March 1966

MATERIALS DATA HANDBOOK

Aluminum Alloy 2219

Edited by

John Sessler
Volker Weiss

Sponsored by

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

SYRACUSE UNIVERSITY RESEARCH INSTITUTE

DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY

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DEPARTMENT OF CHEMICAL ENGINEERING AND METALLURGY
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PREFACE

This Materials Data Handbook on the aluminum alloy 2219, was prepared by personnel and associates of the Department of Chemical Engineering and Metallurgy, Syracuse University, as part of a program sponsored by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama.

It is intended that this Handbook present, in the form of a single document, a comprehensive summary of the materials property information presently available on the 2219 alloy.

The scope of the information included herein includes physical and mechanical property data at cryogenic, ambient and elevated temperatures, supplemented with useful information in such areas as material procurement, metallurgy of the alloy, corrosion, environmental effects, fabrication and joining techniques. Design data are presented, where available, and these data are complemented with information on the typical behavior of the alloy. The major source for the design data used is the Department of Defense document, Military Handbook - 5.

The Handbook is divided into twelve (12) chapters as outlined below:

Chapter	1	General Information
	2	Procurement Information
	3	Metallurgy
	4	Production Practices
	5	Manufacturing Practices
	6	Space Environment Effects
	7	Static Mechanical Properties
	8	Dynamic and Time Dependant Properties
	9	Physical Properties
	10	Corrosion Resistance and Protection
	11	Surface Treatments
	12	Joining Techniques

Information on the alloy is given in the form of Tables and Illustrations supplemented with descriptive text where deemed useful by the authors. Source references for the information presented are listed at the end of each chapter.

ACKNOWLEDGEMENTS

The "Materials Data Handbook, Aluminum Alloy 2219", was prepared by Syracuse University under Contract No. NAS8-11345 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The program was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the Space Flight Center with Mr. Melvin G. Olsen acting as project manager.

Acknowledgement is made to the following Syracuse University personnel and associates for their contributions to the program.

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The editors are also appreciative of the cooperation extended to the program by members of the Mil-Hdbk-5 committee; personnel of the Defense Metals Information Center (DMIC), Battelle Memorial Institute; personnel of the NASA Marshall Space Flight Center; and to the many individuals and organizations (too numerous to mention) that have contributed to the generation of this document.

John G. Sessler, Editor
Volker Weiss, Associate Editor

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TABULAR ABSTRACT

Aluminum 2219

TYPE:

Wrought, heat treatable aluminum alloy

NOMINAL COMPOSITION:

Al-6.3Cu-0.3Mn-0.18Zr-0.1V-0.06Ti

AVAILABILITY:

Bare and clad sheet, plate, forgings, extrusions, drawn tube, rod and bar.

TYPICAL PHYSICAL PROPERTIES:

Density	2.82 gr/cm^3 at RT
Thermal Conductivity	0.41 cal/cm sec C (O temper)
	0.30 cal/cm sec C (T62 temper)
Thermal Coef Expansion	(20-100C), 22.3 in/in/C
Electrical Resistivity	3.90 microhm-cm at RT (O temper)
	5.23 microhm-cm at RT (T62 temper)

TYPICAL MECHANICAL PROPERTIES:

F_{tu}	25,000 psi (O temper)
	61,000 psi (T62 temper)
F_{ty}	10,000 psi (O temper)
	42,000 psi (T62 temper)
e (2 inch)	20 percent (O temper)
	11 percent (T62 temper
E (tension)	10.6 x 10^6 psi

FABRICATION CHARACTERISTICS:

Weldability	Excellent (fusion and resistance methods)
Formability	Slightly superior to 2014 alloy
Machinability	Good in annealed condition

COMMENTS:

Alloy has good mechanical properties at cryogenic temperatures and at elevated temperatures up to 600F. Recommended for applications requiring high strength weldments.

SYMBOLS

a	One-half notch section dimension
A	Area of cross section; "A" basis for mechanical property values (Mil-Hdbk-5)
Å	Angstrom unit
AC	Air cool
AMS	Aerospace Material Specifications
Ann	Annealed
AUS	Austenitize
Av or Avg	Average
B	"B" basis for mechanical property values (Mil-Hdbk-5)
b	Subscript "bending"
bcc	Body centered cubic
BHN	Brinell hardness numer
br	Subscript "bearing"
Btu	British thermal unit (s)
C	Degree (s) Centigrade
c	Subscript "compression"
CD	Cold drawn
CF	Cold finished
cm	Centimeter
cp	Specific heat
CR	Cold rolled
CW	Cold worked
CVM	Consumable vacuum melted
D or Dia	Diameter
DPH	Diamond pyramid hardness
e	Elongation in percent
E	Modulus of elasticity, tension
E_c	Modulus of elasticity, compression
e/D	Ratio of edge distance to hole diameter
E_s	Secant modulus
E_t	Tangent modulus
ev	Electron volt (s)

F	Degree (s) Fahrenheit
f	Subscript "fatigue"
F_{bru}	Bearing ultimate strength
F_{bry}	Bearing yield strength
fcc	Face centered cubic
FC	Furnace cool
F_{cy}	Compressive yield stress
F_{su}	Shear stress; shear strength
F_{tu}	Tensile ultimate strength
F_{ty}	0.2% tensile yield strength (unless otherwise indicated)
G	Modulus of rigidity
HAZ	Heat affected zone in weldments
hcp	Hexagonal close pack
hr	hour (s)
HT	Heat treat
IACS	International annealed copper standards
in	inch
ipm	inches per minute
K	Stress intensity factor; thermal conductivity
K_c	Measure of fracture toughness (plane stress) at point of crack growth instability
K_{Ic}	Plane strain fracture toughness value
KSI or ksi	Thousand pounds per square inch
K_t	Theoretical elastic stress concentration factor
L	Longitudinal
lb	Pound
LT	Long transverse (same as transverse)
M	Bending moment
m	Subscript "mean"
Max	Maximum
MIL	Military
Min	Minimum
N	Cycles to failure
NSR	Notch strength ratio
NTS	Notch tensile strength

OQ	Oil quench
ppm	Parts per million
pt	Point
r	radius
RA	Reduction in area; Rockwell hardness A scale
RB	Rockwell hardness B scale
RC	Rockwell hardness C scale
ρ (rho)	Density
rpm	Revolutions per minute
RT	Room temperature
SA	Solution anneal
sec	second
S-N	S = stress; N = number of cycles
Spec	Specifications; specimen
ST	Solution treat; short transverse
T	Transverse
t	Thickness; Time, hour
Temp	Temperature
typ	Typical
Var	Variable
VHN	Vickers hardness number
W	Width
WQ	Water quench

CHAPTER 1

GENERAL INFORMATION

1.1 Aluminum alloy 2219 is a heat treatable wrought alloy developed by the Aluminum Company of America (Alcoa) in 1954. The alloy was originally developed to meet a need for application of an aluminum alloy at temperatures up to 600F. Typical mechanical properties of 2219 in the 500-600F temperature range are superior to those of any other commercially available aluminum alloy, (Ref. 1.1). The weldability of the alloy is excellent. Mechanical properties of welded and unwelded 2219 at temperatures down to -423F are also excellent.

1.2 The alloy has good tensile and yield strength and good fatigue and creep-rupture properties up to temperatures of 600F. Its forming characteristics are similar and slightly superior to 2014 alloy. The alloy has good machining qualities in the annealed condition. It appears not to be susceptible to stress-corrosion cracking provided that proper heat treating procedures are employed. The 2219 alloy is available as sheet and plate, forgings, extrusions, drawn tubes and rod and bar, (Refs. 1.2, 1.3).

1.3 Typical areas of application for 2219 alloy are aircraft and automotive engine parts, special applications in missiles, space vehicles, and ground support equipment, (Ref. 1.2).

1.4 General Precautions

1.41 Care should be taken when reheat treatment of clad alloy is required, because copper tends to diffuse through the cladding to the surface, thereby decreasing corrosion resistance.

1.42 Any solution heat treatment of clad 2219 should be performed as quickly as is consistent with MIL-H-6088B. As a general rule, no more than one complete reheat treatment should be performed. The number of annealing treatments should be kept to a minimum and performed as rapidly as possible, (Ref. 1.1).

CHAPTER 1 - REFERENCES

1.1 "Aluminum Alloy 2219", Alcoa Green Letter by L. W. Mayer, (November 1963)

1.2 "Alloy Digest - Aluminum 2219", Filing Code Al-96, Aluminum Alloy, Engineering Alloys Digest, Inc., (October 1960)

1.3 "Aerospace Structural Metals Handbook", Vol. II Non-Ferrous Alloys, V. Weiss and J. Sessler (Editors), ASD-TDR-63-741, (1963)

CHAPTER 2

PROCUREMENT INFORMATION

2.1 General. Aluminum 2219 alloy is available as sheet, plate, forging and extrusions, drawn tubes, and rod and bar. Alclad 2219 is available as sheet. Detailed tables of standard sizes available and standard tolerances for the various products are given in Ref. 2.2.

2.2 Procurement Specifications, Table 2.2.

2.21 NASA Specifications

2.211 MSFC-SPEC-144B, "Aluminum Alloy Forgings, Premium Quality, Heat Treated", (August 13, 1963), Amendment 1, (September 8, 1964). Tempers: T4, T6, T31, T352, T81, T852. Prepared by George C. Marshall Space Flight Center. Custodian: NASA-MSFC.

2.3 Major Producers of the Alloy. (United States only)

Aluminum Company of America
1501 Alcoa Building
Pittsburgh, Pennsylvania

Harvey Aluminum
General Offices
Torrance, California

Kaiser Aluminum and Chemical Sales, Inc.
919 North Michigan Avenue
Chicago, Illinois

Reynolds Metals Co.
6601 West Broad Street
Richmond, Virginia

2.4 Available Forms, Sizes and Conditions

2.41 Commercial sizes available for sheet, sheet circles, plate and plate circles, Table 2.41.

PROCUREMENT SPECIFICATIONS (a)

TABLE 2. 2

Source	(Ref. 2.3, 2.4, 2.6, 2.7, 2.8)					
Alloy	Al 2219					
Product	Temper	Military	Federal	ASTM	SAE	
					AMS	HDBK
Sheet and plate	O	MIL-A-8920A	-	B209-64	4031	-
	F, T31, T351	MIL-A-8920A	-	B209-64	-	-
	T37, T62, T81	MIL-A-8920A	-	B209-64	-	-
	T851, T87	MIL-A-8920A	-	B209-64	-	-
Forgings	T6, T852, T87	-	QQ-A-367F	-	-	-
	T6	-	-	B247-64	4143	-
Bar, rod, shapes,	O, T62	-	-	B221-64	-	-
(tube extruded)	T8510, T8511	-	-	B221-64	-	-

(a) Specified as of May 31, 1965

COMMERCIAL SIZES AND TEMPERS AVAILABLE FOR SHEET, SHEET CIRCLES, PLATE AND PLATE CIRCLES

TABLE 2.41

Source	Ref. 2.2 (c)			
Product	Temper	Thickness (inch)	Size (max) (a)(b)	
			Width (in)	Length (in)
Alclad and bare sheet and sheet circles (flat, mill finish)	O, T31, T81	0.014-0.022	48	180
		0.023-0.029	60	180
		0.030-0.036	60	180
		0.037-0.059	84	200
		0.060-0.075	90	300
		0.076-0.095	90	300
		0.096-0.119	96	360
		0.120-0.249	102	360
Alclad and bare sheet and sheet circles (flat, mill finish)	T37, T87	0.020-0.031	24	-
		0.032-0.039	36	-
		0.040-0.059	48	-
		0.060-0.124	72	72
		0.125-0.249	84	84
Alclad and bare plate and plate Circles (flat, mill finish)	T37, T87	0.250-0.374	90	90

(a) Maximum diameter of circle same as maximum width of sheet.
(b) Sizes greater than indicated can be supplied subject to inquiry.
(c) Consult producers of alloy for further information.

CHAPTER 2 - REFERENCES

2.1 Alcoa Product Data, "Specifications", Section A 12A, Aluminum Co. of America, (July 1, 1963)

2.2 "Alcoa Aluminum Handbook", Aluminum Co. of America, (1962)

2.3 "SAE Aerospace Material Specifications", Soc. Automotive Eng. Inc., (latest Index, February 15, 1965)

2.4 "Index of Specifications and Standards", Department of Defense, Part I Alphabetical Listing, Supplement, (May 31, 1965)

2.5 ASTM Standards, Part 6, "Light Metals and Alloys", (October 1964)

CHAPTER 3

METALLURGY

3.1 Chemical Composition

3.11 Nominal chemical composition of 2219 in percent, (Ref. 3.1):

Cu	6.3
Mn	0.3
Ti	0.06
V	0.10
Zr	0.18
Al	Balance

3.111 Sheet and plate are available in the Alclad condition. Cladding material is 7072 alloy. Nominal composition of 7072 alloy in percent, (Ref. 3.2):

Zn	0.8-1.3
Si + Fe	0.7
Mn	0.1 max
Cu	0.1 max
Mg	0.1 max
Others	
Each	0.05 max
Total	0.15
Al	Balance

The nominal cladding thickness per side is 10 percent of the total thickness of the composite if the latter is below 0.040 inch and 5 percent for a total thickness of composite products of 0.040 inch to 0.099 inch. For a total thickness of 0.100 inch or more the nominal cladding thickness on each side is 2.5 percent, (Ref. 3.3).

3.12 Chemical composition limits, in percent, (Ref. 3.2):

Si	0.20 max
Fe	0.30 max
Cu	5.8 to 6.8
Mn	0.2 to 0.4
Mg	0.02 max
Zn	0.10 max
Ti	0.02 to 0.10
V	0.05 to 0.15
Zr	0.10 to 0.25
Others	
Each	0.05 max
Total	0.15
Al	Balance

These composition limits are normally checked by spectrochemical analysis or in accordance with the procedures outlined in ASTM E34, "Standard Methods for Chemical Analysis of Aluminum and Aluminum Base Alloys", (Ref. 3.4).

3.13 Alloying elements. Copper is the primary hardening agent with vanadium and zirconium acting as grain refiners by increasing the recrystallization temperature. Zirconium and manganese improve the strength properties, particularly at elevated temperatures. The primary precipitation hardening agent is $CuAl_2$ (see Fig. 3.13). Since Mg and Si are held to extremely low composition limits, the occurrence of their low melting eutectics (Al-Cu-Mn-Si) is essentially eliminated and the alloy can be solution treated just below the Al-Cu eutectic which occurs at 548C. At this temperature, most of the $CuAl_2$ will go into solution, (Ref. 3.5). Copper and the other alloying elements decrease the corrosion resistance of aluminum. The Al-Cu constituent is more cathodic than Al and more anodic than the solid solution containing more than 2.5% Cu, (Ref. 3.6, p. 918). Since initial precipitation usually occurs along grain boundaries, zones lean in solutes will develop near the grain boundaries. These anodic zones may corrode selectively by an electrochemical process producing notches that cause stress concentrations. However, this does not occur in properly heat treated and aged commercial tempers, (Ref. 3.12). As the alloy structure, (i.e. precipitate and solid solution relationship) is modified by heat treatment, its resistance to corrosion, stress corrosion, and weathering will be altered. The amount of protection provided by the cladding depends on the thickness and the purity of the cladding material, and also on the annealing and heat treatment practice, (see section 3.111).

3.2 Strengthening Mechanisms

3.21 General. The alloy can be strengthened by precipitation hardening and cold work. The precipitation hardening mechanisms are clearly evident from the phase diagram in Fig. 3.13. After quenching from the solution temperature to room temperature, slow precipitation occurs in the form of submicroscopic particles which represent obstacles to plastic flow and thus cause hardening. Cold working greatly accentuates precipitation hardening in this alloy. This is a general property of most aluminum alloys and is related to the crystal structure (fcc) and the stacking fault energy. Various processing operations utilize the effects of both mechanisms (i.e. cold working of the solution treated alloy at room temperature and subsequent aging at room or elevated temperatures).

Caution should be used when reheat treatment of alloy is contemplated. Studies at the Naval Air Material Center, (Ref. 3.7) have indicated that only one reheat treatment of 2219-T6 Alclad sheet was possible before copper began to diffuse through the clad material to the surface.

3.22 Heat Treatment.

Annealing: (O Condition): The annealing treatment for precipitation hardening alloys is essentially an overaging treatment. Two to three hours at 400 to 413C followed by slow cooling at 28C/hour maximum to at least 260C is recommended, (Ref. 3.8). Intermediate anneals during repeated cold working operations should be carried out at 344C for no more than 30 minutes at a time.

Solution Treatment: (T4 Condition): Heat to 532 to 543C and hold from 20 minutes to 4.5 hours depending on thickness and equipment, followed by rapid cold water quench. The proper designation is T42 if the operation is performed by the user. It should be noted that the solution treating temperatures should be closely controlled. Higher temperatures may cause solid solution grain boundary melting, high temperature oxidation and eutectic melting which cannot be repaired by subsequent heat treating operations. Lower temperatures may result in incomplete solution of the hardening constituents and thus a loss in hardening potential of the alloy. Rapid quenching is also important because of possible precipitation and consequently reduced corrosion resistance on slow cooling from the solution treating temperature. Maximum allowable quench delay times are listed below:

Nominal Thickness, Inch	Maximum Time, Seconds
$\leq$ 0.016	5
0.017 to 0.031	7
0.032 to 0.090	10
$\geq$ 0.091	15

Aging Treatment: (T6 Condition): Heat T4 or T42 condition to 180 to 194C and hold for 36 hours. If performed by user, for plate and extrusions, the correct temper designation is T62.

Cold Work and Combined Treatments: All cold work and combined treatments together with the solution and aging treatments for various products are summarized in Table 3.22, (Ref. 3.3).

3.3 Critical Temperatures. Melting range 543 to 644C. The oxidation resistance in atmosphere is generally good until the melting temperature is approached.

3.4 Crystal Structure, Face centered cubic. The lattice parameter depends primarily on the amount of Cu in solution. For pure aluminum a_o = 4.0413 Å; for 5.5% Cu, a_o = 4.0290 Å, (Ref. 3.9, p. 49).

3.5 Microstructure. References 3.10 and 3.11 are recommended as excellent sources of information on the identification of constituents in aluminum alloys.

3.6 Metallographic Procedures: In general, mechanical polishing is preferred to electropolishing, especially where larger microconstituents are present and the material is relatively soft, as objectionable relief effects produced by the electrolytic polishing technique may cause a misinterpretation of the microstructure, (Ref. 3.11, p. 106). For homogeneous alloys, and for those conditions containing only finely dispersed particles, the electrolytic method is excellent. Preparatory polishing on metallographic polishing papers 0 to 000 should be performed wet with a solution of 50g paraffin in 1 liter kerosene to keep the specimen bright and avoid imbedding of grinding compound particles into the soft specimen surface. Rough polishing on a "Kitten's Ear" broadcloth at 250 to 300 RPM with heavy magnesium oxide powder is recommended, (Refs. 3.9 and 3.10).

An alternate and popular method consists of the following steps:

a) Wet polishing (flowing water with 240 grit silicon carbide paper at approximately 250 RPM.
b) Wet polishing with 600 grit silicon carbide paper at approximately 250 RPM.
c) Polishing with 9 micron diamond paste on nylon cloth at 150 to 200 RPM using a mild soap solution for lubrication.
d) Final polish on a vibratory polisher using a microcloth containing a slurry of methyl alcohol and 0.1 micron aluminum oxide powder. A slurry of 0.1 micron aluminum oxide powder in a 10% solution of glycerine in distilled water may also be used for this step.

Etching reagents have to be suited to the objective of the study. Kellers etch reveals microstructural details and grain boundaries satisfactorily. A 10 percent solution of NaOH gives better detail of the microstructural constituents but does not delineate the grain boundaries. Study of the "as polished" surface prior to etching may also give valuable information on the types of constituents present, especially when attention is paid to the colors of the various particles. Macroscopic studies for cracks, gross defects, forging lines and grain structure should be made with the following etching solutions: 10% NaOH (cracks, gross defects), Tucker's etch, modified Tucker's etch and Flick's etch from ASM Table I, p. 95, (Ref. 3.9, p. 95). These etching solutions for revealing the macrostructure are given in Table 3.1.

ETCHING SOLUTIONS FOR REVEALING MACROSTRUCTURE

TABLE 3.1

Source	Ref. 3.9	
Solution	**Concentration (a)**	**Specific Use**
Sodium Hydroxide	NaOH 10g Water 90 ml	For cleaning surfaces, revealing unsoundness, cracks and gross defects
Tucker's	HCl (conc.) 45 ml HNO_3 (conc.) 15 ml HF (48%) 15 ml Water 25 ml	For revealing structure of castings, forgings, etc.
Modified Tucker's	HCl (conc.) 10 ml HNO_3 (conc.) 10 ml HF (48%) 5 ml Water 75 ml	For revealing structure of all castings and forgings except high silicon alloys.
Flick's	HCl (conc.) 15 ml HF (48%) 10 ml Water 90 ml	For revealing grain structure of duralumin type alloys. Surface should be machined or rough polished

(a) All of these solutions are used at room temperature.

TEMPERS AND AGING TREATMENTS FOR ALUMINUM ALLOYS
2219 SHEET, PLATE, BAR AND ROD

TABLE 3.22 a

Temper	Sheet	Plate	Rod, Bar
T31	Sol HT (d) + Stretch (e)	-	-
T351, T352 (a)	-	Sol HT (d) + 1.5-3% stretch (e)	Sol HT (d) + 1-3% stretch (e)
T37	Sol HT (d) + approx. 8% CW (e)		-
T42	Sol HT (d)(f)		
T62	T42 Aged 36 Hr at 190C (Alclad 18 Hr at 190C)		
T81	T31 Aged 18 Hr at 177C	-	-
T851, T852 (a)	-	T351 Aged 18 Hr at 177C	T351 Aged 18 Hr at 190C
T87	T37 Aged 24 Hr at 163C		-

(Ref. 3.3)

(a) Forgings only
(b) By compression
(c) Hand forgings only
(d) Solution HT at 532-543C, cold water quench
(e) By Producer
(f) By Customer

TEMPERS AND AGING TREATMENTS FOR ALUMINUM ALLOY 2219 EXTRUSIONS, DRAWN TUBING, AND FORGINGS

TABLE 3.22 b

Temper	Extrusions	Drawn Tube	Forgings
T31	-	Sol. HT (d) + stretch (e)	-
T351 T352 (a)	-	-	Sol. HT (d) + 2.5% CW (b)(e)
T3511 T3510	Sol. HT (d) + 1% stretch (e)	-	-
T37	-	-	Sol. HT (d) + approx. 8% CW (e)
T4	-	-	Sol. HT (d) (e) or (f)
T42	Sol. HT (f)		-
T6	-	-	T4 aged, 26 hr at 190C
T62	T42 aged 36 hr at 190C (Alclad 18 hr at 190C)		-
T81	-	T31 aged 18 hr at 190C	-
T851 T852 (a)	-	-	T352 aged 18 hr at 177C
T8511 T8510	T351 aged 18hr at 190C	-	-
T87	-	-	T37 aged 24 hr at 163C (c)

(a) Forgings only
(b) By compression
(c) Hand forgings only
(d) Solution HT at 532 to 543C, cold water quench
(e) By producer
(f) By customer

(Ref. 3.3)

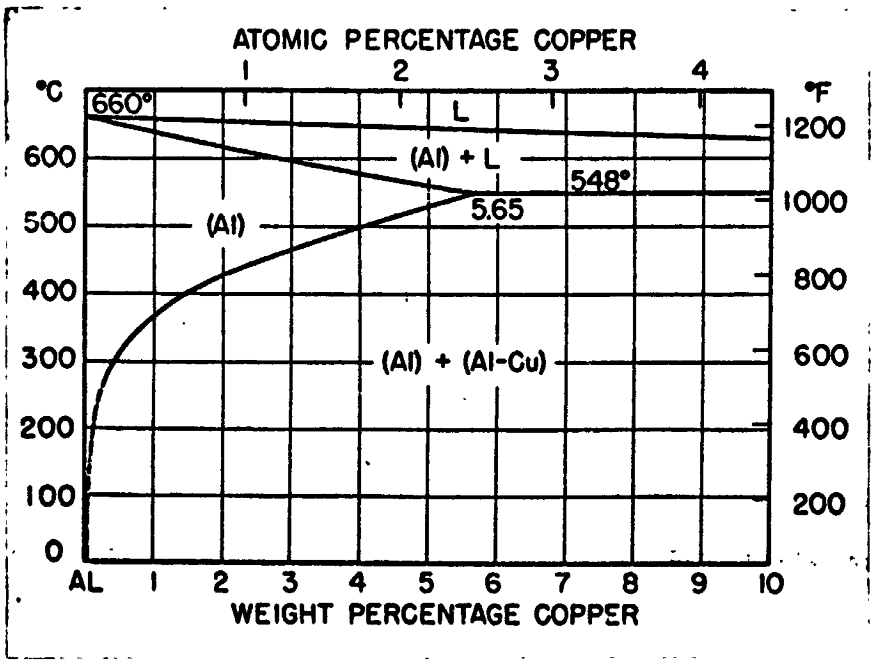

FIG. 3.13 BINARY PHASE DIAGRAM OF THE ALUMINUM RICH PORTION OF THE Al-Cu EQUILIBRIUM DIAGRAM

(Courtesy Aluminum Company of America)

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CHAPTER 4

PRODUCTION PRACTICES

4.1 General. In the United States, aluminum and its alloys are produced from an ore of impure hydrated aluminum oxide known as "bauxite", Important sources of bauxite are located in Arkansas, Dutch Guiana and Jamaica. The impure ore is converted into pure aluminum oxide (alumina) through a series of chemical processes. Oxygen is removed from the alumina by smelting in carbon-lined electric furnaces known as reduction pots. Pure molten aluminum is deposited at the bottom of the pot, and is periodically siphoned off and poured into molds to form "pigs" and "sows". A separate furnace operation is used to form "alloy pig" from the pure aluminum by the addition of alloying elements and this metal is cast into ingots for further processing, (Ref. 4.1).

For the 2219 alloy, the main additional alloying elements are copper and manganese. Small amounts of titanium, zirconium and vanadium are also added. Generally, this phase of production practice involves the melting, alloying and casting of large 20,000 to 50,000 pound ingots, carefully controlled. After the ingots are scalped and preheated in vertical electric soaking pits, they are ready for further processing to a particular form of product.

4.2 Manufacture of Wrought Products

4.21 Bar and rod are normally produced by hot rolling or extruding. Cold finished bar and rod are produced by hot working to a size slightly larger than specified and reducing to final dimensions by cold working. A better surface finish and closer dimensional tolerances are obtained in this manner, (Ref. 4.2).

4.22 A similar process is used to produce rolled structural shapes; special rolls being required. Finishing operations include roller or stretch straightening, and heat treatment.

4.23 Roll form-shapes are produced by passing strip through a series of roller dies. Each successive pair of rolls cause the work to assume a cross-section shape more nearly approaching that desired. The final desired shape is produced at the last pair of rolls.

4.24 Plate is produced by hot rolling of ingots to slabs (approximately 60 percent reduction), usually in a 4 high reversible mill. The slabs are then further reduced 50 percent in a reversible 2 high mill. The last stage of hot rolling is done in a hot reversing mill, where the plate is progressively rolled to the final hot mill dimensions. Plate may be

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CHAPTER 3 - REFERENCES

3.1 "The Aluminum Data Book", Reynolds Metals Co., (1965)

3.2 "Alcoa Aluminum Handbook", Aluminum Company of America, (1962)

3.3 Alcoa Green Letter, "Alcoa Aluminum Alloy 2219" by L. W. Mayer, (October 1960, last revision November 1963)

3.4 "Standards for Wrought Aluminum Mill Products", Fifth Edition, The Aluminum Association, New York, (October 1962)

3.5 "Summary Information Regarding Aluminum Alloy 2219", Martin-Denver Evaluation Report No. 1, MI-61-44, (November 1961)

3.6 "Metals Handbook", Eighth Edition, Vol. I, ASM, Metals Park, Novelty, Ohio, (1961)

3.7 R. G. Mahorter, Jr. and W. F. Emmons, "A Study of Creep Resistance, Formability and Heat Treatment of Clad X 2219-T6 Aluminum Alloy", Report No. NAMC-AML-AE 1100 Naval Air Material Center, (August 1959)

3.8 "Alcoa Alloy 2219", Aluminum Company of America, Development Division, (March 1959)

3.9 W. L. Fink, et al., "Physical Metallurgy of Aluminum Alloys", American Society for Metals, (1958)

3.10 F. Keller and G. W. Wilcox, "Identification of Constituents of Aluminum Alloys", Technical Paper No. 7, Aluminum Company of America, (1942), Revised (1958)

3.11 J. P. Vidosic, "Study of Phase Identification in Steel and Aluminum Alloys", Georgia Institute of Technology, Final Report, Project No. A-641, NASA Contract NAS8-5117, (September 1963)

3.12 J. A. Nock, Jr., et al., "A New High Strength Aluminum Alloy", Metal Progress, (September 1961)

subjected to "stress relief" stretching (about 2 percent permanent set) to improve flatness and reduce warpage upon machining. Plate is then sheared or sawed to the required dimensions, (Ref. 4.2).

4.25 Sheet is usually produced from plate by cold rolling to final sheet thickness, followed by trimming, annealing, heat treating, stretching and other finishing operations.

4.26 Wire is produced by drawing rod through a series of progressively smaller dies to obtain the desired dimensions.

4.27 Extrusions are produced by subjecting re-heated cast billets to enough pressure to force the metal to flow through a die orifice, forming a product whose cross-section shape and size conforms to that of the orifice. Speeds, pressures and temperatures must be closely controlled to insure uniform quality of extruded products.

4.28 Tube is produced by extruding, by drawing or by welding. Extruded tube is forced thru an orifice as described in 4.27. A die and mandrel are used. Drawn tube is manufactured by a cold process which is similar to drawing bar and rod. A mandrel is used with one end fixed and a bulb attached to the other end. The tube is drawn over the mandrel bulb and through a die at the same time. Welded tube is produced by slitting coil stock into strips and passing the strips through a series of rolls to form tube. The longitudinal seam is welded as the tube leaves the last roll forming station.

4.29 Forgings are made by pressing (press forging) or hammering (drop forging). Relatively heavy equipment is required since aluminum is not as plastic at its forging temperature as steel. Aluminum forgings compare favorably with structural steel in unit strength at about one-third the weight. With comparable strength and with a lower elastic modulus, aluminum alloys have a much higher impact-energy-absorbing capacity than mild steel.

4.3 Casting of Alloy Ingots

4.31 Metal for wrought products is alloyed in large 10 to 25 ton double hearth furnaces, carefully controlled and instrumented. The direct chill (DC) method is generally used for casting these ingots. Molten metal is poured into a mold and a hydraulic piston descends slowly as the metal solidifies. Water is sprayed on the outside of the mold to promote rapid solidification. Additional processing may include scalping (machining of outside surfaces) or homogenizing, (Refs. 4.2 and 4.3).

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CHAPTER 5

MANUFACTURING METHODS

5.1 General. This heat-treatable alloy is available bare and in the Alclad condition. Although the alloy was originally developed for forged parts to be used up to 600F, it is now available in many forms as shown in Table 5.1.

5.2 Forming

5.21 Sheet and Plate. The alloy 2219 exhibits equal or superior formability characteristics to 2024 and 7075 for comparable tempers, (Ref. 5.3). Results of Olsen cupping tests indicate that the 2219 alloy is slightly more formable than 2024. Both alloys were tested clad and bare, in both "O" and "T6" conditions. Dimpling for riveting, on the basis of 3/16 inch dimples in 0.064 inch sheet, was satisfactory when performed at room temperature. However, 2219-T6 exhibited slight edge cracking when dimpled at room temperature. This was eliminated by hot-dimpling at 350F, (Ref. 5.12).

5.211 Cold Forming. The formability of alloy 2219 sheet and plate is directly related to the temper strength and ductility. As with other aluminum alloys high elongation as well as considerable spread between yield and ultimate strength will be indicative of good formability. The simplest and most widely used forming method is probably that of bending. Table 5.2111 indicates the ease of forming in terms of recommended minimum bend radii as a function of temper and sheet and plate thickness using typical mechanical properties for 0.100 inch sheet.

Formability, is at a maximum in the annealed temper and is equal to or slightly superior to that of other high strength aluminum alloys such as 2024 and 7075, (Ref. 5.1). In general, severe forming and drawing operations should be done with annealed stock, and the tools must be clean and free of scratches. Less severe operations may be done on material in the T42, T31 and T37 tempers. Although some mild forming operations can be performed on artificially aged material, the more critical operations should be done while the material is in the solution-treated or naturally aged condition. Forming may be performed during the heat treatment cycle. Table 5.2112 indicates the heat treatments which are used and the resulting tempers for the alloy. The solution treatment for all products consists of heating to 995F ± 10F and quenching into cold water. The alloy is then artificially aged. Since the alloy ages very slowly at room temperature, solution-treated and naturally aged material retains good formability for a considerable period of time. In comparison, alloys 2014 and 2024 age rapidly enough at room temperature to develop high strength properties within four days. Artificial aging, upon completion of a forming operation, leads to much higher strength in the final structure. Aluminum sheets are normally formed using operations such as

1. Bending
2. Flanging
3. Rolling
4. Drawing
5. Pressing
6. Stretching
7. Embossing
8. Coining
9. Stamping
10. Spinning
11. Contour Forming
12. Bulging and Expanding
13. Beading and Roll Flanging
14. Necking
15. Curling

The factors influencing bending of 2219 sheet as spelled out previously also influence the fourteen other forming operations in the same general manner.

Because of the lower modulus of elasticity of aluminum compared with steel, a much greater "springback" is expected and indeed is encountered. Over-forming is the common way of correcting the tendency. All of the bending precautions described in the handbook on alloy 2014 should be considered.

5.22 Shapes, Tubes and Pipes. The use of aluminum shapes of the 2219 alloy have been limited but this is a reflection of the fact that the manufacture of the alloy has only been from about 1960. However, the alloy is amenable to the standard production techniques.

5.23 Forging. Forgings are made using either the open die or closed die methods and by impact or pressure. Small runs are made using the hand forging open die techniques. Hand forgings over a ton in weight can be made. As in all forgings there is a grain flow in 2219 which is characteristic of the forging process. The resulting grain pattern results in anisotropy of properties and this must be considered for the property evaluations. The process for most production forgings starts with the stock which can vary from 3/8 inch to 8 inches diameter round stock; from 3/8 inch to 4 inches square stock; and rectangles from 3/8 inch for the minimum dimension to as much as 10 inches on the maximum dimension. Conditioning to remove localized surface defects is permitted at this point. The stock is carefully heated in the range of 650 to 875F. After preheating, the stock can be forged to shape in one step or in the case of complicated parts in several operations, involving several reheatings. Dies in the forging operation are heated with auxiliary gas or electric heaters. The flash resulting from excess metal overfilling the mold is removed by hot or cold trimming, sawing or grinding. Holes in the forging are pressed to produce "punchouts" in the forging. Sometimes the punchout is combined with the trim operation. Very close tolerances can be met in the standard forging by die coining (cold) to precise dimensions, usually within a few thousands of an inch. Straightening after heat treatment is often a required operation. Templates combined with indicators and other gages are used to determine the out-of-tolerances. Straightening ranges from hand straightening to "cold restrike" operations.

The forgings are inspected for grain flow, mechanical properties, dimensions and ultrasonic soundness.

5.3 Machining

5.31 Conventional machining. This alloy has good machining qualities in the annealed state, (Ref. 5.2). Since most of the machining is done in the heat treated condition, lathe tools should be ground to 10 - 20° side rake, and 8 - 10° clearance. Parting tools should have a 15 - 20° top rake with a 4 - 5° side rake. Planer and shaper tools for roughing cuts should have a 12 - 15° top rake, 32 - 38° side rake and a 8 - 10° front and side clearance. Finishing tools should have 45 - 50° top rake, 50 - 60° side rake, 8 - 10° front clearance, and little or no side clearance. Twist drills should have larger spiral angles than standard highly polished deep flutes, narrow lands, and up to 18° lip clearance. Threading taps should have highly polished flutes and should be undercut, spiral fluted taps are usually better than straight fluted. The rake angles should be increased to 12 - 18°. Soluble oil emulsions, kerosene, and kerosene-lard oil mixtures are recommended for most machining operations, but high viscosity lubricants are recommended for tapping operations.

It is difficult to produce a precise tabulation of machining parameters for each of the different types of operations. However, Table 5.31 is a compilation of typical factors for many common machining operations, (Ref. 5.8) and can be used as a guide. Grinding typically uses a wheel speed of 6000 ft/min and a table speed of 60 ft/min. A down feed will produce a rough finish if it is kept about 0.001 inch per pass; a fine finish if the down feed is kept below 0.0005 inch per pass. The cross feed is approximately one-third of the wheel width.

5.32 Electro-Chemical and Chemical Machining

5.321 General Remarks. Weight reductions are important for space vehicle components, particularly large boosters, where the fuel and oxygen tanks are fabricated from precurved cylindrical and spherical sections of high-strength aluminum alloys. The use of sections which are "integrally stiffened" by ribs, which are left intact while the bulk of the metal stock is removed has been examined for both electro-chemical and chemical methods.

5.322 Electro-Chemical Milling. In the electro-chemical milling section for the 2014 alloy the basic principles of this method were discussed. In electro-chemical metal removal, Faraday's Law of Electrolysis controls the rate of metal removal. Because this ECM is the reverse of electro-deposition or electroplating the anode is the work piece. Hydrogen is evolved in most cases at the tool which is the cathode. The tool configuration depends upon the particular type of metal removal geometry desired. The shape of the tool cross-section can vary from simple squares, ovals, rounds and D-shapes to rather complicated design shapes. A 5 - 10% NaCl solution is supplied under pressure (about 100 - 250 psi) and escapes through the clearance between the end of the tool and the work piece, (Ref. 5.9). At 10,000 amperes, a metal removal rate of 1.26 cubic inches will be removed in one minute. Voltages of 10 - 15 volts yield excellent results. The temperature of the electrolyte of about 120F will yield good quality finishes.

5.323 Chemical Milling. The removal of metal stock by chemical dissolution or "chemical milling", in general, has many potential advantages over conventional milling methods. However, variations in etch rate, undercutting, and surface finish are a result of certain metallurgical factors which interfere with the "normal" electro-chemical phenomena, (Ref. 5.10). Buffered caustic etchants with wetting and sequestering agents plus complex fluorides to improve surface finish are employed. When subjected to the chemical attack, the presence of high copper intermetallic precipitate at random sites over the surface results in small local cells (the copper areas become strongly cathodic). The formation of smut (complex hydroxide, silicates, etc.) adheres to the surface providing an undesirable masking effect. In addition, differential quenching conditions in the heat treatment or differential effects of mechanical working provide various amounts and dispersions of $CuAl_2$ particles. This leads to a difference in the physical form of the "smut" produced during chem-milling. In the "slow-attack" zones a well cemented coherent, adherent "paste" is produced which does not easily fall off the metal surface. In the "rapid-attack" zones the placement of $CuAl_2$ particles is evidently such that no cohesion is established as the matrix is dissolved away. Work at IITRI is continuing to improve the method, (Ref. 5.10). For Bomarc fuel tanks between 20 and 45% of the original thickness (0.160 and 0.250 inches) is chem-milled from selected shell areas for weight reduction, (Ref. 5.6).

Studies at Martin-Denver, (Ref. 5.11) have indicated that the 2219 alloy can be successfully chem-milled by Martin Process DP 65043 in the O temper and in fully heat treated tempers. Solution treated materials results in a rough surface (up to 350 RMS) when chem-milled. The results of chem-milling tests on 2219 alloy sheet are presented in Table 5.323.

AVAILABILITY OF FORMS

TABLE 5.1

Source	Ref. 5.1, p. 91
Alloy	Forms
2219	Sheet, plate, rod, bar, extruded shapes, tubes and forgings
Alclad 2219	Sheet and plate

SUGGESTED MINIMUM BEND RADII FOR 90 DEGREE COLD BENDS (a)(b)

TABLE 5.2111

Thickness, in	1/64	1/32	1/16	1/8	3/16	1/4	3/8	1/2	3/4	1
0	0	0	$\frac{1}{2}$–$1\frac{1}{2}$t	$\frac{1}{2}$–$1\frac{1}{2}$t	$\frac{1}{2}$–$1\frac{1}{2}$t	1–2t	1–2t	2–3t	2–3t	3–4t
T42	0–1t	0–1t	1–2t	1–2t	$1\frac{1}{2}$–$2\frac{1}{2}$t	$1\frac{1}{2}$–$2\frac{1}{2}$t	2–3t	$2\frac{1}{2}$–$3\frac{1}{2}$t	3–4t	$3\frac{1}{2}$–$4\frac{1}{2}$t
T31	$\frac{1}{2}$–$1\frac{1}{2}$t	1–2t	$1\frac{1}{2}$–$2\frac{1}{2}$t	$1\frac{1}{2}$–3t	2–4t	2–4t	$2\frac{1}{2}$–4t	3–5t		
T37	$\frac{1}{2}$–$1\frac{1}{2}$t	1–2t	$1\frac{1}{2}$–3t	$2\frac{1}{2}$–4t	3–$4\frac{1}{2}$t	$3\frac{1}{2}$–5t	4–6t	5–7t		
T62	2–$3\frac{1}{2}$t	$2\frac{1}{2}$–4t	3–5t	4–6t	4–6t	5–7t	5–7t	6–9t		
T81	2–$3\frac{1}{2}$t	$2\frac{1}{2}$–4t	3–5t	4–6t	4–6t	5–7t	5–7t	6–9t		
T87	$2\frac{1}{2}$–4t	3–5t	4–6t	5–7t	$5\frac{1}{2}$–8t	6–9t	7–10t	8–11t		

(a) These values are given as a function of the actual material thickness (t), and should be used as a guide only.

(b) Alclad 2219 can be bent over radii slightly smaller than those for the corresponding bare material.

