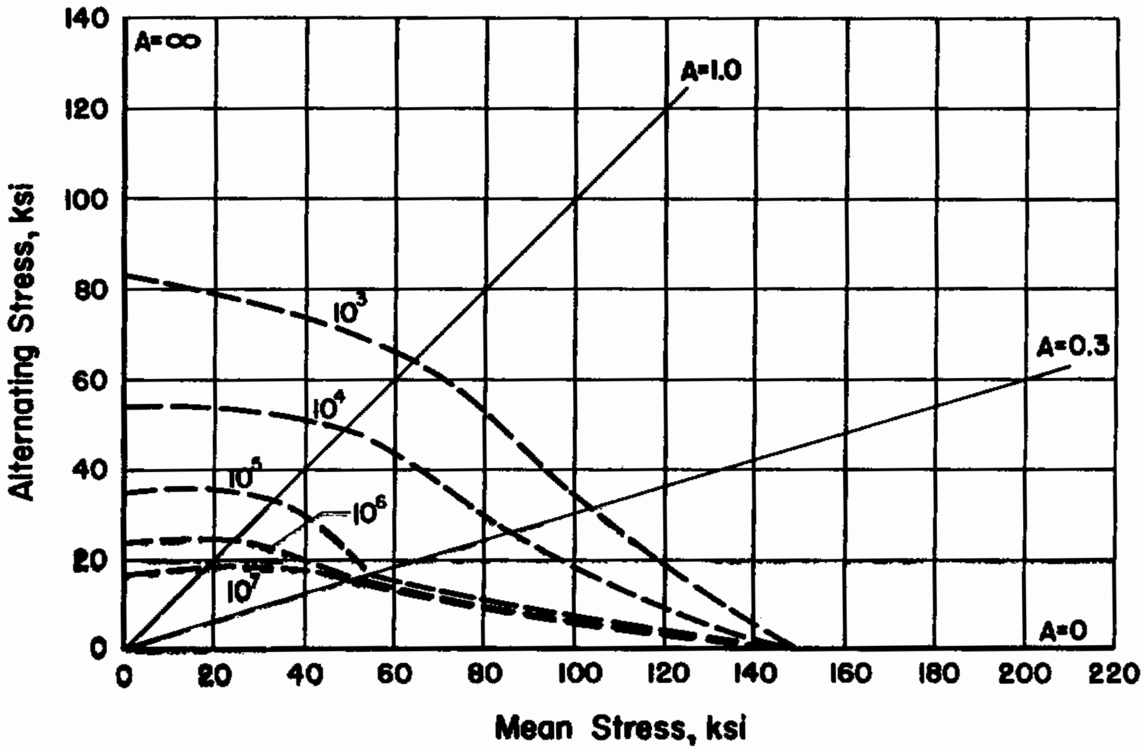

FIGURE 5.3.6(hh). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.063 inch thick sheet).

