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16. Abstract

Pertinent mechanical and physical properties of six high conductivity metals were determined. The metals include Amzirc, NARloy Z, OFHC copper, electroformed copper, fine silver, and electroformed nickel. Selection of these materials was based on their possible use in high performance reusable rocket nozzles.

The typical room temperature properties determined for each material include tensile ultimate strength, tensile yield strength, elongation, reduction of area, modulus of elasticity, Poisson's ratio, density, specific heat, thermal conductivity, and coefficient of thermal expansion.

Typical static tensile stress-strain curves, cyclic stress-strain curves, and low-cycle fatigue life curves are also presented.

Properties versus temperature are presented in graphical form for temperatures from 27.6K (-410°F) to 810.9K (1000°F).

17. Key Words (Suggested by Author(s))
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FOREWORD

This report was prepared by the Boeing Aerospace Company, a division of The Boeing Company, Seattle, Washington, for the Lewis Research Center of the National Aeronautics and Space Administration. The physical and mechanical properties of six candidate rocket nozzle materials are presented in accordance with the Task I requirements of Contract NAS3-17838, "Thrust Chamber Life Prediction." This program was under the cognizance of Gary R. Halford and R. J. Quentmeyer of the Lewis Research Center.

The literature search and documentation of the physical and mechanical properties was conducted by John J. Esposito and Ronald F. Zabora of the Structural Methods and Allowables organization. The technical leader was W. H. Armstrong, reporting to the Program Manager, J. S. Andrews.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

SUMMARY

Physical and mechanical properties of six candidate high performance rocket nozzle materials are documented in this report. Material properties used in life prediction studies were established for Amzirc, NARloy Z, OFHC copper, electroformed copper, fine silver, and electroformed nickel. Typical room temperature properties and typical properties at temperatures from 27.6K (-410°F) to 810.9K (1000°F) were determined for these materials.

A literature search was conducted and the data from the reference sources collected. The available data is from test programs, supplier literature, data compilations, materials handbooks and materials studies. The quantity of data available for the determination of the desired properties was very limited for these six materials. Due to this lack of data only typical properties were established for all the materials. The use of typical properties in the life analysis studies minimizes bias in the analytical results due to varying uncertainties in the input properties. To confidently establish minimum design properties, more test data, tighter material specification requirements and additional material service experience is required.

The typical mechanical properties and physical properties were established from the data base collected from the references, using suitable analysis procedures and engineering judgment to come up with the most representative properties for each of the materials.

1.0 INTRODUCTION

The advent of the Space Shuttle has brought a new era in the design and fabrication of rocket nozzles. The requirement of high-performance coupled with weight and volume limitations, has necessitated the design of rocket nozzles to operate at chamber pressures in excess of 3000 psia. This has elevated the throat heat flux from 20 Btu/in^2-sec for present day high performance rocket nozzles to the range of 80-100 Btu/in^2-sec for the Space Shuttle main engine. A further requirement for future high performance rocket nozzles is reusability. For example, the nozzle may have the requirement that it be capable of operating for 300 major thermal cycles for a total duration of 10 hours.

The combination of high performance and reusability has created major design problems. One of the critical aspects of the nozzle design is the fatigue life analysis. This has become a major design problem since a portion of the nozzle, particularly the throat section, is subjected to cyclic plastic strain due to the high temperature differential between the hot inner wall and the relatively cool outer shell during the engine start-stop transients as well as during steady state operation. This has a major impact on nozzle life and creates the need to accurately predict when an engine may fail.

An essential part of any life analysis program is the availability of the appropriate physical and mechanical properties, which are needed as functions of temperature, for the materials used in fabrication of high performance rockets. Section 2 defines those physical and mechanical properties necessary in predicting the rocket nozzle life.

2.0 MATERIALS PROPERTIES

Typical mechanical and physical properties data are presented in this section for six candidate high performance rocket nozzle materials. Room temperature properties are given in tabular form for all materials. The properties at temperature are presented in Figures 1 through 41.

*2.1: *AMZIRC*

General Information

Amzirc is a copper base alloy containing a nominal 0.15 percent zirconium. This zirconium-copper alloy combines high electrical and thermal conductivity with good strength retention at high temperatures. The alloy is readily cold worked in the solution-annealed condition. The strength of the material increases with the amount of cold working without sacrificing ductility or conductivity. After cold working, the material should be aged for 1 hour at 700°F to 800°F to obtain the improved strength and conductivity.

*American Metal Climax, Inc. – Tradename for a zirconium-copper alloy

Room Temperature Properties			
Material	Amzirc		
Condition	Annealed	Quarter Hard	Half Hard
Mechanical Properties			
Tensile Ultimate, MN/m^2 (ksi)	241 (35)	338 (49)	344 (50)
Tensile Yield, MN/m^2 (ksi) 0.2% Offset	46 (6.7)	296 (43)	317 (46)
Elongation, %	40	20	26
Reduction of Area, %	88	51	81
Modulus of Elasticity, GN/m^2 (10^6psi)	115 (16.7)	115 (16.7)	115 (16.7)
Poisson's Ratio	.34	.34	.34
Physical Properties			
Density, kg/m^3 (lb/in^3)	8885 (.321)		
Specific Heat, J $kg^{-1} K^{-1}$ (cal/g/K)	385 (.092)		
Thermal Conductivity, W m^{-1} K^{-1}	390		
Coefficient of Thermal Expansion,			
294K to 533K , 10^{-6}[m/m] K^{-1}	17.2		
70°F to 500°F , 10^{-6}(in/in/°F)	(9.5)		