HEAT TREATMENTS FOR VARIOUS PRODUCTS AND TEMPERS

TABLE 5.2112

Source	Ref. 5.13
Alloy	2219
Temper	Product and Treatment
T4(a)	Solution treated and quenched in cold water
T31	Solution treat and stretch. (Sheet and drawn tube)
T37	Solution treat and cold reduce by rolling. (Sheet, plate and forgings)
T42	Material in any form or temper, resolution treated by the user.
T6	Solution treated and artificially aged. (Forgings)
T62	Material in any form or temper, resolution treated and aged by the user.
T81	Solution treated, stretched and artificially aged. (Sheet and drawn tube)
T87	Solution treated, cold reduced by rolling and artificially aged. (Sheet, plate and forgings)

(a) Forgings only

MACHINING RECOMMENDATIONS FOR SOLUTION TREATED AND AGED 2219 ALLOY

TABLE 5.31

Source	Ref. 5.8						
Operation	Cutting Conditions*	High Speed Tool Speed fpm	High Speed Tool Feed ipr	High Speed Tool Tool mat'l	Carbide Tool Speed fpm	Carbide Tool Feed ipr	Carbide Tool Tool mat'l
Single point Turning	0.250 inch depth of cut	600	0.015	T1, M1	1100	0.015	C-1
	0.050 inch depth of cut	800	0.008	T1, M1	1400	0.008	C-2
Form tool, turning	0.500 inch form tool width	450	0.0035	T1, M1,	1000	0.0035	C-2
	0.750 inch form tool width	450	0.0035	HSS	1000	0.0035	C-2
	1.000 inch form tool width	450	0.003	HSS	1000	0.003	C-2
	1.500 inch form tool width	450	0.0025	HSS	1000	0.002	C-2
	2.000 inch form tool width	450	0.002	HSS	1000	0.002	C-2
Boring	0.010 inch depth of cut	600	0.008	T1, M1,	1100	0.010	C-1, C-3
	0.050 inch depth of cut	570	0.010	HSS	1050	0.015	C-1, C-3
	0.100 inch depth of cut	540	0.015	HSS	1000	0.020	C-1, C-3
Planing	0.500 inch depth of cut	300	0.060	T1, M1	300	0.060*	C-2
	0.050 inch depth of cut	300	0.050	T1, M1	300	0.050	C-2
	0.010 inch depth of cut	300	3/4**	T1, M1	300	3/4**	C-2
Face milling	0.250 inch depth of cut	800	0.020*	T1, M1	max	0.018*	C-2
	0.050 inch depth of cut	1000	0.022*	T1, M1	max	0.020*	C-2
End milling (Profiling)	3/4 inch cutter diameter	700	0.006*	M1, M10	1200	0.005*	C-2
	1/2 inch cutter diameter	700	0.009*	M1, M10	1200	0.008*	C-2
	1/8 inch cutter diameter	1000	0.0007*	M1, M10	1800	0.0005*	C-2
	3/8 inch cutter diameter	1000	0.005*	M1, M10	1800	0.004*	C-2
	3/4 inch cutter diameter	1000	0.007*	M1, M10	1800	0.006*	C-2
	1 to 2 inch cutter diameter	1000	0.010*	M1, M10	1800	0.009*	C-2
Drilling	1/8 inch nominal hole diameter	250	0.003	M1, M10			
	1/4 inch nominal hole diameter	250	0.007	HSS			
	1/2 inch nominal hole diameter	250	0.012	HSS			
	3/4 inch nominal hole diameter	250	0.016	HSS			
	1 inch nominal hole diameter	250	0.020	HSS			
	1 1/2 inch nominal hole diameter	250	0.025	HSS			
	2 inch nominal hole diameter	250	0.030	HSS			
	3 inch nominal hole diameter	250	0.030	HSS			

* Feed - inches per tooth

** Feed - 3/4 the width of square nose finishing tool

RESULTS OF CHEMICAL MILLING TEST ON 2219 ALLOY SHEET

TABLE 5.323

Source	Ref. 5.11			
Alloy	2219 (0.088 and 0.100 Inch Sheet)			
Test	Chemical Milling (11 in x 12 in Test Panels) (a)			
Temper	Weight Loss (grams)	Metal Thickness removed (mils)	Weight Loss (grams)	Metal Thickness removed (mils)
0	118.1	19 to 21	215.3	47 to 69
T42	93.3	20 to 21	185.7	33 to 35
T31	96.8	13 to 15	163.4	33 to 41
T62	110.9	22 to 25	204.7	40 to 42
T81	113.7	23 to 24	215.1	41 to 43
T62 +(b)	124.2	23 to 27	222.5	45 to 49
T81 +(c)	124.8	24 to 26	196.6	44 to 46
T62	109.4	21 to 23	194.4	41 to 43

(a) Chem-milled area was approximately 100 in^2 (Martin Co. Process DP65043).
(b) Aged to T62 from "SW" condition (Solution treated and refrigerated).
(c) Aged from T31 to T81.

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CHAPTER 6

SPACE ENVIRONMENT EFFECTS

6.1 General. Aluminum alloys have been used in both structural and non-structural applications in launch vehicles and spacecraft with excellent success since, in general, the aluminum alloys are relatively insensitive to degradation in the typical space environmental conditions. The vapor pressures of the structural aluminum alloys are sufficiently high, (Fig. 6.1) so that the combined temperature-vacuum effects generally are negligible. Structural alloys such as 2219 are sufficiently hardened so that nuclear and space indigenous radiation induced defects do not significantly affect mechanical and physical properties, at room ambient and elevated temperatures, below accumulated doses of about 10^{22} particles/cm^2. When irradiated at cryogenic temperatures, the threshold may be lowered one or two decades, but the probabilities of experiencing doses on this order of magnitude are extremely remote except in the vicinity of nuclear reactors.

Elevated temperatures, hard vacuums, high energy radiations, and micrometeoroids can singularly and collectively influence surface characteristics of 2219 by desorption processes and erosion. These phenomena might be of great importance if optical properties, lubrication, certain electrical properties, etc., were critical design parameters.

Sputtering of the surface by atomic or molecular particles can deteriorate surface finishes in a relatively short period. A 300 Å coating of aluminum (10^{-5} gm/cm^2) can be destroyed in one month during a period of low intensity solar wind or in several hours during a solar storm, for example. Threshold energies for sputtering reactions are quite low, in the order of 6, 11, and 12 ev for O, N_2 and O_2 particles, respectively. Estimates of surface erosion by sputtering are given in Tables 6.1 and 6.2 for aluminum alloys.

Micrometeoroids can produce surface erosion similar to sputtering, although perhaps on a more macroscopic scale, as well as punctures. Micrometeoroids vary widely in mass, composition, velocity, and flux; generalizations about the rates of erosion and penetration, therefore, must be used with care. The predicted frequency of impact as a function of meteoroid mass is given in Fig. 6.2. Data are given in Figs. 6.3 and 6.4 on the penetration and cratering of aluminum alloy skins of various thicknesses.

The surface erosion of 2219 due to corpuscular radiation is probably insignificant, amounting to something on the order of 10 μ per year. Indigenous space radiation, however, will tend to accelerate the removal of surface films on the 2219. The removal of such films might result in loss of lubricity and an increased propensity to "cold weld". The interaction of indigenous radiation with desorption gases might cause some spurious, transient electrical conditions when 2219 is used for electrical applications. The interaction of indigenous radiation with the 2219 will produce some internal heating that might be significant for small items and some induced radioactivity.

IMPACT FLUX, MASS FLUX, PARTICLE CONCENTRATION, AND DENSITY FOR THE PARTICLE BELT SURROUNDING THE EARTH

TABLE 6.1

Source		Ref. 6.3			
Zone	Altitude[a]	Flux Impact (m^{-2} - sec^{-1})	Flux Mass (gm-cm^{-2}-sec^{-1})	Particle Concentration (cm^{-3})	Density (gm-cm^{-3})
1	100km < h < 400km	10^{-1} to 10^{0}	10^{-13} to 10^{-12}	4×10^{-11} to 4×10^{-10}	4×10^{-19} to 4×10^{-18}
2	400km < h < $2R_E$	10^{-4} to 10^{-2}	10^{-16} to 10^{-14}	4×10^{-14} to 4×10^{-12}	4×10^{-22} to 4×10^{-20}
3	h > $2R_E$	5×10^{-6} to 10^{-4}	5×10^{-18} to 10^{-16}	2×10^{-15} to 4×10^{-14}	2×10^{-23} to 4×10^{-22}
	Zodiacal cloud	2×10^{-6} to 1.2×10^{-3}	10^{-17} to 10^{-15}	10^{-15} to 10^{-13}	3×10^{-23} to 3×10^{-21}

(a) h is distance from earth's surface in km unless given in R_E (earth radii).

ESTIMATED RATE OF REMOVAL AND TIME TO REMOVE 1 Å OF ALUMINUM BY SPUTTERING

TABLE 6.2

Source	Ref. 6.2			
	Orbiting Vehicle		Escaping Vehicle	
Height (Km)	Rate (atom cm^{-2} sec^{-1})	Time (sec/Å)	Rate (atom cm^{-2} sec^{-1})	Time (sec/Å)
100	3.1×10^{16}	1.9×10^{-2}	3.4×10^{17}	1.8×10^{-3}
220	2.0×10^{13}	30	2.0×10^{17}	3.0×10^{-3}
700	2.2×10^{9}	2.7×10^{5}	3.4×10^{11}	1.8×10^{3}
2500	4.3×10^{5}	1.4×10^{9}	1.6×10^{8}	3.8×10^{6}

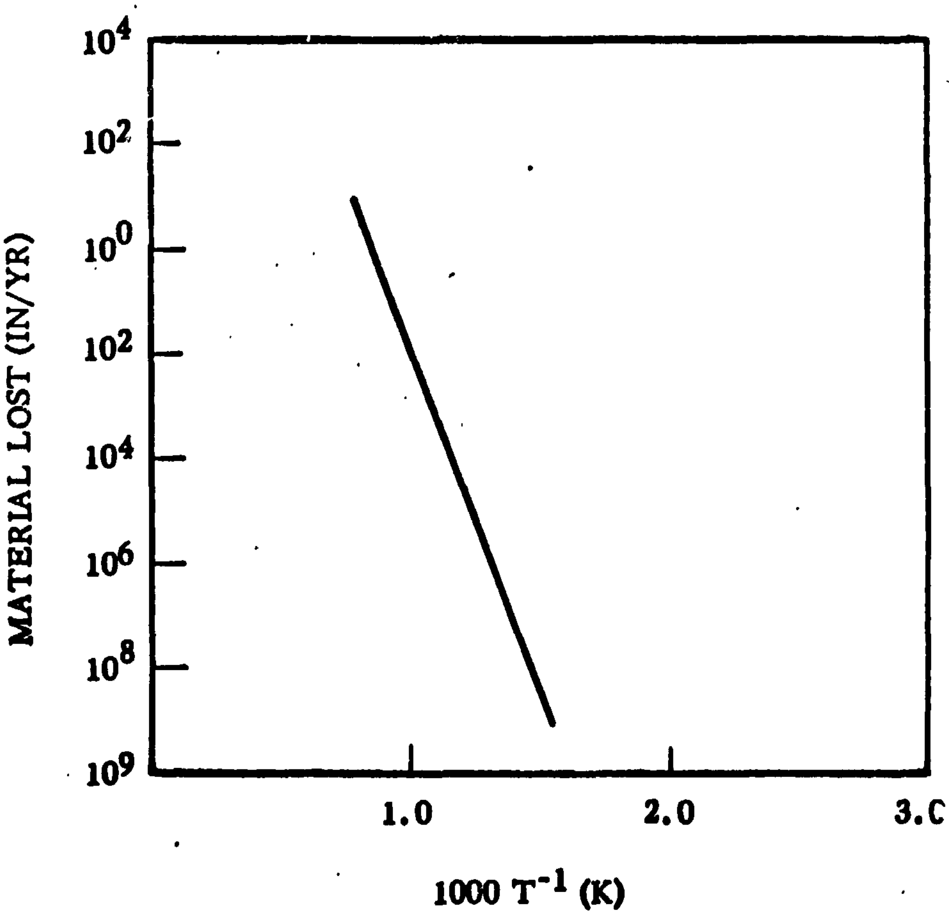

FIG. 6.1 EVAPORATION RATE FOR ALUMINUM (Ref. 6.1)

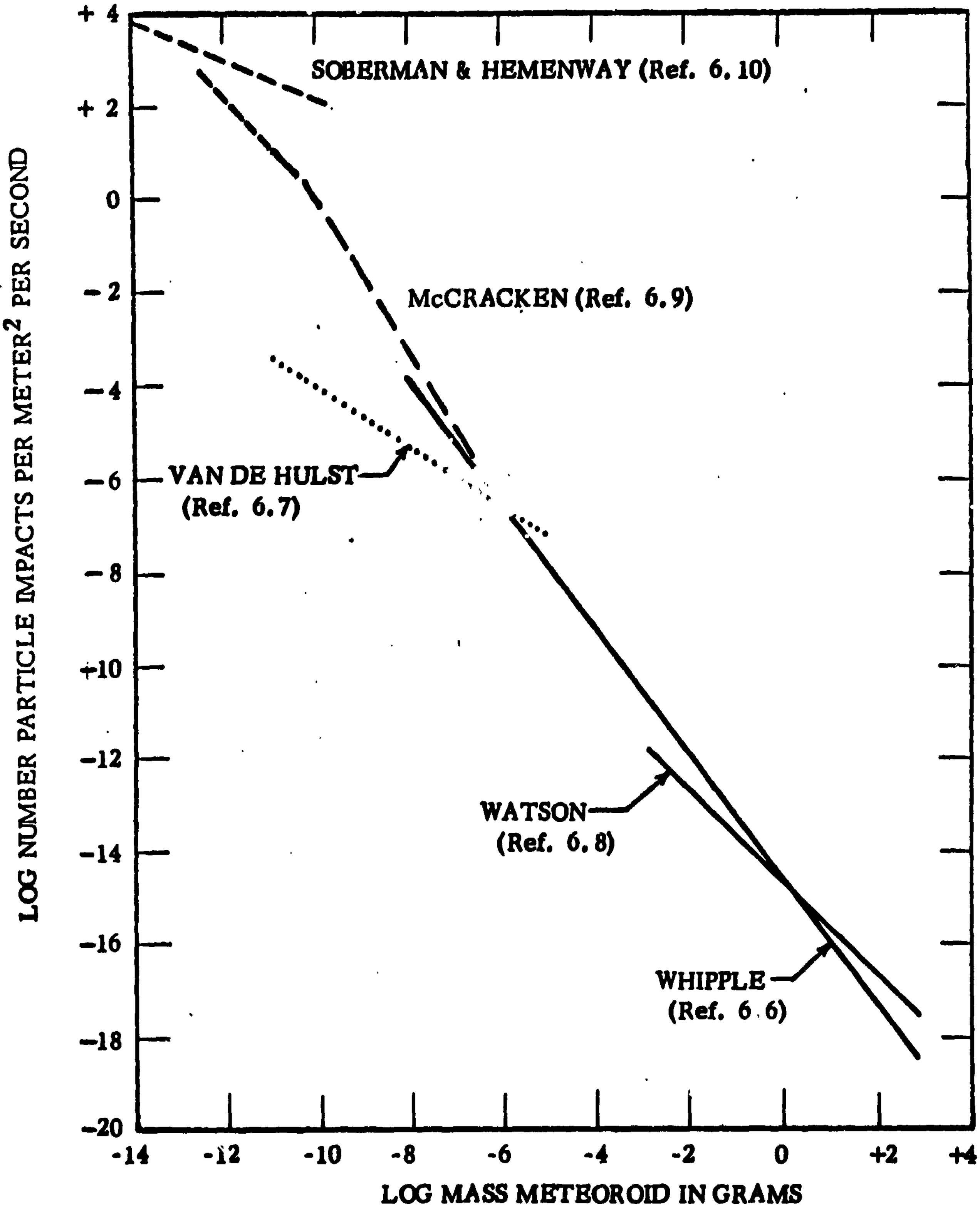

FIG. 6.2 CUMULATIVE METEOROID IMPACT RATES NEAR THE EARTH (Ref. 6.1)

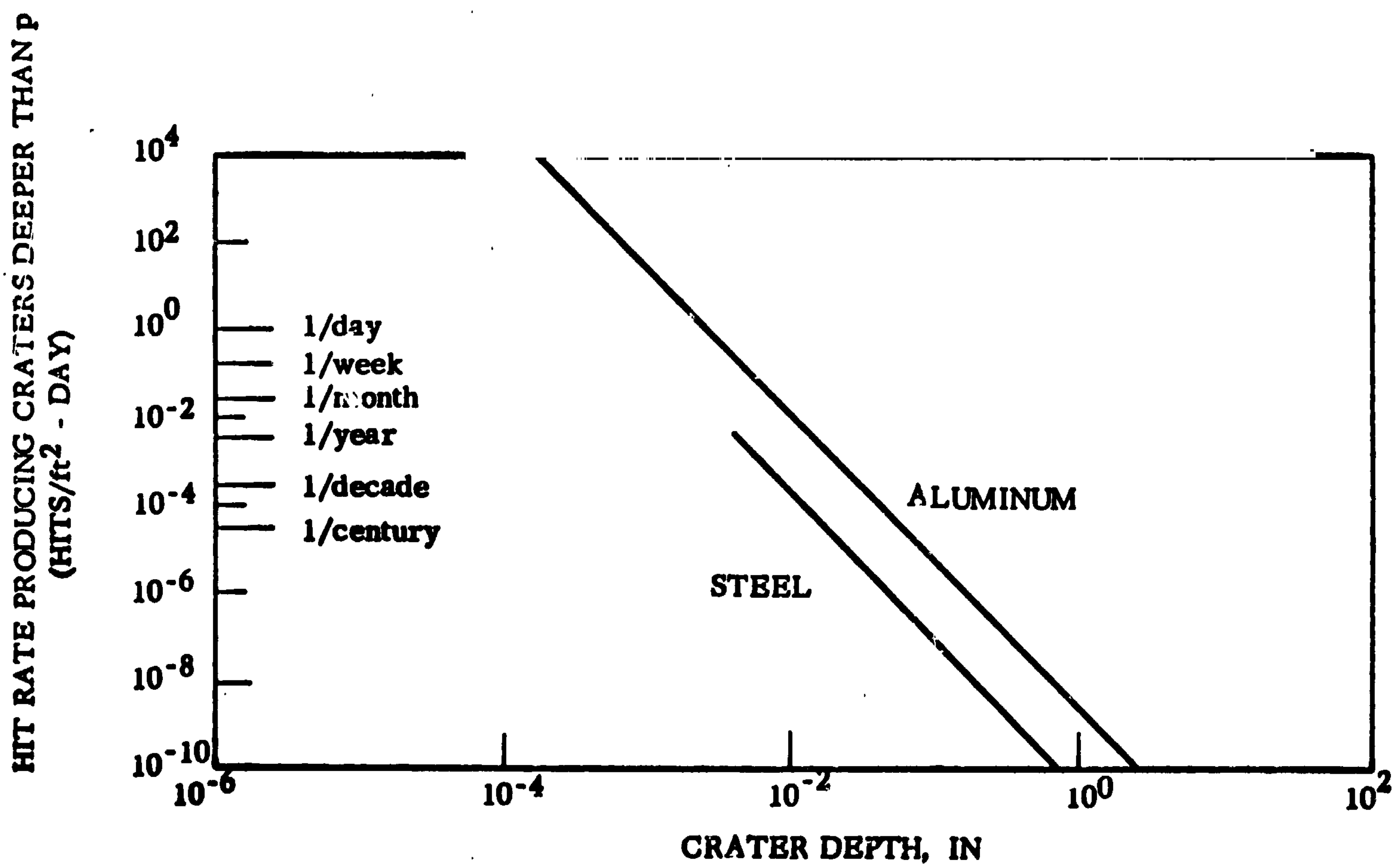

FIG. 6.3 HIT RATE vs CRATER DEPTH IN THE EARTH NEIGHBORHOOD BUT WITHOUT EARTH SHIELDING

(Ref. 6.4)

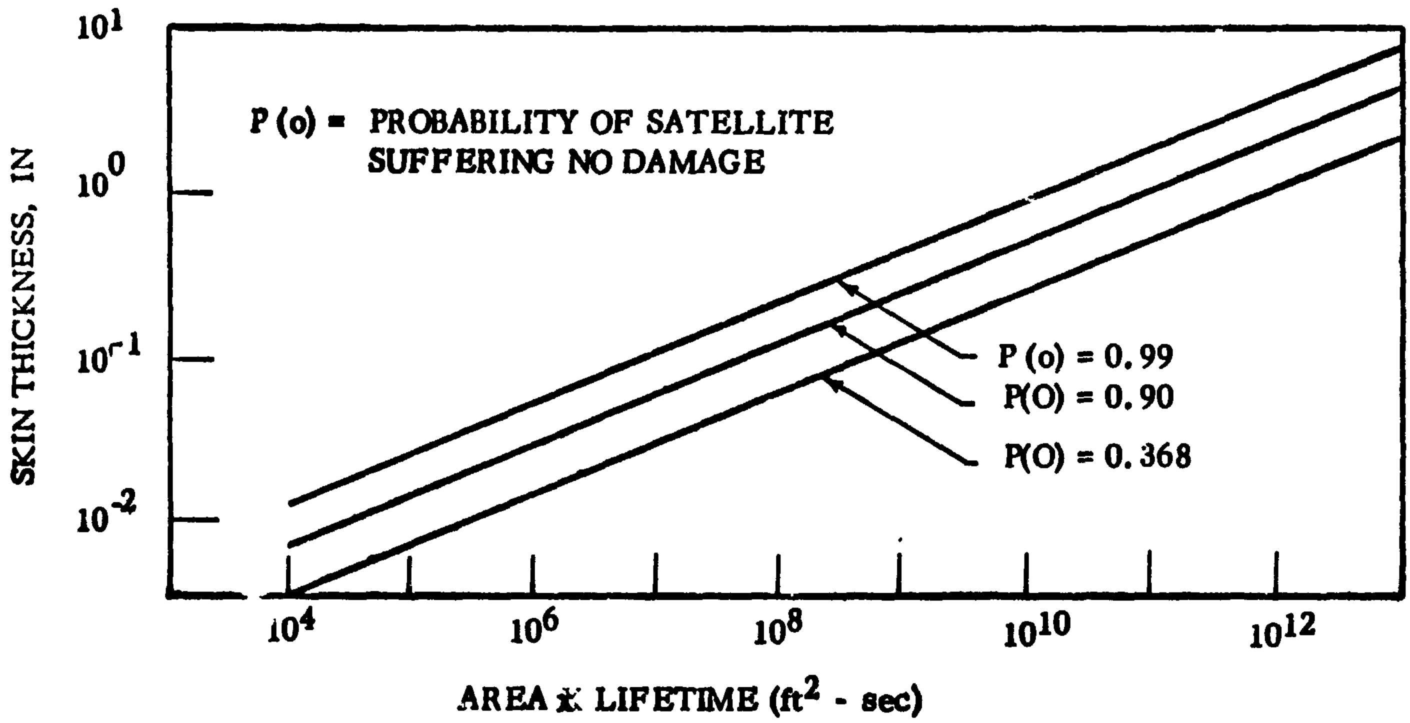

FIG. 6.4 ALUMINUM SKIN THICKNESS REQUIRED FOR METEOROID PROTECTION (Ref. 6.5)

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CHAPTER 7

STATIC MECHANICAL PROPERTIES

7.1 Specified Properties
7.11 NASA Specified Properties
7.111 NASA specified mechanical properties for die forgings and separately forged test bars, Table 7.111.
7.112 NASA specified mechanical properties for hand forgings, Table 7.112.
7.12 AMS Specified Properties
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7.222 Effect of elevated temperatures on modulus of elasticity, Fig. 7.222.
7.223 Effect of low temperatures on modulus of elasticity of T81 sheet, Fig. 7.223.
7.23 Compression modulus, E_c
7.231 Design value of E_c at room temperature for sheet and plate, $E = 10.8 \times 10^3$ ksi, (Ref. 7.1).
7.24 Modulus of rigidity (shear modulus), G
7.241 Design value of G at room temperature for sheet and plate, $G = 4.0 \times 10^3$ ksi, (Ref. 7.1)
7.25 Tangent modulus
7.26 Secant modulus

7.3 Hardness

7.31 Brinell scale (500 kg, 10 mm ball)

Cond	T31, T351	96
	T37	110
	T62	113
	T81, T851	123
	T87	128, (Ref. 7.23).

7.4 Strength Properties. (See also 7.1)

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7.414 Effect of test temperature on tensile properties.

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7.4211 Design compressive yield strength (F_{cy}) for sheet and plate, see Tables 7.4111 and 7.4112.
7.4212 Typical compressive yield strength for various tempers, see Table 7.414.
7.4213 Typical F_{cy} for T62 sheet and plate, Fig. 7.4213.
7.43 Bending
7.44 Shear and torsion
7.441 Design shear properties
7.4411 Design shear strength (F_{su}) for sheet and plate, see Tables 7.4111 and 7.4112.
7.4412 Typical F_{su} for alloy in various tempers, see Table 7.4113.
7.4413 Effect of low temperature on shear strength of sheet, Fig. 7.4413.
7.4414 Typical F_{su} curve for T62 sheet and plate, Fig. 7.4414.
7.45 Bearing
7.451 Design bearing properties
7.4511 Design bearing properties for sheet and plate, see Tables 7.4111 and 7.4112.
7.4512 Typical bearing properties for alloy in various tempers, see Table 7.4113.
7.4513 Typical bearing strength of alloy in T31 and T81 conditions, Fig. 7.4513.
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7.4612 Effect of stress concentration factor on notch strength of T62 and T81 sheet, Fig. 7.4612.
7.4613 Effect of test temperature on net fracture strength of T81 sheet, Fig. 7.4613.

NASA SPECIFIED MECHANICAL PROPERTIES FOR DIE FORGINGS AND SEPARATELY FORGED TEST BARS

TABLE 7.111

Alloy	2219-T6 (b)	
Specification	NASA-MSFC-SPEC-144B	
Product	Die Forgings and Separately Forged Test Bars	
Max. sect, thick, in	4	
Orientation	A	B
F_{tu}, -min-ksi (a)	58.0	56.0
F_{ty}, -min-ksi (a)	38.0	36.0
e(2 in or 4D), -min-percent	8	4

A Test specimen parallel to forging flow lines

B Test specimen not parallel to forging flow lines

(a) Tensile and yield strength test requirements may be waived for material in any direction in which the dimension is less than 2 inches because of the difficulty in obtaining a tension test specimen suitable for routine control testing.

(b) Die forgings in some configurations of this alloy can be purchased in the heat treated and mechanically stress relieved T652 temper conforming to the mechanical properties requirements specified for the T6 temper.

NASA SPECIFIED MECHANICAL PROPERTIES FOR HAND FORGINGS

TABLE 7.112

Alloy		2219			
Specification		NASA-MSFC-SPEC-144B			
Product		Hand Forgings (a)			
Temper	Thickness, in (b)	Axis of Test Specimen	F_{tu}, ksi (min) (c)	F_{ty}, ksi (min) (c)	e(2 in or 4D) (min) percent
T6	≤ 4.000	L	58.0	40.0	6
		LT	55.0	37.0	4
		ST	53.0	35.0	2
T852	≤ 4.000	L	62.0	50.0	6
		LT	62.0	49.0	4
		ST	60.0	46.0	3
T352	≤ 4.000	L	42.0	25.0	12
		LT	40.0	23.0	8
		ST	39.0	20.0	7

(a) Maximum cross-sectional area is 256 square inches.
(b) Thickness is measured in the short transverse direction and applies to the dimension "as forged", before machining.
(c) Tensile property requirements may be waived for directions in which the dimension is less than 2 inches.

AMS SPECIFIED TENSILE PROPERTIES FOR SHEET AND PLATE

TABLE 7.121

Alloy	2219			
Property	Tensile (a)(b)			
Form	Sheet and Plate			
Specification	AMS 4031			
Condition	0		T4 or T42	
Thickness, in	0.040 to 0.499	0.500 to 2.000	0.040 to 1.000	1.000 to 2.000
F_{tu}, max-ksi	30.0	30.0	54.0	56.0
F_{ty}, max, ksi	16.0	-	36.0	36.0
e(2in) min, percent	12	-	6	6

(a) Test specimens shall conform to ASTM E8-57T except from material less than 3/4 inch wide, and shall be cut across the direction of rolling except from material less than 9 inches wide.

(b) e applies only to material 3/4 inch and over in width.

AMS SPECIFIED BEND FACTORS FOR SHEET AND PLATE

TABLE 7.122

Alloy	2219					
Property	Bend Factor (a)					
Form	Sheet and Plate					
Specification	AMS 4031					
Condition	0			T4 and T42		
Thickness, in	$\leq$ 0.250	0.250 to 0.750	0.750 to 1.000	$\leq$0.0625	0.0625to 0.250	0.250 to 0.500
Bend factor	4T	6T	8T	8T	12T	16T

(a) Axis of bend parallel to direction of rolling

ALUMINUM ASSOCIATION TENSILE PROPERTY LIMITS FOR SHEET AND PLATE

TABLE 7.161

Source	Ref. 7.4					
Alloy	2219					
Property	Tensile					
Form	Sheet and Plate (a)					
Standards	Aluminum Association Mill Products					
Temper	Thickness(s) (inch)	Ftu, ksi Min	Ftu, ksi Max	Fty, ksi Min	Fty, ksi Max	e(2in or 4D) Min-Percent
0	0.020-2.000	-	32.0	-	16.0	12
T31	0.020-0.039	46.0	-	29.0	-	8
T31, T351(d)	0.040-0.249	46.0	-	28.0	-	10
	0.250-2.000	46.0	-	28.0	-	10
	2.001-3.000	44.0	-	28.0	-	10
	3.001-4.000	42.0	-	27.0	-	9
	4.001-5.000	40.0	-	26.0	-	9
	5.001-6.000	39.0	-	25.0	-	8
T37	0.020-0.039	49.0	-	38.0	-	6
	0.040-2.000	49.0	-	37.0	-	6
	2.001-2.500	49.0	-	37.0	-	6
	2.501-3.000	47.0	-	36.0	-	6
	3.001-4.000	45.0	-	35.0	-	5
	4.001-5.000	43.0	-	34.0	-	4
T62(b)	0.020-2.000	54.0	-	36.0	-	6
T81	0.020-0.039	59.0	-	44.0	-	6
	0.040-0.249	61.0	-	44.0	-	6
T81, T851(d)	0.250-2.000	61.0	-	44.0	-	6
	2.001-3.000	59.0	-	44.0	-	6
	3.001-4.000	57.0	-	43.0	-	5
	4.001-5.000	55.0	-	42.0	-	5
	5.001-6.000	54.0	-	41.0	-	4
T87	0.020-0.039	61.0	-	49.0	-	5
	0.040-2.500	63.0	-	50.0	-	5
	2.501-3.000	61.0	-	49.0	-	5
	3.001-4.000	59.0	-	48.0	-	4
	4.001-5.000	57.0	-	47.0	-	3

Footnotes, see page 52.

ALUMINUM ASSOCIATION TENSILE PROPERTY LIMITS FOR ALCLAD SHEET AND PLATE

TABLE 7.162

Source	Ref. 7.4					
Alloy	2219					
Property	Tensile					
Form	Alclad Sheet and Plate (a)					
Standards	Aluminum Association Mill Products					
Temper	Thickness(s) (inch)	F_{tu}, ksi		F_{ty}, ksi		e(2 in or 4D)
		Min	Max	Min	Max	Min-percent
0	0.040-2.000	-	32.0	-	16.0	12
T31	0.040-0.099	42.0	-	25.0	-	10
	0.100-0.249	44.0	-	26.0	-	10
T31, T351(d)	0.250-0.499	44.0	-	26.0	-	10
T37	0.040-0.099	45.0	-	34.0	-	6
	0.100-0.249	47.0	-	35.0	-	6
	0.250-0.499	47.0	-	35.0	-	6
T62(b)	0.040-0.099	47.0	-	32.0	-	6
	0.100-0.249	51.0	-	34.0	-	6
	0.250-0.499	51.0	-	34.0	-	6
T81	0.040-0.099	55.0	-	40.0	-	6
	0.100-0.249	58.0	-	42.0	-	6
T81, T851(d)	0.250-0.499	58.0	-	42.0	-	6
T87	0.040-0.099	57.0	-	46.0	-	5
	0.100-0.249	59.0	-	48.0	-	5
	0.250-0.499	59.0	-	48.0	-	5

Footnotes, see page 52.

ALUMINUM ASSOCIATION TENSILE PROPERTY LIMITS FOR ROLLED OR COLD-FINISHED BAR, ROD AND WIRE

TABLE 7.163

Source	Ref. 7.4					
Alloy	2219					
Property	Tensile					
Form	Bar, Rod and Wire (rolled or cold finished) (f)					
Standards	Aluminum Association Mill Products					
Temper	Diameter (inch)	F_{tu}, ksi		F_{ty}, ksi		e(2 in or 4D)
		Min	Max	Min	Max	min, percent
T851	0.500-2000	58.0	-	40.0	-	4
	2.001-4.000	57.0	-	39.0	-	4

Footnotes, see page 52.

ALUMINUM ASSOCIATION TENSILE PROPERTY LIMITS FOR EXTRUDED BAR, ROD, SHAPES AND TUBING

TABLE 7.164

Source	Ref. 7.4							
Alloy	2219							
Property	Tensile							
Form	Bar, Rod, Shapes and Tubing (extruded) (f)							
Standards	Aluminum Association Mill Products							
Temper	Thickness (inch)	Area (sq in)	F_{tu}, ksi		F_{ty}, ksi		e(2in or 4D) min,percent	
			Min	Max	Min	Max		
0 (c)	All	All	-	32.0	-	18.0	12	
T31, T3510, T3511(d)	≤ 0.499	≤25	42.0	-	26.0	-	14	
	0.500-2.999	≤ 25	45.0	-	27.0	-	14	
T62 (b)	≤ 0.999	≤ 25	54.0	-	36.0	-	6	
	≥ 1.000	≤ 32	54.0	-	36.0	-	6	
T81, T8510, T8511(d)	≤ 2.999	≤ 25	58.0	-	42.0	-	6	

Footnotes, see page 52.

ALUMINUM ASSOCIATION TENSILE PROPERTY AND HARDNESS LIMITS FOR DIE FORGINGS

TABLE 7.165

Source	Ref. 7.4						
Alloy	2219						
Property	Tensile						
Form	Die Forgings						
Standards	Aluminum Association Mill Products						
Temper	Grain	Brinell Hardness*	F_{tu}, ksi		F_{ty}, ksi		e(2 in or 4D)
			Min	Max	Min	Max	Min, percent
T6	A(n)	100	58.0	-	38.0	-	10
T6	B(μ)	100	56.0	-	36.0	-	4

* 500 kg load, 10 mm ball

A Parallel to grain flow

B Not parallel to grain flow

ALUMINUM ASSOCIATION TENSILE PROPERTY LIMITS FOR HAND FORGINGS

TABLE 7.166

Source	Ref. 7.4									
Alloy	2219									
Property	Tensile									
Form	Hand Forgings (p)(q)									
Standards	Aluminum Association Mill Products									
Temper	Thickness	F_{tu}, ksi			F_{ty}, ksi			e(2 in or 4D)		
	(inch) (r)	L	LT	ST	L	LT	ST	L	LT	ST
T6	≤ 4.000	58.0	55.0	53.0	40.0	37.0	35.0	6	4	2
T852	≤ 4.000	62.0	62.0	60.0	50.0	49.0	46.0	6	4	3

L - Longitudinal (m)
LT - Long Transverse
ST - Short Transverse

Footnotes, see page 52.

FOOTNOTES FOR ALUMINUM ASSOCIATION STANDARDS

(a) Test specimens taken transverse to rolling direction for widths ≥ 9 inches and parallel to rolling direction for widths < 9 inches.

(b) Material heat treated from any temper by the user should attain the properties applicable to this temper.

(c) O temper material shall be capable of developing properties for T6 temper after heat treatment.

(d) For stress relieved tempers, properties other than those specified may differ from the corresponding properties of the basic temper.

(e) For plate 0.500 inches or over in thickness, the listed properties apply to core material only. Strengths of composite (core plus clad) are slightly lower depending on thickness of cladding.

(f) Specimens taken parallel to direction of extrusion, rolling or drawing.

(g) O temper material within the size limitations specified for T4 temper, shall upon heat treatment be capable of developing properties applicable to T4 temper.

(h) For rounds (rod) maximum diameter is 8000 inches; for square, rectangular, hexagonal or octagonal bar maximum thickness is 4 inches and 36 square inches cross-section area.

(j) Round tube 2 inches or less in diameter and square tube 1.5 inches or less on a side are tested in full-section.

(k) For round tube over 2 inches diameter, for square tube over 1.5 inches on a side, for all sizes other than round or square or when full section cannot be used, a cut-out specimen is employed.

(m) Tensile tests are performed and properties guaranteed only when specifically required by purchase order or contract.

(n) These values apply to standard 0.5 inch diameter test specimens machined from separately forged coupons representative of the forgings. For specimens machined from forgings up to 4 inches in thickness or diameter with specimen axis substantially parallel to direction of grain flow, requirements apply except minimum e shall be 70 percent of values in the Table.

(p) Maximum cross-sectional area is 256 square inches.

(q) These properties are not applicable to upset biscuit forgings or to rolled or forged ring forgings.

(r) Thickness measured in short transverse direction.

(s) Applies to all available widths of sheet and plate.

(t) The measurement of e and F_{ty} is not required for wire less than 0.125 inch in thickness.

(u) These values apply to standard specimens machined from forgings up to 4 inches with the specimen axis not parallel to the direction of grain flow.

DESIGN PROPERTIES FOR SHEET AND PLATE

TABLE 7.4111

Alloy	2219														
Form	Sheet and Plate														
Condition	-T62		-T81		-T851						-T87				
Thickness or diameter, in.	0.040–2.300		0.040–0.249		0.250–2.000		2.001–3.000	3.001–4.000	4.001–5.000	5.001–6.000	0.040–2.500		2.501–3.000	3.001–4.000	4.001–5.000
Basis	A	B	A	B	A	B	A	A	A	A	A	B	A	A	A
Mechanical properties:															
F_{tu}, ksi															
L	54	55	60	61	60	61	...	...	...	...	62	63	...	...	...
T	54	55	61	62	61	62	59	57	55	54	63	64	61	59	57
F_{ty}, ksi															
L	36	37	45	46	45	46	...	...	...	...	50	51	...	...	...
T	36	37	44	45	44	45	44	43	42	41	50	51	49	48	47
F_{cy}, ksi															
L	38	39	46	47	46	47	...	...	...	...	50	51	...	...	...
T	38	39	47	48	47	48	...	...	...	...	53	54	...	...	...
F_{su}, ksi	32	32	35	36	35	36	...	...	...	...	36	37	...	...	...
F_{bru}, ksi:															
$e/D=1.5$	81	82	88	90	88	90	...	...	...	...	91	92	...	...	...
$e/D=2.0$	108	110	116	118	116	118	...	...	...	...	120	121	...	...	...
F_{bry}, ksi:															
$(e/D=1.5)$	58	59	66	67	66	67	...	...	...	...	70	71	...	...	...
$(e/D=2.0)$	68	70	75	76	75	76	...	...	...	...	80	82	...	...	...
e, percent:															
LT	6	...	6	...	6	...	6	5	5	4	5	...	5	4	3

(Ref. 7.1)

DESIGN PROPERTIES FOR ALCLAD SHEET AND PLATE

TABLE 7.4112

Source	Ref. 7.23						
Alloy	2219						
Form	Alclad Sheet and Plate						
Temper	T62		T81		T851	T87	
Thickness, inch	0.040-0.099	0.100-2.000	0.040-0.099	0.100-0.249	0.250-2.000	0.040-0.099	0.100-2.000
F_{tu}, ksi - L	49	52	55	57	57	57	59
- T	49	52	56	58	58	58	60
F_{ty}, ksi - L	32	34	40	42	42	45	47
- T	32	34	39	41	41	45	47
F_{cy}, ksi - L	34	36	40	42	42	45	47
- T	34	36	41	43	43	48	50
F_{su}, ksi	29	31	32	33	33	33	34
F_{bru}, (e/D=1.5) ksi	74	78	81	84	84	84	87
(e/D=2.0) ksi	98	104	106	110	110	110	114
F_{bry}, (e/D=1.5) ksi	51	54	58	61	61	63	66
(e/D=2.0) ksi	61	65	66	70	70	72	75
e(2 in or 4D) percent - T	6	6	6	6	6	5	5

TYPICAL MECHANICAL PROPERTIES FOR VARIOUS TEMPERS OF SHEET AND PLATE

TABLE 7.4113

Source	Ref. 7.23						
Alloy	2219						
Form	Bare Sheet and Plate						
Temper	O	T42	T31 T351	T37	T62	T81 T851	T87
F_{tu}, ksi - L	-	-	52	56	58	66	68
- T	25	50	52	56	58	66	68
F_{ty}, ksi - L	-	-	36	45	40	50	56
- T	11	25	34	44	40	50	56
e(2 in), - L	-	-	20	12	10	10	10
- T	18	20	16	10	10	10	10
F_{cy}, ksi - L	-	-	-	-	44	53	57
- T	-	-	-	-	44	54	60
F_{su}, ksi	-	-	-	-	36	38	40
F_{bru}, (e/D=1.5) ksi	-	-	-	-	90	96	100
(e/D=2.0) ksi	-	-	-	-	120	125	131
F_{bry}, (e/D=1.5) ksi	-	-	-	-	67	76	80
(e/D=2.0) ksi	-	-	-	-	80	87	91
Hardness, Brinell (500 kg, 10 mm ball)	-	-	96	110	113	123	128

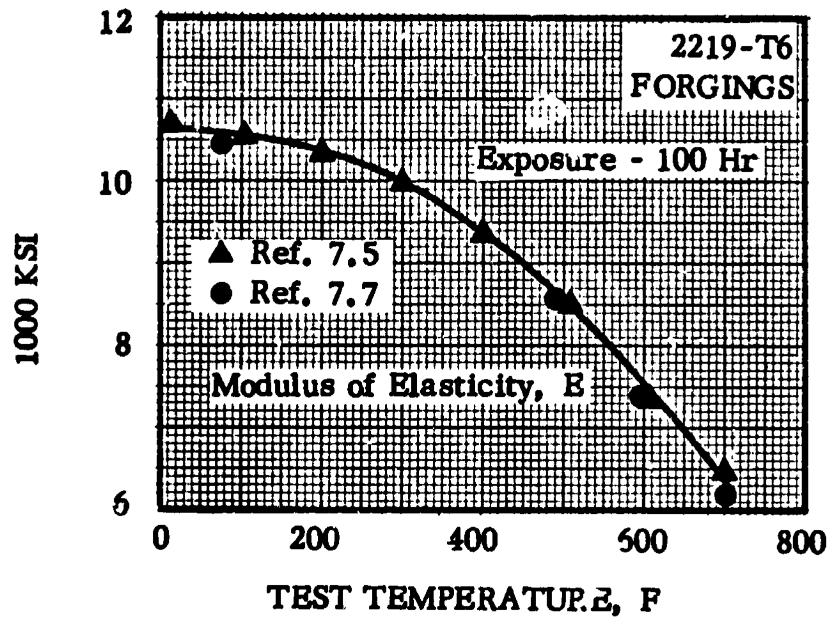

FIG. 7.222 EFFECT OF ELEVATED TEMPERATURES ON MODULUS OF ELASTICITY

(Ref. 7.7)

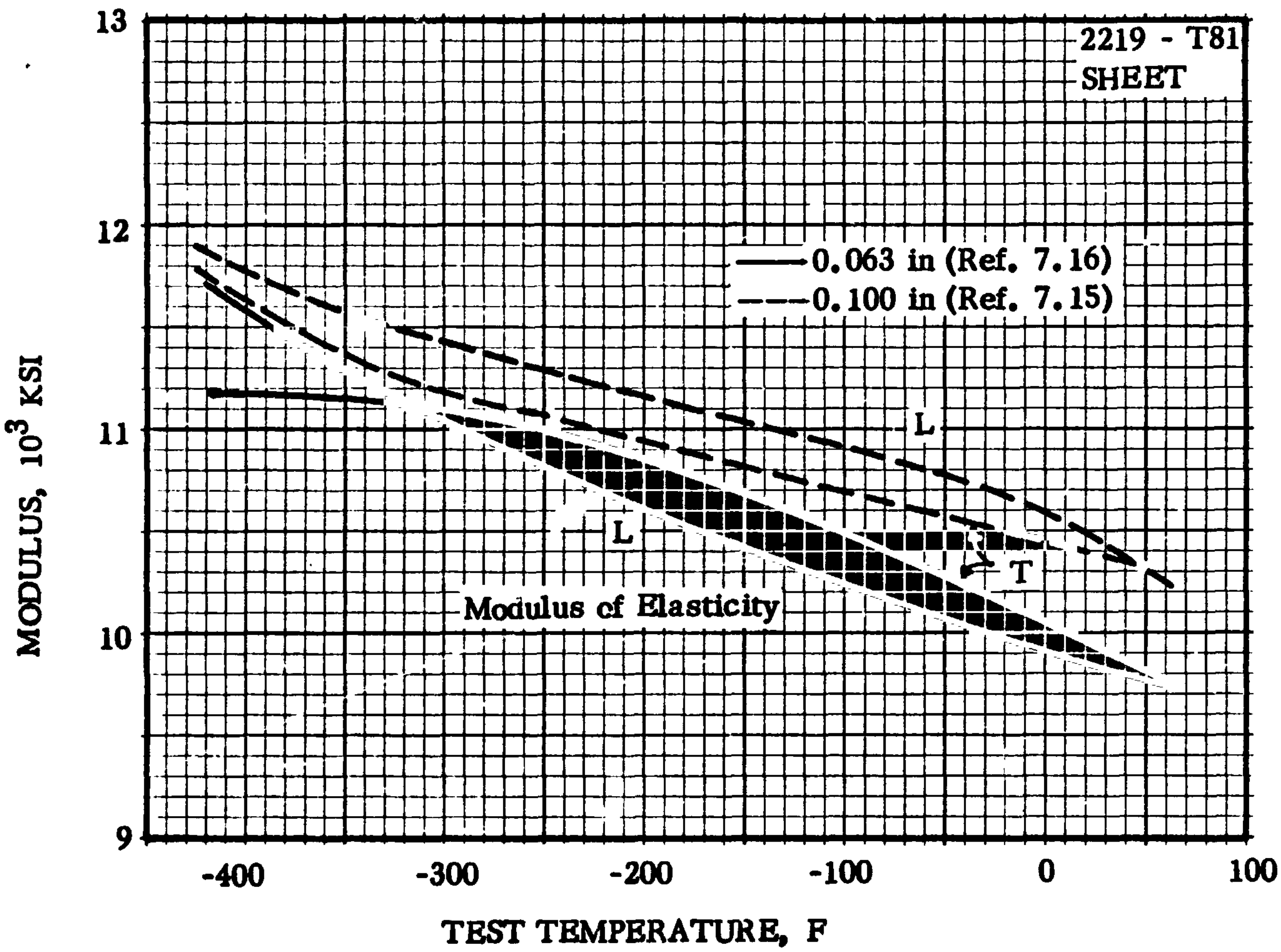

FIG. 7.223 EFFECT OF LOW TEMPERATURE ON MODULUS OF ELASTICITY OF T81 SHEET

(Refs. 7.15 and 7.16)

