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Atlas of Time-Temperature Diagrams for Nonferrous Alloys

Edited by
George F. Vander Voort
Carpenter Technology Corporation
Reading PA

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Preface

Transformation diagrams, chiefly those developed under isothermal or continuous cooling conditions, that is, isothermal transformation (IT) or continuous cooling transformation (CCT) diagrams, have been of enormous value to the ferrous physical metallurgist and to the heat treater. Instrumental in establishing an understanding of non-equilibrium phase transformations, they have brought heat treating from a confused art, at best, to a reproducible, predictable science. Despite our vastly improved knowledge since the 1930 publication of Davenport and Bain's epic paper, these diagrams are still the mainstay for planning or troubleshooting heat treatment practices.

The writer has compiled iron and steel IT (TTT) and CCT diagrams published worldwide as well as other useful time-temperature type diagrams, e.g., time-temperature-precipitation, -embrittlement, or -sensitization. This collection has been published by ASM International as the *Atlas of Time-Temperature Diagrams for Irons and Steels.*

The need for a similar compilation of nonferrous IT, CCT and allied time-temperature diagrams has been evident to the writer for some time. There are a few nonferrous systems with heat treatment characteristics similar to steels, aluminum bronzes and titanium alloys, for example. Other alloys can be strengthened by precipitation of submicroscopic particles, such as certain aluminum, copper, nickel or magnesium alloys. Still other systems exhibit allotropic transformations of commercial significance. High temperature exposure or service may result in precipitation or oxidation reactions. These processes can be followed in graphical format, either under isothermal or continuous cooling conditions. Alternatively, resultant property changes or behavior may be shown graphically, for example, as iso-property lines, the start of intergranular attack, or the change to cracking under certain conditions. Obviously, the wide range of nonferrous alloy systems available and the wide range of possible time-temperature plots make such a compilation a formidable task!

This is the first compilation of time-temperature type plots for nonferrous alloys. Despite our best efforts, it is impossible for any one person to find all of the available published diagrams and there were works that we tried to obtain but could not. Nevertheless, we have made a valiant first try and we hope that knowledgeable readers will forward literature containing things that were missed.

The editor would like to thank the many people who helped him collect diagrams. In particular, I would like to acknowledge Dr. James T. Staley of the Alcoa Laboratories for his help with the aluminum section and Daniel K. Wells of Carpenter Technology Corporation for his help with the nickel section. I would also like to acknowledge the excellent support from the ASM staff, particularly Mrs. Veronica Flint who coordinated many of the acquisitions, all of the permissions to republish the diagrams, and who handled the mechanics of publication. She was a delight to work with on this project! I would also like to thank the management of Carpenter Technology Corporation for their understanding and support throughout this work.

George F. Vander Voort, Editor
Carpenter Technology Corporation
Reading PA, USA

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Table of Contents

ALUMINUM-BASE ALLOYS

Aluminum-Lithium Alloys

Al - 4% Li 3
Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.05% Si - 0.10% Ti 10
Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.05% Si - 0.10% Ti 11

Aluminum-Magnesium Alloy

Al - 12.5 (at.%) Mg 4

Aluminum-Zinc Alloys

Al - 21.6 at.% Zn 5
Al - 22 at.% Zn - 0.1 at.% Sn 6
Al - 22.5 at.% Zn - 0.1 at.% Mg 7

Aluminum-Manganese Alloys

Al - 0.9% Mn - 0.35% Fe - 0.04% Si 8
Al - 0.9% Mn - 0.35% Fe - 0.04% Si 8
Al - 0.9% Mn - 0.35% Fe - 0.04% Si 9

2024 Alloy 12
2036 Alloy 15
2219 Alloy 15

6007 Alloy

Al - 0.81% Mg - 1.18% Si - 0.14% Cr - 0.09% Zr - 0.14% Mn - 0.39% Fe - 0.02% Cu - 0.01% Zn - 0.03% Ti 16

6010 Alloy 16

6061 Alloys

Al - 0.55% Mg - 0.68% Si - 0.01% Cr - 0.014% Mn - 0.11% Fe - 0.036% Cu - 0.01% Ti - 0.002% B 17
Al - 0.98% Mg - 0.66% Si - 0.12% Cr - 0.12% Mn - 0.38% Fe - 0.23% Cu - 0.07% Zn - 0.014% Ti - 0.001% B 17

6063 Alloy

Al - 0.60% Mg - 0.30% Si - 0.02% Mn - 0.16% Fe - 0.01% Zn - 0.02% Ti 18

6205 Alloy

Al - 0.53% Mg - 0.76% Si - 0.12% Cr - 0.109% Zr - 0.11% Mn - 0.138% Fe - 0.04% Zn - 0.01% Ti 18

A-U4G Alloy

Al - 4.08% Cu - 0.72% Mg - 0.62% Mn - 0.60% Si - 0.27% Fe - 0.03% Ti 19

A-U4SG Alloy

Al - 4.19% Cu - 0.46% Mg - 0.78% Mn - 0.82% Si - 0.33% Fe - 0.05% Ti 20-22

6351 Alloy 23
7075 Alloy 23-25
7017 Alloy 26

8090 Alloy

Al - 2.28% Li - 0.86% Cu - 0.90% Mg - 0.13% Zr - 0.13% Fe - 0.06% Si 27-30

Experimental Aluminum Alloys

Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti 31-37

Al-Zr-Mg Alloy

Al - 4.5 (at.%) Zr - 2.25 (at.%) Mg 38

Al-Cu-Mg-Mn Alloys
Al - 4.64% Cu - 1.48% Mg - 0.82% Mn - 0.02% Si - 0.49% Fe 39
Al - 4.08% Cu - 0.009% Mg - 0.008% Mn - 0.006% Si - 0.002% Fe 40, 42
Al - 4.60% Cu - 0.007% Mg - 0.009% Mn - 0.010% Si - 0.002% Fe 40
Al - 3.70% Cu - 11.70% Mg - 0.03% Mn 40, 42
Al - 4.60% Cu - 0.89% Mg - 0.02% Mn - <0.01% Si - <0.01% Fe 40, 42
Al - 4.28% Cu - 1.23% Mg - 0.02% Mn 40, 42
Al - 4.72% Cu - 0.12% Mg - 0.71% Mn - <0.06% Si - <0.01% Fe 40
Al - 4.19% Cu - 1.30% Mg - 0.06% Mn - 0.47% Si - <0.01% Fe 40
Al - 4.60% Cu - 1.40% Mg - 0.90% Mn - 0.01% Si - 0.01% Fe 40
Al - 4.64% Cu - 1.48% Mg - 0.82% Mn - 0.02% Si - 0.49% Fe 40, 42
Al - 4.74% Cu - 1.80% Mg - 0.38% Mn - 0.11% Si - 0.08% Fe 41
Al - 4.75% Cu - 1.74% Mg - 0.95% Mn - 0.15% Si - 0.09% Fe 41, 42
Al - 4.30% Cu - 1.56% Mg - 0.65% Mn - 0.13% Si - 0.07% Fe 41, 42
Al - 3.77% Cu - 1.74% Mg - 0.38% Mn - 0.13% Si - 0.10% Fe 41
Al - 3.83% Cu - 1.83% Mg - 0.86% Mn - 0.12% Si - 0.12% Fe 41
Al - 3.82% Cu - 1.16% Mg - 0.43% Mn - 0.10% Si - 0.09% Fe 41, 42
Al - 3.62% Cu - 1.20% Mg - 0.85% Mn - 0.08% Si - 0.10% Fe 41

COBALT-BASE ALLOYS

Co-Cr Alloy
Co - 20% Cr 45

Co-W Alloy
Co - 25% W 45

Co-5W-0.23C Alloy
Co - 4.69% W - 0.23% C 46

Co-10W-0.49C Alloy
Co - 9.38% W - 0.49% C 47

Co-10W-0.75C Alloy
Co - 9.37% W - 0.75% C 48

Co-15W-0.71C Alloy
Co - 14.10% W = 0.71% C 49

Co-Cr-Ti-Alloys
Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C 50
Co - 17.6% Cr - 4.4% Ti - 3.0% Mo - 0.015% C 50
Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C 51-53
Co - 17.3% Cr - 4.4% Ti - 3.0% Mo - 11.5% Ni - 0.017% C 53

Wrought Cobalt-Base Alloy
Co - 20.2% Cr - 15.8% Ni - 14.8% W - 1.2% Ti - 0.53% Al - 0.07% Mn - 0.05% Si - 0.25% Fe - 0.11% C . 53

Co-Cr-Mo-C Investment-Cast Implant Alloy
Co - 0.25% C - 0.60% Mn - 0.60% Si - 27% Cr - 3% Ni - 5% Mo - 1% Fe 54

Co-W Heat-Resisting Alloy
Co - 25% W - 1.0% Ti - 0.5% Zr - 3.0% Cr - 0.5% C 55

Haynes Alloy No. 188, Cobalt-Base Superalloy
Co - 20-24% Cr - 20-24% Ni - 13-16% W - 0.05-0.15% C - 0.03-0.15% La -
0.20-0.50% Si - up to 3% Fe - up to 1.25% Mn 56

L-605, Cobalt-Base Superalloys
Co - 0.05% C - 20.06% Cr - 9.81% Ni - 14.88% W - 1.56% Mn - 0.85% Si - 0.23% Fe 56
Co - 20.0% Cr - 14.84% W - 10.02% Ni - 3.12% Fe - 1.39% Mn - 0.47% Si - 0.003% P - trace Zr 57

Co-Fe Alloys

Co - 50% Fe 58
Co - 48.8% Fe - 2.5% V 58
Co - 49.8% Fe - 0.4% Cr 58
Co - 47.34% Fe - 2.00% V - 0.007% C - 0.105% Si - 0.22% Ni 59
Co - 48% Fe - 3.5% Ni - 1.5% V 60

Al-Ni-Co Alloys

Fe - 8% Al - 14% Ni - 3% Cu - 18-32% Co 61
Fe - 8% Al - 12-16% Ni - 3% Cu - 24% Co 62

COPPER-BASE ALLOYS

Copper-Aluminum Alloys

Cu - 11.87% Al - 0.06% Fe - 0.02% Si - 0.01% Sn 65
Cu - 11.89% Al - 0.02% Fe - 0.01% Mn 66
Cu - 11.9% Al 67
Cu - 13.5% Al 68
Cu - 11.3% Al 68
Cu - 12.0% Al 69
Cu - 12.35% Al 69
Cu - 12.4% Al 70
Cu - 12.7% Al 71
Cu - 13.0% Al 72
Cu - 11.8% Al - 0.19% Fe - 0.07% Si 73
Cu - 10.5% Al 73
Cu - 11.87% Al 74
Cu - 13.5% Al 74
Cu - 11.2% Al 75
Cu - 11.7% Al 75
Cu - 12.4% Al 76
Cu - 11.06% Al 77
Cu - 11.60% Al 78
Cu - 12.16% Al 79
Cu - 12.78% Al 80
Cu - 13.31% Al 81
Cu - 11.8% Al 83
Cu - 10.5% Al 84
Cu - 10.5% Al - 4.8% Fe 85
Cu - 10.5% Al - 5% Ni 86
Cu - 10.5% Al - 4.6% Fe - 5.0% Ni 87
Cu - 8.8% Al - 5.4% Fe - 5% Ni - 0.9% Mn 88
Cu - 9.9% Al - 5.3% Fe - 5.1% Ni - 0.9% Mn 89
Cu - 11.5% Al - 5.3% Fe - 5.1% Ni - 0.9% Mn 90
Cu - 12.5% Al - 4.9% Fe - 5.1% Ni 91
Cu - 8% Al - 6% Mn - 3% Fe - 2% Ni 92
Cu - 12% Mn - 8% Al - 3% Fe - 2% Ni 93
Cu - 8% Al - 1% Be - 0.5% Co 94
Cu - 11.54% Al - 0.08% Fe - 0.59% Ag 95
Cu - 11.55% Al - 0.08% Fe - 1.08% Ag 95
Cu - 11.58% Al - 0.08% Fe - 2.63% Ag 95
Cu - 11.83% Al - 0.06% Fe - 0.025% Cd 96
Cu - 11.68% Al - 0.05% Fe - 0.43% Cd 96
Cu - 11.21% Al - 0.05% Fe - 0.64% Cd 96
Cu - 11.73% Al - traces Fe - 0.53% In 97
Cu - 11.79% Al - traces Fe - 0.97% In 97
Cu - 11.84% Al - traces Fe - 2.44% In 97
Cu - 11.74% Al - 0.01% Fe - 0.52% Sn 98
Cu - 11.84% Al - 0.01% Fe - 1.18% Sn 98
Cu - 11.58% Al - 0.01% Fe - 2.53% Sn 98
Cu - 12.06% Al - 0.05% Fe - 0.1% Sb 99
Cu - 11.95% Al - 0.05% Fe - 0.45% Sb 99
Cu - 11.95% Al - 0.05% Fe - 0.73% Sb 99
Cu - 11.75% Al - traces Fe - 0.48% Be 100
Cu - 11.71% Al - traces Fe - 0.88% Be 100
Cu - 11.42% Al - traces Fe - 2.14% Be 100
Cu - 11.65% Al - traces Fe - 0.59% Zn 101
Cu - 11.59% Al - traces Fe - 1.05% Zn 101
Cu - 11.44% Al - traces Fe - 2.42% Zn 101
Cu - 11.04% Al - 0.01% Fe 102
Cu - 10.57% Al - 0.02% Fe - 1.02% Ni-trace Si 102
Cu - 10.54% Al - trace Fe - 3.03% Ni 103

Cu - 12.20% Al - 0.04% Fe - trace Si 104
Cu - 12.41% Al - 0.87% Ni - trace Fe 105
Cu - 12.07% Al - 3.08% Ni - trace Fe 106
Cu - 11.9% Al 107
Cu - 11.7% Al - 0.50% Mn 108
Cu - 11.6% Al - 0.96% Mn 108
Cu - 11.7% Al - 0.52% Co 109
Cu - 11.8% Al - 1.1% Co 109
Cu - 11.7% Al - 0.41% Fe 110
Cu - 11.6% Al - 0.93% Fe 110
Cu - 10.5% Al 114
Cu - 11.2% Al 115
Cu - 11.8% Al 116
Cu - 12.0% Al 117
Cu - 12.4% Al 118

ASTM B148-954 Alloy
Cu - 10.50% Al - 4.1% Fe 82

Aluminum-Bronze Alloy
Cu - 12.31% Al - 3.68% Fe - 0.28% Ni - 0.03% Mn 107

Copper-Aluminum-Zinc Alloys
Cu - 10.6% Al - 3.0% Zn 111
Cu - 11.0% Al - 3.1% Zn 112
Cu - 11.5% Al - 3.1% Zn 113

Copper-Aluminum-Nickel Alloy
Cu - 12.8% Al - 7.7% Ni 119

Beryllium-Bronze Alloy
Cu - 5.965% Be - trace Fe 119

Copper-Beryllium Alloys
Cu - 1.77% Be - 0.24% Co 120
Cu - 1.99% Be - 0.09% Co 120
Cu - 1.87% Be - 0.14% Co 120
Cu - 1.81% Be - 0.20% Co 120
Cu - 1.77% Be - 0.24% Co 120
Cu - 1.5% Be 121-122
Cu - 2% Be 121-122
Cu - 1.8% Be - 0.2% Co 121-122
Cu - 6.39% Be 123

Copper-Gallium Alloy
Cu - 23.7 at.% Ga 123

Copper-Indium Alloys
Cu - 31.36% In 124
Cu - 32.3% In 125

Copper-Antimony Alloy
Cu - 30.5% Sb 126

Copper-Silicon Alloy
Cu - 8.35% Si 126

Copper-Tin Alloys
Cu - 32.5% Sn 127
Cu - 16.5 at.% Sn 127-128
Cu - 23.6% Sn - 0.02% Pb - 0.01% Fe - 0.01% Ni - 0.02% Zn - <0.01% P 128

Copper-Zinc Alloys
Cu - 40.5% Zn 129
Cu - 41.6% Zn 130
Cu - 43.0% Zn 131
Cu - 44.1% Zn 132
Cu - 39.8% Zn 133
Cu - 39.5% Zn 133

Copper-Gold-Zinc Alloys
Cu - 39.9% Zn - 4.2% Au 134
Cu - 40.1% Zn - 9.3% Au 134

Copper-Zinc-Aluminum Alloys
Cu - 27.4% Zn - 3.72% Al 135
Cu - 28.2% Zn - 3.14% Al 135

GOLD-BASE ALLOYS

Au-Co Alloy
Au - 4.8 at.% Co 139

MAGNESIUM-BASE ALLOYS

Magnesium-Manganese Alloy
Mg - 1.58% Mn 143

Magnesium-Thorium Alloy
Mg - 5.1% Th 143

Magnesium-Zinc Alloys
Mg - 52% Zn 144
Mg - 55% Zn 144

NICKEL-BASE ALLOYS

Nickel-Indium Alloys
Ni - 5.52 at.% In 147

Nickel-Titanium Alloys
Ni - 12.2 at.% Ti - <0.02 at.% Al - <10 ppm B - 0.02 wt.% Si - 0.03 wt.% Fe - 0.01-0.02 wt.% C - <0.01 wt.% Co - <0.005 wt.% Mn - <0.001 wt.% Mg - <0.001 wt.% Cu 148
Ni - 48 at.% Ti 149-150

Nickel-Tungsten Alloys
Ni - 45% W 150
Ni - 45% W - 10% Co 150

Nickel-Aluminum-Molybdenum Alloy
Ni - 6.8% Al - 14.4% Mo - 6.1% W - 0.04% C 151

IN-100
Ni - 0.17% C - 10.30% Cr - 14.30% Co - 2.89% Mo - 4.73% Ti - 5.79% Al - 0.016% B - 0.076% Zr - 0.93% V 152
Ni - 0.17% C - 10.30% Cr - 15.00% Co - 2.93% Mo - 4.68% Ti - 5.53% Al - 0.016% B - 0.082% Zr - 0.94% V 153
Ni - 15% Co - 10% Cr - 5.5% Al - 4.7% Ti - 3% Mo - 0.95% V 232-235
Ni - 0.18% C - 14.26% Co - 10.26% Cr - 2.97% Mo - 5.35% Ti - 5.60% Al - 0.30% Fe - 0.92% V - 0.012% B - 0.05% Zr 236

IN-100 Nb-modified (PM)
Ni - 11.9% Cr - 17.7% Co - 3.3% Mo - 5.2% Al - 4.2% Ti - 1.4% Nb - 0.024% B - 0.06% Zr - 0.09% C .. 238

IN-100 Nb-modified (CE)
Ni - 12.1% Cr - 17.4% Co - 3.2% Mo - 5.3% Al - 4.4% Ti - 1.5% Nb - 0.028% B - 0.06% Zr - 0.08% C .. 238

B-1900
Ni - 0.10% C - 7.96% Cr - 9.70% Co - 5.89% Mo - 1.08% Ti - 6.06% Al - 0.015% B - 0.084% Zr - 4.25% Ta 154
Ni - 0.10% C - 8.25% Cr - 9.50% Co - 5.89% Mo - 1.07% Ti - 5.98% Al - 0.016% B - 0.10% Zr - 4.19% Ta 155
Ni - 10% Co - 8% Cr - 6% Mo - 6% Al - 4% Ta - 1% Ti+C+Zr+B 156-158

Inconel 702
Ni - 0.08% C - 0.6% Ti - 3.2% Al - 15.5% Cr - 1.0% max Fe 158

Udimet-700
Ni - 0.08% C - 15.0% Cr - 18.5% Co - 5.2% Mo - 3.5% Ti - 4.3% Al - 0.030% B 159
Ni - 0.07% C - 15.10% Cr - 18.30% Co - 5.33% Mo - 3.34% Ti - 4.29% Al - 0.024% B 160

René 80
Ni - 14% Cr - 9.5% Co - 4% Mo - 4% W - 5% Ti - 3% Al 161

René 41
Ni - 0.08% C - 19.31% Cr - 10.82% Co - 9.77% Mo - 2.34% Fe - 3.23% Ti - 1.51% Al - 0.006% B 162
Ni - 0.08% C - 0.50% Fe - 19.00% Cr - 11.00% Co - 9.75% Mo - 3.15% Ti - 1.50% Al - 0.006% B 163
Ni - 0.08% C - 19.31% Cr - 10.82% Co - 9.77% Mo - 3.23% Ti - 1.51% Al - 0.006% B - 2.34% Fe 164

Unitemp AF2-1D
Ni - 0.35% C - 11.92% Cr - 14.05% Co - 4.94% Mo - 4.87% W - 3.02% Ti - 4.60% Al -
0.013% B - 0.10% Zr - 1.56% Ta 165
Ni - 0.33% C - 11.93% Cr - 14.20% Co - 5.05% Mo - 3.04% Ti - 4.60% Al - 4.93% W -
0.014% B - 0.10% Zr - 1.48% Ta 166

Inco 713C
Ni - 0.12% C - 13.25% Cr - 4.28% Mo - 0.81% Ti - 6.40% Al - 0.009% B - 0.05% Zr - 2.66% Nb 167

MAR-M200
Ni - 0.14% C - 9.51% Cr - 10.3% Co - 2.06% Ti - 5.05% Al - 12.15% W - 0.010% B -
0.048% Zr - 0.99% Nb 168

MAR-M246
Ni - 0.15% C - 9.00% Cr - 10.0% Co - 2.50% Mo - 1.50% Ti - 5.50% Al - 10.0% W -
0.010% B - 0.05% Zr - 1.5% Ta 168

TRW-NASA IVY
Ni - 0.15% C - 5.85% Cr - 4.82% Co - 2.04% Mo - 1.08% Ti - 5.25% Al - 5.36% W -
0.023% B - 0.039% Zr - 8.17% Ta - 0.89% Nb - 2.01% Hf - 0.90% Re 169

TRW-NASA VIA
Ni - 0.16% C - 6.03% Cr - 7.19% Co - 2.24% Mo - 0.98% Ti - 5.26% Al - 5.78% W -
0.018% B - 0.12% Zr - 8.32% Ta - 0.34% Nb - 0.46% Hf - 0.57% Re 170
Ni - 0.13% C - 5.92% Cr - 2.05% Mo - 1.01% Ti - 5.27% Al - 7.46% Co - 0.38% Hf -
8.97% Ta - 5.92% W - 0.32% Re - 0.10% Zr - 0.020% B - 0.47% Nb 171-172

Inconel 718
Ni - 0.06% C - 18.86% Cr - 2.99% Mo - 0.93% Ti - 0.57% Al - 5.25% Nb - 17.48% Fe 173
Fe - 53% Ni - 0.05% C - 1.0% Ti - 0.7% Al - 19.0% Cr - 3.0% Mo - 5.3% Nb+Ta -
0.006% B - 0.03% Zr - 0.2% Mn - 0.3% Si 174
Fe - 52% Ni - 19% Cr - 3% Mo - 5% Nb+Ta - 0.8% Ti - 0.6% Al - 0.05% C 196
Ni - 18.49% Cr - 16.79% Fe - 5.07% Nb+Ta - 3.11% Mo - 0.95% Ti - 0.51% Al - 0.30% Si -
0.28% Mn - 0.05% Cu - 0.04% C - 0.011% P - 0.007% S - 0.0023% B 197
Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti -
0.4% Al - 0.04% C - 0.007% S 198-201
Fe - 53.8% Ni - 18.0% Cr - 3.00% Mo - 5.24% Nb+Ta - 1.00% Ti - 0.59% Al - 0.05% C -
0.003% S - 0.004% B 202
Ni - 0.04% C - 0.20% Mn - 0.30% Si - 18.6% Cr - 3.1% Mo - 5.0% Nb - 18.5% Fe - 0.9% Ti - 0.4% Al 203
Ni - 18.16% Cr - 19.5% Fe - 2.96% Mo - 0.82% Ti - 0.70% Al - 5.18% Nb 204
Ni - 18.59% Cr - 21% Fe - 2.85% Mo - 0.72% Ti - 0.63% Al - 3.99% Nb 204
Ni - 18.97% Cr - 17% Fe - 7.03% Mo - 0.59% Ti - 0.63% Al - 3.41% Nb 204
Ni - 18.90% Cr - 16.4% Fe - 7.00% Mo - 0.90% Ti - 0.74% Al - 3.85% Nb 204
Fe - 52.5% Ni - 0.04% C - 19.0% Cr - 0.90% Ti - 0.50% Al - 0.005% B - 3.05% Mo - 5.30% Nb 205
Fe - 0.08% max C - 0.35% max Mn - 0.35% max Si - 0.015% max P - 0.015% max S -
17.0-21.0% Cr - 1.0% max Co - 2.80-3.30% Mo - 4.75-5.50% Nb+Ta - 0.65-1.15% Ti -
0.20-0.80% Al - 0.30% max Cu - 50.0-55.0 Ni+Co - 0.006% max B 206
Ni - 17.58% Fe - 18.83% Cr - 0.98% Ti - 2.97% Mo - 5.13% Nb - 0.53% Al - 0.05% Ta -
0.30% Co - 0.09% Mn - 0.04% C - 0.004% S - 0.01% P - 0.17% Si - 0.09% Cu 207
Ni - 0.95% Ti - 0.46% Al - 5.26% Nb - 18.25% Fe - 3.05% Mo - 18.00% Cr - 0.031% C -
0.003% B - 0.001% Mg 208
Ni - 1.34% Ti - 0.63% Al - 5.28% Nb - 18.30% Fe - 3.05% Mo - 17.80% Cr - 0.028% C -
0.004% B - 0.001% Mg 208

Ni - 0.96% Ti - 0.53% Al - 4.32% Nb - 18.30% Fe - 3.02% Mo - 18.15% Cr - 0.031% C - 0.003% B - 0.004% Mg 208
Ni - 0.96% Ti - 0.87% Al - 5.42% Nb - 18.00% Fe - 3.02% Mo - 17.80% Cr - 0.031% C - 0.004% B - 0.001% Mg 208
Ni - 17.8-19.1% Fe - 0.03-0.05% C- 0.21-1.12% Si - 17.9-18.3% Cr - 3.0-3.06% Mo - 5.11-5.17% Nb+Ta - 0.96-1.0% Ti - 0.42-0.47% Al 209
Cast alloy 718 210
Ni - 20.2% Fe - <0.05% Co - 3.20% Mo - 5.28% Nb+Ta - 0.94% Ti - 0.46% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.007% S - 0.004% P - <0.01% Cu 212, 212
Ni - 9.8% Fe - <0.05% Co - 3.20% Mo - 5.13% Nb+Ta - 0.96% Ti - 0.58% Al - 0.04% Mn - 0.06% Si - 0.02% C - 0.001% B - 0.006% S - 0.002% P - <0.01% Cu 212, 216
Ni - <0.05% Fe - <0.05% Co - 3.02% Mo - 5.14% Nb+Ta - 0.93% Ti - 0.53% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.003% B - 0.008% S - 0.004% P - <0.01% Cu 213. 216
Ni - 10.1% Fe - 8.6% Co - 3.10% Mo - 5.05% Nb+Ta - 0.90% Ti - 0.48% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.006% S - 0.005% P - 0.01% Cu 213, 216
Ni - 0.25% Fe - 17.6% Co - 3.19% Mo - 5.31% Nb+Ta - 0.92% Ti - 0.48% Al - 0.03% Mn - 0.04% Si - 0.04% C - 0.003% C - 0.006% S - 0.005% P - 0.01% Cu 214, 216
Ni - <0.05% Fe - 8.8% Co - 3.0% Mo - 5.09% Nb+Ta - 0.86% Ti - 0.47% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.002% B - 0.006% S - 0.004% P - 0.01% Cu 215-216
Ni - 20.2% Fe - <0.05% Co - 3.20% Mo - 5.28% Nb+Ta - 0.94% Ti - 0.46% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.007% S - 0.004% P - <0.01% Cu 216
Ni - 17.4% Cr - 18.7% Fe - 5.16% Nb - 2.96% Mo - 0.99% Ti - 0.48% Al - 0.06% C - 0.07% Mn - 0.10% Si - <0.01% B - 0.003% S 217
Ni - 19.9% Fe - 18.2% Cr - 5.1% Nb - 2.9% Mo - 1.15% Ti - 0.57% Al - 0.035% Cr 218-220

Waspaloy

Ni - 0.06% C - 19.30% Cr - 14.60% Co - 4.39% Mo - 3.08% Ti - 1.42% Al - 0.051% Zr 175

A-286

25.1% Ni - 14.5% Cr - 1.20% Mo - 2.00% Ti - 0.30% V - 0.25% sol. Al - 0.052% C - 0.11% Mn - 0.20% Si - 0.009% S - 0.007% P - 0.0023% N 176
Fe - 24.7% Ni - 14.4% Cr - 2.2% Ti - 1.1% Mo - 0.26% Al 177

ATS 28 - X-5NiCrTi 26 15, (similar to A-286)

Fe - 26% Ni - -15% Cr - 1.3% Mo - 1.8% Ti - 0.03% Ca - 0.3% V 178

Pyromet CTX-1

Fe - 37.7% Ni - 16.0% Co - 3.0% Nb - 1.75% Ti - 1.0% Al - 0.008% B - 0.03% C 179

Incoloy 909

Fe - 38.3% Ni - 12.9% Co - 4.70% Nb - 1.58% Ti - 0.35% Si - 0.04% Al - 0.01% C - 0.01% Cr 179

Incoloy 800

Fe - 31.85% Ni - 0.23% Cu - 0.06% C - 0.81% Mn - 0.007% S - 0.32% Si - 21.81% Cr 180
Fe - 31.1% Ni - 21.4% Cr - 0.90% Mn - 0.28% Si - 0.037% C - 0.02% N - 0.01% P - 0.007% S - 0.5% Al - 0.3% Ti 181-184

Inconel 600

Ni - 7.92% Fe - 0.15% Cu - 0.06% C - 0.17% Mn - 0.007% S - 0.22% Si - 15.40% Cr 185
Ni - 15.6% Cr - 8.1% Fe - 0.2% Ti - 0.03% Mo - 0.03% N - 0.03% Cu - 0.16% Al - 0.040% C - 0.27% Si - 0.13% Mn 186-189
Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr 264-267
Ni - 0.04% C - 15.36% Cr - 9.98% Fe - 0.40% Mn - 0.17% Si - 0.38% Cu - 0.17% Al - 0.20% Ti - 0.05% Co - 0.011% S 268

Inconel 706

Ni - 37% Fe - 16% Cr - 2.9% Nb - 1.8% Ti 190

Nimonic PE16

Fe - 17.1% Cr - 42.5% Ni - 3.1% Mo - 1.2% Ti - 1.3% Al - 0.03% Zr - 0.05% Mn - 0.0003% B - 0.08% C 191

Incoloy 825

Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo 192-194

Inconel X-750
Ni - 0.05% C - 0.57% Mn - 6.56% Fe - 0.25% Si - 0.05% Cu - 15.66% Cr - 0.70% Al - 2.35% Ti - 0.92% Nb 194

IN 939
Ni - 0.15% C - 22.5% Cr - 19.0% Co - 2.0% W - 1.0% Nb - 1.4% Ta - 3.7% Ti - 1.9% Al - 0.1% Zr - 0.01% B 195

Udimet 700
Ni - 14.5% Cr - 17.5% Co - 5.1% Mo - 3.7% Ti - 4.1% Al - 0.015% B - 0.08% C 221
Ni - 15.0% Cr - 0.15% Fe - 19.0% Co - 5.15% Mo - 3.49% Ti - 4.45% Al - 0.10% Si - 0.10% Mn - 0.028% B - 0.06% C 226-227

IN-700
Ni - 16.0% Cr - 0.1% C - 3.0% Mo - 29.5% Co - 2.5% Ti - 3.0% Al 222
Ni - 15.0% Cr - 0.07% C - 5.3% Mo - 18.5% Co - 3.5% Ti - 4.3% Al - 0.03% B 222

Udimet-520
Ni - 0.03% C - 18.8% Cr - 11.8 Co - 6.0% Mo - 0.9% W - 2.9% Ti - 2.1% Al - 0.02% B 223

Udimet-710
Ni - 0.06% C - 17.7% Cr - 15.1% Co - 3.0% Mo - 1.4% W - 4.8% Ti - 2.4% Al - 0.02% B 223

Rene´41
Ni - 19.05% Cr - 0.71% Fe - 10.93% Co - 9.91% Mo - 3.10% Ti - 1.48% Al - 0.06% Si - 0.06% Mn - 0.004% B - 0.11% C - 0.008% S 224-225
Ni - 20.10% Cr - 2.03% Fe - 0.089% C - 0.25% Si - 11.55% Co - 0.05% Mn - 10.17% Mo - 1.60% Al - 3.17% Ti - 0.0056% B - 0.016% S 228-229
Ni - 18.64% Cr - 0.20% Fe - 0.075% C - 0.05% Si - 10.76% Co - 0.05% Mn - 9.76% Mo - 1.62% Al - 3.13% Ti - 0.009% B - 0.008% P - 0.007% S 229
Ni - 19.02% Cr - 0.30% Fe - 0.07% C - 0.06% Si - 10.84% Co - 0.04% Mn - 9.84% Mo - 1.45% Al - 3.18% Ti - 0.0056% B - 0.005% P - 0.005% S 230-231
Ni - 19.73% Cr - 2.03% Fe - 0.067% C - 0.18% Si - 11.12% Co - 0.05% Mn - 10.09% Mo - 1.60% Al - 3.10% Ti - 0.0045% B - 0.020% S 230

Waspaloy
Ni - 20% Cr - 14% Co - 4% Mo - 3% Ti - 1% Al 232
Ni - 0.071% C - 0.014% Si - 0.062% Mn - 0.002% P - 0.004% S - 19.36% Cr - 13.9% Co - 0.20% Fe - 1.10% Mo - 1.55% Al - 3.93% Ti - 0.62% Zr 232

Alloy 713C
Ni - 12.77% Cr - 0.07% Fe - 0.10% C - 0.22% Si - 0.012% B - 4.52% Mo - 5.94% Al - 0.80% Ti - 2.08% Nb+Ta - 0.12% Zr 237

AF-2-1DA Nb-C-modified (PM)
Ni - 12.1% Cr - 10.0% Co - 5.7% W - 2.9% Mo - 4.8% Al - 3.1% Ti - 1.5% Nb - 1.5% Ta - 0.018% B - 0.08% Zr - 0.09% C 238

AF-2-1DA Nb-C-modified (CE)
Ni - 12.0% Cr - 10.3% Co - 5.5% W - 2.9% Mo - 4.7% Al - 2.9% Ti - 1.4% Nb - 1.6% Ta - 0.020% B - 0.11% Zr - 0.09% C 238

IN-738
Ni - 0.12% C - 15.86% Cr - 8.40% Co - 1.93% Mo - 2.60% W - 3.42% Al - 3.50% Ti - 0.92% Nb - 1.80% Ta - 0.070% Zr - 0.0105% B 239
Ni - 0.086% C - 18.57% Cr - 7.88% Co - 1.80% Mo - 2.53% W - 3.35% Al - 3.43% Ti - 0.92% Nb - 1.72% Ta - 0.048% Zr - 0.0115% B 239
Ni - 0.078% C - 16.61% Cr - 8.39% Co - 1.99% Mo - 3.32% W - 3.32% Al - 3.42% Ti - 0.89% Nb - 1.75% Ta - 0.048% Zr - 0.0118% B 239
Ni - 0.077% C - 16.60% Cr - 8.40% Co - 1.75% Mo - 2.55% W - 3.56% Al - 3.70% Ti - 1.15% Nb - 1.86% Ta - 0.05% Zr - 0.0115% B 239