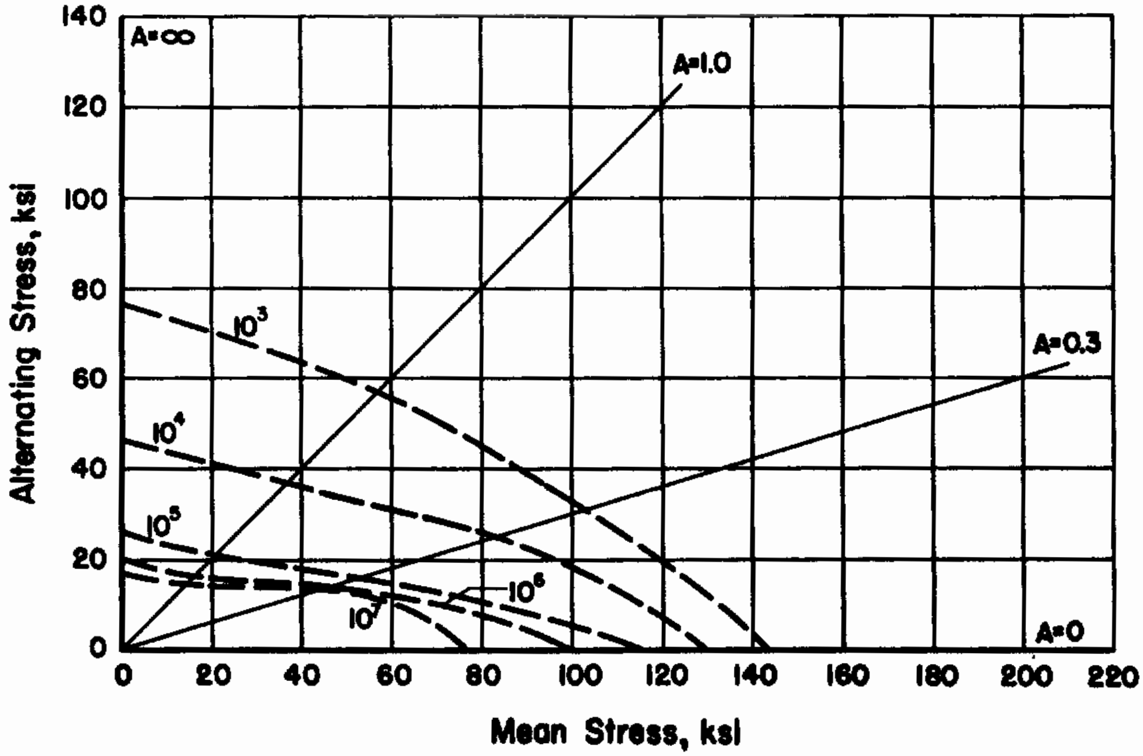

FIGURE 5.3.6(ii). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.063 inch thick sheet).

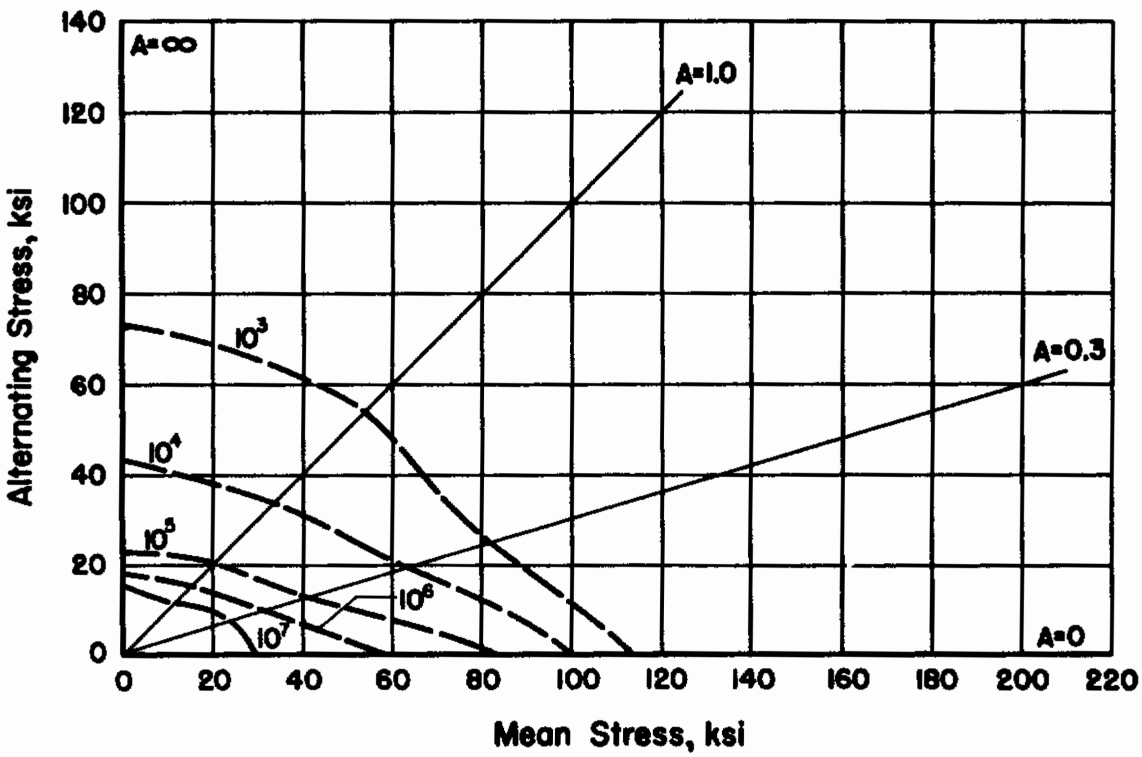

FIGURE 5.3.6(jj). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.063 inch thick sheet).