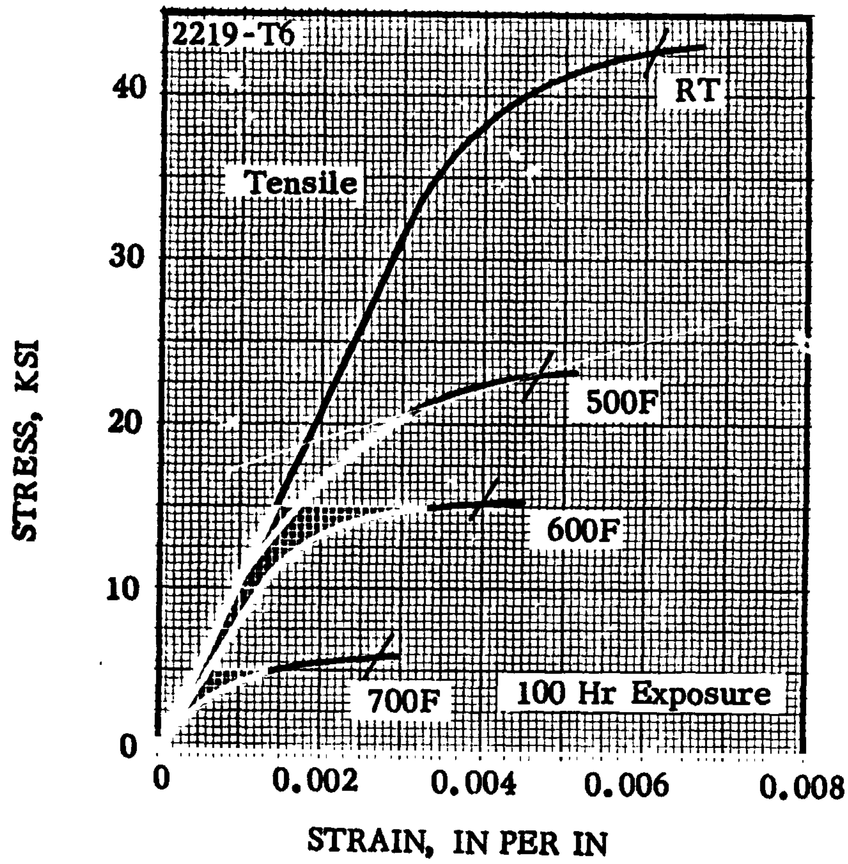

FIG. 7.4121 STRESS-STRAIN CURVES FOR ALLOY IN T6 CONDITION AT ROOM AND ELEVATED TEMPERATURES

(Ref. 7.7)

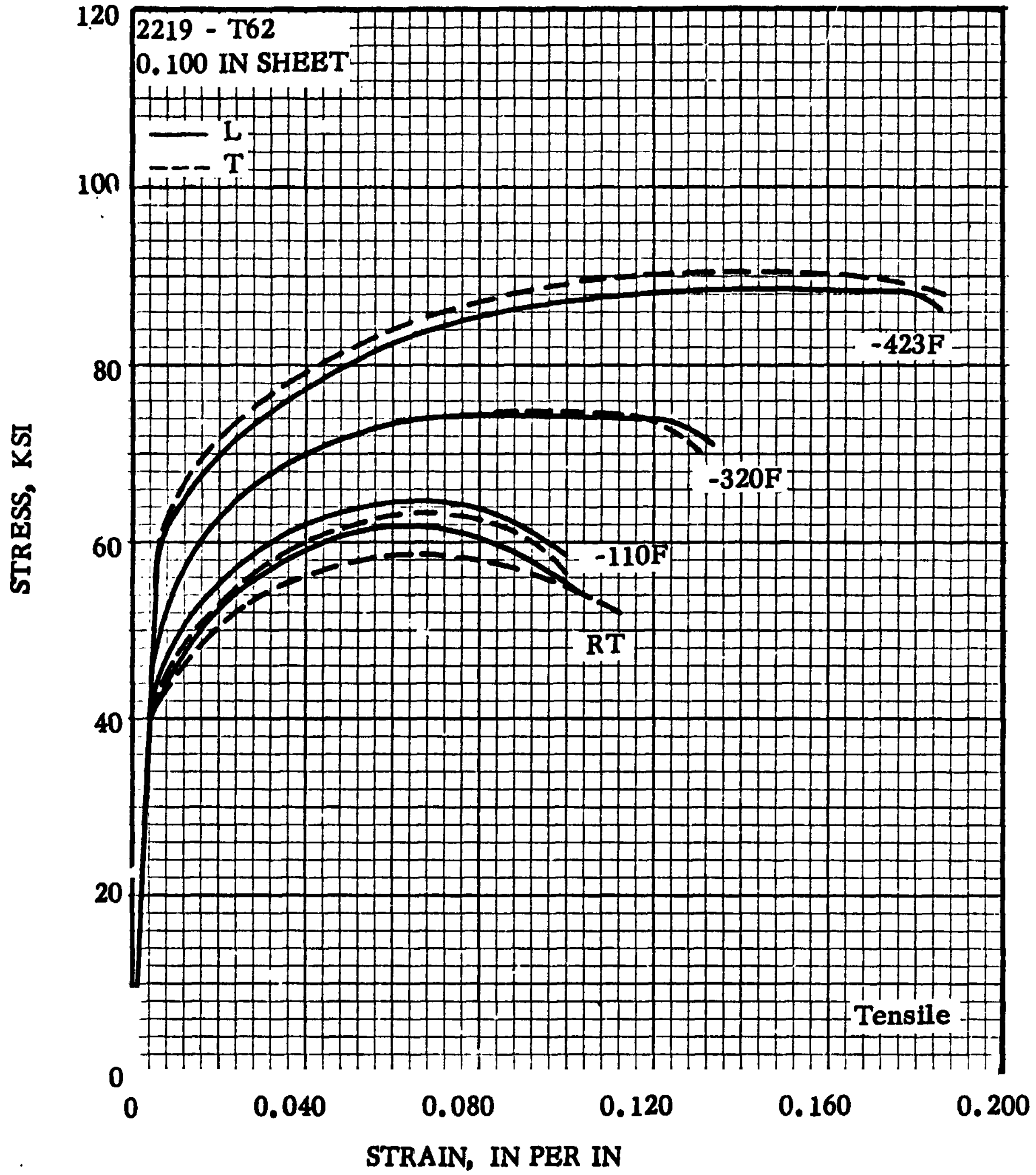

FIG. 7.4122 STRESS-STRAIN CURVES FOR T62 SHEET AT LOW TEMPERATURES (Ref. 7.15)

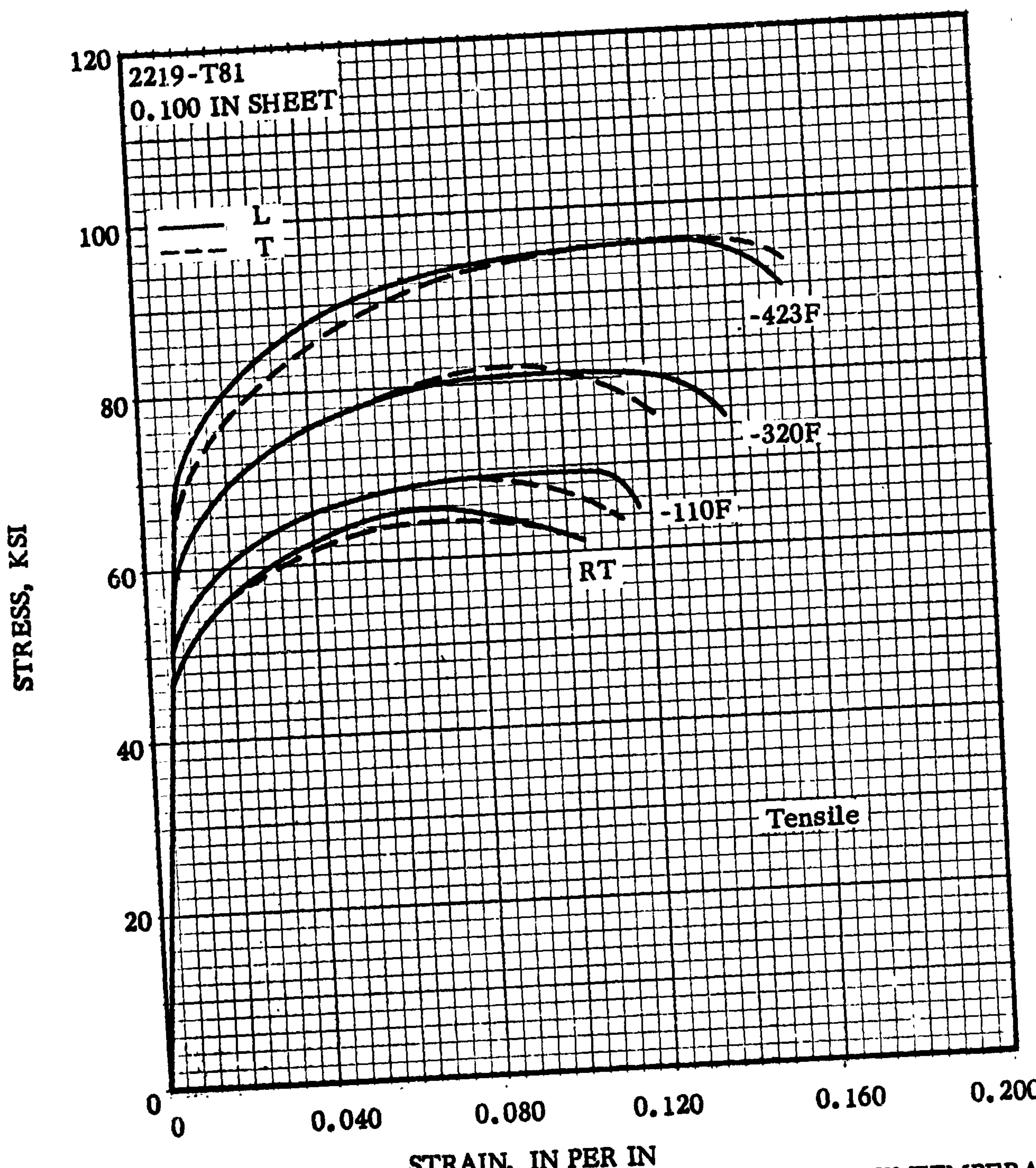

FIG. 7.4123 STRESS-STRAIN CURVES FOR T81 SHEET AT LOW TEMPERATURES (Ref. 7.15)

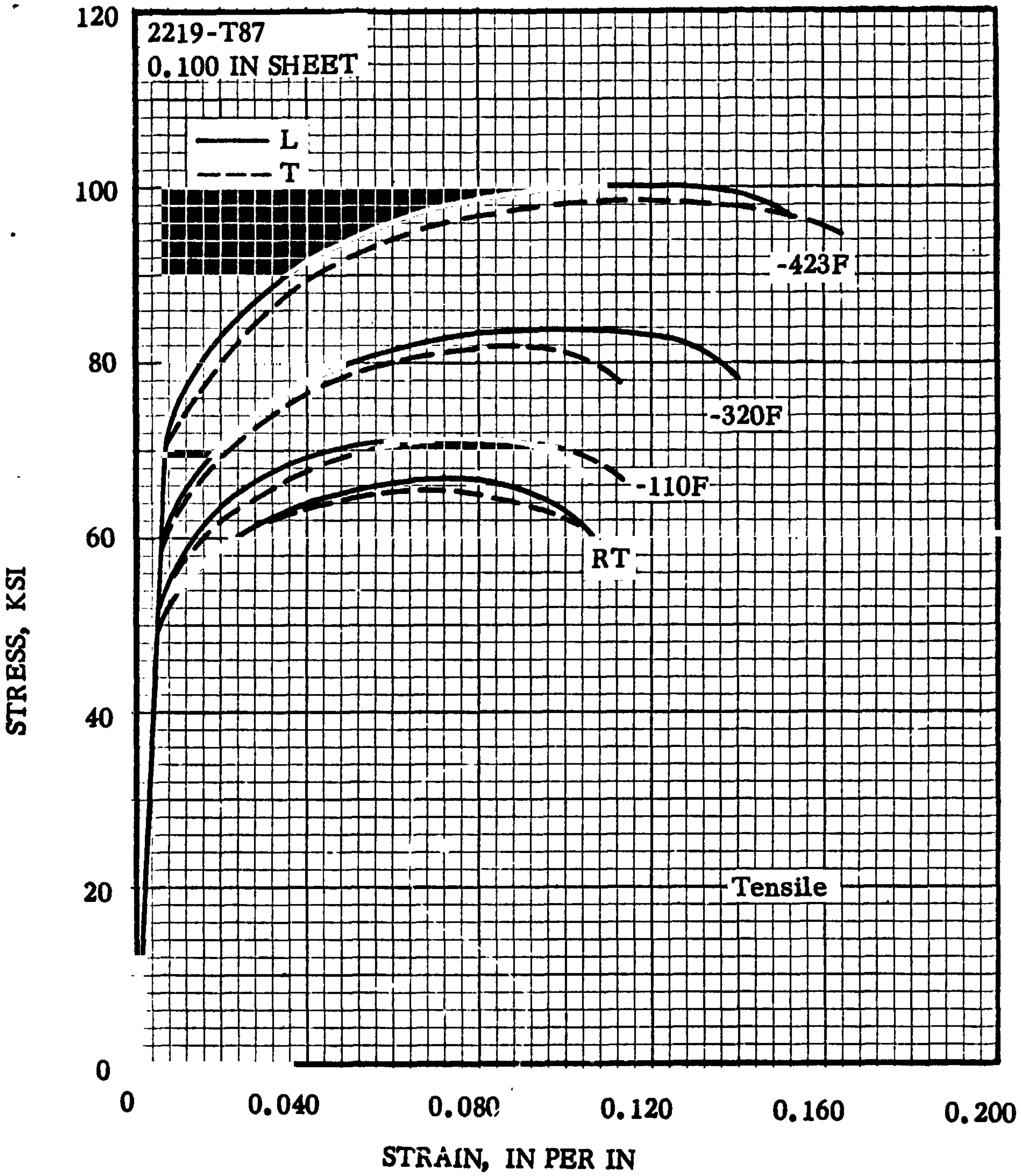

FIG. 7.4124 STRESS-STRAIN CURVES FOR T87 SHEET AT LOW TEMPERATURES (Ref. 7.15)

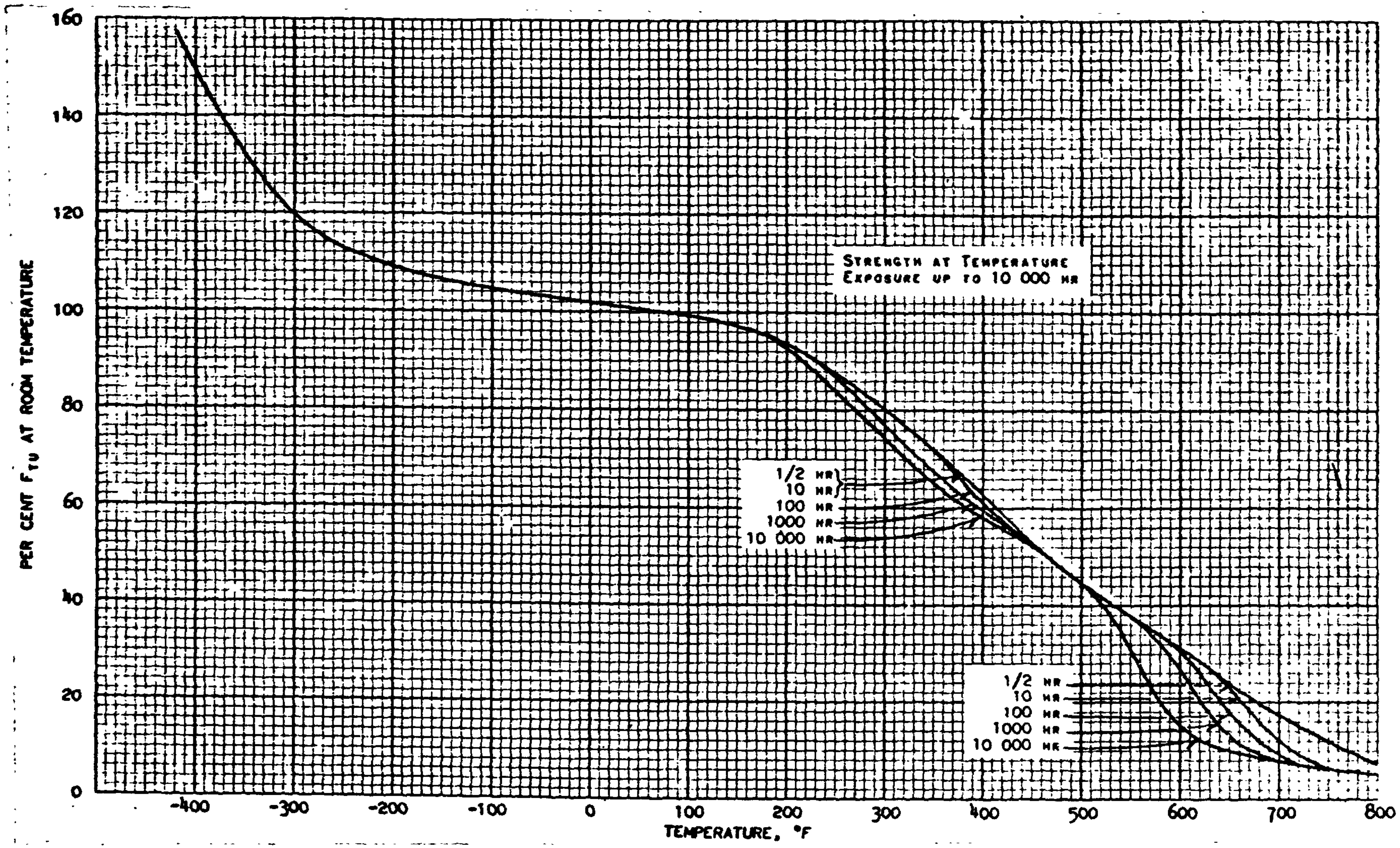

FIG. 7.4131 *Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219–T62 aluminum alloy (bare and clad sheet and plate 0.040–1.000 in. thick).*

Ref. 7.1

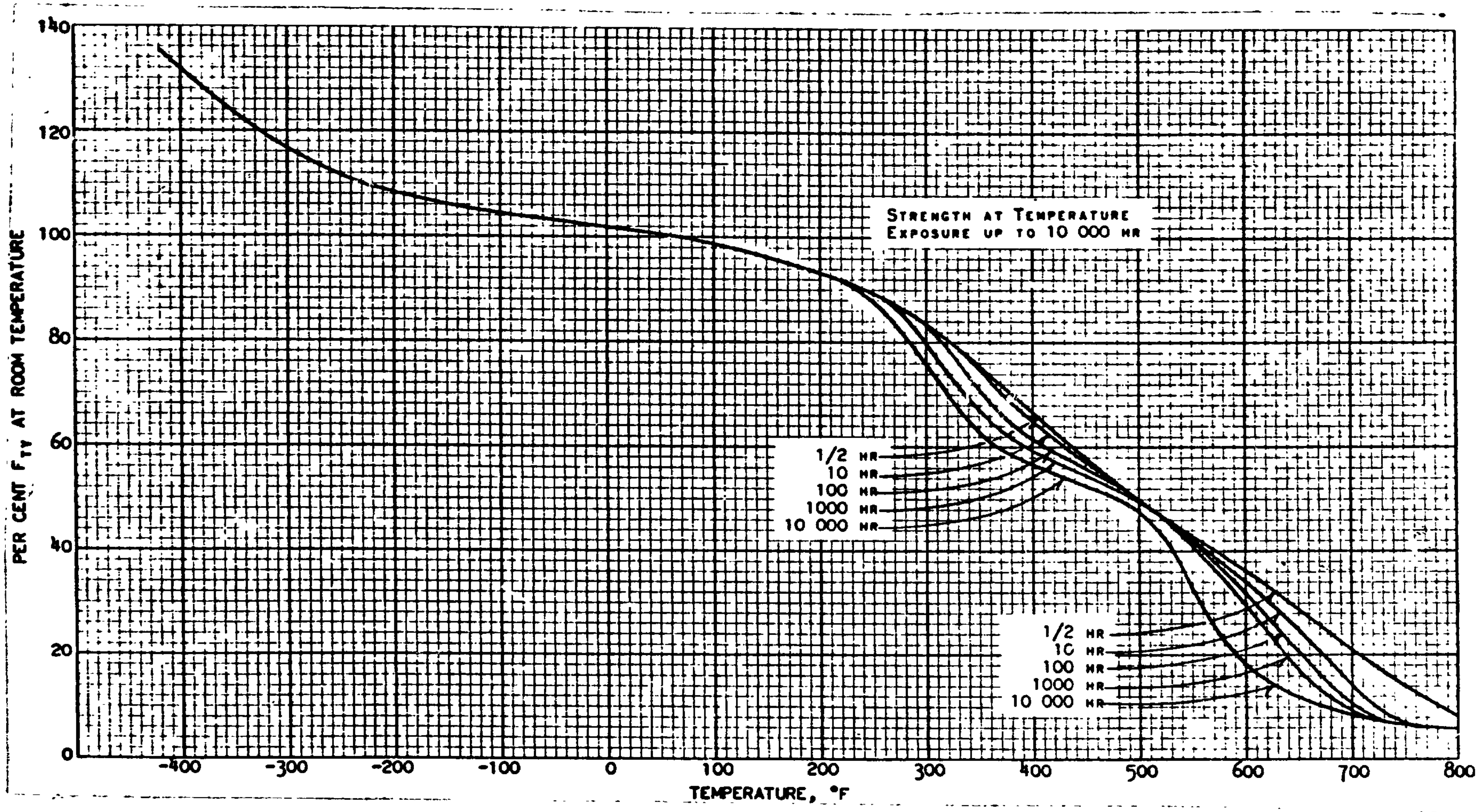

FIG. 7.4132 *Effect of temperature on the tensile yield strength (F_{ty}) of 2219–T62 aluminum alloy (bare and clad sheet and plate 0.040–1.000 in. thick).*

Ref. 7.1

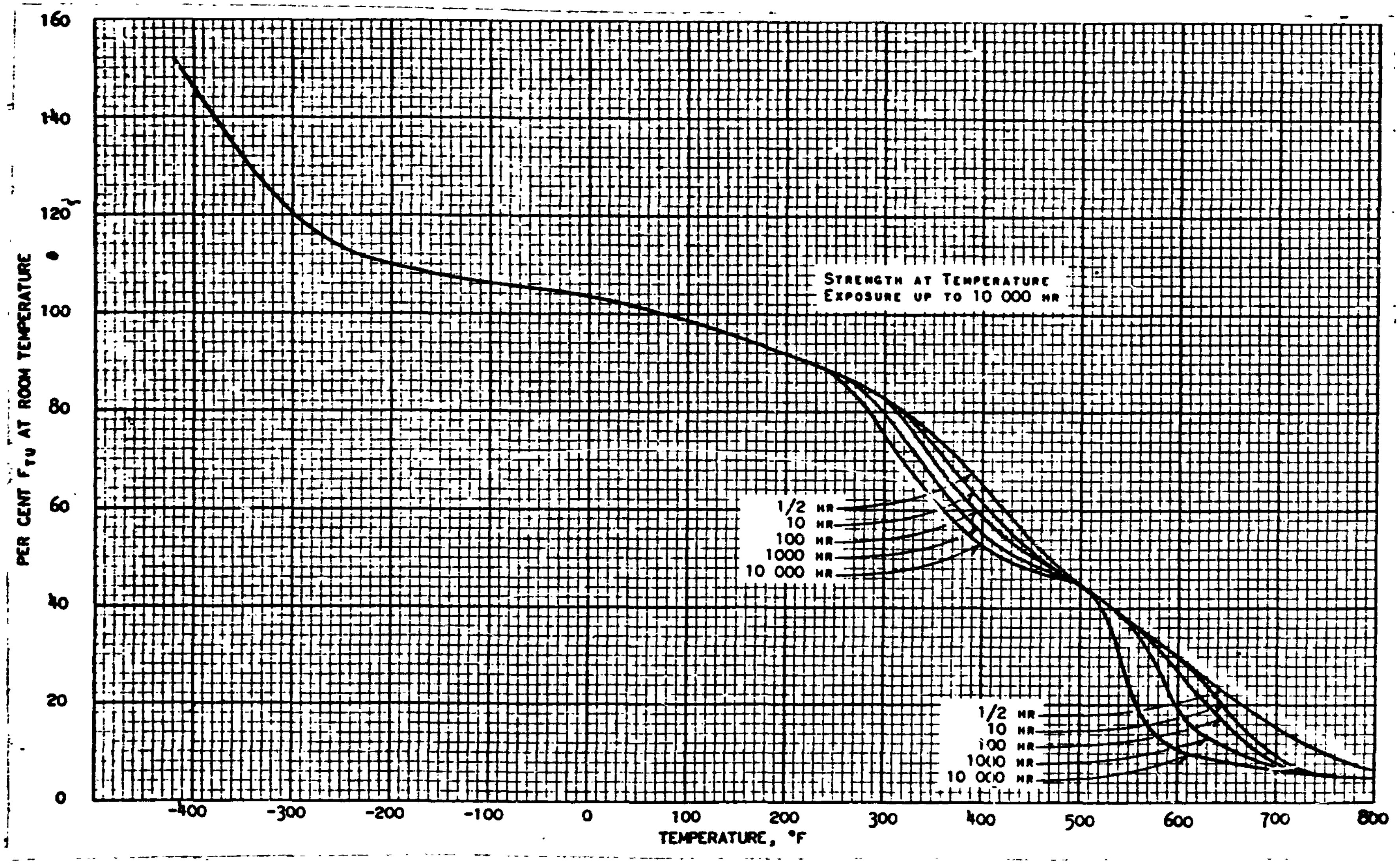

FIG. 7.4133

Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219–T81 aluminum alloy (bare and clad sheet and plate).

Ref. 7.1

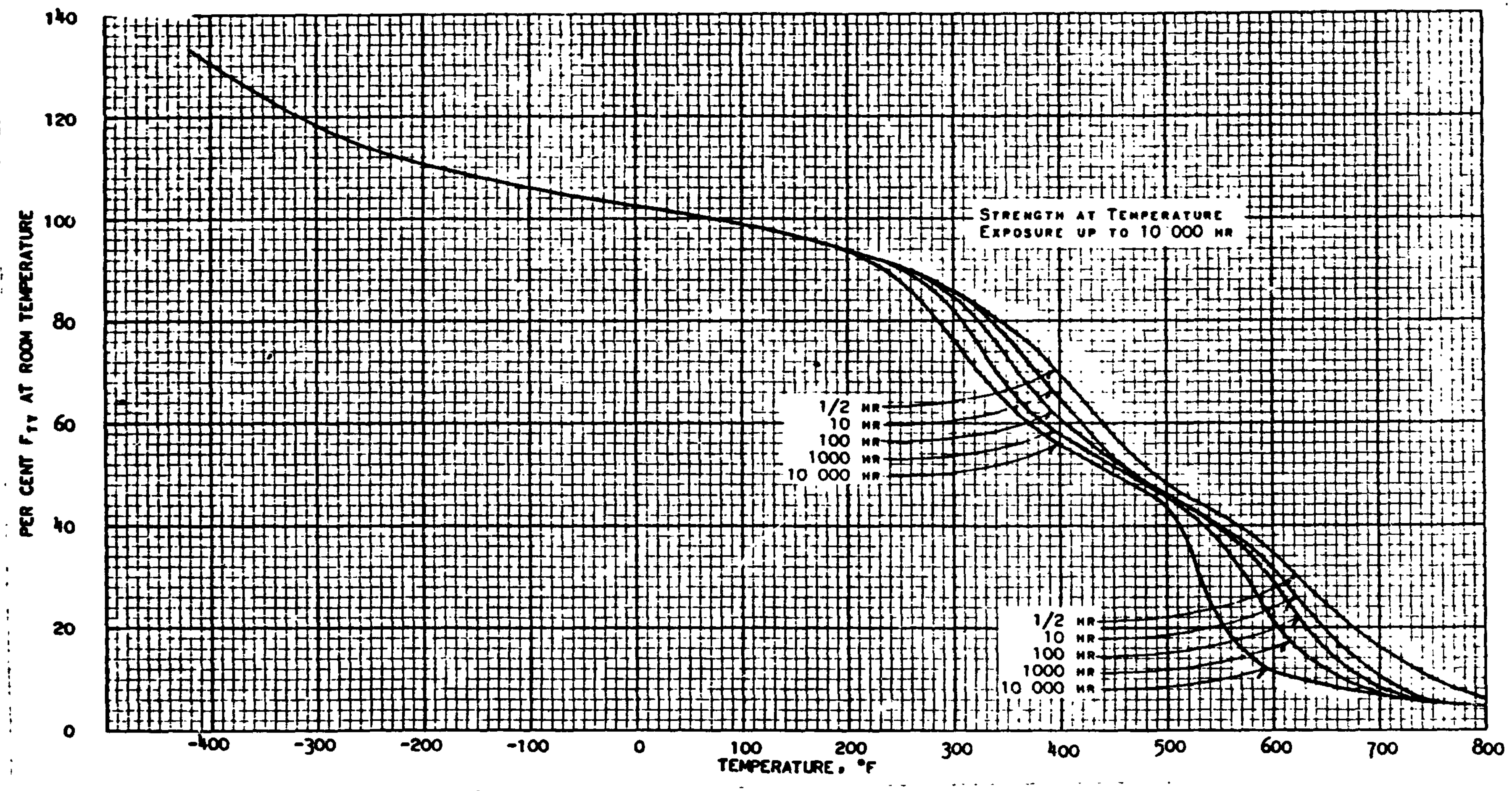

FIG. 7.4134

Effect of temperature on the tensile yield strength (F_{ty}) of 2219–T81 aluminum alloy (bare and clad sheet and plate).

Ref. 7.1

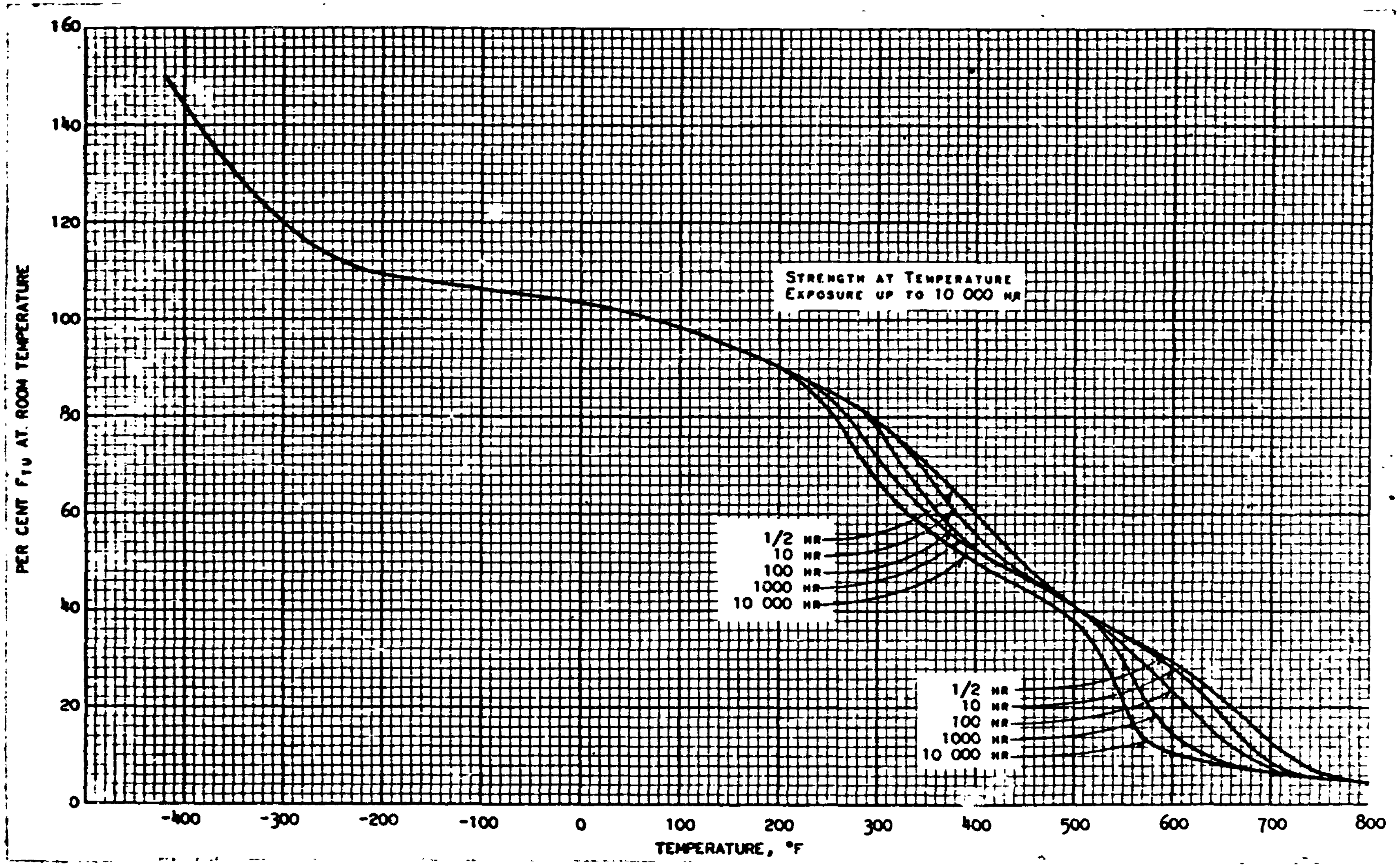

FIG. 7.4135

Effect of temperature on the ultimate tensile strength (F_{tu}) of 2219–T87 aluminum alloy (bare and clad sheet and plate).

Ref. 7.1

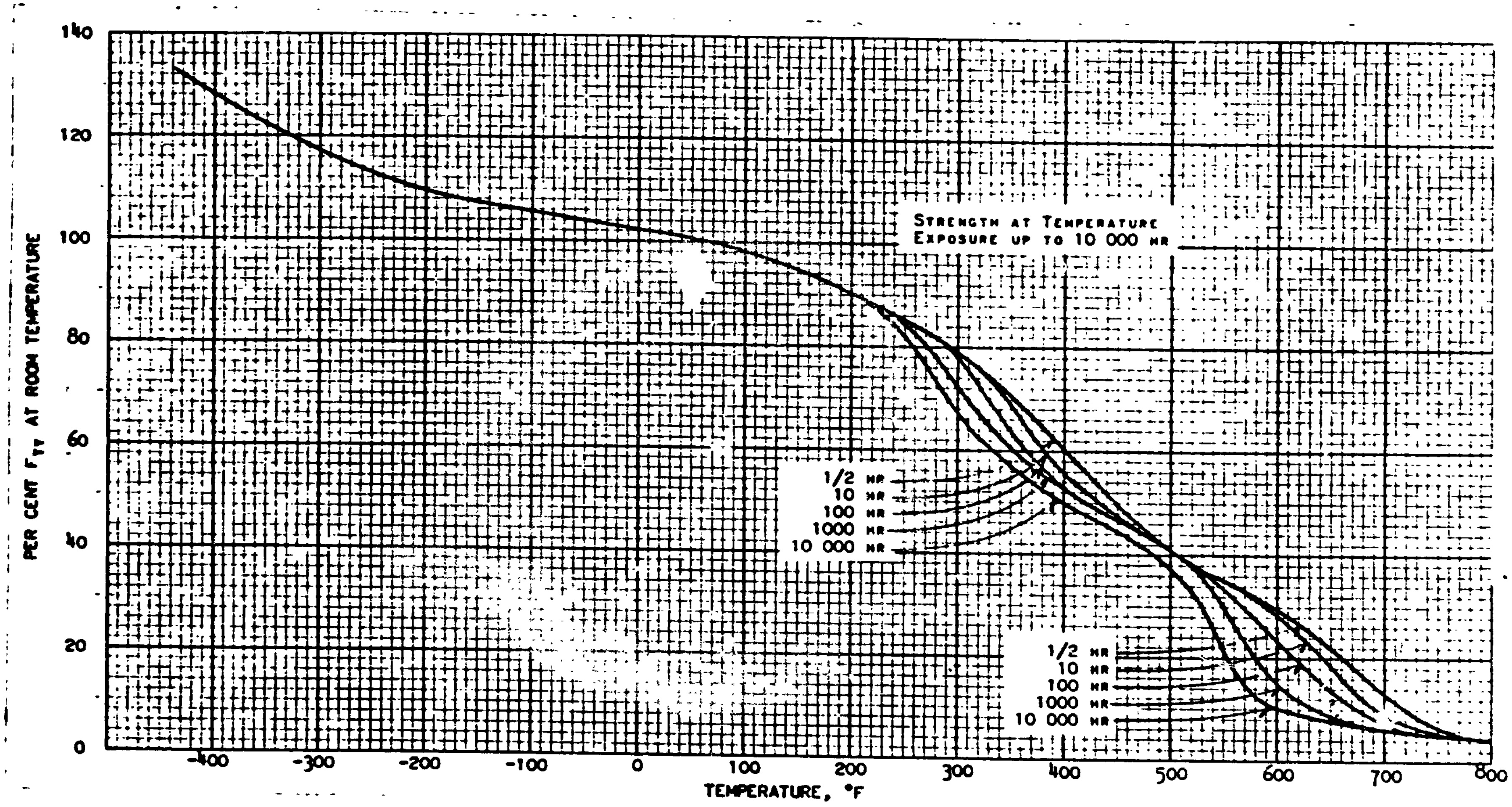

FIG. 7.4136 *Effect of temperature on the tensile yield strength (F_{ty}) of 2219–T87 aluminum alloy (bare and clad sheet and plate).*

Ref. 7.1

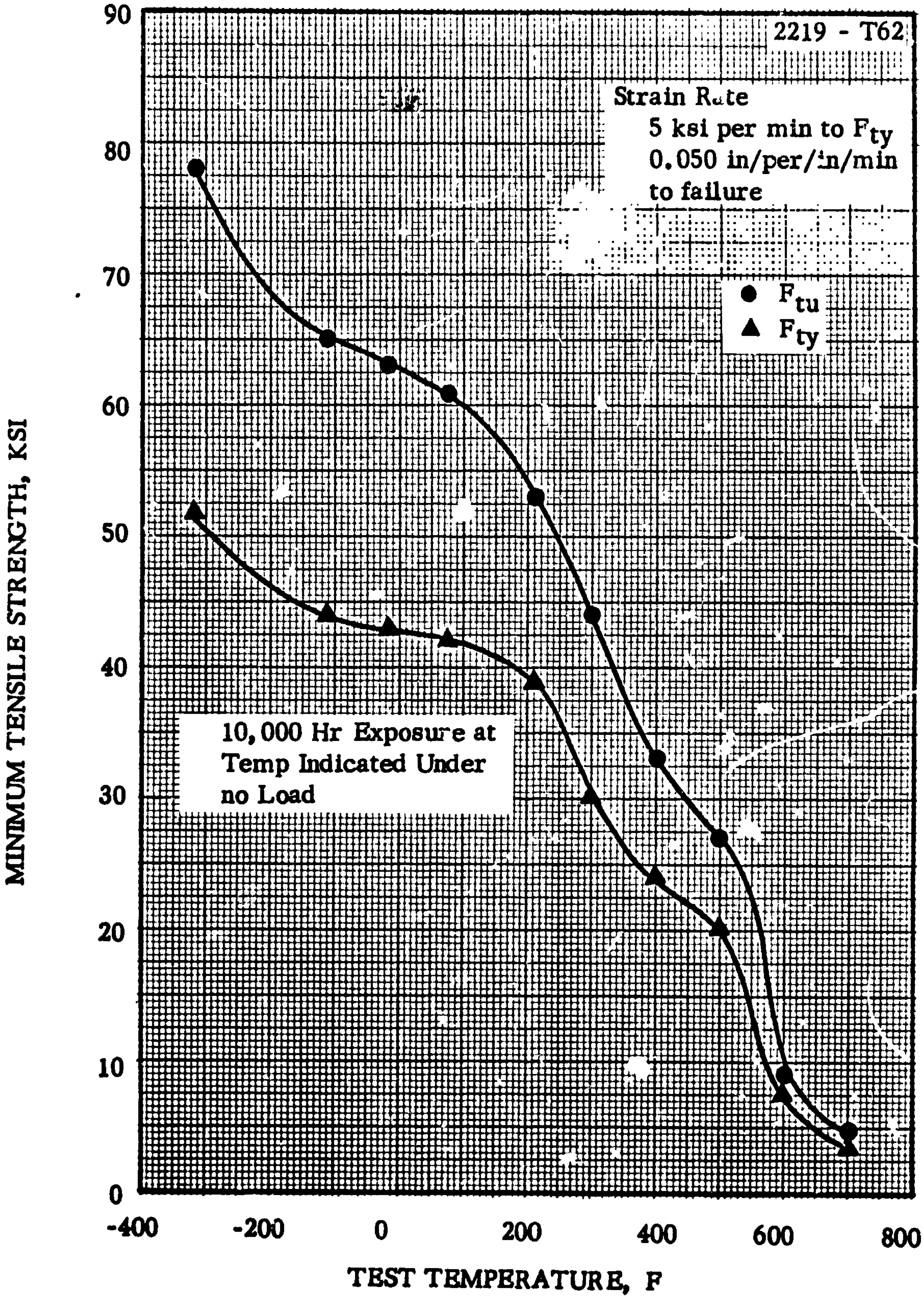

FIG. 7.4137 MINIMUM TENSILE PROPERTIES FOR 2219-T62 AFTER 10,000 HOURS EXPOSURE

(Ref. 7.6)