Inconel 625
Ni - 0.03% C - 0.10% Mn - 0.25% Si - 0.008% S - 0.011% P - 22.1% Cr - 1.89% Fe - 0.20% Al - 0.22% Ti - 9.1% Mo - 3.35% Nb+Ta - 0.20% W - 40 ppm B - 50 ppm O - 480 ppm N 239
Ni - 0.016% C - 0.3% Si - 0.05% Mn - 0.005% P - 0.006% S - 21.8% Cr - 0.027% Co - 9.05% Mo - 0.2% Ti - 0.1% Al - 2.4% Fe - 0.023% Cu - 3.7% Nb+Ta - 1 ppm B 240
Ni - 0.029% C - 0.34% Si - 0.38% Mn - 0.009% P - 0.004% S - 22.67% Cr - 1.33% Fe - 8.75% Mo - 0.17% Ti - 3.72% Nb - 0.15% Al - 0.0071% N 241
61.0% Ni+Co - 21.5% Cr - 9.0% Mo - 3.65% Nb+Ta - 2.5% Fe - 0.05% C - 0.25% Mn - 0.008% S - 0.25% Si - 0.2% Al - 0.2% Ti 242-245
60.95% Ni - 22.21% Cr - 3.61% Fe - 8.97% Mo - 3.50% Nb+Ta - 0.19% Al - 0.27% Ti - 0.26% Si - 0.05% Mn - 0.006% P - 0.004% S - 0.08% Cu - 0.03% C 246
60.64% Ni - 0.02% C - 0.09% Mn - 0.19% Si - 22.14% Cr - 4.06% Fe - 9.0% Mo - 3.39% Nb+Ta - 0.22% Al - 0.24% Ti - 0.001% B - 0.05% Co 247-248
60.96% Ni - 0.02% C - 0.12% Mn - 0.31% Si - 21.94% Cr - 3.82% Fe - 8.94% Mo - 3.47% Nb+Ta - 0.21% Al - 0.20% Ti - 0.06% Co - 0.001% B 249
Ni - 0.06% C - 3% Fe - 21.5% Cr - 9% Mo - 4% Nb 250

Custom Age 625 PLUS
61% Ni - 0.01% C - 21% Cr - 8% Mo - 3.4% Nb - 1.3% Ti - 0.2% Al - 5% Fe 250

Alloy 625 (Nicrofer 6020 hMo)
Ni - 22.25% Cr - 9.27% Mo - 2.05% Fe - 0.1% Mn - 0.04% Si - 0.3% Ti - 3.42% Nb+Ta - 0.14% Al - 0.011% C 251
Ni - 21.9% Cr - 8.94% Mo - 1.4% Fe - 0.03% Mn - 0.04% Si - 0.18% Ti - 3.74% Nb+Ta - 0.16% Al - 0.03% C 251

Alloy 625
Ni - 20.5% Cr - 8.2% Mo - 4.3% Fe - 3.6% Nb - 0.1% Co - 0.1% Al - 0.1% Ti - 0.1% Si - 0.1% Mn - 0.03% C 252

Inconel X-750
Ni - 0.03% C - 0.56% Mn - 6.51% Fe - 0.007% S - 0.27% Si - 0.06% Cu - 15.24% Cr - 0.76% Al - 2.50% Ti - 0.85% Nb+Ta 253
Ni - 0.06% C - 0.19% Mn - 7.82% Fe - 0.001% S - 0.40% Si - 0.37% Cu - 14.82% Cr - 0.85% Al - 2.49% Ti - 0.98% Nb+Ta 254

Hastelloy C
Ni - 17% Mo - 15% Cr - 4.5% W - 6% Fe 255
Ni - 0.04% C - 0.50% Si - 0.010% P - 0.010% S - 16.00% Mo - 4.00% W - 1.00% Co - 5.00% Fe - 0.35% Mn - 16.00% Cr - 0.20% V 258
Ni - 14.94-16.46% Cr - 15.47-16.47% Mo - 3.38-4.02% W - 5.05-6.77% Fe - 0.74-1.86% Co - 0.42-0.69% Mn - 0.42-0.73% Si - 0.22-0.32% V - 0.04-0.08% C - 0.004-0.012% P - 0.005-0.011% S 259

Hastelloy C-4
Ni - <0.015% C - <2% Co - 16% Cr - 15.5% Mo - <0.7% Ti - <3% Fe - <1% Mn - <0.08% Si 255
Ni - 16% Cr - 0.15% W - 0.3% Fe - <0.01% C - 0.03% Si - 0.1% Co - 0.05% Mn - 0.03% V - 15% Mo - 0.45% Ti 257

Hastelloy Alloy C-276
Ni - 13% Cr - 16% Mo - <2.5% Co - 3.75% W - 5.5% Fe - <0.02% C - <1% Mn 255
Ni - 16% Cr - 3.4% W - 6% Fe - 0.01% C - 0.02% Si - 1% Co - 0.45% Mn - 0.2% V - 16% Mo 256
Ni - 0.004% C - <0.01% Si - 0.010% P - 0.003% S - 0.22% Al - 16.25% Mo - <0.01% Zr - 3.70% W - 0.04% Cu - 1.08% Co - 5.98% Fe - 0.34% Mn - 16.38% Cr - 0.21% V - 0.026% Mg 258

Hastelloy B-2
Ni - 1.00% max Co - 1.00% max Cr - 26.00%-30.00% Mo - 2.00% max Fe - 0.10% max Si - 1.00% max Mn - 0.02% max C - 0.040% max P - 0.030% max S 260-261

Hastelloy B-282
Ni - 0.40% Cr - 4.80% Fe - 0.02% C - 0.31% Si - 0.52% Mn - 37.50% Mo - 0.33% V 261

Single Crystal Alloy 800
Ni - 8.0% Cr - 7.5% Co - 1.5% Mo - 4.0% W - 5.0% Ta - 1.5% Ti - 5.8% Al - 3.0% Re 262
Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 3.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 1.0% Re 262
Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 2.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 2.0% Re 262
Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 1.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 3.0% Re 262
Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 12.0% Ta - 1.0% Ti - 5.0% Al - 4.0% Re 262

Nimonic 80A
Ni - 0.08% C - 20% Cr - 2.4% Ti - 1.4% Al 263

Alloy 600
Ni - 0.029% C - 0.211% Mn - 8.05% Fe - 0.003% S - 0.180% Si - 0.219% Cu - 14.09% Cr - 0.464% Al - 0.259%Ti - 0.034% Co - 0.007% P - 0.002% B - 0.026% Mg 269

NIOBIUM-BASE ALLOYS

Niobium-Zirconium Alloys
Nb - 33 at.% Zr 273-275
Nb - 25 at.% Zr 273

PLUTONIUM-BASE ALLOYS

Beta Plutonium 279
Electrorefined Plutonium 280
Pure Plutonium 281

Dilute Plutonium Alloys
Unalloyed plutonium 282
Pu - 0.82 at.% Ti 283
Pu - 1.3 at.% Np 284
Pu - 0.90% Ti 285
Pu - 1.3% Np 286

Plutonium-Titanium Alloys
Pu - 0.23 at.% Ti 286
Pu - 1.05 at.% Ti 287

SILVER-BASE ALLOYS

Ag-Al Alloy
Ag - 7.02% Al 291

Ag-Cd Alloy
Ag - 49.2% Cd 291

Ag-Cu Alloys
Ag - 38.3% at.% Cu 292
Ag - 28.2 at.% Cu 293

Ag-Sb Alloy
Ag - 26.0% Sb 293

TITANIUM-BASE ALLOYS

TTT Diagrams

Ti-Al Alloy
Ti - 8% Al 297

Titanium Alloys
Ti - 3.1% Bi 298
Ti - 5.2% Co 298
Ti - 4.6% Cu 298
Ti - 4.5% Fe 298
Ti - 8.6% Mn 298
Ti - 3.3% Ni 298

Ti - 5.3% Pb 298
Ti - 8.0% Co 299
Ti - 14.0% Cr 299
Ti - 5.5% Cu 299
Ti - 13.0% Fe 299
Ti - 5.1% Ni 299

Ti-Cr Alloys
Ti - 2.35% Cr 300
Ti - 4.64% Cr 300
Ti - 7.54% Cr 301
Ti - 5.0% Cr 302
Ti - 7.0% Cr 302
Ti - 9.0% Cr 303
Ti - 17.0% Cr 303
Ti - 3.0% Cr 304-306
Ti - 7.5% Cr 307-308
Ti - 12.0% Cr 309
Ti - 7.22% Cr 310
Ti - 8.0% Cr 310
Ti - 10.8% Cr 311
Ti - 17.42% Cr 311

Ti-Cu Alloy
Ti - 5% Cu 312

Ti-Mn Alloys
Ti - 2.91% Mn 312
Ti - 7.72% Mn 312
Ti - 12.3% Mn 312
Ti - 6.0% Mn 313
Ti - 10.0% Mn 313

Ti-Mo Alloys
Ti - 1.0% Mo 314
Ti - 3.0% Mo 314, 317
Ti - 5.0% Mo 315
Ti - 7.0% Mo 315, 318
Ti - 9.0% Mo 316
Ti - 11.0% Mo 316, 319
Ti - 5.16% Mo 320
Ti - 5.21% Mo - 0.46% C 320
Ti - 11.0% Mo vs O 321
Ti - 12% Mo 322
Ti - 13.0% Mo 322
Ti - 15.0% Mo 323
Ti - 4.57% Mo 358

Ti-Mo-Pd Alloy
Ti - 15% Mo - 0.2% Pd 323

Ti-Mo-Zr Alloy
Ti - 15% Mo - 5% Zr 324

Ti-V Alloys
Ti - 12.5% V 325
Ti - 15.0% V 326-328
Ti - 20.0% V 328-329
Ti - 24.0% V 329

Ti-Ni Alloys
Ti - 7 at.% Ni 330
Ti - 10 at.% Ni 330
Ti - 3.03% Ni 358

Ti-Nb Alloy 331

Ti-V-Al Alloys
Ti - 16.0% V - 2.5% Al 332-335

Ti-Al-Cr Alloys

Ti - 2.0% Al - 2.0% Cr 336
Ti - 4.0% Al - 2.0% Cr 336
Ti - 6.0% Al - 2.0% Cr 336
Ti - 2.0% Al - 4.0% Cr 337
Ti - 4.0% Al - 4.0% Cr 337
Ti - 6.0% Al - 4.0% Cr 337
Ti - 2.0% Al - 6.0% Cr 338
Ti - 4.0% Al - 6.0% Cr 338
Ti - 6.0% Al - 6.0% Cr 338

Ti-Al-Mo Alloys

Ti - 2.0% Al - 2.0% Mo 339
Ti - 4.0% Al - 2.0% Mo 339
Ti - 6.0% Al - 2.0% Mo 339
Ti - 2.0% Al - 6.0% Mo 340
Ti - 4.0% Al - 6.0% Mo 340
Ti - 6.0% Al - 6.0% Mo 340
Ti - 2.0% Al - 10.0% Mo 341
Ti - 4.0% Al - 10.0% Mo 341
Ti - 6.0% Al - 10.0% Mo 341
Ti - 2.6% Al - 7.5% Mo 361

Ti-Al-V Alloys

Ti - 3.1% Al - 2.4% V - 0.006% C - 0.064% Fe 342, 359
Ti - 6.0% Al - 4.0% V 342

Ti-Cr-Mo Alloys

Ti - 4.0% Cr - 2.0% Mo 343-344

Ti-Cu-Al Alloys

Ti - 5.0% Cu - 3.0% Al 345
Ti - 8.0% Cu - 3.0% Al 345

Ti-V-Cr-Al Alloy

Ti - 12.6% V - 11.1% Cr - 4.1% Al 346
Ti - 12.8% V - 11.1% Cr - 4.1% Al 347
Ti - 13.6% V - 10.5% Cr - 2.9% Al 348
Ti - 13.2% V - 11.2% Cr - 3.15% Al 349

Ti-1Al-8V-5Fe

Ti - 0.8-1.8% Al - 7.5-8.5% V - 4.0-6.0% Fe - max 0.05% C 346

Ti-10-2-3

Ti - 10% V - 2% Fe - 3% Al 347

Ti-Al-Mo-V Alloys

Ti - 4.1% Al - 2.9% Mo - 1.0% V 349-350
Ti - 7.6% Al - 1.0% Mo - 1.0% V 363

Ti-Cu-Al-Sn Alloys

Ti - 5.0% Cu - 5.0% Al - 2.0% Sn 350
Ti - 8.0% Cu - 3.0% Al - 2.0% Sn 351

Beta III

Ti - 11.5% Mo - 6% Zr - 4.5% Sn - 0.17% O 351
Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn 352
Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn - 0.28% O_2 353

Ti-V-Fe Alloy

Ti - 9.70% V - 2.08% Fe - 2.98% Al 354

Ti-6242

Ti - 6% Al - 2% Sn - 4% Zr - 2% Mn 354

Ti-17
Ti - 4.5-5.5% Al - 2.5-2.5% Sn - 1.5-2.5% Zr - 3.5-4.5% Mn - 3.5-4.5% Cr - 0.08-0.13% O - max 0.30% Fe 355

Ti-Al-V-Cr-Mo-Zr Alloy]
Ti - 3.4% Al - 8.3% V - 5.8% Cr - 4.2% Mo - 3.9% Zr 355

Ti-V-Cr-Sn-Al Alloys]
Ti - 14.52% V - 3.04% Cr - 2.90% Sn - 3.40% Al 356
Ti - 15.25% V - 2.47% Cr - 3.05% Sn - 3.19% Al 356
Ti - 11.76% V - 2.28% Cr - 3.03% Sn - 3.49% Al 356

Ti-679
Ti - 10.50-11.50% Sn - 4.00-6.00% Zr - 2.00-2.50% Al - 0.80-1.20% Mo - 0.15-0.27% Si - max 0.12% Fe - max 0.04% C 357

Ti-Al-Sn Alloy
Ti - 4.75% Al - 2.5% Sn 360

Ti-15Al-21Nb
Ti - 14.80% Al - 21.30% Nb - 0.065% Fe - 0.058% O - 0.006% N 362

CCT Diagrams

IMI 685
Ti - 6.17% Al - 4.07% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N 364
Ti - 6.17% Al - 4.97% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N 365-368

IMI 550
Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N 369-373

Ti-6242
Ti - 6% Al - 2% Sn - 4% Zr - 2% Mo 374-375
Ti - 6.63% Al - 2.08% Sn - 3.91% Zr - 1.99% Mo - 0.066% O_2 376-380

Ti-6246
Ti - 6.1% Al - 2.1% Sn - 4% Zr - 6.3% Mo - 0.10% O_2 381-384

Ti-6248
Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O 385-391

Ti-17
Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N 392-398

Ti-11
Ti - 5.86% Al - 2.05% Sn - 1.69% Zr - 1.01% Mo - 0.315% Bi - 0.102% Si - 0.067% Fe - 0.097% O - 0.006% N - 0.0180% H 399-401

URANIUM-BASE ALLOYS

Uranium-Chromium Alloys
U - 0.3 at.% Cr 405
U - 0.45 at.% Cr 406
U - 0.6 at.% Cr 407
U - 1.8 at.% Cr 408
U - 4.0 at.% Cr 408
U - 0.96% Cr 409-410

Uranium-Gallium Alloy
U - 1.6 at.% Ga 411

Uranium-Molybdenum Alloys
U - 6 at.% (2.5 wt.%) Mo 412-413
U - 5.4% Mo 414, 417
U - 5.4 to 12% Mo 415-416
U - 8% Mo 418-419
U - 10% Mo 420
U - 10.8% Mo 421
U - 14.3% Mo 421
U - 16.1% Mo 422

Uranium-Niobium Alloys
U - 10% Nb 423-424
U - 20% Nb 423-424

Uranium-Platinum Alloy
U - 1 at.% Pt 433

Uranium-Chromium-Molybdenum Alloys
U - 0.25 at.% Cr - 0.5 at.% Mo 425
U - 0.5% Cr - 0.5% Mo 425

Uranium-Niobium-Molybdenum Alloys
U - 0.5% Nb - 0.5% Mo 426
U - 8% Mo - 1.5% Nb 427-429
U - 8% Mo - 3% Nb 427-429

Uranium-Molybdenum-Platinum Alloy
U - 8% Mo - 1% Pt 428-430

Uranium-Molybdenum-Titanium Alloys
U - 8% Mo - 0.5% Ti 431
U - 8% Mo - 1% Ti 432

Uranium-Niobium-Platinum Alloy
U - 1.56% at.% Nb - 0.35 at.% Pt 433

ZINC-BASE ALLOYS

Zinc-Aluminum Alloys
Zn - 22.5% Al 437
Zn - 22.5% Al 438
Zn - 22% Al 439
Zn - 22% Al 440
Zn - 22% Al - 0.15% Mg - 0.5% Cu 441
Zn - 22% Al 442
Zn - 22% Al - 0.15% Mg - 0.5% Cu 442
Zn - 23% Al - 0.92% Cu - 0.034% Mg - 0.026% Ca 443
Zn - 18% Al - 0.87% Cu - 0.037% Mg - 0.024% Ca 443
Zn - 23% Al - 0.92% Cu - 0.034% Mg - 0.026% Ca 444

Zinc-Nickel Alloy
Zn - 43.7% Ni 445

ZIRCONIUM-BASE ALLOYS

Zirconium-Molybdenum Alloys
Zr - 1.3% Mo 449
Zr - 3.3% Mo 449
Zr - 5.4% Mo 450
Zr - 7.5% Mo 450

Zirconium-Uranium Alloys
Zr - 8.85% U 451
Zr - 11.1% U 452
Zr - 14.3% U 453
Zr - 20.7% U 453

Zirconium-Uranium-Hydrogen Alloy
Zr - 0.92% H - 0.0875% O - 0.0038% N - 0.0909% Fe - 0.0048% Si - 0.0052% Al - 0.0025% Mn 454

AMORPHOUS METALS

Copper-Cadmium Alloy
$Cu_{60}Cd_{40}$ 457

Copper-Zirconium Alloy
$Cu_{60}Zr_{40}$ 457

Iron-Boron Alloys
$Fe_{80}B_{20}$ 458

Nickel-Titanium Alloy
$Ni_{85}Ti_{15}$ 459

Niobium-Silicon Alloy
$Nb_{80}Si_{20}$ 460

Palladium-Nickel-Silicon Alloys
$Pd_{70}Ni_{10}Si_{20}$ 460
$Pd_{50}Ni_{30}Si_{20}$ 461-462
$Pd_{55}Ni_{30}Si_{15}$ 461

Palladium-Silicon Alloys
$Pd_{80}Si_{20}$ 463, 465
$Pd_{82}Si_{0.18}$ 464

Palladium-Silicon-Copper Alloy
$Pd_{0.775}Si_{0.165}Cu_{0.06}$ 464

Iron-Phosphorus-Carbon Alloy
$Fe_{80}P_{13}C_7$ 465-466

Cobalt-Silicon-Boron Alloy
$Co_{75}Si_{15}B_{10}$ 465

Nickel-Silicon-Boron Alloy
$Ni_{75}Si_8B_{17}$ 465

Salol 467
SiO_2 Silica 468
Salol-Like Material 468

INTERMETALLIC COMPOUNDS

Cobalt-Platinum Alloy
$CoPt_3$ (24.9 at.% Co) 471

Iron-Aluminum Alloys
Fe_3Al 471-472

Nickel-Molybdenum Alloys
Ni - 20% Mo 473
Ni_4Mo 474

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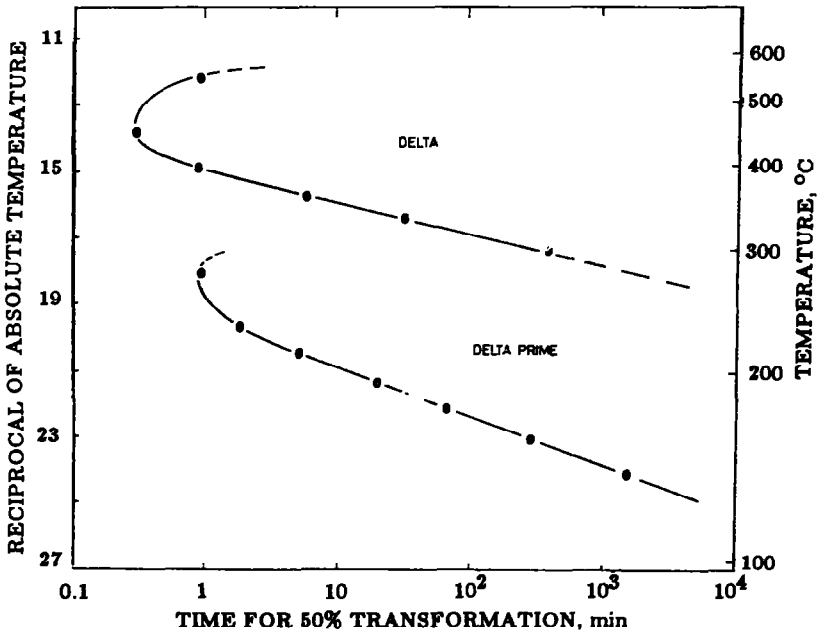
Aluminum-Base Alloys

Aluminum-Lithium Alloy

Composition: Al - 4% Li

Treatment: Alloys containing 4.0% lithium were prepared by melting superpurity aluminum and 99.99% lithium under argon in an induction furnace. The chill-cast ingots were extruded, homogenized, and cold rolled to 1.25 mm strip. All solution-treatments were carried out at 580°C (1076°F) under argon, followed by a quench into water at 20°C (68°F)



LIVE GRAPH
Click here to view

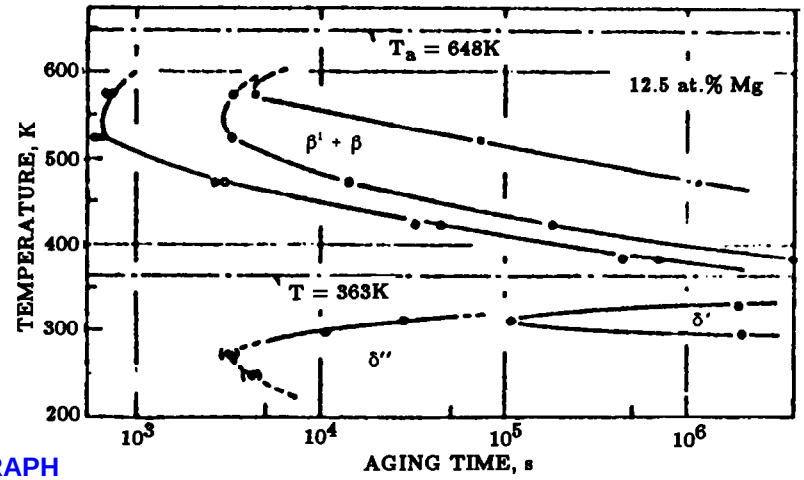
Time-temperature precipitation diagram

delta = AlLi
delta prime = Al_3Li

SOURCE: B. Noble, G.E. Thompson, "Precipitation Characteristics of Aluminium-Lithium Alloys," Metal Science Journal, Vol 5, 1971, pp 114-120

Aluminum-Magnesium Alloy

Composition: Al - 12.5 (at.%) Mg



LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
Times required to attain a certain stage of precipitation, as a function of aging-temperature

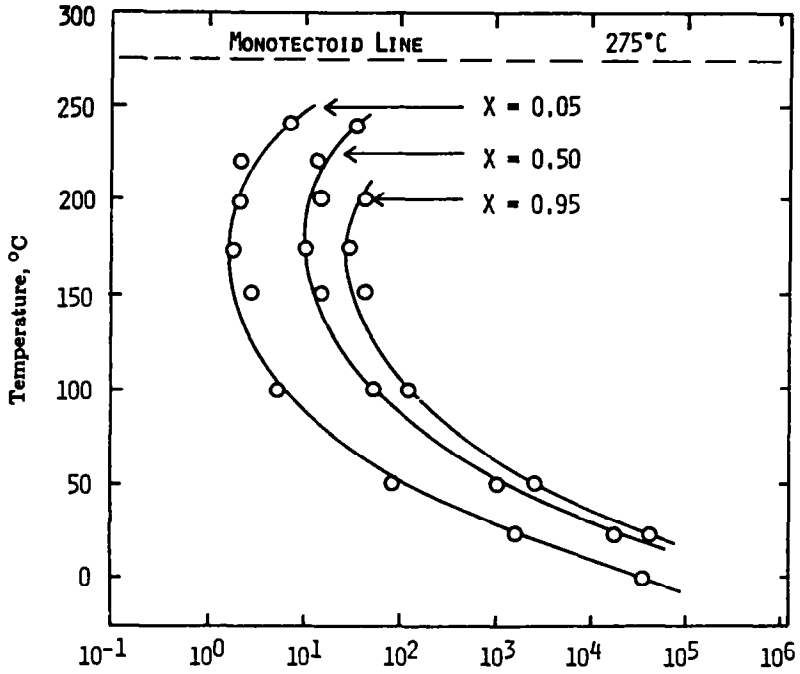
O = time to attain an initial energy increase of 2 kJ/kg^{-1}
x = time to finish all of energy increase
⊖ = time to begin age-hardening
⊗ = time to attain the maximum hardness

SOURCE: R. Nozato, S. Ishihara, "Calorimetric Study of Precipitation Process in Al-Mg Alloys," Trans. Japan Institute of Metals, Vol 21, No. 9, September 1980, pp 580-588

Aluminum-Zinc Alloys

Composition: Al - 21.6 at.% Zn

Treatment: Specimens were homogenized in air at 400°C (752°F) for approx. 30 min and then quenched into a water or oil bath located directly beneath the homogenization furnace. Isothermal aging was accomplished in a silicone oil bath controlled to with 1° over the temperature range 50 to 240°C (122 to 464°F). Room temperature aging was carried out in an insulated oil bath and a 0°C (32°F) aging treatment was done in an alcohol bath immersed in a slurry of ice and water



LIVE GRAPH
Click here to view

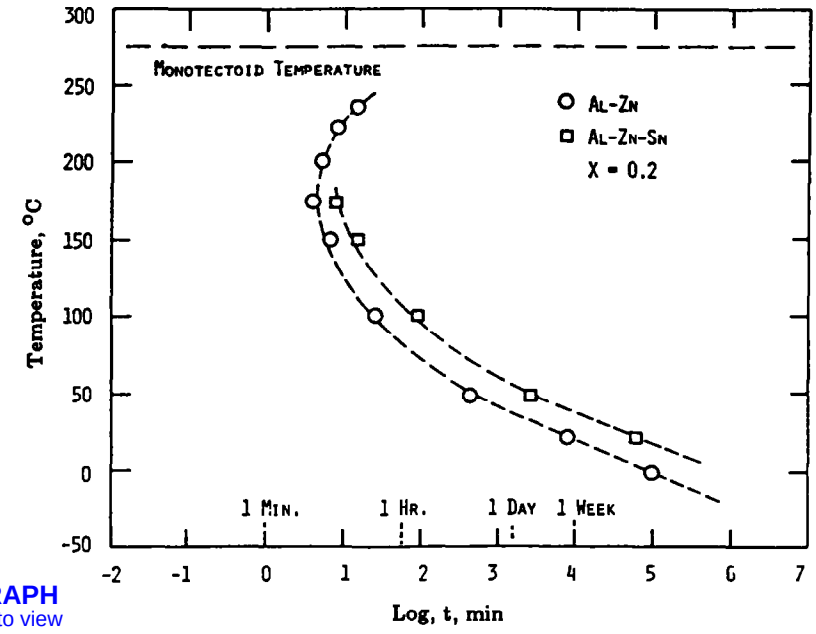
Time-temperature-precipitation diagram
TTT curve for discontinuous precipitation
X = fraction transformed (i.e. 0.05 = 5%, 0.50 = 50%, 0.95 = 95%)
L = 10×10^{-3} cm, average intercept distance (measure of the grain size)

SOURCE: U.K. Malhotra, K.B. Rundman, "Discontinuous Precipitation in Aluminum-Base Zinc Alloys," Met. Trans. Vol 3, June 1972, 1521-1528

Aluminum-Zinc Alloys

Composition: Al - 22 at.% Zn - 0.1 at.% Sn

Treatment: Specimens were homogenized in air at 400°C (752°F) for approx. 30 min and then quenched into a water or oil bath located directly beneath the homogenization furnace. Isothermal aging was accomplished in a silicone oil bath controlled to with 1° over the temperature range 50 to 240°C (122 to 464°F). Room temperature aging was carried out in an insulated oil bath and a 0°C (32°F) aging treatment was done in an alcohol bath immersed in a slurry of ice and water



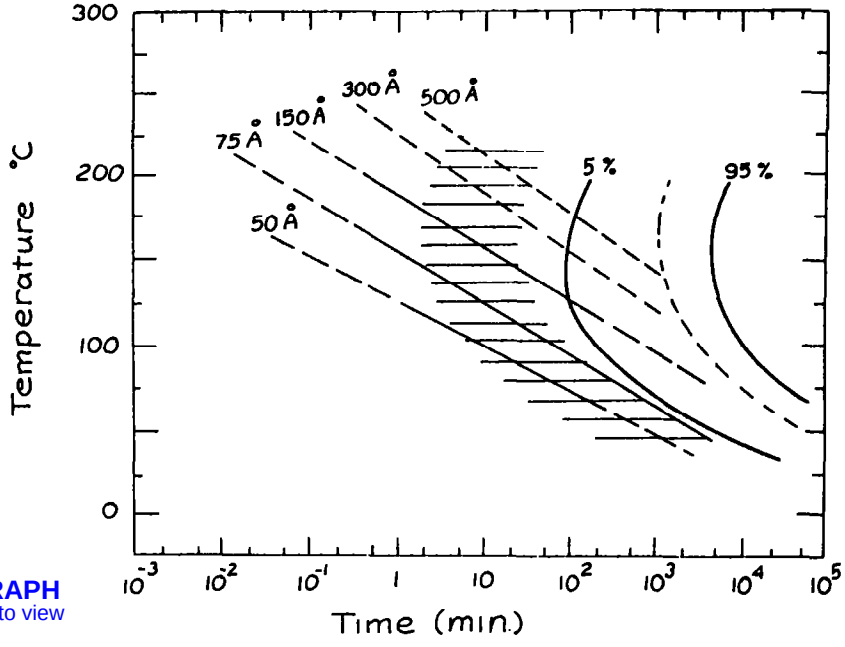
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
TTT curve for discontinuous precipitation of the cellular alpha + beta phases in water quenched and aged alloys for a volume fraction transformed of:
X = 20%
L = 10×10^{-3} cm, average intercept distance (measure of the grain size)

SOURCE: U.K. Malhotra, K.B. Rundman, "Discontinuous Precipitation in Aluminum-Base Zinc Alloys," Met. Trans. Vol 3, June 1972, 1521-1528

Aluminum-Zinc Alloys

Composition: Al - 22.5 at.% Zn - 0.1 at.% Mg
Treatment: Hot rolled to a thickness of 0.317 cm and then cold rolled to a final thickness of 0.0061 cm. Polycrystalline specimens 1.02 x 12.7 cm were cut from the center of the cold rolled material, homogenized within 3° at 400°C (752°F) for 1 h, and quenched into an ice bath directly below the furnace. All isothermal heat treatments were made at 75, 100, 125, 150, and 175°C (164, 212, 257, 392, and 347°F) in a silicone oil bath controlled to within 1°



LIVE GRAPH
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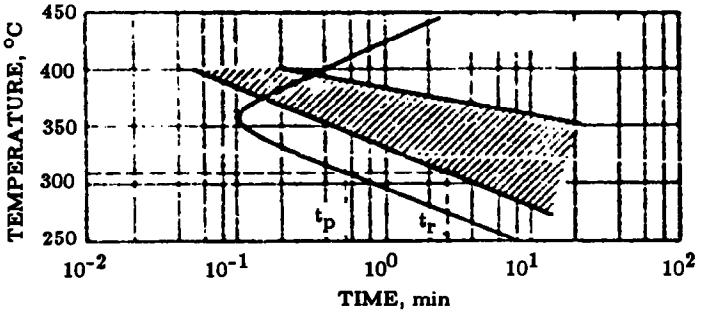
Time-temperature-precipitation diagram

- the horizontal lined area represents the TTT diagram for the cellular alpha + beta transformation in the binary Al-22 at.% Zn alloy
- the solid C-curves represent the TTT diagram for the formation of the beta phase in the Al-22 at.%Zn 0.1 at.% Mg alloy
-the straight lines cutting across both of the TTT diagrams represent isowavelength plots

SOURCE: T.L. Bartel, K.B. Rundman, "Decomposition in Al-Zn Alloys: Part 1. Isothermal Decomposition in an Al-22 At. Pct Zn-0.1 At. Pct Mg Alloy," Met. Trans. A, Vol 6A, October 1975, pp 1887-1893

Aluminum-Manganese Alloys

Composition: Al - 0.9% Mn - 0.35% Fe - 0.04% Si
A commercially strip-cast AlMn alloy exhibiting a uniform primary particle structure with a secondary dendrite spacing similar to that reported by Moritz and Ostermann *
Heat treatment: Material annealed to 570°C (1058°F) for 6 h, resulting in a resistivity drop of 25%, or about 0.5% Mn in solid solution, then reduced 85% at room temperature, and recrystallized at different temperatures and times



Time-temperature recrystallization and precipitation diagrams

Shaded region = range for recrystallization
Solid line = start of decomposition of the supersaturated Al-Mn matrix

LIVE GRAPH
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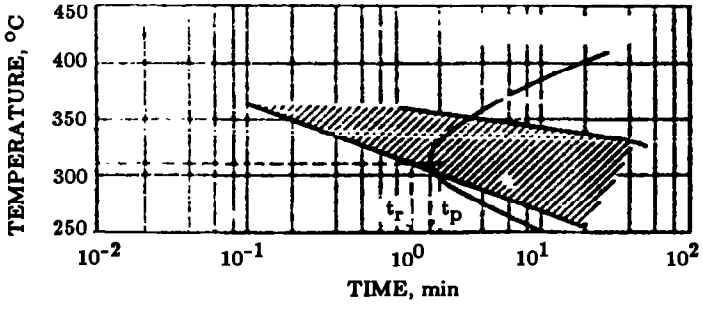
Composition: Al - 0.9% Mn - 0.35% Fe - 0.04% Si
A commercially strip-cast AlMn alloy exhibiting a uniform primary particle structure with a secondary dendrite spacing similar to that reported by Moritz and Ostermann *
Heat treatment: Material annealed at 570°C (1058°F) for 4 h, then cooled to 520°C (968°F) at a rate of about 100°C (212°F)/h and kept at this temperature for 17 h. This gave a reduction in resistivity of about 31% or a manganese concentration in solution of about 0.4%. The material was then reduced 85% at room temperature, and recrystallized at different temperatures and times



Time-temperature recrystallization and precipitation diagrams

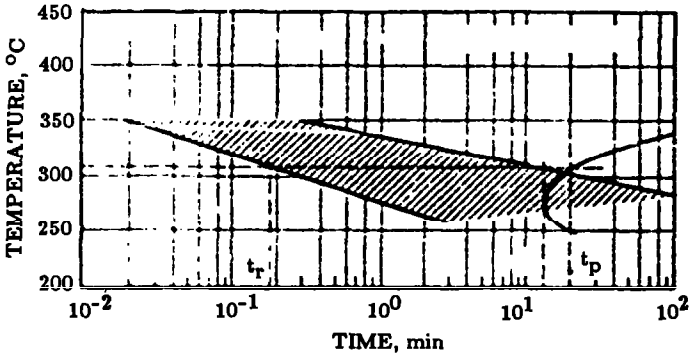
Shaded region = range for recrystallization
Solid line = start of decomposition of the supersaturated Al-Mn matrix