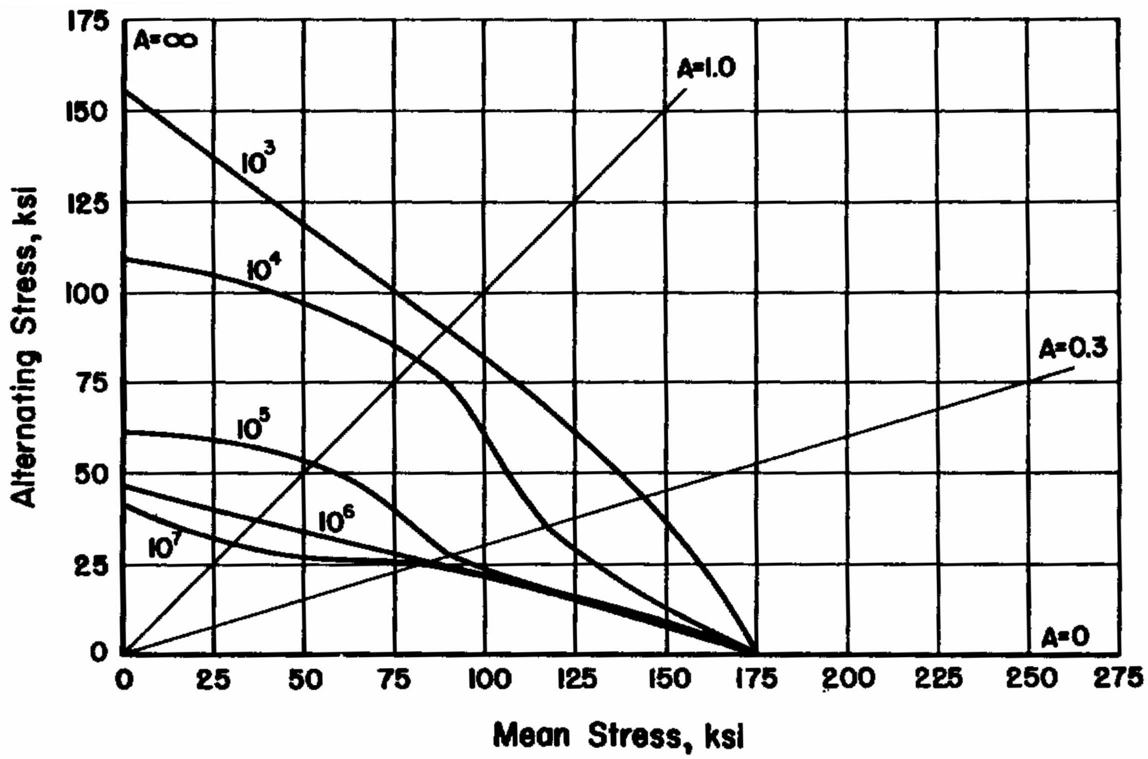

FIGURE 5.3.6(k). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 1.0 (0.125 inch thick sheet).

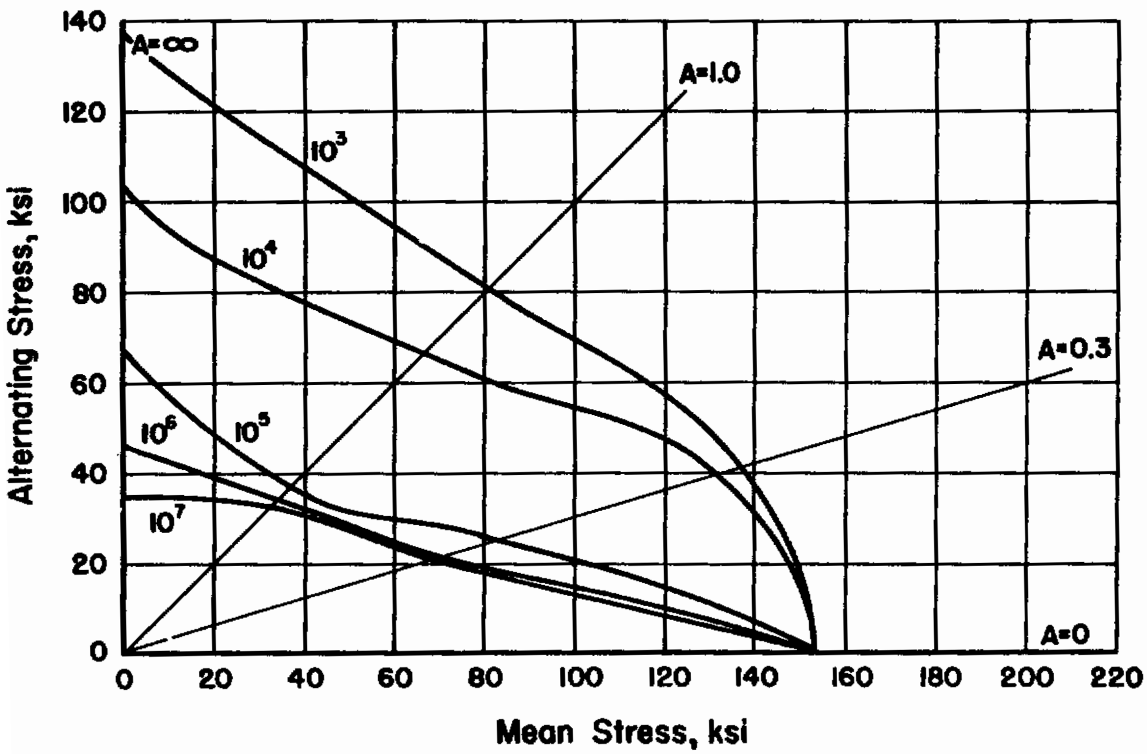

FIGURE 5.3.6(l). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 1.0 (0.125 inch thick sheet).