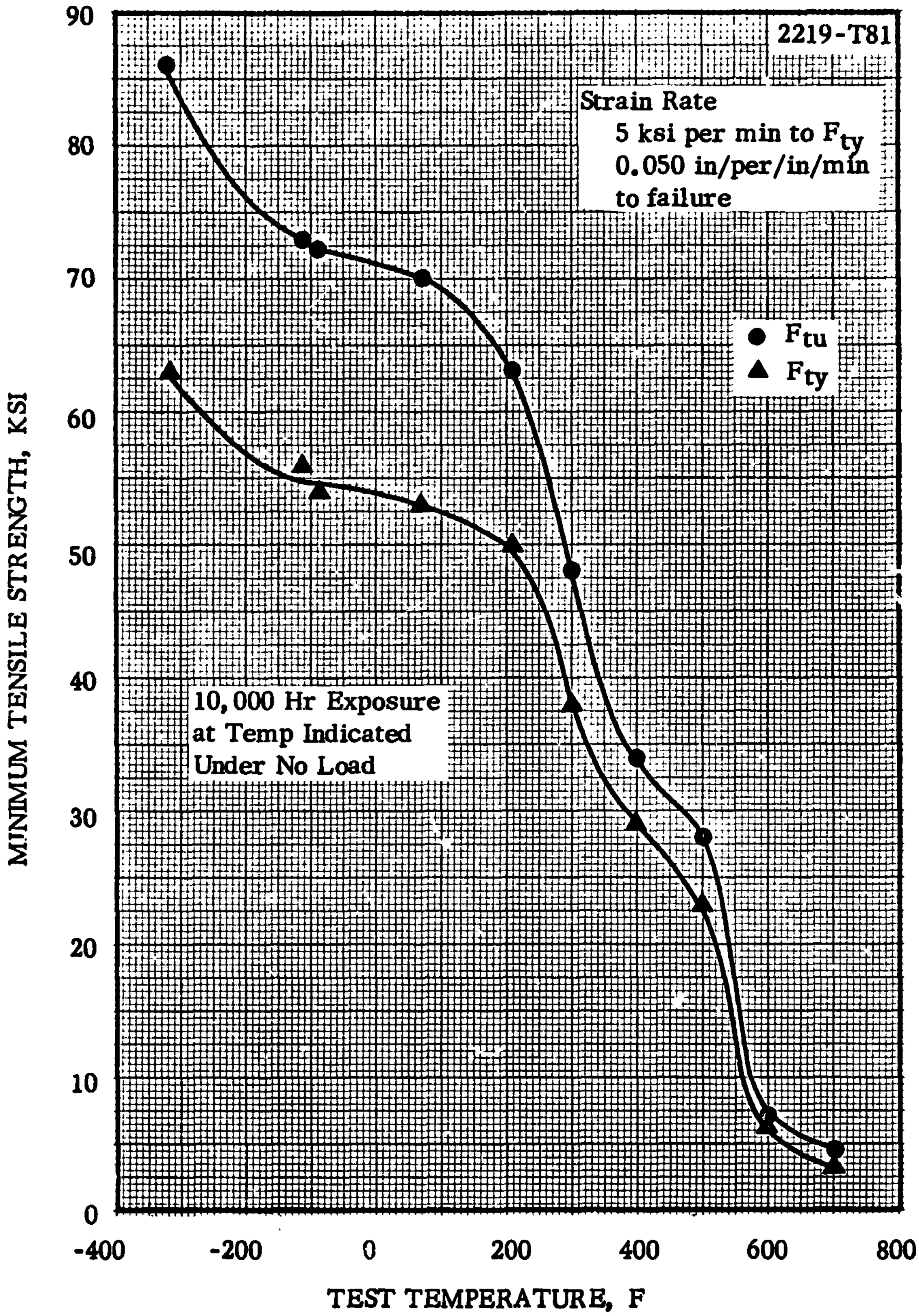

FIG. 7.4138 MINIMUM TENSILE PROPERTIES FOR 2219-T81 AFTER 10,000 HOURS EXPOSURE

(Ref. 7.6)

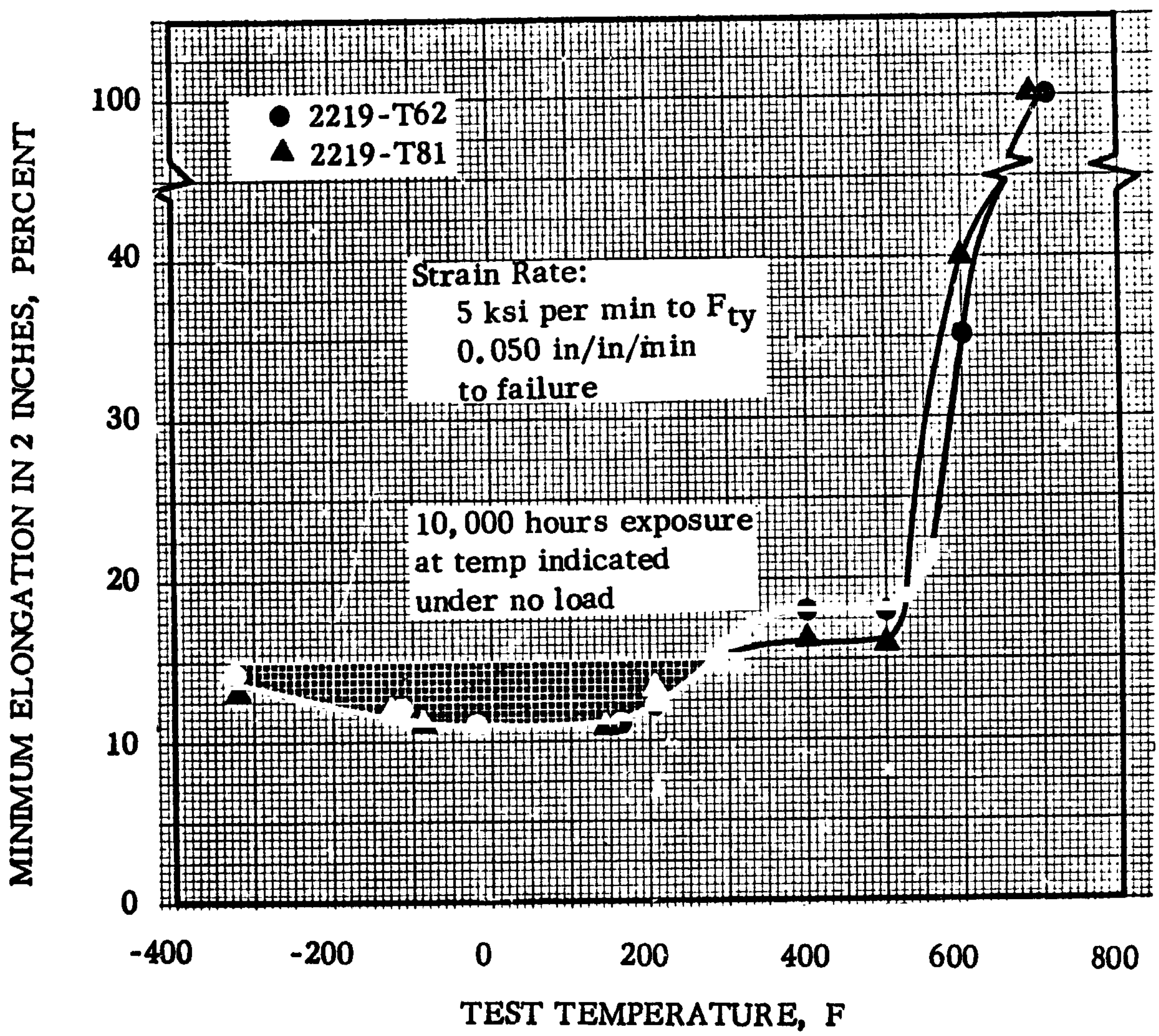

FIG. 7.4139 MINIMUM TENSILE ELONGATION FOR 2219 ALLOY IN T62 AND T81 CONDITIONS AFTER 10,000 HOURS EXPOSURE (Ref. 7.6)

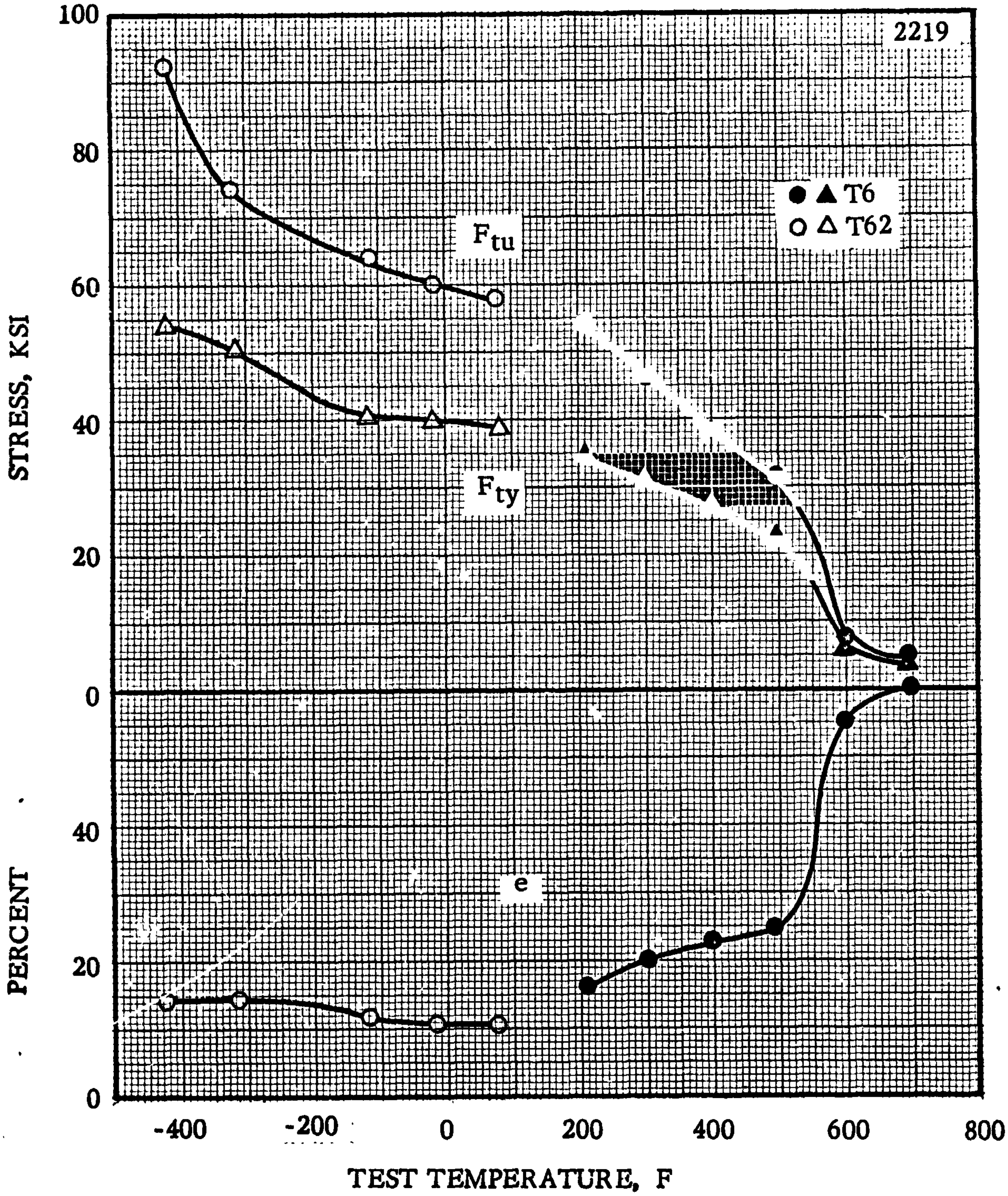

FIG. 7.4141 TYPICAL TENSILE PROPERTIES AT LOW AND ELEVATED TEMPERATURES FOR ALLOY IN T6 AND T62 CONDITIONS (Ref. 7.13)

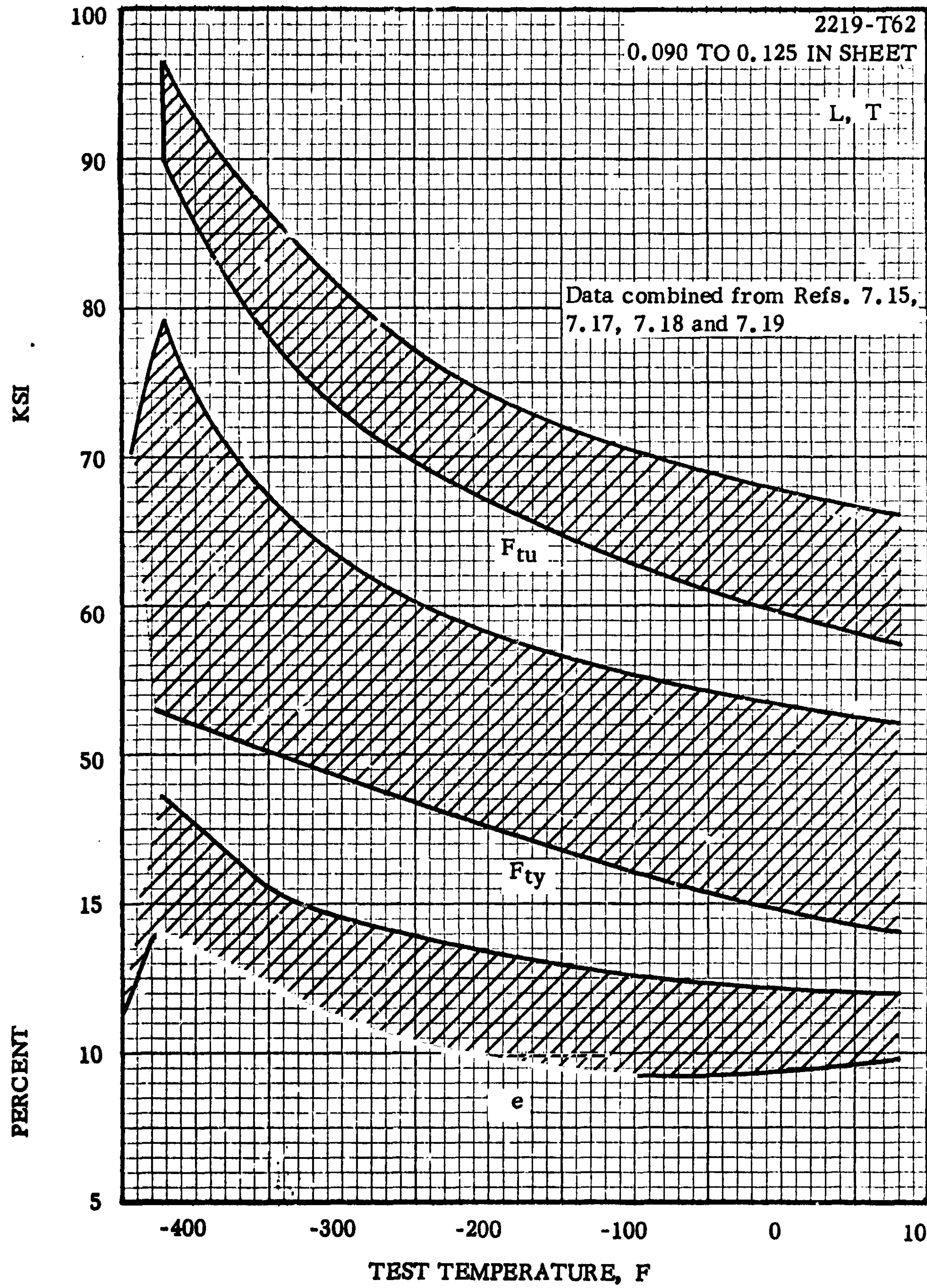

FIG. 7.4142 TENSILE PROPERTY BANDS FOR T62 SHEET AT LOW TEMPERATURES (Refs. 7.15, 7.17, 7.18 and 7.19)

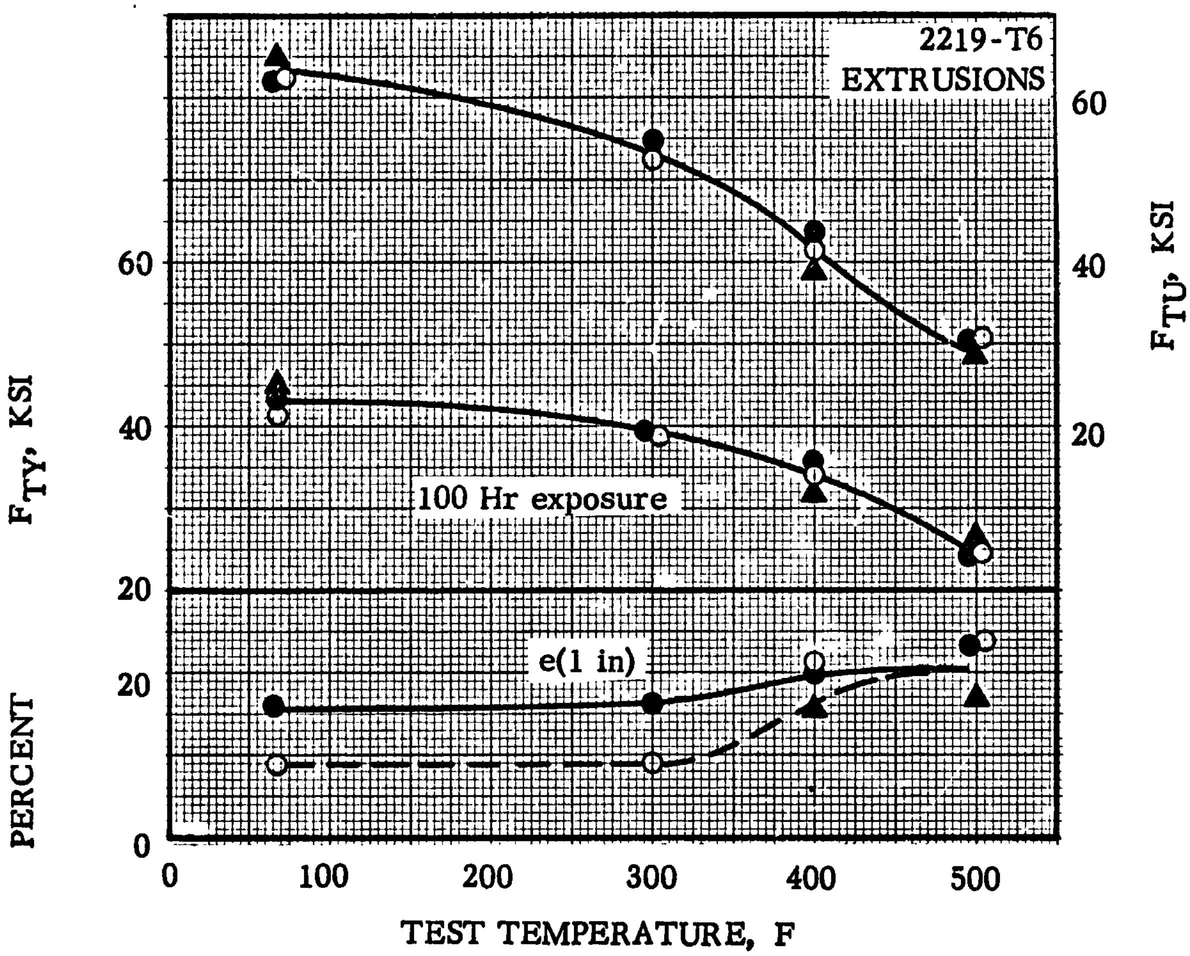

FIG. 7.4143 TENSILE PROPERTIES OF T6 EXTRUSIONS AT ELEVATED TEMPERATURES

(Ref. 7.8)

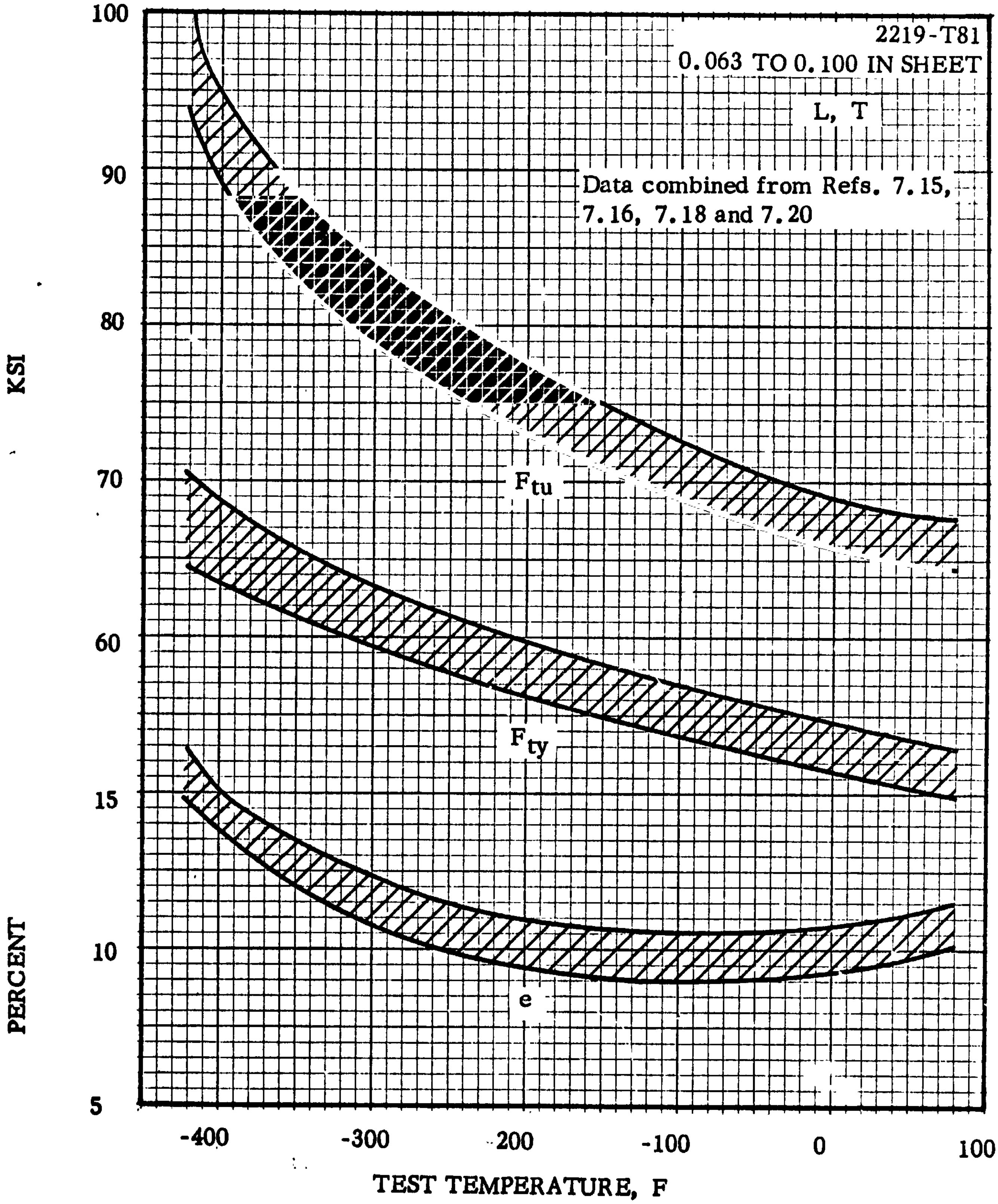

FIG. 7.4144 TENSILE PROPERTY BANDS FOR T81 SHEET AT LOW TEMPERATURES (Refs. 7.15, 7.16, 7.18 and 7.20)

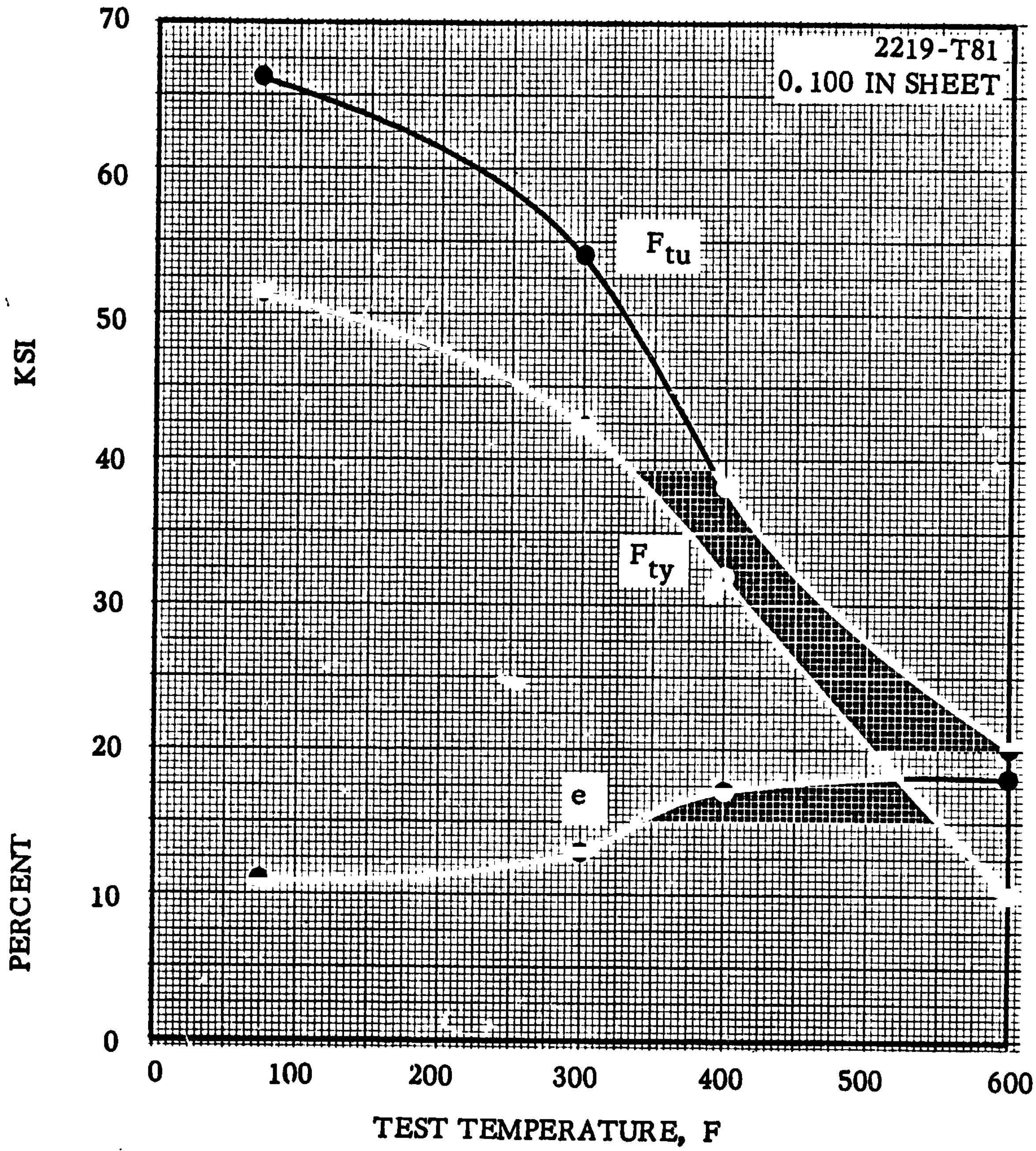

FIG. 7.4145 TYPICAL TENSILE PROPERTIES OF T81 SHEET AT ELEVATED TEMPERATURES

(Ref. 7.14)

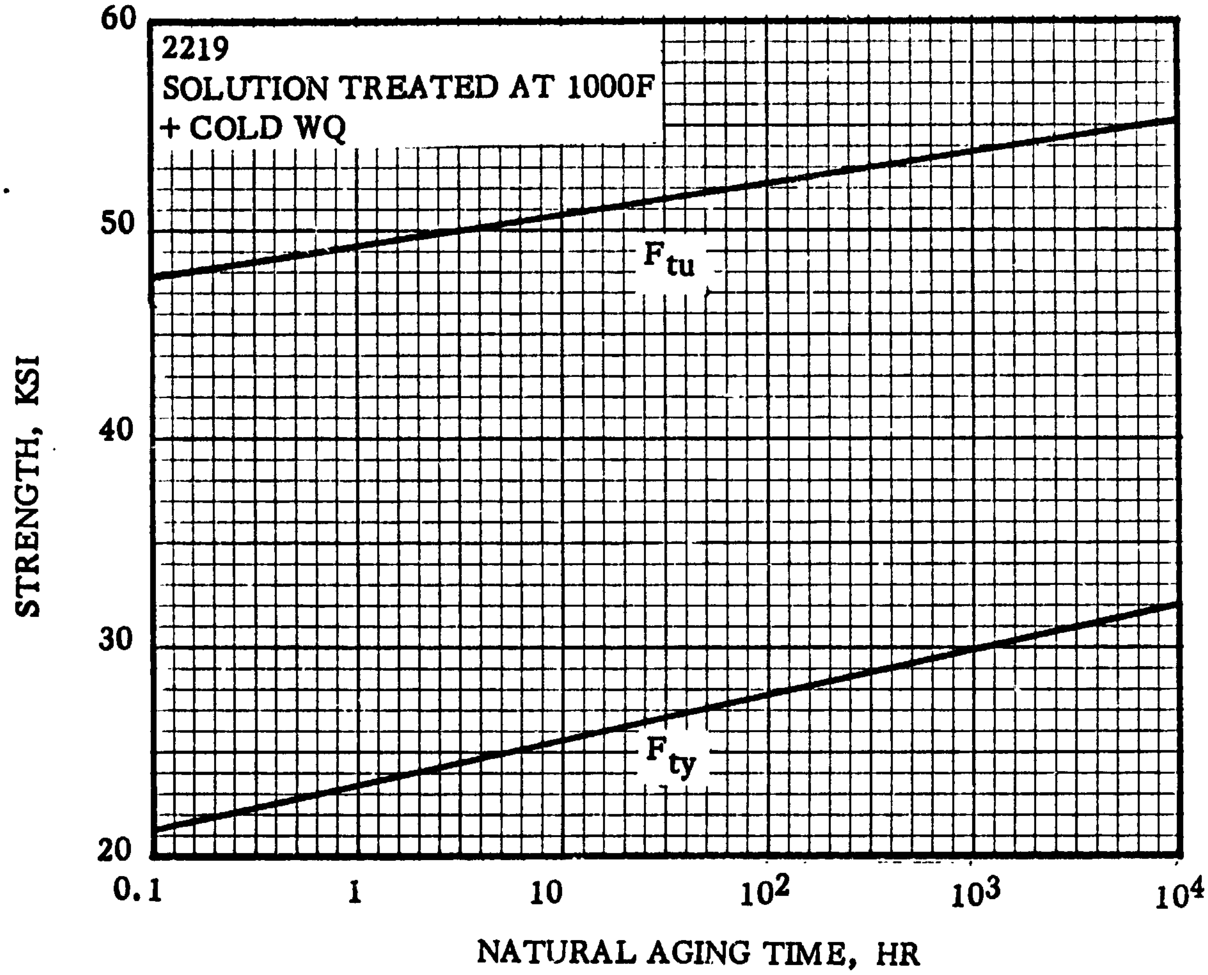

FIG. 7.4146 NATURAL AGING RESPONSE OF SOLUTION TREATED ALLOY (Ref. 7.23)

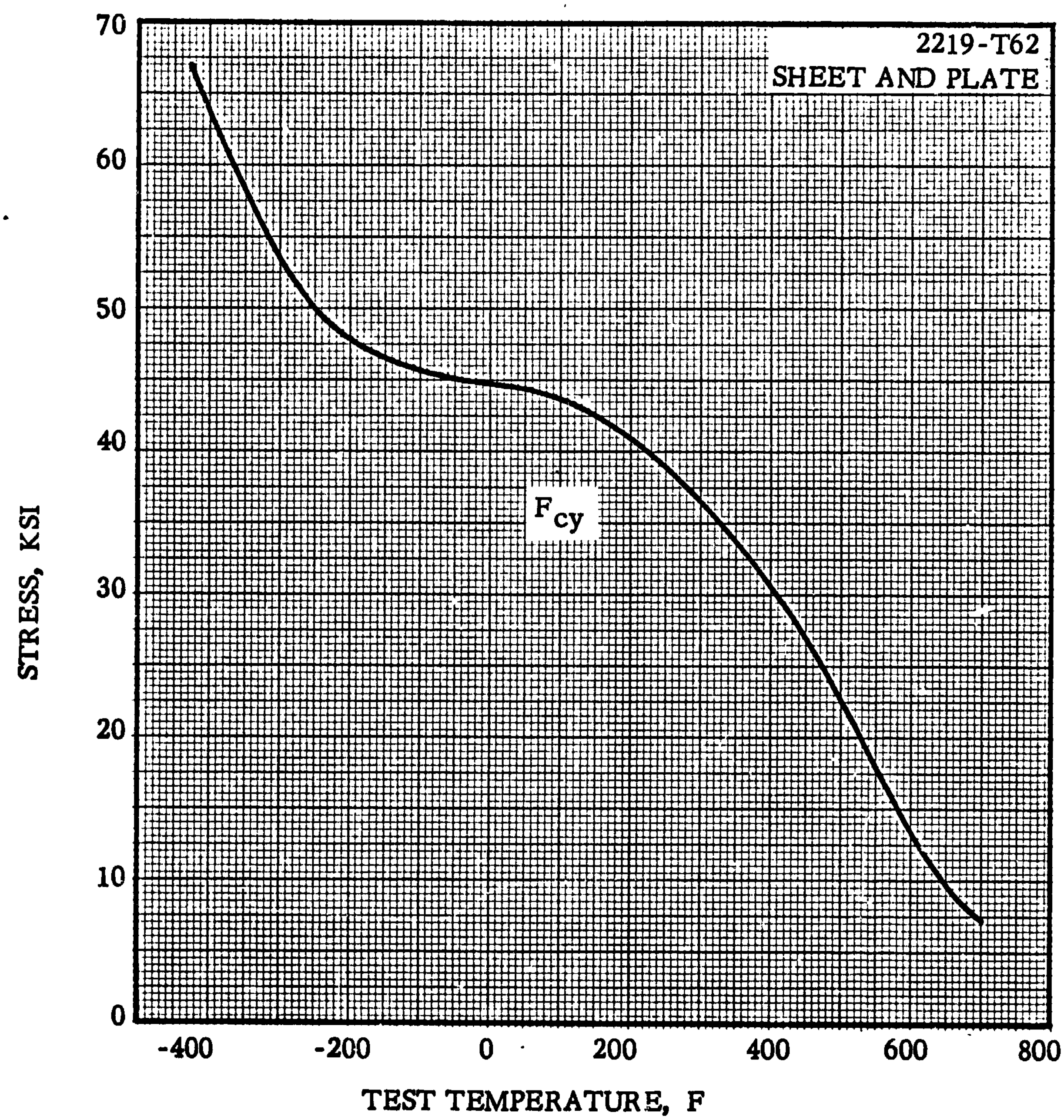

FIG. 7.4213 TYPICAL F_{CY} FOR T62 SHEET AND PLATE

(Ref. 7.5)

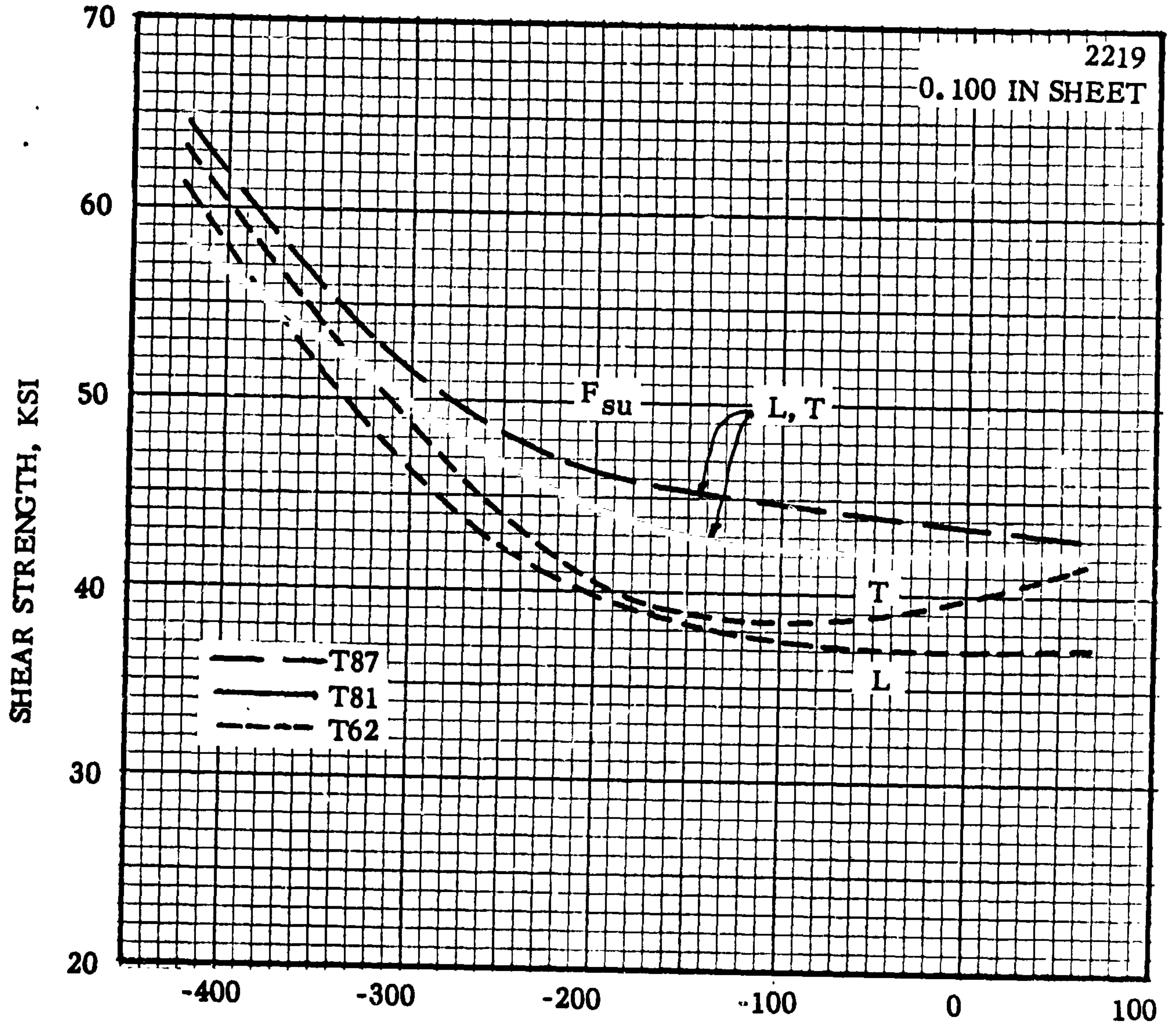

FIG. 7.4413 EFFECT OF LOW TEMPERATURE ON SHEAR STRENGTH OF SHEET (Ref. 7.15)

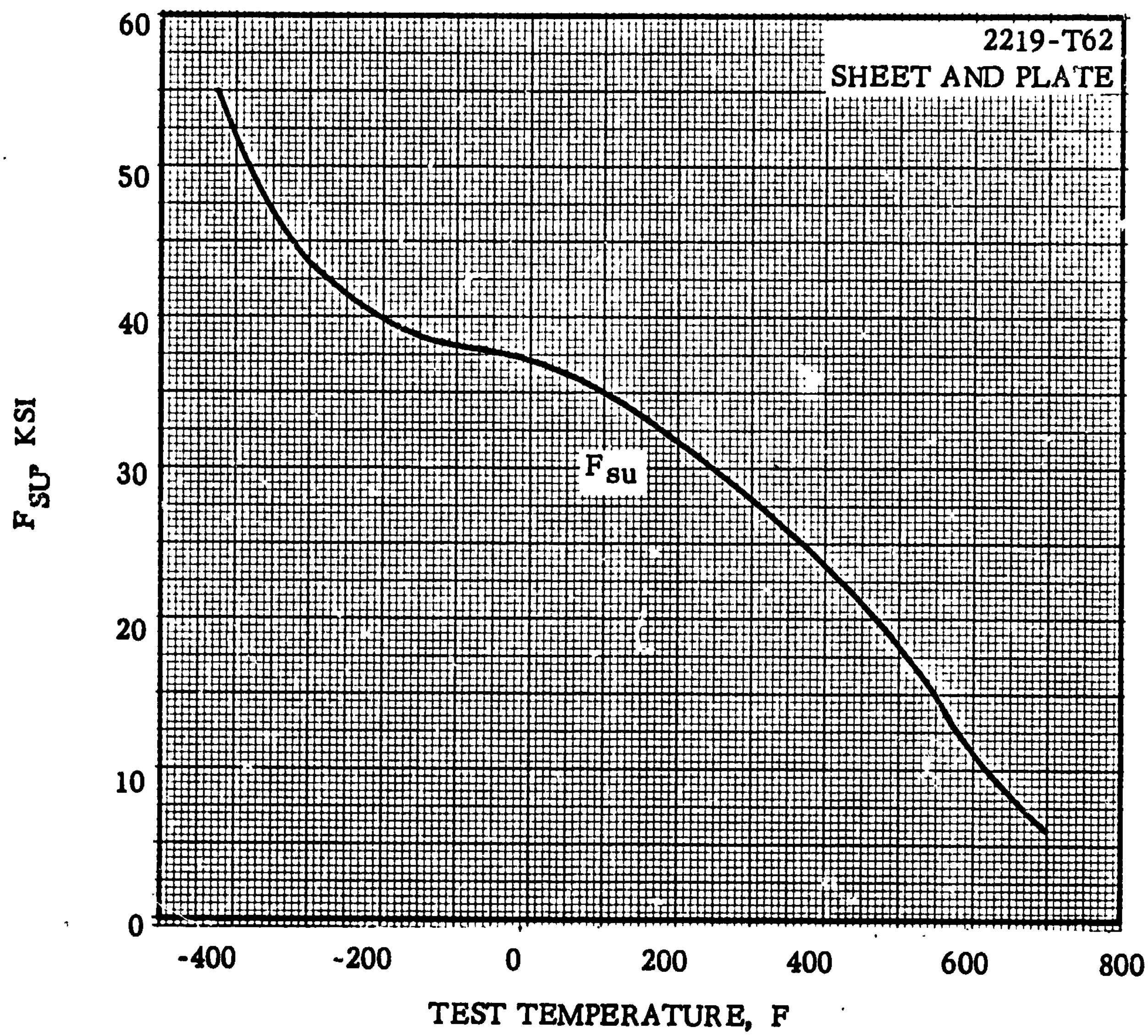

FIG. 7.4414 TYPICAL F_{SU} CURVE FOR T62 SHEET AND PLATE
(Ref. 7.5)

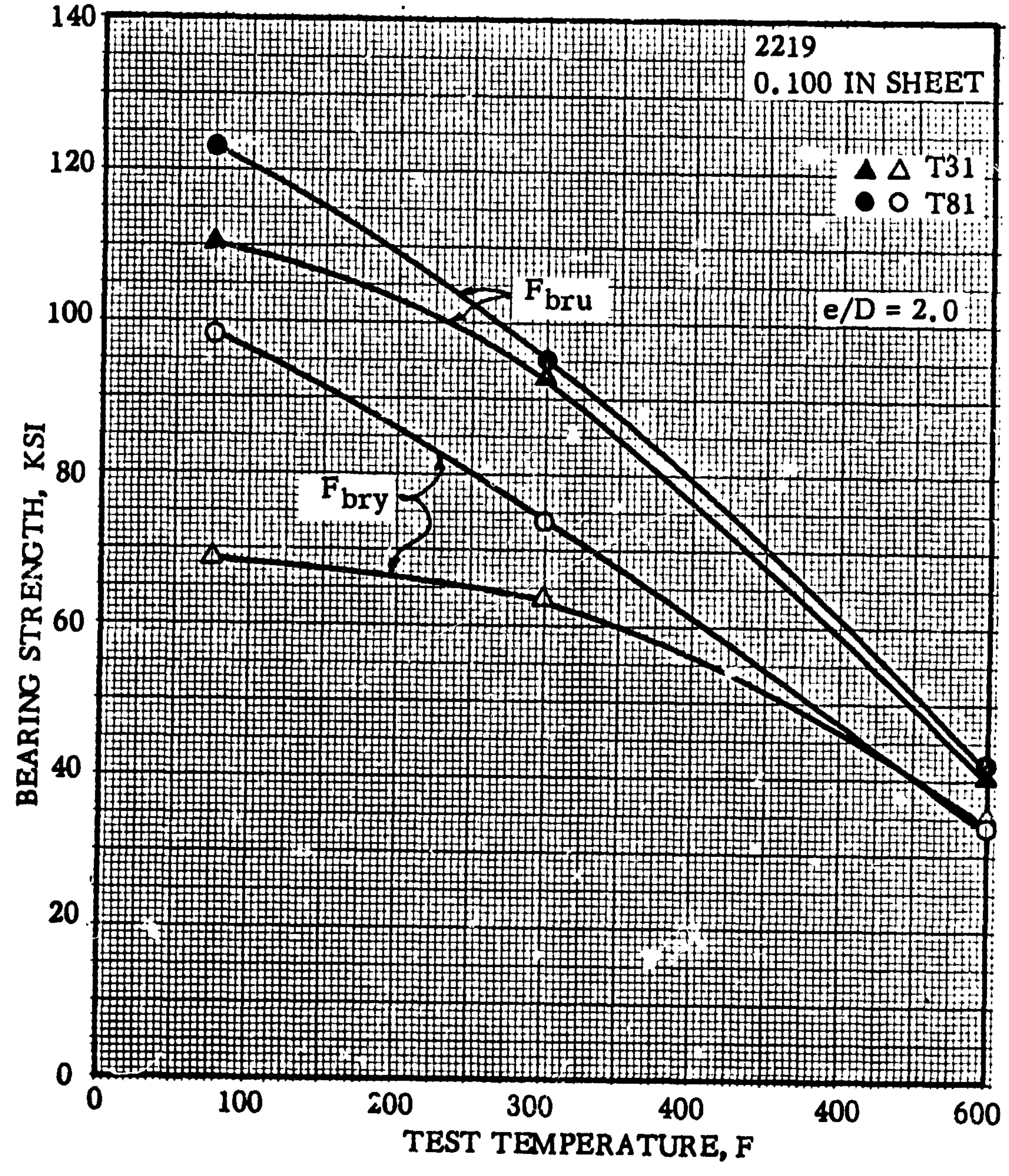

FIG. 7.4513 TYPICAL BEARING STRENGTH OF ALLOY IN T31 AND T81 CONDITION (Ref. 7.14)