*** "The Effective and Economic use of the Special Characteristics of Aluminium and its Alloys," The Institute of Metals, London 1972, p 54**

SOURCE: E. Nes, "The Concept of a "Grain Size Diagram" in the Analysis of the Recrystallization Behaviour of AlMn Alloys," Aluminium, Vol 52, No. 9, September 1976, pp 560-563

Aluminum-Manganese Alloys

Composition: Al - 0.9% Mn - 0.35% Fe - 0.04% Si
A commercially strip-cast AlMn alloy exhibiting a uniform primary particle structure with a secondary dendrite spacing similar to that reported by Moritz and Ostermann *
Heat treatment: Material annealed at 570°C (1058°F) for 6 h, then cooled at a rate of about 100°C (212°F)/h to 450°C (842°F) and kept at this temperature for an additional period of 41 h. The resulting decrease in resistivity was 36%, or about 0.3% Mn in solid solution. The material was then reduced 85% at room temperature, and recrystallized at different temperatures and times



LIVE GRAPH
Click here to view

* "The Effective and Economic use of the Special Characteristics of Aluminium and its Alloys," The Institute of Metals, London 1972, p 54

Time-temperature recrystallization and precipitation diagrams

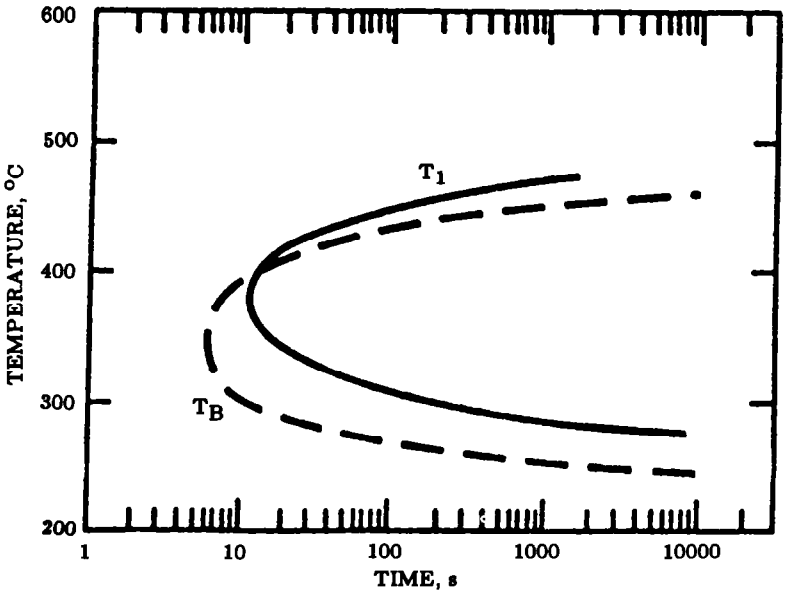
Shaded region = range for recrystallization
Solid line = start of decomposition of the supersaturated Al-Mn matrix

SOURCE: E. Nes, "The Concept of a "Grain Size Diagram" in the Analysis of the Recrystallization Behaviour of AlMn Alloys," Aluminium, Vol 52, No. 9, September 1976, pp 560-563

Aluminum-Lithium Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.05% Si - 0.10% Ti

Treatment: Panels of the 3.5 mm thick section were taken from the midthickness of the plate and solution treated at 550°C (1022°F) for 30 min in molten metal, then transferred to molten metal baths operating at either 500, 450, 400, 350 or 300°C (932, 842, 752, 662, or 572°F) for times ranging to 10,000 s. They were then quenched in cold water



LIVE GRAPH
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Time-temperature-precipitation diagram

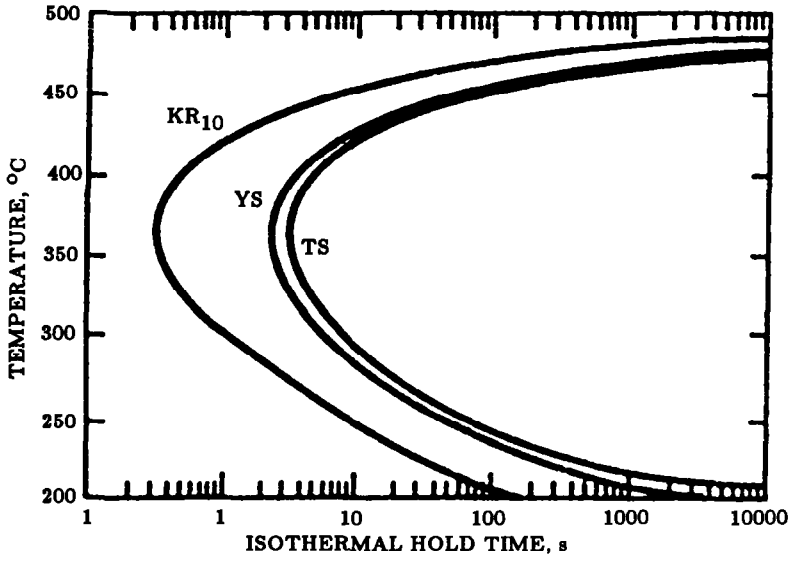
$T_1 = Al_2CuLi$
$T_B = Al_7Cu_4Li$

SOURCE: J.T. Staley, R.D. Doherty, "Quench Sensitivity of an Al-Cu-Li Alloy Plate," proceedings of the 5th International Aluminum-Lithium Conference, Williamsburg VA, 27-31 March 1989, Aluminum-Lithium Alloys, T.H. Sanders, Jr., E.A. Starke, Jr., eds., Materials and Component Engineering Publications Ltd., 1989, pp 345-354

Aluminum-Lithium Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.05% Si - 0.10% Ti

Treatment: Panels of the 3.5 mm thick section were taken from the midthickness of the plate and solution treated at 550°C (1022°F) for 30 min in molten metal, then transferred to molten metal baths operating at either 500, 450, 400, 350 or 300°C (932, 842, 752, 662, or 572°F) for times ranging to 10,000 s. They were then quenched in cold water

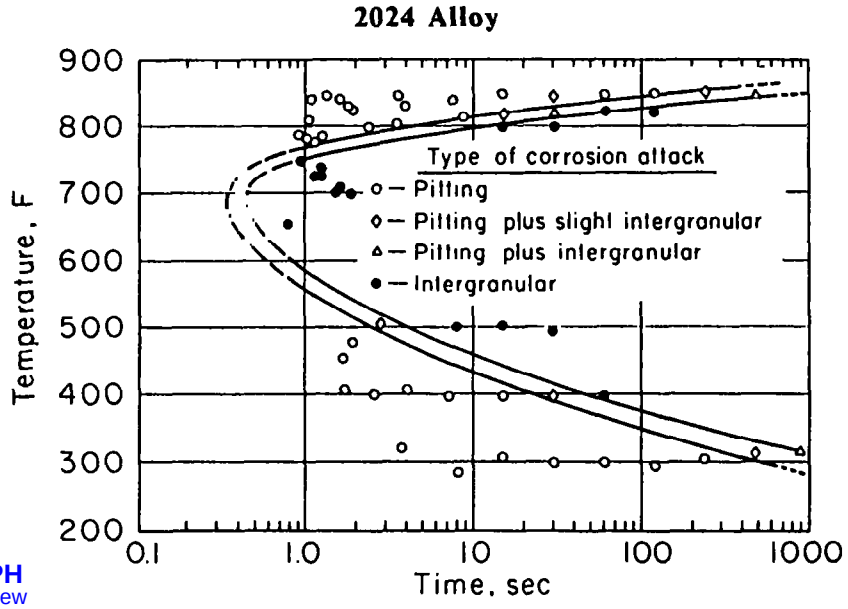


Time-temperature-property diagram

KR_{10} = toughness indicator
YS = yield strength
TS = tensile strength

Slow aging, temperature plus time for maximum properties - toughness and strength

SOURCE: J.T. Staley, R.D. Doherty, "Quench Sensitivity of an Al-Cu-Li Alloy Plate," proceedings of the 5th International Aluminum-Lithium Conference, Williamsburg VA, 27-31 March 1989, Aluminum-Lithium Alloys, T.H. Sanders, Jr., E.A. Starke, Jr., eds., Materials and Component Engineering Publications Ltd., 1989, pp 345-354



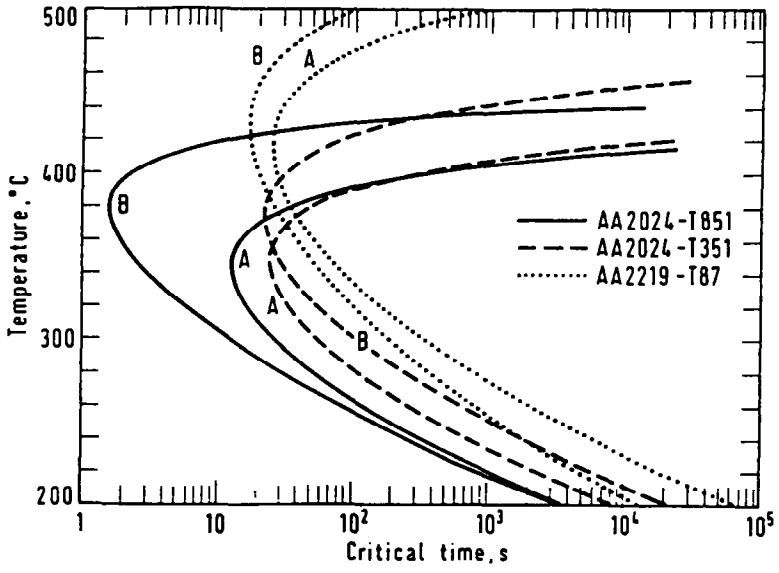
LIVE GRAPH
Click here to view

Time-temperature-corrosion diagram
Effect of temperature and time in interrupted-quenching experiments on type of corrosion attack developed in 2024-T4 sheet by an accelerated corrosion test

SOURCE: L.A. Willey, Alcoa Research Laboratories, as published in Aluminum, Vol 1, Properties, Physical Metallurgy and Phase Diagrams, Kent R. Van Horn, ed., ASM, 1967

2024 Alloy

Treatment:
Sequence A = Specimens were quenched directly into a salt bath at 250-475°C (482-886°F)
Sequence B = Specimens were first quenched to room temperature, then heated in the salt bath
All specimens were quenched in cold water to complete the sequences after hold times of 2 s to 1 h, stretched to 5% plastic strain, and then aged for 16 h at 172°C (342°F)



LIVE GRAPH
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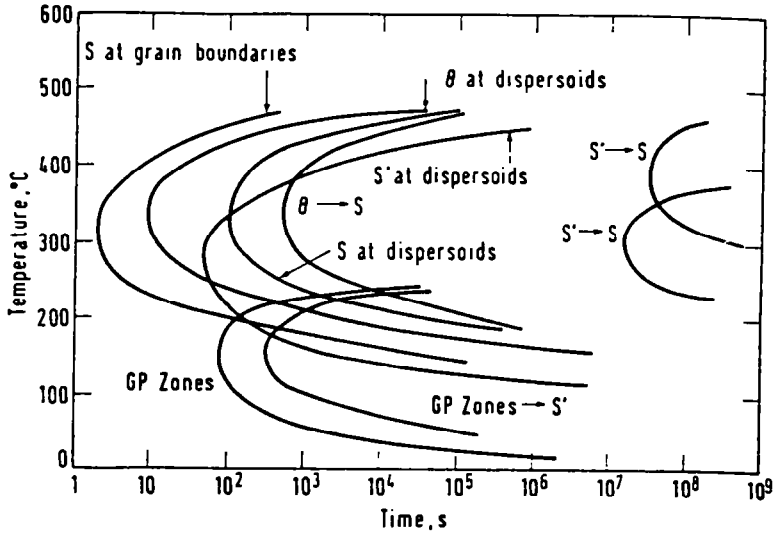
Time-temperature-property diagram
Comparison of yield strength (0.2% offset) C-curves for sequence A and B treatments of AA 2024-T851, AA 2024-T351, and AA 2219-787

Corresponding yield strengths are 90% of values obtained from direct quench
415 MN m^{-2} for AA 2024-T851
345 MN m^{-2} for AA 2024-T351
345 MN m^{-2} for AA 2219-T-87

SOURCE: I. Ives, et al., "Processing/Microstructure/Property Relationships in 2024 Aluminium Alloy Plates," Report NBS 83-2669, National Bureau of Standards, Washington DC, 1983 and J.T. Staley, "Quench Factor Analysis of Aluminium Alloys," Materials Science and Technology, Vol 3, November 1987, pp 923-935

2024 Alloy

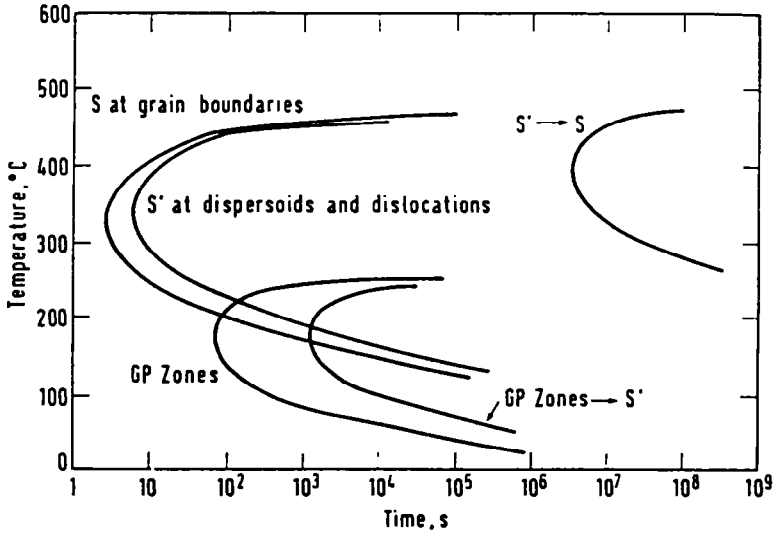
Treatment:
Sequence A = Specimens were quenched directly into a salt bath at 250-475°C (482-886°F)



Time-temperature-nucleation diagram
Schematic representation of nucleation curves for sequence A

LIVE GRAPH
Click here to view

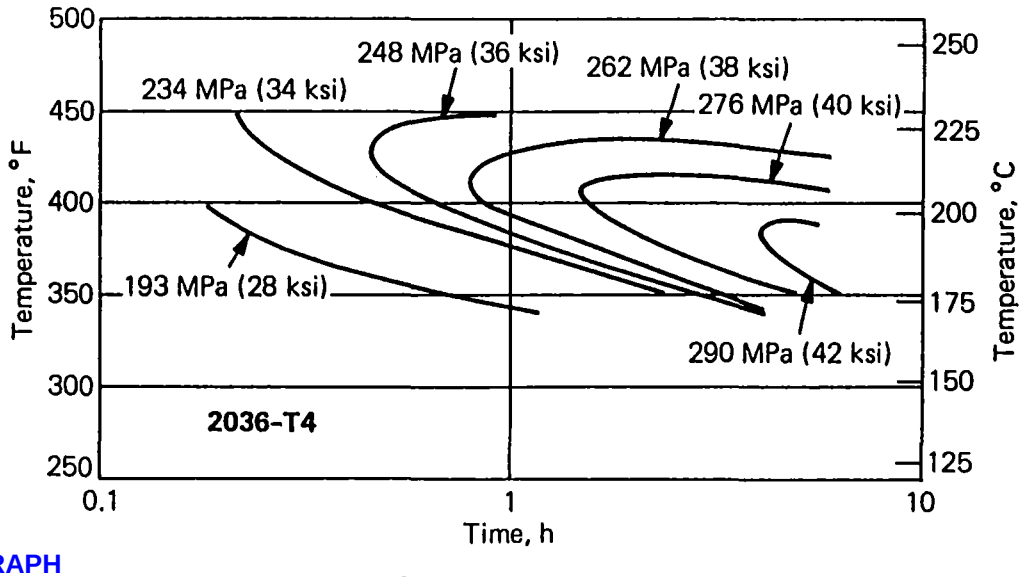
Treatment:
Sequence B = Specimens were first quenched to room temperature, then heated in the salt bath
All specimens were quenched in cold water to complete the sequences after hold times of 2 s to 1 h, stretched to 5% plastic strain, and then aged for 16 h at 172°C (342°F)



Schematic representation of nucleation curves for sequence B treatment

SOURCE: I. Ives, et al., "Processing/Microstructure/Property Relationships in 2024 Aluminium Alloy Plates," Report NBS 83-2669, National Bureau of Standards, Washington DC, 1983 and J.T. Staley, "Quench Factor Analysis of Aluminium Alloys," Materials Science and Technology, Vol 3, November 1987, pp 923-935

2036 Alloy



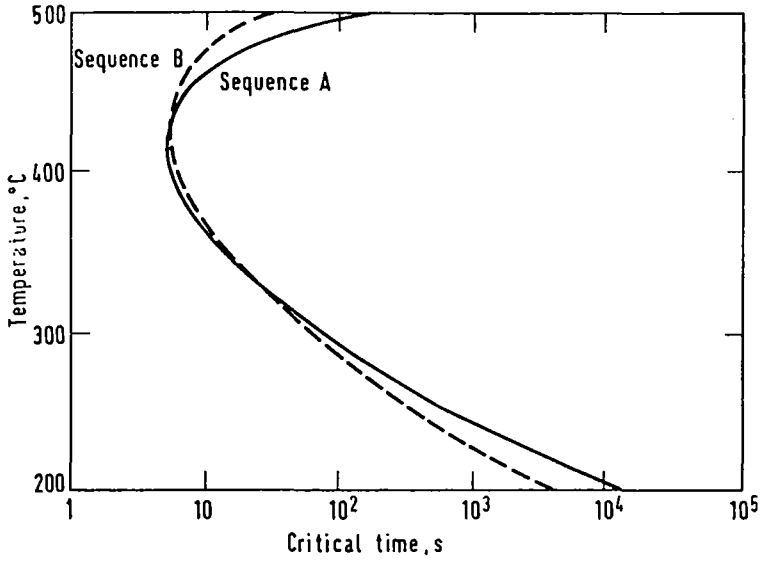
LIVE GRAPH
Click here to view

Time-temperature-property diagram
Effect of aging time and temperature on longitudinal yield strength of 2036-T4

SOURCE: Aluminum Properties and Physical Metallurgy, John E. Hatch, ed., ASM, 1984

2219 Alloy

Treatment:
Sequence A = Specimens were quenched directly into a salt bath at 250-475°C (482-886°F)
Sequence B = Specimens were first quenched to room temperature, then heated in the salt bath
All specimens were quenched in cold water to complete the sequences after hold times of 2 s to 1 h, stretched to 5% plastic strain, and then aged for 16 h at 172°C (342°F)



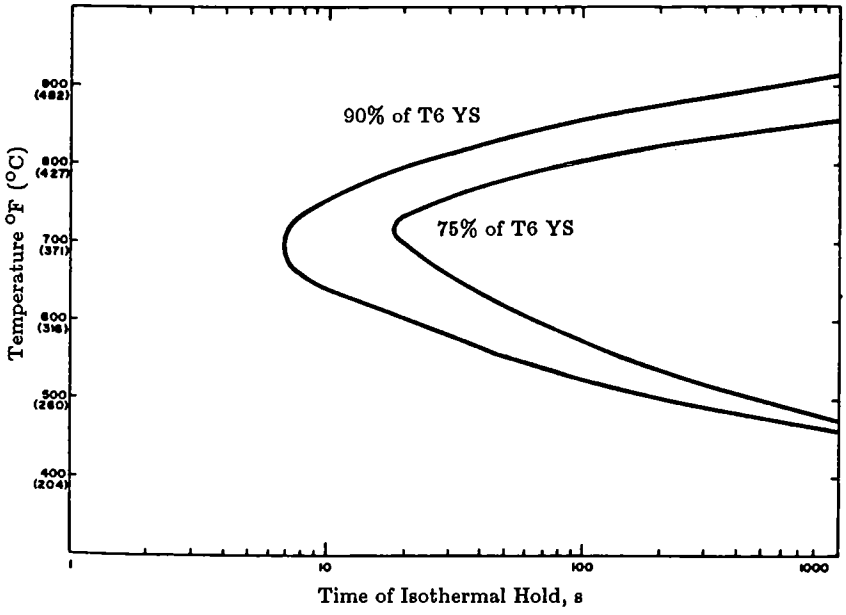
LIVE GRAPH
Click here to view

Time-temperature-property diagram
C-curve for AA 2219-T87 of 370 MN m^{-2} yield strength

SOURCE: L. Swartzendruber, et al., "Nondestructive Evaluation of Nonuniformities in 2219 Aluminium Alloy Plate - Relationship to Processing," Report NBSIR 80-2069, National Bureau of Standards, Washington DC, 1980, and J.T. Staley, "Quench Factor Analysis of Aluminium Alloys," Materials Science and Technology, Vol 3, November 1987, pp 923-935

6007 Alloy

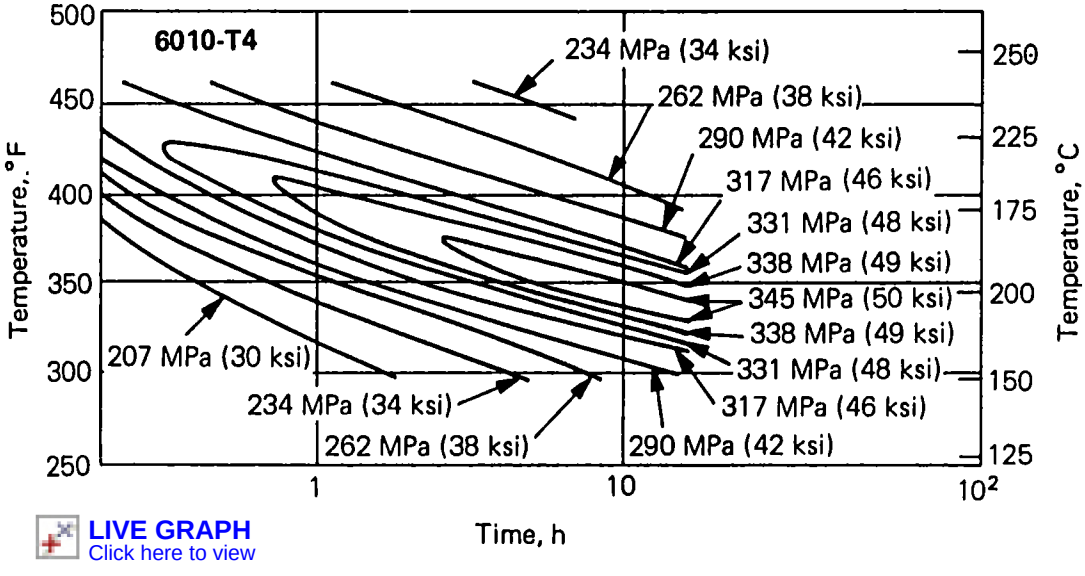
Composition: Al - 0.81% Mg - 1.18% Si - 0.14% Cr - 0.09% Zr - 0.14% Mn - 0.39% Fe - 0.02% Cu - 0.01% Zn - 0.03% Ti
Treatment: Solution heat-treated at 550°C (1020°F) for 1 to 1.5 h, down quenched to various temperatures into molten salt, held at temperature for varying times, water quenched, and aged



Time-Temperature-property diagram (I-T)
Maximum quenched and aged yield strength 47.5 ksi (328 MPa)
Iso-yield curve is 90% of quenched and aged yield strength

SOURCE: D.V. Gullotti, J. Crane, W.C. Setzer, "Isothermal Transformation Characteristics of Several 6XXX Series Alloys," proceedings of 2nd International Aluminum Extrusion Technology Seminar, 15-17 November, 1977, Atlanta, Vol 1, Billet and Extrusion, pp 249-256

6010 Alloy



LIVE GRAPH
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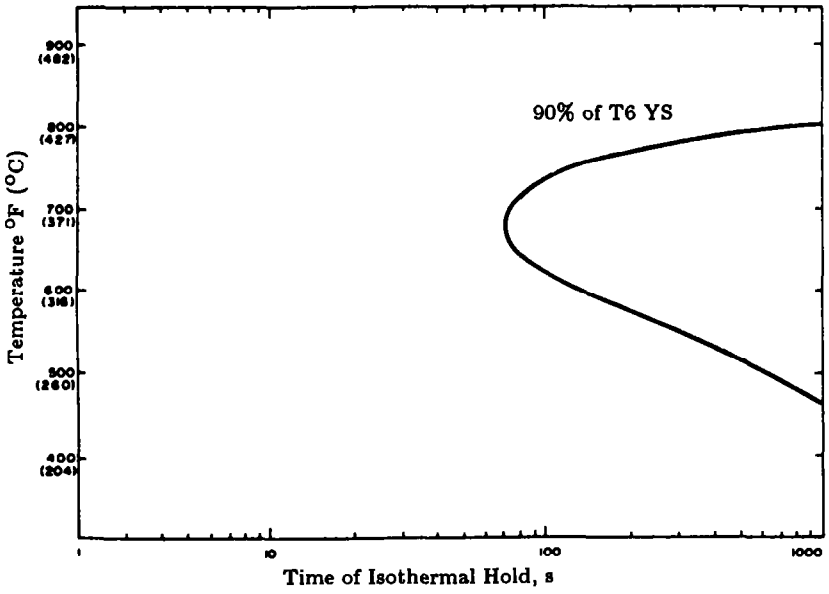
Time-temperature-property diagram
Effect of aging time and temperature on longitudinal yield strength of 6010-T4

SOURCE: Aluminum Properties and Physical Metallurgy, John E. Hatch, ed., ASM, 1984

6061 Alloy

Composition: Al - 0.55% Mg - 0.68% Si - 0.01% Cr - 0.014% Mn - 0.11% Fe - 0.036% Cu - 0.01% Ti - 0.002% B

Treatment: Solution heat-treated at 550°C (1020°F) for 1 to 1.5 h, down quenched to various temperatures into molten salt, held at temperature for varying times, water quenched, and aged

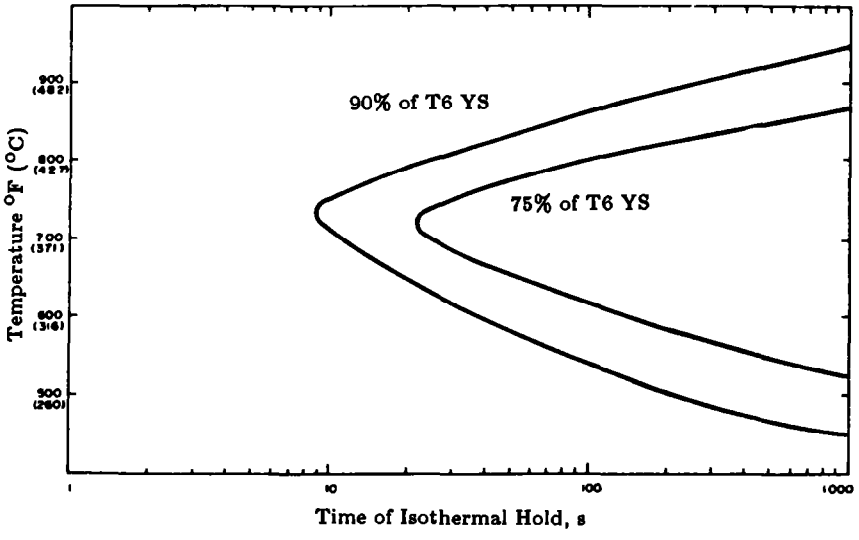


Time-temperature-property diagram (I-T)
Maximum quenched and aged yield strength 38.4 ksi (264 MPa)
Iso-yield curve is 90% of quenched and aged yield strength

6061 Alloy

Composition: Al - 0.98% Mg - 0.66% Si - 0.12% Cr - 0.12% Mn - 0.38% Fe - 0.23% Cu - 0.07% Zn - 0.014% Ti - 0.001% B

Treatment: Solution heat-treated at 540°C (1000°F) for 1 to 1.5 h, down quenched to various temperatures into molten salt, held at temperature for varying times, water quenched, and aged



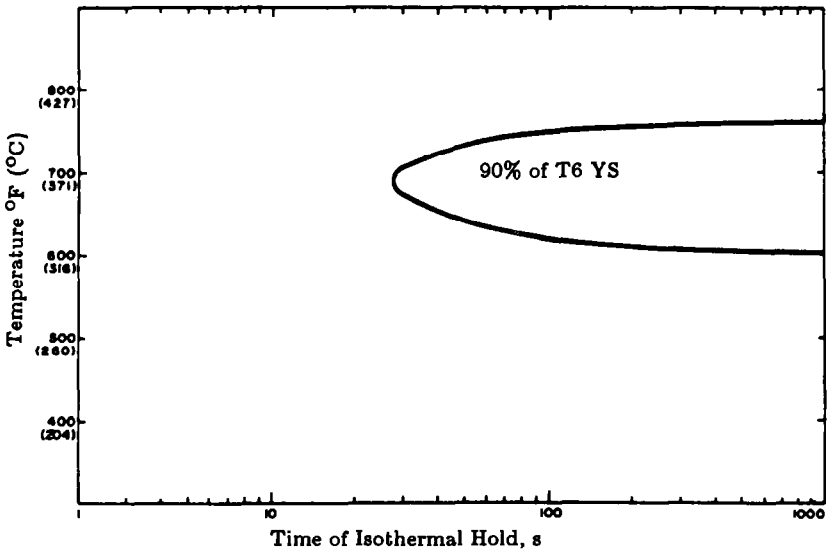
LIVE GRAPH
Click here to view

Time-temperature-property diagram (I-T)
Maximum quenched and aged yield strength 40.5 ksi (280 MPa)
Iso-yield curve is 90% of quenched and aged yield strength

SOURCE: D.V. Gullotti, J. Crane, W.C. Setzer, "Isothermal Transformation Characteristics of Several 6XXX Series Alloys," proceedings of 2nd International Aluminum Extrusion Technology Seminar, 15-17 November, 1977, Atlanta, Vol 1, Billet and Extrusion, pp 249-256

6063 Alloy

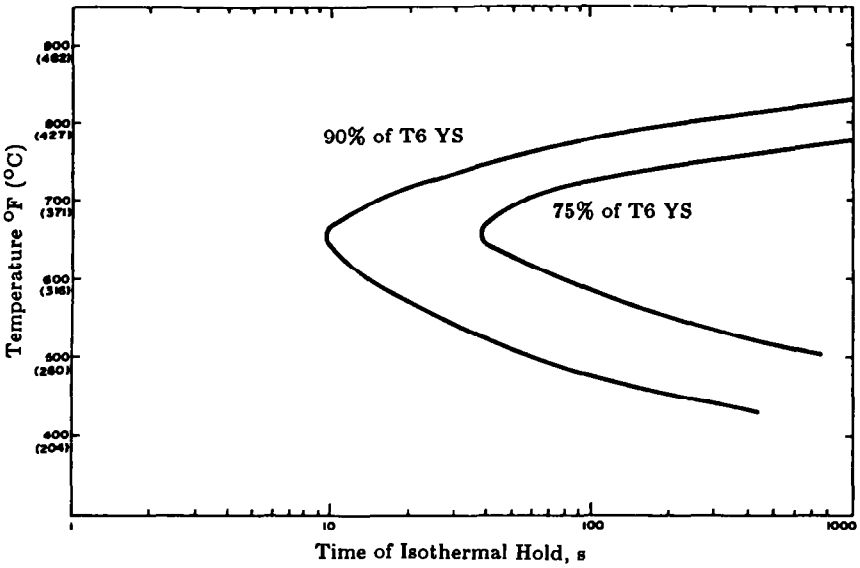
Composition: Al - 0.60% Mg - 0.30% Si - 0.02% Mn - 0.16% Fe - 0.01% Zn - 0.02% Ti
Treatment: Solution heat-treated at 540°C (1000°F) for 1 to 1.5 h, down quenched to various temperatures into molten salt, held at temperature for varying times, water quenched, and aged



Time-temperature-property diagram (I-T)
Maximum quenched and aged yield strength 25.9 ksi (178 MPa)
Iso-yield curve is 90% of quenched and aged yield strength

6205 Alloy

Composition: Al - 0.53% Mg - 0.76% Si - 0.12% Cr - 0.109% Zr - 0.11% Mn - 0.138% Fe - 0.04% Zn - 0.01% Ti
Treatment: Solution heat-treated at 540°C (1000°F) for 1 to 1.5 h, down quenched to various temperatures into molten salt, held at temperature for varying times, water quenched, and aged



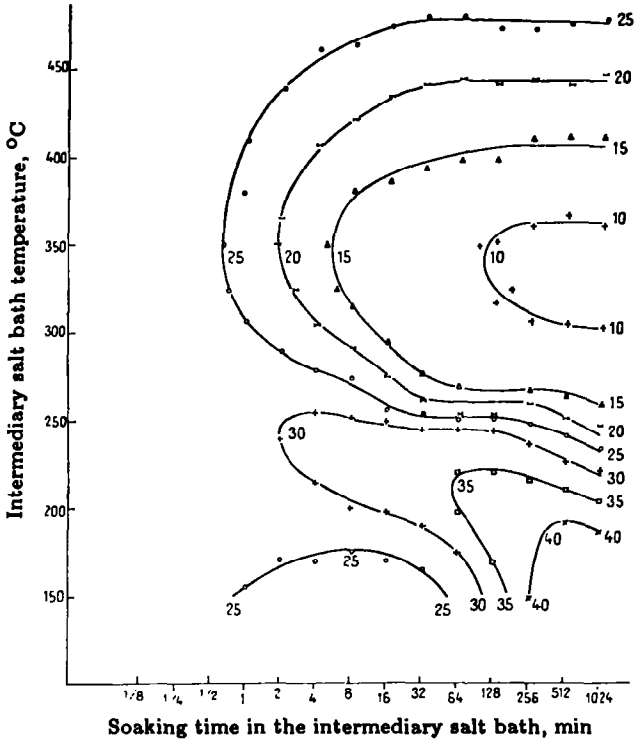
LIVE GRAPH
Click here to view

Time-temperature-property diagram (I-T)
Maximum quenched and aged yield strength 37.2 ksi (256 MPa)
Iso-yield curve is 90% of quenched and aged yield strength

SOURCE: D.V. Gullotti, J. Crane, W.C. Setzer, "Isothermal Transformation Characteristics of Several 6XXX Series Alloys," proceedings of 2nd International Aluminum Extrusion Technology Seminar, 15-17 November, 1977, Atlanta, Vol 1, Billet and Extrusion, pp 249-256

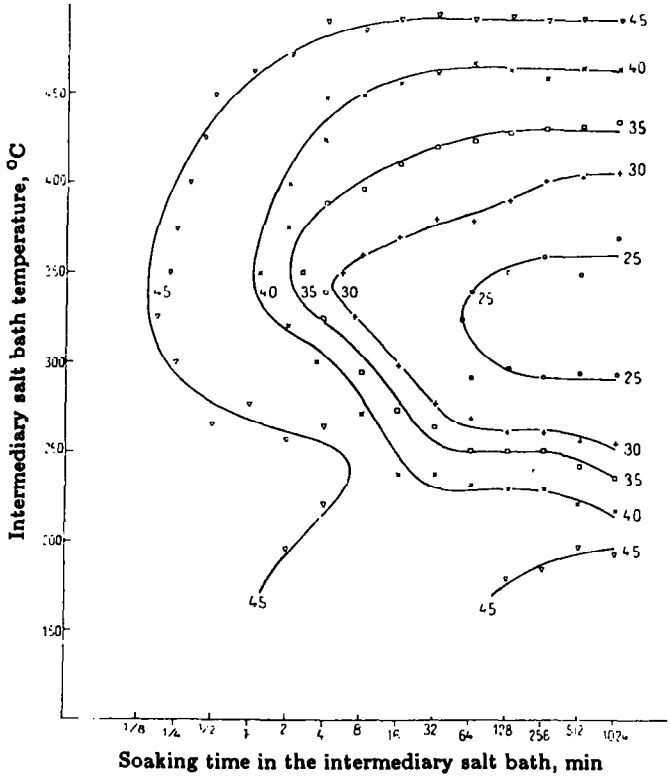
A-U4G Alloy

Composition: Al - 4.08% Cu - 0.72% Mg - 0.62% Mn - 0.60% Si - 0.27% Fe - 0.03% Ti
Treatment: 4 mm diameter wire specimens solution annealed at 500°C (932°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then naturally aged at about 20°C (68°F) for 7 days before testing