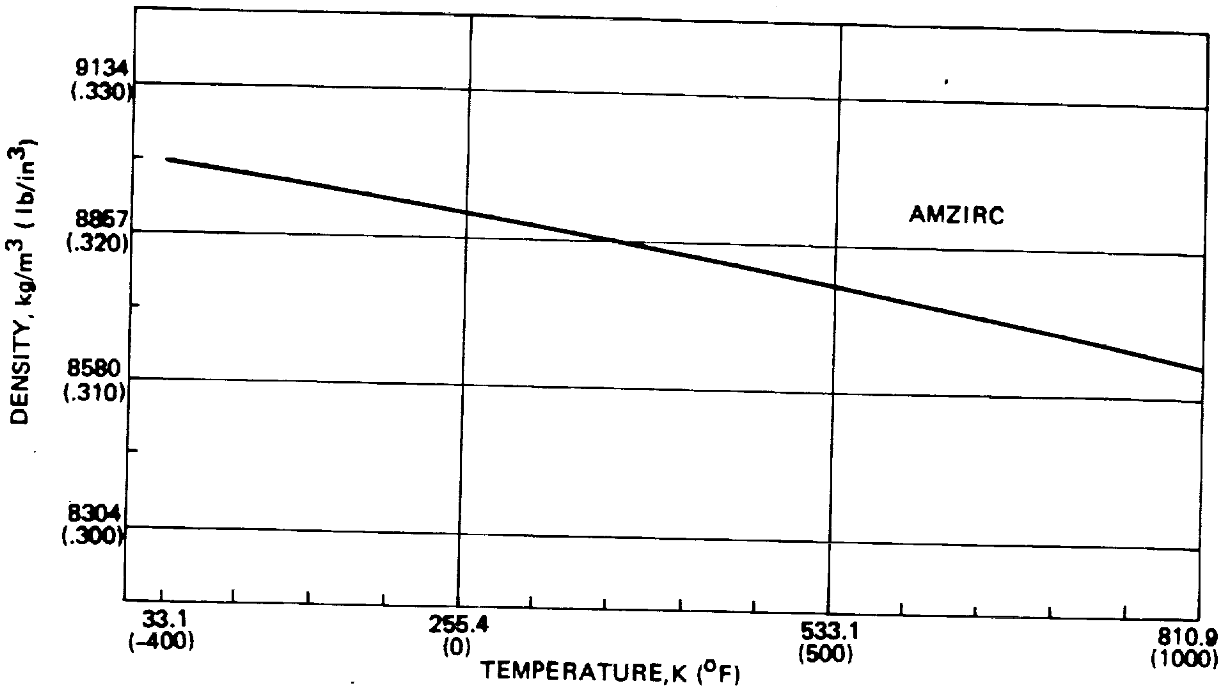

Figure 1 Density vs Temperature for Amzirc

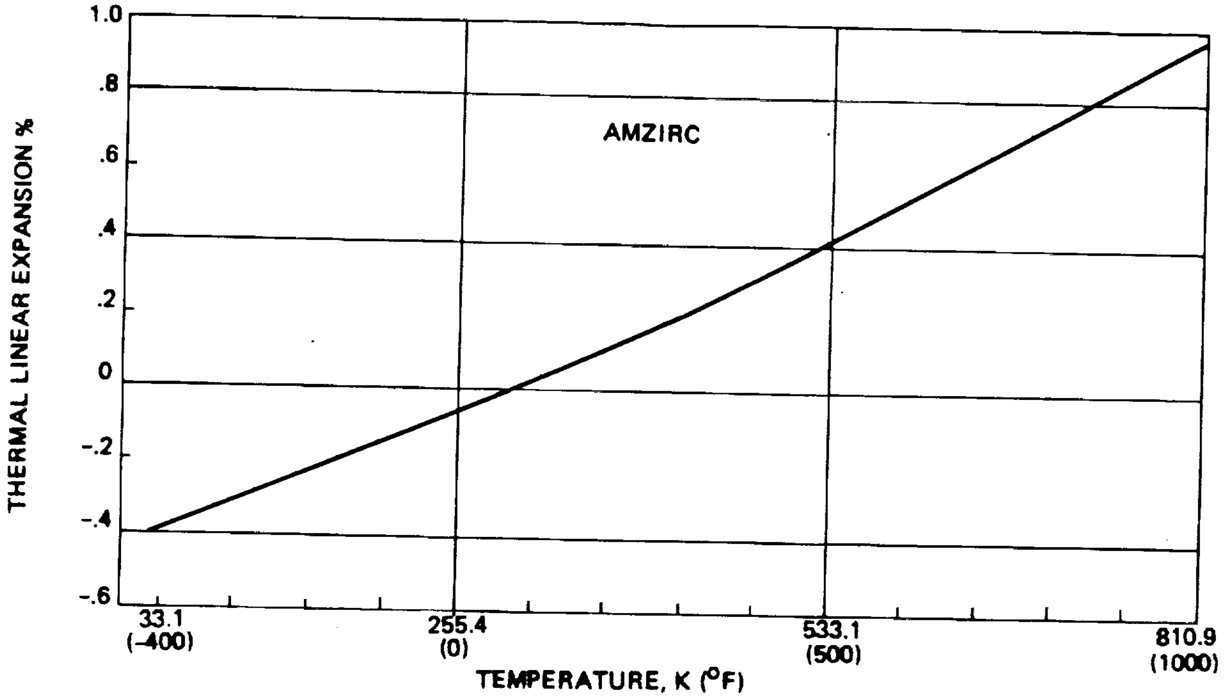

Figure 2 Thermal Linear Expansion vs Temperature for Amzirc

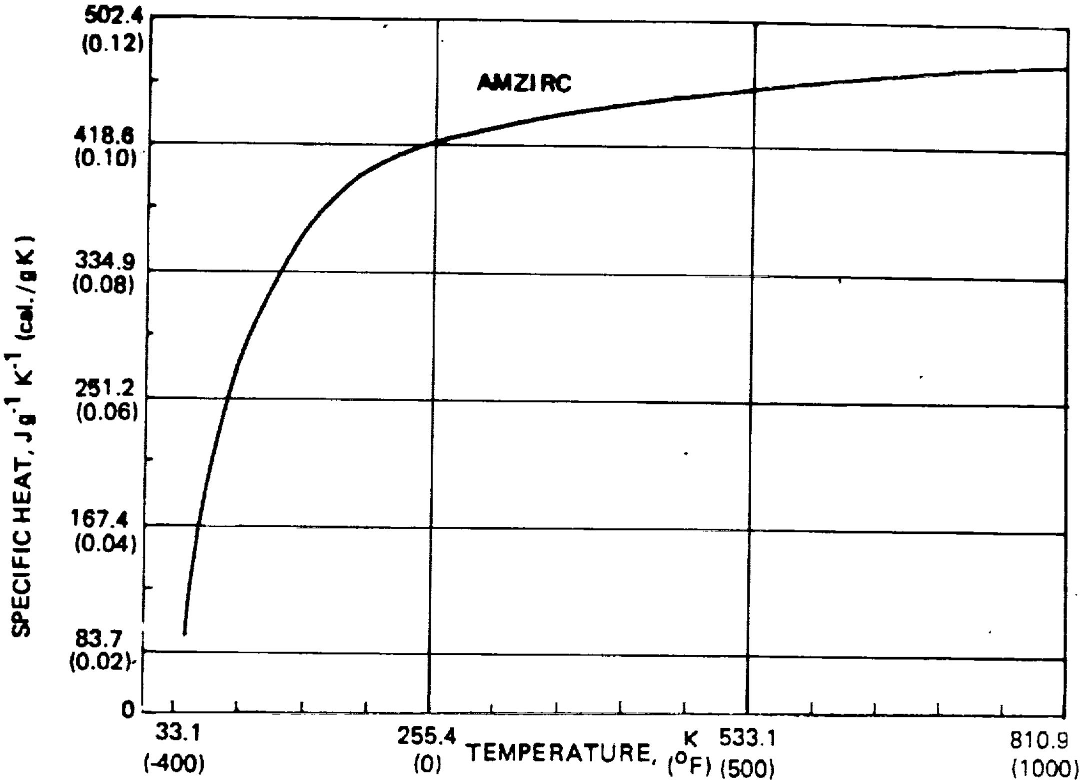

Figure 3 Specific Heat vs Temperature for Amzirc

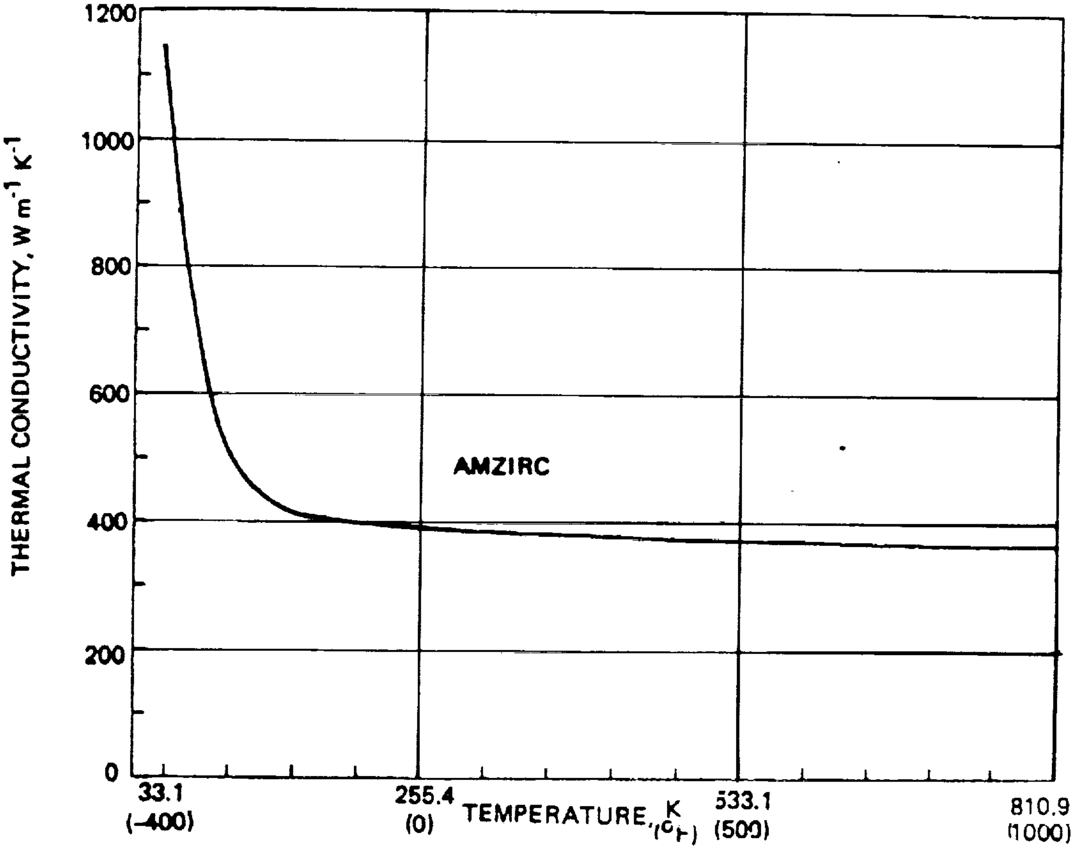

Figure 4 Thermal Conductivity vs Temperature for Amzirc

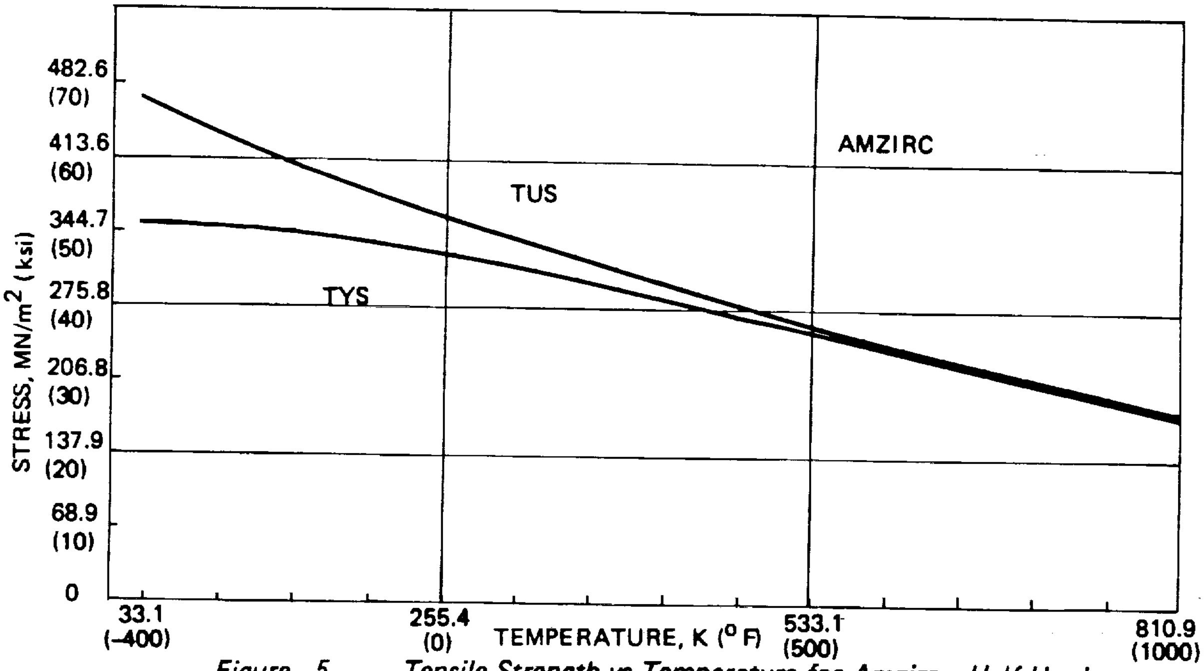

Figure 5 Tensile Strength vs Temperature for Amzirc - Half Hard

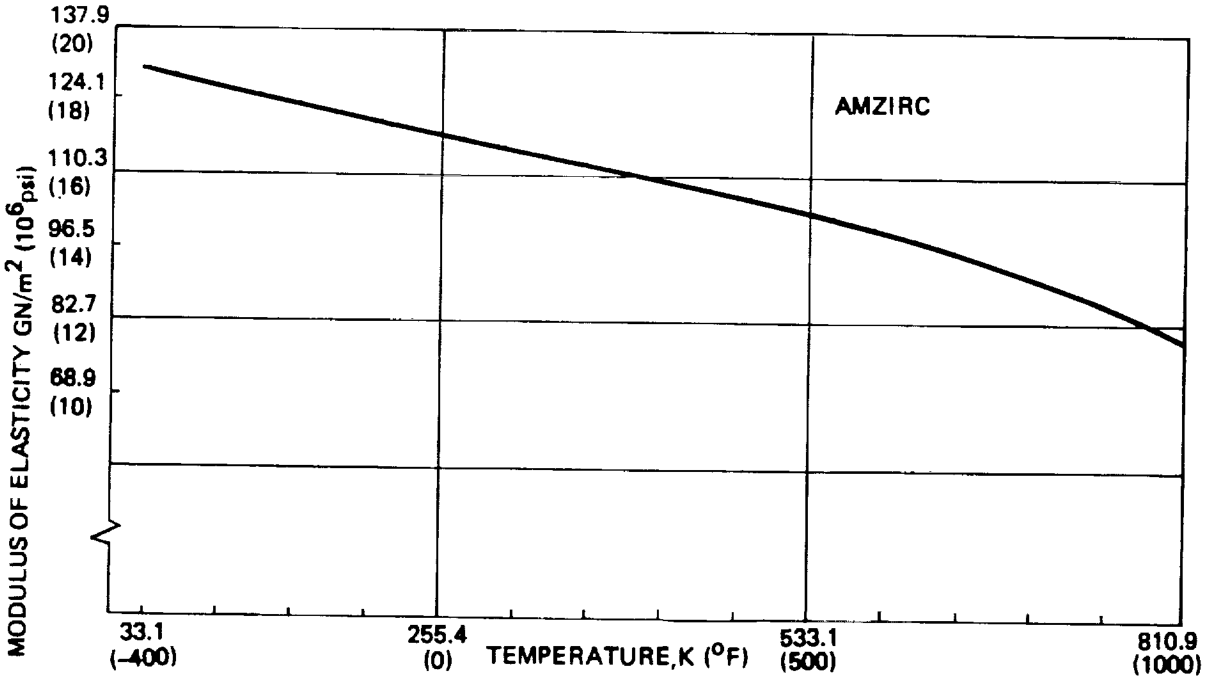

Figure 6 Modulus of Elasticity vs Temperature for Amzirc

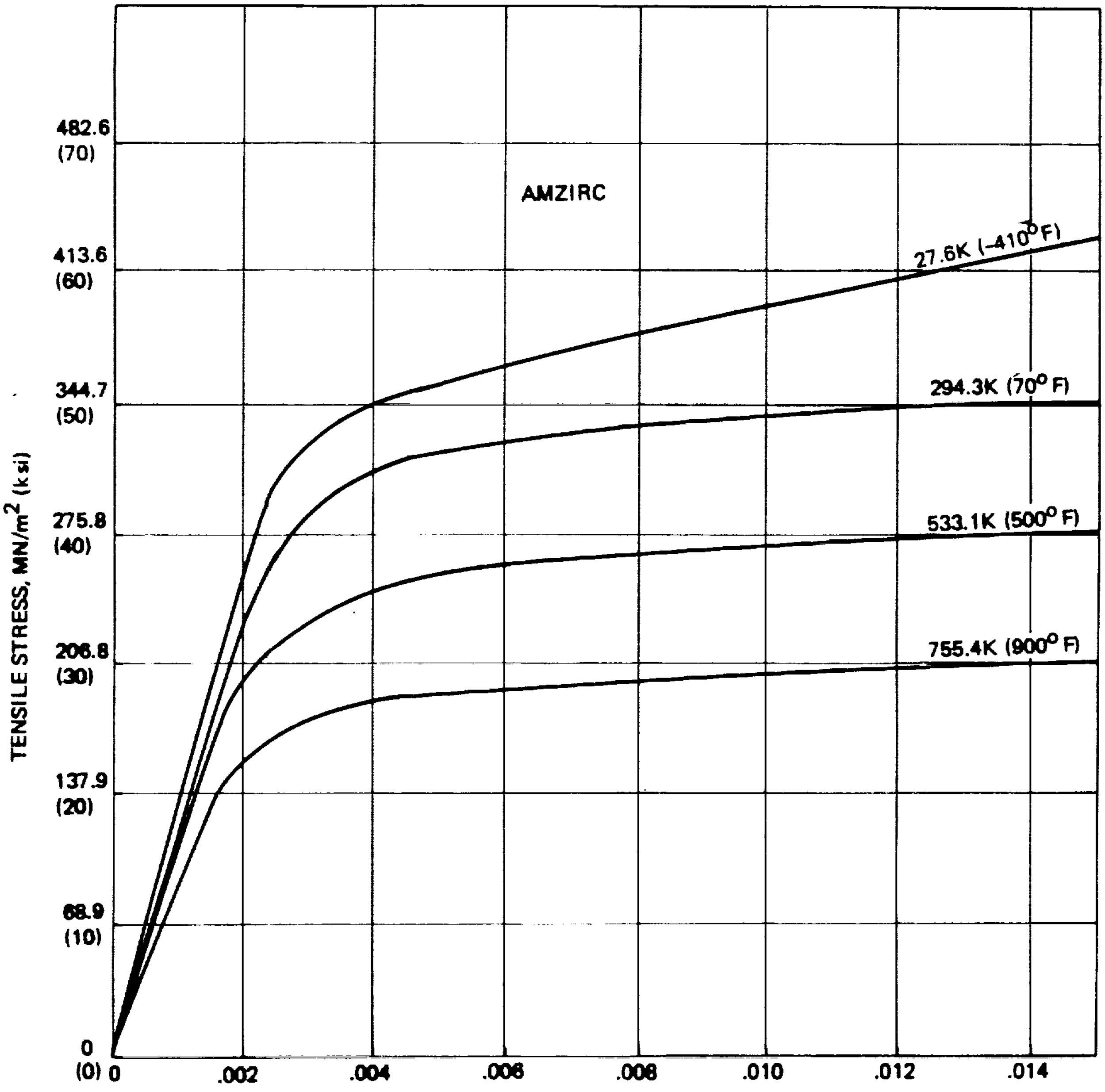

Figure 7 Typical Tensile Stress-Strain Curves for Amzirc-Half Hard Condition

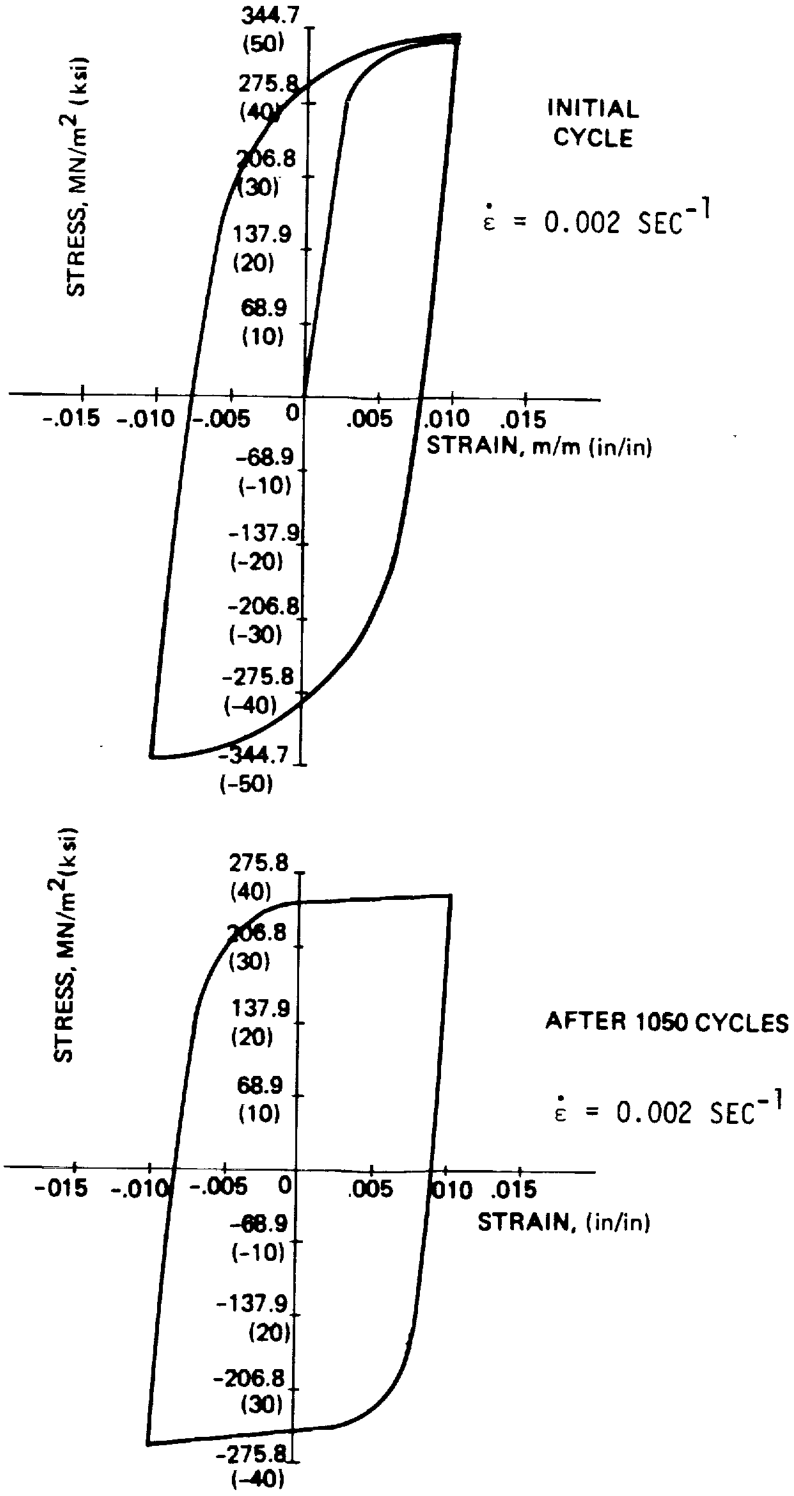