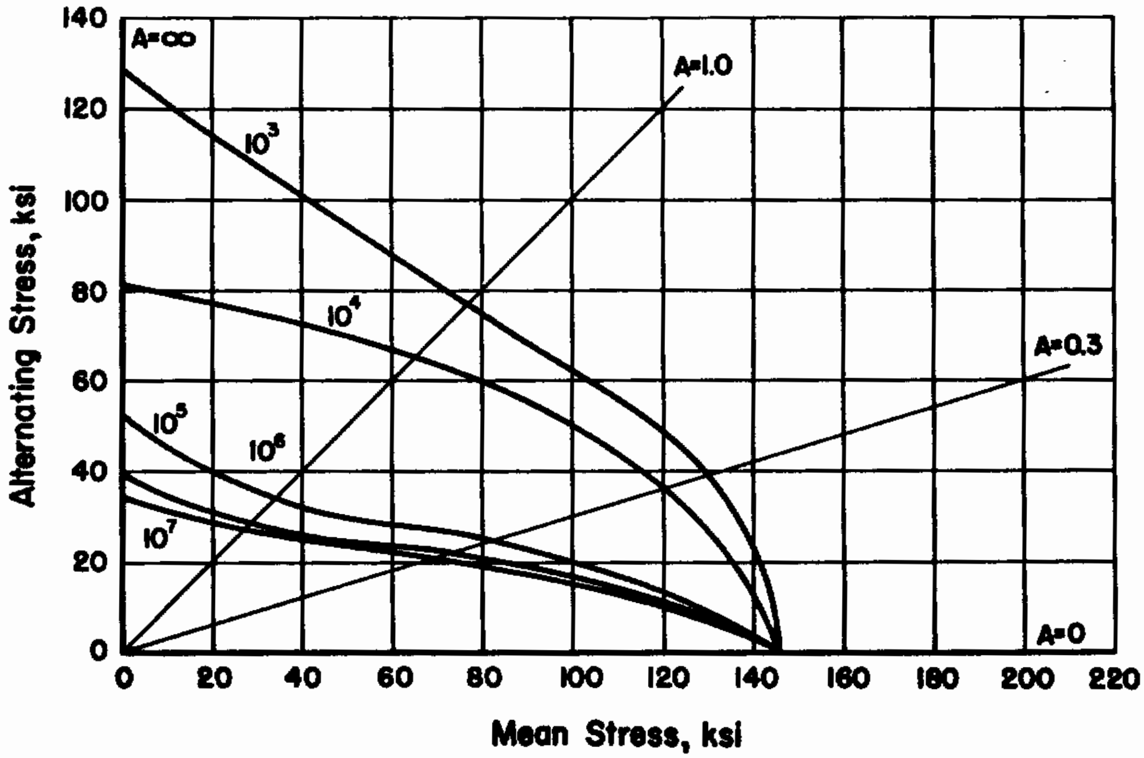

FIGURE 5.3.6(m). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 1.0 (0.125 inch thick sheet).