Time-temperature-properties diagram
Curves show constant values of the elastic limit, E, in kg/mm^2

Composition: Al - 4.08% Cu - 0.72% Mg - 0.62% Mn - 0.60% Si - 0.27% Fe - 0.03% Ti
Treatment: 4 mm diameter wire specimens solution annealed at 500°C (932°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then naturally aged at about 20°C (68°F) for 7 days before testing



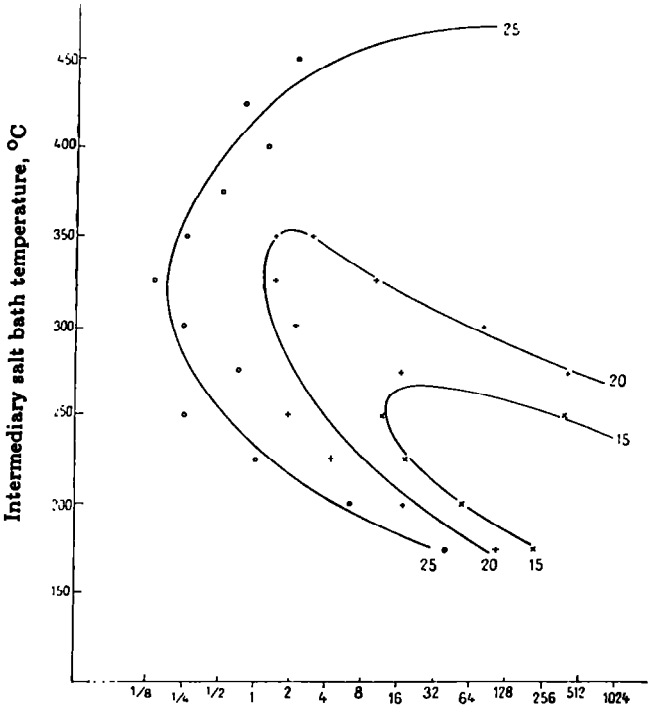
Time-temperature-properties diagram
Curves show constant values of ultimate tensile strength, R, in kg/mm^2

LIVE GRAPH
Click here to view

SOURCE: M. Renouard, "Value of Time-Temperature-Properties Diagrams for Heat-Treatment of Light Alloys," Mem. Sci. Rev. Met., Vol 56, 1959, pp 517-522

A-U4G Alloy

Composition: Al - 4.08% Cu - 0.72% Mg - 0.62% Mn - 0.60% Si - 0.27% Fe - 0.03% Ti
Treatment: 4 mm diameter wire specimens solution annealed at 500°C (932°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then naturally aged at about 20°C (68°F) for 7 days before testing



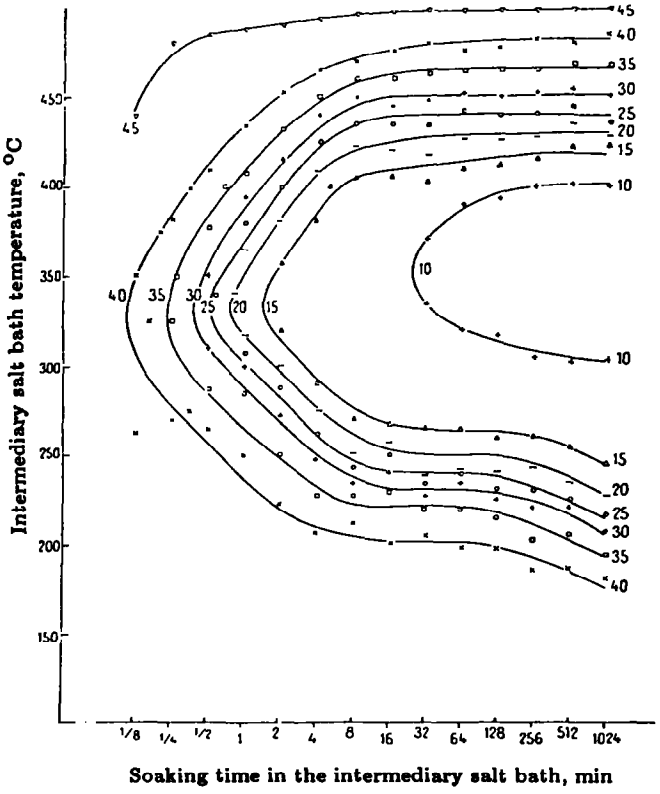
Time-temperature-properties diagram
Curves show constant values of the % elongation, A
Gage length is $8.16\sqrt{s}$, where s is the wire diameter

LIVE GRAPH
Click here to view

SOURCE: M. Renouard, "Value of Time-Temperature-Properties Diagrams for Heat-Treatment of Light Alloys," Mem. Sci. Rev. Met., Vol 56, 1959, pp 517-522

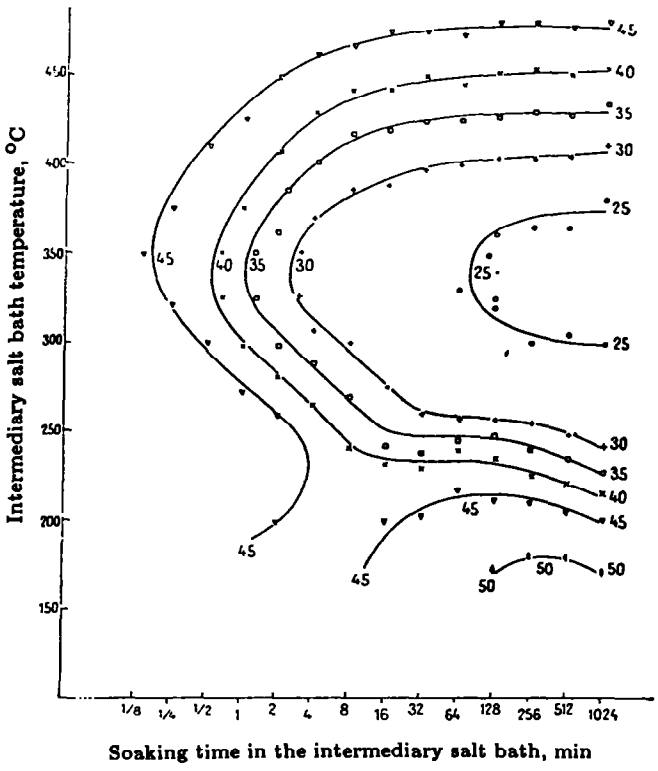
A-U4SG Alloy

Composition: Al - 4.19% Cu - 0.46% Mg - 0.78% Mn - 0.82% Si - 0.33% Fe - 0.05% Ti
Treatment: 4 mm diameter wire specimens solution annealed at 505°C (941°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then artificially aged at about 175°C (475°F) for 7 days before testing



Time-temperature-properties diagram
Curves show constant values of the elastic limit, E, in kg/mm^2

Composition: Al - 4.19% Cu - 0.46% Mg - 0.78% Mn - 0.82% Si - 0.33% Fe - 0.05% Ti
Treatment: 4 mm diameter wire specimens solution annealed at 505°C (941°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then naturally aged at 20°C (68°F) for 7 days before testing



Time-temperature-properties diagram
Curves show constant values of the ultimate tensile strength, R, in kg/mm^2

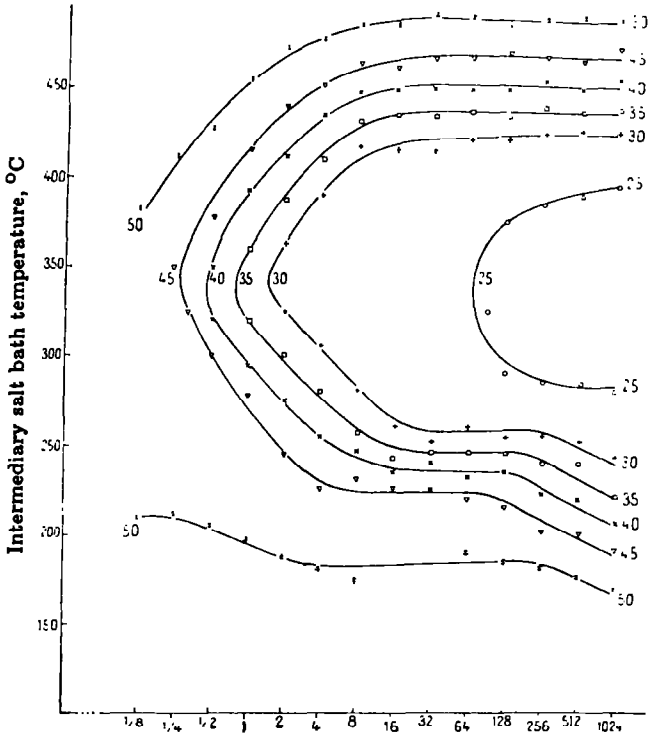
LIVE GRAPH
Click here to view

SOURCE: M. Renouard, "Value of Time-Temperature-Properties Diagrams for Heat-Treatment of Light Alloys," Mem. Sci. Rev. Met., Vol 56, 1959, pp 517-522

A-U4SG Alloy

Composition: Al - 4.19% Cu - 0.46% Mg - 0.78% Mn - 0.82% Si - 0.33% Fe - 0.05% Ti

Treatment: 4 mm diameter wire specimens solution annealed at 505°C (941°F) for 30 min, isothermally aged for various times between 175 and 475°C (347 and 887°F), then artificially aged at 175°C (475°F) for 7 days before testing



LIVE GRAPH
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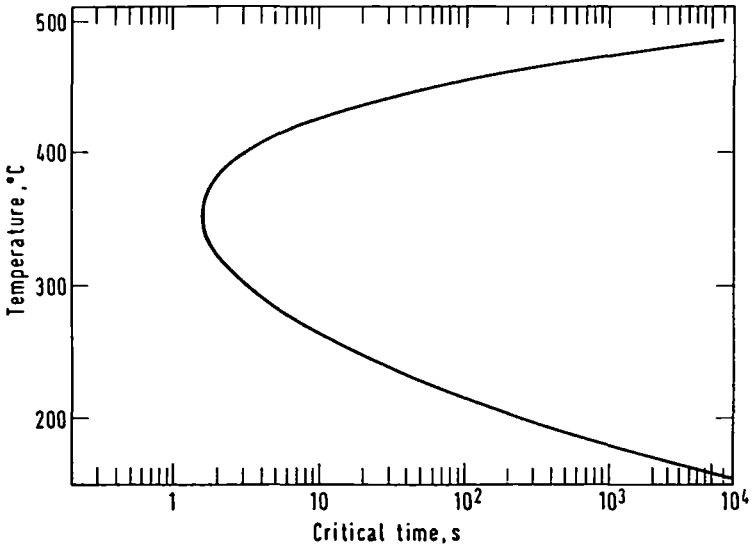
Soaking time in the intermediary salt bath, min

Time-temperature-properties diagram
Curves show constant values of the ultimate tensile strength, R, in kg/mm^2

SOURCE: M. Renouard, "Value of Time-Temperature-Properties Diagrams for Heat-Treatment of Light Alloys," Mem. Sci. Rev. Met., Vol 56, 1959, pp 517-522

6351 Alloy

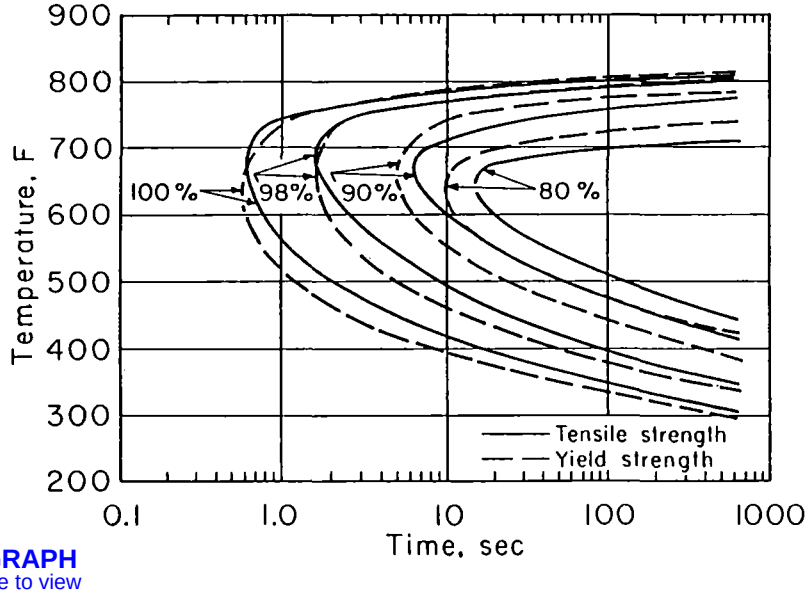
Treatment: T6 condition (aged at 173°C (340°F) for 8 h



Time-temperature-property diagram
C-curve for 99.5% maximum yield strength of AA 6351-T6 extrusion

SOURCE: J.W. Evancho, "Effects of Quenching on Strength and Toughness of 6351 Extrusions," Report 13-73-HQ40, Alcoa Laboratories, 1973, and J.T. Staley, "Quench Factor Analysis of Aluminium Alloys," Materials Science and Technology, Vol 3, November 1987, pp 923-935

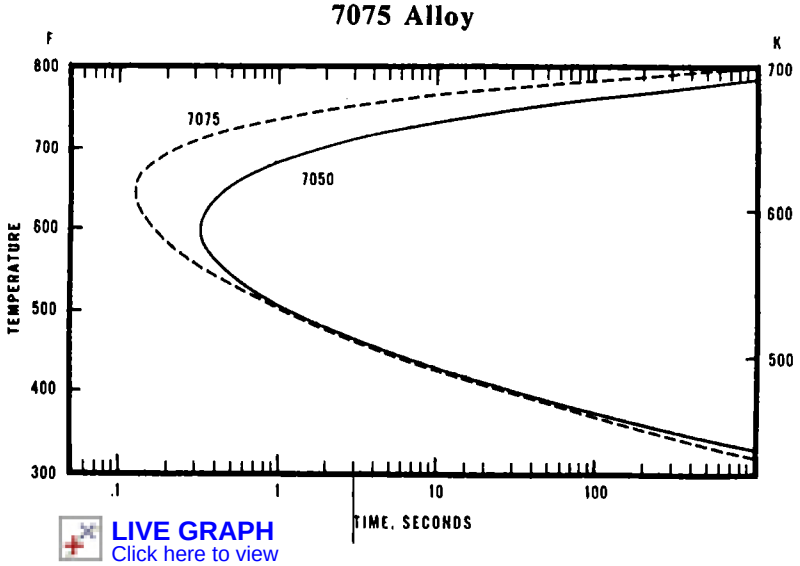
7075 Alloy



LIVE GRAPH
Click here to view

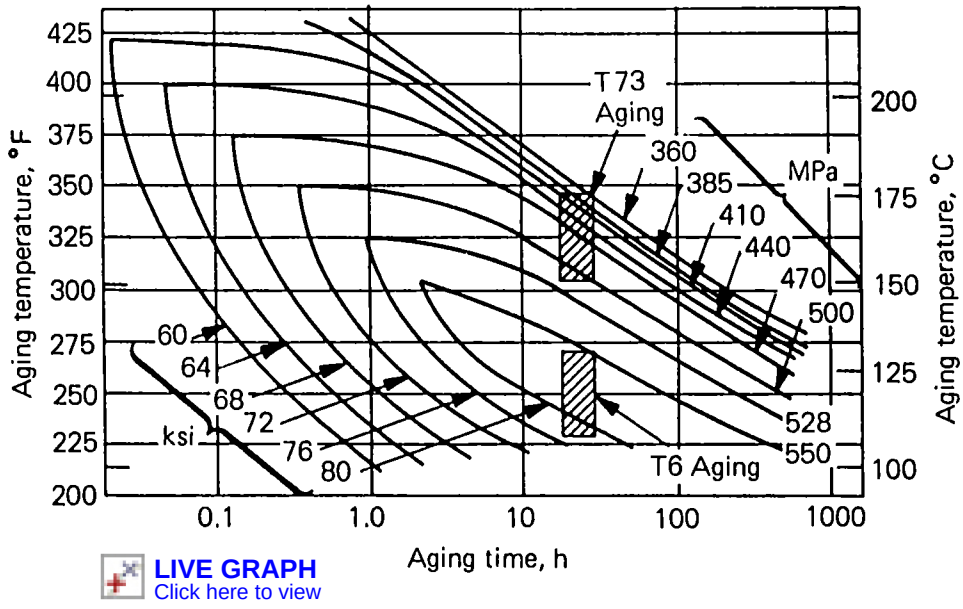
Time-temperature-property diagram
Effect of time and temperature in interrupted quenching experiments on tensile and yield strength of alloy 7075, expressed as percentages of strengths obtained by quenching without interruption

SOURCE:. W.L. Fink, L.A. Willey, Trans. AIME, Vol 175, 1948, pp 414-427



Time-temperature-property diagram
Comparison of yield strength C-curves for 7050-T76 and 7075-T6 sheet

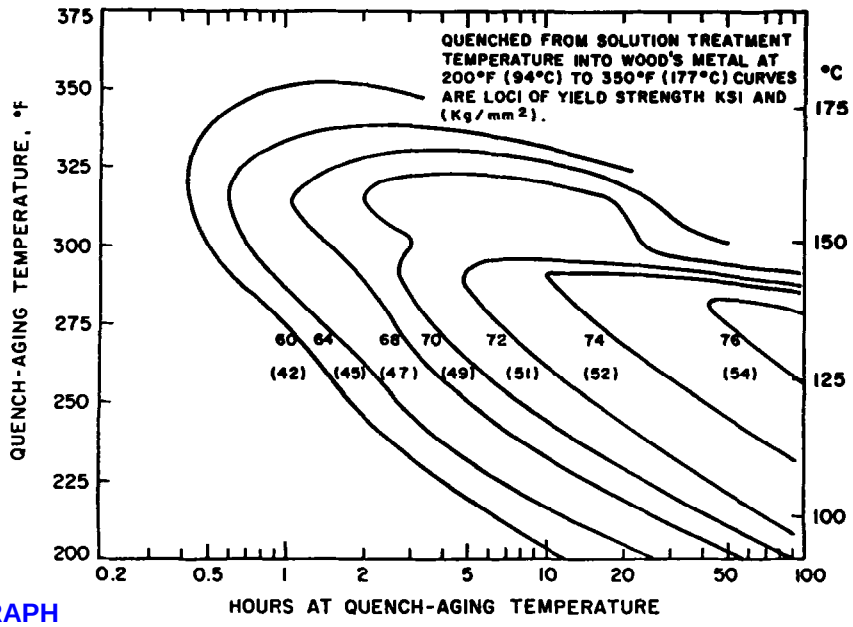
SOURCE: J.W. Evancho, J.T. Staley, "Kinetics of Precipitation in Aluminum Alloys During Continuous Cooling," Met. Trans., Vol 5, ASM, January 1974, pp 43-47



Time-temperature-property diagram
Iso yield strength curves

SOURCE: Aluminum Properties and Physical Metallurgy, John E. Hatch, ed., ASM, 1984

7075 + Ag Plate



LIVE GRAPH
Click here to view

Time-temperature-property diagram
Effects of precipitation treatment time and temperature on strength of 7075 plate quenched directly to the precipitation treatment temperature

SOURCE: J.T. Staley, R.H. Brown, R. Schmidt, "Heat Treating Characteristics of High Strength Al-Zn-Mg-Cu Alloys With and Without Silver Additions," paper presented at 1970 Western Metal and Tool Conference, Los Angeles, 11 March 1970

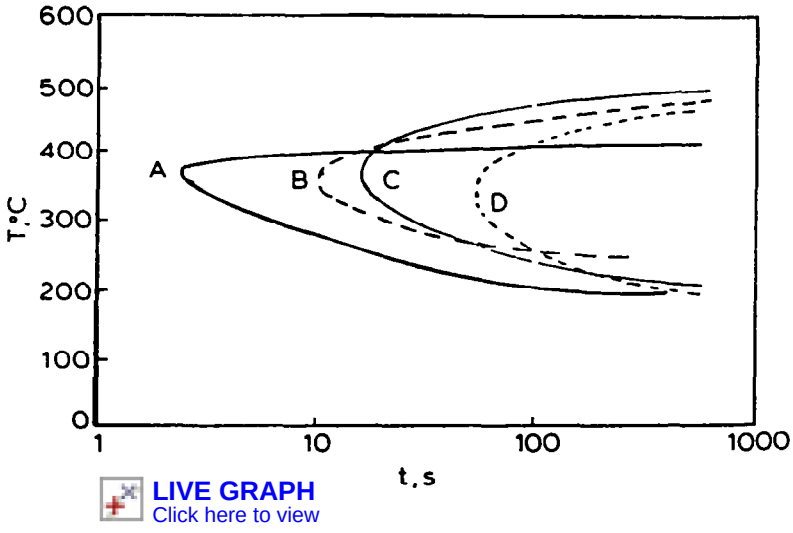
7075, 7017, 6061 and 6063 Alloys

A = 7075
(W.L. Fink, L.A. Willey, Trans. AIME, Vol 175, 1948, pp 414-427)

B = 2017
(M. Renouard, Mem. Sci. Rev. Metall., Vol 56, No. 5, 1959, p 517)

C = 6061
(D. Marchive, R. Deschamps, Rev. Metall., Vol 76, 1979, p 18)

D = 6063
(D.V. Gulati, et al., in Proc. 2nd Int. Tech. Sem. on Aluminium Extrusion," Aluminum Association, Vol 1, 1977, p 249)



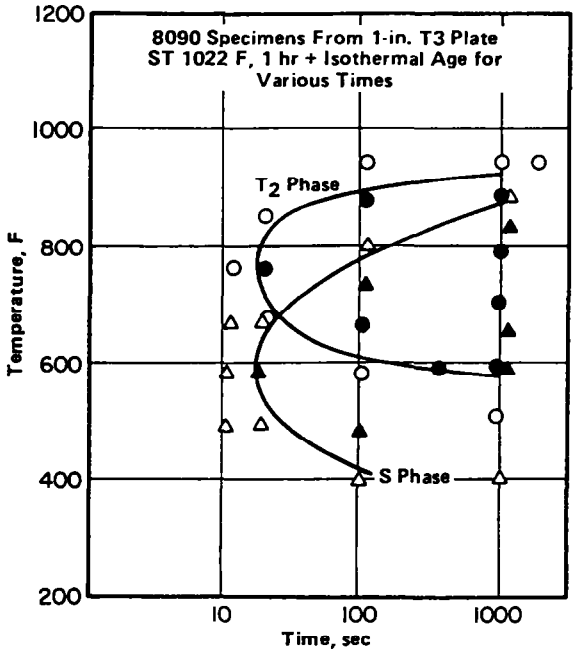
LIVE GRAPH
Click here to view

Time-temperature-property diagram
Curves at 95% of maximum tensile stress for various alloys

SOURCE: T. Sheppard, "Press Quenching of Aluminium Alloys," Materials Science and Technology, Vol 4, July 1988, pp 635-643

8090 Alloy

Composition: Al - 2.28% Li - 0.86% Cu - 0.90% Mg - 0.13% Zr - 0.13% Fe - 0.06% Si



LIVE GRAPH
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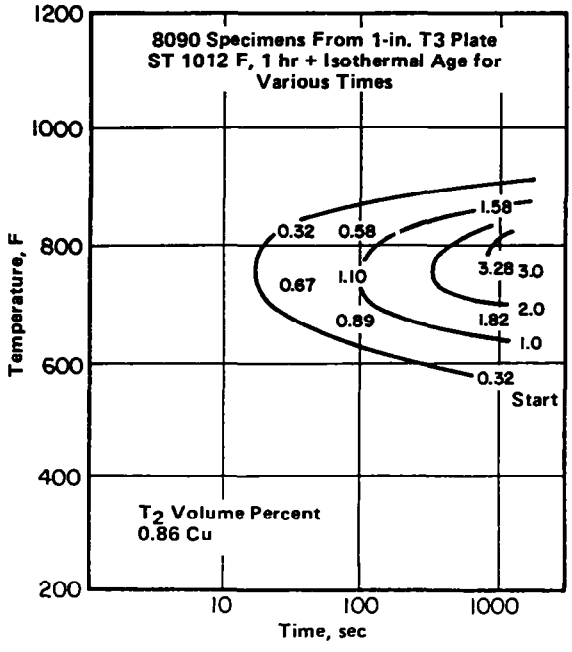
Time-temperature-precipitation diagram
Nucleation start curves

Composition: Al - 2.28% Li - 0.86% Cu - 0.90% Mg - 0.13% Zr - 0.13% Fe - 0.06% Si



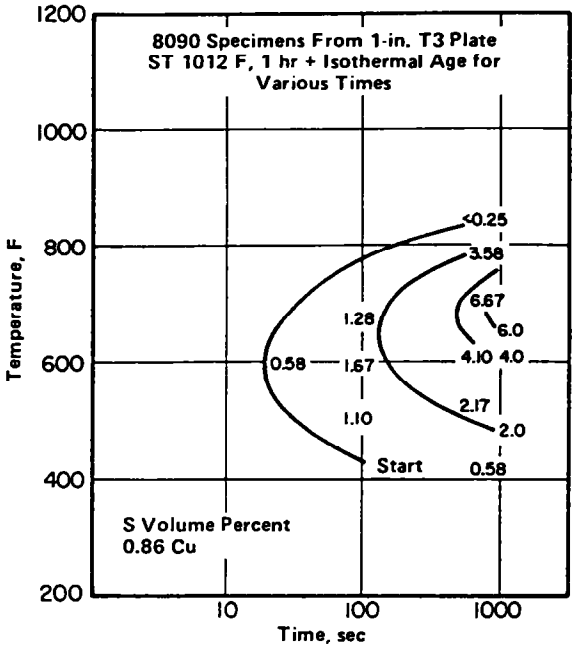
Time-temperature-precipitation diagram
Volume fractions of the T_2 phase

LEGEND:
S phase = Al_2CuMg
T_2 phase = Al_6CuLi_3

SOURCE: G.M. Colvin, E.A. Starke, Jr., SAMPE Q., July 1988, Vol 19, No. 4, pp 10-21, as published in Aerospace Structural Handbook for Nonferrous Alloys, June 1990

8090 Alloy

Composition: Al - 2.28% Li - 0.86% Cu - 0.90% Mg - 0.13% Zr - 0.13% Fe - 0.06% Si



LIVE GRAPH
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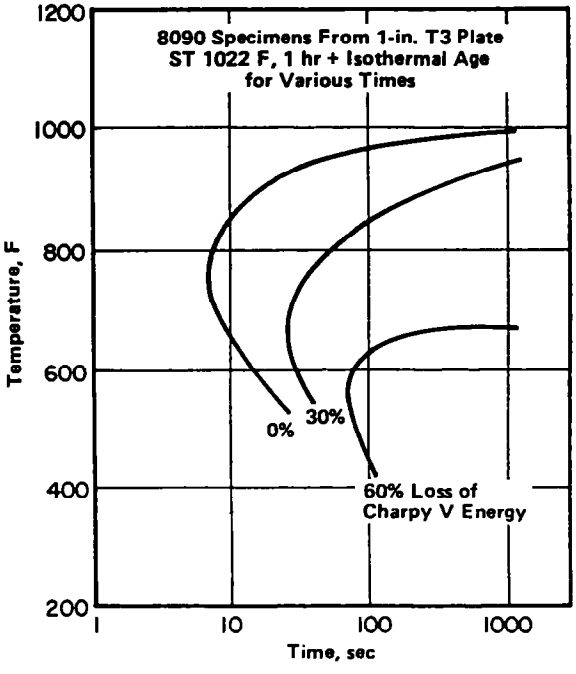
Time-temperature-precipitation diagram
Volume fractions of the S phase (Al_2CuMg)

Composition: Al - 2.28% Li - 0.86% Cu - 0.90% Mg - 0.13% Zr - 0.13% Fe - 0.06% Si



LIVE GRAPH
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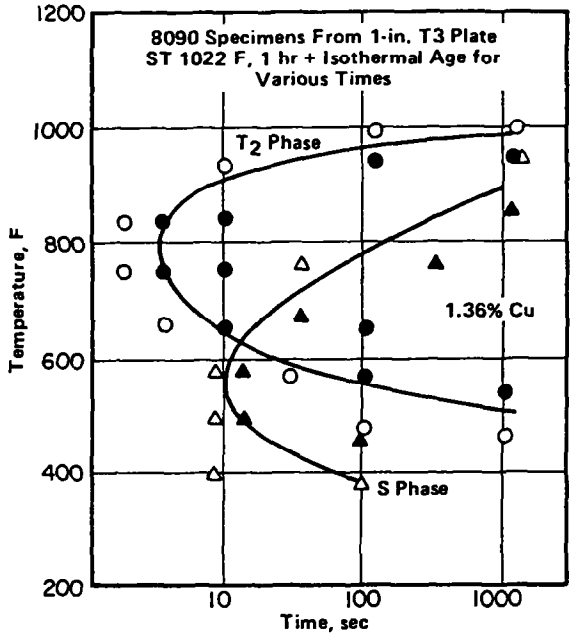
Time-temperature-embrittlement diagram
Loss in Charpy V energy relative to as-quenched condition for isothermal aging

SOURCE: G.M. Colvin, E.A. Starke, Jr., SAMPE Q., July 1988, Vol 19, No. 4, pp 10-21, as published in Aerospace Structural Handbook for Nonferrous Alloys, June 1990

8090 Alloy

Composition: Al - 2.58% Li - 1.36% Cu - 0.89% Mg - 0.13% Zr - 0.17% Fe - 0.04% Si



LIVE GRAPH
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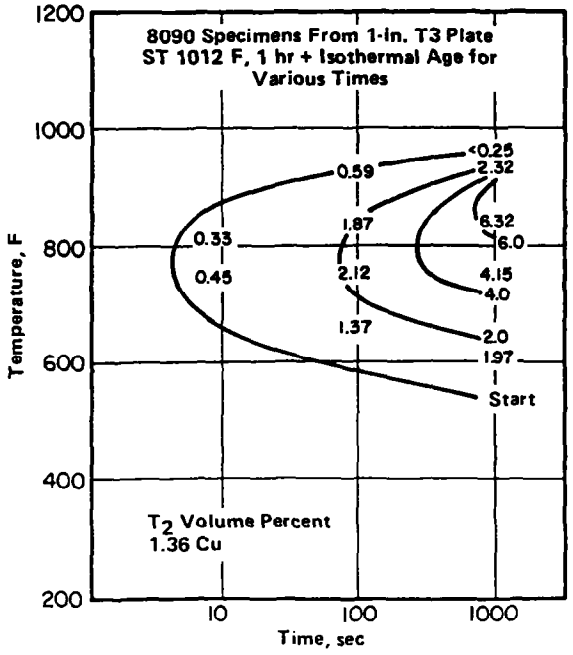
Time-temperature-precipitation diagram
Nucleation start curves

Composition: Al - 2.58% Li - 1.36% Cu - 0.89% Mg - 0.13% Zr - 0.17% Fe - 0.04% Si



LIVE GRAPH
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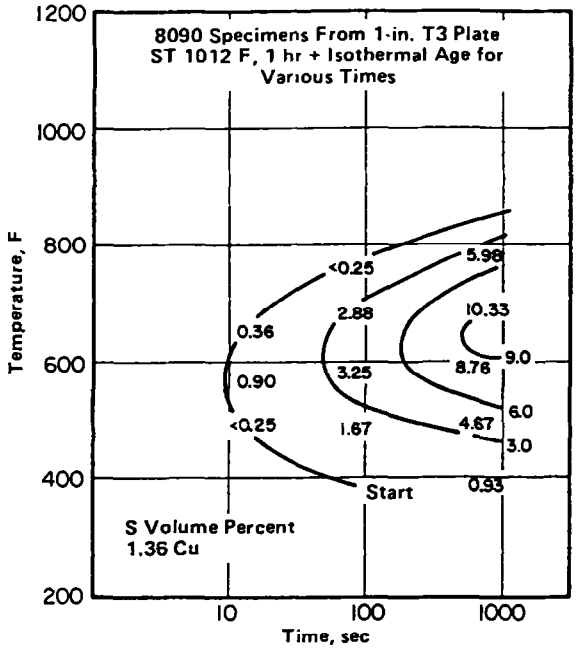
Time-temperature-precipitation diagram
Volume fractions of the T_2 phase

LEGEND:
S phase = Al_2CuMg
T_2 phase = Al_6CuLi_3

SOURCE: G.M. Colvin, E.A. Starke, Jr., SAMPE Q., July 1988, Vol 19, No. 4, pp 10-21, as published in Aerospace Structural Handbook for Nonferrous Alloys, June 1990

8090 Alloy

Composition: Al - 2.58% Li - 1.36% Cu - 0.89% Mg - 0.13% Zr - 0.17% Fe - 0.04% Si



LIVE GRAPH
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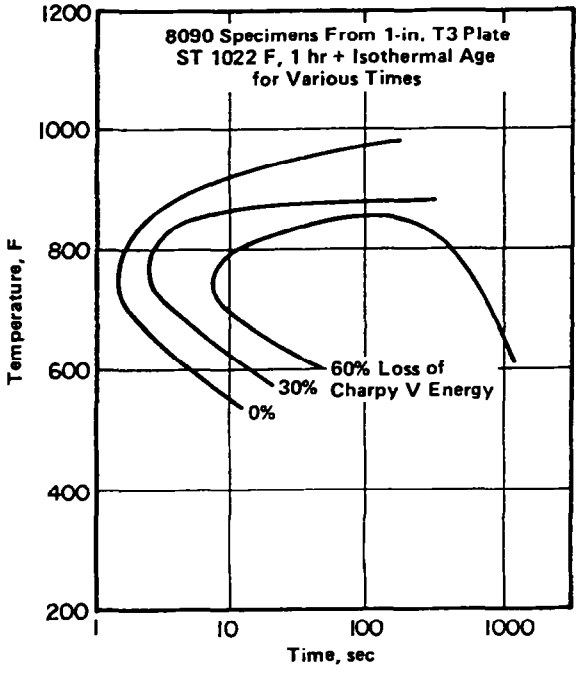
Time-temperature-precipitation diagram
Volume fractions of the S phase (Al_2CuMg)

Composition: Al - 2.58% Li - 1.36% Cu - 0.89% Mg - 0.13% Zr - 0.17% Fe - 0.04% Si