Figure 8 Room Temperature Cyclic Stress-Strain Curves for Amzirc- Half Hard Condition

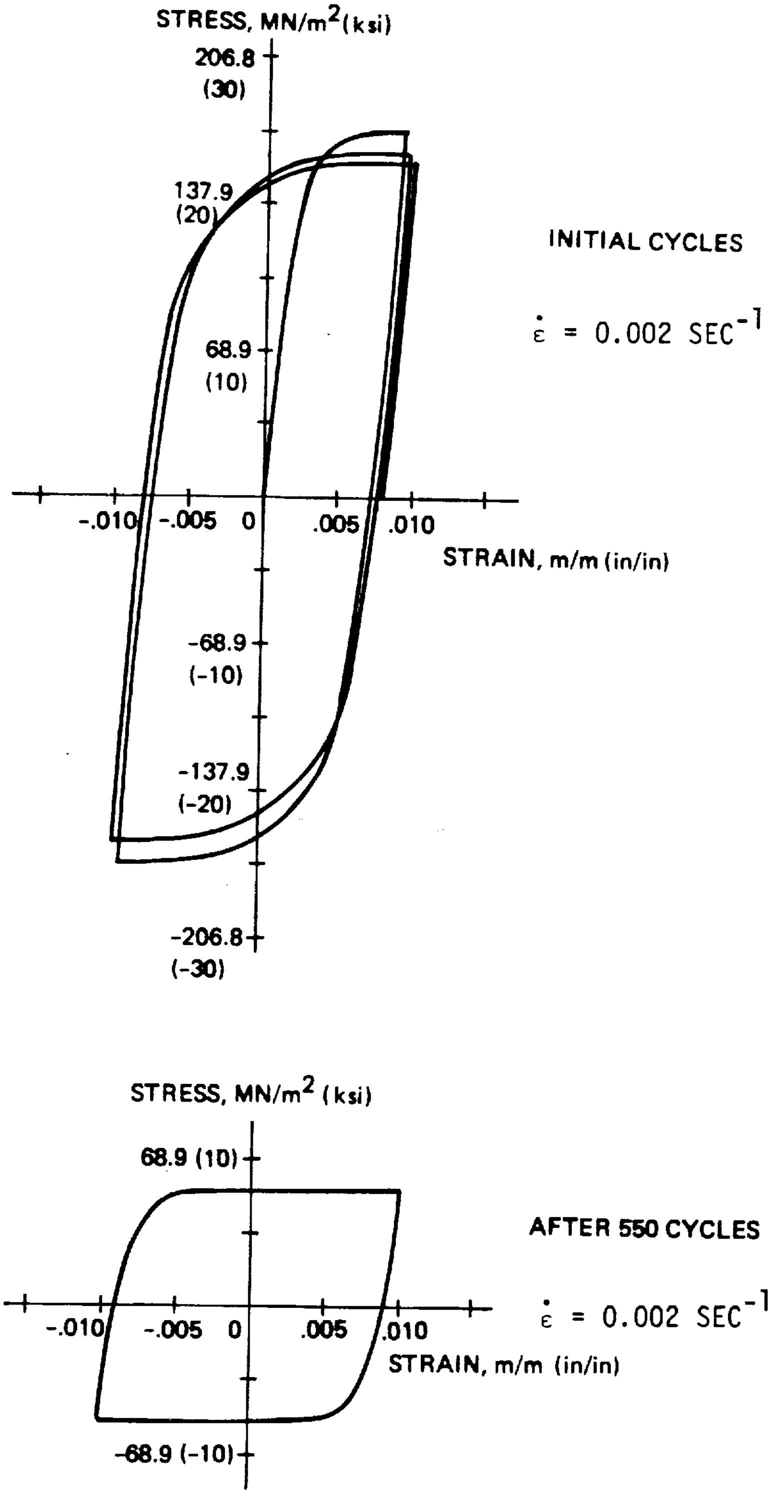

Figure 9 810.9K (1000°F) Cyclic Stress-Strain Curves for Amzirc-Half Hard Condition

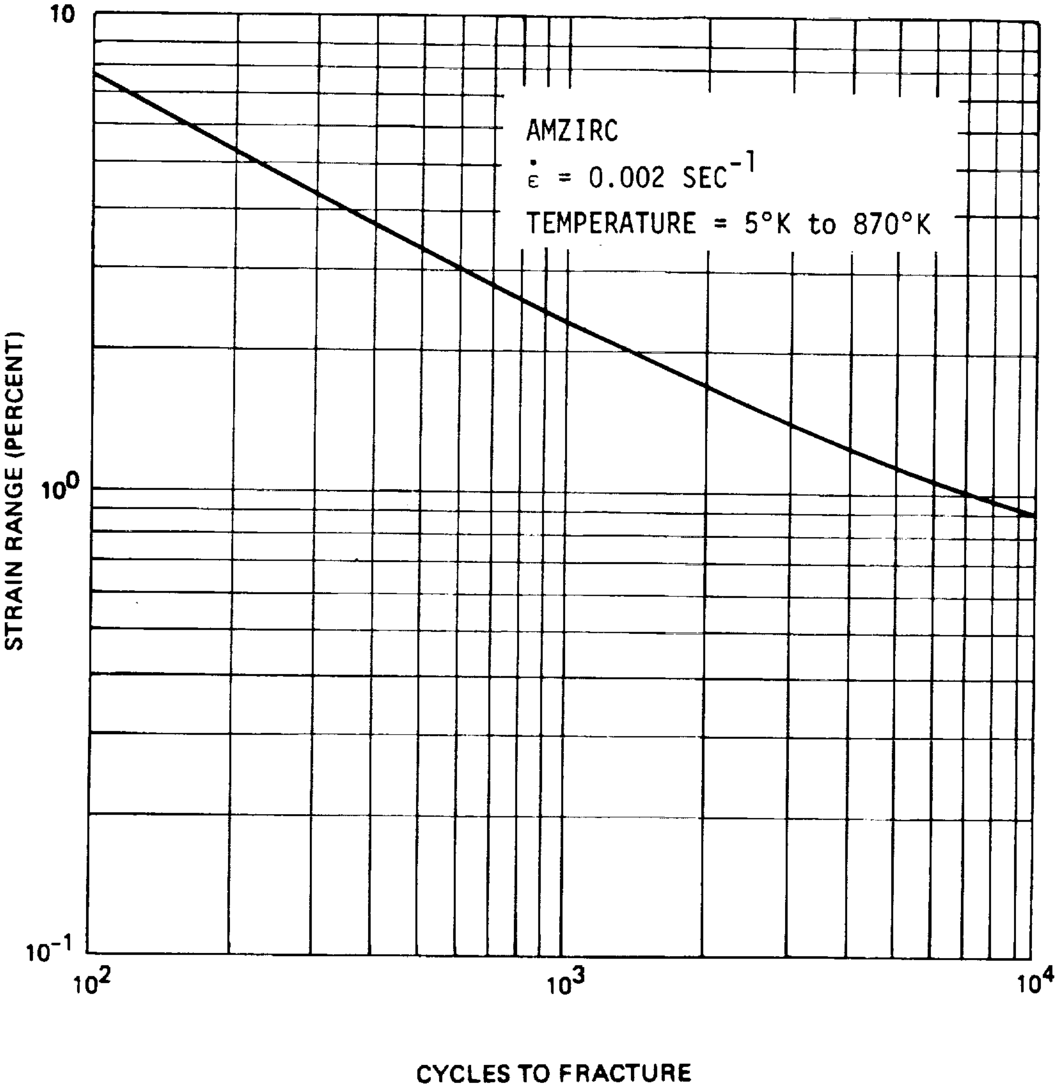

Figure 10 Typical Low-Cycle Fatigue Life of Amzirc - Half Hard Condition

*2.2 NARloy - Z**

General Information

NARloy-Z is a copper base alloy containing a nominal 3-percent silver and .5 percent zirconium. The silver-zirconium-copper alloy combines high electrical and thermal conductivity with moderate strength retention at high temperatures. The alloy is strengthened by heat treatment and is normally used in the solution annealed and aged condition.