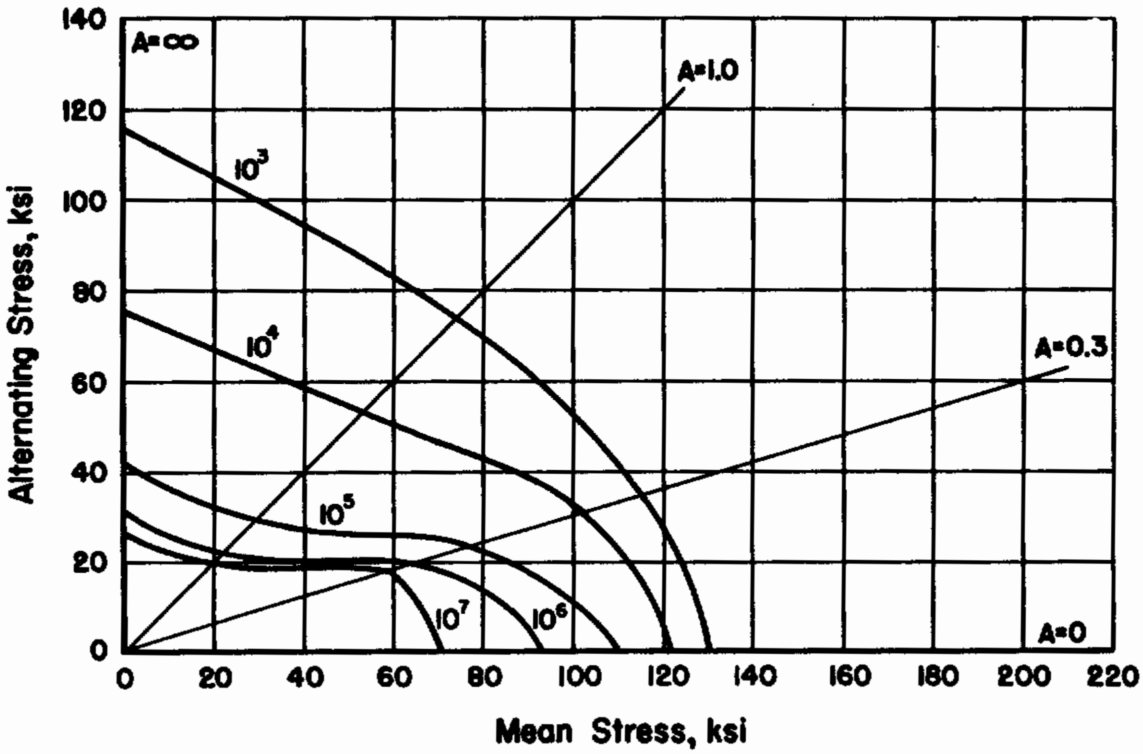

FIGURE 5.3.6(n). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 1.0 (0.125 inch thick sheet).

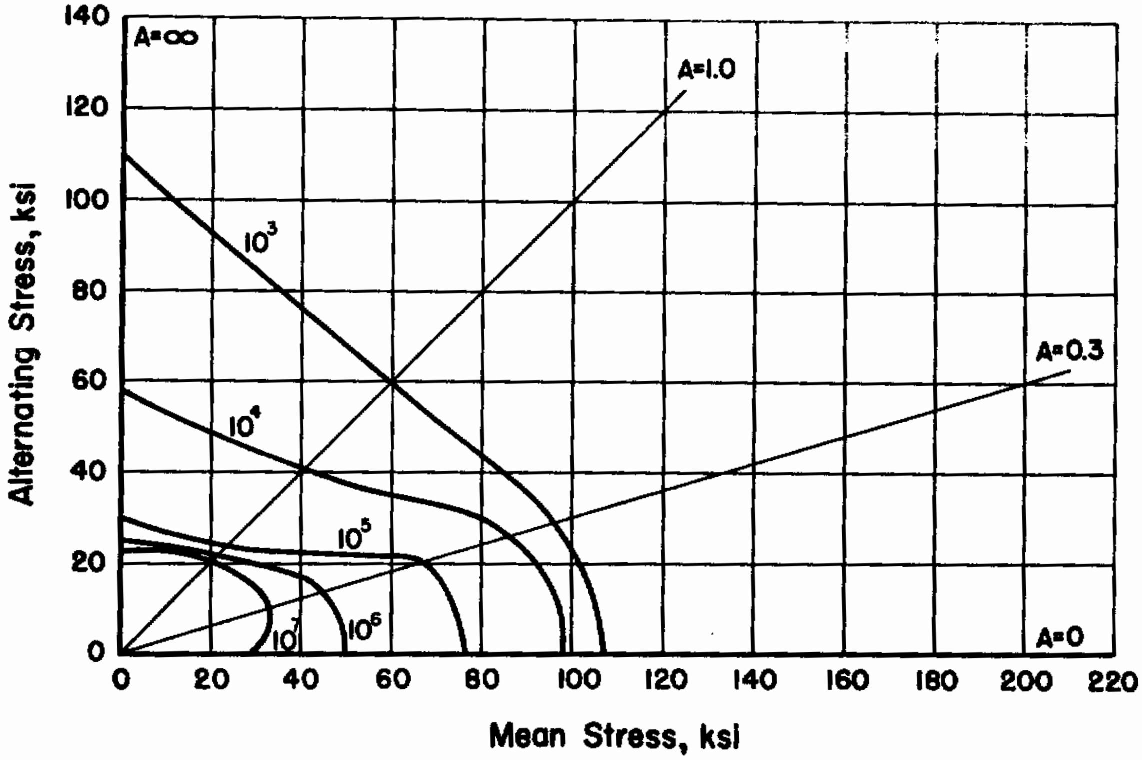

FIGURE 5.3.6(o). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 1.0 (0.125 inch thick sheet).