LIVE GRAPH
Click here to view

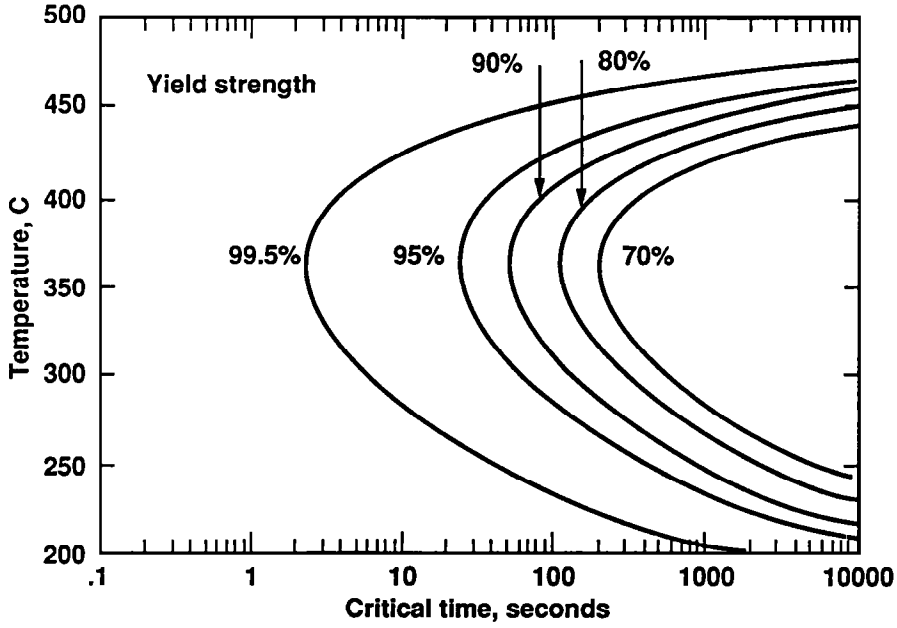
Time-temperature-embrittlement diagram
Loss in Charpy V energy relative to as-quenched condition for isothermal aging

SOURCE: G.M. Colvin, E.A. Starke, Jr., SAMPE Q., July 1988, Vol 19, No. 4, pp 10-21, as published in Aerospace Structural Handbook for Nonferrous Alloys, June 1990

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti

Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



LIVE GRAPH
Click here to view

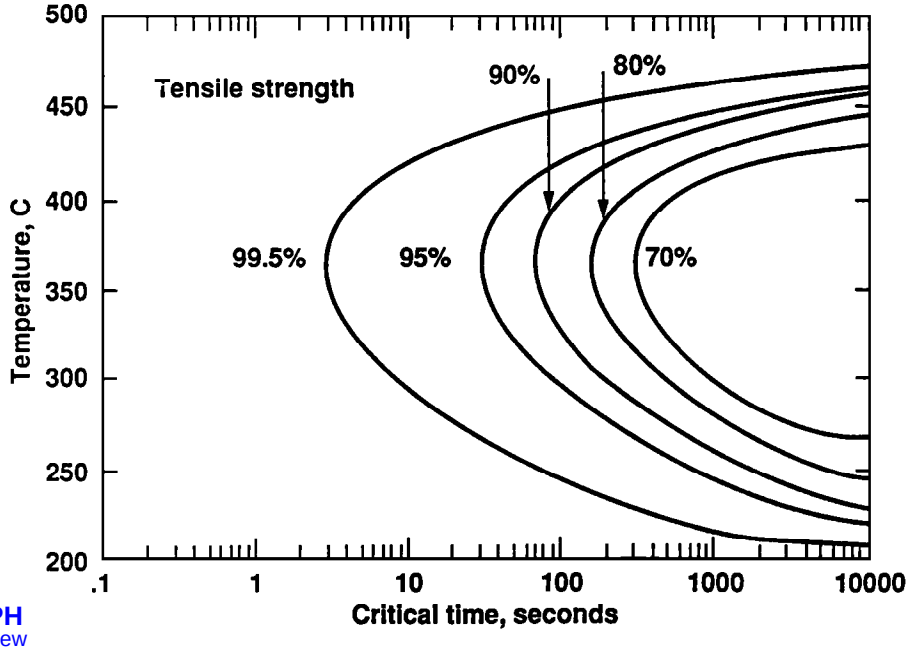
Time-temperature-property diagram
Yield strength C-curve
Results shown are a percentage of the theoretical maximum

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti

Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



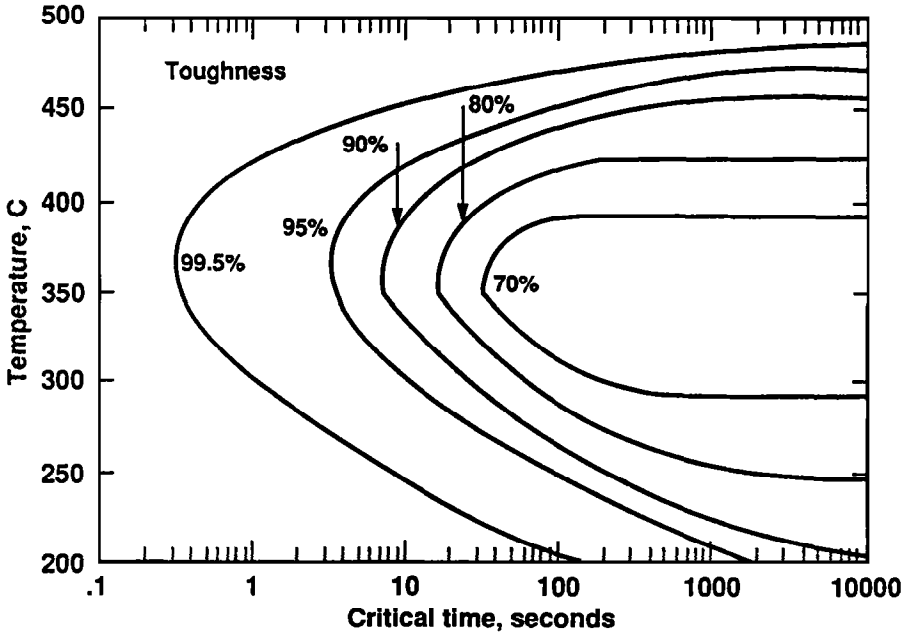
LIVE GRAPH
Click here to view

Time-temperature-property diagram
Tensile strength C-curves
Results shown are a percentage of the theoretical maximum

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti
Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



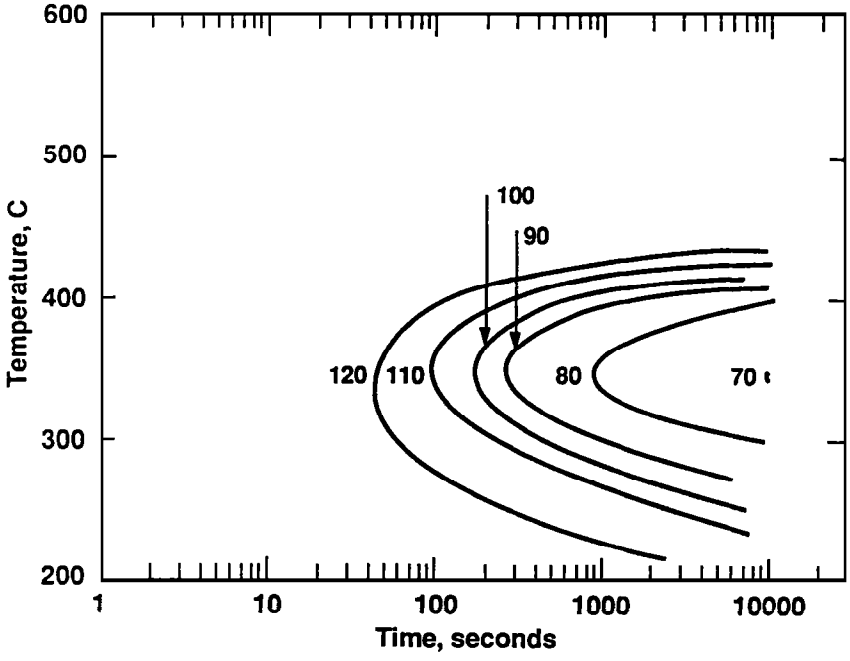
LIVE GRAPH
Click here to view

Time-temperature-property diagram
Toughness C-curves
Results shown are a percentage of the theoretical maximum

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti
Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



LIVE GRAPH
Click here to view

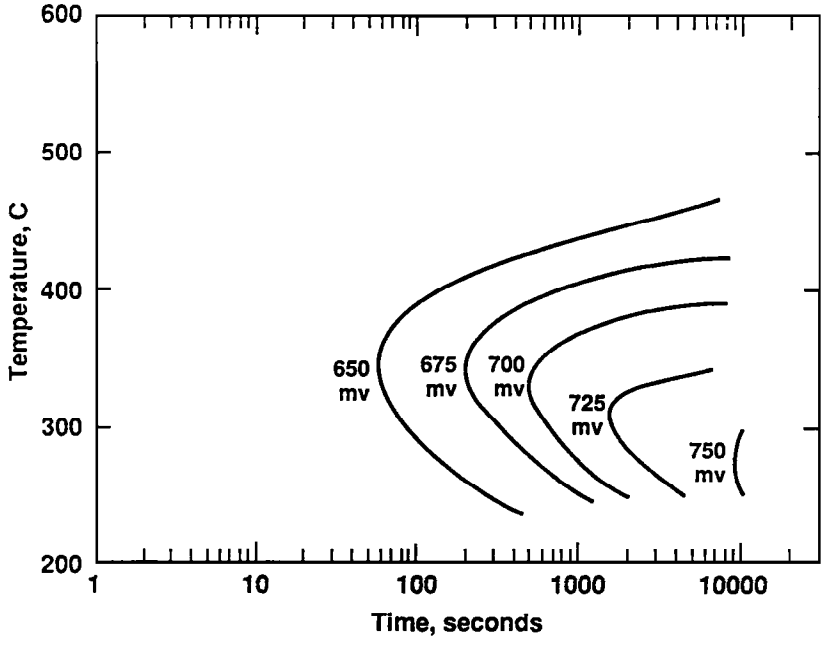
Time-temperature-property diagram
C-curves for hardness
Graph shows iso-hardness lines where the numbers given are Vickers hardness values determined with a 5 kgf test load

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti

Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



LIVE GRAPH
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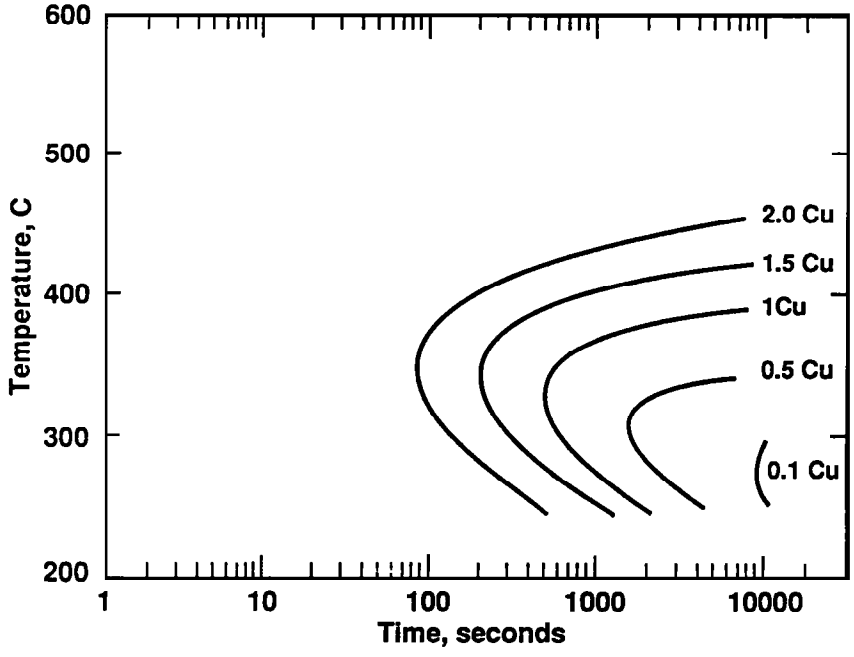
Time-temperature-property diagram
C-curves for solution potentials
Information developed according to the method described in ASTM G 69-81

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti

Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



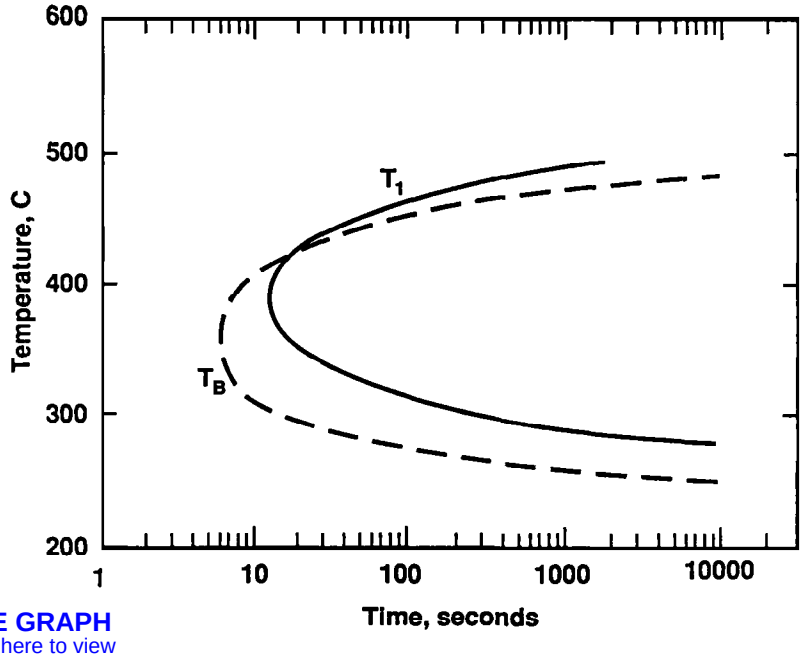
Time-temperature-property diagram
C-curves for % Cu in solution
Information determined from the data in the preceding figure

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Experimental Aluminum Alloys

Composition: Al - 2.7% Cu - 1.6% Li - 0.09% Zr - 0.05% Fe - 0.005% Si - 0.1% Ti

Treatment: Solution annealed at 550°C (1022°F) for 30 min, then transferred to a molten metal bath for the isothermal holds, water quenched, stretched 6% and aged at 163°C (325°F) for 24 h



LIVE GRAPH
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Time-temperature-precipitation diagram
C-curves for first indication of T_1 and T_B by x-ray

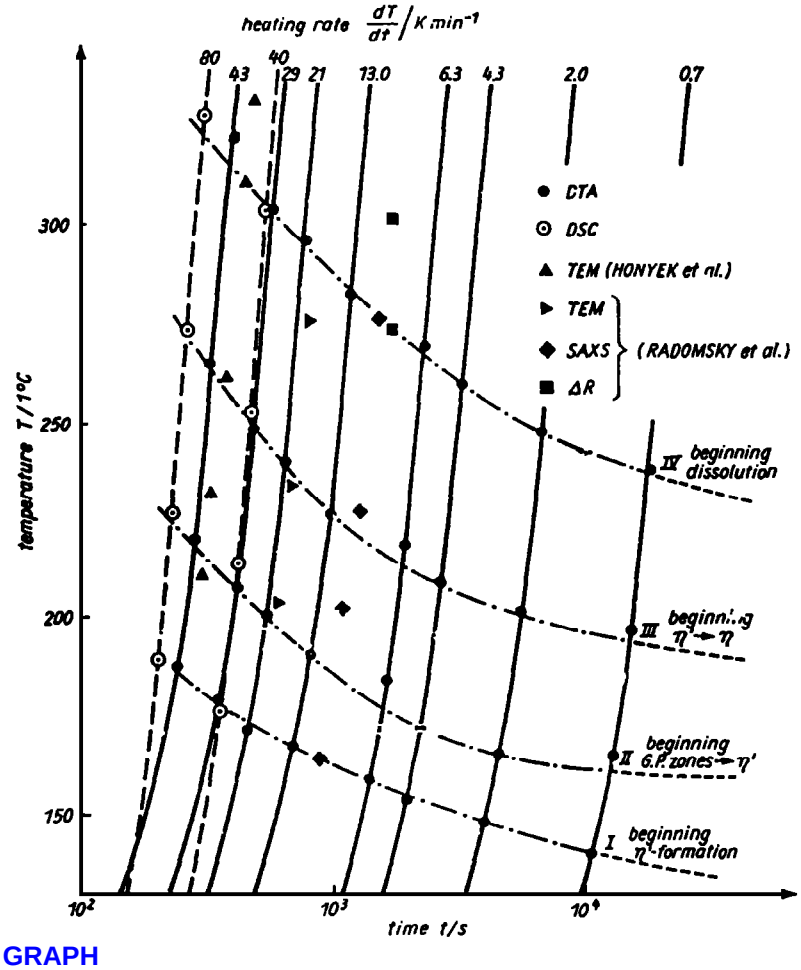
T_1 phase = Al_2CuLi

T_B phase is either = Al_6Cu_4Li or Al_7Cu_4Li

SOURCE: James T. Staley, Aluminum Company of American, Alcoa Center PA, to be published

Al-Zr-Mg Alloy

Composition: Al - 4.5 (at.%) Zr - 2.25 (at.%) Mg
Treatment: Solution treated at 490°C (914°F) for 1 h and water quenched. A special DTA (differential thermal analysis) device was used to heat specimens at various rates after they had been aged at room temperature for 1 h. The solid lines are for heating rates from room temperature; the 2 dotted curves are for heating rates that started at -50°C (-58°F). Characteristic points on the DTA curves were plotted on the heat rate curves and then connected to represent the lower limit of formation or dissolution of precipitates or phase transformations



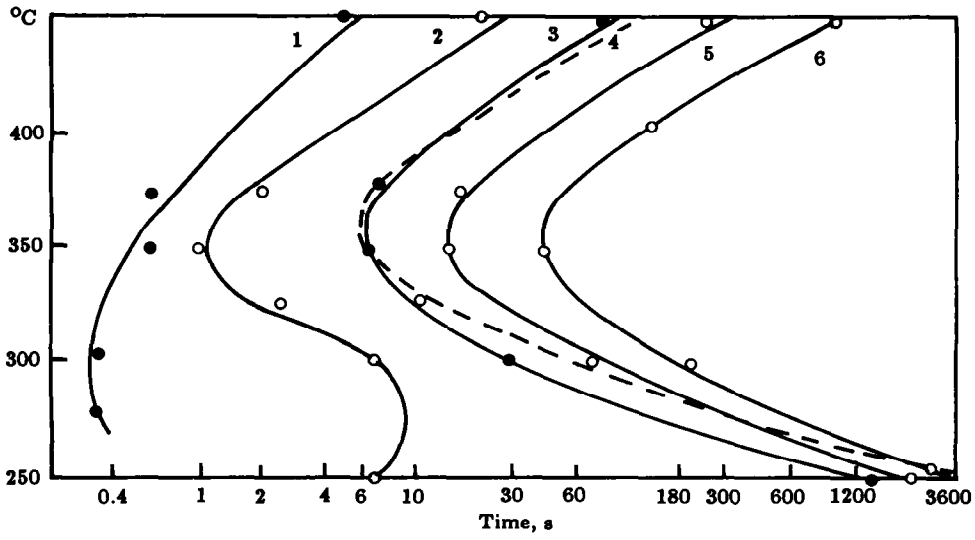
LIVE GRAPH
Click here to view

Dynamic time-transition-temperature diagram

SOURCE: E. Becker, W. Heyroth, "The Dynamic TTT-Diagram of an Al-4.5at.%Zn-2.25at.%Mg Alloy Attained from Thermal Analysis," Crystal Research & Technology, Vol 20, No. 2, 1985, pp 263-266

Aluminum Alloys

Composition: Al - 4.64% Cu - 1.48% Mg - 0.82% Mn - 0.49% Fe - 0.02% Si



LEGEND:
1 = sensitization to intercrystalline corrosion
2 = conditions to obtain an ultimate tensile strength of 49.0 kg/mm^2
3 = condition for 95% of the ultimate tensile strength
4 = conditions to obtain 95% of the 0.2% offset yield strength
5 = condition for 90% of the ultimate tensile strength
6 = condition for 85% of the ultimate tensile strength

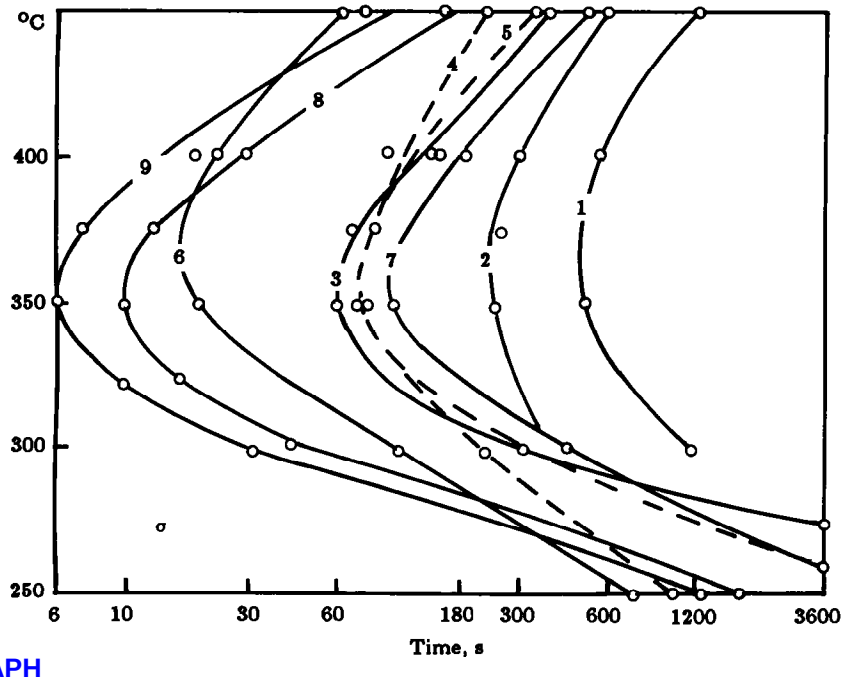
LIVE GRAPH
Click here to view

SOURCE: V.G. Davydov, I.I. Novikov, E.D. Zakharov, "C-Curves of the Decomposition of a Supersaturated Solid Solution in Duralumin-Type Alloys," Mosk. Inst. Stali Splavov, Moscow, USSR, Izv. Vyssh. Ucheb. Zaved., Tsvet. Met. Vol 11, No. 4, 1968, pp 117-123

Aluminum Alloys

Compositions:

Alloy 1: Al - 4.08% Cu - 0.009% Mg - 0.008% Mn - 0.006% Si - 0.002% Fe
Alloy 2: Al - 4.60% Cu - 0.007% Mg - 0.009% Mn - 0.010% Si - 0.002% Fe
Alloy 3: Al - 3.70% Cu - 1.70% Mg - 0.03% Mn
Alloy 4: Al - 4.60% Cu - 0.89% Mg - 0.02% Mn - <0.01% Si - <0.01% Fe
Alloy 5: Al - 4.28% Cu - 1.23% Mg - 0.02% Mn
Alloy 6: Al - 4.72% Cu - 0.12% Mg - 0.71% Mn - <0.06% Si - <0.01% Fe
Alloy 7: Al - 4.19% Cu - 1.30% Mg - 0.06% Mn - 0.47% Si - <0.01% Fe
Alloy 8: Al - 4.60% Cu - 1.40% Mg - 0.90% Mn - 0.01% Si - 0.01% Fe
Alloy 9: Al - 4.64% Cu - 1.48% Mg - 0.82% Mn - 0.02% Si - 0.49% Fe



LIVE GRAPH
Click here to view

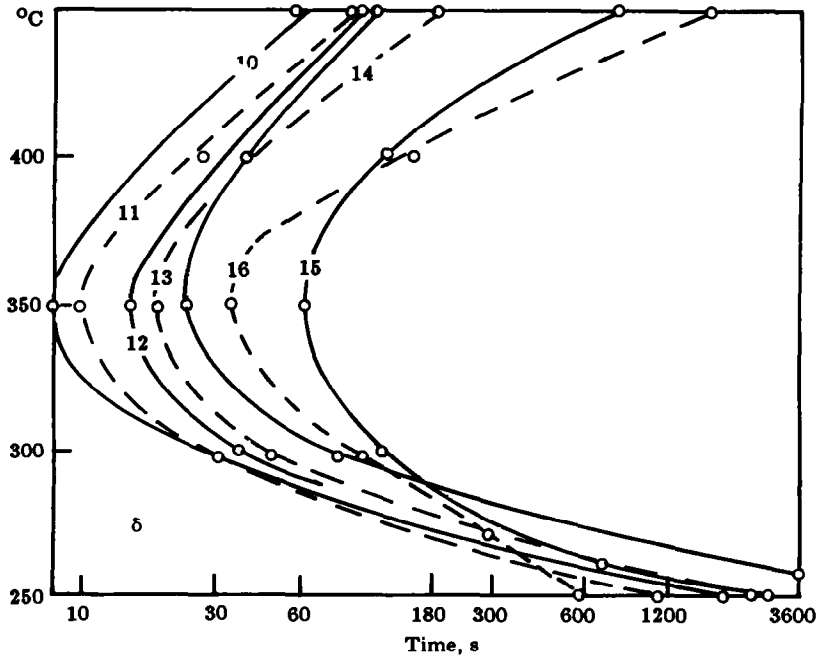
Time-temperature-property diagram for aluminum alloys overaged to produce a 5% decrease from the ultimate tensile strength

SOURCE: V.G. Davydov, I.I. Novikov, E.D. Zakharov, "C-Curves of the Decomposition of a Supersaturated Solid Solution in Duralumin-Type Alloys," Mosk. Inst. Stali Splavov, Moscow, USSR, Izv. Vyssh. Ucheb. Zaved., Tsvet. Met. Vol 11, No. 4, 1968, pp 117-123

Aluminum Alloys

Compositions:

Alloy 10: Al - 4.74% Cu - 1.80% Mg - 0.38% Mn - 0.11% Si - 0.08% Fe
Alloy 11: Al - 4.75% Cu - 1.74% Mg - 0.95% Mn - 0.15% Si - 0.09% Fe
Alloy 12: Al - 4.30% Cu - 1.56% Mg - 0.65% Mn - 0.13% Si - 0.07% Fe
Alloy 13: Al - 3.77% Cu - 1.74% Mg - 0.38% Mn - 0.13% Si - 0.10% Fe
Alloy 14: Al - 3.83% Cu - 1.83% Mg - 0.86% Mn - 0.12% Si - 0.12% Fe
Alloy 15: Al - 3.82% Cu - 1.16% Mg - 0.43% Mn - 0.10% Si - 0.09% Fe
Alloy 16: Al - 3.62% Cu - 1.20% Mg - 0.85% Mn - 0.08% Si - 0.10% Fe



Time-temperature-property diagram for aluminum alloys overaged to produce a 5% decrease from the ultimate tensile strength

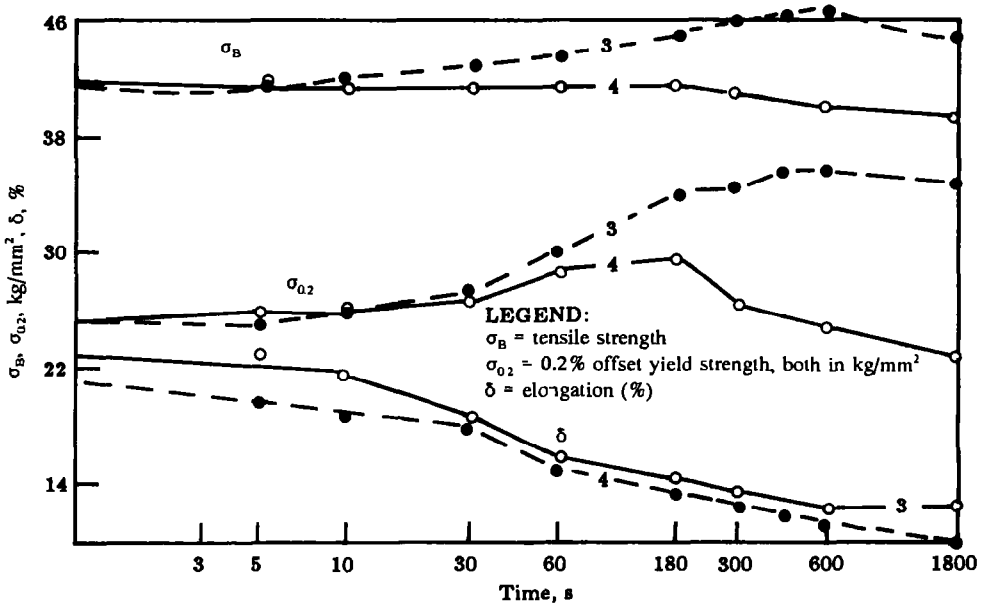
SOURCE: V.G. Davydov, I.I. Novikov, E.D. Zakharov, "C-Curves of the Decomposition of a Supersaturated Solid Solution in Duralumin-Type Alloys," Mosk. Inst. Stali Splavov, Moscow, USSR, Izv. Vyssh. Ucheb. Zaved., Tsvet. Met. Vol 11, No. 4, 1968, pp 117-123

Aluminum Alloys

Composition:

Alloy 3: Al - 3.70% Cu - 1.70% Mg - 0.03% Mn

Alloy 4: Al - 4.60% Cu - 0.89% Mg - 0.02% Mn - <0.01% Si - <0.01% Fe



LIVE GRAPH
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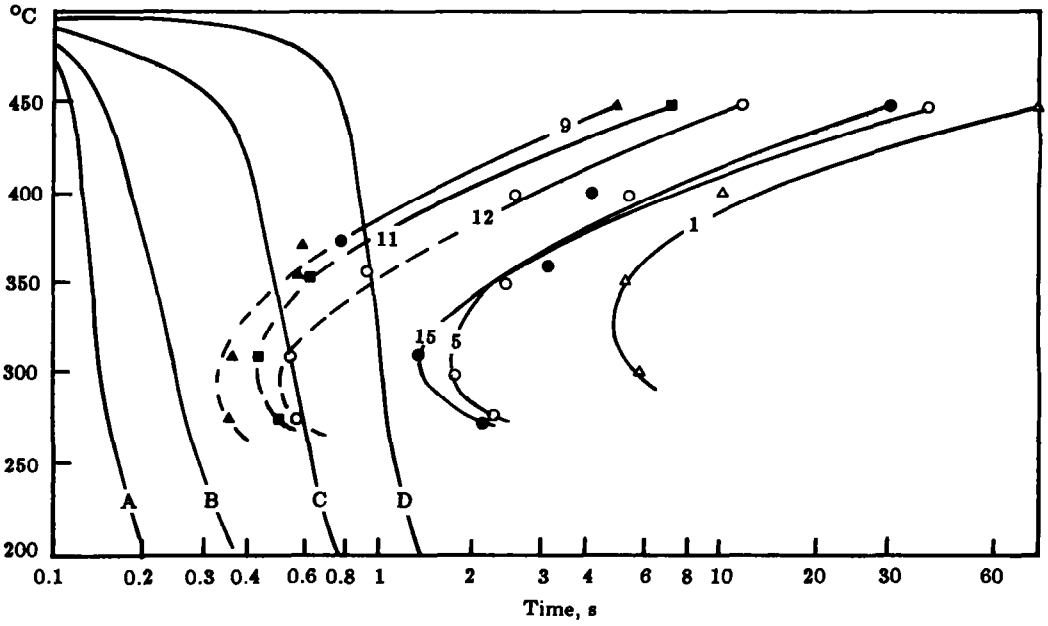
Tensile properties of alloys aged at 250°C (482°F)

Compositions:

Alloy 1: Al - 4.08% Cu - 0.009% Mg - 0.008% Mn - 0.006% Si - 0.002% Fe
Alloy 5: Al - 4.28% Cu - 1.23% Mg - 0.02% Mn
Alloy 9: Al - 4.64% Cu - 1.48% Mg - 0.82% Mn - 0.02% Si - 0.49% Fe
Alloy 11: Al - 4.75% Cu - 1.74% Mg - 0.95% Mn - 0.15% Si - 0.09% Fe
Alloy 12: Al - 4.30% Cu - 1.56% Mg - 0.65% Mn - 0.13% Si - 0.07% Fe
Alloy 15: Al - 3.82% Cu - 1.16% Mg - 0.43% Mn - 0.10% Si - 0.09% Fe



LIVE GRAPH
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Time-temperature-sensitization diagram
Cooling curves A to D are for aluminum sheets of 1.2, 3.1, 5.0 and 9.3 mm thickness, respectively

SOURCE: V.G. Davydov, I.I. Novikov, E.D. Zakharov, "C-Curves of the Decomposition of a Supersaturated Solid Solution in Duralumin-Type Alloys," Mosk. Inst. Stali Splavov, Moscow, USSR, Izv. Vyssh. Ucheb. Zaved., Tsvet. Met. Vol 11, No. 4, 1968, pp 117-123

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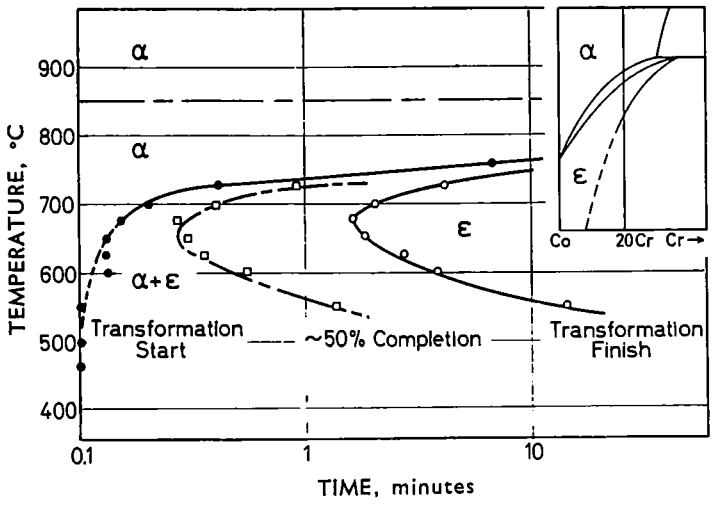
Cobalt-Base Alloys

Co-Cr Alloy

Composition: Co - 20% Cr



LIVE GRAPH
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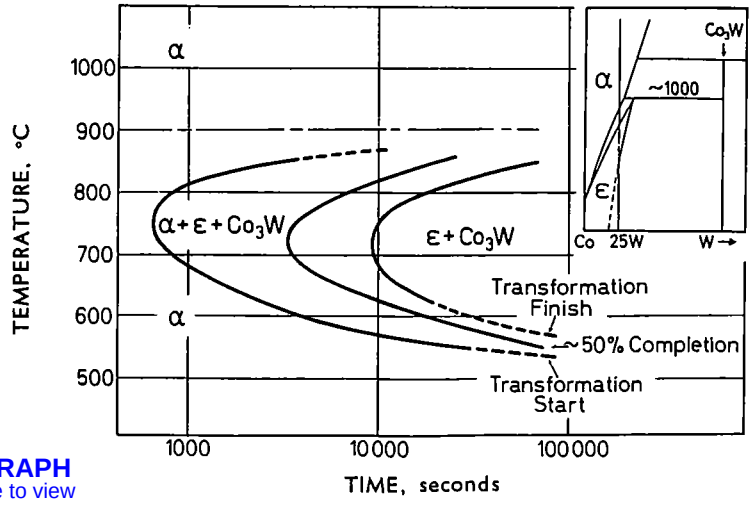
Time-temperature-transformation diagram
Obtained from quenching-dilatometer studies

SOURCE: A.F. Giamei, J. Burma, S. Rabin, M. Cheng, E.J. Freise, "The Role of the Allotropic Transformation in Cobalt-Base Alloys," Cobalt, Vol 40, Cobalt Development Institute, Slough UK, September 1968, pp 140-155