* Rockwell International' Inc. - Tradename for a silver-zirconium-copper alloy

Room Temperature Properties	
Material	NARloy Z
Condition	Solution Treated and Aged
Mechanical Properties	
Tensile Ultimate, MN/m^2 (ksi)	314 (45.6)
Tensile Yield, MN/m^2 (ksi) 0.2% Offset	192 (27.9)
Elongation, %	31
Reduction of Area, %	54
Modulus of Elasticity, $GN/m^2 (10^6 psi)$	127 (18.5)
Poisson's Ratio	.34
Physical Properties	
Density, kg/m^3 (lb/in^3)	9134 (.330)
Specific Heat, $J\ kg^{-1} K^{-1}$ (cal/g/K)	373 (.089)
Thermal Conductivity, $W\ m^{-1} K^{-1}$	295
Coefficient of Thermal Expansion,	
294 to 533K , $10^{-6} [m/m]\ K^{-1}$	17.2
$70^{\circ}F$ to $500^{\circ}F$, $10^{-6} (in/in/^{\circ}F)$	(9.5)

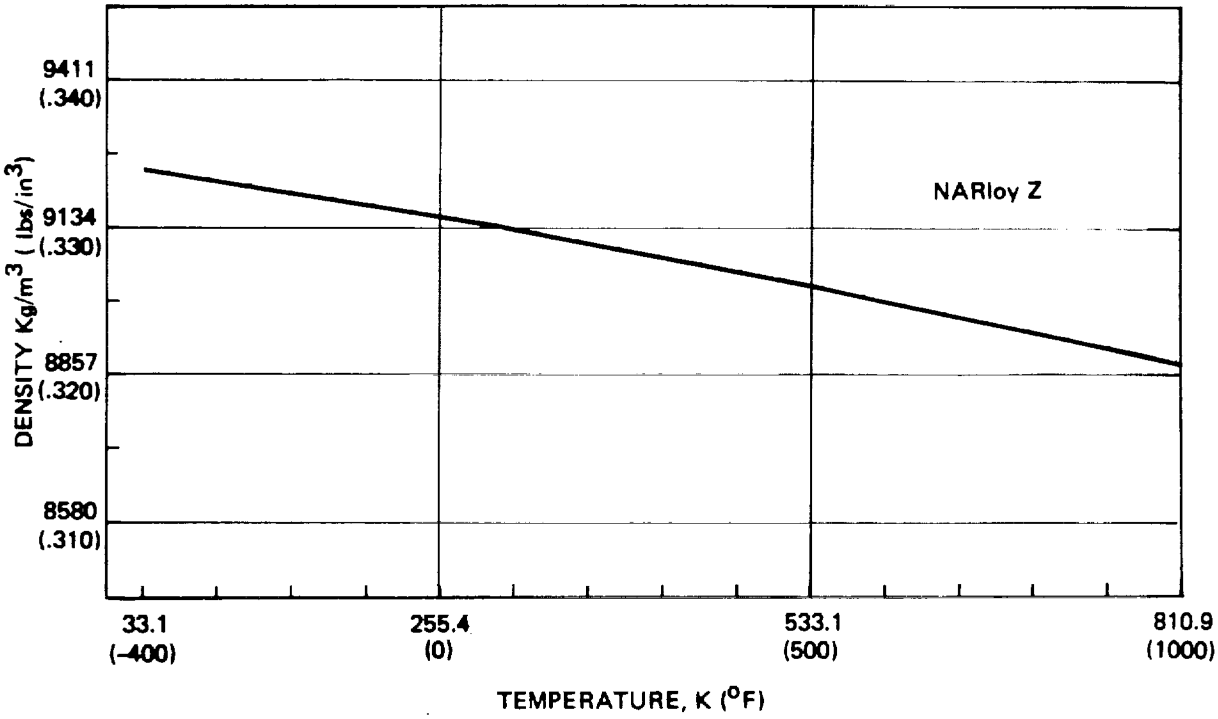

Figure 11 Density vs Temperature for NARloy Z

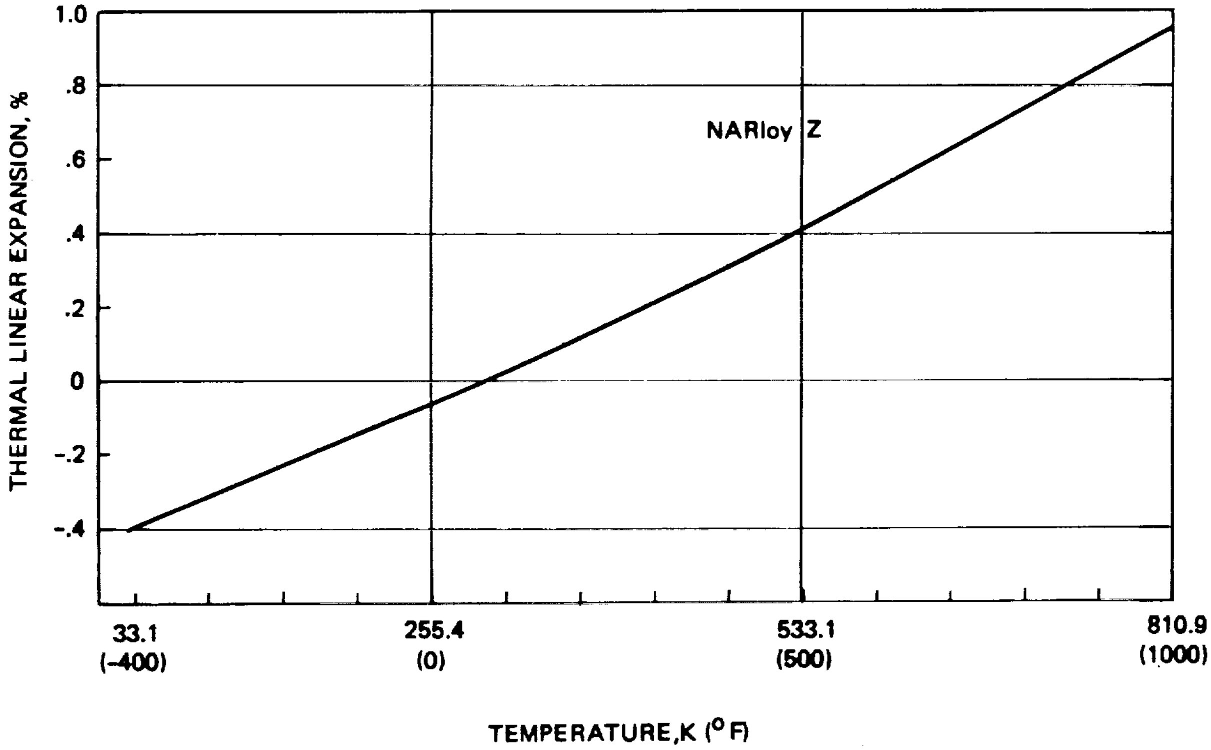

Figure 12 Thermal Linear Expansion vs Temperature for NARloy Z

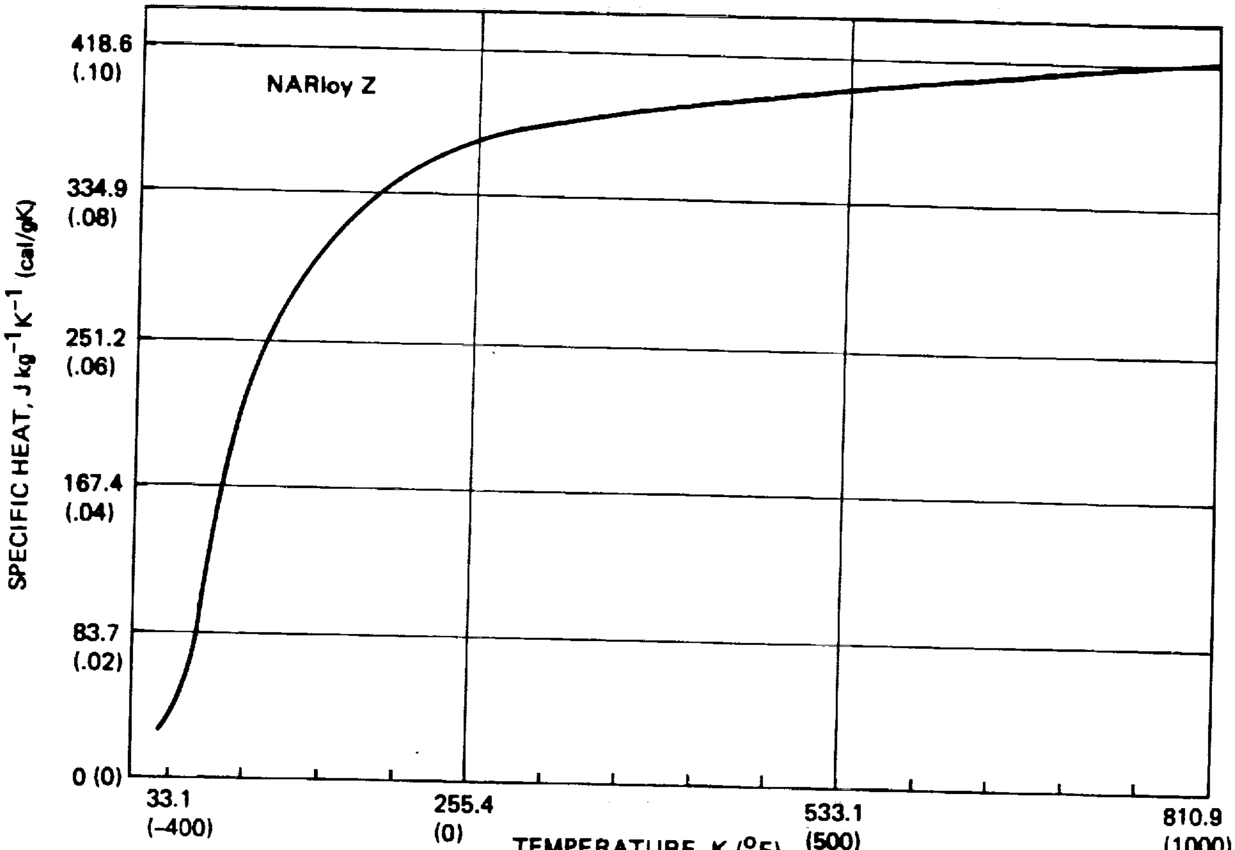

Figure 13 Specific Heat vs Temperature for NARloy Z

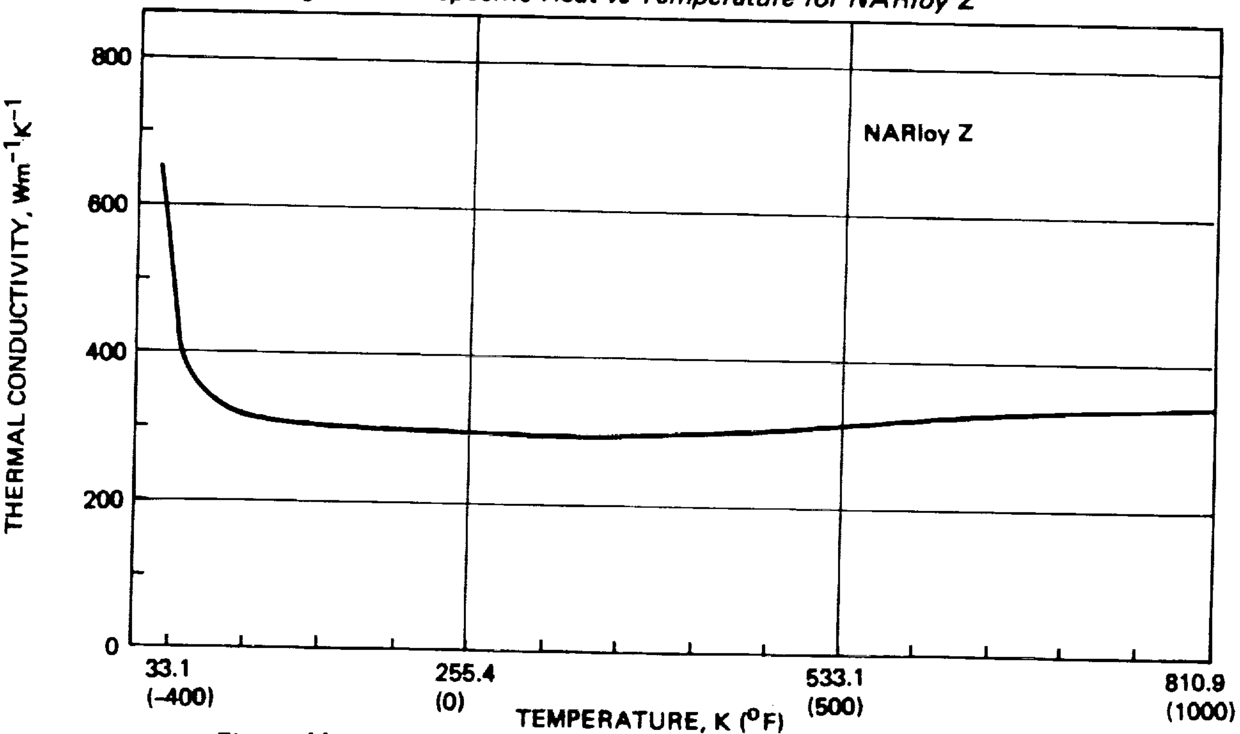

Figure 14 Thermal Conductivity vs Temperature for NARloy Z

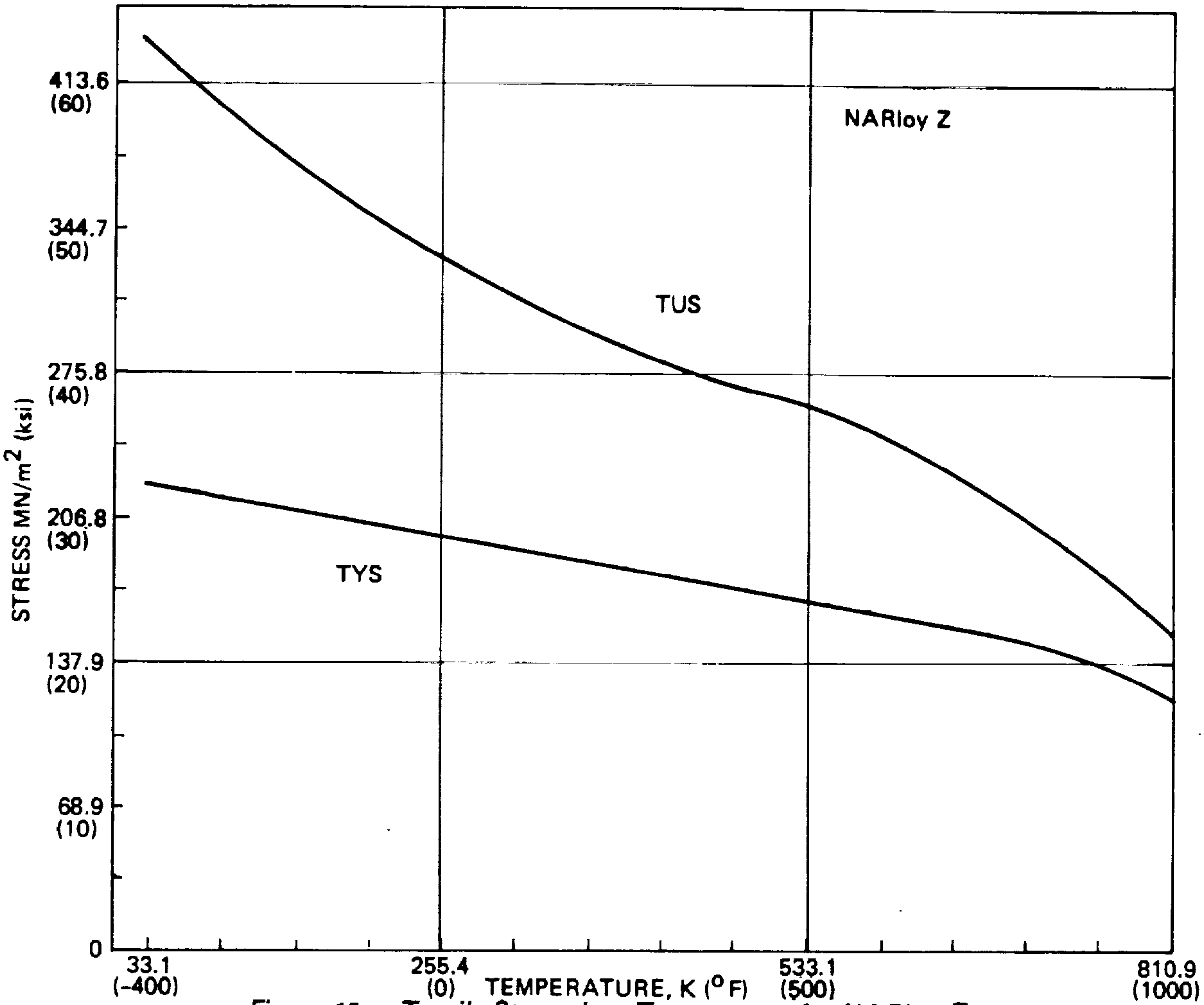

Figure 15 Tensile Strength vs Temperature for NARloy Z

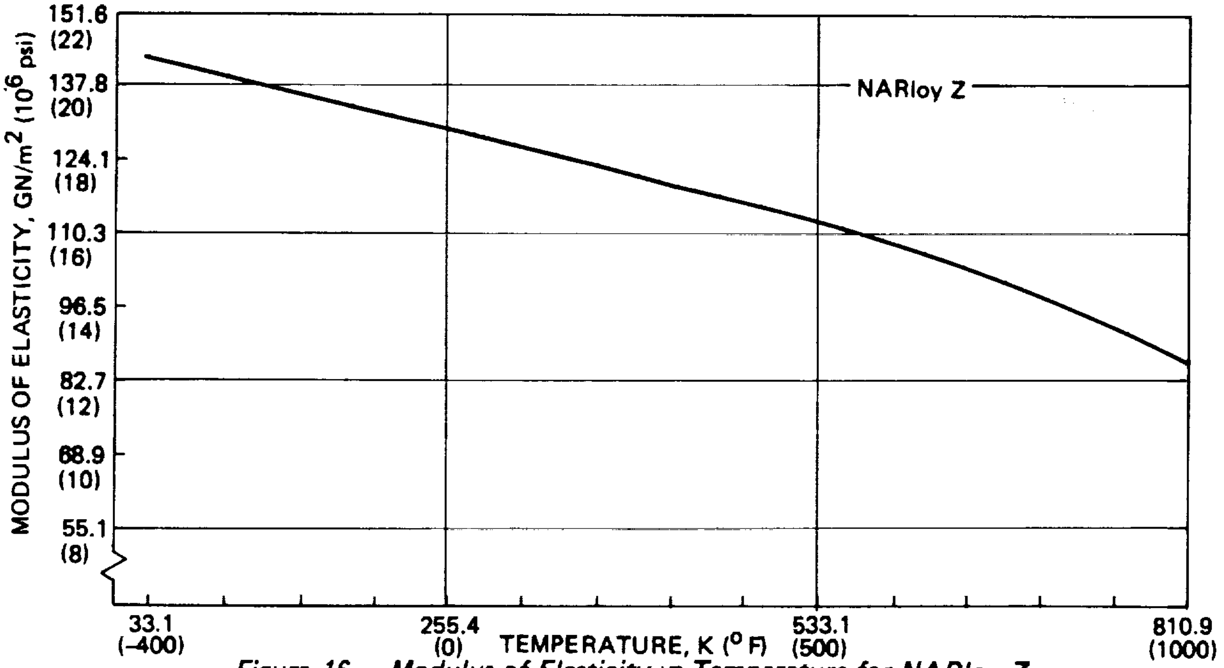

Figure 16 Modulus of Elasticity vs Temperature for NARloy Z

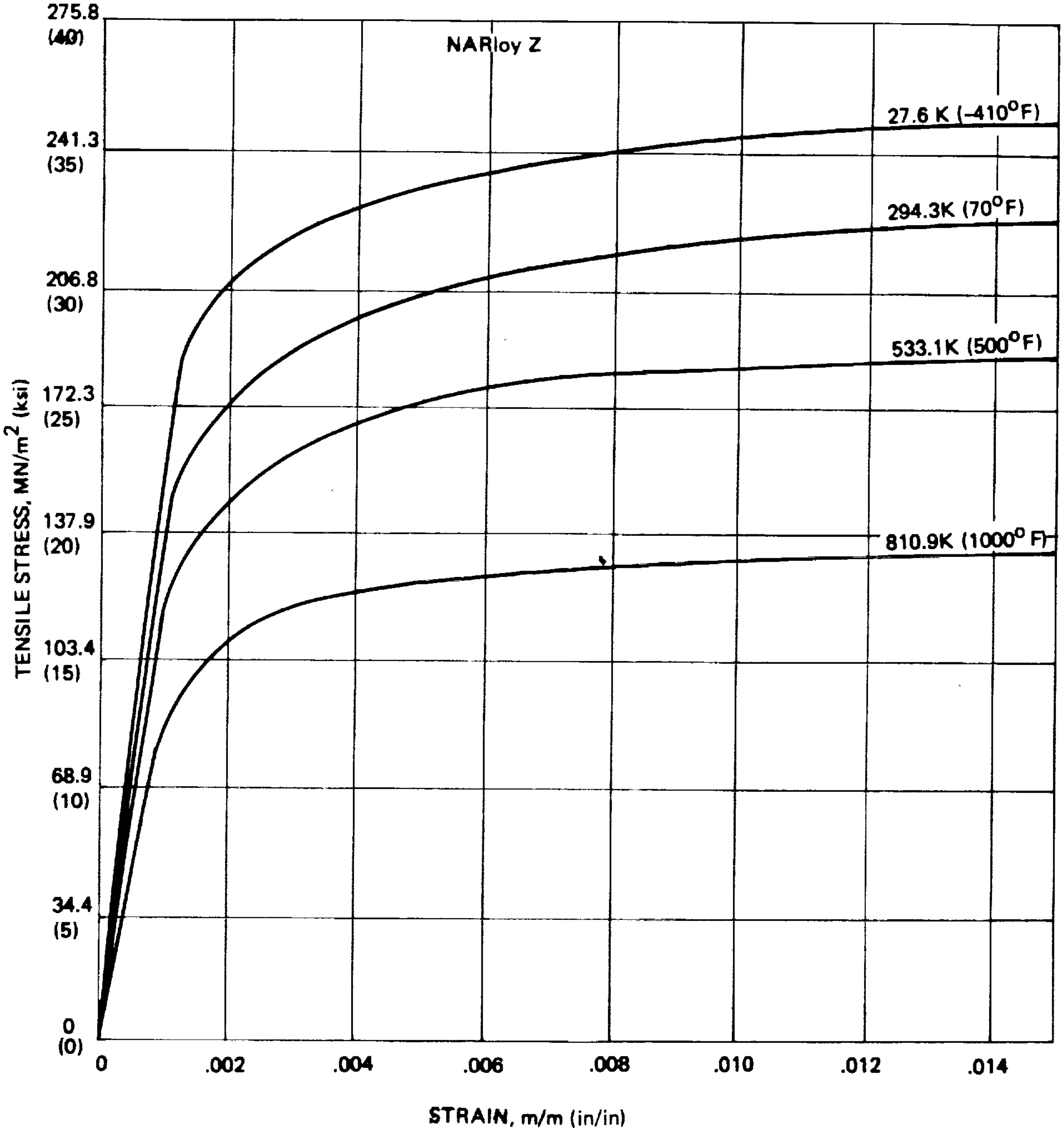

Figure 17 Typical Stress-Strain Curves for NARloy Z