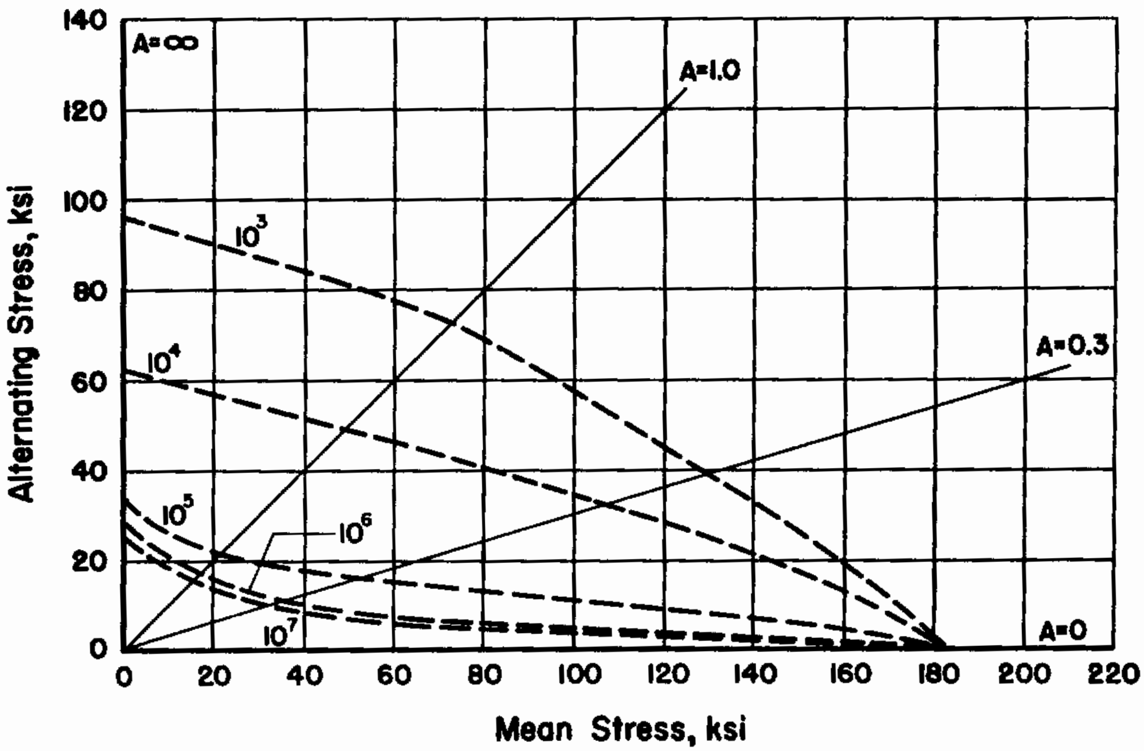

FIGURE 5.3.6(kk). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at room temperature, K_t = 2.82 (0.125 inch thick sheet).

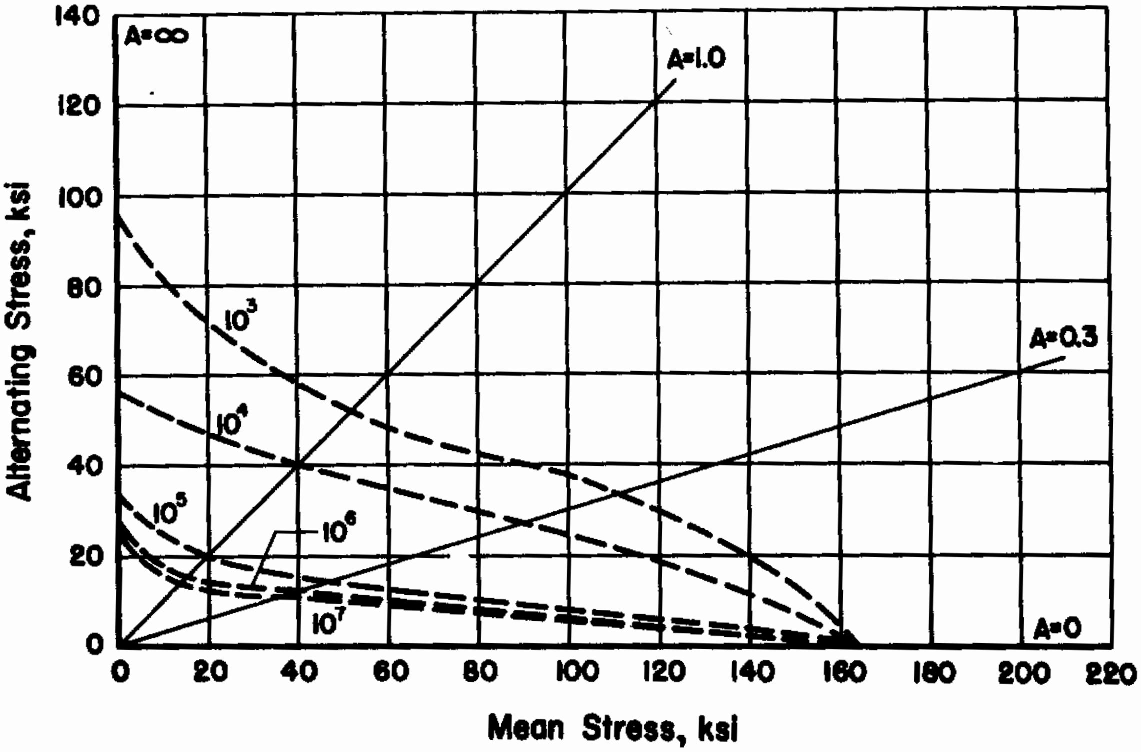

FIGURE 5.3.6(ll). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 400°F, K_t = 2.82 (0.125 inch thick sheet).