Co-W Alloy

Composition: Co - 25% W



LIVE GRAPH
Click here to view

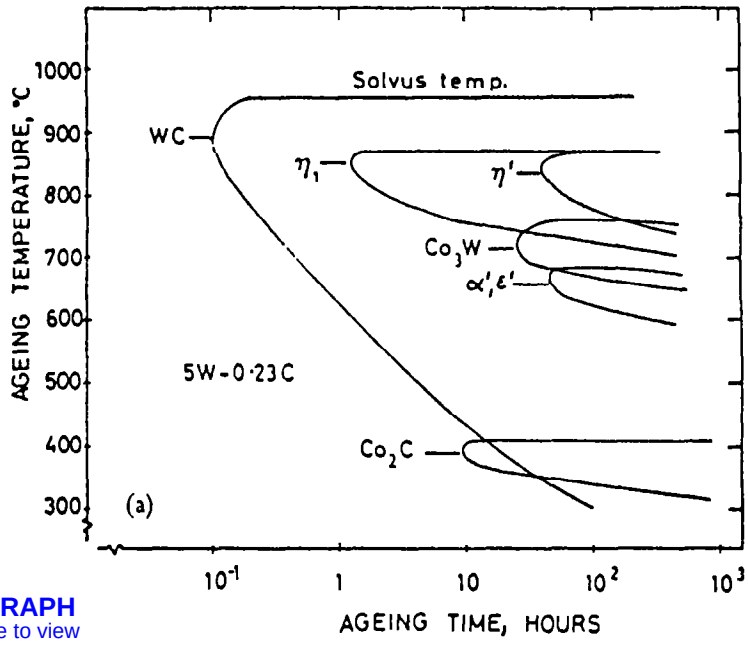
Time-temperature-transformation diagram

SOURCE: T. Toda, Trans. Japan Inst. Metals, Vol 6, 1965, p 139

Co-5W-0.23C Alloy

Composition: Co - 4.69% W - 0.23% C

Treatment: Solution treated at 1250°C (2282°F) for 2 h and quenched before aging. The interval between the aging temperatures was 50°C (122°F); the aging times were 1/4, 1, 4, 16, 64, and 256 h at each temperature (when appropriate, larger intervals were used)



LIVE GRAPH
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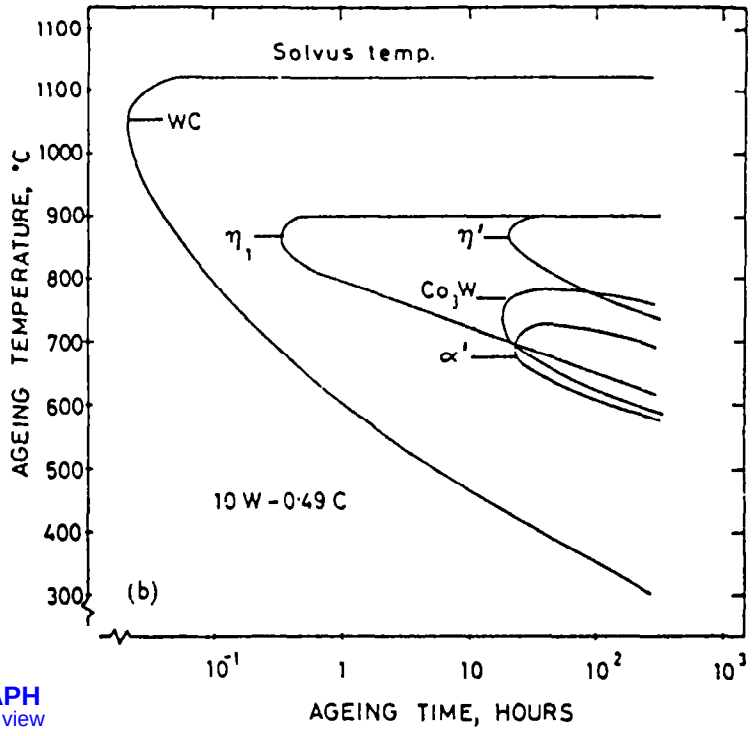
Time-temperature-aging diagram
Showing the occurrence of the various phases after an isothermal treatment

SOURCE: H. Jonsson, B. Aronsson, "Microstructure and Hardness of Cobalt-Rich Co-W-C Alloys after Ageing in the Temperature Range 400-1000°C," Journal of the Institute of Metals, Vol 97, 1969, pp 281-288

Co-10W-0.49C Alloy

Composition: Co - 9.38% W - 0.49% C

Treatment: Solution treated at 1250°C (2282°F) for 2 h and quenched before aging. The interval between the aging temperatures was 50°C (122°F); the aging times were 1/4, 1, 4, 16, 64, and 256 h at each temperature (when appropriate, larger intervals were used)



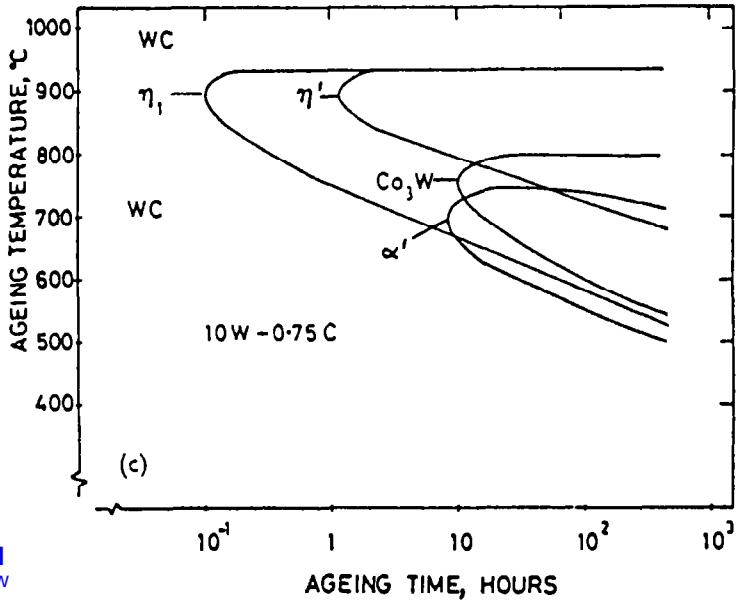
LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Showing the occurrence of the various phases after an isothermal treatment

SOURCE: H. Jonsson, B. Aronsson, "Microstructure and Hardness of Cobalt-Rich Co-W-C Alloys after Ageing in the Temperature Range 400-1000°C," Journal of the Institute of Metals, Vol 97, 1969, pp 281-288

Co-10W-0.75C Alloy

Composition: Co - 9.37% W - 0.75% C
Treatment: Solution treated at 1250°C (2282°F) for 2 h and quenched before aging. The interval between the aging temperatures was 50°C (122°F); the aging times were 1/4, 1, 4, 16, 64, and 256 h at each temperature (when appropriate, larger intervals were used)



LIVE GRAPH
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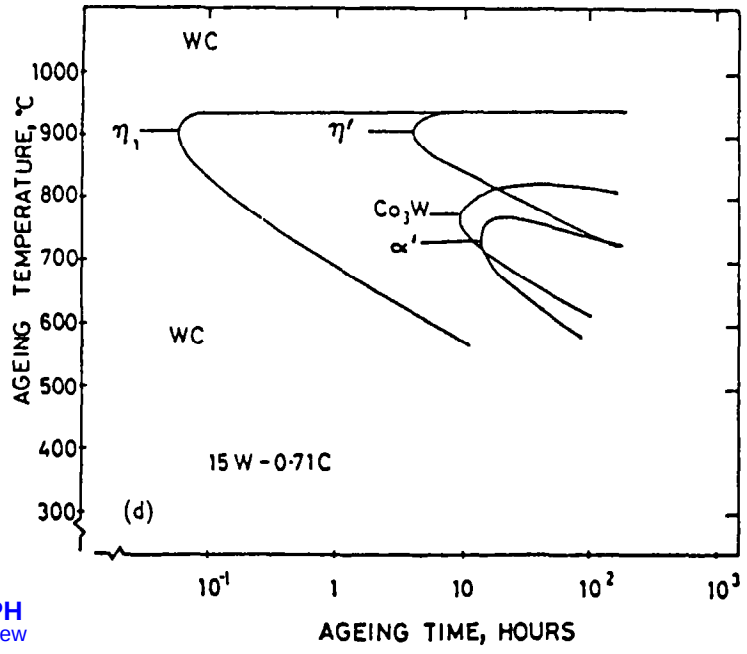
Time-temperature-aging diagram
Showing the occurrence of the various phases after an isothermal treatment

SOURCE: H. Jonsson, B. Aronsson, "Microstructure and Hardness of Cobalt-Rich Co-W-C Alloys after Ageing in the Temperature Range 400-1000°C," Journal of the Institute of Metals, Vol 97, 1969, pp 281-288

Co-15W-0.71C Alloy

Composition: Co - 14.10% W - 0.71% C

Treatment: Solution treated at 1250°C (2282°F) for 2 h and quenched before aging. The interval between the aging temperatures was 50°C (122°F); the aging times were 1/4, 1, 4, 16, 64, and 256 h at each temperature (when appropriate, larger intervals were used)



LIVE GRAPH
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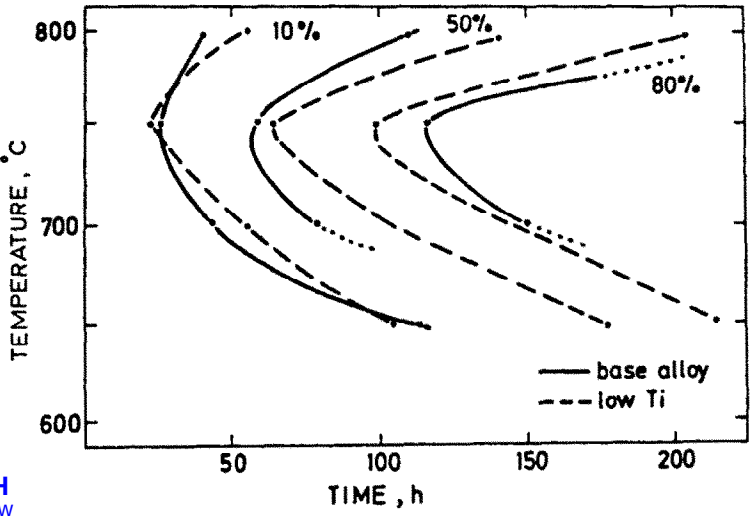
Time-temperature-aging diagram
Showing the occurrence of the various phases after an isothermal treatment

SOURCE: H. Jonsson, B. Aronsson, "Microstructure and Hardness of Cobalt-Rich Co-W-C Alloys after Ageing in the Temperature Range 400-1000°C," Journal of the Institute of Metals, Vol 97, 1969, pp 281-288

Co-Cr-Ti Alloys

Base alloy - Composition: Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C
Low Ti - Composition: Co - 17.6% Cr - 4.4% Ti - 3.0% Mo - 0.015% C
Treatment: Converted to powder, the powders were encapsulated, homogenization treated at 1200°C (2192°F) for 16 h, extruded at 1050°C (1922°F). The as-extruded alloys were heated treated between 600 and 800°C (1112 and 1472°F) and water quenched



LIVE GRAPH
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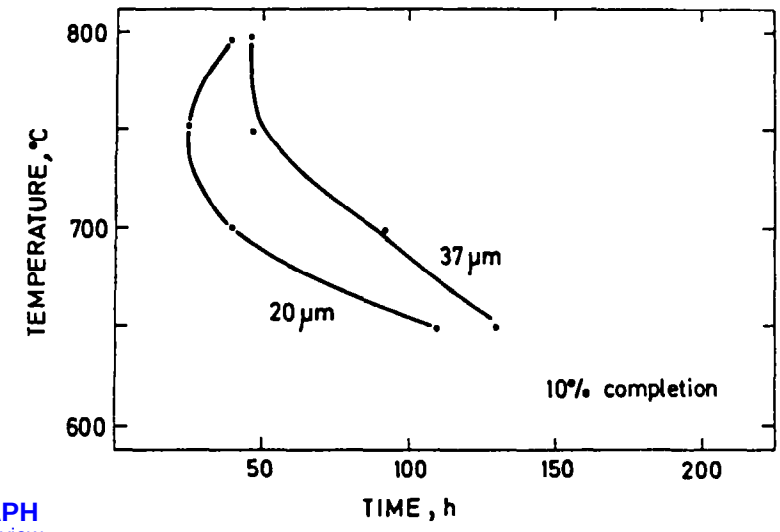
Time-temperature-transformation diagram
For overall transformation (discontinuous + hcp) in base alloy and low Ti alloy

SOURCE: N.-G. Ingesten, R. Warren, M. Dahlen, "Microstructural Stability of Gamma-prime Strengthened Co-Cr-Ti Alloys," Metal Science, Vol 17, April 1983, pp 159-166

Co-Cr-Ti Alloys

Base alloy - Composition: Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C

Treatment: Converted to powder, the powders were encapsulated, homogenization treated at 1200°C (2192°F) for 16 h, extruded at 1050°C (1922°F). The as-extruded alloys were heated treated between 600 and 800°C (1112 and 1472°F) and water quenched



LIVE GRAPH
Click here to view

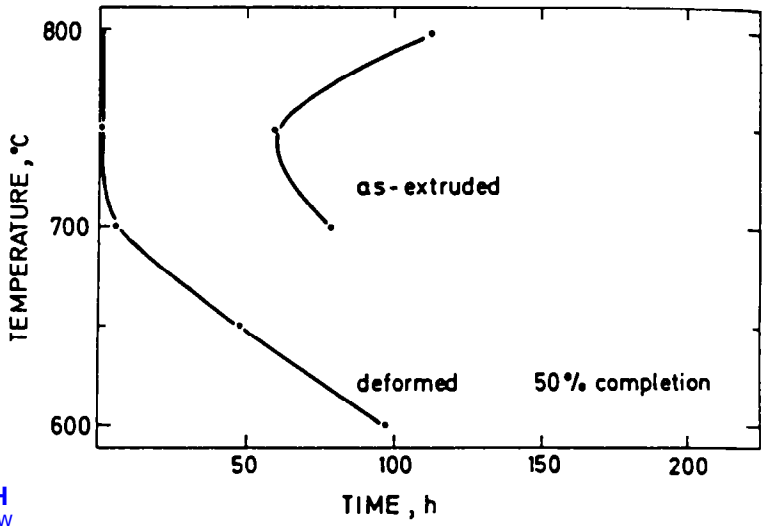
Time-temperature-transformation diagram
Effect of gamma grain size on overall transformation of base alloy

SOURCE: N.-G. Ingesten, R. Warren, M. Dahlen, "Microstructural Stability of Gamma-prime Strengthened Co-Cr-Ti Alloys," Metal Science, Vol 17, April 1983, pp 159-166

Co-Cr-Ti Alloys

Base alloy - Composition: Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C

Treatment: Converted to powder, the powders were encapsulated, homogenization treated at 1200°C (2192°F) for 16 h, extruded at 1050°C (1922°F). The as-extruded alloys were heated treated between 600 and 800°C (1112 and 1472°F) and water quenched



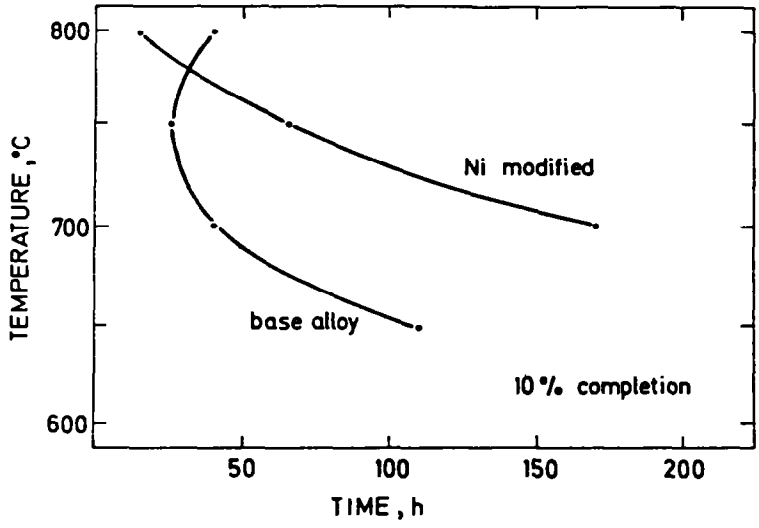
LIVE GRAPH
Click here to view

Time-temperature transformation diagram
Effect of cold work (30% reduction by rolling) on overall transformation of base alloy

SOURCE: N.-G. Ingesten, R. Warren, M. Dahlen, "Microstructural Stability of Gamma-prime Strengthened Co-Cr-Ti Alloys," Metal Science, Vol 17, April 1983, pp 159-166

Co-Cr-Ti Alloys

Base alloy - Composition: Co - 16.0% Cr - 5.0% Ti - 3.0% Mo - 0.005% C
Ni-Modified - Composition: Co - 17.3% Cr - 4.4% Ti - 3.0% Mo - 11.5% Ni - 0.017% C
Treatment: Converted to powder, the powders were encapsulated, homogenization treated at 1200°C (2192°F) for 16 h, extruded at 1050°C (1922°F). The as-extruded alloys were heated treated between 600 and 800°C (1112 and 1472°F) and water quenched



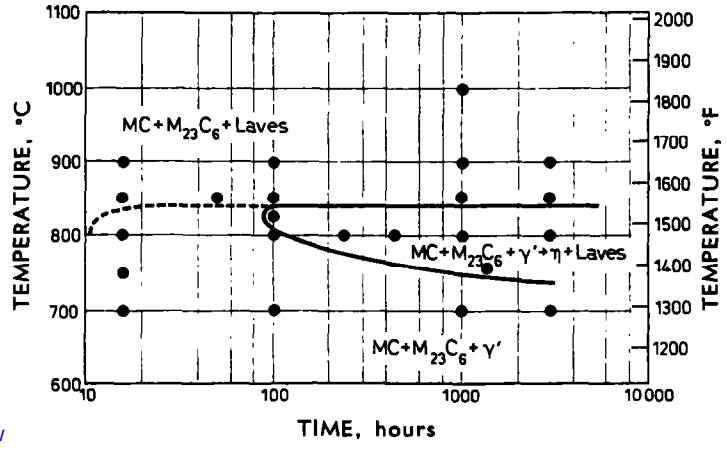
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
For overall transformation
Base vs Ni-modified alloy

SOURCE: N.-G. Ingesten, R. Warren, M. Dahlen, "Microstructural Stability of Gamma-prime Strengthened Co-Cr-Ti Alloys," Metal Science, Vol 17, April 1983, pp 159-166

Wrought Cobalt-Base Alloy

Composition: Co - 20.2% Cr - 15.8% Ni - 14.8% W - 1.2% Ti - 0.53% Al - 0.07% Mn - 0.05% Si - 0.25% Fe - 0.11% C



LIVE GRAPH
Click here to view

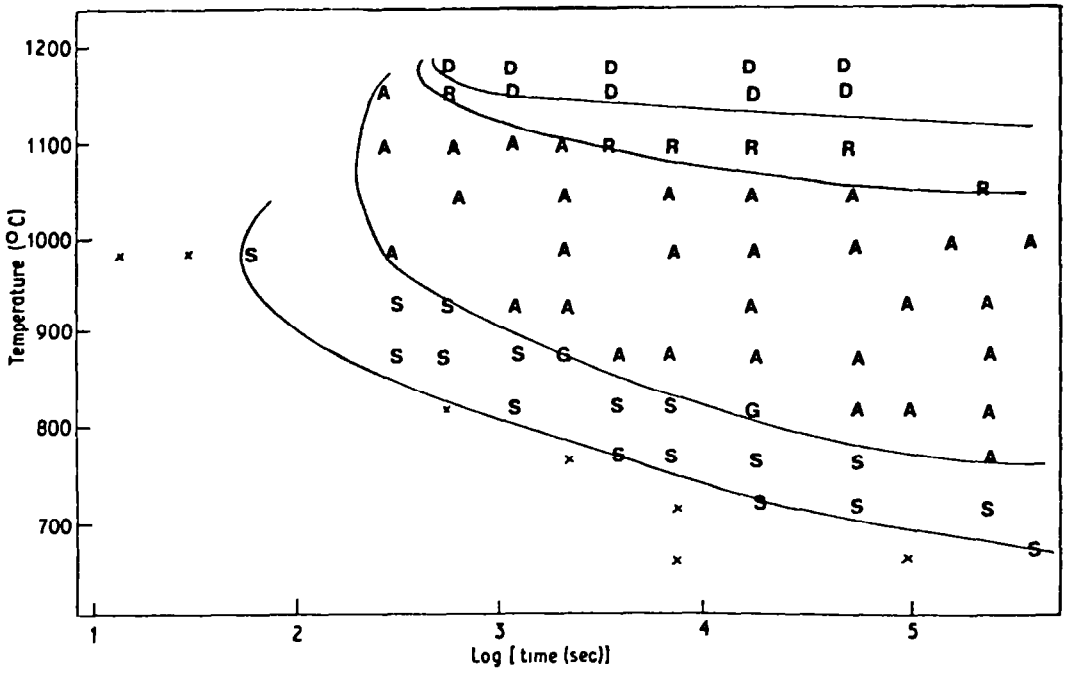
Time-temperature-precipitation diagram
Summarizing the structural changes that take place on prolonged aging

SOURCE: P. Viatour, J.M. Drapier, D. Coutsouradis, L. Habraken, "Structure and Properties of CM-7, a Wrought Precipitation-Hardening Cobalt-Base Alloy," Cobalt, Vol 51, Cobalt Development Institute, Slough UK, June 1971, pp 67- 76

Co-Cr-Mo-C Investment-Cast Implant Alloy

Nominal Composition: Co - 0.25% C - 0.60% Mn - 0.60% Si - 27% Cr - 3% Ni - 5% Mo - 1% Fe

Treatment: Solution treatment consisting of a 2 h soak at 1250°C (2282°F) followed by water quenching. After aging all specimens were rapidly quenched in water



LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
Indicates the various changes in morphology of the $M_{23}C_3$ carbide on aging

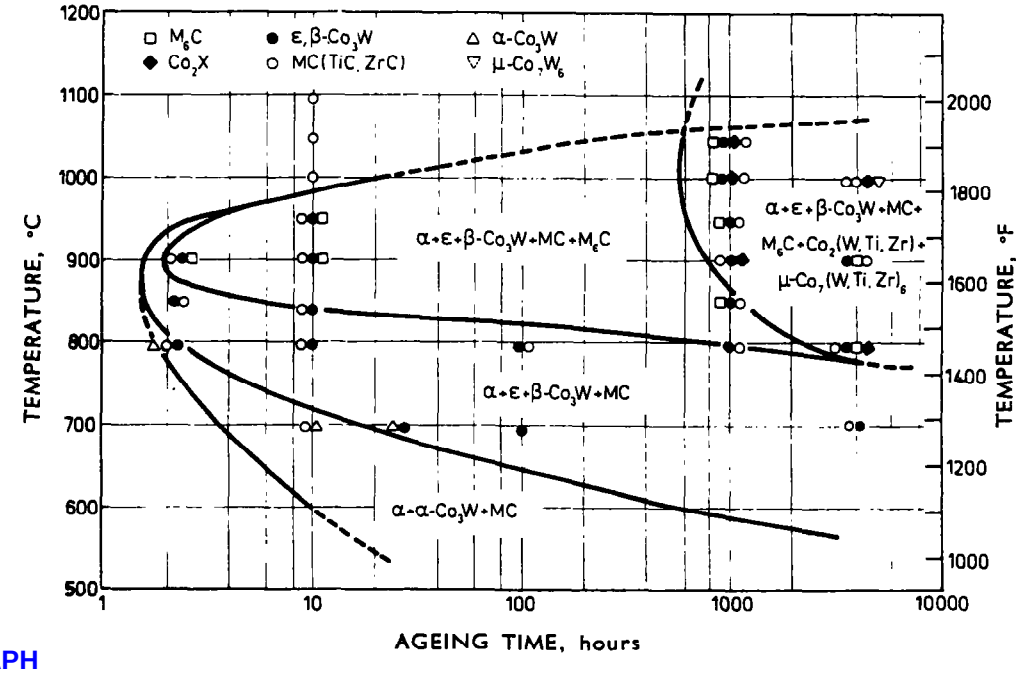
LEGEND:
x = grain boundaries only
S = intragranular striations
A = change to a blocky morphology
R = spheroidization of the precipitates
D = dissolution
G = grain-boundary carbides ($M_{23}C_6$) present

SOURCE: R.N.J. Taylor, R.B. Waterhouse, "The Metallography of a Cobalt-Based Implant Alloy After Solution Treatment and Ageing," Journal of Materials Science, Vol 21, No. 6, June 1986, pp 1990-1996

Co-W Heat-Resisting Alloy

Nominal Composition: Co - 25% W - 1.0% Ti - 0.5% Zr - 3.0% Cr - 0.5% C

Treatment: Annealed at 1290°C (2355°F) for 30 min and water quenched then held at temperatures between 700 and 1100°C (1290 and 2010°F) for times up to 3000 h



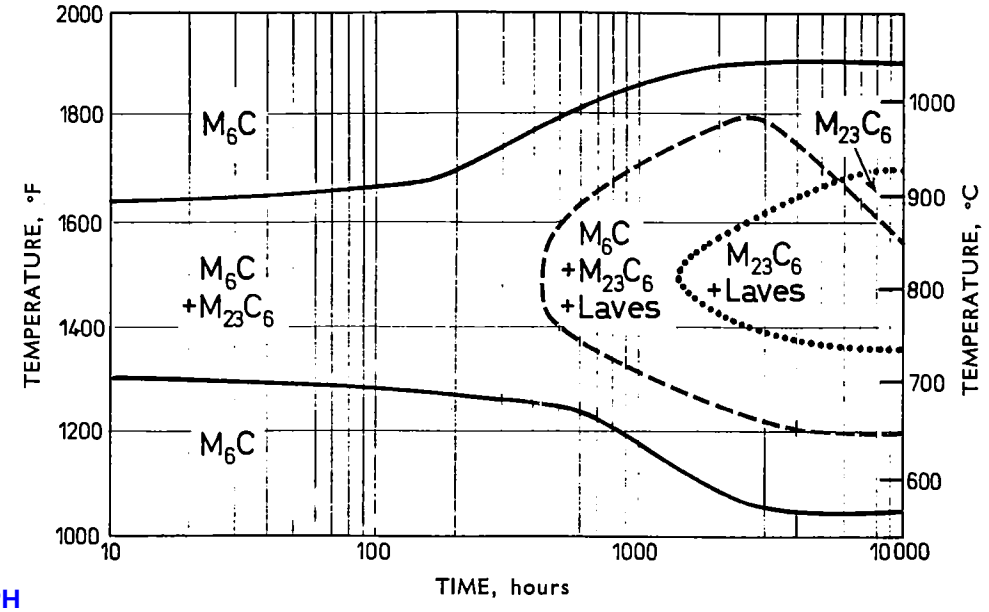
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
Showing the structural reactions that occur during high-temperature aging

SOURCE: J.M. Drapier, P. Viatour, D. Coutsouradis, "Structural Stability of a Co-W Heat-Resisting Alloy," Cobalt, Vol 52, Cobalt Development Institute, Slough UK, September 1971, pp 147-155

Haynes Alloy No. 188, Cobalt-Base Superalloy

Nominal Composition: Co - 20-24% Cr - 20-24% Ni - 13-16% W - 0.05-0.15% C - 0.03-0.15% La - 0.20-0.50% Si - up to 3% Fe - up to 1.25% Mn



LIVE GRAPH
Click here to view

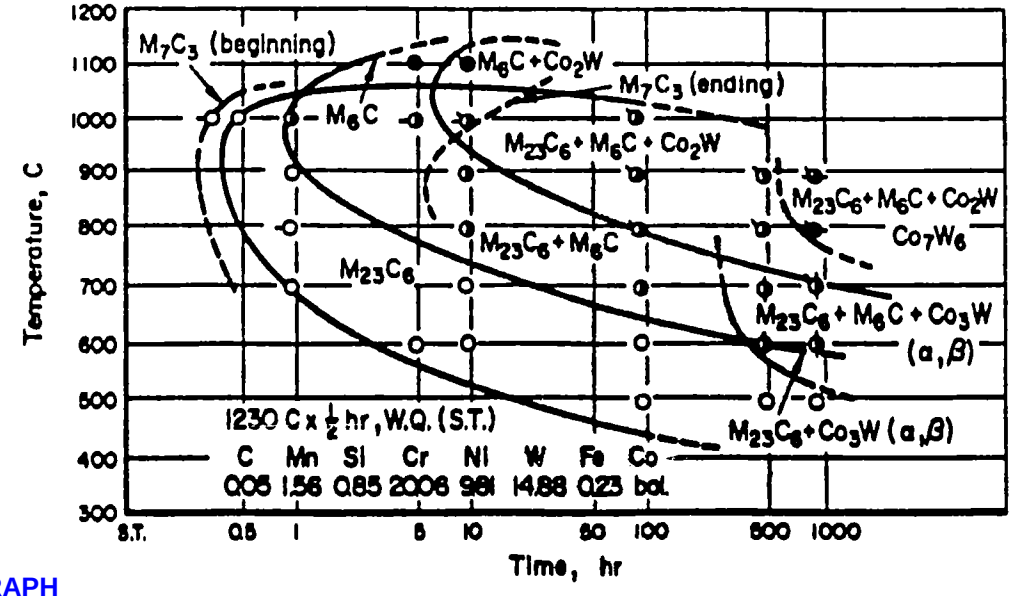
Time-temperature-precipitation diagram on aging

SOURCE: R.B. Herchenroeder, S.J. Matthews, J.W. Tackett, S.T. Wlodek, "Haynes Alloy No. 188," Cobalt, Vol 54, Cobalt Development Institute, Slough UK, March 1972, pp 3-13

L-605, Cobalt-Base Superalloy

Composition: Co - 0.05% C - 20.06% Cr - 9.81% Ni - 14.88% W - 1.56% Mn - 0.85% Si - 0.23% Fe

Treatment: Solution treated at 1230°C (2246°F) for 30 min, water quenched



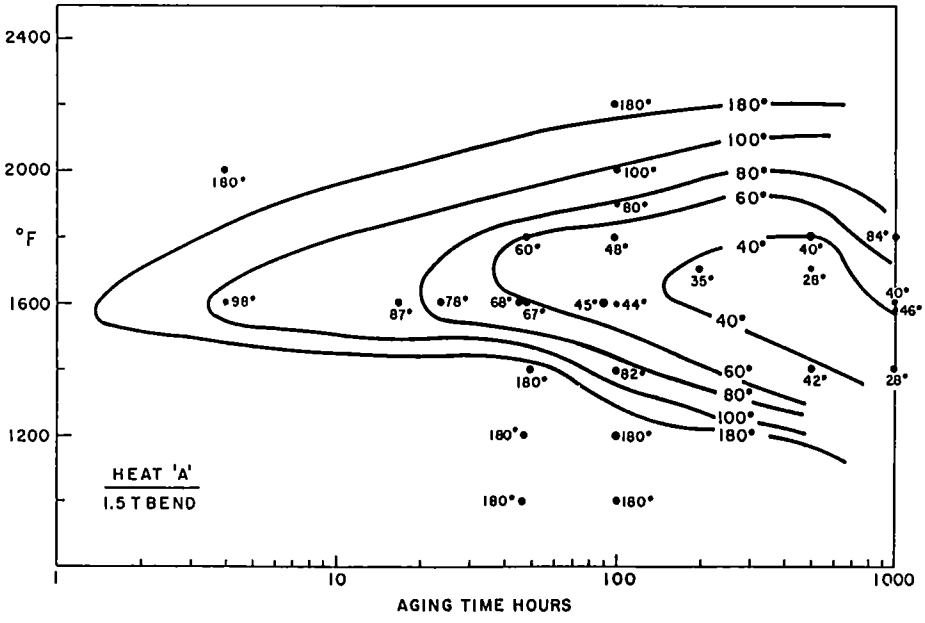
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beginning and ending of the various phases

SOURCE: S. Takeda, N. Yukawa, Nippon Kinzoku Gakkai-ho, 6, 11, 12, 1967, pp 785-802, 850-855

L-605, Cobalt-Base Superalloy

Composition: Co - 20.0% Cr - 14.84% W - 10.02% Ni - 3.12%
Fe - 1.39% Mn - 0.47% Si - 0.003% P - trace Zr
Grain size: 2 to 6
Treatment: Solution-annealed at 1232°C (2250°F) for 30 min

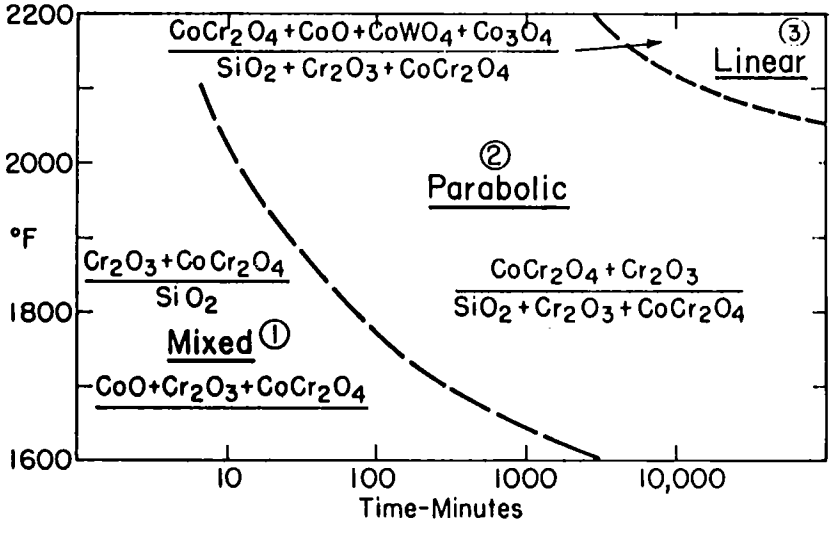


LIVE GRAPH
Click here to view

Time-temperature-embrittlement diagram
Loss of ductility is due to precipitation of Laves phase
Note evidence of slight return of 1.5T bend ductility in samples aged at 982°C (1800°F) for about 1000 h

SOURCE: S.T. Wlodek, "Embrittlement of a Co-Cr-W (L-605) Alloy," Trans. ASM, Vol 56, 1963, pp 287-303

L-605, Cobalt-Base Superalloy



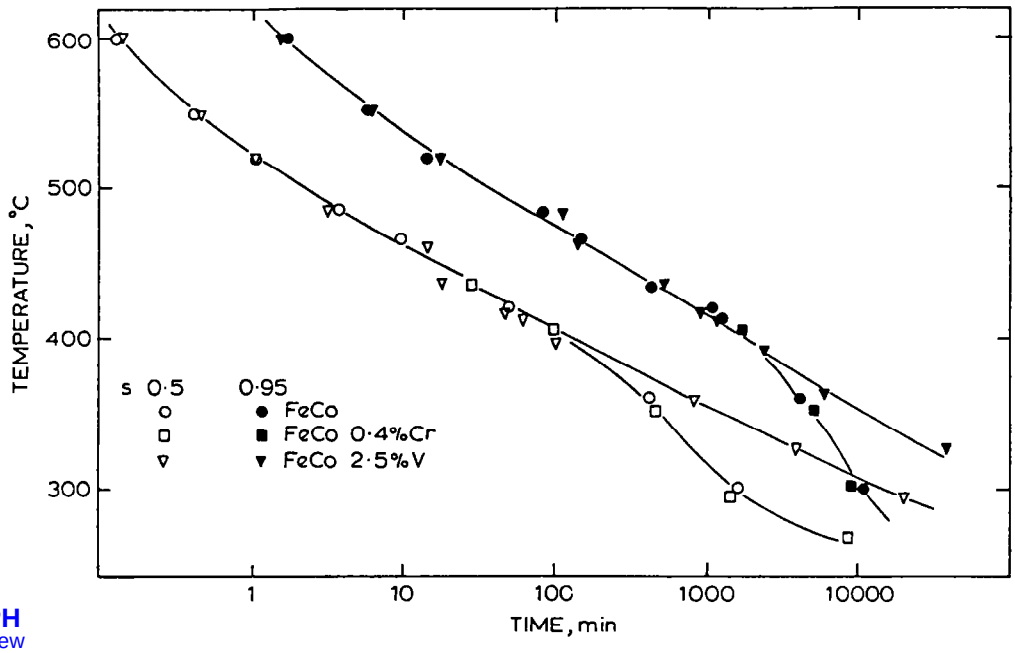
LIVE GRAPH
Click here to view

Time-temperature-oxidation diagram

SOURCE: S.T. Wlodek, "The Oxidation of L-605 and X-40," General Electric Report R64FPD12, Cincinnati, 1964