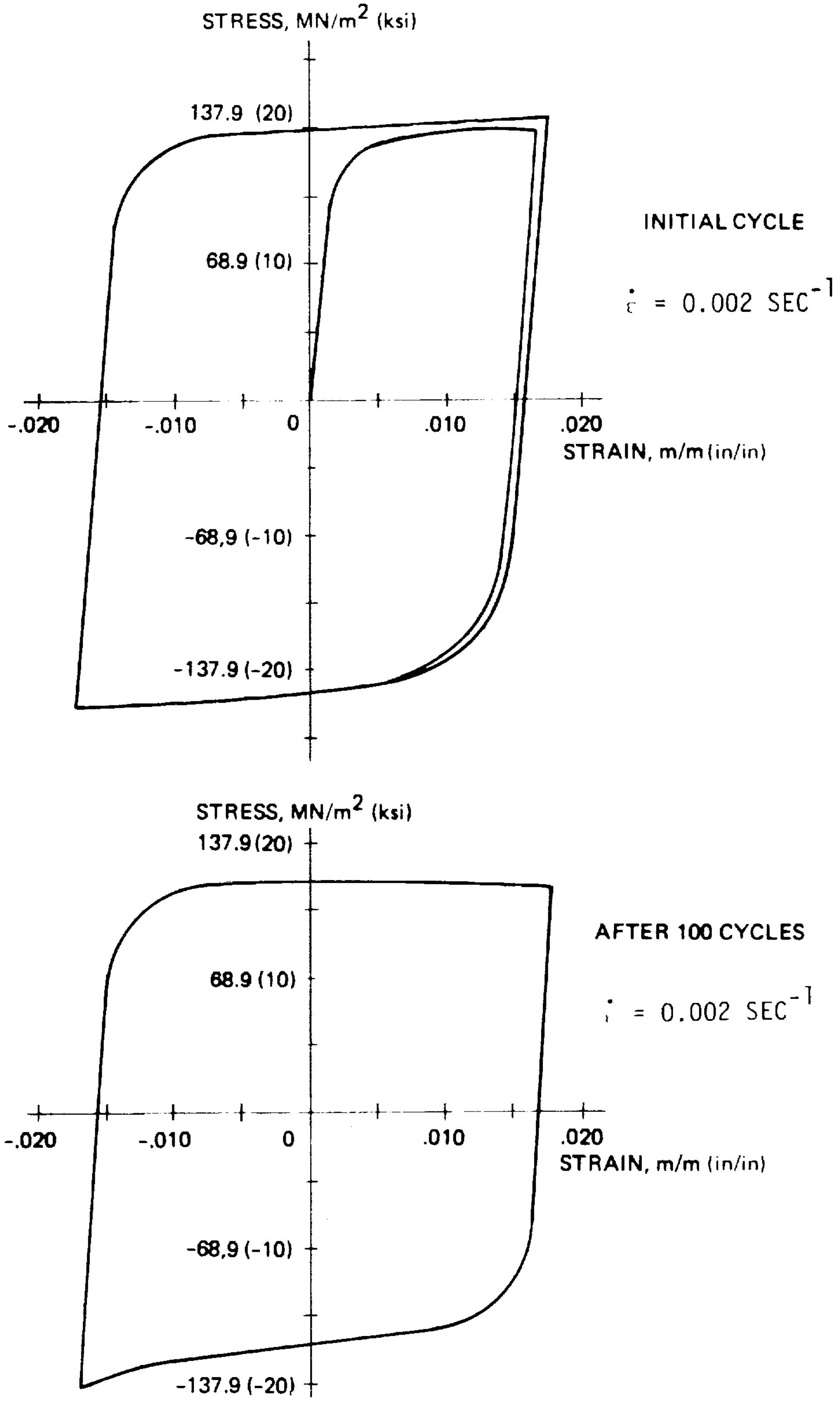

Figure 16 810.9K (1000°F) Cyclic Stress Strain Curves for NARloy Z

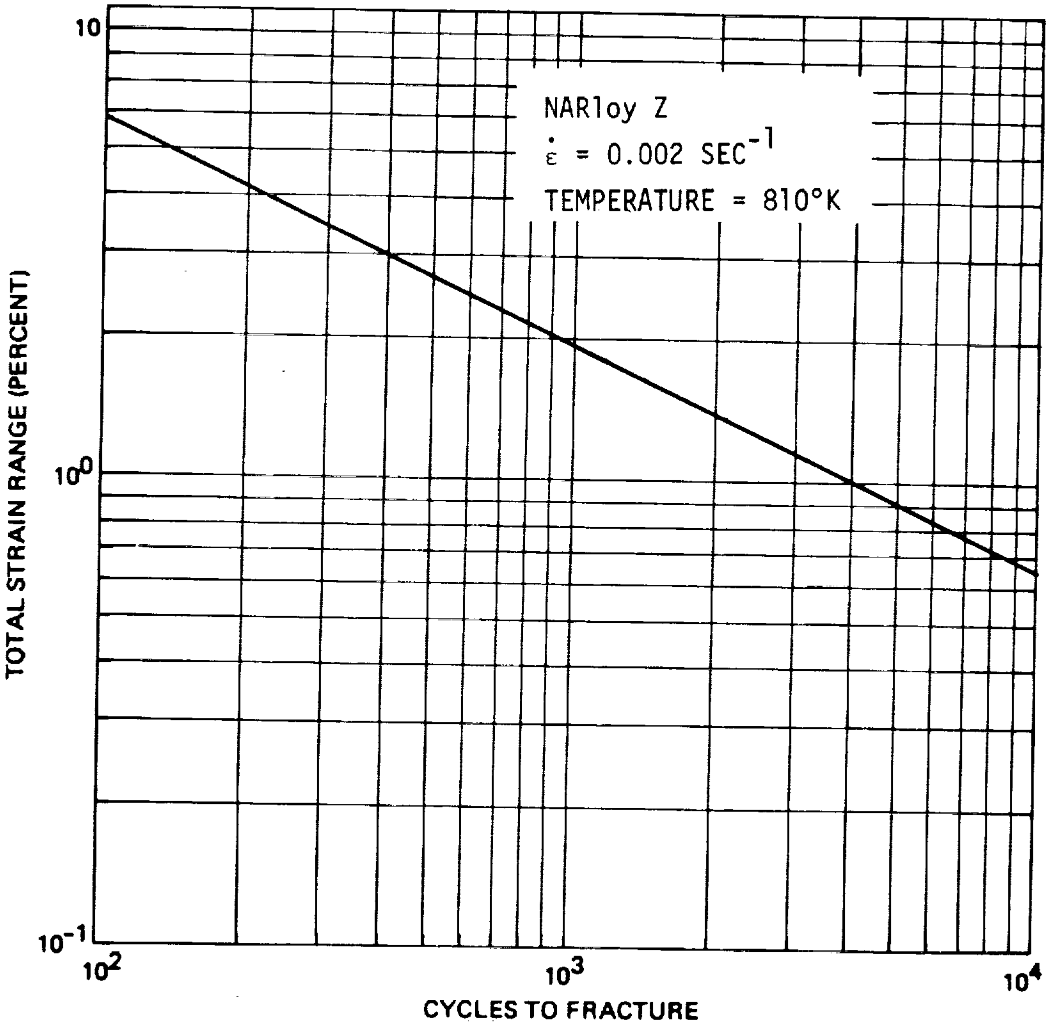

Figure 19 Typical Low-Cycle Fatigue Life of NARloy Z

2.3 *OFHC Copper

General Information

OFHC copper an oxygen free grade of essentially pure copper. The material has very high electrical and thermal conductivity combined with a high melting point.
The material is readily hot or cold worked and the strength of the material increases with the amount of working. In the annealed condition the material has a relatively low strength.
At cryogenic temperatures the material exhibits high ductility.

*American Metal Climax, Inc. – Tradename for an Oxygen-Free High-Conductivity copper.

Room Temperature Properties			
Material	OFHC Copper		
Condition	Annealed	Quarter Hard	Half Hard
Mechanical properties			
Tensile Ultimate, MN/m^2 (ksi)	202 (32)	330 (48)	344 (50)
Tensile Yield, MN/m^2 (ksi) 0.2% Offset	53 (7.7)	310 (45)	317 (46)
Elongation, %	45	20	25
Reduction of Area, %	80	65	80
Modulus of Elasticity, GN/m^2(psi 10^6)	114 (16.6)	114 (16.6)	114 (16.6)
Poisson's Ratio	.33	.33	.33
Physical Properties			
Density, kg/m^3 (lb/in^3)	8913 (.322)		
Specific Heat, J $kg^{-1}K^{-1}$ (cal/g/K)	385 (.092)		
Thermal Conductivity, $Wm^{-1}K^{-1}$	390		
Coefficient of Thermal Expansion,			
294K to 533K , 10^{-6} [m/m] K^{-1}	17.2		
70°F to 500°F , 10^{-6} (in/in/°F)	(9.5)		