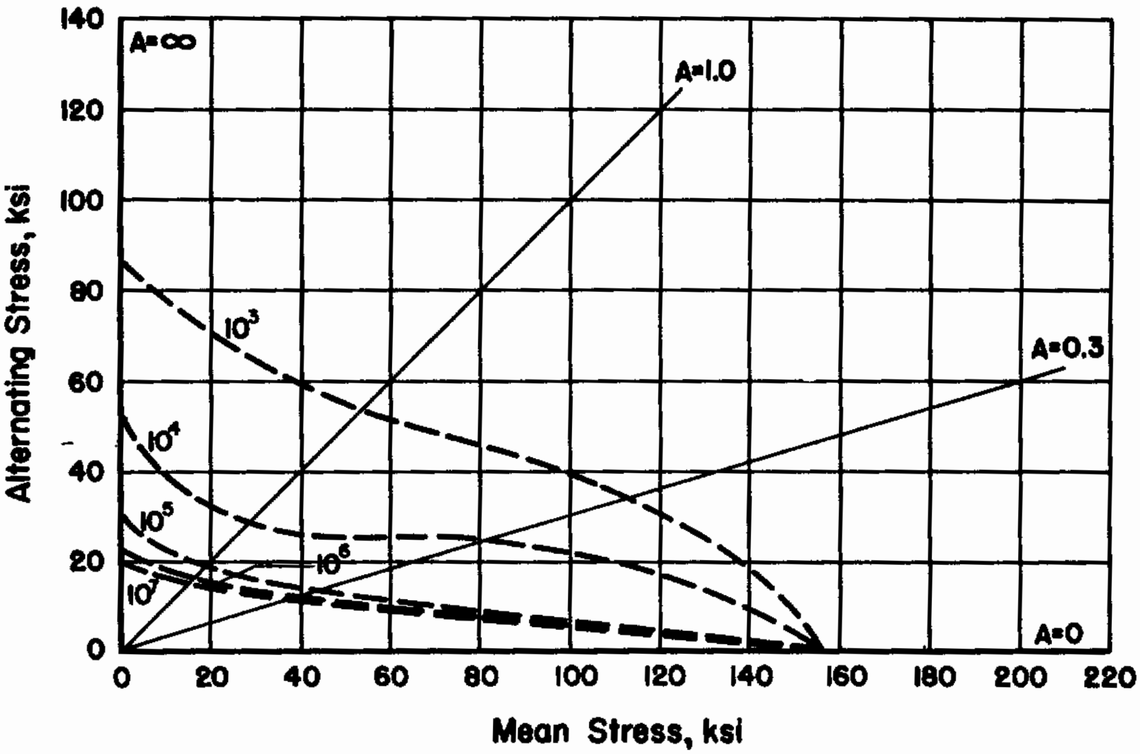

FIGURE 5.3. (mm). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 600°F, K_t = 2.82 (0.125 inch thick sheet).