Co-Fe Alloys

CoFe - Composition: Co - 50% Fe
CoFeV - Composition: Co - 48.8% Fe - 2.5% V
CoFeCr - Composition: Co - 49.8% Fe - 0.4% Cr



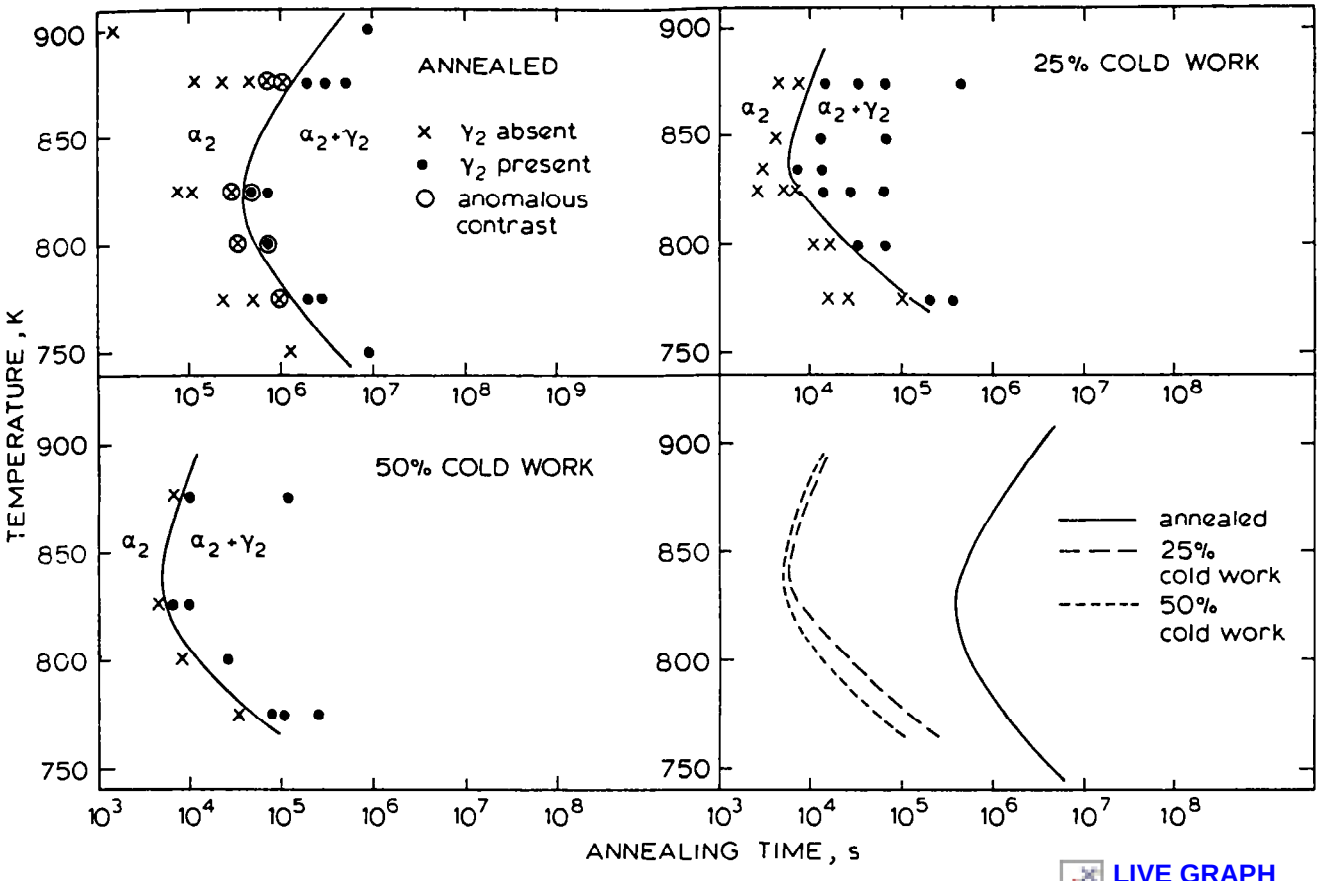
LIVE GRAPH
Click here to view

Time-temperature-ordering diagram

SOURCE: R.A. Buckley, "Microstructure and Kinetics of the Ordering Transformation in Iron-Cobalt Alloys, FeCo, FeCo-0.4%Cr, FeCo-2.5%V," Metal Science, Vol 9, 1975, pp 243-247

Fe-Co-2% V Alloy

Composition: Co - 47.34% Fe - 2.00% V - 0.007% C - 0.105% Si - 0.22% Ni



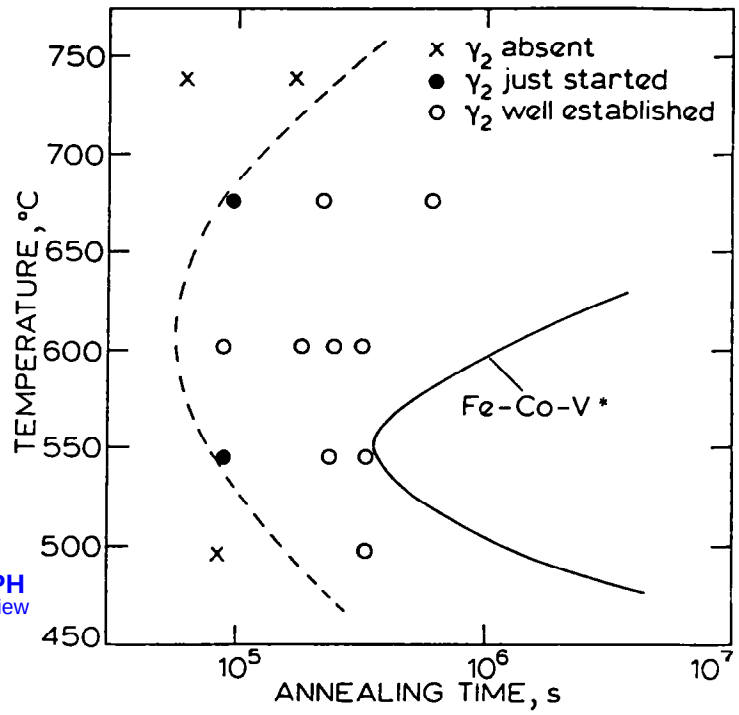
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
For an annealed and cold-worked alloy
These curves do not include grain-boundary precipitation and refer exclusively to the much finer precipitate dispersions which form within the grains in the temperature range 477-627°C (890-1160°F)

SOURCE: J.A. Ashby, H.M. Flower, R.D. Rawlings, "Gamma Phase in an Fe-Co-2%V Alloy," Metal Science, Vol 11, March 1977, pp 91-96

Fe-Co-V-Ni Alloy

Composition: Co - 48% Fe - 3.5% Ni - 1.5% V
Treatment: Quenched from 800°C (1472°F) and aged for various times between 500 and 750°C (932 and 1382°F)



LIVE GRAPH
Click here to view

*** this refers to the diagrams on previous page (p 59)**

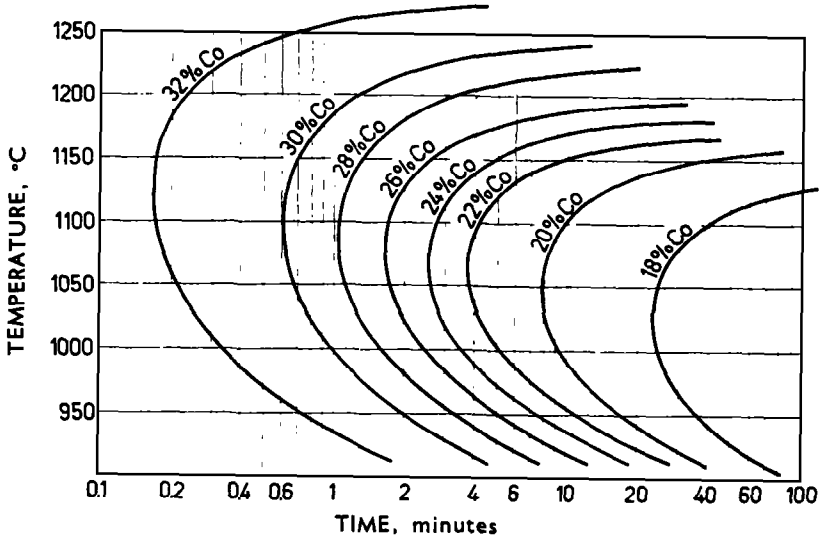
Time-temperature-transformation diagram
For annealed Fe-Co-V-3.5%Ni alloy compared with ternary Fe-Co-V

The curve refers to the fine-precipitate dispersions which were formed within the grains
Comparison with the corresponding TTT curve for the annealed ternary alloy shows that nickel increases the rate of precipitation and raises the temperature of the nose of the curve to about 600°C (1112°F)

SOURCE: C.D. Pitt, R.D. Rawlings, "Microstructure of Fe-Co-2V and Fe-Co-V-Ni Alloys Containing 1.8-7.4 wt-%Ni," Metal Science, Vol 15, August 1981, pp 369-376

Al-Ni-Co Alloys

Composition: Fe - 8% Al - 14% Ni - 3% Cu - 18-32% Co
Treatment: Homogenized at 1350°C (2462°F) for 1 h, rapidly cooled to holding temperatures ranging from 1280 to 900°C (2336 to 1652°F) and held from 5 s to 120 min and water quenched



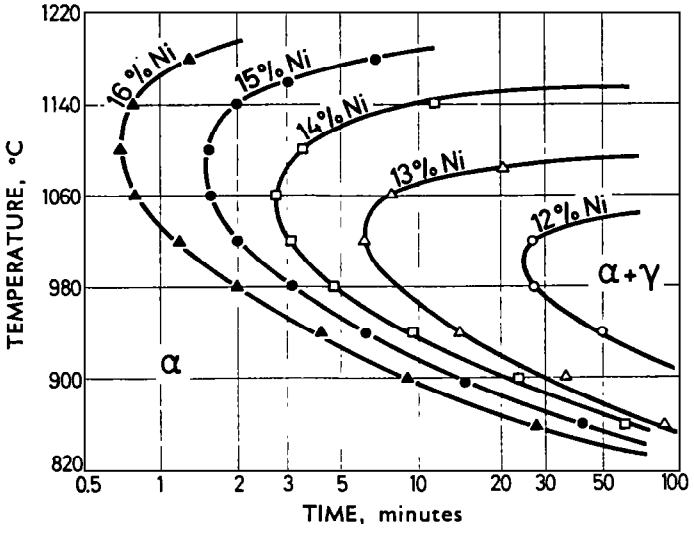
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of the alpha to gamma isothermal decomposition

SOURCE: G. Marcon, C. Bronner, R. Peffen, "Study of the Influence of Cobalt on the Kinetics of the Alpha to Gamma Transformation in Al-Ni-Co Alloys," Cobalt Vol 51, Cobalt Development Institute, Slough UK, June 1970, pp 99-104

Al-Ni-Co Alloys

Standard composition: 24% Co - 12-16% Ni - 8% Al - 3% Cu - bal Fe; nickel content modified at the expense of iron in 1% increments between 11% and 16%
Treatment: Specimens were homogenized at 1300°C (2372°F) for 30 mins, cooled very rapidly to temperatures between 1180 and 850°C (2156 and 1562°F), held for 30 s to 2 h, then water quenched



Time-temperature-transformation diagram
Effect of nickel on alpha to gamma transformation

SOURCE: T. Tran Duc, C. Bronner, G. Marcon, R. Peffen, "Influence of Nickel on the Kinetics of the Alpha to Gamma Transformation in Al-Ni-Co Alloys," Cobalt, Vol 2, Cobalt Development Institute, Slough UK, 1974, pp 45-48

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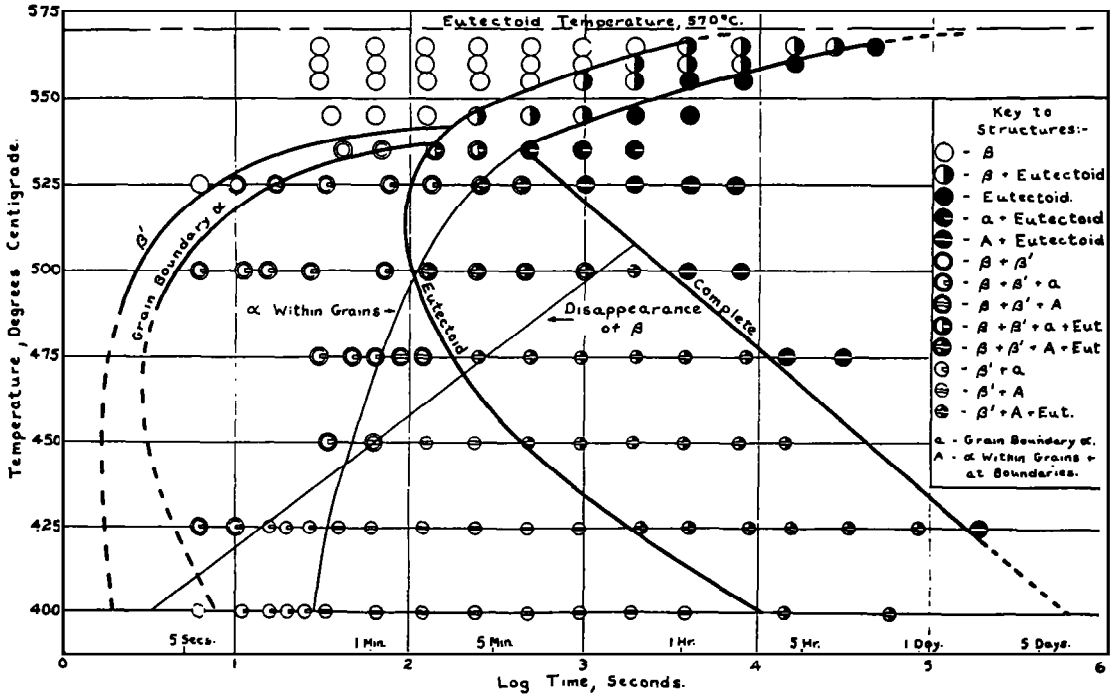
Copper-Base Alloys

Designation	Description	Alloy System	Crystallographic Structure
Equilibrium Phases in Cu-Al Alloy Systems			
α	Copper-rich solid solution	All Cu-Al-X	fcc
β	High-temperature solid solution	All Cu-Al-X	bcc
γ_2	Intermetallic compound with wide solubility range	Cu-Al Cu-Al-Fe Cu-Al-Ni Cu-Al-Co Cu-Al-Mn	Cubic, γ-brass type
α_2	Peritectoid α-phase	Cu-Al Cu-Al-X?	Supersaturated α Short-range ordered
δ_{Fe}	δ-iron	Cu-Al-Fe	bcc
Fe_3Al	Intermetallic compound	Cu-Al-Fe	BiF_3 type
FeAl (κ)	Intermetallic compound with wide solubility range	Cu-Al-Fe	CsCl type
NiAl (κ)	Intermetallic compound with wide solubility range	Cu-Al-Ni	CsCl type
κ	Intermetallic compound with wide solubility range (Fe, Ni, Cu)Al	Cu-Al-Fe-Ni Cu-Al-Mn-Fe-Ni Cu-Al-Co-Fe, and others	CsCl type
T_3	Intermetallic compound	Cu-Al-Mn	bcc
γ_{Be} or β''	Intermetallic compound	Cu-Al-Be	CsCl type
γ_{Si}	Intermetallic compound	Cu-Al-Si	β-Mn type
κ_{Si}	Intermetallic compound	Cu-Al-Si	hcp
FeSi	Intermetallic compound	Cu-Al-Si	Cubic
Fe_5Si_3	Intermetallic compound	Cu-Al-Si	Hexagonal
Metastable Phases in Cu-Al Alloy Systems			
α'	Bainitic α phase supersaturated	Cu-Al Cu-Al-Fe Cu-Al-Ni	. . . . . fcc . . . . .
β_1	Intermetallic compound Cu_3Al	Cu-Al Cu-Al-Fe Cu-Al-Ni Cu-Al-Mn	bcc ordered . . . .
	Massive martensite	Cu-Al	. . . . .
σ'_1	. . . . .	Cu-Al	. . . . .
β'	Non-ordered martensite	Cu-Al Cu-Al-Fe Cu-Al-Ni Cu-Al-Fe-Ni	fcc with periodical stacking faults of high density
	Ordered martensite	Cu-Al Cu-Al-Fe Cu-Al-Ni Cu-Fe-Ni	Orthorhombic ordered with periodic stacking faults of high density
β''_1	. . . . .	Cu-Al	. . . . .
γ'_1	Ordered Al-rich martensite	Cu-Al Cu-Al-Fe Cu-Al-Ni Cu-Al-Fe-Ni	Orthorhombic ordered
β	General designation for all transformation products of β phase consisting mainly of β, β_1, β', β'_1, γ'_1, α', e.g. bainite, etc.		
κ	Intermetallic compound (Fe, Ni, Cu)Al	Cu-Al-Fe-Ni	. . . . .
κ_I	Precipitated from melt		. . . . .
κ_{II}	Precipitated from β		CsCl type
κ_{III}	Eutectoid component from $\beta \rightarrow \alpha + \kappa_{III}$		CsCl type
κ_{IV}	Globular precipitate from α		CsCl type
κ_V	Lath precipitate from α		. . . . .

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 11.87% Al - 0.06% Fe - 0.02% Si - 0.01% Sn
Treatment: Annealed at 900°C (1652°F) for 1 h, quenched into salt at desired temperature, held at temperature, quenched in ice water



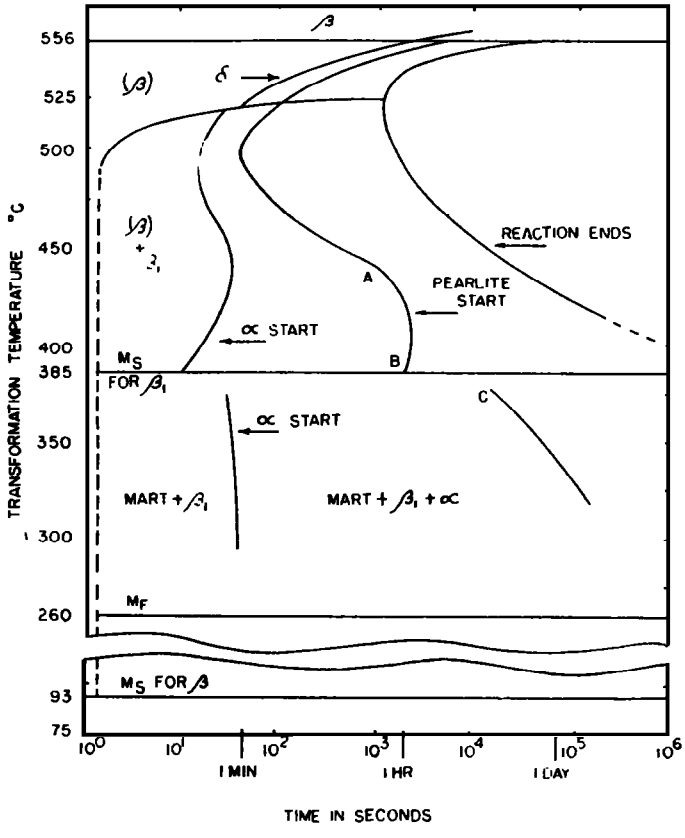
Time-temperature-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: C.S. Smith, W.E. Lindlief, "A Micrographic Study of the Decomposition of the Beta Phase in the Copper-Aluminum System," Trans. AIME, Vol 104, 1933, pp 69-115

Copper-Aluminum Alloys

Composition: Cu - 11.89% Al - 0.02% Fe - 0.01% Mn



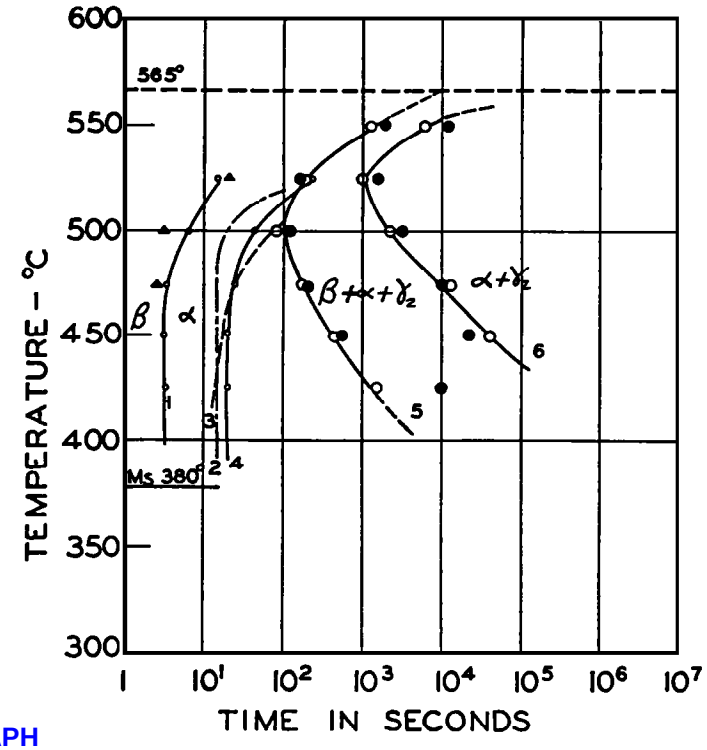
Revised Time-temperature-transformation diagram following discussion of original work

SOURCE: D.J. Mack, "The Isothermal Transformation of a Eutectoid Aluminum Bronze," Trans. AIME, Vol 175, 1948, pp 241-261

Copper-Aluminum Alloys

Composition: Cu - 11.9% Al

Treatment: Heated at 950°C (1742°F) for 10 min, quenched at desired temperature, held, and quenched in a 10% aqueous solution of sodium hydroxide



LIVE GRAPH
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LEGEND:

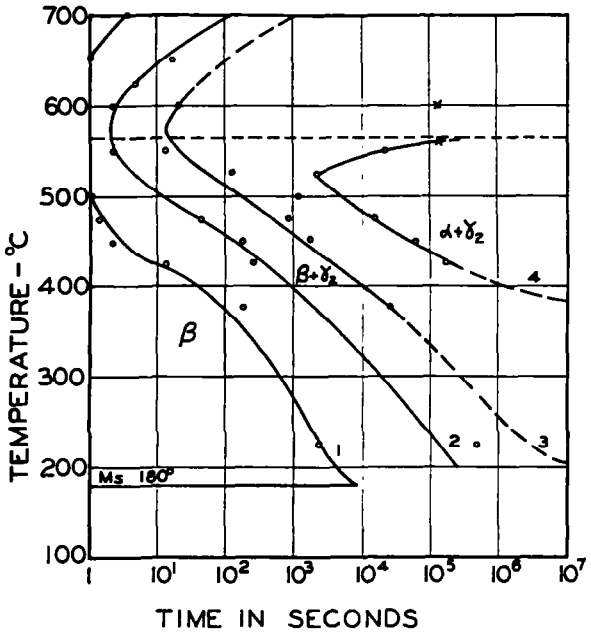
Curve 1. α precipitation at grain boundaries. 1/32 in. stock.
Curve 2. α precipitation at grain boundaries. 1/8 in. stock.
Curve 3. α precipitation in grains. 1/8 in. stock.
Curve 4. α precipitation in grains. 1/32 in. stock.
Curve 5. Beginning of pearlite reaction.
Curve 6. End of pearlite reaction.
▲ Beginning of β″ precipitation.

Time-temperature-transformation

SOURCE: E.P. Klier, S.M. Grymko, "The Transformations in Beta-CuAl Alloys," Trans. AIME, Vol 185, September 1949, pp 611-620

Copper-Aluminum Alloys

Composition: Cu - 13.5% Al
Treatment: Heated at 950°C (1742°F) for 10 min, quenched at desired temperature, held, and quenched in a 10% aqueous solution of sodium hydroxide

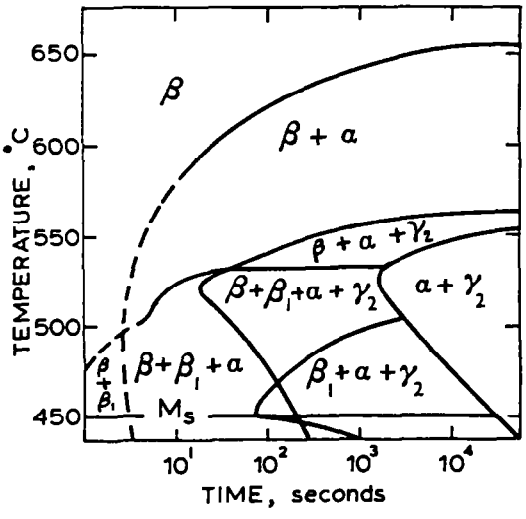


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: E.P. Klier, S.M. Grymko, "The Transformations in Beta-CuAl Alloys," Trans. AIME, Vol 185, September 1949, pp 611-620

Composition: Cu - 11.3% Al
Treatment: Solution treated at 800°C (1472°F)



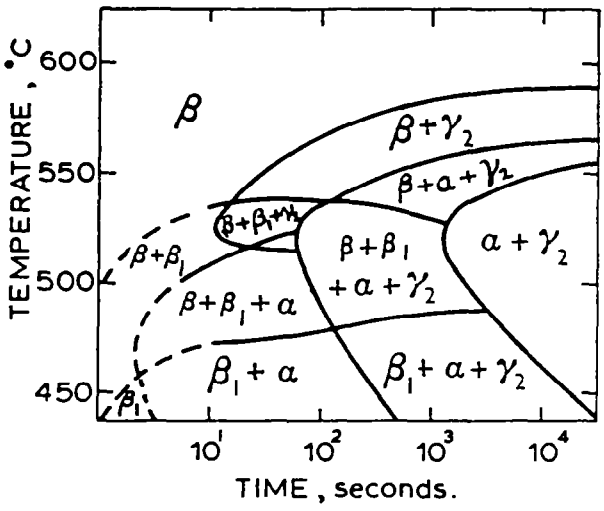
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D. Lloyd Thomas, "Metastable Systems Involving Beta and Beta-One Phases in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 94, 1966, pp 250-254

Copper-Aluminum Alloys

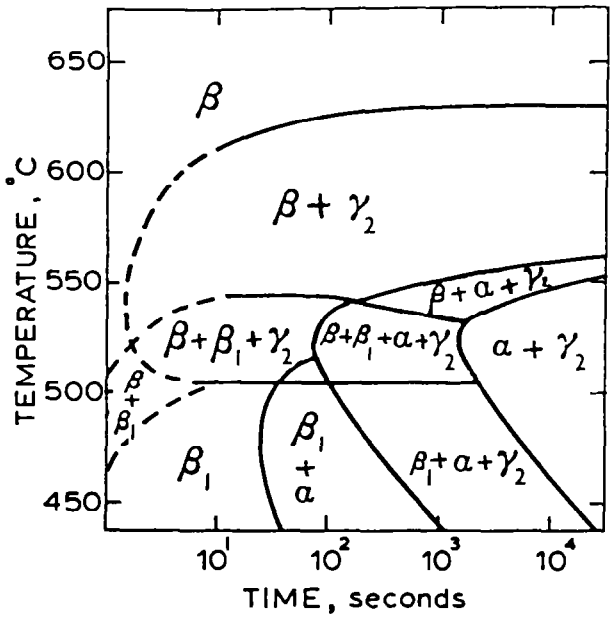
Composition: Cu - 12.0% Al
Treatment: Solution treated at 800°C (1472°F)



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Cu - 12.35% Al
Treatment: Solution treated at 800°C (1472°F)



LIVE GRAPH
Click here to view

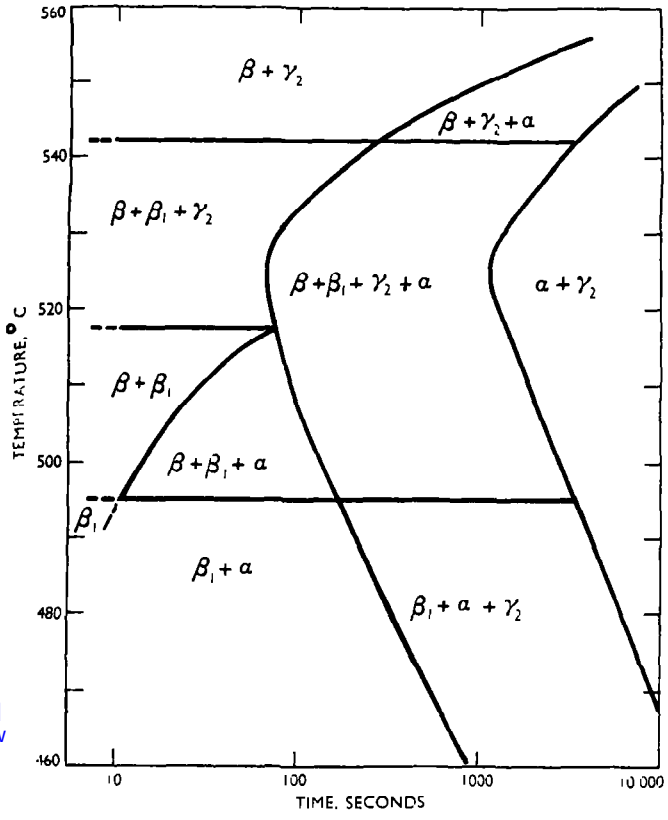
Time-temperature-transformation diagram

SOURCE: D. Lloyd Thomas, "Metastable Systems Involving Beta and Beta-One Phases in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 94, 1966, pp 250-254

Copper-Aluminum Alloys

Composition: Cu - 12.4% Al

Treatment: Solution treated in an air furnace at 820°C (1508°F) for 30 min, then quenched at various temperatures between 570 and 460°C (1058 and 860°F)



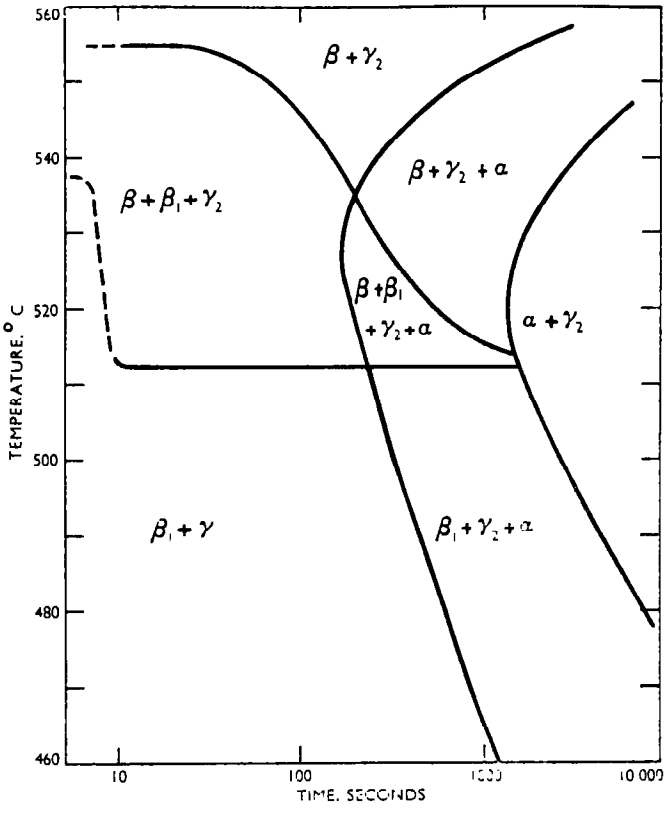
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: H. Butler, A.J. Fletcher, "The Decomposition of the Beta Phase in Certain Hypereutectoid Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 16-19

Copper-Aluminum Alloys

Composition: Cu - 12.7% Al
Treatment: Solution treated in an air furnace at 820°C (1508°F) for 30 min, then quenched at various temperatures between 570 and 460°C (1058 and 860°F)



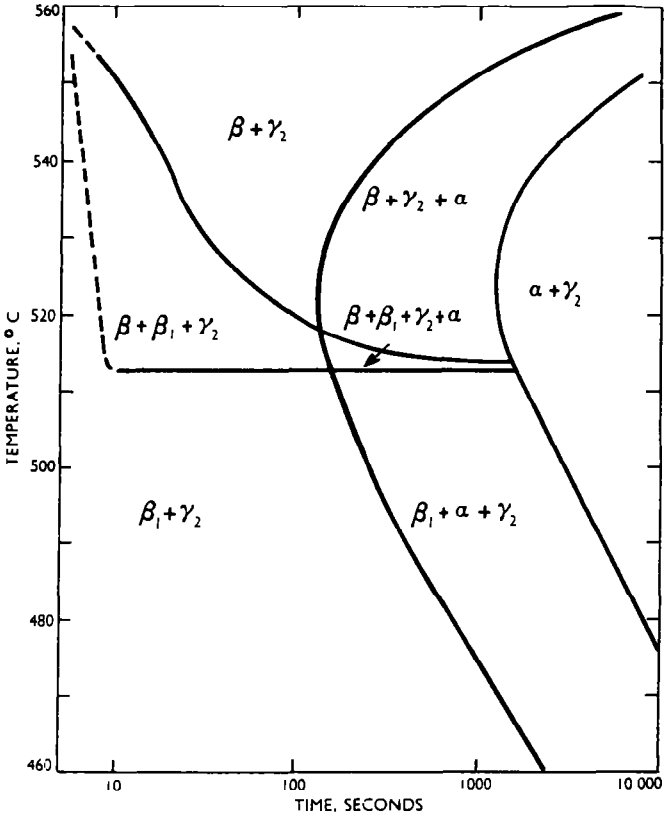
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: H. Butler, A.J. Fletcher, "The Decomposition of the Beta Phase in Certain Hypereutectoid Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 16-19

Copper-Aluminum Alloys

Composition: Cu - 13.0% Al
Treatment: Solution treated in an air furnace at 820°C 1508°F) for 30 min, the quenched at various temperatures between 570 and 460°C (1058 and 860°F)