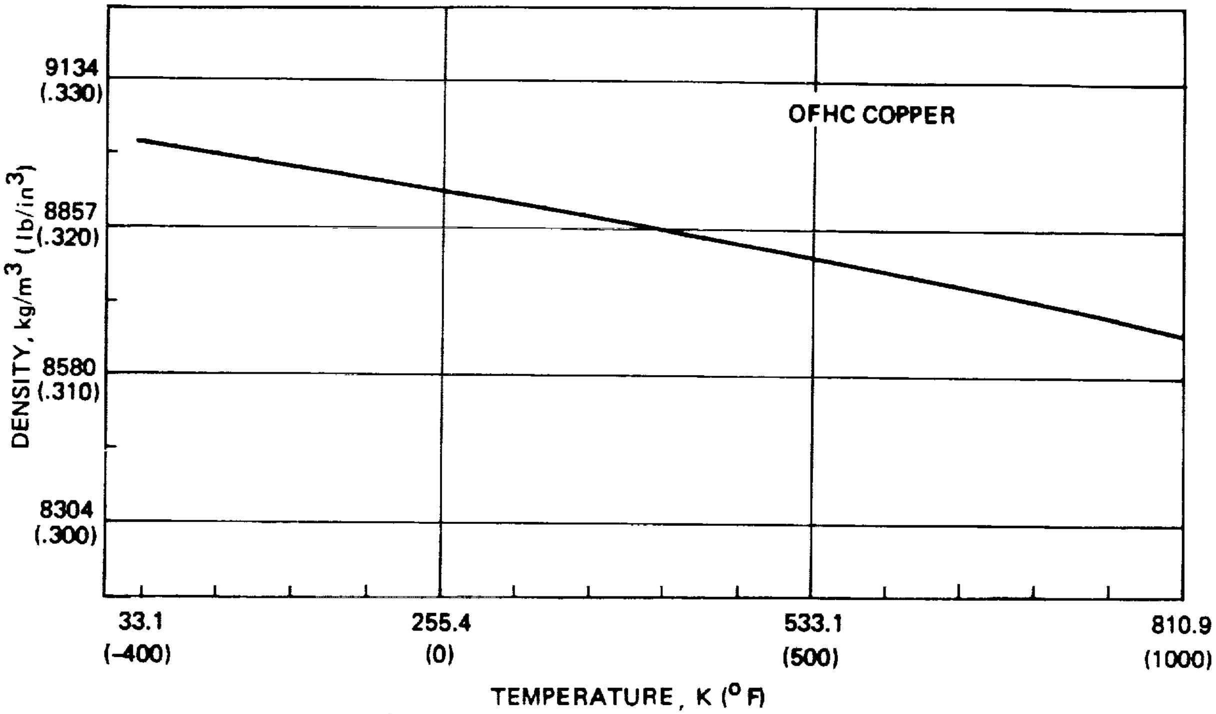

Figure 20 Density vs Temperature for OFHC Copper

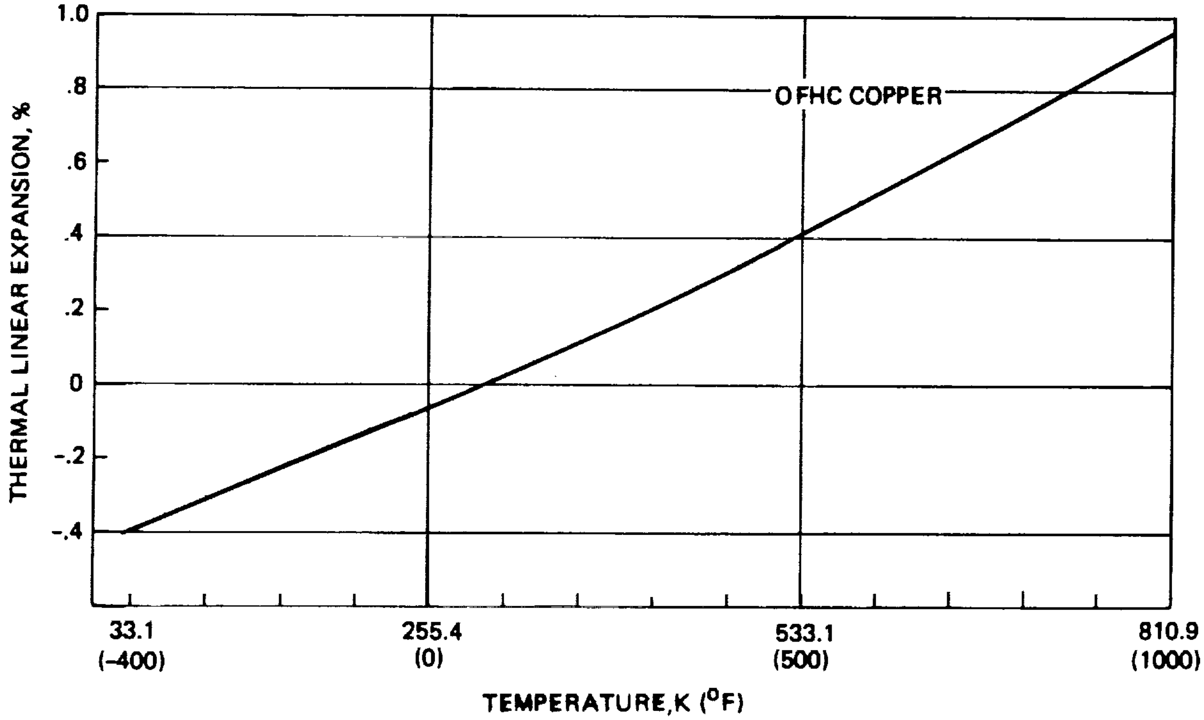

Figure 21 Thermal Linear Expansion vs Temperature for OFHC Copper

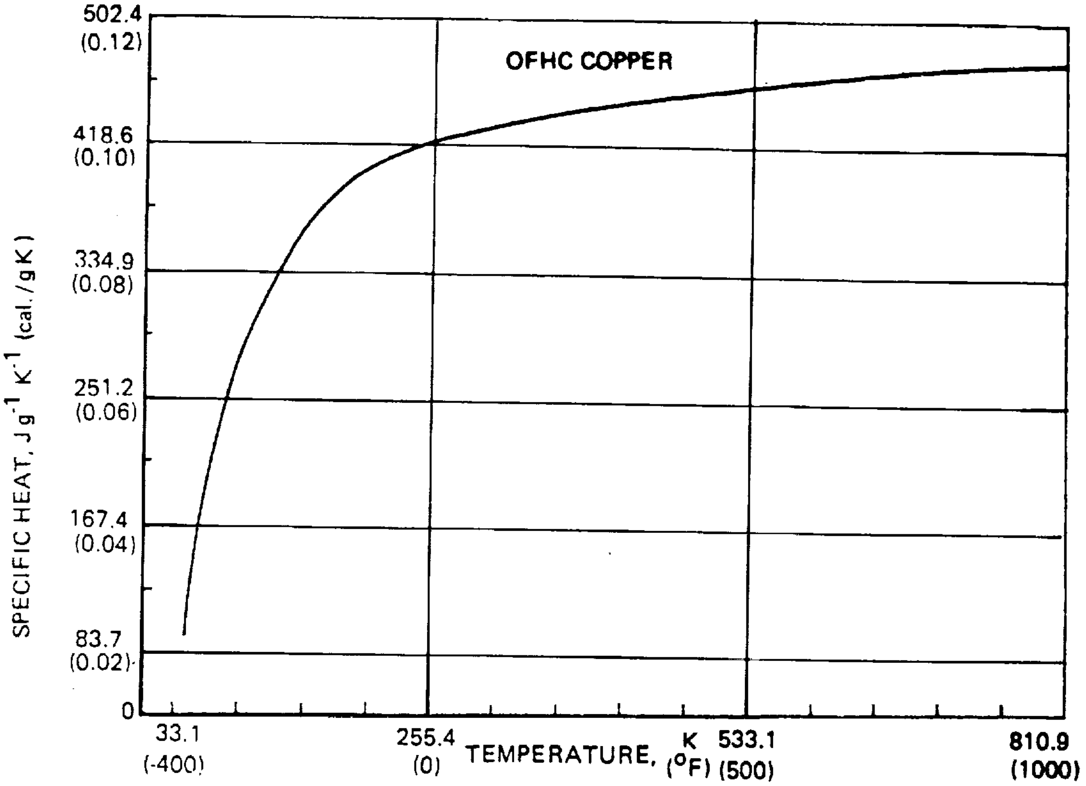

Figure 22 . Specific Heat vs. Temperature for OFHC Copper

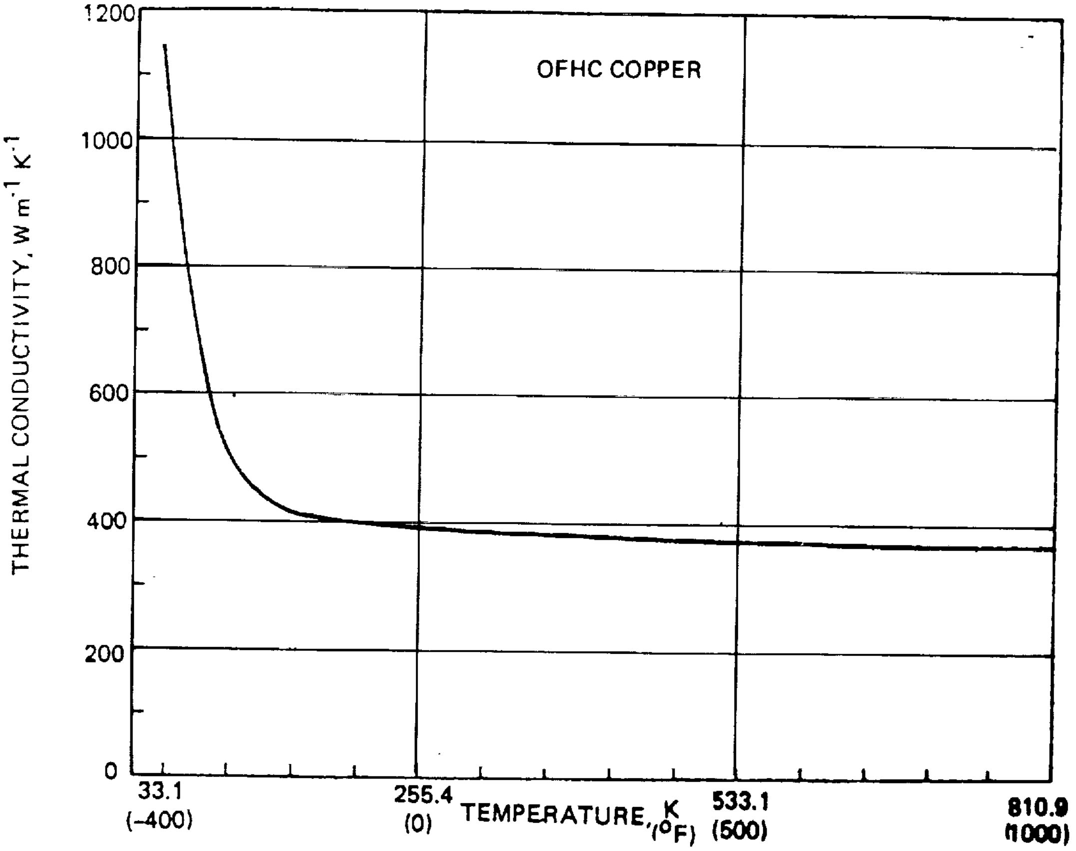

Figure 23 Thermal Conductivity vs Temperature for OFHC Copper

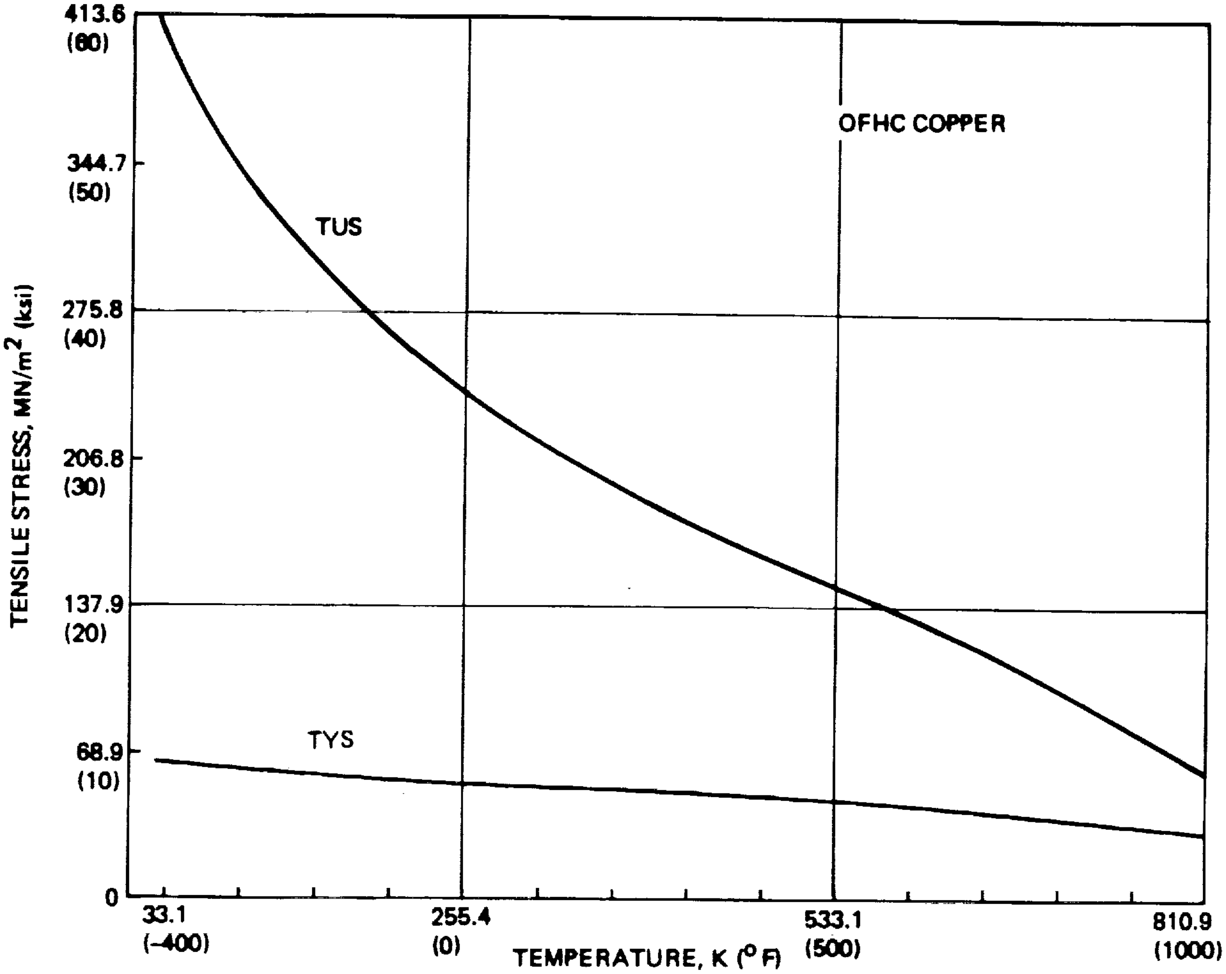

Figure 24 Tensile Strength vs Temperature for OFHC Copper Annealed Condition

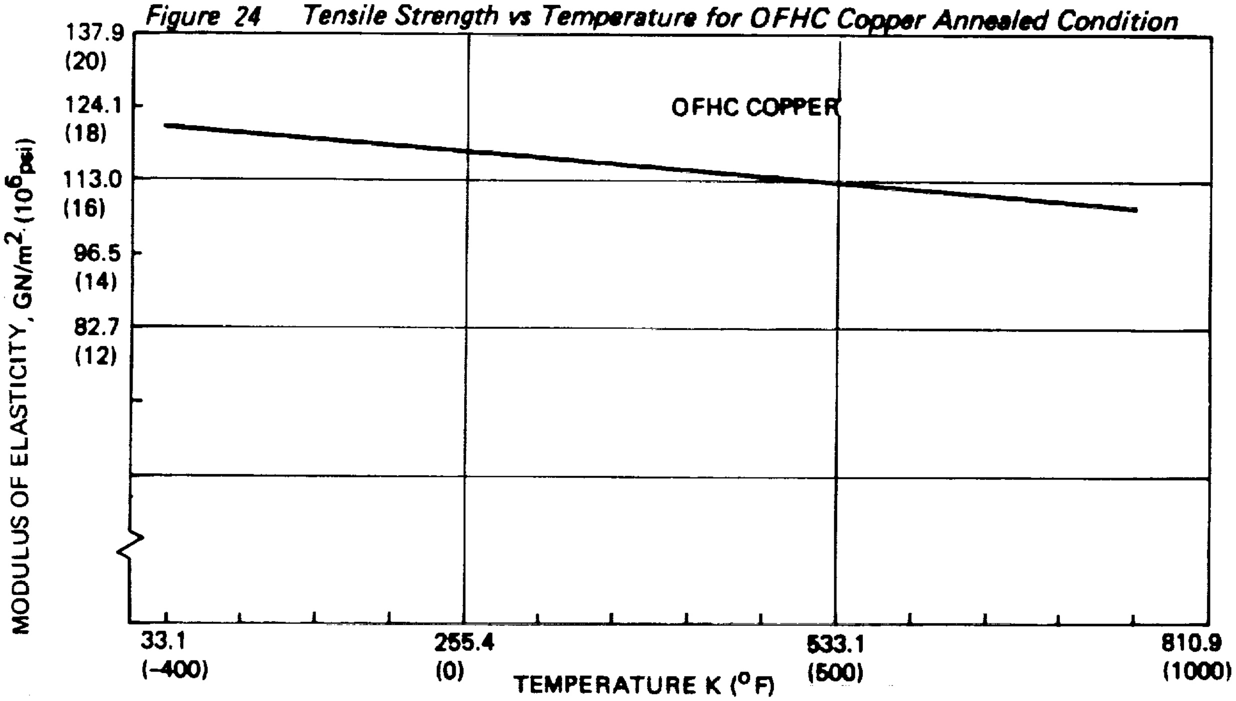

Figure 25 Modulus of Elasticity vs Temperature for OFHC Copper

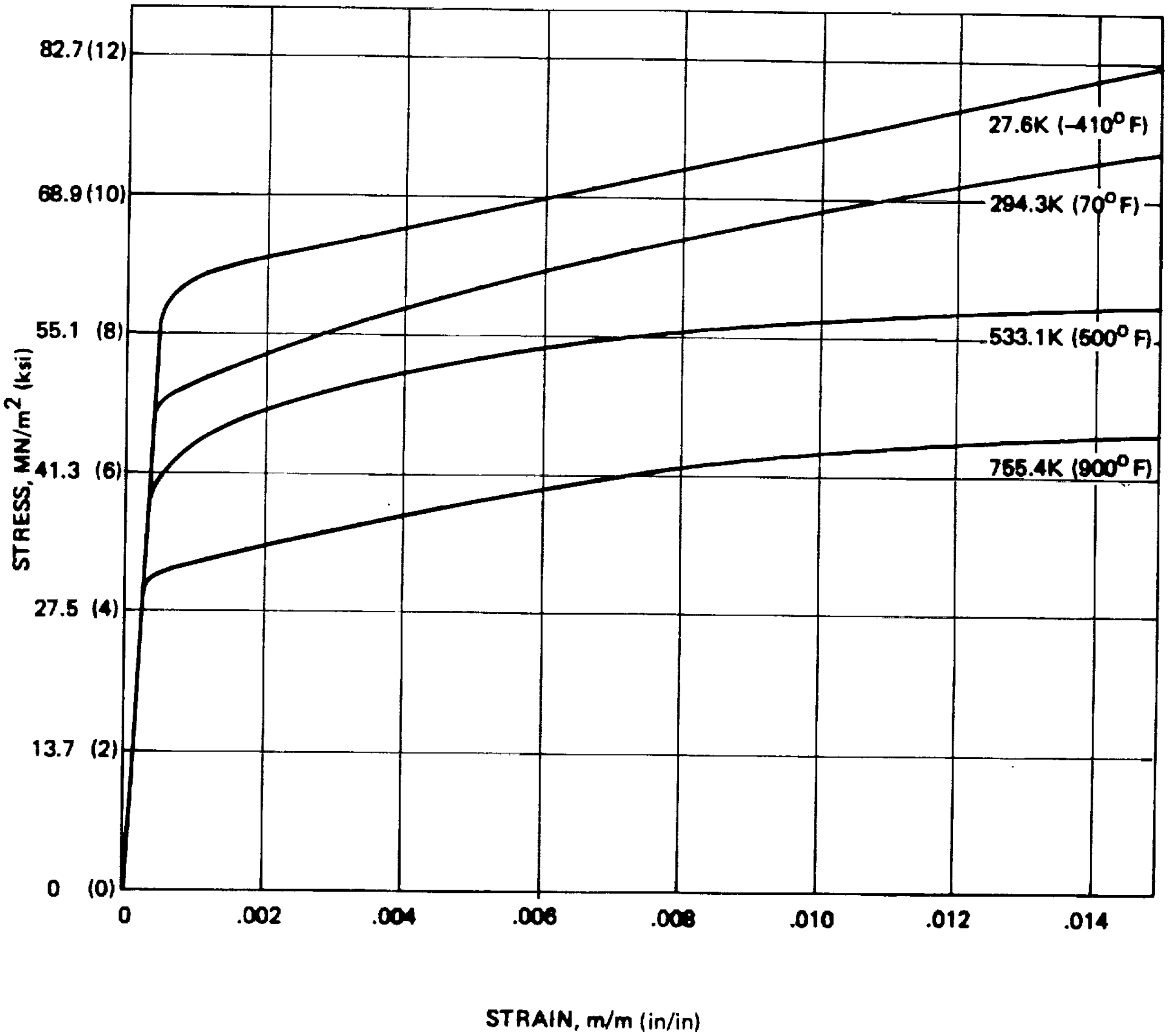

Figure 26 Typical Stress-Strain Curves for OFHC Copper Annealed Condition

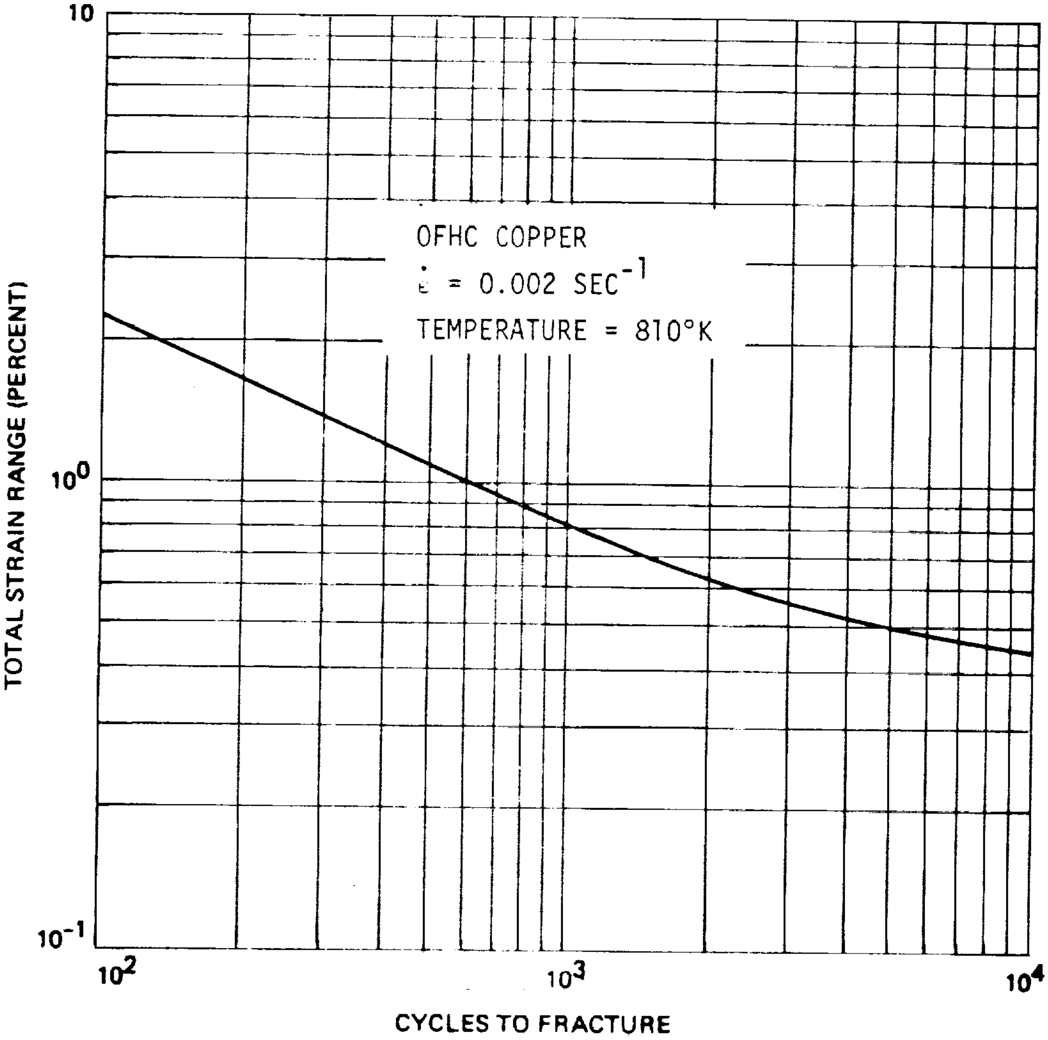

Figure 27 Typical Low-Cycle Fatigue Life of OFHC Copper Annealed Condition

2.4 Electroformed Copper

General Information

Electroformed copper is essentially pure copper obtained from an electro-chemical process. The technique involves the deposition of copper ions from a sulfate electrolyte onto a mandrel. The copper deposits may be bonded to or sandwiched between other deposits to provide integral heat sinks. The material can be joined to other materials using the same methods that would be employed for wrought copper. The electroformed copper has very high electrical and thermal conductivity, relatively low strengths, and is non-magnetic.

Room Temperature Properties		
Material:	Electroformed Copper	
Condition:	As Formed	
Mechanical Properties		
Tensil Ultimate, MN/m^2 (ksi)	227	(33.0)
Tensile Yield, MN/m^2 (ksi) 0.2% offset	107	(15.5)
Elongation, %	20	
Reduction of Area, %	53	
Modulus of Elasticity, GN/m^2 (10^6 psi)	114	(16.6)
Poisson's Ratio	.33	
Physical Properties		
Density, kg/m^3 (lb/in.^{3})	8913	(.322)
Specific Heat, J kg^{-1} K^{-1} (cal/g/K)	385	(.092)
Thermal Conductivity, W m^{-1} K^{-1}	390	
Coefficient of Thermal Expansion,		
294K to 533K, 10^{-6} [m/m] K^{-1}	17.2	
70°F to 500°F, 10^{-6} (in./in./°F)	(9.5)	