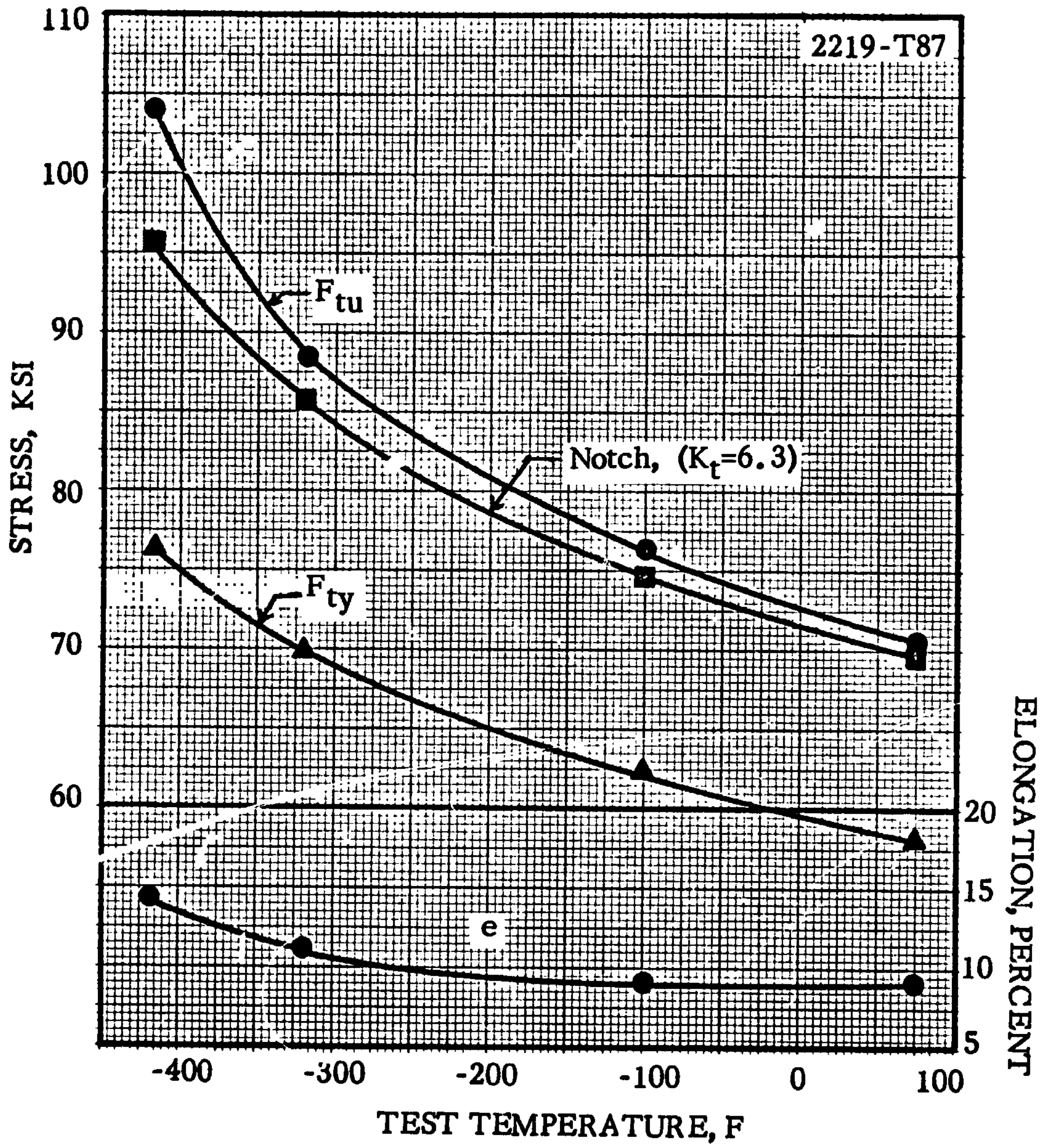

FIG. 7.4611 EFFECT OF LOW TEST TEMPERATURES ON TENSILE AND NOTCH PROPERTIES

(Ref. 7.21)

7.15 Data obtained for Cryogenic Materials Data Handbook by Martin Co., Denver, under Air Force Contract AF 33(657)-9161

7.16 J. L. Christian and A. Hurlich, "Physical and Mechanical Properties of Pressure Vessel Materials for Application in Cryogenic Environment", ASD-TDR-62-258, Part II, General Dynamics/Astronautics, (April 1963)

7.17 M. P. Hanson, et al., "Sharp-Notch Behavior of Some High Strength Aluminum Alloys and Welded Joints at 75, -320 and -423F", ASTM-STP 287, (1960)

7.18 F. R. Schwartzberg and R. D. Keys, "Mechanical Properties of 2000 Series Aluminum Alloys at Cryogenic Temperatures", R-61-32, Martin Co., Denver, (October 1961)

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7.20 J. L. Christian, "Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures", MRG-190, Convair/Astronautics, (December 1962)

7.21 J. L. Christian, J. E. Chafey, A. Hurlich, J. F. Watson and W. E. Witzell, "Structural Alloys for Cryogenic Service", Metals Progress, Vol. 83, No. 3, (March 1963)

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7.23 L. W. Mayer, "Alcoa Aluminum Alloy 2219", Alcoa Green Letter, (October 1960, latest revision November 1963)

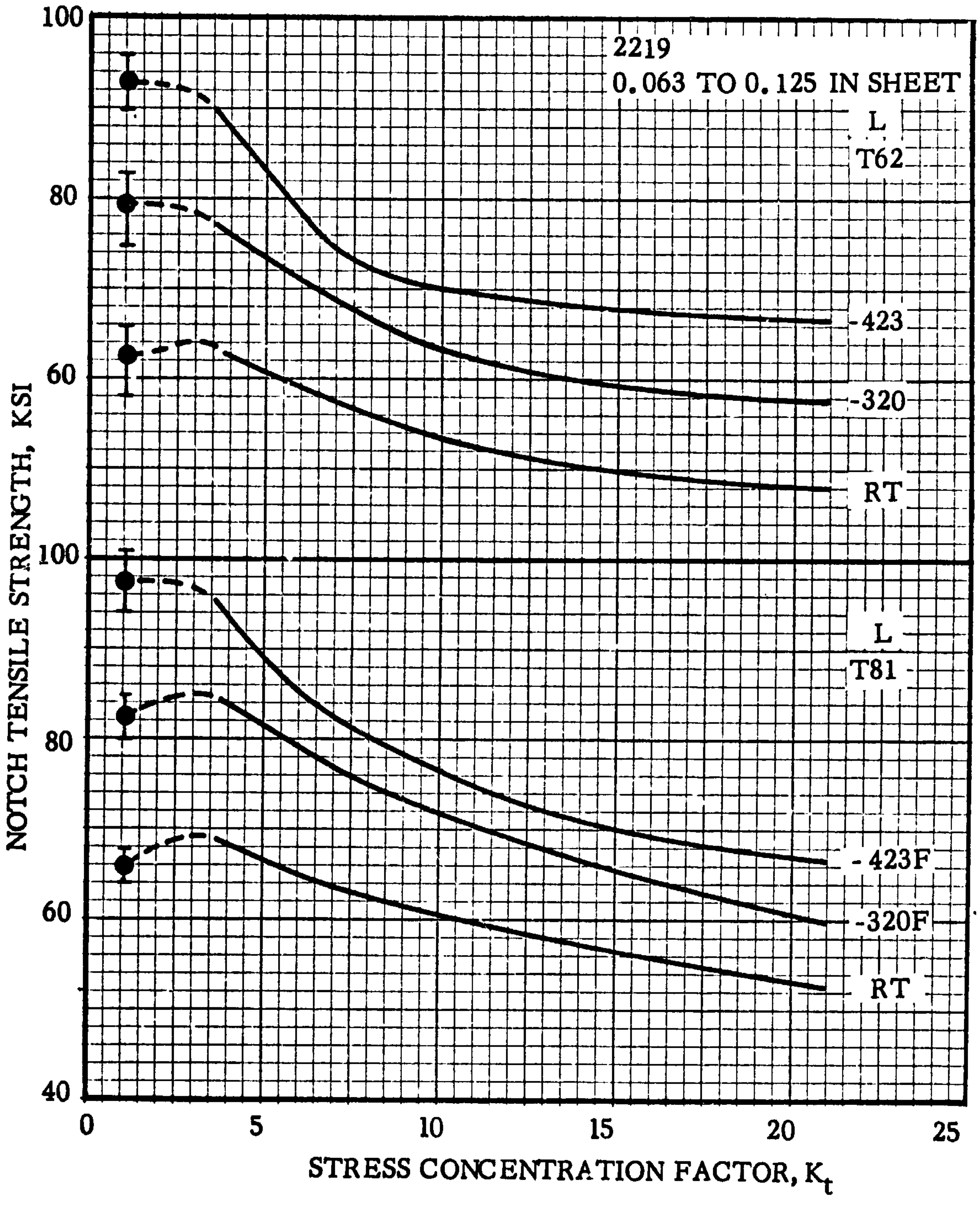

FIG. 7.4612 EFFECT OF STRESS CONCENTRATION FACTOR ON NOTCH STRENGTH OF T62 AND T81 SHEET

(Ref. 7.15, 7.16, 7.17, 7.18 and 7.20)

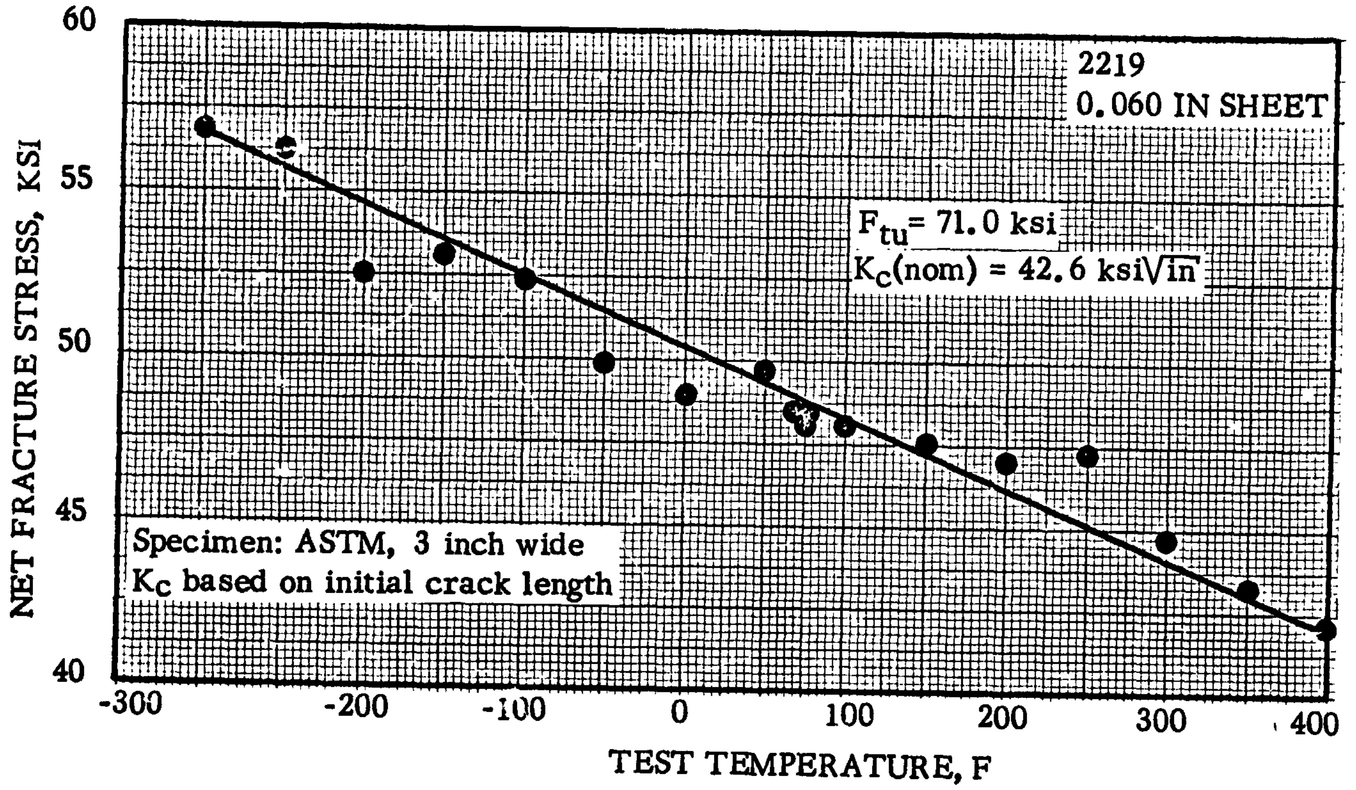

FIG. 7.4613 EFFECT OF TEST TEMPERATURE ON NET FRACTURE STRENGTH OF T81 SHEET (Ref. 7.11)

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7.2 "Aerospace Structural Metals Handbook", V. Weiss and J. Sessler (Editors), ASD-TDR-63-741, Vol. II, (March 1963)

7.3 Alcoa, "Aluminum Sheet and Plate - General Information, Mechanical Properties, Physical Properties", Section AC2A Product Data, Aluminum Co. of America, (December 1961)

7.4 "Standards for Aluminum Mill Products", Seventh Edition, The Aluminum Association, (October 1964)

7.5 "Materials Properties Data Book", Report No. 2275 to AEC-NASA, NERVA Program, Aerojet-General Corp., (Revised - July 1964)

7.6 "Alcoa Aluminum Handbook", Aluminum Co. of America, (1962)

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7.8 P. L. Hendricks, "Metallurgical Investigation of Aluminum Alloy X 2219-T6", WADC TR-58-57, (June 1958).

7.9 "Alcoa Alloy 2219", Aluminum Co. of America, Development Division, (March 1959)

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7.11 J. Viglione and W. F. Worden, "Fracture Toughness Properties of Some Alloy Steels and Aluminum and Titanium Alloys", Report No. NAEC-AML-2111, Naval Air Eng. Center, (March 1965)

7.12 R. G. Mahorter, Jr. and W. F. Emmons, "A Study of Creep Resistance, Formability and Heat Treatment of Clad X2219-T6 Aluminum Alloy", Report No. NAMC-AML-AE 1100, Naval Air Material Center, (August 1959)

7.13 "The Aluminum Data Book", Reynolds Metals Co., (1965)

7.14 "Summary Information Regarding Aluminum Alloy 2219", Martin-Denver Evaluation Report No. 1, MI-61-44, (November 1961)

CHAPTER 8

DYNAMIC AND TIME DEPENDENT PROPERTIES

8.1 General. Aluminum alloy 2219 exhibits good fatigue and creep-rupture properties up to temperatures of about 600F..

8.2 Specified Properties

8.3 Impact

8.31 Impact strength of T87 plate at low temperatures, Fig. 8.31.

8.4 Creep

8.41 Creep-rupture curves for extrusions in T6 Condition at 400 and 600F, Fig. 8.41.

8.42 Creep and creep-rupture curves for alloy in T6 Condition from 300 to 700F, Fig. 8.42.

8.43 Creep data for clad sheet in T6 Condition at 400F, Fig. 8.43.

8.44 Creep data for clad sheet in T6 Condition at 500F, Fig. 8.44.

8.45 Creep data for clad sheet in T6 Condition at 600F, Fig. 8.45.

8.5 Stability

8.51 Effect of exposure temperature on room temperature transverse tensile properties of plate, Fig. 8.51.

8.52 Effect of exposure temperature on room temperature tensile properties of 2219-T6 forged rod, Fig. 8.52.

8.53 Effect of exposure and test temperature on tensile properties of forged rod, Fig. 8.53.

8.54 Effect of exposure and test temperature on transverse tensile properties of plate, Fig. 8.54.

8.6 Fatigue

8.61 Fatigue limit in rotating beam tests at 5×10^8 cycles, Table 8.61.

8.62 Fatigue strength of forged rod at elevated temperatures, Table 8.62.

8.63 Fatigue strength of extrusions at elevated temperatures, Table 8.63.

8.64 S-N curves for forgings at 400 and 600F, Fig. 8.64.

8.65 Fatigue strength of sheet in T87 Condition at room temperature and low temperature, Fig. 8.65.

TABLE 8.61

Source	Ref. 8.4	
Alloy	2219	
Test	Rotating Beam Fatigue (5×10^8 cycles)	
Condition	T6	T86
Fatigue Limit, ksi	15	15

TABLE 8.62

Source	Ref. 8.2				
Alloy	2219-T6				
Form	Forged Rod				
Data	Rotating Beam Fatigue (R = -1)				
Temp, (F)	Fatigue Strength (at cycles shown), ksi				
	10^5	10^6	10^7	10^8	5×10^8
RT	30	25	21	18.5	17.5
300	27	22	17.5	14.5	13.5
400	25	20	15	12	11
500	22	17	12	9	8
600	18	13	9	7	6.5

TABLE 8.63

Source	Ref. 8.1			
Alloy	2219-T6			
Form	Extrusions			
Data	Direct Stress Fatigue Tests (R = 0)			
Temp, (F)	Thickness (inch)	Fatigue Strength (at cycles), ksi		
		10^5	10^6	10^7
400	1.5	36	28	22
600	1.5	25	20	14
600	0.125	25	20	16

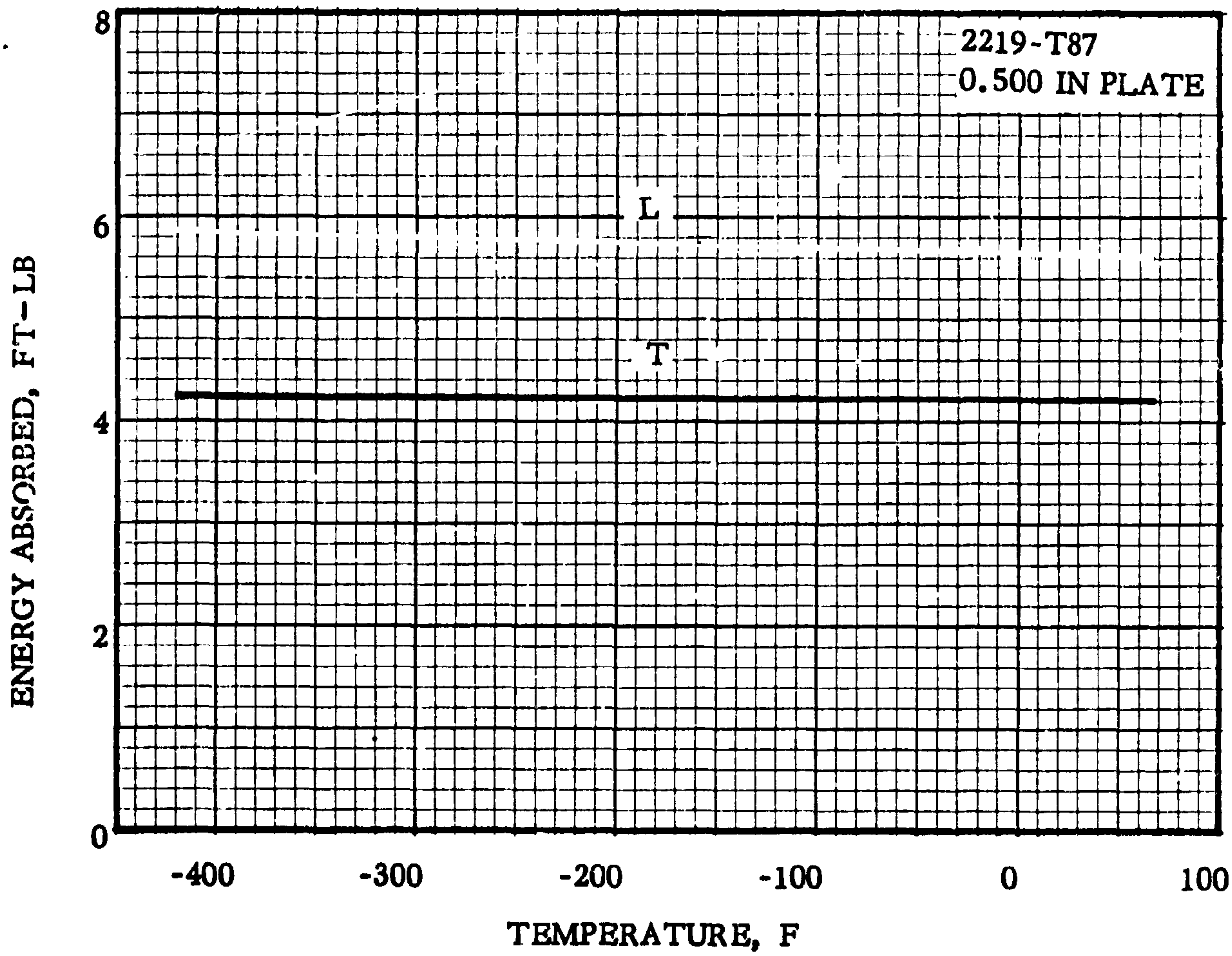

FIG. 8.31 IMPACT STRENGTH OF T87 PLATE AT LOW TEMPERATURES (Ref. 8.6)

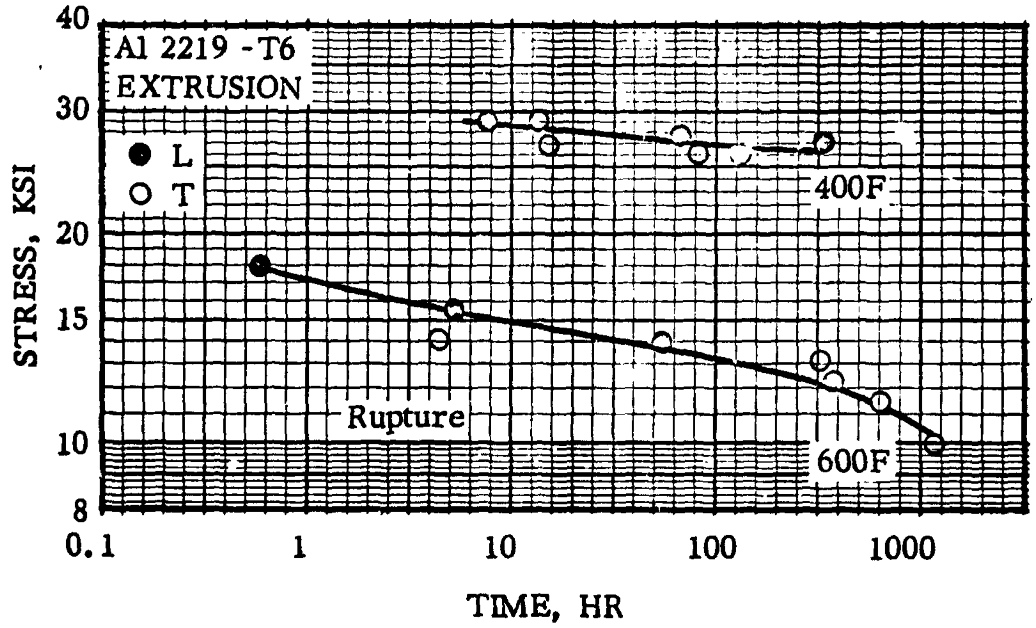

FIG. 8.41 CREEP RUPTURE CURVES FOR EXTRUSION IN T6 CONDITION AT 400 AND 600F

(Ref. 8.1)

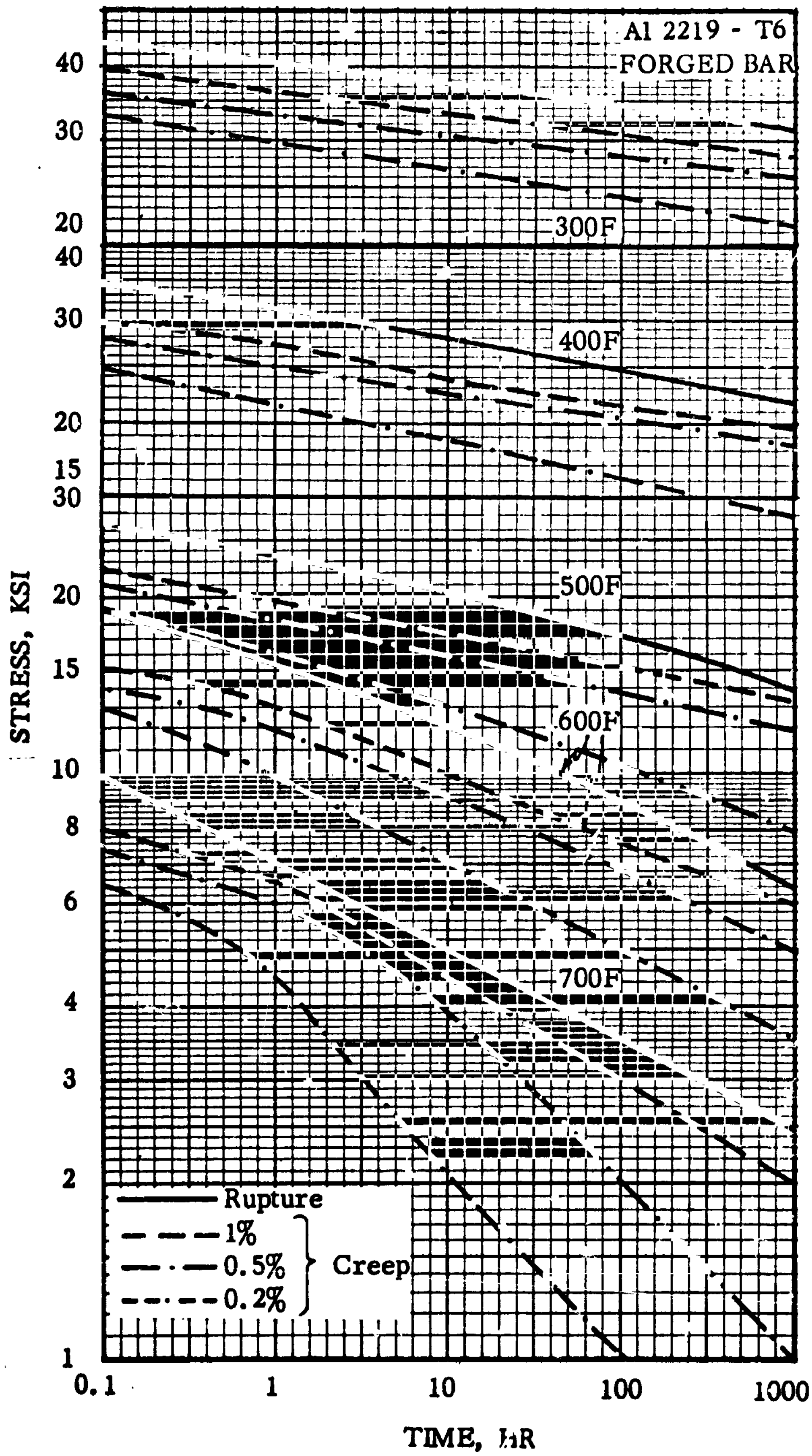

FIG. 8.42 CREEP AND CREEP RUPTURE CURVES FOR ALLOY IN T6 CONDITION FROM 300 TO 700F

(Ref. 8.2)

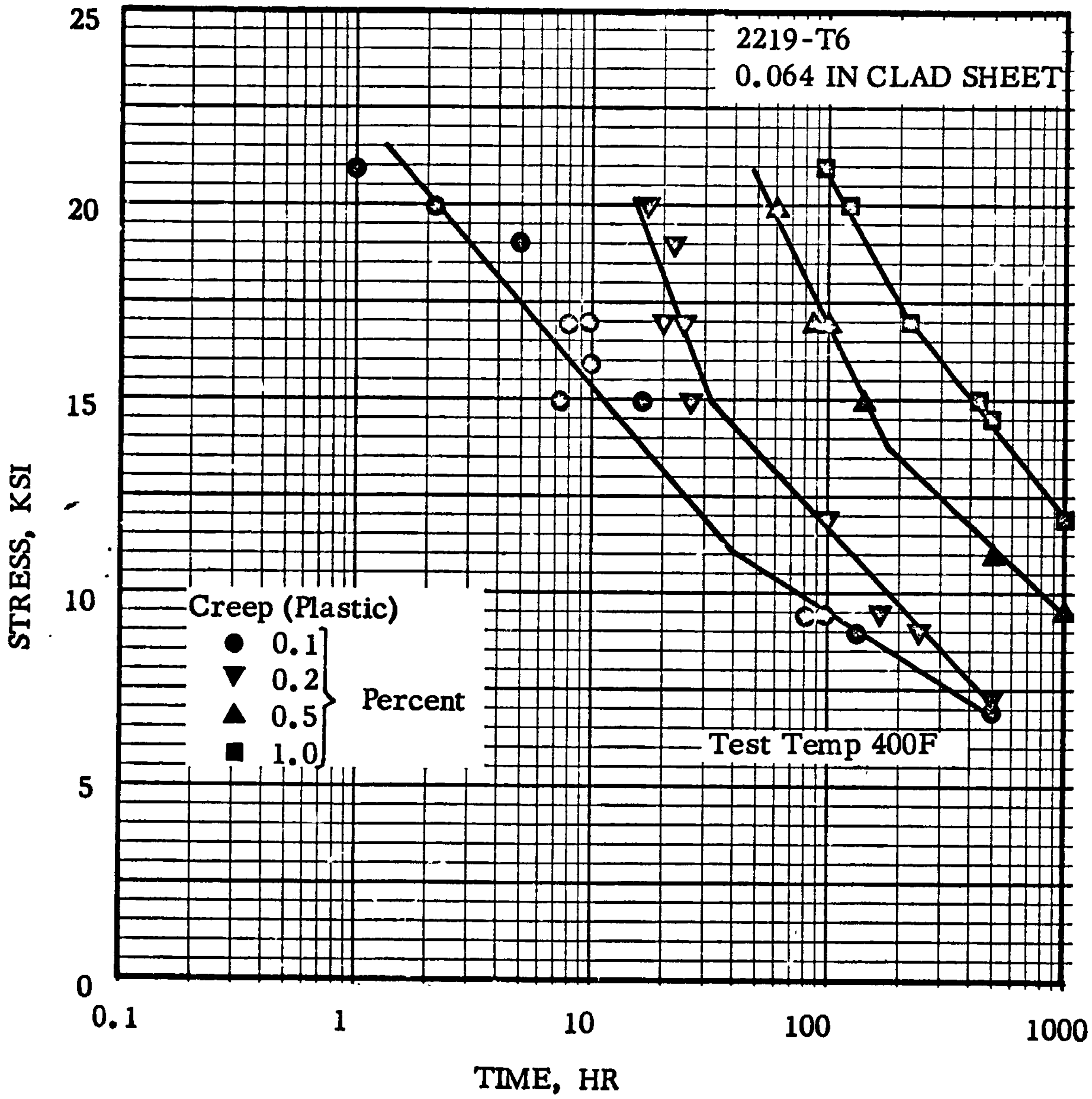

FIG. 8.43 CREEP DATA FOR CLAD SHEET IN T6 CONDITION AT 400F (Ref. 8.7)

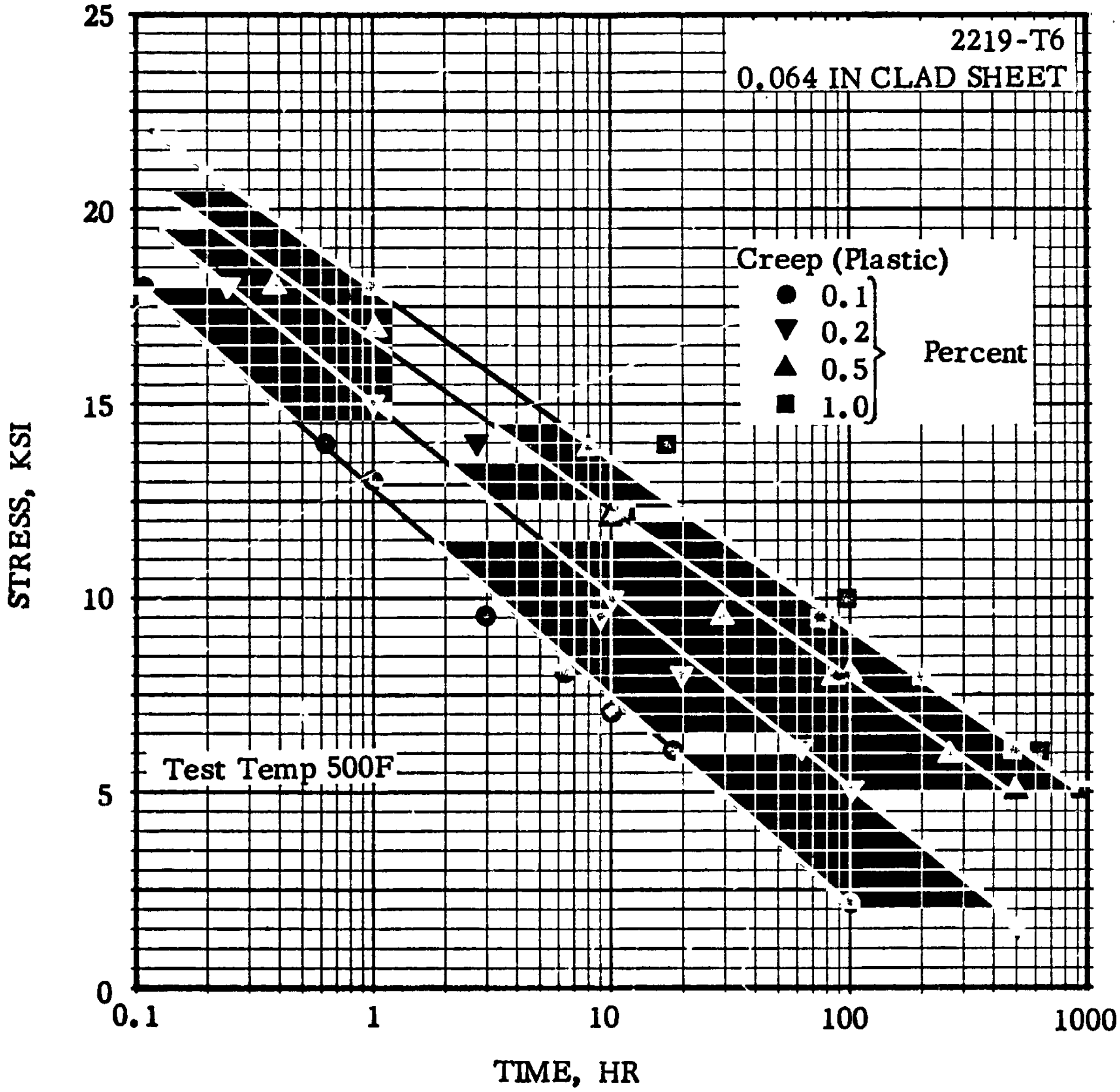

FIG. 8.44 CREEP DATA FOR CLAD SHEET IN T6 CONDITION AT 500F (Ref. 8.7)

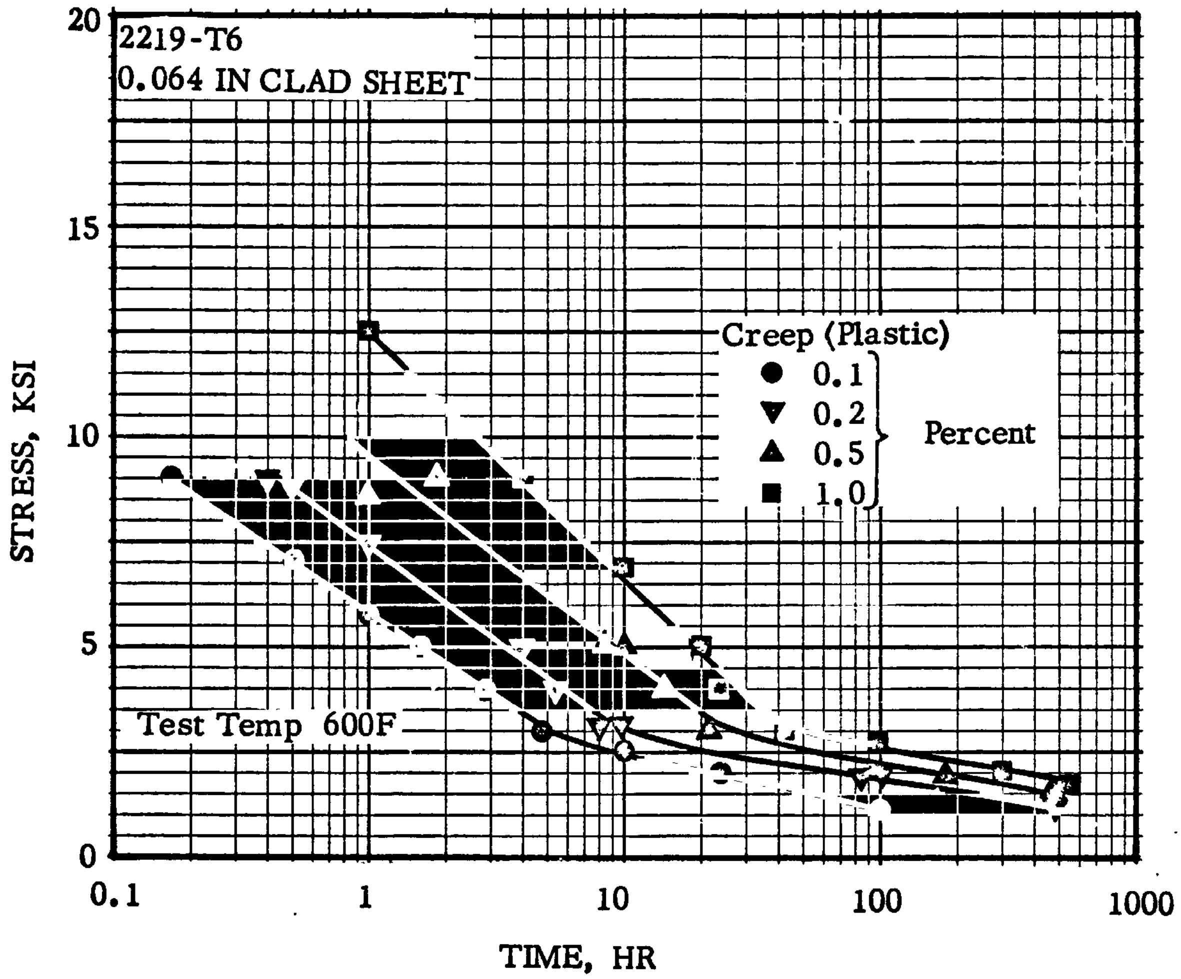

FIG. 8.45 CREEP DATA FOR CLAD SHEET IN T6 CONDITION AT 600F (Ref. 8.7)

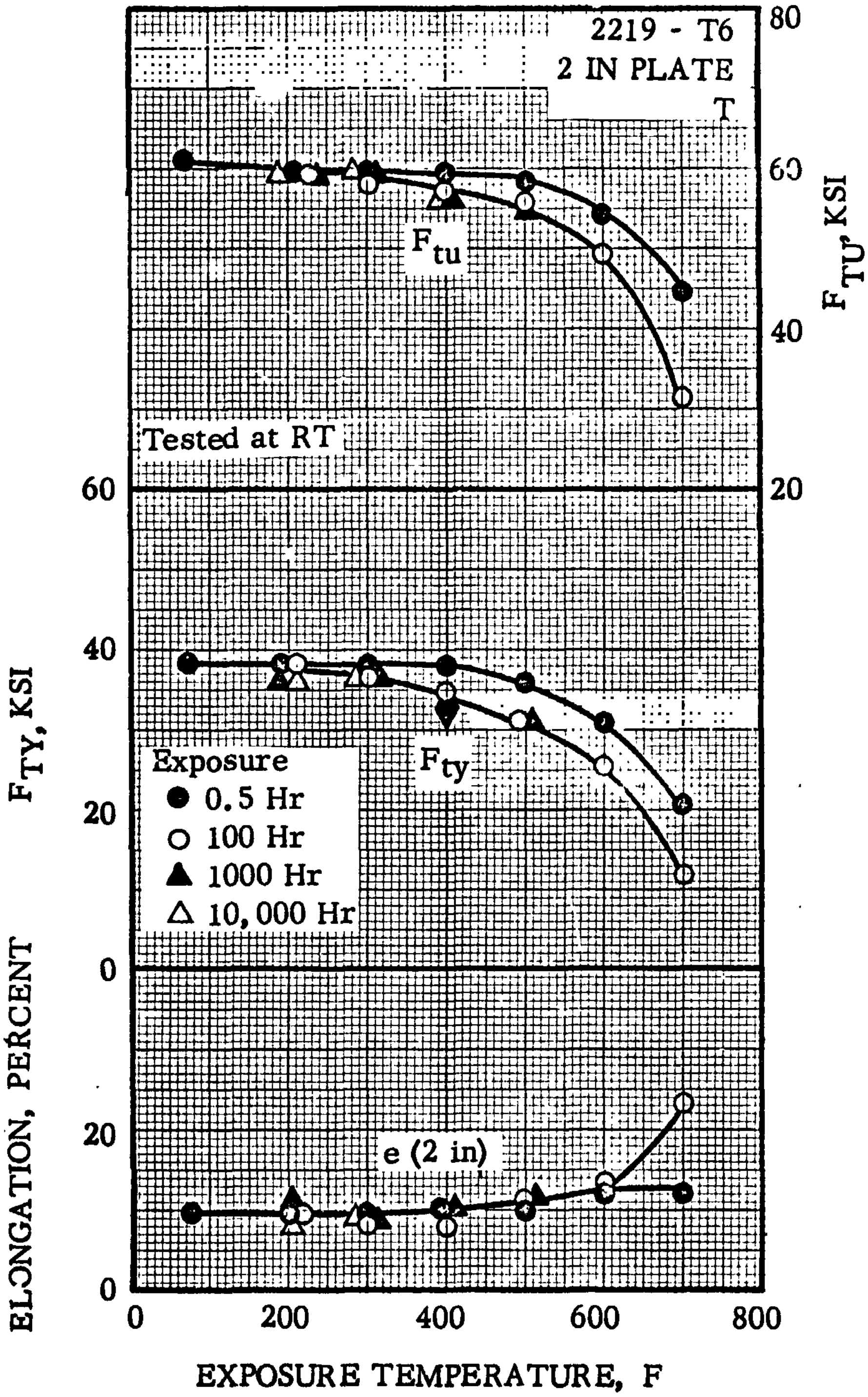

FIG. 8.51 EFFECT OF EXPOSURE TEMPERATURE ON ROOM TEMPERATURE TRANSVERSE TENSILE PROPERTIES OF PLATE (Ref. 8.3)