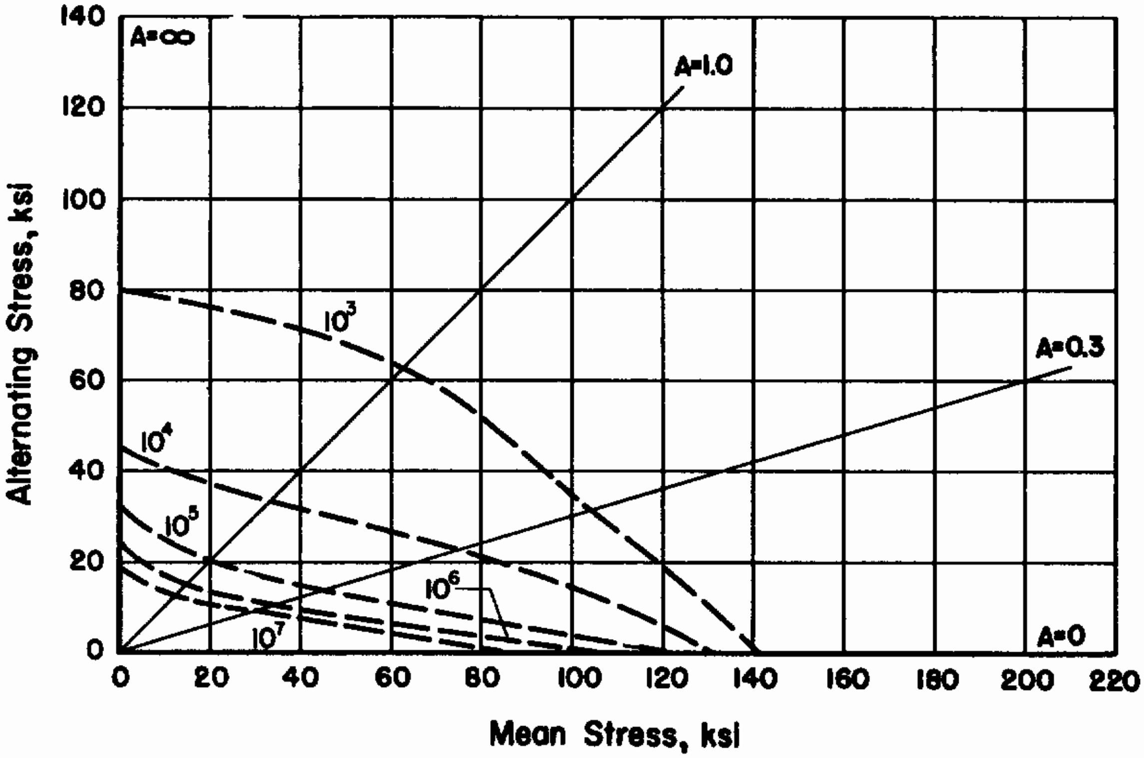

FIGURE 5.3.6(nn). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 800°F, K_t = 2.82 (0.125 inch thick sheet).

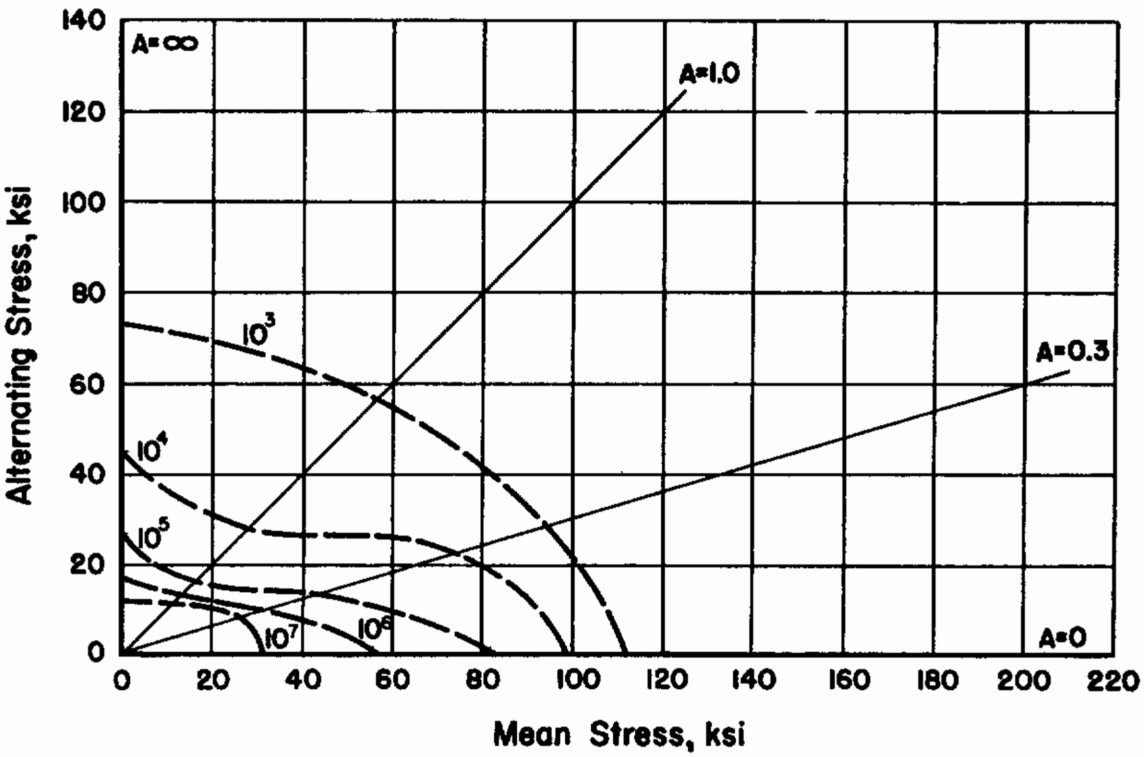

FIGURE 5.3.6(oo). Direct stress fatigue properties of 2.5Al-16V solution treated and aged titanium alloy at 900°F, K_t = 2.82 (0.125 inch thick sheet).

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4. Statistical Research Group, Columbia University, "Techniques of Statistical Analysis", McGraw-Hill Book Company, Inc., New York, 1947.