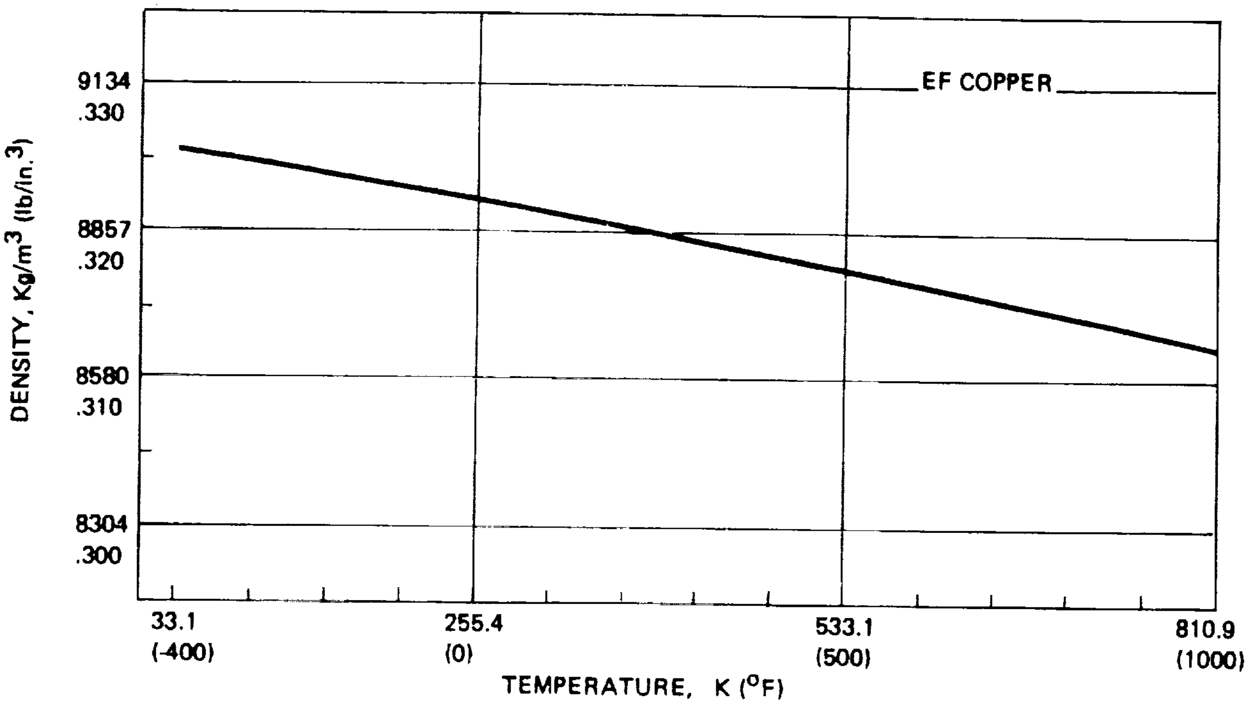

Figure 28 Density vs Temperature for Electroformed Copper

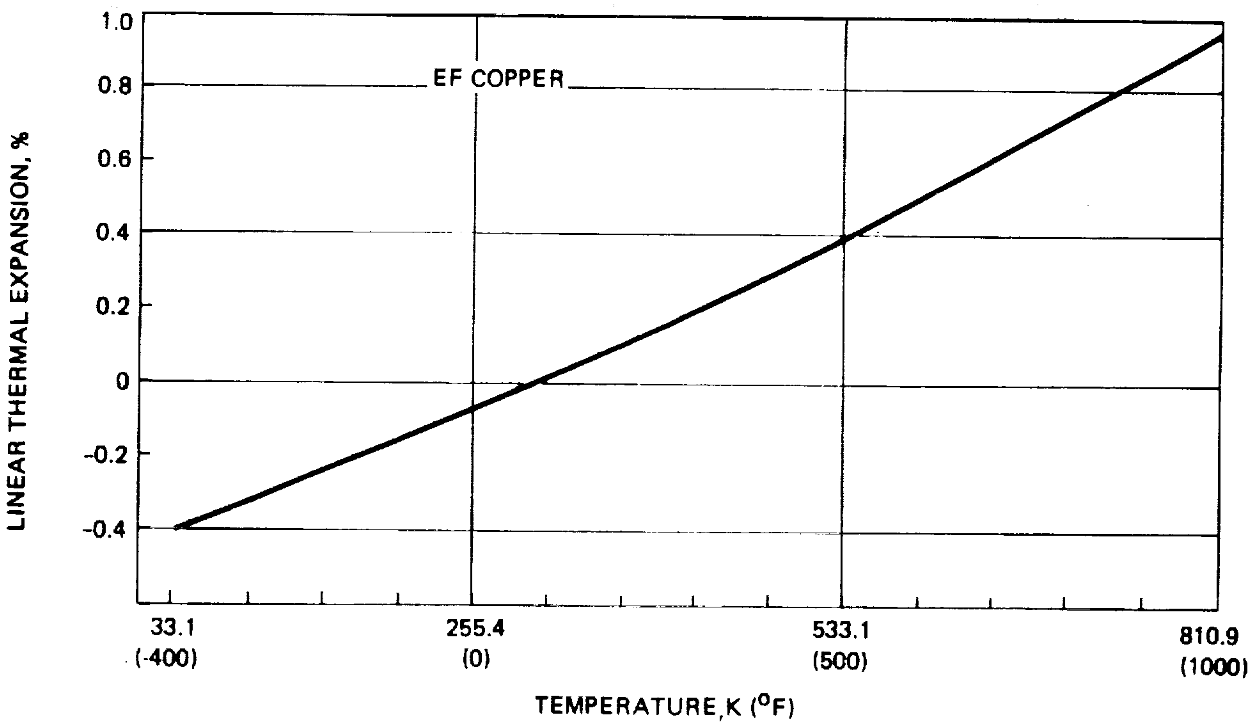

Figure 29 Thermal Linear Expansion vs. Temperature for Electroformed Copper

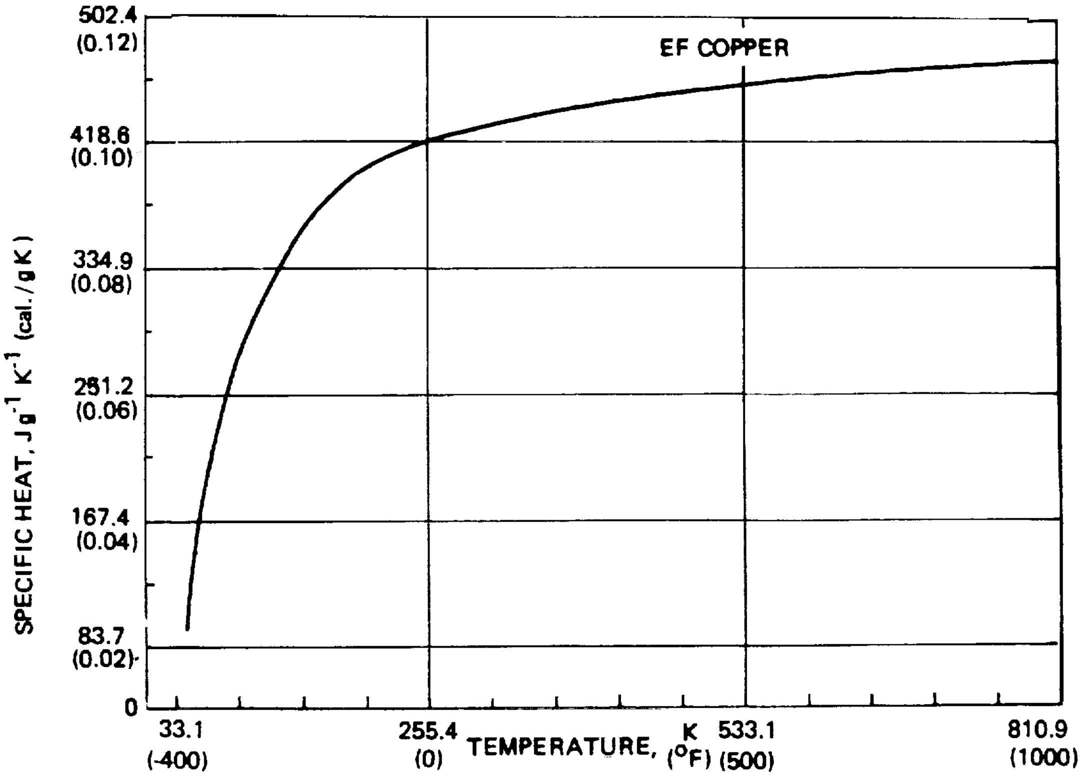

Figure 30 · Specific Heat vs. Temperature for Electroformed Copper

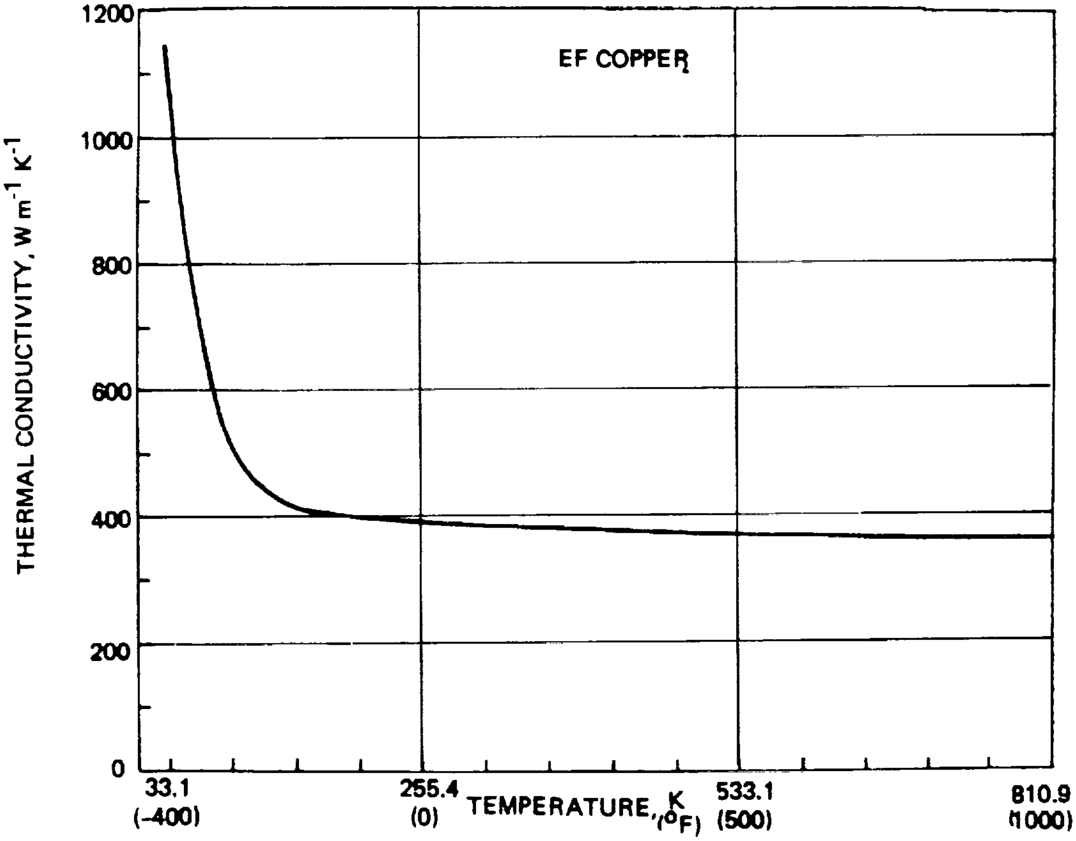

Figure 31 Thermal Conductivity vs. Temperature for Electroformed Copper

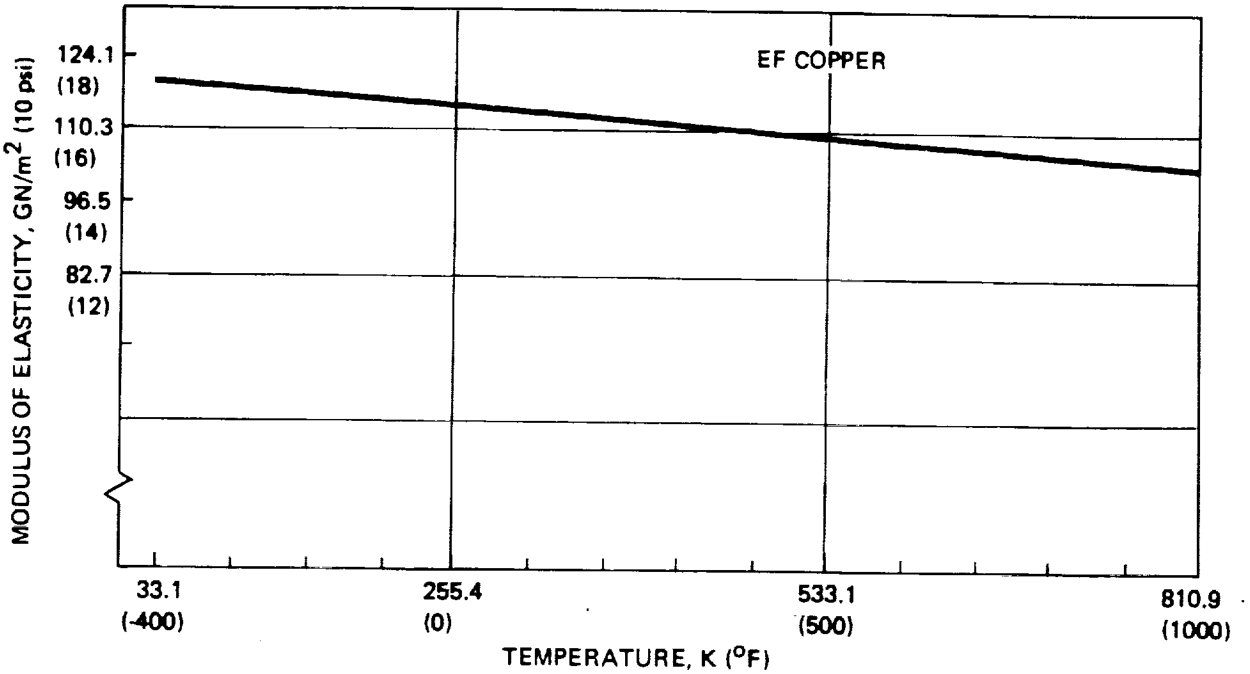

Figure 32 Modulus of Elasticity vs. Temperature for Electroformed Copper

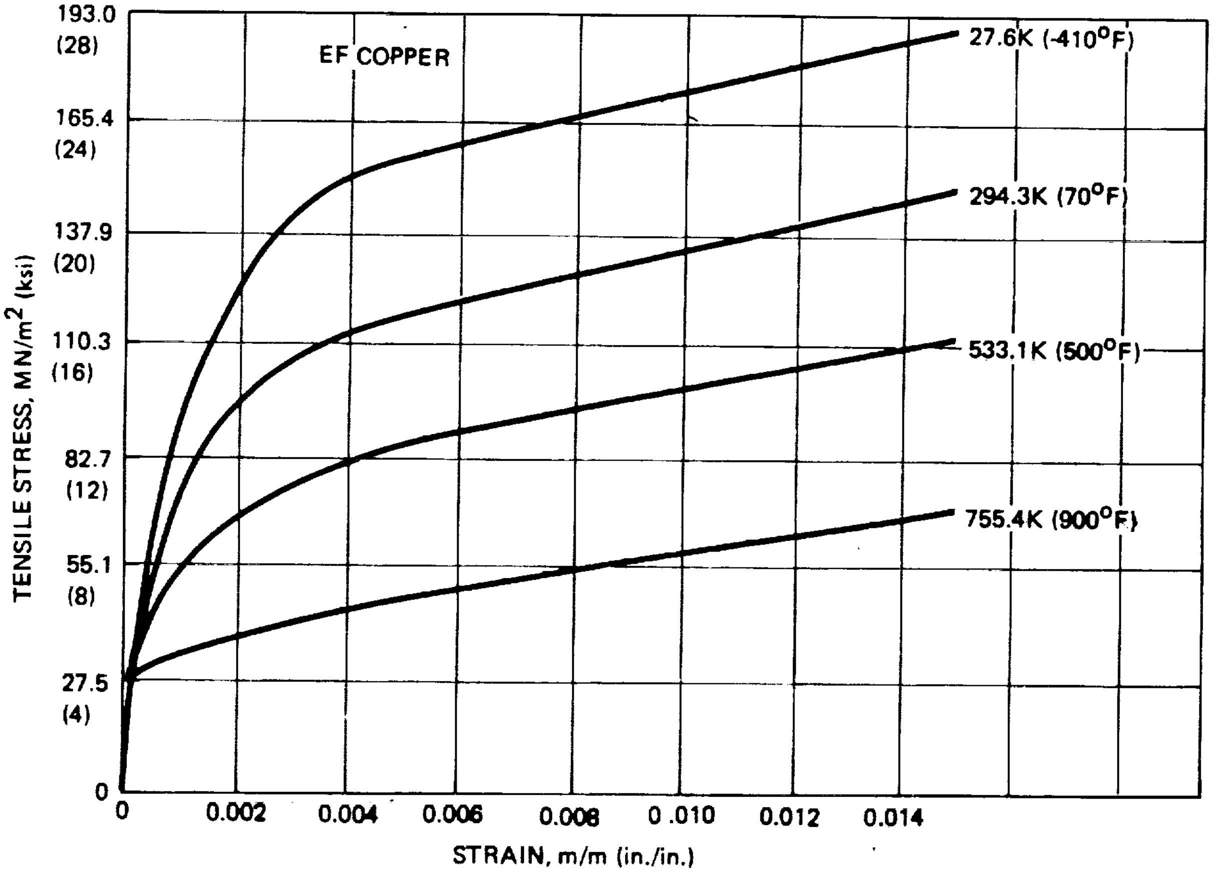

Figure 33 Typical Stress-Strain Curves for Electroformed Copper – As Formed Condition

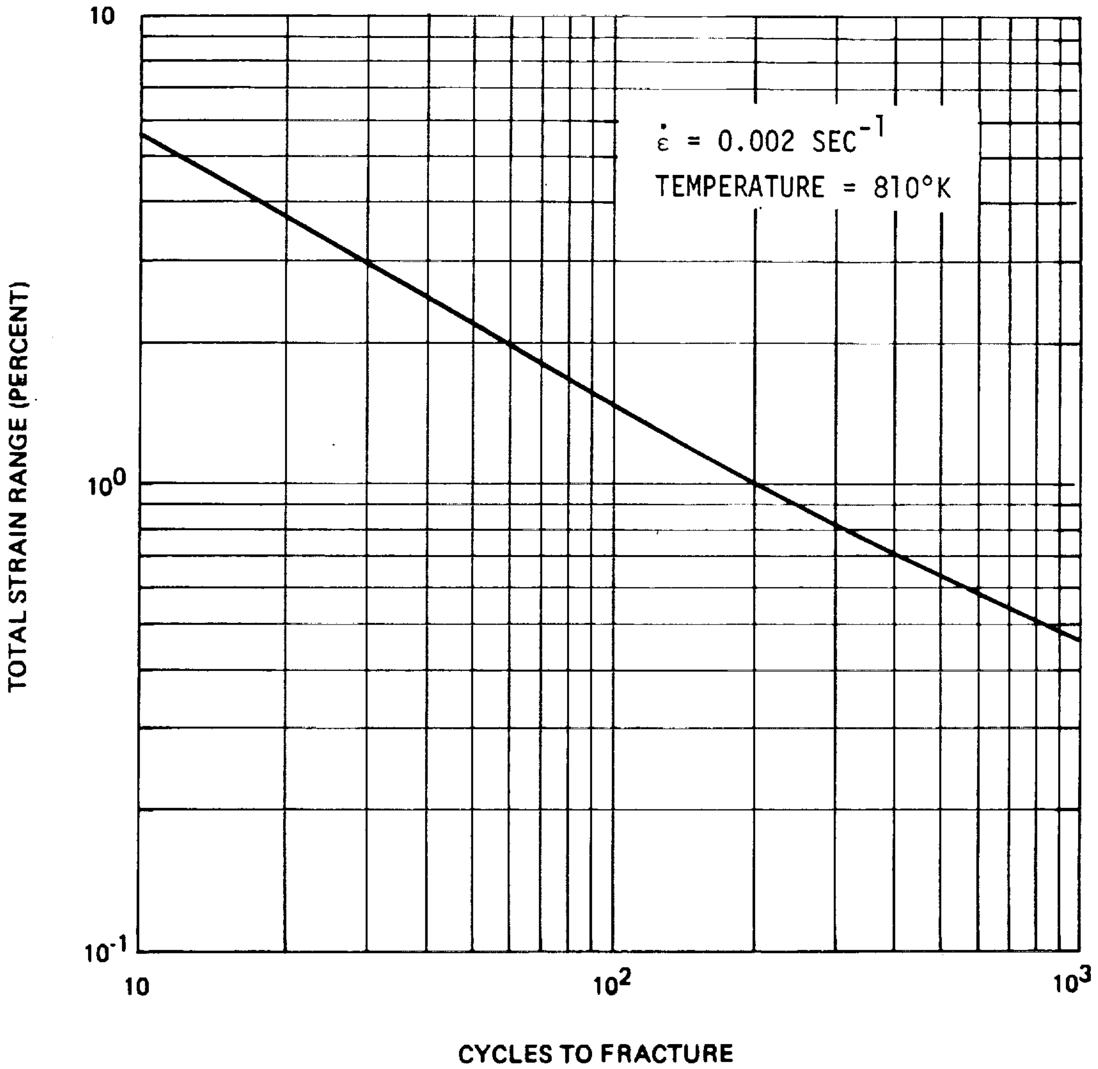

Figure 34 Typical Low-Cycle Fatigue Life of Electroformed Copper – As Formed Condition

2.5 Fine Silver

General Information

Fine silver, often called commercial fine silver, has a maximum of 0.10 percent total impurities. Fine silver has the highest electrical and thermal conductivity of all metals and only gold is more ductile and malleable. The metal has rather low strength even after severe cold work and it cannot be hardened by any thermal treatment. Silver can be readily hot or cold worked and is relatively difficult to machine, particularly in the annealed condition. The material can be annealed at low temperatures. Therefor, if the maximum hardening effect of cold work is desired, care must be taken to avoid an appreciable rise in temperature due to working the material too rapidly.

Room Temperature Properties	
Material	Fine Silver
Condition	As Drawn
Mechanical Properties	
Tensile Ultimate, MN/m^2 (ksi)	289 (42)
Tensile Yield, MN/m^2 (ksi) 0.2% Offset	283 (41)
Elongation, %	5
Reduction of Area, %	85
Modulus of Elasticity, GN/m^2(10^{6}psi)	71 (10.3)
Poisson's Ratio	.37
Physical Properties	
Density, kg/m^3 (lb/in^3)	10,490 (.379)
Specific Heat, J kg^{-1}K^{-1} (cal/g/K)	237 (.0566)
Thermal Conductivity, Wm^{-1}K^{-1}	400
Coefficient of Thermal Expansion,	
294K to 533K , 10^{-6}[m/m] K^{-1}	19.5
70°F to 500°F , 10^{-6}(in/in/°F)	(10.3)