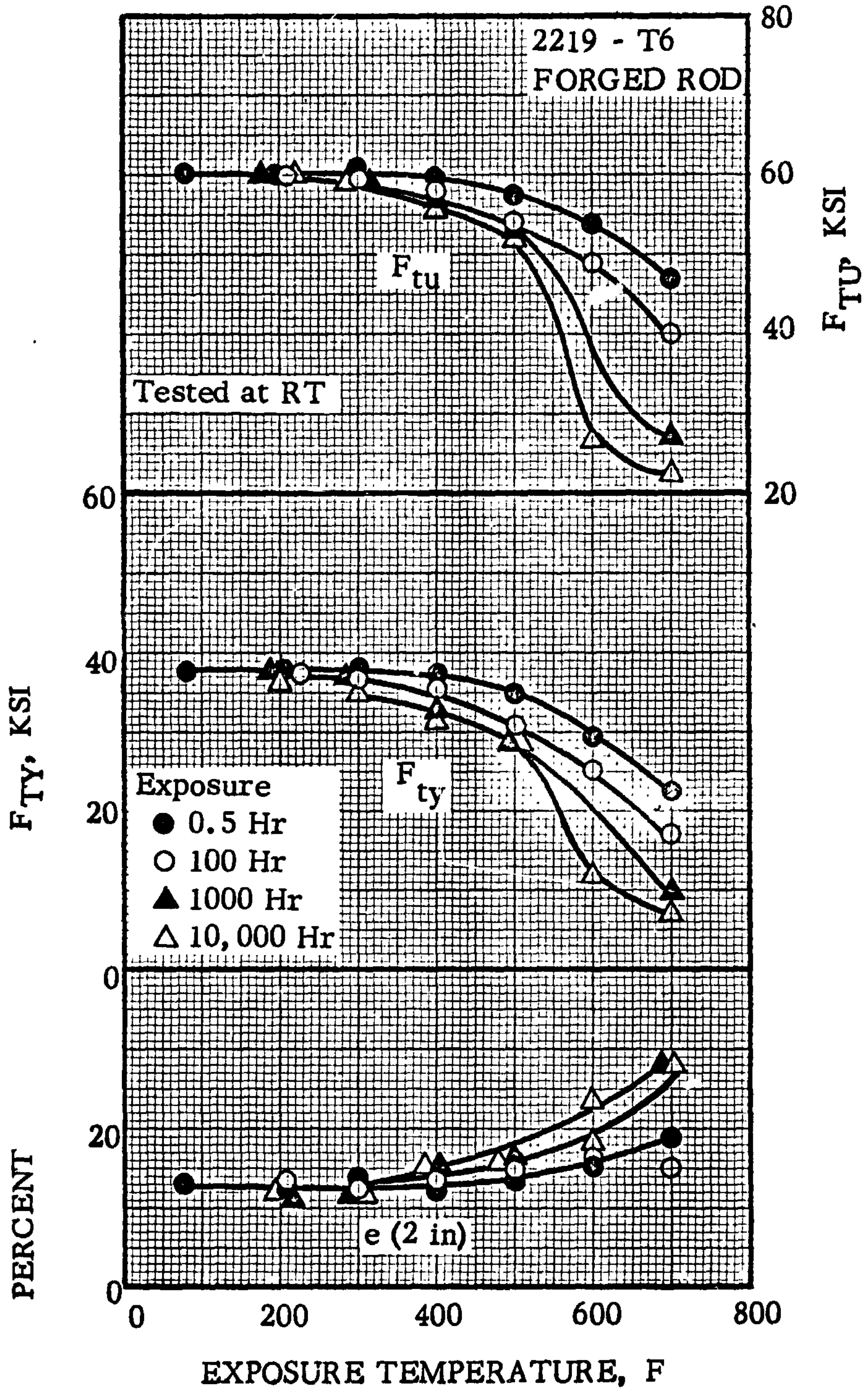

FIG. 8.52 EFFECT OF EXPOSURE TEMPERATURE ON ROOM TEMPERATURE TENSILE PROPERTIES OF 2219-T6 FORGED ROD (Ref. 8.3)

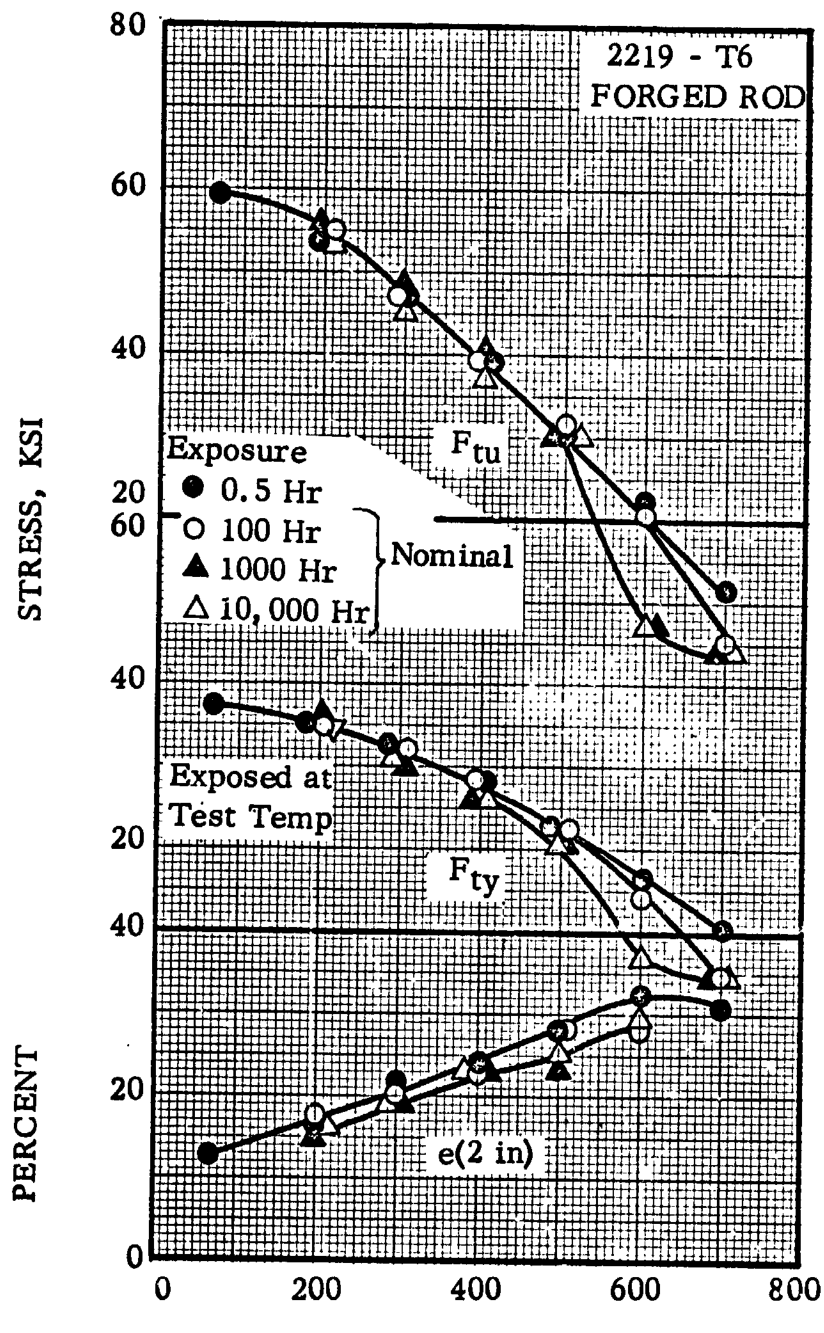

FIG. 8.53 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TENSILE PROPERTIES OF FORGED ROD

(Ref. 8.3)

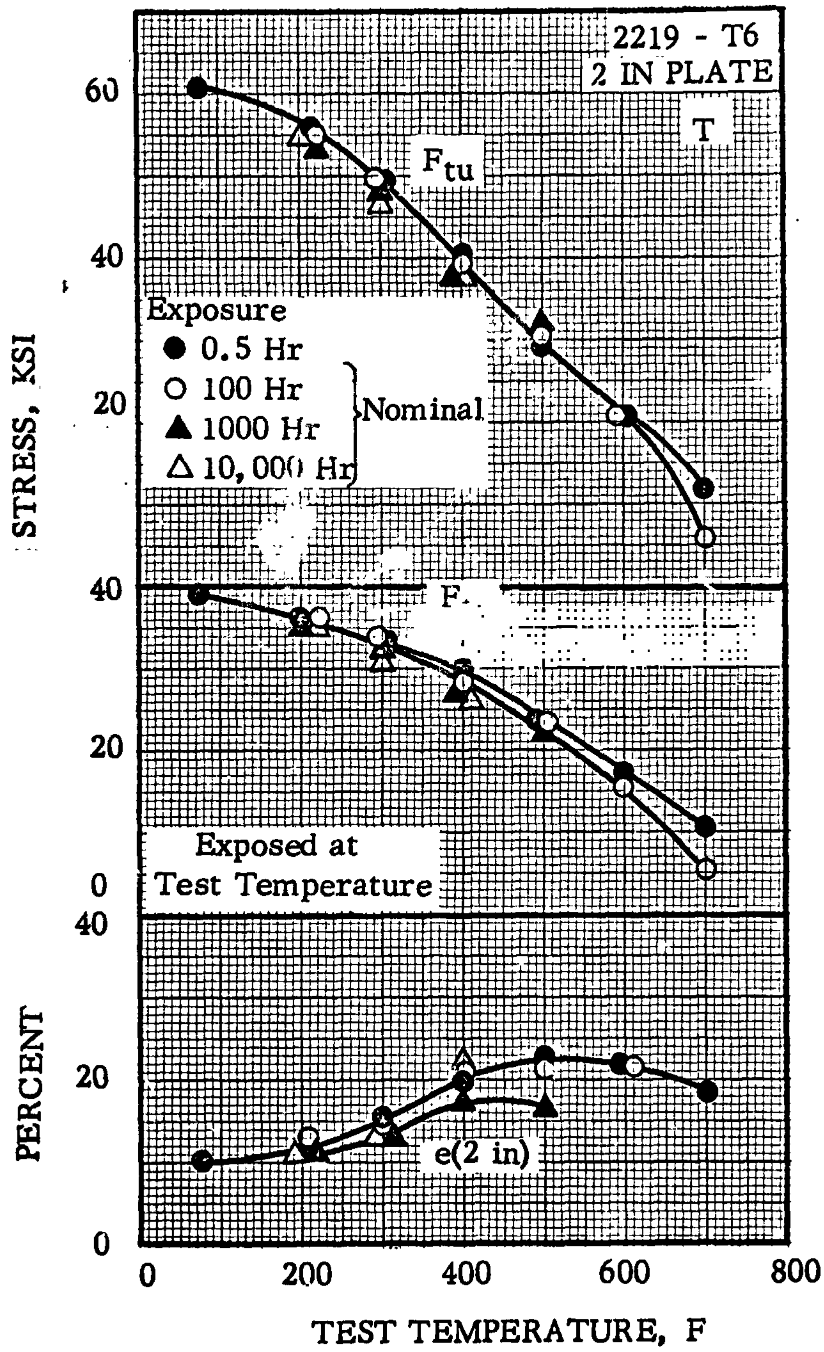

FIG. 8.54 EFFECT OF EXPOSURE AND TEST TEMPERATURE ON TRANSVERSE TENSILE PROPERTIES OF 2219 - T6 PLATE

(Ref. 8.3)

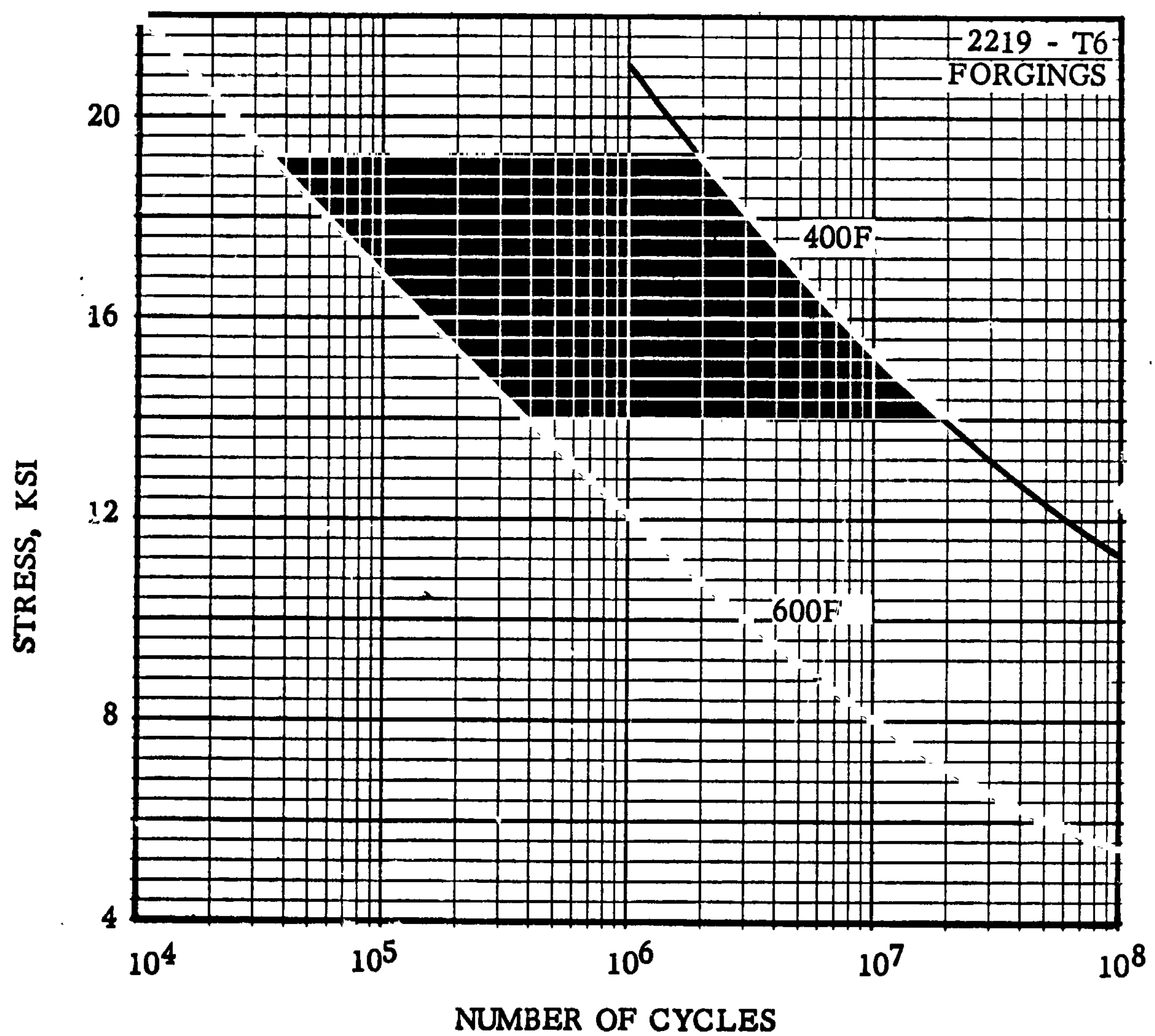

FIG. 8.64 S-N CURVES FOR ALLOY AT 400 AND 600F

(Ref. 8.5)

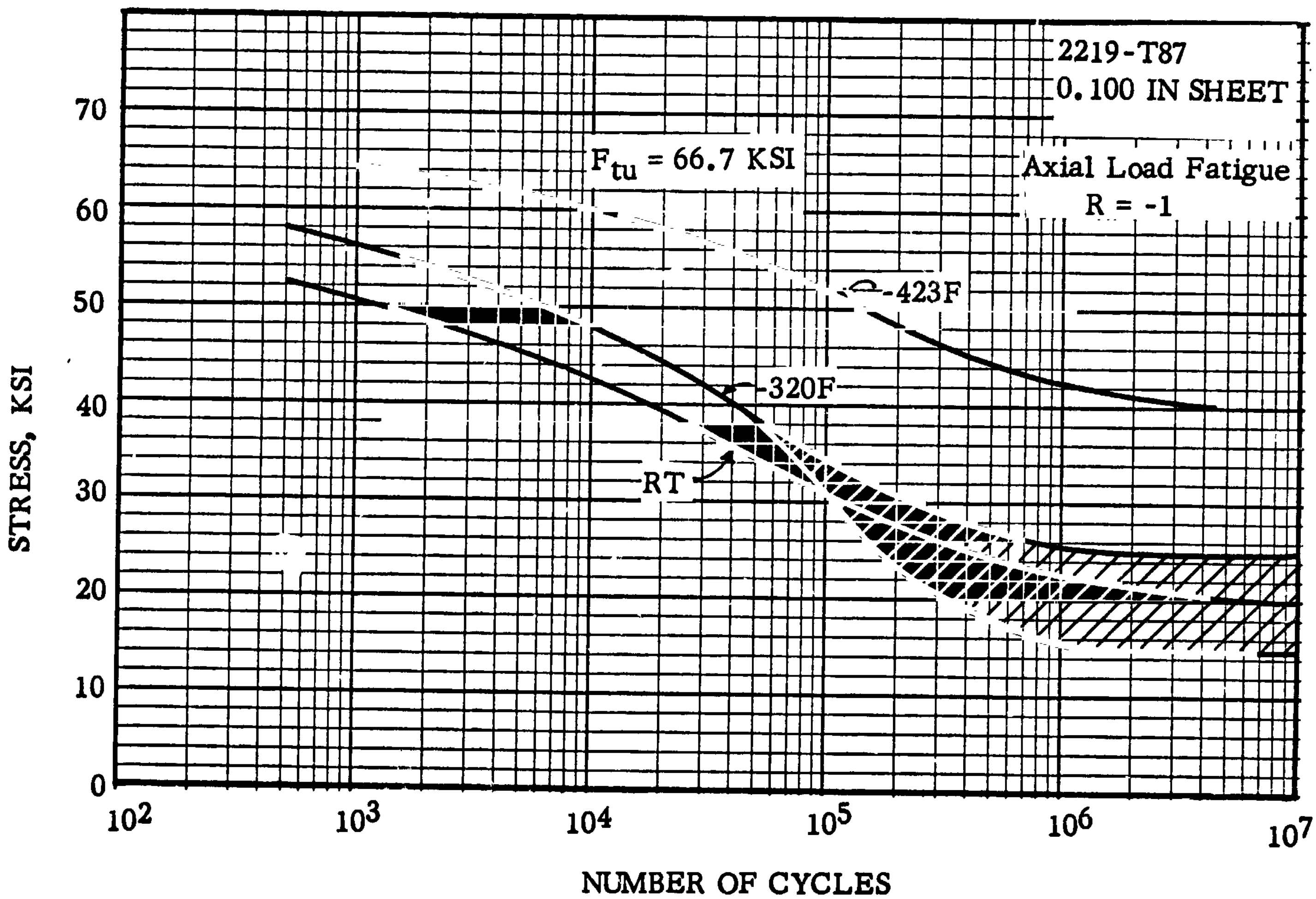

FIG. 8.65 FATIGUE STRENGTH OF SHEET IN T87 CONDITION AT ROOM TEMPERATURE AND LOW TEMPERATURES

(Ref. 8.8)

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CHAPTER 9

PHYSICAL PROPERTIES

9.1 Density (ρ)

Fig. 9.1 gives the density (ρ) as a function of temperature. Values were calculated from room temperature data ($\rho = 0.102$ lb per cu in), and the average thermal expansion coefficient, α_{av}, using the relation:

$$\rho(t) = \rho(68\,°F) \left[1 - 3\ \alpha_{av}(t - 68\,°F)\right],$$

(Ref. 9.1, p. 36, 39-41).

9.11 Specific gravity. 2.83 gr per cm^3, (Ref. 9.4).

9.2 Thermal Properties

9.21 Thermal conductivity (K), Table 9.21.

9.211 Critical appraisal of data

The thermal conductivity of 2219 aluminum is, at room temperature, much lower than that of electrical conductor grade. Therefore, the heat transfer depends markedly on temper and composition. The allowed composition range for secondary elements is rather large, (Ref. 9.1). This should produce a corresponding variation in the thermal conductivity. Data of K can be regarded only as nominal.

9.22 Thermal expansion (α), Fig. 9.22.

9.221 Thermal expansion of plate at low temperatures, Fig. 9.221.

9.23 Specific heat (c_p)

No data found.

9.24 Thermal diffusivity

No data found.

9.3 Electrical Properties

9.31 Electrical resistivity, Table 9.31.

9.311 Critical appraisal of data

The electrical resistivity depends markedly on impurity concentration and distribution. The allowed composition change for secondary elements is rather large. Therefore, the electrical resistance will change noticably from heat to heat of material, even with identical heat treatments.

9.4 Magnetic Properties

9.41 Permeability. The alloy is not ferromagnetic.

9.42 Susceptibility. The susceptibility changes strongly with heat treatment. Reversible and irreversible micro-structural changes can be determined from susceptibility measurements. This makes it possible to use these measurements for studies on the kinetics of precipitation processes in Al-Cu alloy systems.

9.5 <u>Nuclear Properties</u>

No data found.

9.6 <u>Other Physical Properties</u>

9.61 Emissivity. No data found.

9.62 Damping capacity. No data found.

THERMAL CONDUCTIVITY

TABLE 9.21

Source	Ref. 9.1			
Alloy	2219			
Condition	K(cal/cm sec C)	T(C)	K(Btu ft/ft^2 hr F)	T (F)
O	0.41	25	99	77
T31, T37	0.27	25	65	77
T62, T81, T87	0.30	25	76	77

ELECTRICAL RESISTIVITY

TABLE 9.31

Source	Ref. 9.3	
Alloy	2219	
Condition	Microhm-in at RT	Microhm-cm at RT
0	1.54	3.90
T31, T37	2.42	6.14
T62, T81, T87	2.06	5.23

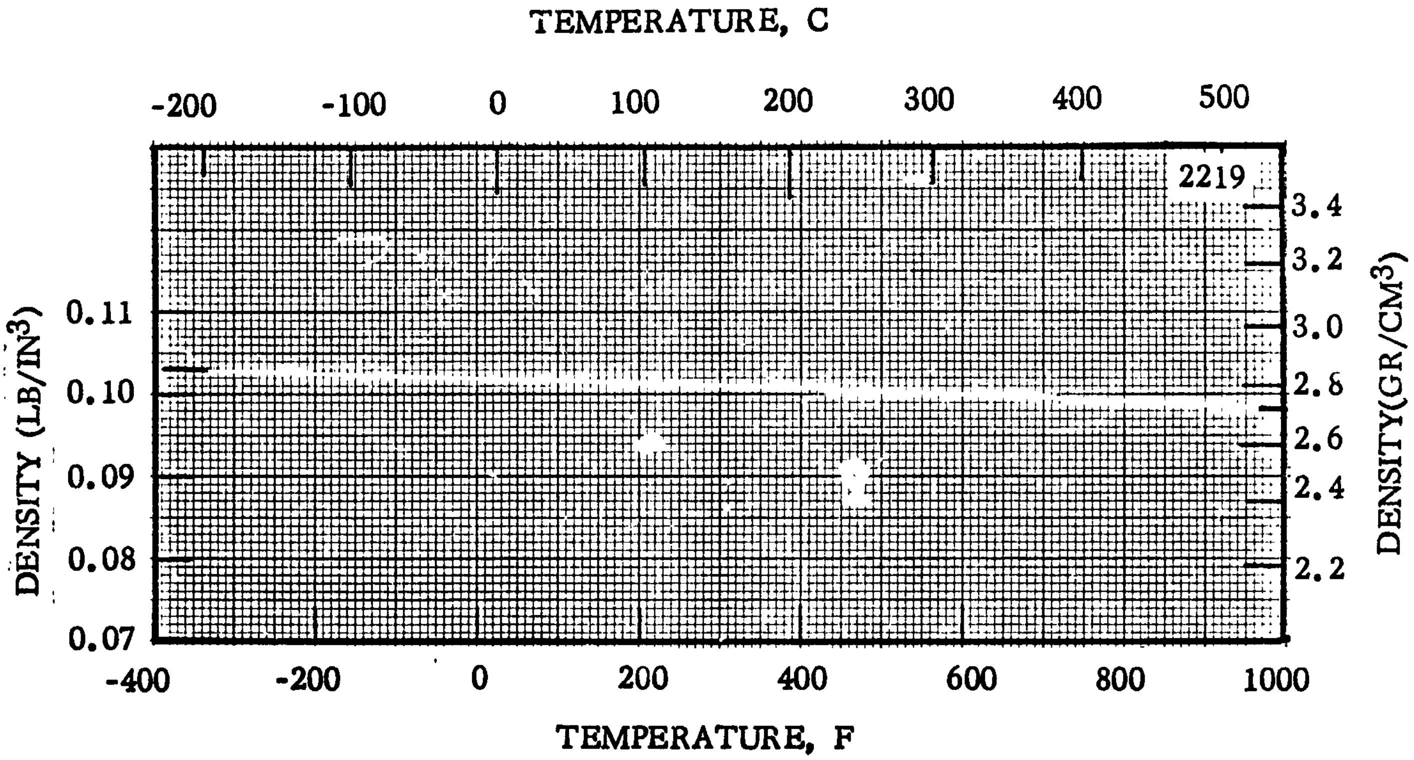

FIG. 9.1 DENSITY (Ref. 9.1)

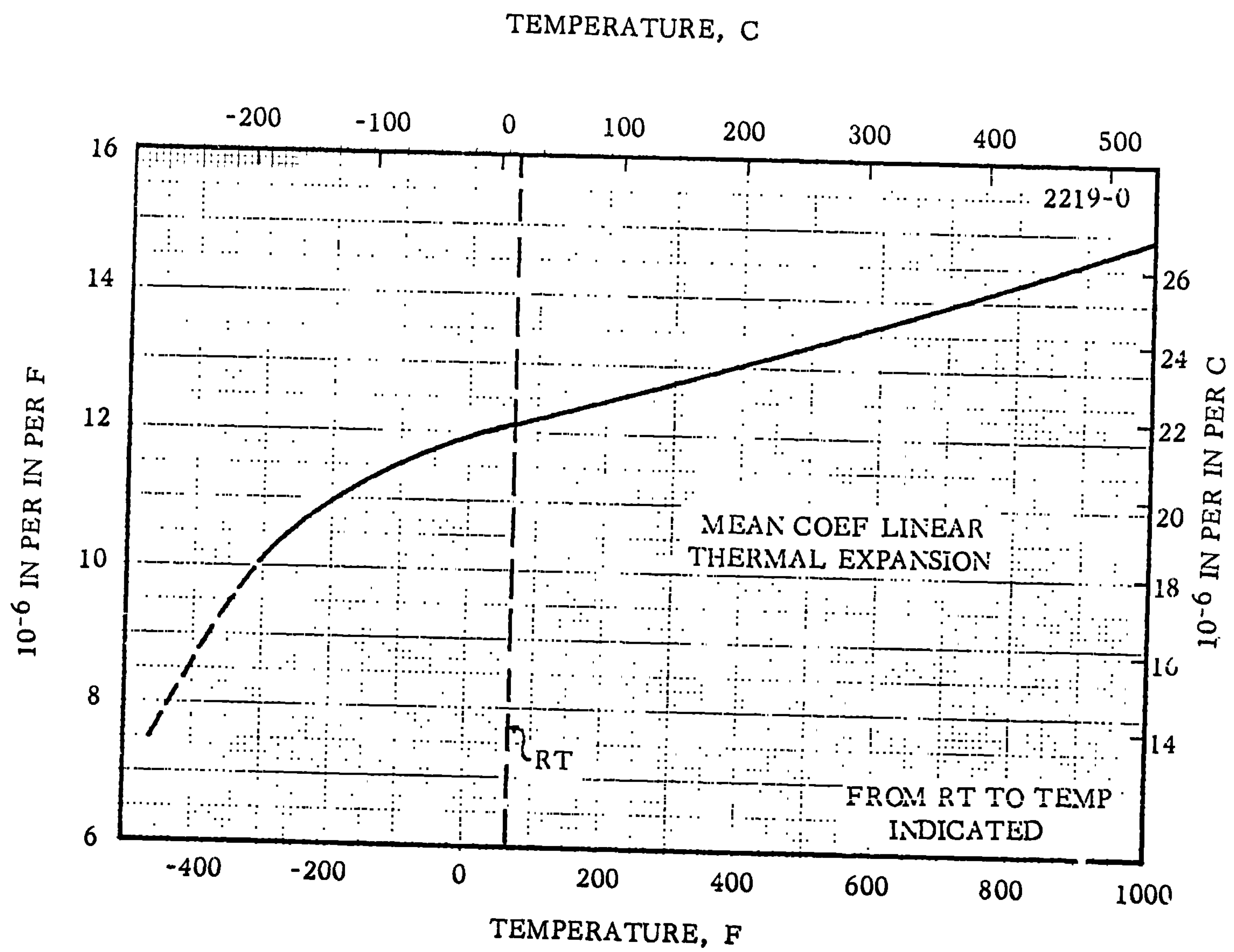

FIG. 9.22 AVERAGE COEFFICIENT OF THERMAL EXPANSION

(Ref. 9.1)

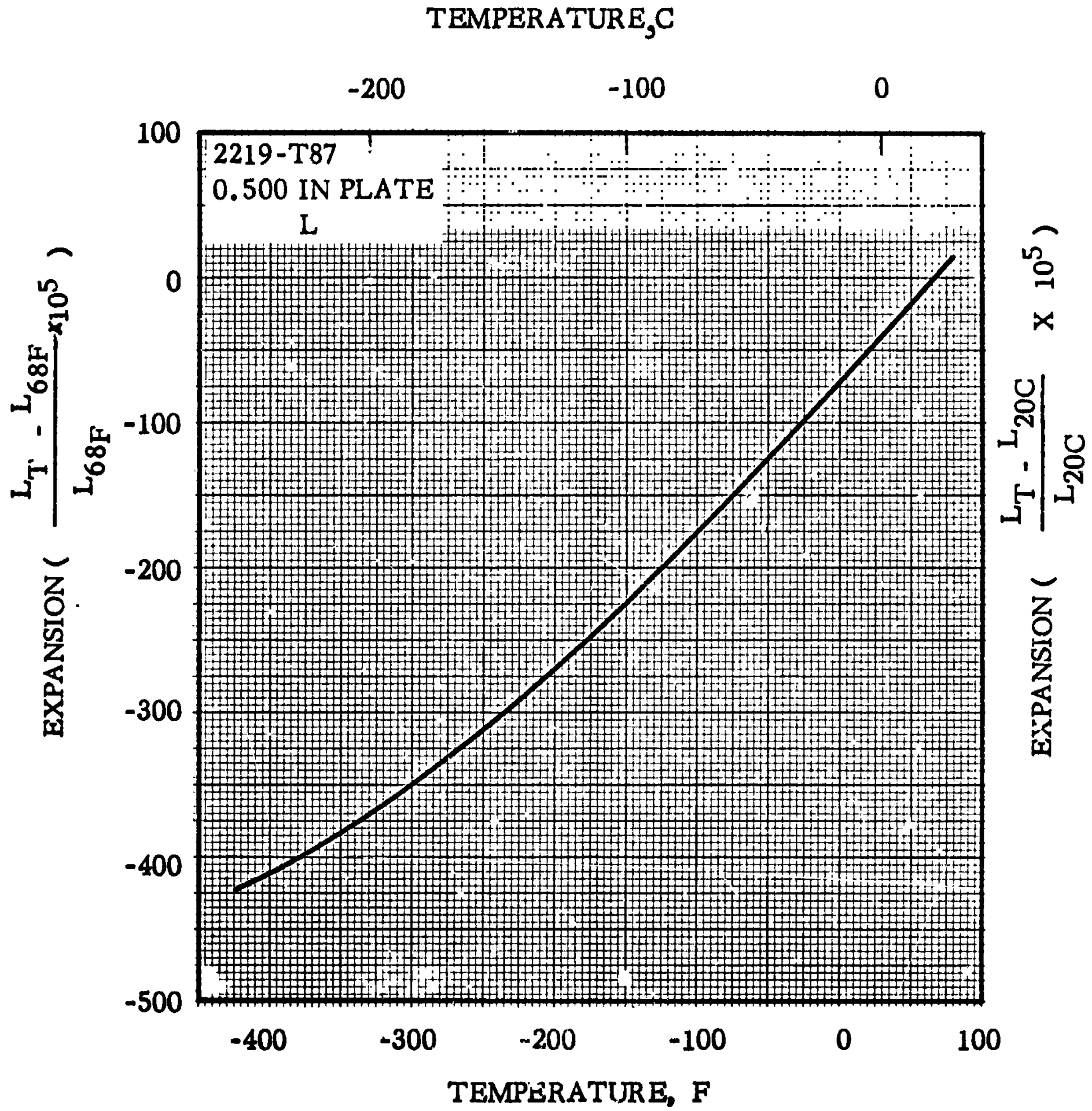

FIG. 9.221 THERMAL EXPANSION

(Ref. 9.2)

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CHAPTER 10

CORROSION RESISTANCE AND PROTECTION

10.1 General. Despite its high chemical reactivity and affinity for oxygen, aluminum exhibits excellent corrosion resistance in most common environments, because it passivates spontaneously and very rapidly under normal oxidizing conditions. The passive film is a hard strongly adhering layer of aluminum oxide, estimated as 200-100Å thick on aluminum exposed to air, (Ref. 10.1), which protects the metal from direct attack. Thus the corrosion rate of aluminum generally decreases with time, except under severe or specific exposure conditions which tend to disrupt the passive film. Outdoors, aluminum and its alloys weather to a pleasant gray color, with some initial superficial pitting which gradually ceases, (Ref. 10.2). Industrial soot, sulfur dioxide, sulfur trioxide and marine spray ter[illegible] increase atmospheric corroion, but hydrogen sulfide and carbon dioxide do not, (Ref. 10.3). Twenty-year tests at several marine, industrial and rural sites have shown that atmospheric attack on aluminum takes place principally in the first year and progresses very slowly beyond the second year, (Ref. 10.4). Even at high temperatures in dry atmospheres, aluminum is highly resistant to most common gases, except the halogens, (Ref. 10.2).

In aqueous environments, corrosion resistance of aluminum is greatest under neutral or slightly acid conditions, where the protective oxide film is most stable (pH 5.5-8.5 at room temperature, 4.5-7 at 95C), (Refs. 10.1 and 10.5). Strong alkalies and strong-non-oxidizing acids destroy the oxide and greatly accelerate corrosion. Pitting attack occurs in waters containing chloride or other halogen ions, particularly at crevices or stagnant areas where passivity breakdown is accelerated by differential aerative effects. Traces of copper, iron, and mercury ions are also effective in promoting localized attack via galvanic cells formed between aluminum and metal deposited by replacement reactions, (Ref. 10.1). Since aluminum is strongly anodic to most other common metals, galvanic coupling with them generally produces severe attack on the aluminum, especially in sea water, (Ref. 10.2).

Aluminum and its alloys are rather resistant to most molten salts. However, molten metals generally attack aluminum, particularly zinc and tin, which form alloys, (Ref. 10.2). Even a small amount of mercury is especially harmful, since it breaks down passivity and amalgamates, causing rapid perforation of aluminum piping or sheet, (Ref. 10.1). Aluminum exhibits very poor resistance to uninhibited chlorinated solvents and may even react explosively with them, (Ref. 10.6).

Aluminum purity significantly affects its corrosion resistance. High purity metal is more resistant than commercially pure aluminum, which in turn is generally more resistant than most alloys, (Ref. 10.1). Corrosion resistance of specific alloys is affected by composition, heat treatment and stress conditions, as discussed further below.

10.2 Aluminum - Copper Alloys. For maximum corrosion resistance, the composition of an alloy should be kept as homogeneous as possible since non-homogeneities frequently initiate localized attack. This principle applies to the Al-Cu alloys, of which 2219 is a typical example. Copper generally depresses the electrode potential of aluminum in the cathodic (noble) direction, but the copper concentration and distribution are significant. For optimium corrosion resistance of Al-Cu alloys, copper should be maintained in solution by rapid quenching from above the homogenizing temperature (about 900F). If the cooling rate is not rapid enough, the compound $CuAl_2$ forms preferentially along the grain boundaries. This can result in copper depletion adjacent to the intermetallic compound, making the grain boundaries anodic to the grains and susceptible to intergranular corrosion, (Refs. 10.1 and 10.7).

Tensile stress in the presence of moisture may lead to intergranular stress corrosion cracking. Susceptibility toward this type of attack is heightened by the presence of grain boundary precipitates, although authorities disagree on the details of the mechanism involved, (Refs. 10.1, 10.7 and 10.9). Attack is particularly severe in the presence of chloride ions which weaken the protective oxide films.

10.3 Resistance of Aluminum Alloy 2219. The 2219 alloy has somewhat less resistance to atmospheric corrosion than other Al-Cu alloys such as 2014 and 2024. This is less than the lower strength alloys such as 6061 alloy, (Ref. 10.10). General surface corrosion characteristics of naturally aged tempers, T31 and T37, are similar to those of 2024-T3. The corrosion resistance of the artificially aged tempers, particularly T81 and T87, appears to vary considerably from lot to lot and has led to some disagreement in the literature when the resistance of the naturally aged tempers is compared with the artificially aged tempers. One source reports that the corrosion resistance of the artificially aged tempers is superior to that of the naturally aged tempers. Data supporting this contention is presented in Table 10.1, (Ref. 10.11). Another investigation compared the difference in corrosion behavior between 2219-T37 and 2219-T87. Weight loss and type and depth of attack were obtained, with and without an Iridite coating after 1, 3, 5 and 7 days in 5 percent continuous salt spray. This data is shown in Table 10.2. A greater weight loss with the T87 temper and the beneficial effect of the Iridite coating in reducing attack of both tempers was noted. Depth of attack values was greater with the T37 temper since corrosion was intergranular as ppposed to a pitting attack with the T87 temper; although the depth of attack was less for the T87 temper, the total amount of corrosion was greater, (Ref. 10.14)

Studies now in progress indicate that the stress-corrosion resistance of 2219-T87 is equal to 7075-T73 alloy in the short transverse grain direction, (Ref. 10.15). The stress corrosion resistance of the T62, T6, T81 and T87 tempers is reported as excellent provided that no deviation is made from the recommended heat treatment methods, (Ref. 10.10). Also see Table 10.3, (Ref. 10.11). The artificially aged tempers (T81 and T87) have shown a high resistance to exfoliation in 3.5% NaCl (intermittent spray) and Miami tidewater exposure tests. Tests on forgings, in the T6 and T852 tempers, and T62 and T81 extrusions have also indicated high resistance to exfoliation and stress corrosion cracking, (Ref. 10.11).

The salt spray corrosion resistance of anodized bare 2219-F sheet was evaluated after 24 hours exposure at 600F. It was found that bare 2219-F with Type I or Type II anodized coatings (applied per MIL-A-8625A) exhibited no corrosion after a 24 hour heat soak at 600F followed by 250 hours salt spray exposure. The same alloy with 0.001 inch Hardas coating showed an average of 2.6 pits/sq. inch of exposed surface, (Ref. 10.12). Metallographic examinations were made of parent metal test panels of 2219 sheet in various tempers after 20 percent salt spray exposure for different exposure times, (Ref. 10.13). The results on this particular lot of material showed that the solution heat treat condition was the most resistant and the annealed condition the least resistant to salt spray attack. The effect of salt-spray corrosion on the tensile properties of sheet in various tempers is shown in Fig. 10.1. Studies have also indicated that 2219-T81 alloy is resistant to corrosion by dry nitrogen tetroxide and Aerozine 50 in long term applications. The alloy is compatible with liquid oxygen and liquid hydrogen.

It is reported that no adverse effect on corrosion resistance is encountered on reheating of any properly artificially aged temper of 2219. The recommended maximum reheating times are given in Table 10.4.

10.4 Protective Measures. Anodic coatings are widely used for the corrosion protection of aluminum alloys. These oxide coatings are hard and are abrasion and corrosion resistant. Cathodic protection has also proved effective in retarding both general dissolution and localized attack, although overprotection by this method should be avoided to insure against harmful accumulation of alkali at the cathode surface, (Ref. 10.1).

Paints and inorganic inhibitors have also been applied successfully in specific cases, (Ref. 10.2).

The 2219 alloy is available as Alclad sheet and plate, which is bare 2219 with a thin coating of 7072 alloy on both sides. The clad material is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 2219 core to afford electrochemical protection.

It is also important that careful heat treatment and proper fabrication techniques be used with this alloy to avoid localized tensile stresses and structural crevices so as to minimize localized attack and stress corrosion cracking. Surface treatments are discussed in more detail in Chapter 11.

10.5 Solution Potential and Electrical Conductivity Measurements. Solution potential and electrical conductivity measurements were obtained on 2219 alloy samples, with and without an Iridite coating, to determine the effect of temper on the response of the alloy. This data is shown in Table 10.5. The similarity of the potential values of the bare and Iridite coated samples indicates that the Iridite coating does not provide a complete barrier against the corrosive media. It was postulated that the primary protective properties are a result of the hexavalent chromium content serving as an anodic inhibitor. The difficulty in forming an impervious chemical conversion coating of any type on high copper alloys was noted, (Ref. 10.14).

CORROSION RESISTANCE OF HEAT TREATED SHEET

TABLE 10.1

Source		Ref. 10.11			
Alloy		2219			
Form		Sheet			
Temper	Type of Attack (a)	Loss in Tensile Strength, percent (b) (c)			
		48 Hr AI, NaCl - H_2O_2		12 Wk AI, 3.5% NaCl	
		Not Stressed	Stressed 75% of F_{ty} (d)	Not Stressed	Stressed 75% of F_{ty} (e)
O	P + I	8	-	14	-
T31	I	16	23	25	34
T37	I	18	30	32	43
T62	I	14	17	25	38
T81	P	11	14	17	24
T87	P	11	14	14	26

(a) P = pitting; I = intergranualr (MIL-H-6088B)
(b) Exposed as cross-grain machined tension specimens, 0.064 inch thick.
(c) AI = alternate immersion
(d) Stressed as simple beam with dead weight load.
(e) Stressed by bending in constant-deflection fixtures.

CORROSION OF 2219 ALLOY IN 5% CONTINUOUS SALT SPRAY

TABLE 10.2

Source	Ref. 10.14			
Condition and Temper	Exposure (days)	Weight Loss (a) mg/in^2	Type	Aver. Depth (mils)
Uncoated, T37	1	5.1	Intergranular	4.6
	3	8.7		4.4
	5	12.0		5.2
	7	16.1		4.4
Uncoated, T87	1	6.9	Pitting	1.6
	3	10.3		1.8
	5	13.6		1.4
	7	18.2		1.5
Iridite Coated, T37	1	0.19	Not Determined	-
	3	0.25		-
	5	0.48		-
	7	0.68		-
Iridite Coated, T87	1	0.26		-
	3	0.42		-
	5	0.58		-
	7	0.98		-

(a) Corrosion product was removed by immersion in concentrated nitric acid.

TABLE 10.3

Source	Ref. 10.11			
Alloy	2219			
Form	0.064 inch Sheet			
Temper	Stress-Corrosion Cracking (a)			
	12 Week AI (c) 2.5% NaCl		1 Year Sea Coast Atmosphere	
	F/N (b)	Days to Fail	F/N	Days to Fail
O	-	-	-	-
T31	2/2	7,12	2/2	82,82
T37	2/2	5,7	2/2	82,82
T62	0/2	OK 84	0/2	OK 365
T81	0/2	OK 84	0/2	OK 365
T87	0/2	OK 84	0/2	OK 365

(a) Plastically deformed tension specimen blanks, stressed in constant bend deflection fixtures.
(b) F/N denotes ratio of number of failures to number exposed.
(c) AI = Alternate immersion

RECOMMENDED MAXIMUM REHEATING TIMES

TABLE 10.4

Source	Ref. 10.10
Alloy	2219
Temper	All
Temp, F	Time, Hr (a)
500	To Temperature
450	1/2
425	1
400	5
375	50
350	100
325	1000
300	10,000 plus

(a) These times and temperatures are based on a 5% maximum decrease in mechanical properties

POTENTIAL AND CONDUCTIVITY
MEASUREMENTS ON 2219 ALLOY

TABLE 10.5

Source	Ref. 10.14		
Condition	Temper	Potential (a)	Conductivity
Uncoated	F	802 mv	42.6%IACS
	T37	643 mv	28.7%IACS
	T87	797 mv	32.2%IACS
Iridite Coated	F	801 mv	-
	T37	632 mv	-
	T87	796 mv	-

(a) Against a 0.1 N calomel electrode in 53 g/l NaCl, 9 ml/l 30% H_2O_2.

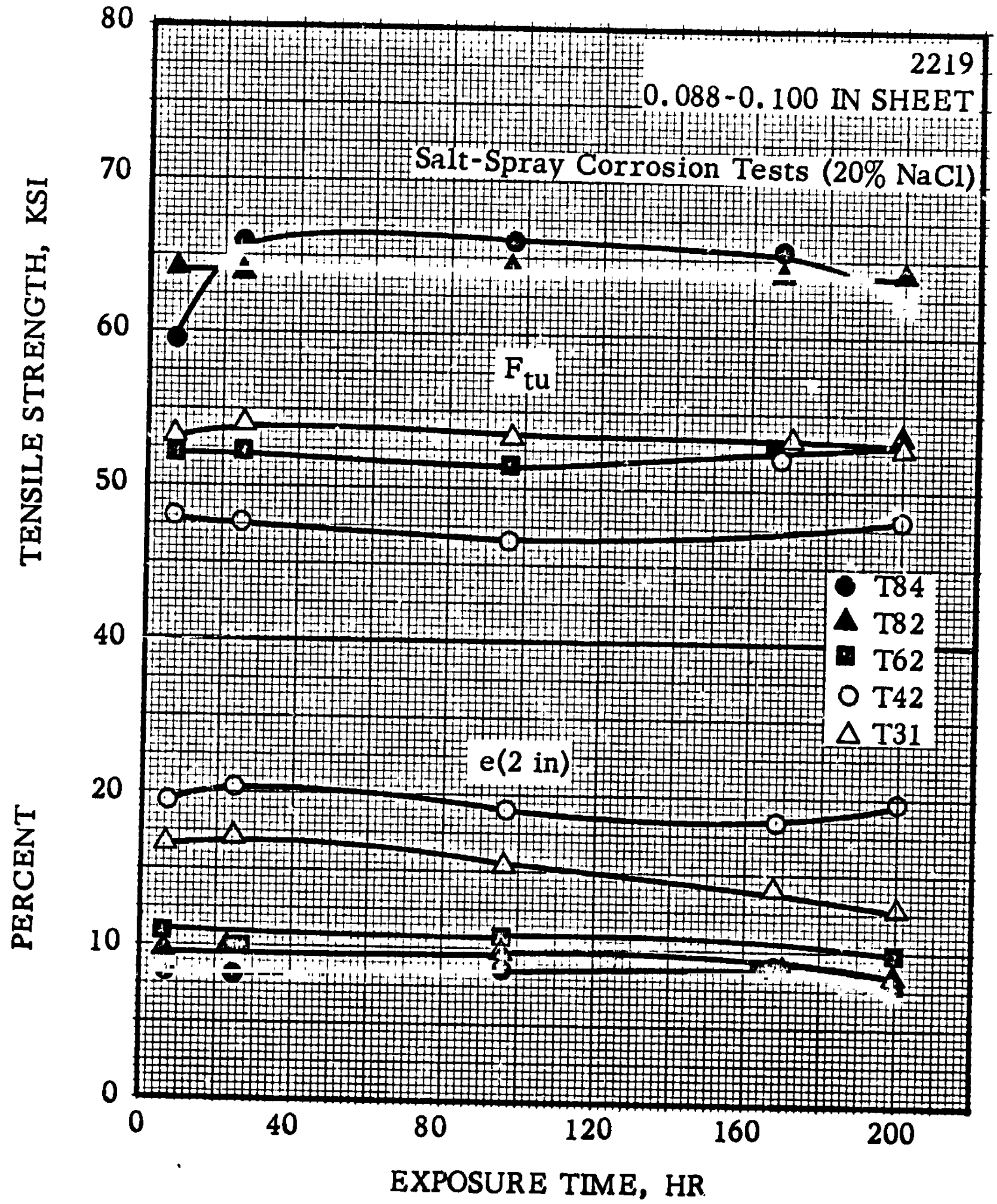

FIG. 10.1 EFFECT OF SALT-SPRAY CORROSION ON TENSILE PROPERTIES OF SHEET IN VARIOUS TEMPERS

(Ref. 10.13)

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CHAPTER 11

SURFACE TREATMENTS

11.1 General. A wide variety of surface treatments can be applied to the 2219 alloy (and other aluminum alloys) to protect and improve the appearance of the surface. These include mechanical, chemical and electrochemical finishes and organic, porcelain and paint coatings. Alclad forms of aluminum alloys have a very high inherent resistance to corrosion and may be used without benefit of protective coatings for some applications, (Ref. 11.1).

11.2 Alclad Products. The 2219 alloy is available as Alclad sheet and plate which consists of bare 2219 core material clad with a thin coating of 7072 alloy on both sides. The clad material is metallurgically bonded to the core material. It is chosen to provide a surface having a high resistance to corrosion and sufficiently anodic to the 2219 core to afford electrochemical protection to it in corrosive environments. Consequently, any spot of attack can penetrate only as deep as the core alloy where further progress is stopped by cathodic protection. Corrosion is thus confined to the clad material only. The life of the cladding is a function of its thickness and severity of the environment. Alclad products, therefore, limit corrosion to a relatively thin clad surface layer, (Refs. 11.2 and 11.8).

11.3 Mechanical Finishes. Mechanical finishes are used to alter the texture of the alloy surface to provide a more decorative appearance or as a treatment prior to other finishing such as painting. Grinding, polishing and buffing result in smoother reflective surfaces. Abrasive blasting (sand or grit) gives a rough matte finish which is often used as a base for organic coatings. Scratch finishing, satin finishing, Butler finishing and skin finishes are scratched-line finishes which remove minor surface defects and provide a decorative effect. Mechanical methods remove the original heavy oxide film. For this reason mechanically finished parts are often given a protective coating by anodizing or lacquering. The possibility of generating an explosive mixture of fine powder and air during mechanical finish operations should be recognized, (Ref. 11.3).

11.4 Anodizing. Anodic coatings are hard, abrasion and corrosion resistant oxide coatings. The alloys can be anodically coated in a number of electrolytes, but most commercial anodizing is done by either the sulfuric acid or chromic acid process. The thickness of the coating is dependent upon the anodizing time. Coatings produced by the sulfuric acid process vary in thickness from 0.0001 to 0.001 inch. Coatings produced in chromic acid vary from 0.00001 to 0.00009 inch. Anodic coatings provide good protection against corrosion and are excellent bases for paint coatings, (Ref. 11.1). However, the chromic acid process does not provide as corrosion resistant a coating as does the sulfuric acid process, (Ref. 11.11).

11.41 In recent years a number of new methods have been developed for producing heavier anodic coatings of from 0.001 to 0.010 inch. These methods require electrolytes which enable the oxide growth process to continue until the desired coating thickness is obtained.
Another recent development in coatings is that of hard anodizing, designated as "hardcoatings". Processes most suitable for a wide range of applications are Alumilite 226 (oxide coatings, 0.002 inch thick) and Martin Hardcoat (coating thicknesses up to 0.004 inch). A flash hardcoat of a very thin film can also be applied by these methods by shortening the normal time cycle. The operating conditions for the two baths employed for these processes are given in Table 11.1. The Martin process should be specified where maximum hardness and corrosion resistance are required along with thickness buildups to 0.004 inch. Alumilite 226 is selected where hardness and corrosion resistance are required and 0.002 inch is the acceptable maximum buildup. Further details of these processes are presented in Ref. 11.9.

11.5 Chemical Finishes. Chemical finishes are of three main types. Finishes used for decorative effects include caustic etching, acid etching and chemical polishing. Etched surfaces have a matte appearance while chemically polished surfaces are highly reflective and require protection by anodizing or lacquering. Conversion coatings can be oxide, phosphate or chromate types and are used primarily as base coatings prior to application of organic coatings. Miscellaneous special-purpose finishes include those produced by the Alrok process, Modified Bauer-Vogel process and processes for staining aluminum alloys.

11.6 Electropolishing. This process produces a highly reflective surface and is often used for surface preparation prior to microscopic examination of metallurgical structure.

11.7 Electroplating of aluminum alloys has gained increased commercial use in recent years. A commonly used finish consists of successive deposits of copper, nickel and chromium. Other metals may be applied over the copper. A satisfactory base surface for electroplating is provided by immersing the aluminum part in a solution of sodium zincate of controlled composition. Brass, iron, silver or chromium can be applied directly over this zinc immersion coating, (Ref. 11.4).

11.8 Painting. When severe conditions of exposure are to be encountered, it is frequently desirable to protect aluminum alloy surfaces with paint. Prior to painting, the surface should be properly prepared before priming. Dirt may be removed by brushing and grease or oil may be removed by means of solvent or degreasing techniques. The parts are then immersed in (or swabbed with) a solution of phosphoric acid and organic grease solvents diluted with water. A number of proprietary solutions of this type are available commercially. Solution temperature should be between 50 and 90F and contact with the metal part should not be for less than 5 minutes.

The part is then rinsed with water and dried thoroughly. Where chemical treatment is impractical, mild sandblasting methods may be employed.
A chemical conversion coating per MIL-C-5541 or an anodize coating is necessary prior to priming with zinc chromate primer per MIL-P-8585. For severe conditions of exposure, both primer and joint compound should be used at joints.
All surfaces except contacting surfaces may be given a second coat of paint consisting of two pounds of aluminum paste pigment (ASTM Spec. D 962, Type II, Class B.) per gallon of varnish which meets Federal Spec. TT-V-86b, Type II or equivalent. The final assembled structure may be finished with one coat of aluminum paint. One or more coats of alkyd base enamel (pigmented to desired color) may be substituted for aluminum paint, (Ref. 11.5).

11.81 To minimize stress-corrosion cracking when the alloy is subjected to sustained surface stresses and corrosive environments, certain surface treatments and protective coatings are effective. The most effective protection is obtained by applying a topcoat of epoxy-polyamide paint to shot-peened or metallized surfaces of the alloy. Satisfactory temporary protection is obtained by an electroplated galvanic coating (3 to 4 mils thick), or a topcoat of paint containing epoxy-polyamide or polyurethane resins. The former is preferred and can be used on unprimed surfaces. Care is necessary to prevent breaking or scratching the paint film. Shot peening alone will provide good surface protection (if all surfaces are treated) when corrosive environment is not severe. Anodic films and zinc-rich paints are the least effective coatings for preventing stress-corrosion cracking, (Ref. 11.6).

11.9 Porcelain enameling. The principal difference between porcelain enameling of aluminum alloys and other metals is the use of porcelain frits which melt at lower temperatures. High lead frits are commonly used and they can be formulated in a wide variety of colors and surface finishes. The enamel slip is sprayed onto chemically cleaned and treated surfaces and then fired at temperatures of 950 to 1050F for a period of 4 to 8 minutes, (Ref. 11.7).

TABLE 11.1

Source	Ref. 11.9	
Alloy	Aluminum Wrought Alloys	
Data	Baths for Hard Anodized Coatings	
	Process	
	Martin (a)	Alumilite (b)
Composition	15% H_2SO_4	12% H_2SO_4 1% $H_2C_2O_4$
Electrolyte Temp, F	[illegible] to 32	48 to 52
Current Density	25 asf	36 asf

(a) Developed by the Martin Co.

(b) Developed by the Aluminum Co. of America

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CHAPTER 12

JOINING TECHNIQUES

12.1 General. The 2219 aluminum alloy can be joined satisfactorily by fusion and resistance welding techniques and by riveting. Brazing, gas welding and soldering are not recommended, since satisfactory materials and methods have not been developed for this alloy. Specifications for welding of aluminum alloys are presented in Table 12.1.

12.2 Welding. Reliable, sound, high quality welds have been made in aluminum alloys for many years. Although aluminum is one of the most readily weldable of all metals, it has individual characteristics which must be well understood for successful welding of the metal or its alloys. Four important factors that must be considered are the low melting point, the presence of an oxide film, low strength at elevated temperatures, and the fact that aluminum exhibits no characteristic color changes even at temperatures up to the melting point. The welding of aluminum alloys requires care to prevent excessive melting of the material. The oxide film must be removed and prevented from reforming by some inhibiting technique before a good bond can be obtained. Parts should be well supported during welding to prevent distortion, (Ref. 12.2).

12.21 Fusion Welding. The 2219 alloy exhibits the best weldability of the 2xxx series of aluminum alloys. In particular its susceptibility to weld cracking is less than that of 2014. This is due to the absence of magnesium and silicon as alloying elements. These elements form ternary and quaternary eutectics of low melting points and thus increase the melting range of the alloy. Both the wide range of melting temperature and the presence of phases with a low melting temperature are known to cause weld cracking as discussed in Ref. 12.3 and 12.4.
The filler rod used to fusion weld 2219 has the same composition as 2219 plus titanium and is designated as 2319.
Frequently the alloy, when fusion welded, is used in the "as welded" condition. To compensate for the low strength in this condition, designers usually arrange to have the welded joint thicker than the parent metal. For highest strength, ductility, toughness, and corrosion resistance a full heat treatment after welding is recommended, (Ref. 12.5).

12.211 Fusion Welding Methods. One of the most important advances in aluminum welding has been the development of inert-gas-shielded methods that do not require a flux. The "tungsten-inert-gas" (TIG) method and the "metal-arc consumable electrode" (MIG) method have both contributed significantly to the advancement of the "state of the art" of aluminum welding. TIG and MIG techniques each have inherent advantages and disadvantages and are discussed in greater detail in Ref. 12.6. The main problem with these fusion welding processes is the occurrence of porosity in the weld which adversely affects the mechanical properties. The factors that can cause porosity seem to be not yet fully known. Studies, however, have indicated that gases (notably hydrogen) trapped in weld zones are the principal cause of porosity in 2219 alloy weldments, (Ref. 12.7). Hydrogen is soluble in liquid aluminum but is nearly insoluble in the solid state. Thus any hydrogen present at solidification is rejected in the form of porosity as the alloy solidifies. At temperatures above 920F, aluminum reacts with water to produce "nascent" hydrogen plus oxygen. The hydrogen dissolves in molten aluminum and the oxygen combines to form aluminum oxide, (Ref. 12.8). The solubility of hydrogen in aluminum is shown in Fig. 12.1. Control of humidity and cleaning of filler wire to remove the oxide surface layer have helped to reduce porosity in 2219 alloy welds. However, hydrogen in the interior of the base metal or filler wire is more difficult to eliminate, (Ref. 12.4). It has also been found that porosity is more prevelant in multipass welds than in single pass welds. Apparently successive beads pick up gas contamination from preceeding beads to cause a cumulative affect, (Ref. 12.9). TIG welding results in slightly lower porosity levels in the weld than MIG welding. The speed of welding has a sizeable influence on the porosity level for both methods as indicated in Fig. 12.2.

Another strength reducing factor is mismatch of the pieces to be joined, as is shown in Fig. 12.3.

The mechanical properties of welded 2219 also depend upon the following factors: Sheet or plate thickness, heat-treatment condition before and after welding, welding method, (i.e. manual or automatic), type of back-up bar used and the testing temperature.

The effect of original temper and post-weld heat treatment on the strength and elongation of TIG and MIG welded sheets and plates of various thicknesses is shown in Table 12.2. The results indicate that the best properties are obtained by welding parts in the solution treated or "as fabricated" condition, which are subsequently solution treated and reaged to the T6 Condition. Material in the T81, T87, T31, or T37 Condition, which is aged after welding or left in the as-welded condition, shows that some increase in strength can be obtained by post-weld aging.

Typical tensile properties of 0.75 inch 2219-T87 welded and unwelded plate are given in Table 12.3.

The effect of cryogenic temperatures on the tensile strength and elongation of 2219 welded sheet in the T81 or T87 Condition is shown in Figs. 12.4 and 12.5. Similar data for the T62 Condition is given in Fig. 12.6.

Both the base metal and the weld strength increase with decreasing elongation. The joint efficiency is about 70 percent and the elongation only about 2 percent. Both values are nearly constant at all testing temperatures. Failure occurred in the weld heat-affected zone before any significant amount of elongation occurred in the parent metal, (Ref. 12.13). The "A" and "B" values shown in Fig. 12.4 are lower bounds on the weld strengths, as defined in MIL-HDBK-5. It should be noted that they are relatively low at -423F which indicates a greater scatter of the tensile data than at higher temperatures.

The effect of high temperatures, welding procedure, elimination of the weld bead, and post weld heat treatment on the tensile strength and the "A" and "B" values, (MIL-HDBK-5) is shown in Fig. 12.7.
The tensile strength of 2219 in all conditions is lowered by increasing the testing temperatures. The "as welded" tensile strength at room temperature is decreased more with respect to the parent material than at 400F and higher temperatures. Furthermore the scatter of the experimental results is higher at room temperature than at elevated temperatures, particularly for the manually welded panels.
The panels with reheat treatment after welding closely approximates the strength and ductility of the parent material. Machine welded panels have slightly higher strength and ductility than manually welded panels. The tension and elongation values of the panels which were reaged after welding are quite similar to the values of the panels in the "as welded" condition. There is no significant difference between machine and manually welded properties.
The room temperature strength of the "as welded" and reaged panels is markedly reduced when the weld beads are ground flush. At elevated temperatures, however, the effect of weld bead reinforcements is generally negligible. Except where weld defects are present, the grinding of weld bead reinforcement do not materially affect the strength of the reheat treated panels.
The strength of a weld in general will be higher when less heat is needed to fusion weld. Thus the weld metal zone and heat affected zone should be as small as possible. This can be achieved by using suitable welding speeds and back-up bars. The effect of these two variables on the limit of the temperature zones above 500F is shown in Figs. 12.8 and 12.9. The temperature gradient caused by the welding process will result in a gradual decrease in strength from the base metal to the weld. This is shown in Fig. 12.10 where the Rockwell "B" hardness across the weld is plotted as a function of welding speed and back-up material. The change in mechanical properties across the weld can also be shown in terms of stress-strain data as indicated in Fig. 12.11. This figure, in which only the initial part of the stress-strain curves is plotted, shows that the strength of the material increases with the distance from the weld. The effect of weld procedures and post-weld heat treatment on bulge properties of 2219 sheet is illustrated in Table 12.4 and in Fig. 12.12. These results indicate that 2219 is the most easily welded and the least sensitive to variations in weld procedures of all of the high strength, heat treatable aluminum alloys. When reheat treated after welding, the alloy consistently develops bulge strengths equal to the tensile strength of the base metal. The T81 and T87 tempers are recommended for assemblies to be left in the "as welded" condition. For assemblies to be post-weld heat treated, the F temper (as-fabricated) is recommended because of its lower cost. Other tempers, however, are also satisfactory. The recommended post-weld heat treatment practice is T62 for maximum bulge strength.
The fatigue properties of butt welded 2219-T87 aluminum are excellent, particularly at -423F where the endurance limit is substantially higher than at room temperature as shown in Fig. 12.13. The low cycle fatigue data of Fig. 12.14 indicates that specimens can be cycled up to 2000 cycles at 75, 85 or 95 percent of the static joint strength without failure. The low temperature strengths are

higher than those at room temperature. S-N curves for T87 sheet are given in Fig. 12.15.
The range of angles to which 2219 in the T6E46 Condition can be bent over a ram of radius 5T is given in Table 12.5.

12.212 Gas Metal Arc Spot Welding (or inert-gas spot welding) is used to make high strength localized welds with light equipment and from one side only. It is a quick and reliable method to join sheet, extrusions, and tubing. The localized welding is accomplished by using very high automatically controlled welding currents for a short period of time with the addition of a small quantity of filler metal, (Ref. 12.26). Filler metals recommended are 2319 and 4043. The tensile shear breaking loads of 0.064 inch thick 2219-T6 aluminum overlap joints, welded with 2319 filler of an experimental investigation, are 696 pounds for a non-penetrating and 1300 pounds for a penetrating weld spot, (Ref. 12.34).

12.22 Electrical Resistance Welding. Resistance welding (spot welding and seam welding) is a most useful, practical and economic method of joining aluminum alloys. The welding process is almost entirely automatic and standard welding machines are capable of handling a wide variety of operations. Resistance welding heats only a small area of metal. Thus there is only a minimum of metallurgical disturbance for a minimum length of time which is important in the welding of aluminum alloys.
Mechanical or chemical cleaning of the contact surfaces is necessary to obtain good spot welds in aluminum as no fluxes are used during spotwelding. In aircraft construction, it is recommended that the contact resistance of the elements to be joined be continually checked to ensure surface cleanliness. Surface contact resistance should not exceed 50 microhms for best results. Details on surface cleaning are given in Ref. 12.25, p. 48.

12.221 Mechanical Properties of Spot Welds. Very little information on spot welding of 2219 is available. The effect of cryogenic temperatures on the cross-tension and tensile shear strength of single spot welds of 2219-T81 sheet is shown in Fig. 12.16. The data indicate that spotwelded 2219-T81 alloy has sufficient strength at cryogenic and room temperatures. The tensile shear curves, however, show a tremendous scatter, as can be seen from the low "A" and "B" strength values. Furthermore, between -320 and -423F the cross-tension strength drops rather sharply, indicating some loss in toughness in this temperature range. The suggested minimum joint overlap and spacing of spot welds is presented in Table 12.6 and the minimum allowable edge distance for spot-welded joints is shown in Table 12.7. Spot weld maximum shear strength standards are given in Table 12.8.

12.3 Brazing. Brazing of the 2219 alloy is not recommended. The melting point of 2219 is lower than that of the commercially available brazing alloys, (Ref. 12.30).

12.4 Riveting. Riveting is a commonly used method for joining aluminum, particularly the heat treatable alloys. It is reliable because riveting is a method that is well understood and highly developed. Also, modern riveting methods are largely independent of the operators skill and thus uniformity of riveted joints can be readily attained, (Ref. 12.2). Specifications for aluminum riveting are presented in Table 12.9.

12.41 Aluminum alloy rivets are preferred for the fabrication of aluminum alloy structures, although cold-driven annealed steel rivets have been used successfully for some applications. To determine the strength of riveted joints, it is necessary to know the strength of the individual rivet. The average shear strength for driven rivets of various aluminum alloys is given in Table 12.10. In most cases, such joints fracture by shearing, by bearing or tearing failure of the sheet or plate. It is customary to use a slightly larger factor of safety for the shear strength of rivets than is employed for other parts of an assembly. The design of joints where rivets are subjected to tensile loads should be avoided. Bolted connections may be used where high tensile stresses preclude the use of riveting. Information in greater detail on the riveting of aluminum alloys is given in Refs. 12.31 and 12.32. Design data on mechanical joints using rivets or bolts may be found in MIL-HDBK-5, (Ref. 12.33).

TABLE 12.1

Source	Ref. 12.1, 12.21, 12.22, 12.23			
Item	Welding specifications			
Product or process	Federal	Military	ASTM	AMS
Weldments (aluminum and aluminum alloys)	-	MIL-W-22248	-	-
Welding of aluminum alloys	-	MIL-W-8604	-	-
Welding (aluminum alloy armor)	-	MIL-W-45206	-	-
TIG welding, aluminum alloy for structures	-	MIL-W-45205	-	-
Welding; resistance, aluminum alloys	-	MIL-W-45210A	-	-
Welding; spot, seam or stitch(Al, steel, Mg and Ti)	-	MIL-W-6858B	-	-
Welding rods (aluminum)	QQ-R-566-2	-	B285-61T	4190A 4191A
Welding electrodes (flux coated)	-	MIL-E-15597C	B184-43T	-
Welding electrode wire	-	MIL-E-16053J	B285-61T	-
Flash welds (rings, flanges)	-	-	-	7488A

TABLE 12.2

Source	Ref. 12.5				
Alloy	2219 Sheet and Plate				
Property	Effect of original temper and post-weld heat treatment on elongation of welded 2219 Al(2319 filler)				
Original temper and heat treatment	Thickness (inch)	No. of samples	F_{tu} (ksi)	F_{ty} (ksi)	e - % (a)
T81 or T87 AW	0.064	22	47	32	3
T81 or T87 AW	0.125	23	43	30	3
T81 or T87 AW	0.250	10	40	-	1
T81 or T87 AW	0.500	4	40	-	1
T31 age - T87	0.064	22	49	43	2
or T37 age - T87	0.125	23	44	38	2
T37 age T87	0.250	10	46	-	0.6
T37 age T87	0.500	4	41	-	1
0 or F age HTAT62	0.064	9	59	40	8
0 or F age HTAT62	0.125	12	57	39	8
0 or F age HTAT62	0.250	5	60	43	4
0 or F age HTAT62	0.500	2	52	-	3

(a) Gauge length 2 in for 0.064 and 0.125 inch sheet
Gauge length 8 in for thickness > 0.125 inch sheet

TABLE 12.3

Source	Ref. 12.12				
Alloy	2219-T87 0.75 inch plate				
Property	Typical tensile properties of welded and unwelded plate				
Weld Method	Condition of weld	Test temp-F	F_{tu} (ksi)	F_{ty} (ksi)	e - % (2 in)
-	Base metal	72	68.2	56.3	13
TIG	As welded	72	43.1	26.7	4.3
MIG	As welded	72	41.5	26.1	3.6
-	Base metal	-320	84.6	68.2	16.3
TIG	As welded	-320	50.8	30.8	4.9
MIG	As welded	-320	5[illegible].7	31.9	4.0

PROPERTIES OF FUSION WELDS IN SHEET

TABLE 12.4

Source	Ref 12.20							
Alloy	2219							
Form	Welded Sheet (f)							
Properties	Tensile and Bulge Tests							
Thickness, in	0.064						0.125	
Weld Method	SA (c)			DCSP (d)				
Temper	T87	T37 (a)	T31 (b)	T87	T37 (a)	T31 (b)	T87	T37 (a)
F_{tu}, -ksi	46	53	52	47	53	53	45	50
F_{ty}, -ksi	37	49	48	34	47	45	29	41
e(2in) -percent	1.9	1.3	1.5	1.5	1.6	1.2	2.2	1.8
S (e)	0.5	1.6	2.4	1.2	1.4	0.4	1.0	1.0
Bulge Tests								
Tensile, ksi	47	54	55	50	44	42	48	47
Height, in	0.37	0.47	0.54	0.42	0.48	0.44	0.45	0.43
S (e)	2.1	1.8	1.4	1.5	0.4	1.4	1.6	1.1

(a) Aged to T87

(b) Aged to T81

(c) SA - MIG welds, "short arc" with 0.030 electrode, 1 He/1 Ar gas mixture.

(d) DCSP - TIG welds, straight polarity, He gas mixture, 1/16 inch cold wire feed.

(e) S = standard deviation = $\sqrt{\frac{(x - \bar{x})^2}{n - 1}}$

(f) All welds made in flat position by completely automatic procedures.

TABLE 12.5

Source	Ref. 12.3				
Alloy	2219-T6E46 = 0.25 inch thick (T) plate				
Property	Bend angle of TIG welded (2319) filler 2219-0 plate with T6E46 post weld heat treatment bend over a ram with a bend radius of5T				
Total No. of Specimens	Type of weld	Repair filler wire	Bend angle, degrees		
			max	min	avg
18	Plate to Plate	None	60	40	53
18		2319	60	16	26
32	Plate to Forging	None	60	19	34
16		2319	47	15	23

TABLE 12.6

Source	Ref. 12.25	
Alloy	Aluminum Alloys	
Data	Suggested minimum joint overlap and spacing of spot welds	
Thinnest sheet in joint, inch	Minimum joint overlap, inch	Minimum weld spacing, in
0.016	5/16	3/8
0.020	3/8	3/8
0.025	3/8	3/8
0.032	1/2	1/2
0.040	9/16	1/2
0.051	5/8	5/8
0.064	3/4	5/8
0.072	13/16	3/4
0.081	7/8	3/4
0.091	15/16	7/8
0.102	1	1
0.125	1 1/8	1 1/4

TABLE 12.7

Source	Ref. 12.33
Alloy	Aluminum Alloys
Property	Minimum allowable edge distances for spot-welded joints (a)(b)(c)
Nominal thickness of the thinner sheet, in	**Edge distance, E, in**
0.016	3/16
0.020	3/16
0.025	7/32
0.032	1/4
0.036	1/4
0.040	9/32
0.045	5/16
0.050	5/16
0.063	3/8
0.071	3/8
0.080	13/32
0.090	7/16
0.100	7/16
0.125	9/16
0.160	5/8

(a) Intermediate gages will conform to the requirement for the next thinner gage shown.

(b) Edge distances less than those specified above may be used provided there is no expulsion of weld metal or bulging of the edge of the sheet or damage to bend radii by electrode.

(c) Values may be reduced for non-structural applications or applications not depended on to develop full weld strength.

SPOT WELD MAXIMUM DESIGN SHEAR STRENGTH IN PANEL
FOR BARE AND CLAD ALUMINUM ALLOYS
(WELD SPEC. MIL-W-6858)

TABLE 12.8

Source	(Ref. 12.33)			
Alloy	Aluminum Alloys, (bare and clad)			
Property	Spot weld maximum design shear strength in panels (a)(b)(c)			
Nominal thickness of thinner sheet, inch	Material ultimate tensile strength			
	≥ 56 (ksi)	20 to 56 (ksi)	19.5 to 28 (ksi)	< 19.5 (ksi)
0.010	48	40	-	-
0.012	60	52	24	16
0.016	88	80	56	40
0.020	112	108	80	64
0.025	148	140	116	88
0.032	208	188	168	132
0.040	276	248	240	180
0.050	372	344	320	236
0.063	536	488	456	316
0.071	660	576	516	360
0.080	820	684	612	420
0.090	1004	800	696	476
0.100	1192	936	752	540
0.112	1424	1072	800	588
0.125	1696	1300	840	628
0.160	2496	1952	-	-
0.190	3228	2592	-	-
0.250	5880	5120	-	-

(a) The reduction in strength of spotwelds due to cumulative effects of time-temperature-stress factors is not greater than the reduction in strength of the parent metal.
(b) Strength based on 80 percent of minimum values specified in MIL-W-6858.
(c) The allowable tensile strength of spotwelds is 25 percent of the shear strength.

TABLE 12.9

Source	Ref. 12.1		
Item	Specifications for Rivets (Aluminum)		
Products	Specifications		
	Federal	Military	AMS
Rivets	FF-R-556a	MIL-R-1150A-1	7220C
	-	MIL-R-5674B-1	7222C
	-	MIL-R-12221B	7223
Rivets, blind	-	MIL-R-7885A-1	-
	-	MIL-R-8814-1	-
	-	MIL-R-27384	-
Rivet, wire	QQ-A-430-1	-	-

TABLE 12.10

Source	Ref. 12.31		
Data	F_{su} (Average) for Driven Rivets (c)		
Alloy and Temper before Driving (a)	Driving Procedure	Alloy and Temper after Driving	F_{su} (Aver) (ksi)
1100-H14	Cold, as received	1100-F	11
2017-T4	Cold, as received	2017-T3	39
2017-T4	Cold, immediately after quenching	2017-T31	34(b)
2024-T4	Cold, immediately after quenching	2024-T31	42(b)
2117-T4	Cold, as received	2117-T3	33
5056-H32	Cold, as received	5056-H321	30
6053-T61	Cold, as received	6053-T61	23
6061-T4	Cold, immediately after quenching	6061-T31	24(b)
6061-T4	Hot, 990 to 1050F	6061-T43	24(b)
6061-T6	Cold, as received	6061-T6	30
7277-T4	Hot, 850 to 975F	7277-T41	38

(a) These designations should be used when ordering rivets.

(b) Immediately after driving, the shear strengths of these rivets are about 75% of the values shown. On standing at ambient temperatures, they age harden to develop full shear strength. This action takes about 4 days for 2017-T31 and 2024-T31 rivets. Values shown for 6061-T31 and 6061-T43 rivets are attained in about 2 weeks. Values of 26 ksi are attained by 6061-T31 rivets about 4 months after driving. Values shown for 7277-T41 rivets are attained in about one week.

(c) These values are for rivets driven with core point heads. Rivets driven with heads requiring more pressure may be expected to develop slightly higher strengths.

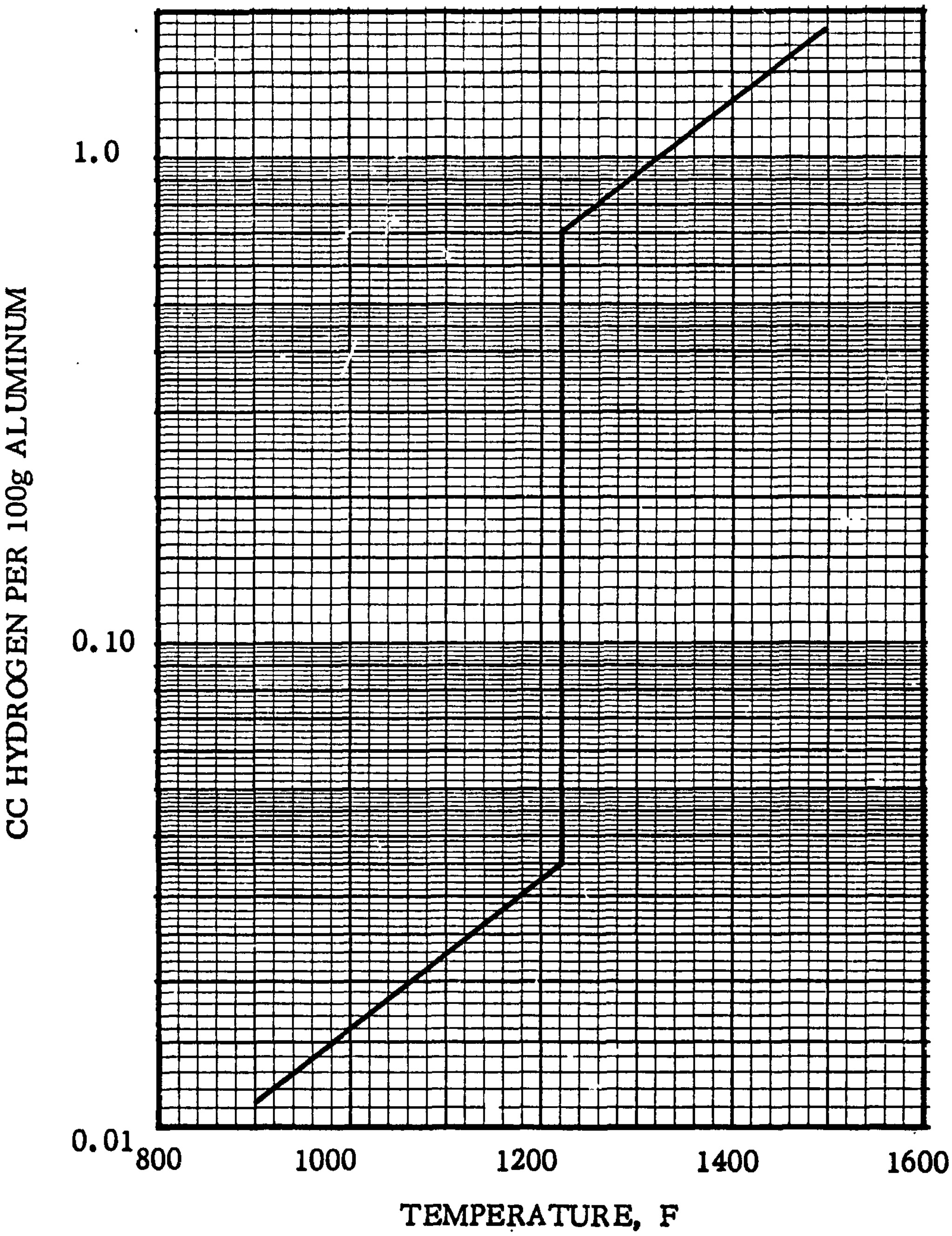

FIG. 12.1 SOLUBILITY OF HYDROGEN IN ALUMINUM (Ref. 12.9)

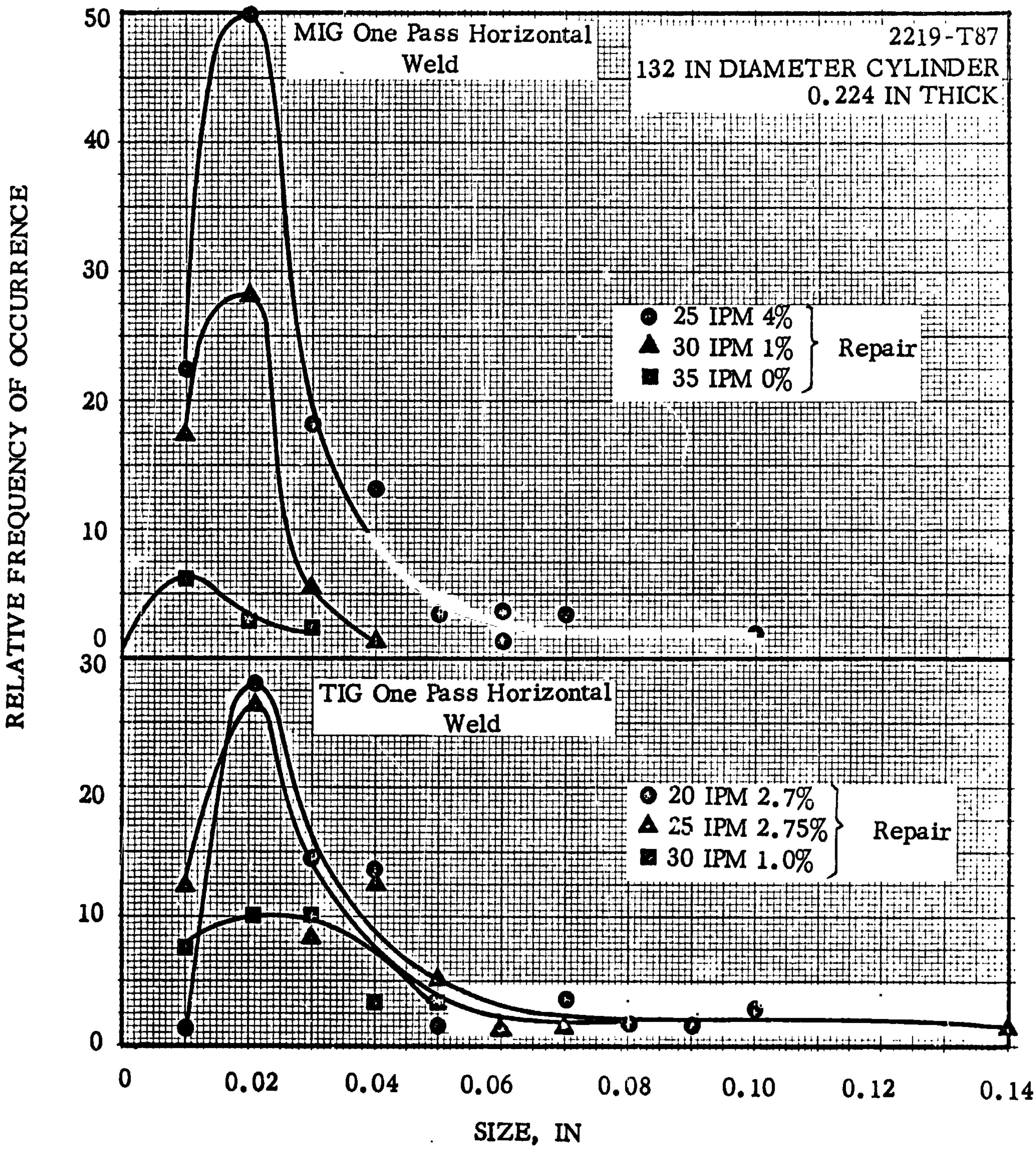

FIG. 12.2 EFFECT OF WELDING SPEED ON THE OCCURRENCE AND SIZE OF POROSITY IN A CYLINDER JOINED BY TIG AND MIG BUTT WELDING (Ref. 12.10)

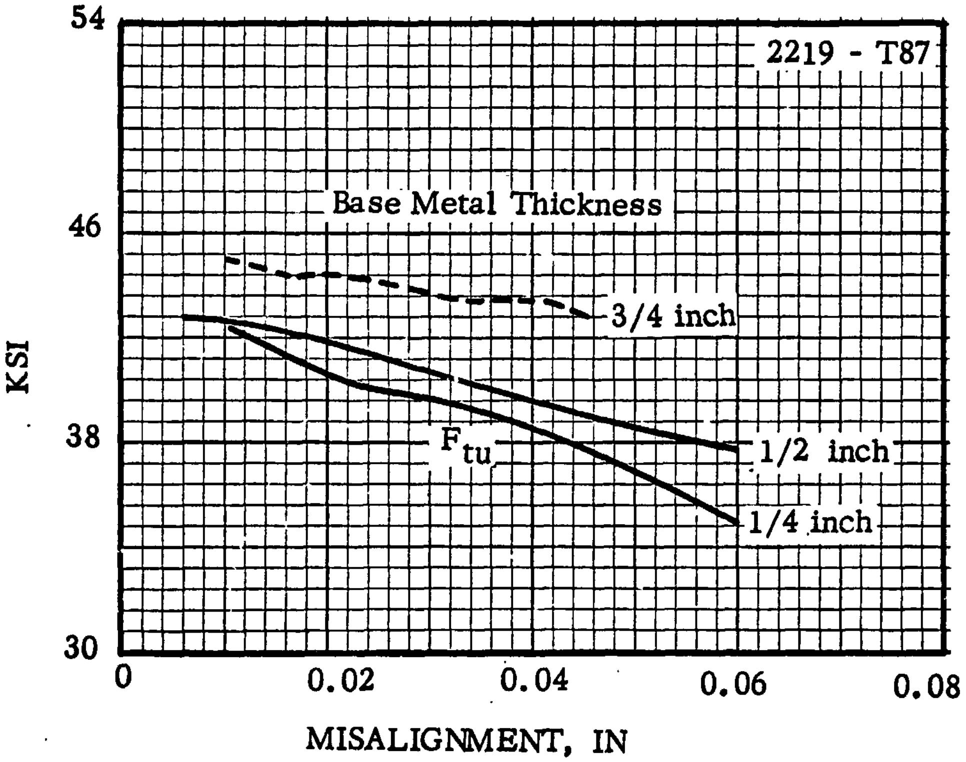

FIG. 12.3 EFFECT OF WELD JOINT MISALIGNMENT ON THE TENSILE STRENGTH OF TIG WELDED 2219 JOINTS

(Ref. 12.11)

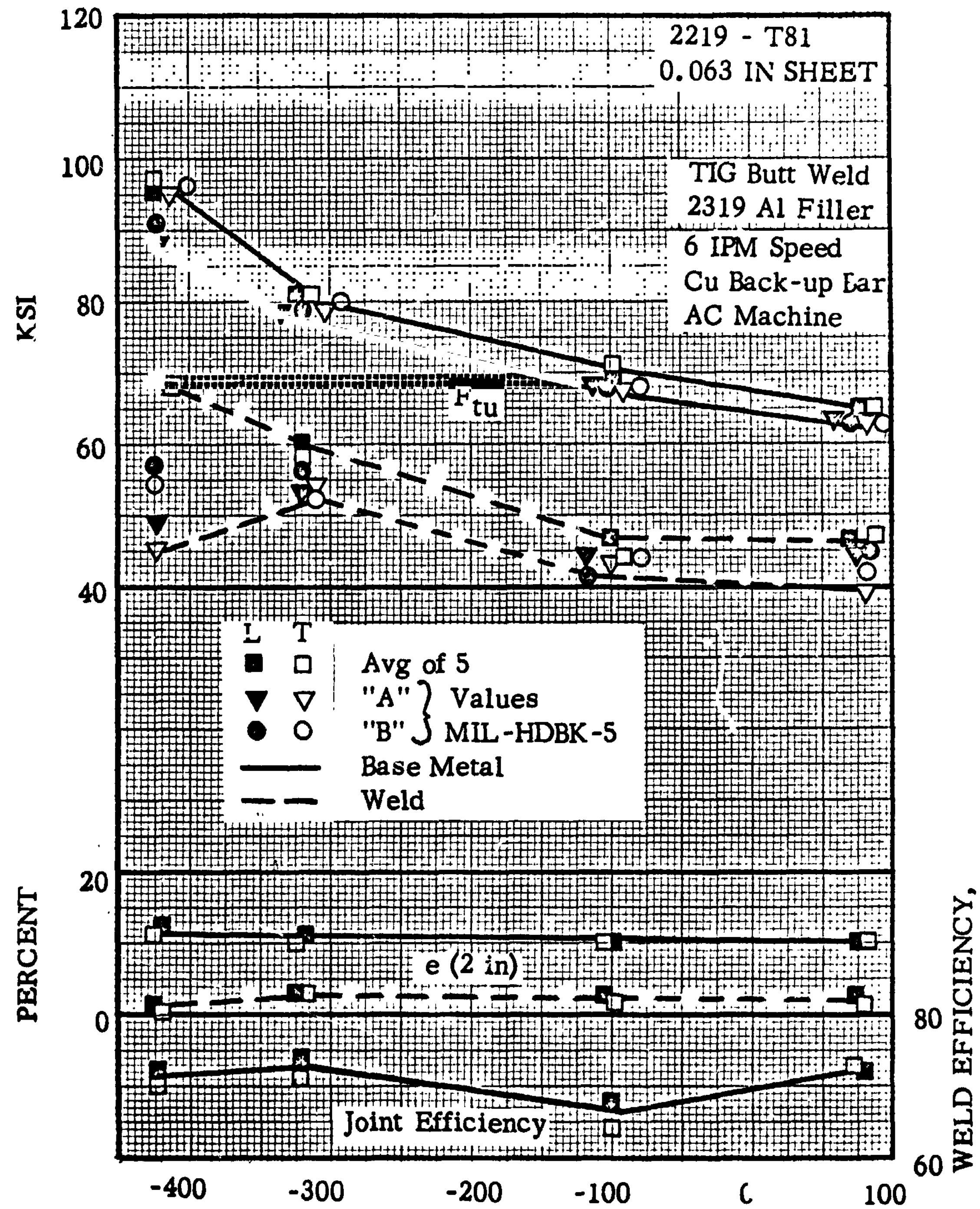

FIG. 12.4 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BASE METAL AND BUTT-WELDED 2219-T81 SHEET