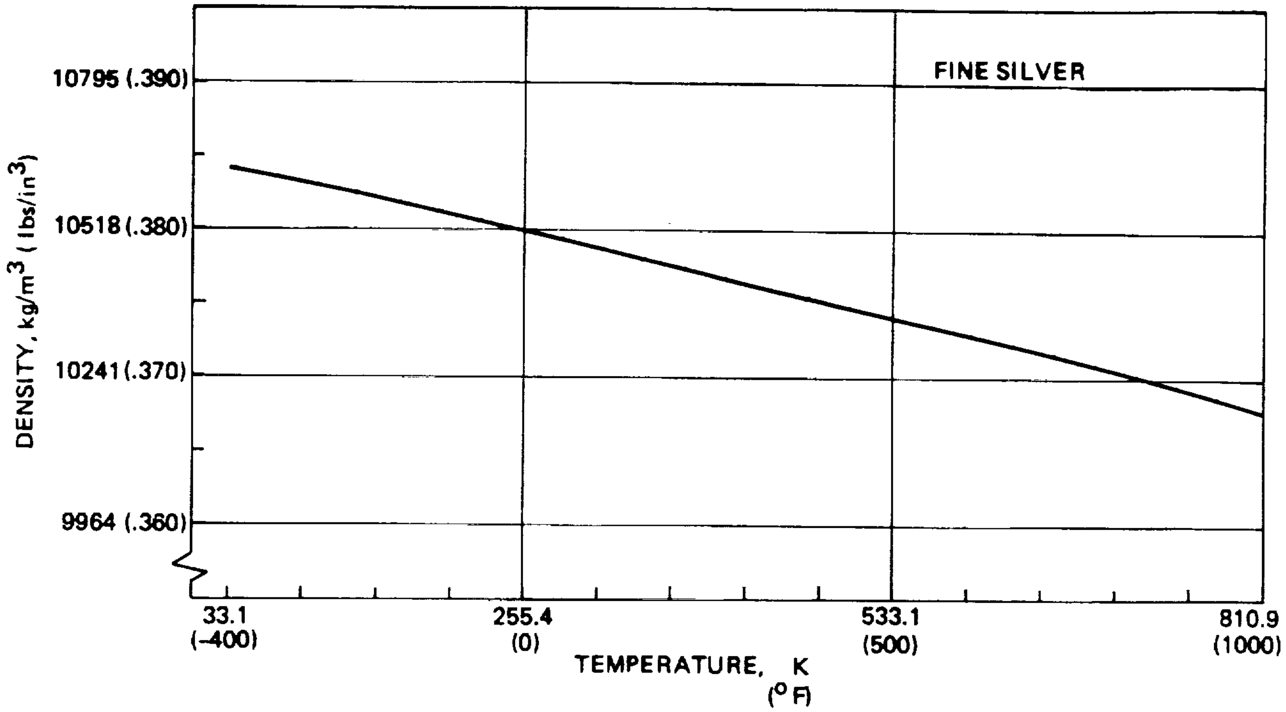

Figure 35 Density vs Temperature for Fine Silver

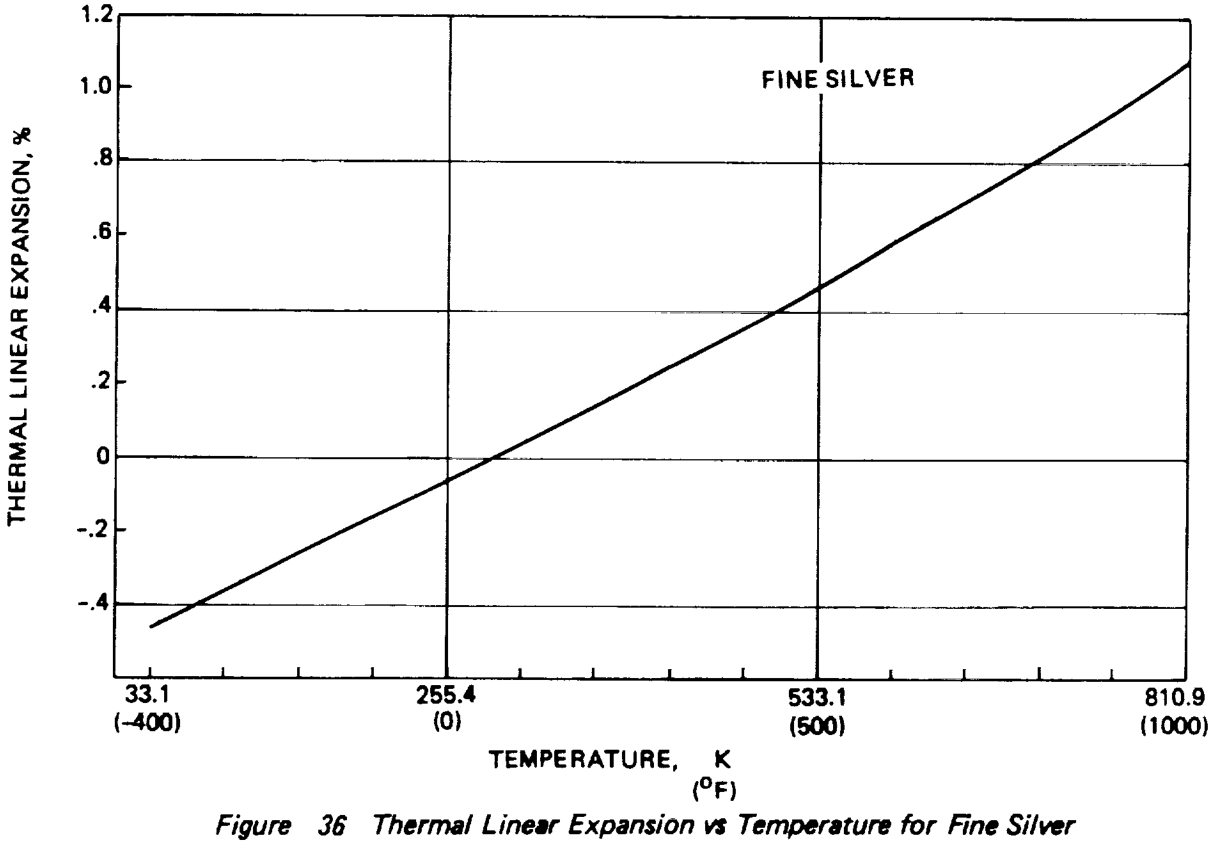

Figure 36 Thermal Linear Expansion vs Temperature for Fine Silver

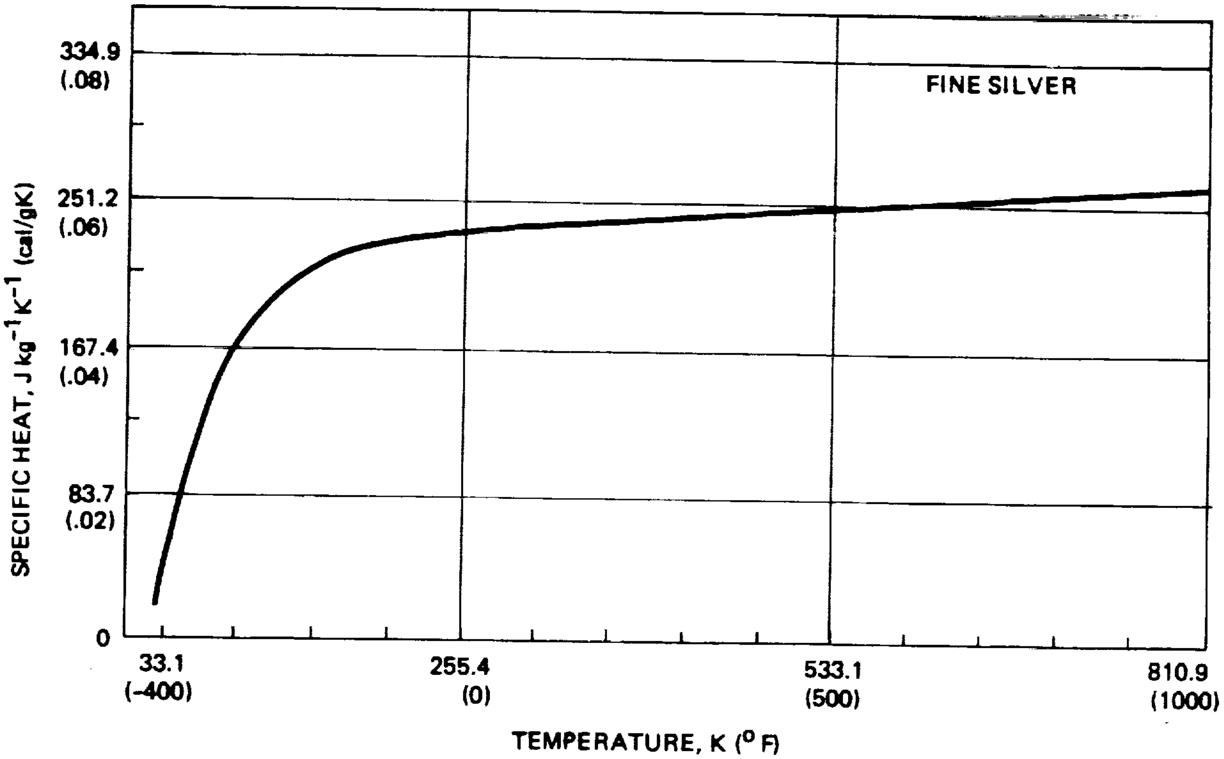

Figure 37 Specific Heat vs Temperature for Fine Silver - As Drawn Condition

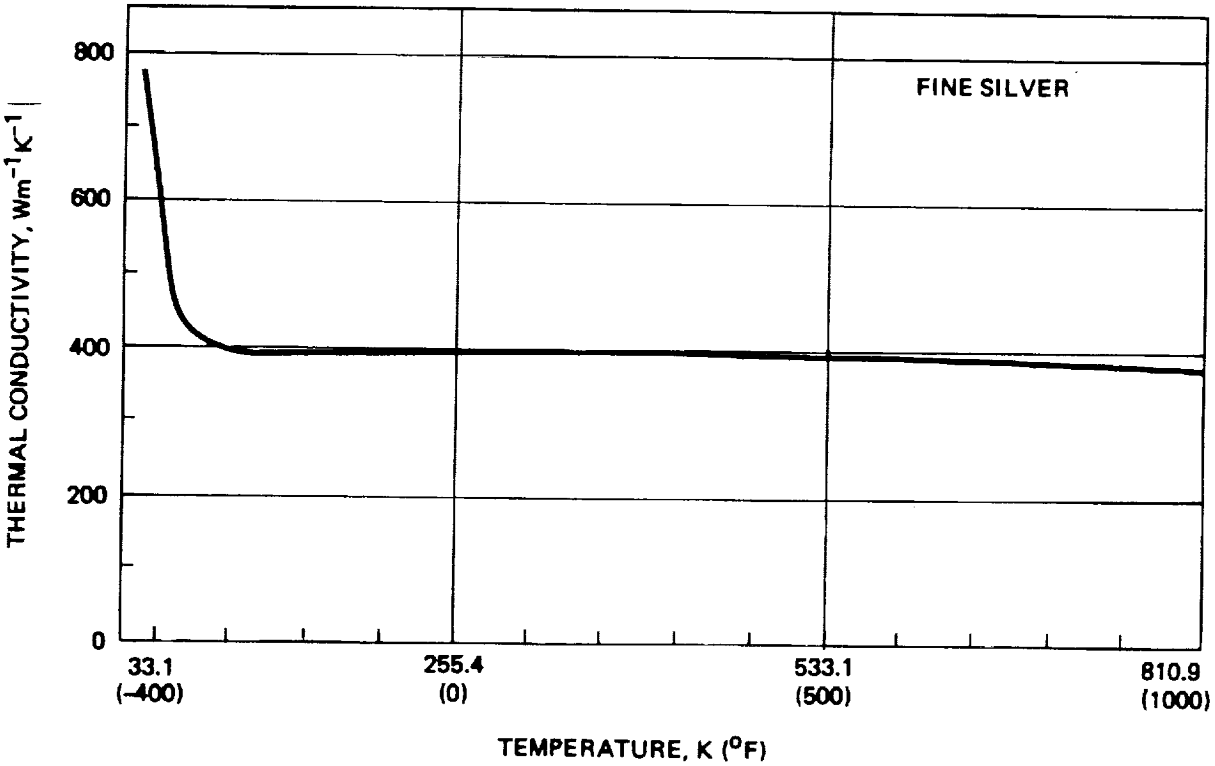

Figure 38 Thermal Conductivity vs Temperature for Fine Silver -As Drawn Condition

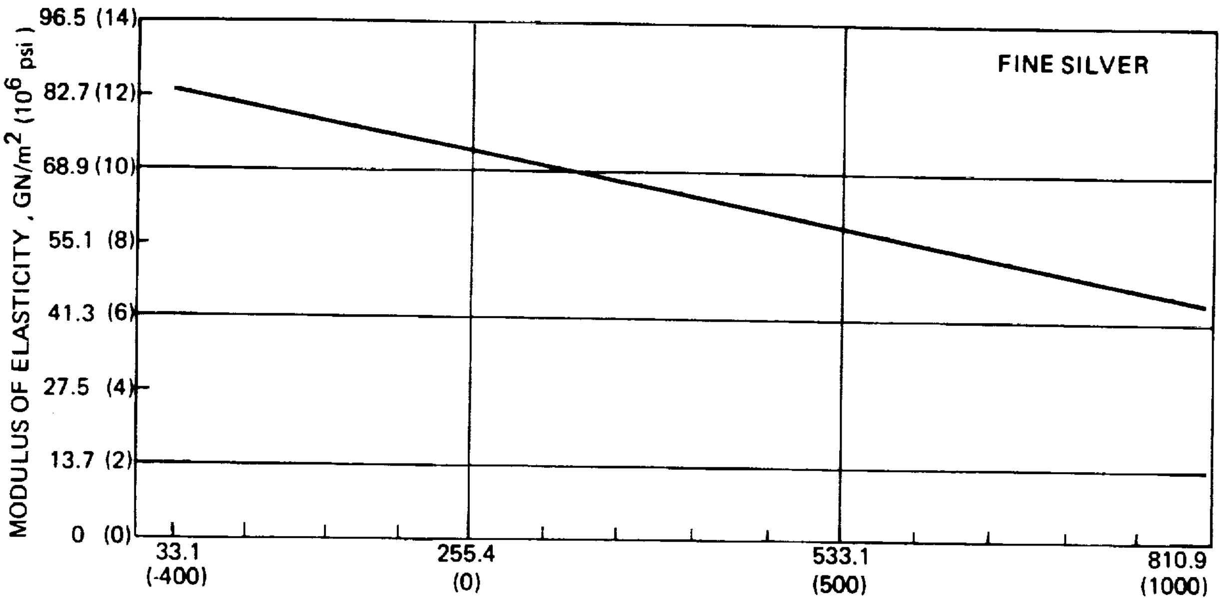

Figure 39 Modulus of Elasticity vs Temperature for Fine Silver—As Drawn Condition

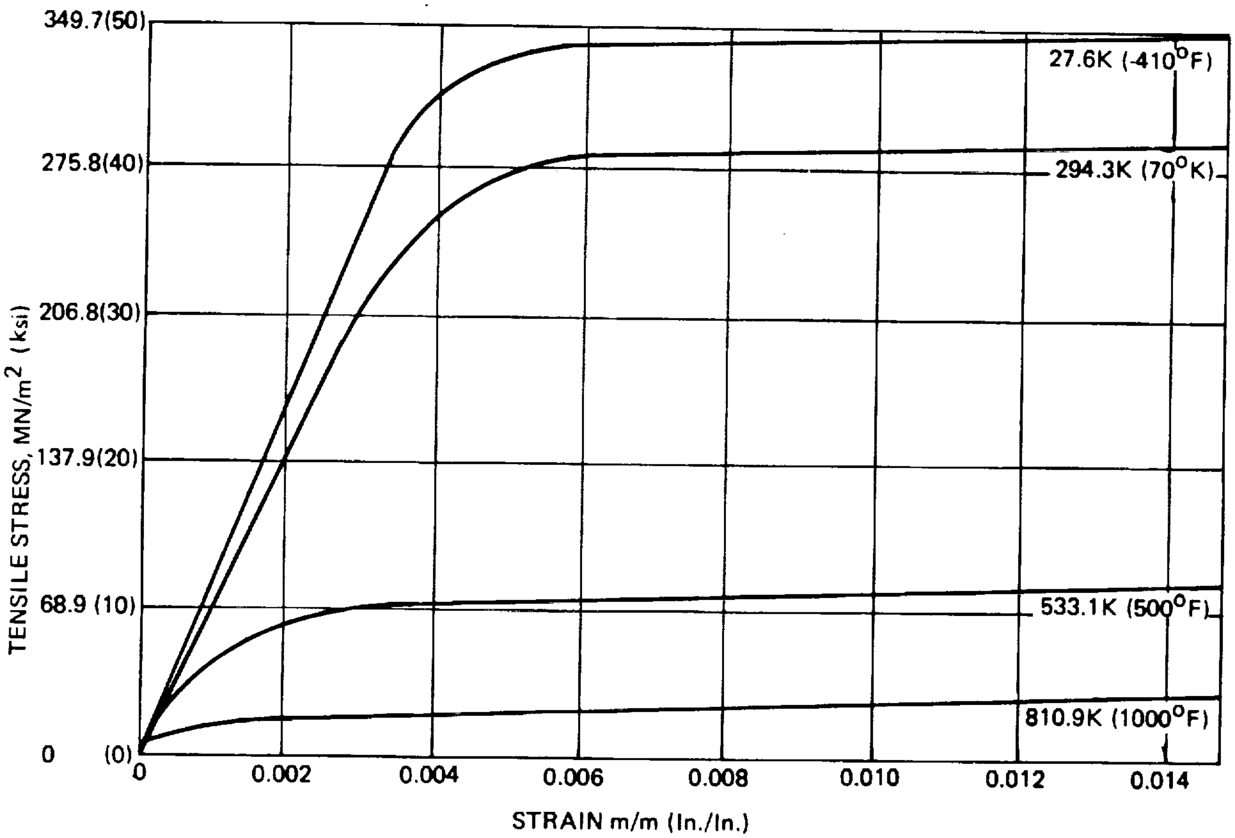

Figure 40 Typical Stress-Strain Curves for Fine Silver—As Drawn Condition

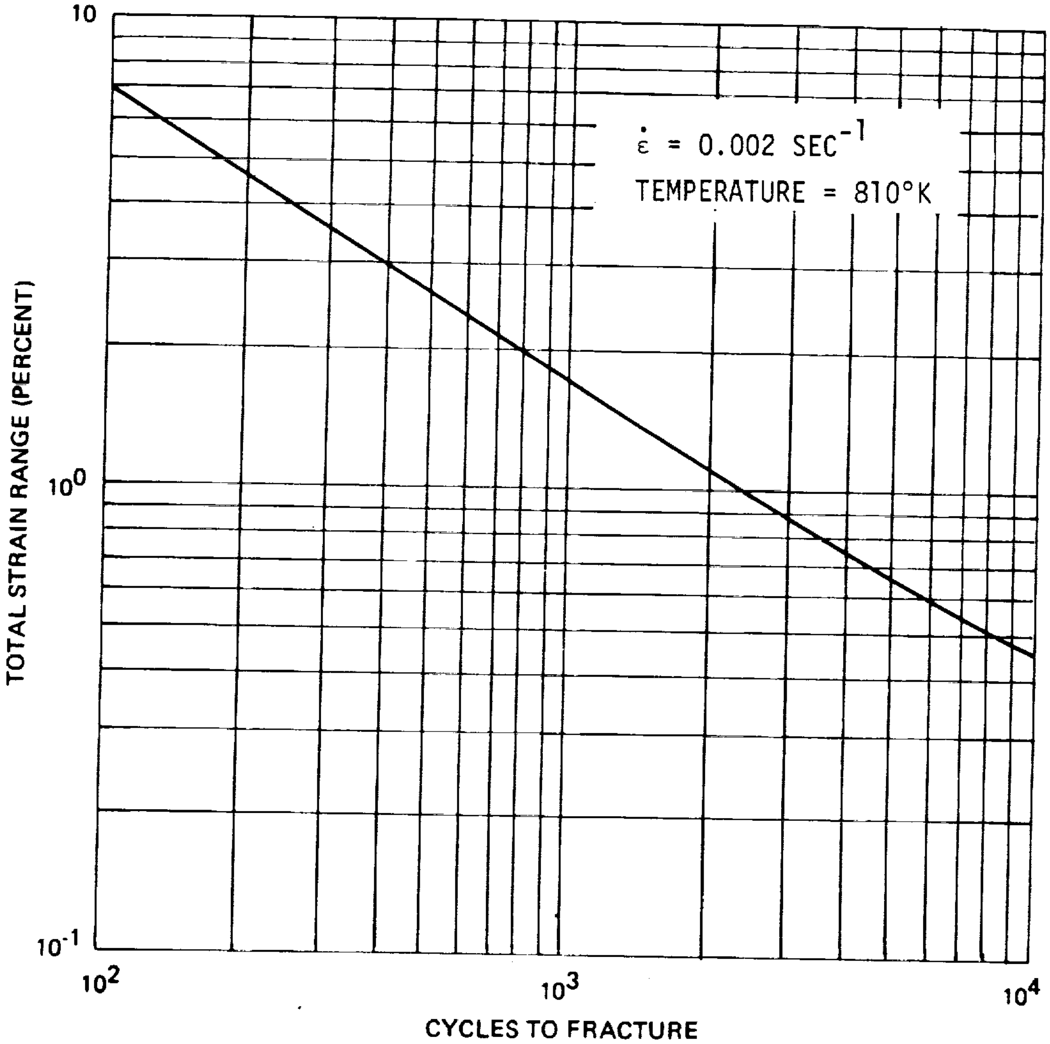

Figure 41 Typical Low-Cycle Fatigue Life of Fine Silver – As Drawn Condition

2.6 Electroformed Nickel

General Information

Electroformed nickel is obtained from an electro-chemical process involving the deposition of nickel ions from an electrolyte onto a mandrel. A sulfamate bath is used to obtain nickel deposites with low internal stresses. The nickel deposits can be bonded to or sandwiched between other material deposits to provide integral heat sinks in an almost unlimited range of regular and irregular configurations. The electroformed nickel is easily joined to other metals by welding, brazing, or soldering with the use of common materials and methods. Mechanical properties of electroformed nickel can be varied over a wide range by the methods of deposition and by the composition of the plating bath. The metallurgical structure is characterized by high-purity, needle-like crystals aligned perpendicular to the mandrel.

Room Temperature Properties	
Material:	Electroformed Nickel (Sulfamate)
Condition:	As Formed
Mechanical Properties:	
Tensile Ultimate, MN/m^2 (ksi)	551 (80)
Tensile Yield, MN/m^2 (ksi) 0.2% offset	344 (50)
Elongation, %	20
Reduction of Area, %	
Modulus of Elasticity, GN/m^2 (10^6 psi)	193 (28)
Poisson's Ratio	.34
Physical Properties	
Density, kg/m^3 (lb/in.^{3})	8913 (.322)
Specific Heat, J kg^{-1} K^{-1} (cal/g/K)	444 (.106)
Thermal Conductivity, W m^{-1} K^{-1}	90
Coefficient of Thermal Expansion,	
294K to 533K, 10^{-6} [m-m] K^{-1}	12.2
70°F to 500°F, 10^{-6} (in./in./°F)	(6.8)

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