(Ref. 12.13)

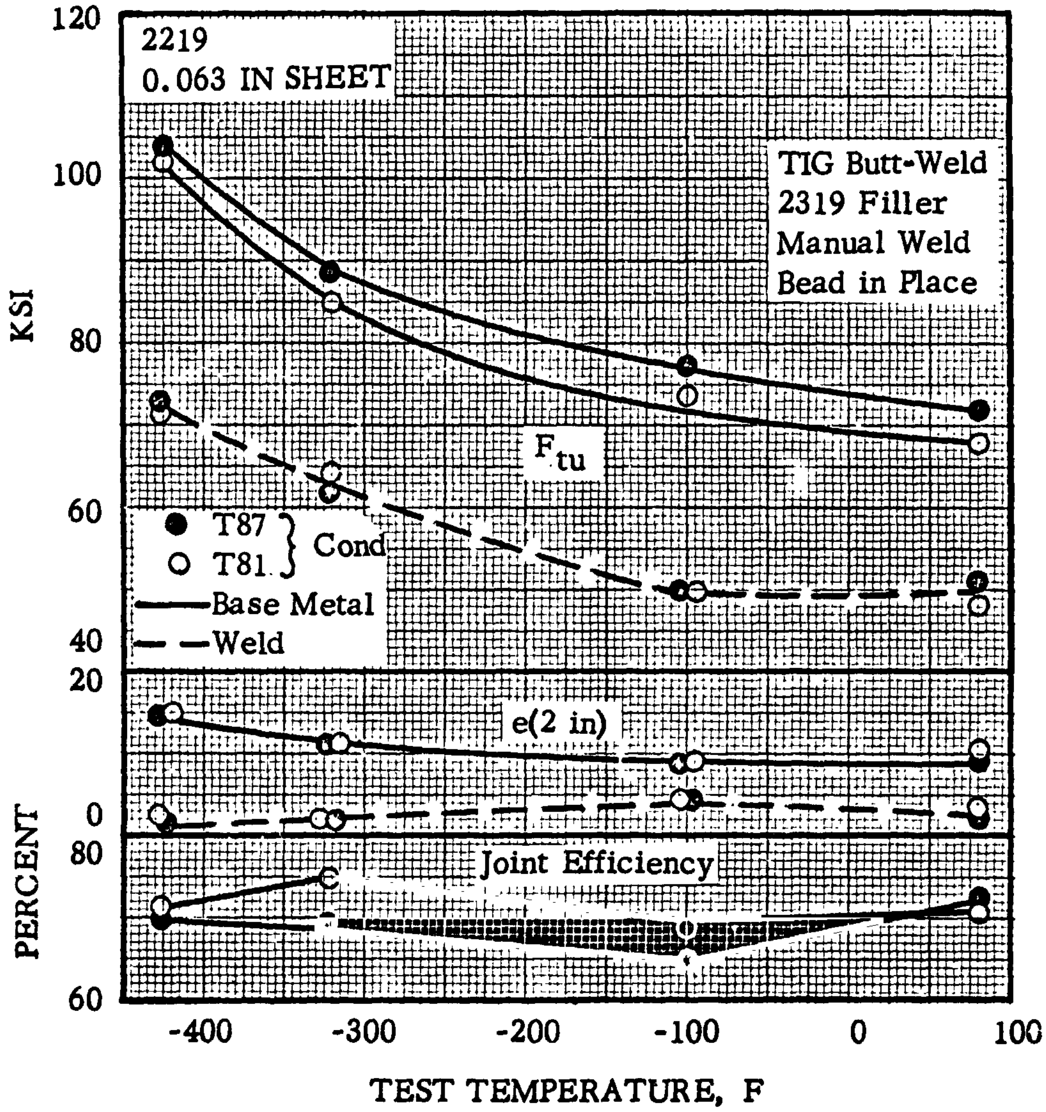

FIG. 12.5 EFFECT OF TEST TEMPERATURE ON TENSILE PROPERTIES OF BASE METAL AND BUTT-WELDED 2219-T87 SHEET

(Ref. 12.14)

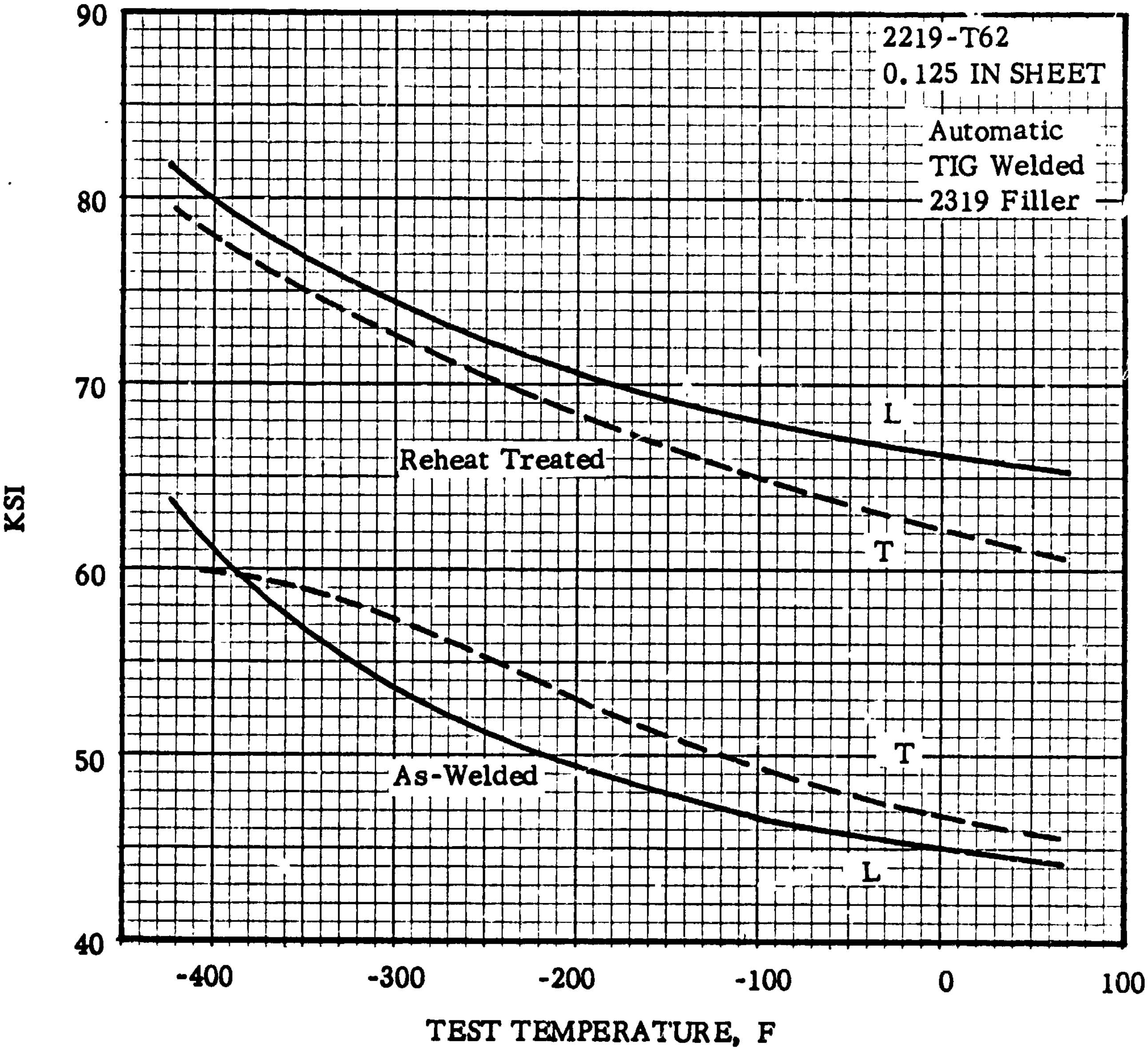

FIG. 12.6 EFFECT OF LOW TEMPERATURE ON TIG WELDED SHEET

(Ref. 12.19)

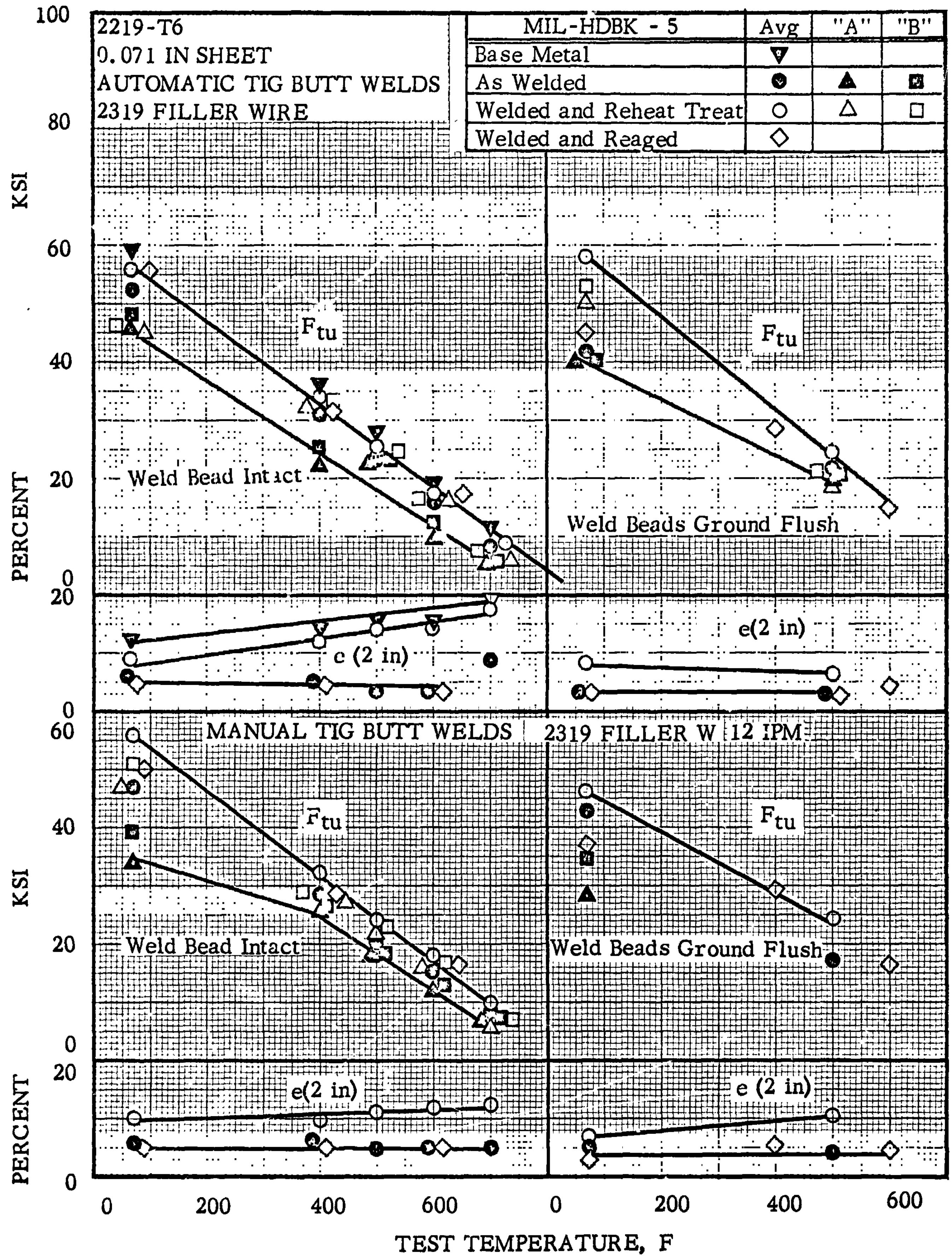

FIG. 12.7 EFFECT OF TEMPERATURE AND WELDING PROCEDURE ON TENSILE STRENGTH AND ELONGATION OF BUTT-WELDED SHEET

(Ref. 12.15)

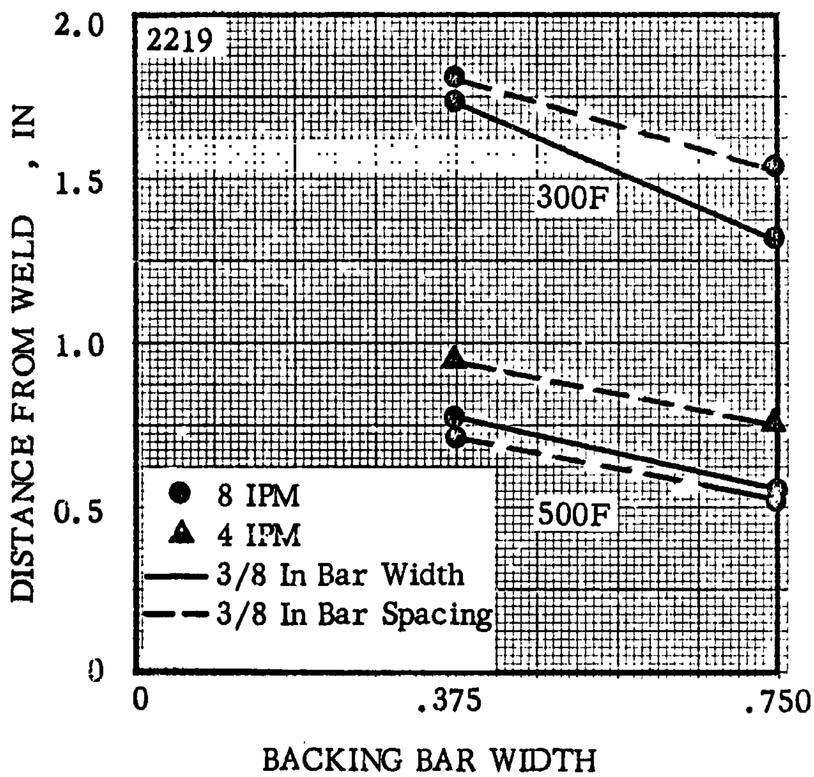

FIG. 12.8 EFFECT OF BACKING MATERIAL, BACKING BAR GAP AND BACKING BAR WIDTH ON TEMPERATURE RISE ABOVE 500F (Ref. 12.16)

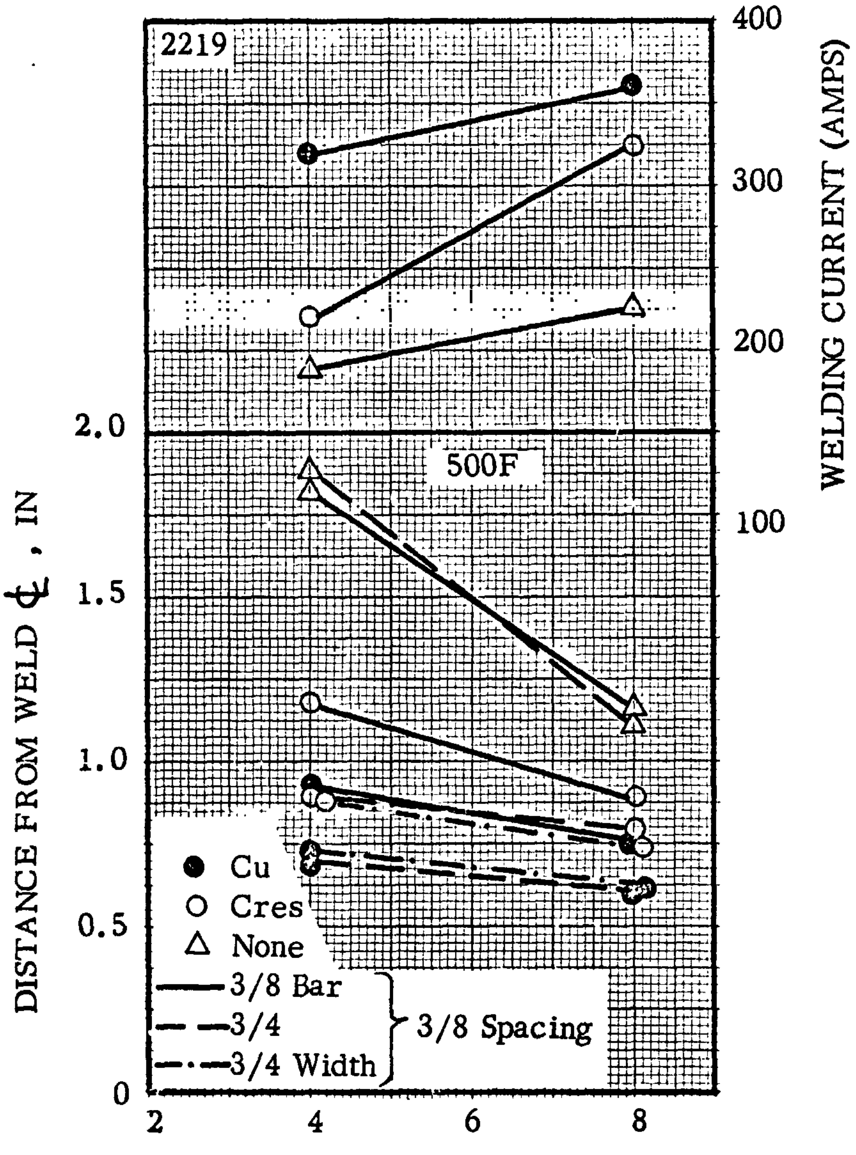

FIG. 12.9 EFFECT OF BACKING MATERIAL, BACKING BAR GAP AND BACKING BAR WIDTH ON TEMPERATURE RISE ABOVE 500F

(Ref. 12.16)

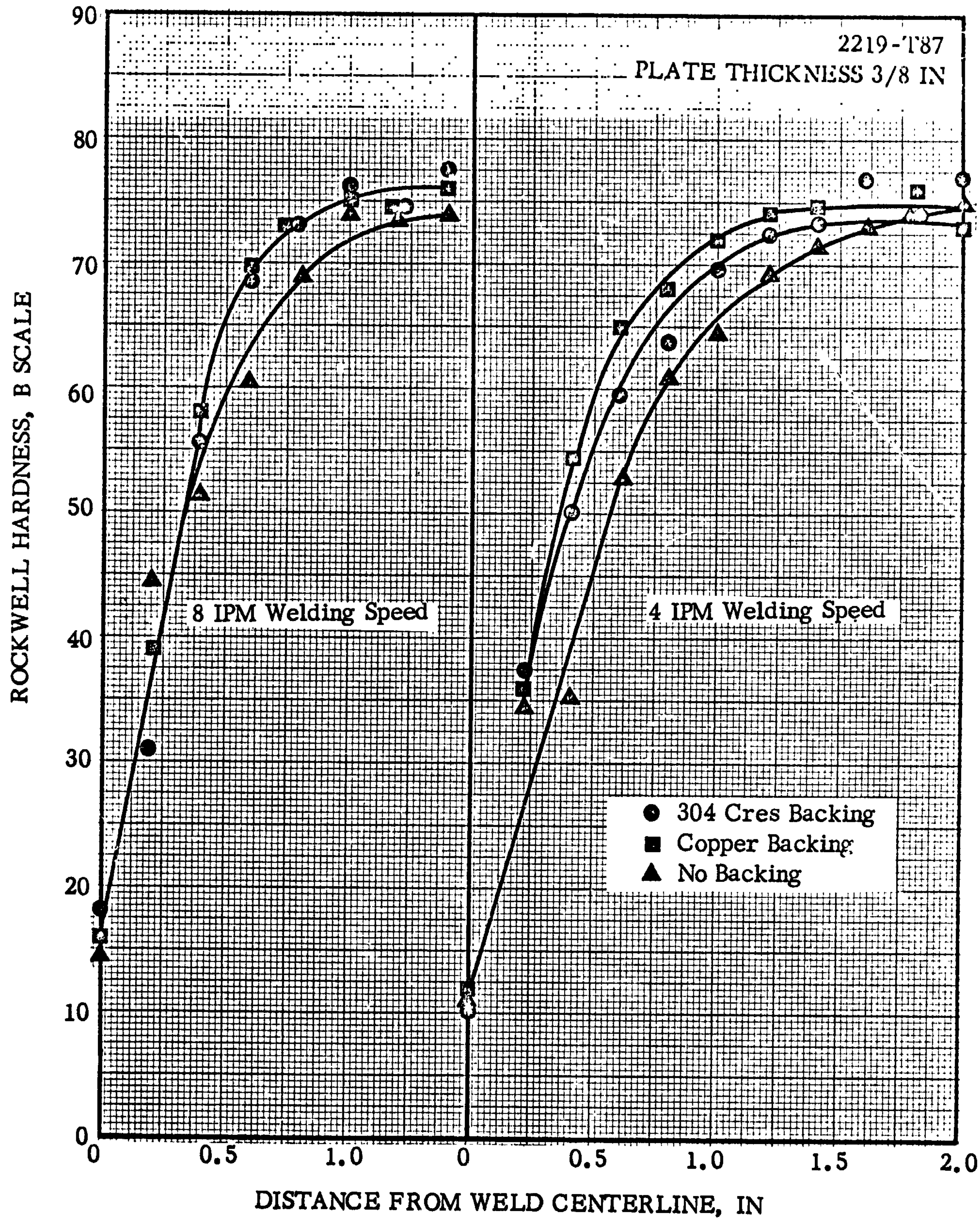

FIG. 12.10 EFFECT OF WELD BACKING AND WELDING SPEED ON HARDNESS VALUES OF TIG BUTT WELDED 2219-T87 PLATE

(Ref. 12.16)

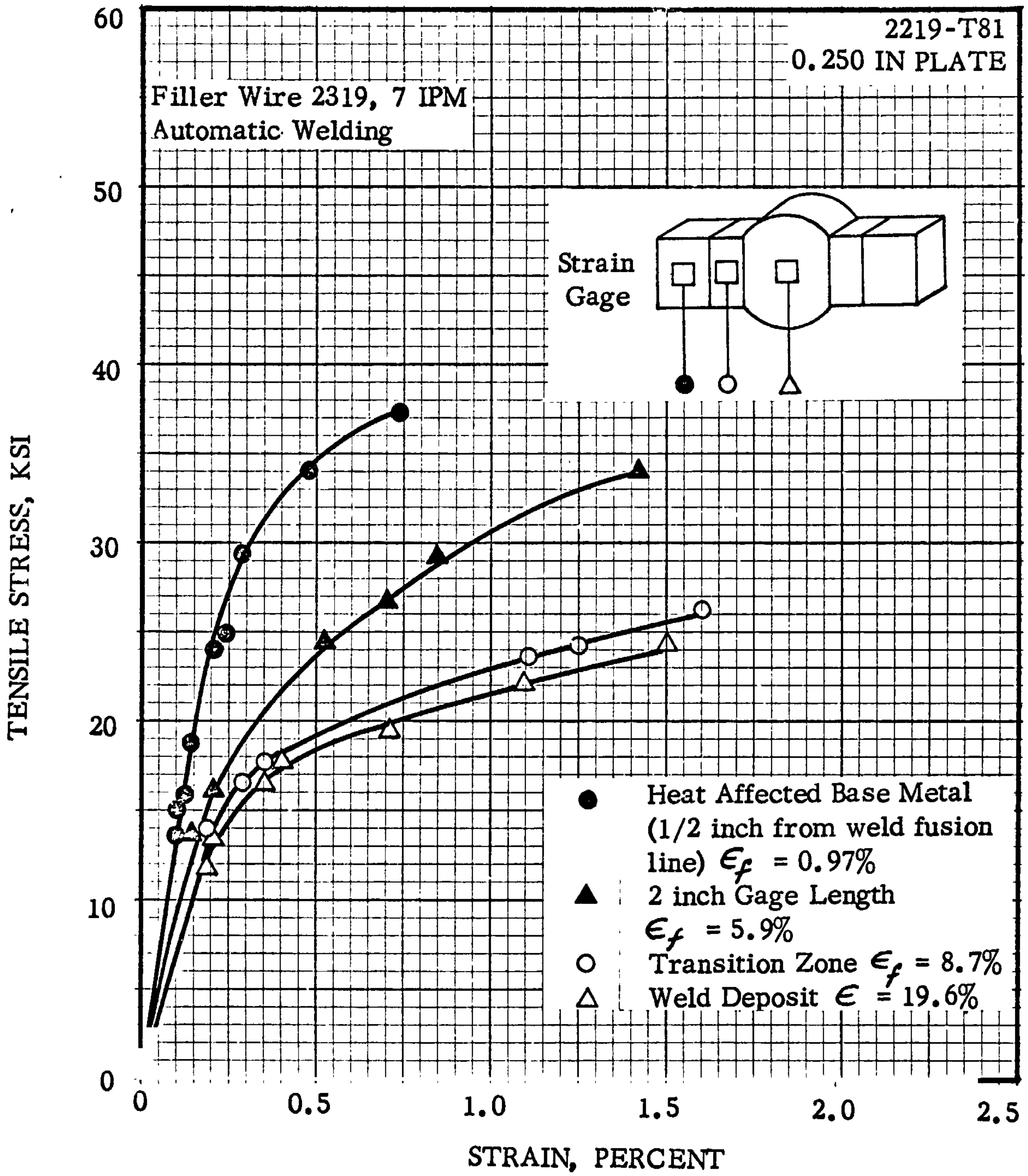

FIG. 12.11 STRESS-STRAIN CURVES OF TIG BUTT-WELDED 2219-T87 PLATE OF VARIOUS LOCATIONS ACROSS THE WELD AS DERIVED FROM MINIATURE STRAIN GAGE DATA

(Ref. 12.36)

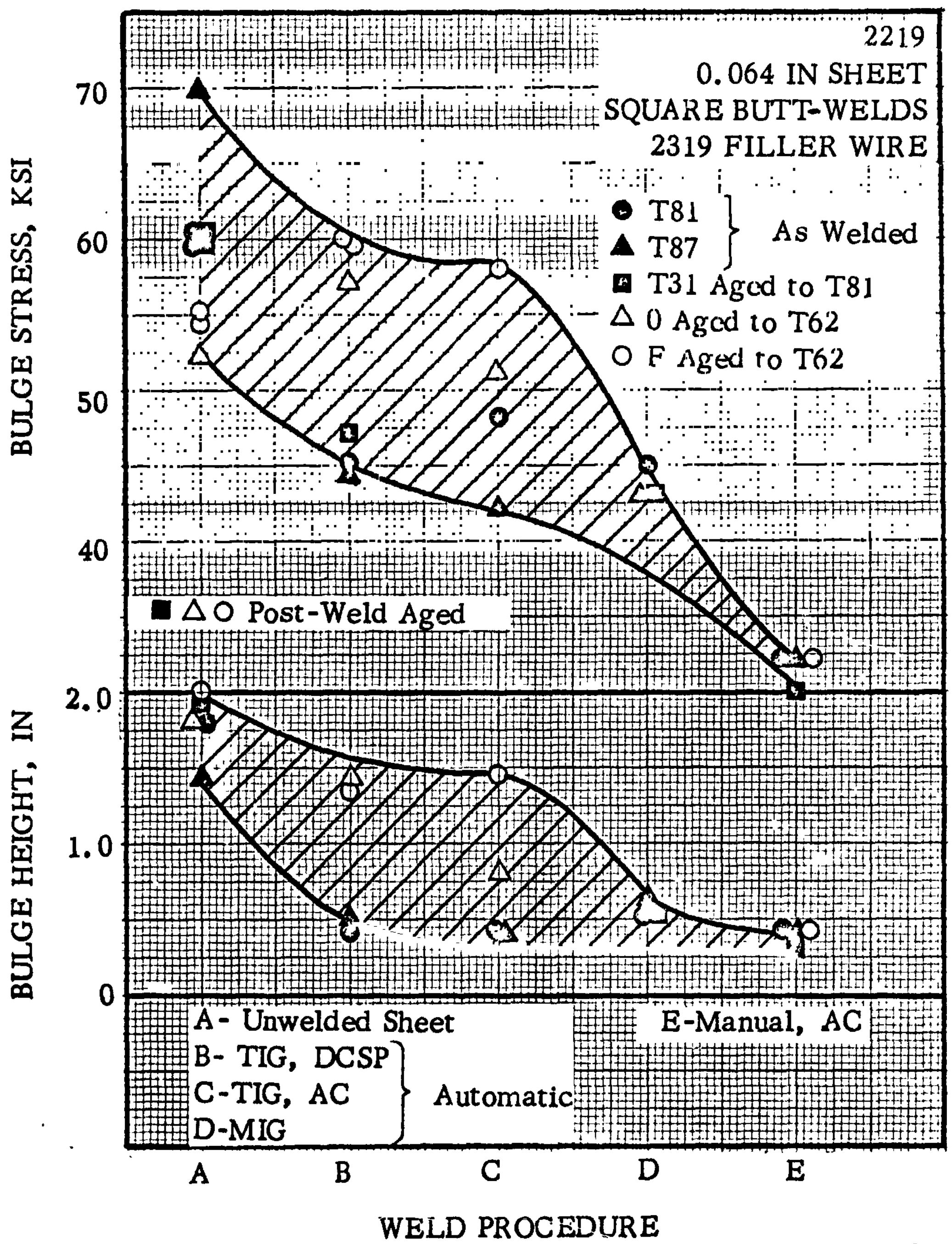

FIG. 12.12 EFFECT OF WELD PROCEDURE AND HEAT TREATMENT ON BULGE PROPERTIES

(Ref. 12.5)

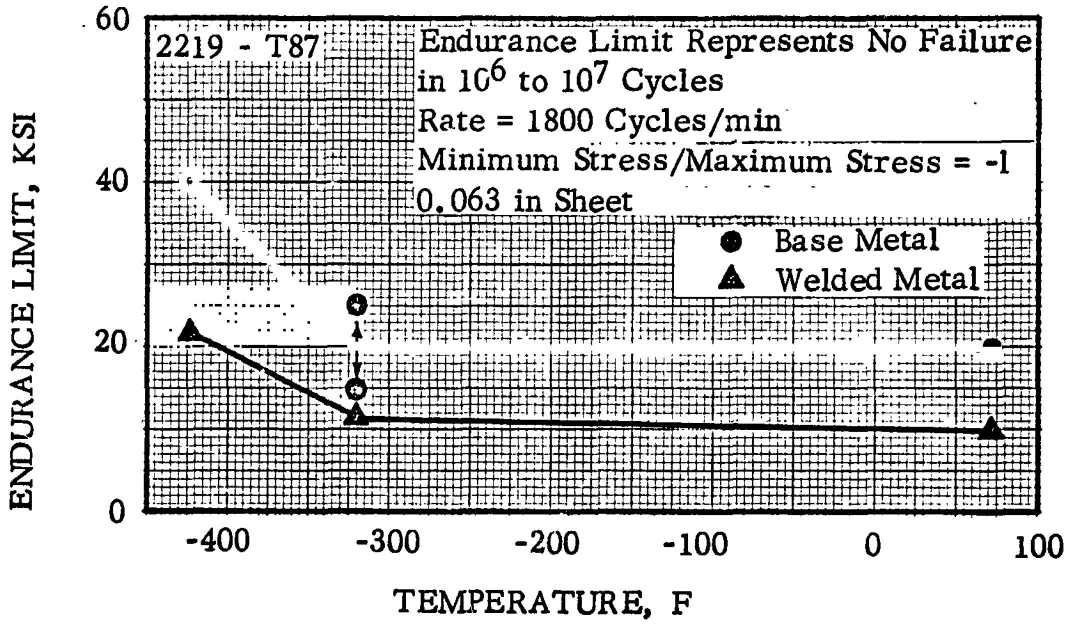

FIG. 12.13 EFFECT OF TEMPERATURE ON ENDURANCE LIMIT OF BASE METAL AND BUTT-WELDED 2219-T87 SHEET

(Ref. 12.17)

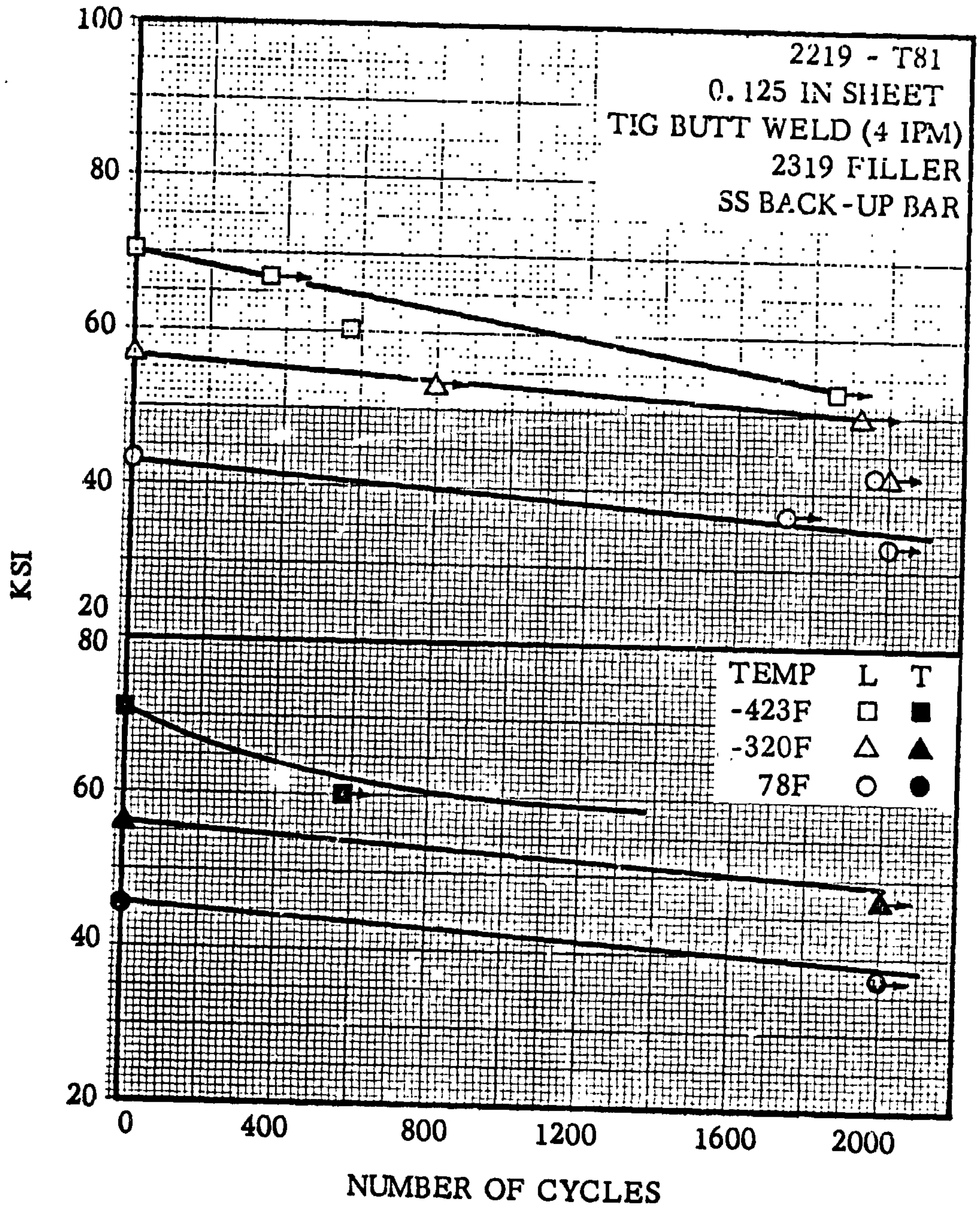

FIG. 12.14 S-N CURVES FOR TIG BUTT-WELDED SHEET AT ROOM AND CRYOGENIC TEMPERATURES

(Ref. 12.13)

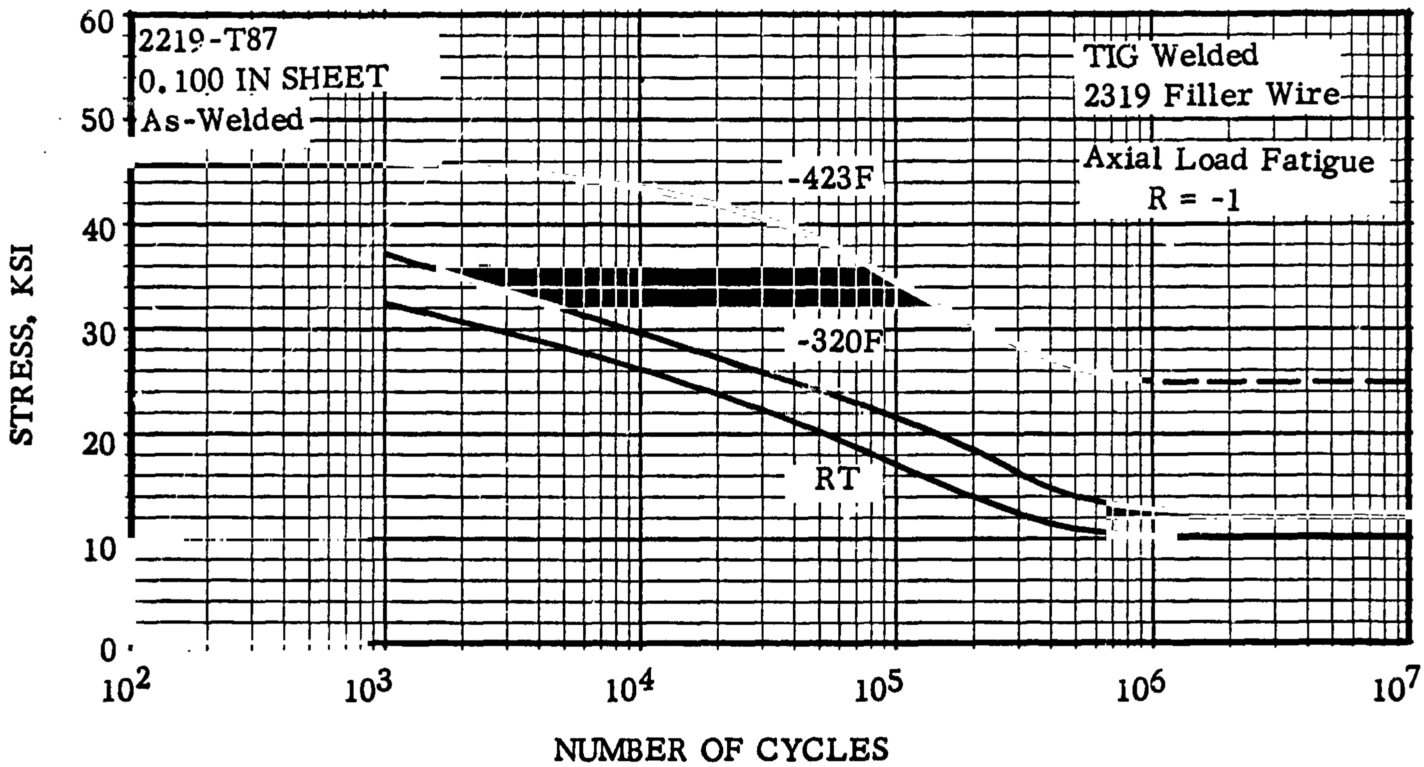

FIG. 12.15 FATIGUE STRENGTH OF TIG WELDED T87 SHEET AT ROOM AND LOW TEMPERATURES (Ref. 12.18)

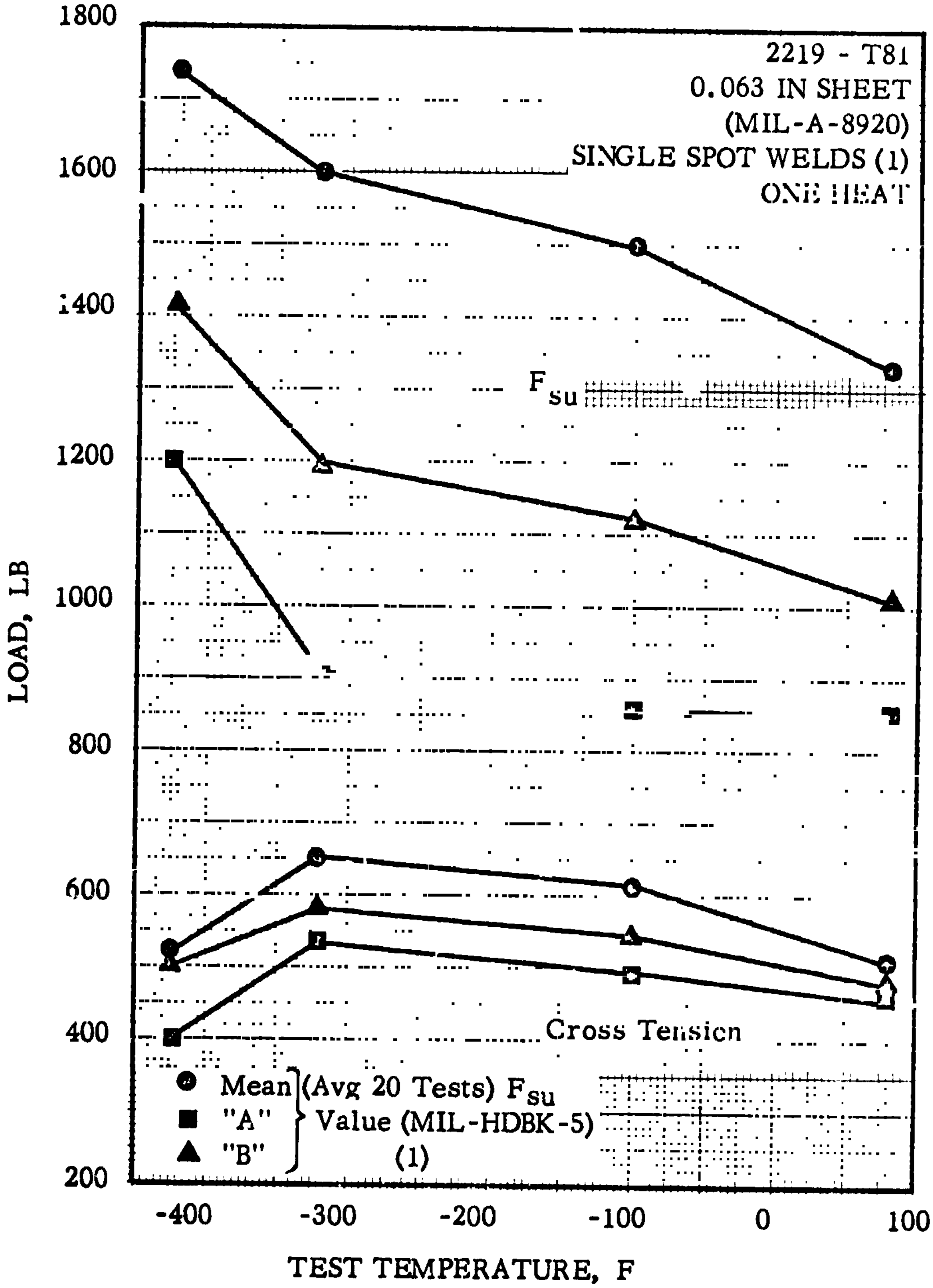

FIG. 12.16 EFFECT OF TEST TEMPERATURE ON CROSS TENSION AND TENSILE SHEAR STRENGTH OF SINGLE SPOT WELDS

(1) Spot welds made with a Thomson Tri-Mono welder, 90 KVA transformer electrode tip radii 5/8 inch (top) 4 inch bottom

CHAPTER 12 - REFERENCES

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