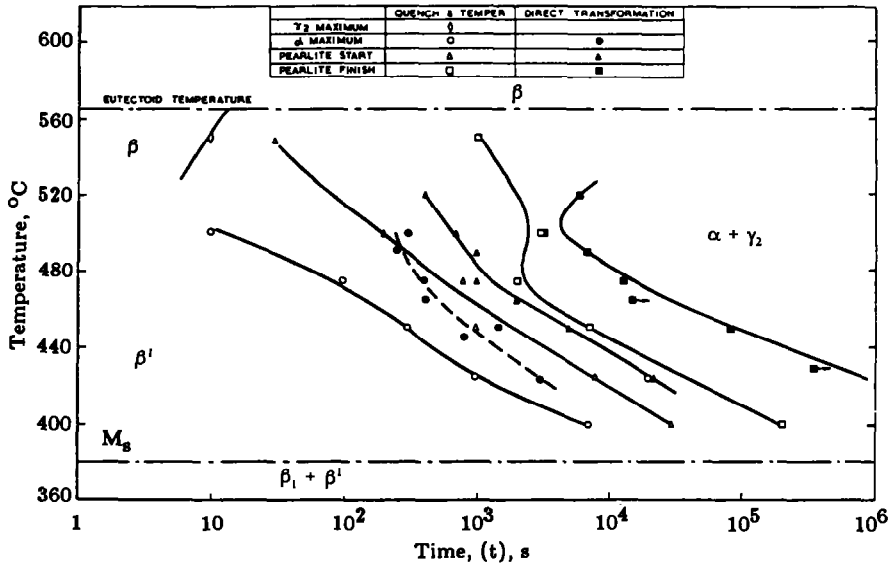
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: H. Butler, A.J. Fletcher, "The Decomposition of the Beta Phase in Certain Hypereutectoid Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 16-19

Copper-Aluminum Alloys

Composition: Cu - 11.8% Al - 0.19% Fe - 0.07% Si
Treatment: Water-quenched from 850°C (1562°F) and tempered in salt baths between 400 and 550°C (752 and 1022°F)

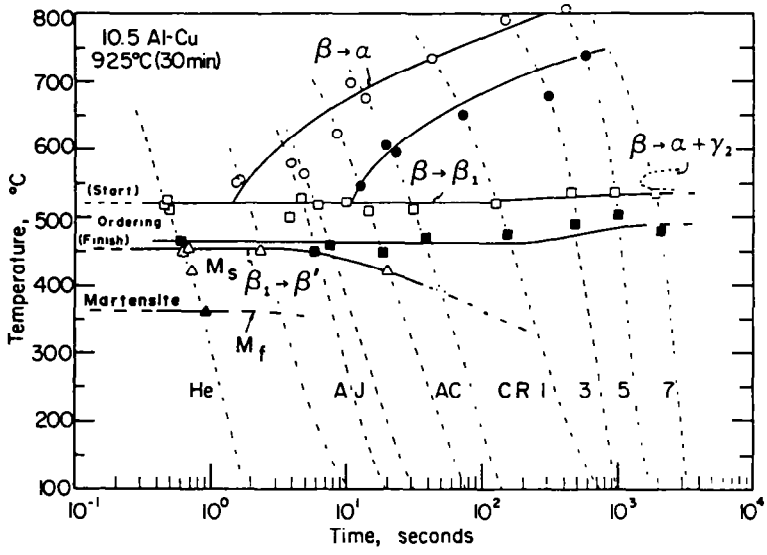


LIVE GRAPH
Click here to view

Time-temperature-aging diagram

SOURCE: E.R. Petty, H. O'Neill, "Hardness and Structural Transformations in Eutectoid Copper-Aluminium and Copper-Beryllium Alloys," Journal of the Institute of Metals, Vol 89, 1961, pp 281-286

Composition: Cu - 10.5% Al



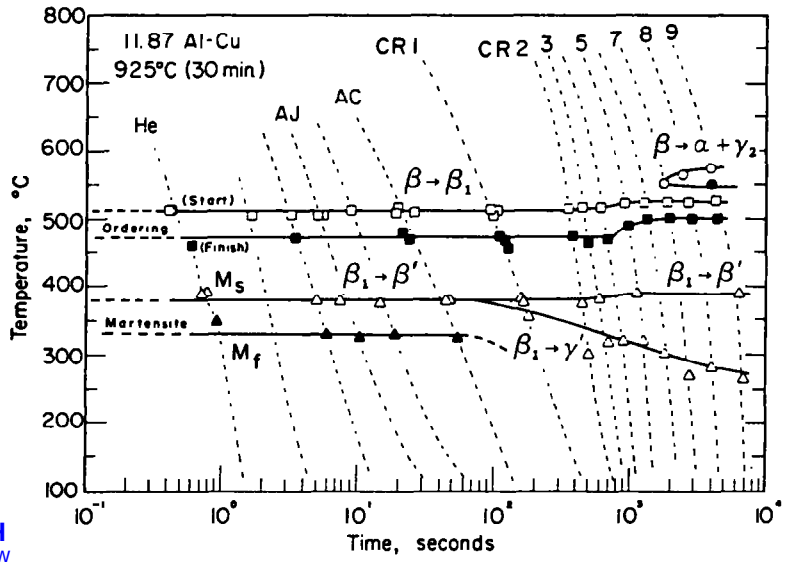
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram
Standard cooling conditions are indicated

SOURCE: J. Jellison, E.P. Klier, "The Cooling Transformations in the Beta Eutectoid Alloys of the Cu-Al System," Trans. AIME, Vol 233, September 1965, pp 1694-1702

Copper-Aluminum Alloys

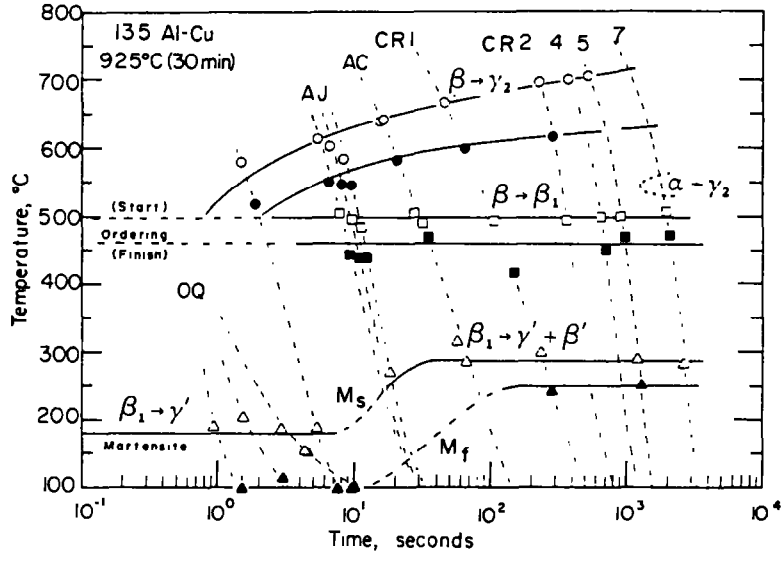
Composition: Cu - 11.87% Al



LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram
Standard cooling conditions are indicated

Composition: Cu - 13.5% Al



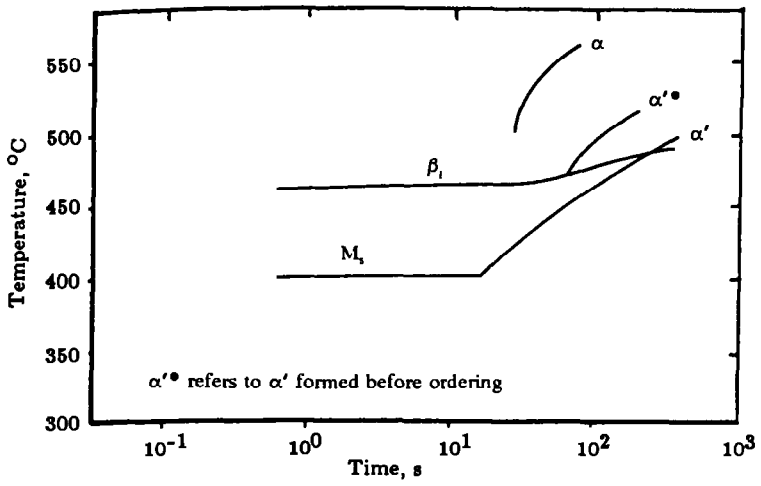
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram
Standard cooling conditions are indicated

SOURCE: J. Jellison, E.P. Klier, "The Cooling Transformations in the Beta Eutectoid Alloys of the Cu-Al System," Trans. AIME, Vol 233, September 1965, pp 1694-1702

Copper-Aluminum Alloys

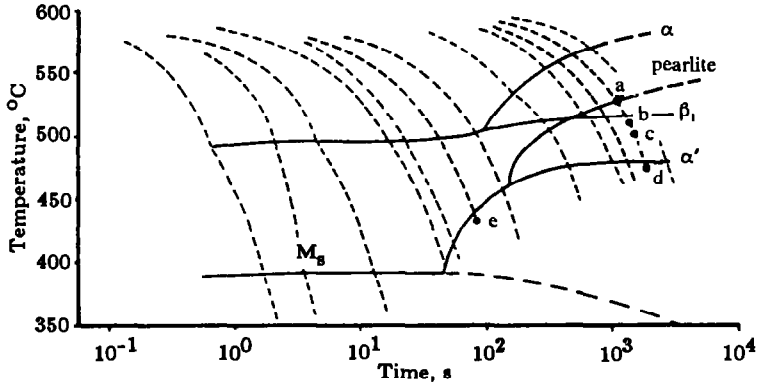
Composition: Cu - 11.2% Al
Treatment: Specimens quenched into cold water from selected temperature points along the cooling curves; the maximum cooling rate of 2000°C/s (3632°F/s) was attained by quenching in a blast of argon



LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

Composition: Cu - 11.7% Al
Treatment: Specimens quenched into cold water from selected temperature points along the cooling curves; the maximum cooling rate of 2000°C/s (3632°F/s) was attained by quenching in a blast of argon



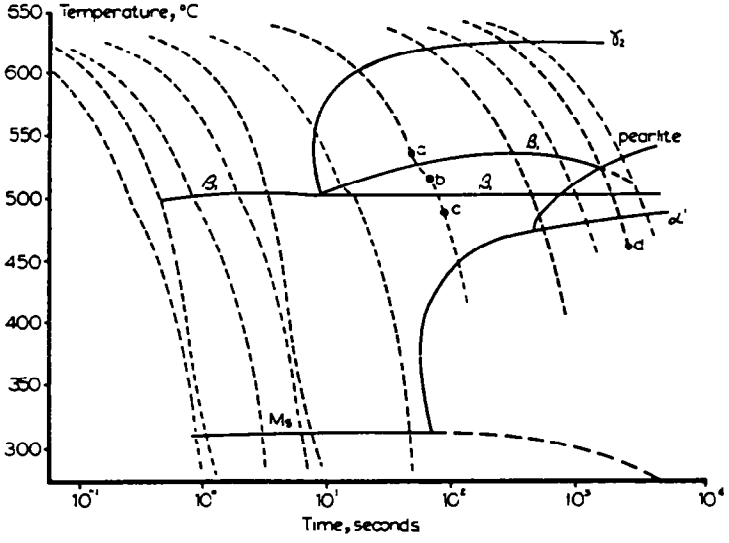
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: J.R. Moon, R.D. Garwood, "Transformation during Continuous Cooling of the Beta Phase in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 96, 1968, pp 17-21

Copper-Aluminum Alloys

Composition: Cu - 12.4% Al
Treatment: Specimens quenched into cold water from selected temperature points along the cooling curves; the maximum cooling rate of 2000°C/s (3632°F/s) was attained by quenching in a blast of argon



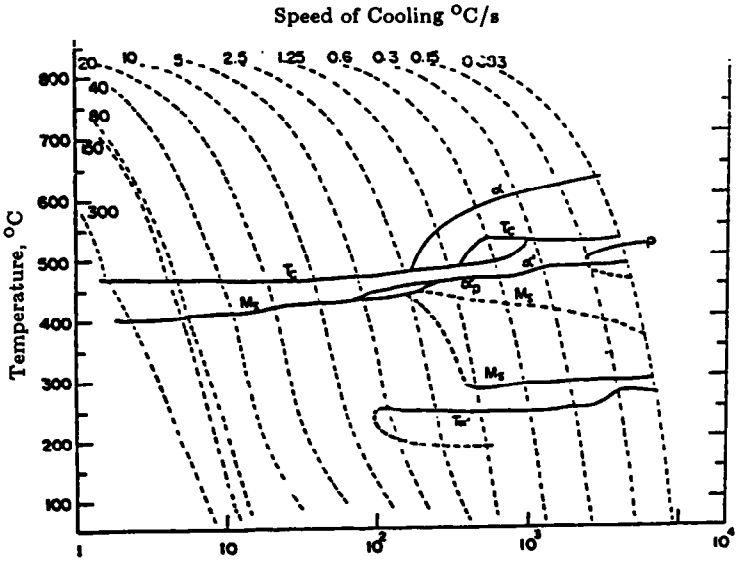
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: J.R. Moon, R.D. Garwood, "Transformation during Continuous Cooling of the Beta Phase in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 96, 1968, pp 17-?1

Copper-Aluminum Alloys

Composition: Cu - 11.06% Al
Treatment: Solution treated 850°C (1562°F) for 30 min



LEGEND:

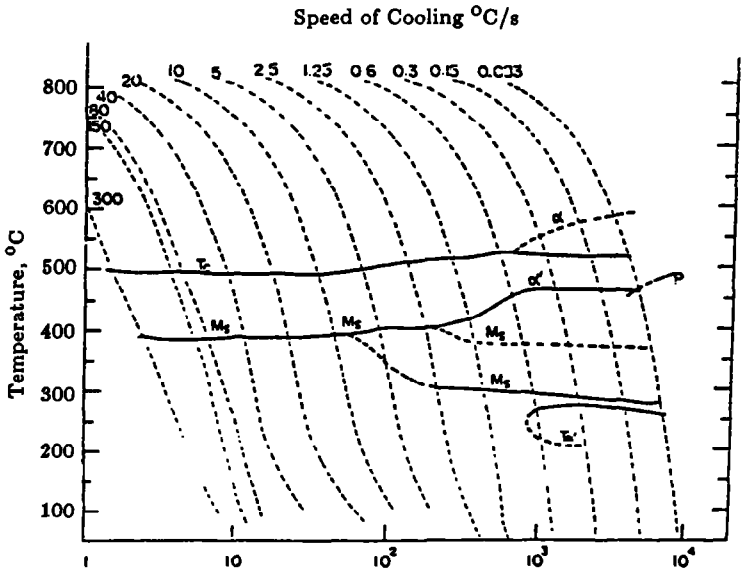
α or γ_2	start of proeutectoid
P	formation of pearlite
T_c	temperature for the start of ordering
α'_p	precipitation of α' phase without martensite transformation
α'	formation of the α' phase with martensite formation
M_s	start of martensite transformation
$T\alpha'$	temperature for the start of ordering of the phase

Continuous-cooling-transformation diagram

SOURCE: Suck-joong L. Kang, M. Stasi, P. Azou, "Transformation au Refroidissement Continu des Alliages Binaires Cuivre-Aluminium," Metaux Corrosion-Industrie, Vol 64, No. 762, February 1989

Copper-Aluminum Alloys

Composition: Cu - 11.60% Al
Treatment: Solution treated 850°C (1562°F) for 30 min



LIVE GRAPH
Click here to view

LEGEND:

α or γ_2	start of proeutectoid
P	formation of pearlite
T_c	temperature for the start of ordering
α'_p	precipitation of α' phase without martensite transformation
α'	formation of the α' phase with martensite formation
M_s	start of martensite transformation
$T\alpha'$	temperature for the start of ordering of the phase

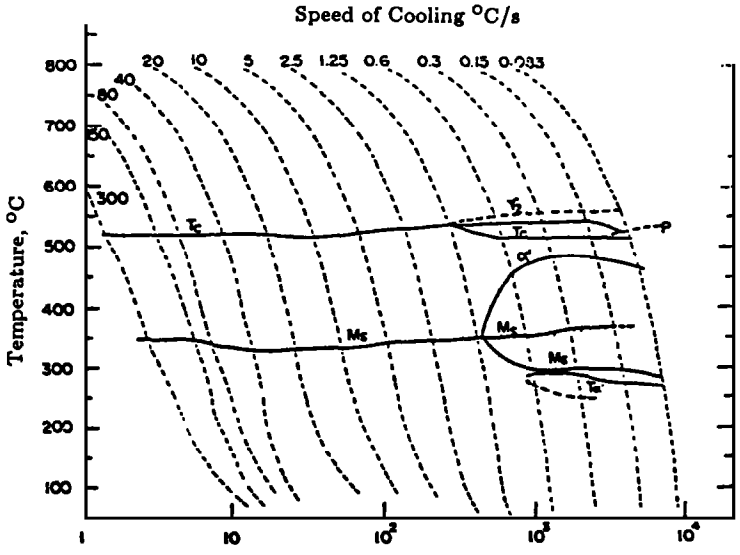
Continuous-cooling-transformation diagram

SOURCE: Suck-joong L. Kang, M. Stasi, P. Azou, "Transformation au Refroidissement Continu des Alliages Binaires Cuivre-Aluminium," Metaux Corrosion-Industrie, Vol 64, No. 762, February 1989

Copper-Aluminum Alloys

Composition: Cu - 12.16% Al

Treatment: Solution treated 850°C (1562°F) for 30 min



Time of cooling from an initial 850°C

LIVE GRAPH
Click here to view

LEGEND:

α or γ_2	start of proeutectoid
P	formation of pearlite
T_c	temperature for the start of ordering
α'_p	precipitation of α' phase without martensite transformation
α'	formation of the α' phase with martensite formation
M_s	start of martensite transformation
$T\alpha'$	temperature for the start of ordering of the phase

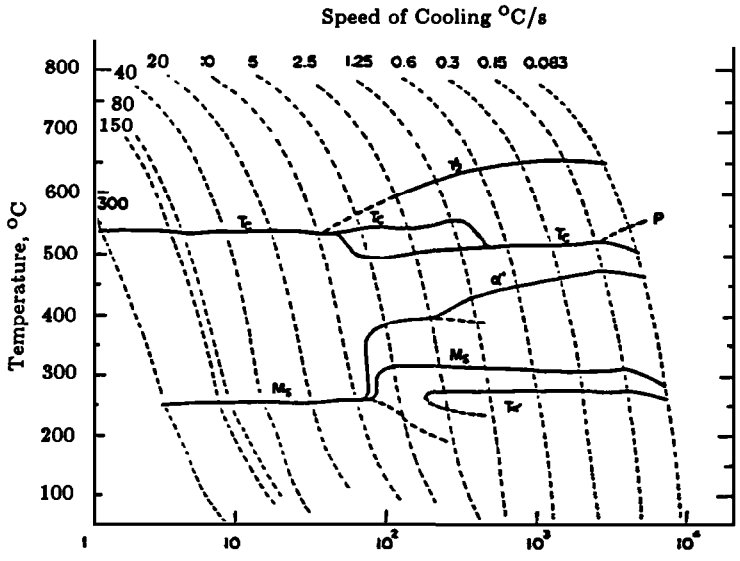
Continuous-cooling-transformation diagram

SOURCE: Suck-joong L. Kang, M. Stasi, P. Azou, "Transformation au Refroidissement Continu des Alliages Binaires Cuivre-Aluminium," Metaux Corrosion-Industrie, Vol 64, No. 762, February 1989

Copper-Aluminum Alloys

Composition: Cu - 12.78% Al

Treatment: Solution treated 850°C (1562°F) for 30 min



LIVE GRAPH
Click here to view

Time of cooling from an initial 850°C

LEGEND:

α or γ_2	start of proeutectoid
P	formation of pearlite
T_c	temperature for the start of ordering
α'_p	precipitation of α' phase without martensite transformation
α'	formation of the α' phase with martensite formation
M_s	start of martensite transformation
$T\alpha'$	temperature for the start of ordering of the phase

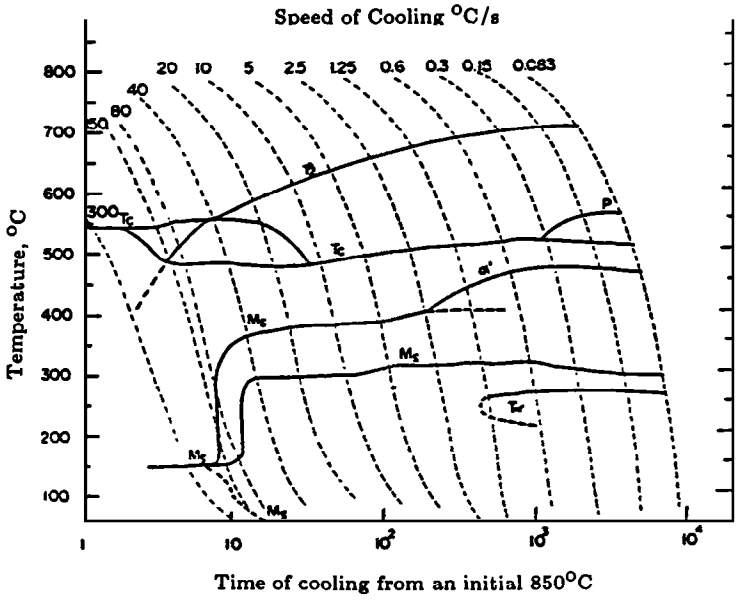
Continuous-cooling-transformation diagram

SOURCE: Suck-joong L. Kang, M. Stasi, P. Azou, "Transformation au Refroidissement Continu des Alliages Binaires Cuivre-Aluminium," Metaux Corrosion-Industrie, Vol 64, No. 762, February 1989

Copper-Aluminum Alloys

Composition: Cu - 13.31% Al

Treatment: Solution treated 850°C (1562°F) for 30 min



LEGEND:

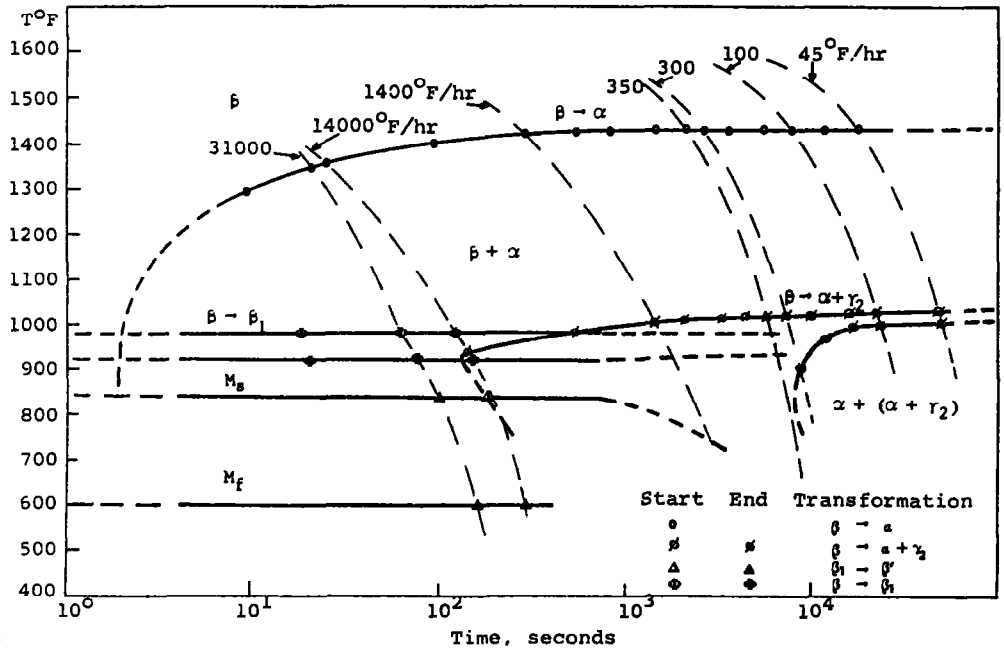
α or γ_2	start of proeutectoid
P	formation of pearlite
T_c	temperature for the start of ordering
α'_p	precipitation of α' phase without martensite transformation
α'	formation of the α' phase with martensite formation
M_s	start of martensite transformation
$T\alpha'$	temperature for the start of ordering of the phase

Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: Suck-joong L. Kang, M. Stasi, P. Azou, "Transformation au Refroidissement Continu des Alliages Binaires Cuivre-Aluminium," Metaux Corrosion-Industrie, Vol 64, No. 762, February 1989

ASTM B148-954 Alloy
Composition: Cu - 10.50% Al - 4.1% Fe



LIVE GRAPH
Click here to view

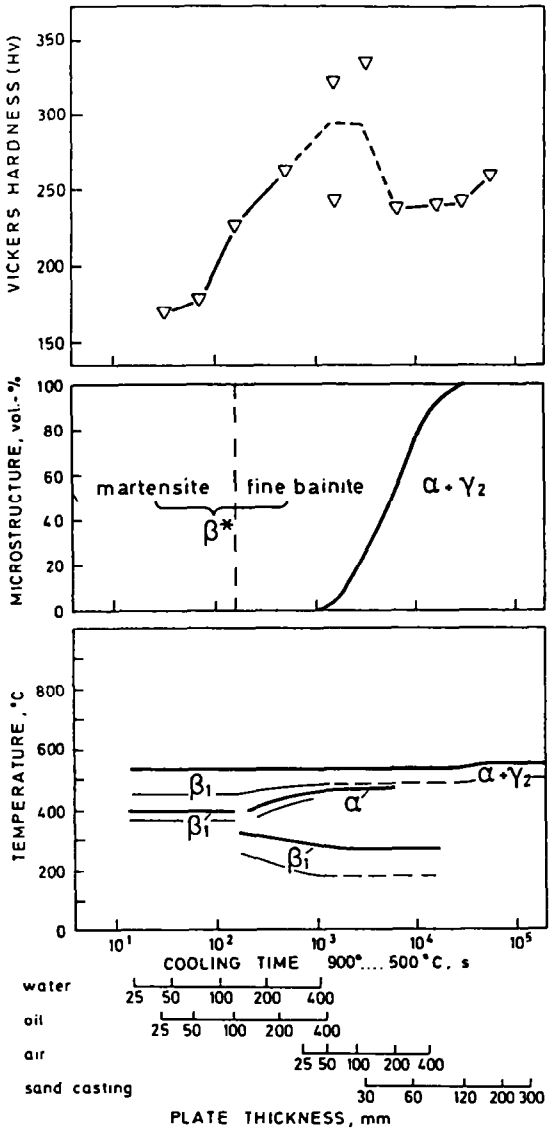
Continuous-cooling-transformation diagram

SOURCE: Roque Calderon, "Continuous Cooling Transformation of a Commercial Aluminum Bronze," MS Thesis, Lehigh University, Bethlehem PA, 1975

Copper-Aluminum Alloys

Composition: Cu - 11.8% Al

Treatment: Solution treated at 900°C (1652°F) for 1 h



LIVE GRAPH
Click here to view

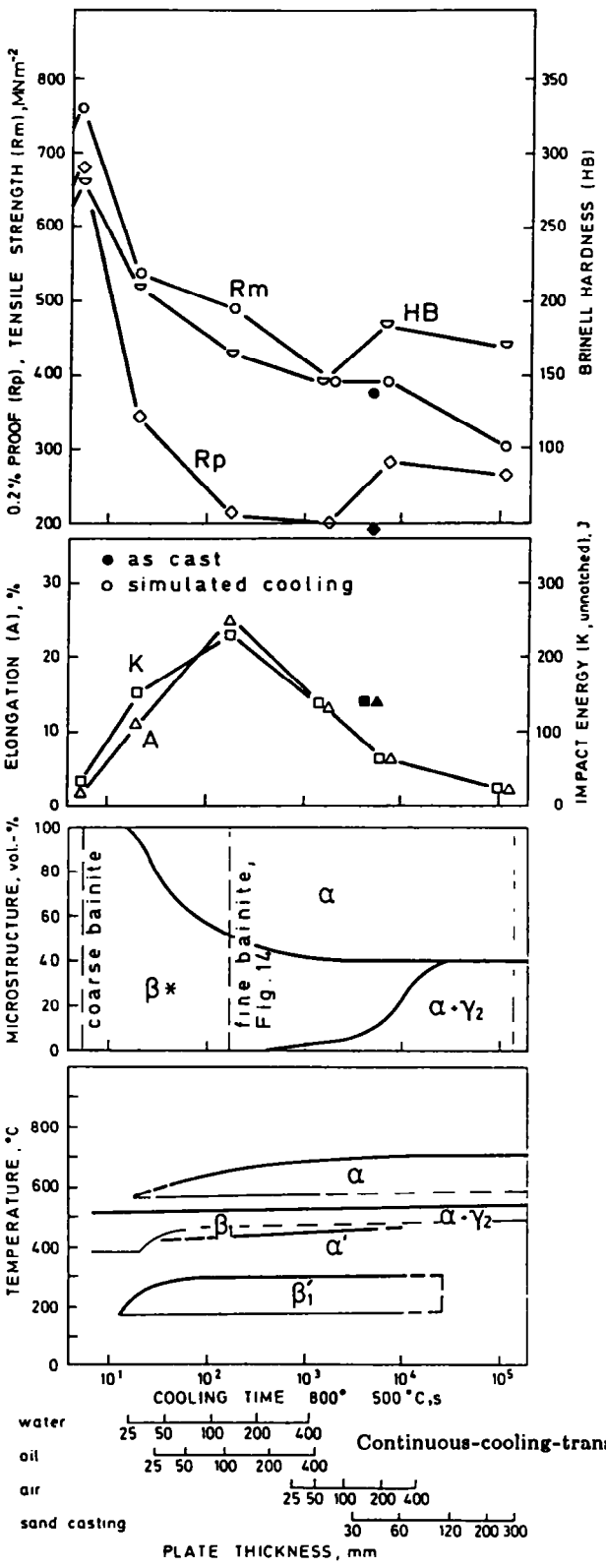
Continuous-cooling-transformation diagram

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 10.5% Al

Treatment: Solution treated at 850°C (1562°F) for 1 h, simulated cooling



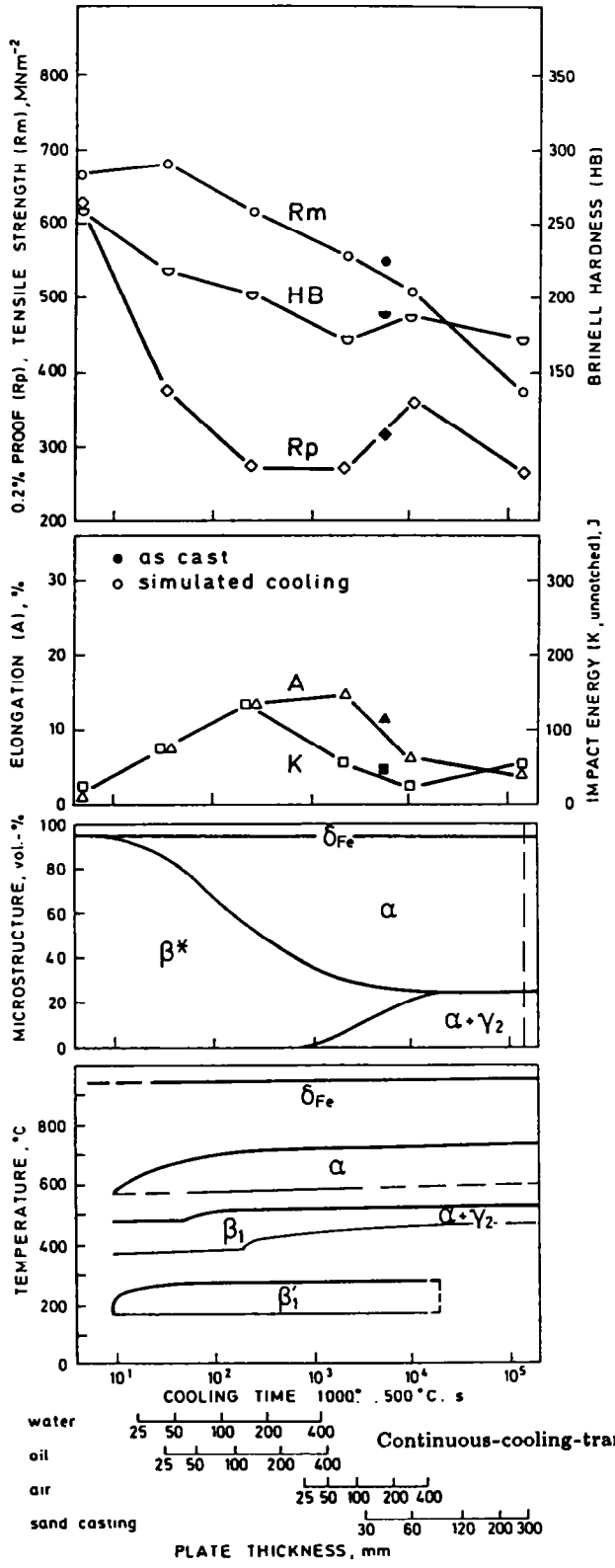
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Bresina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 10.5% Al - 4.8% Fe
Treatment: Solution treated at 1000°C (1832°F) for 1 h, simulated cooling



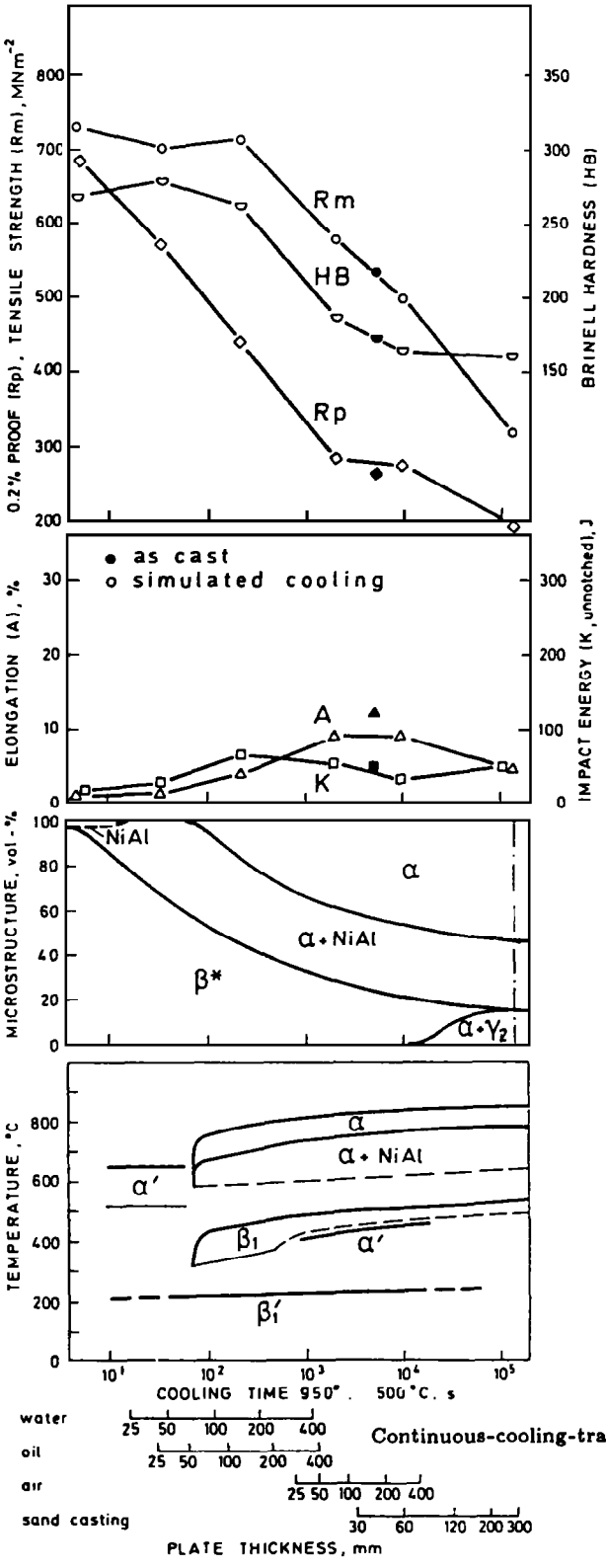
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 10.5% Al - 5% Ni
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



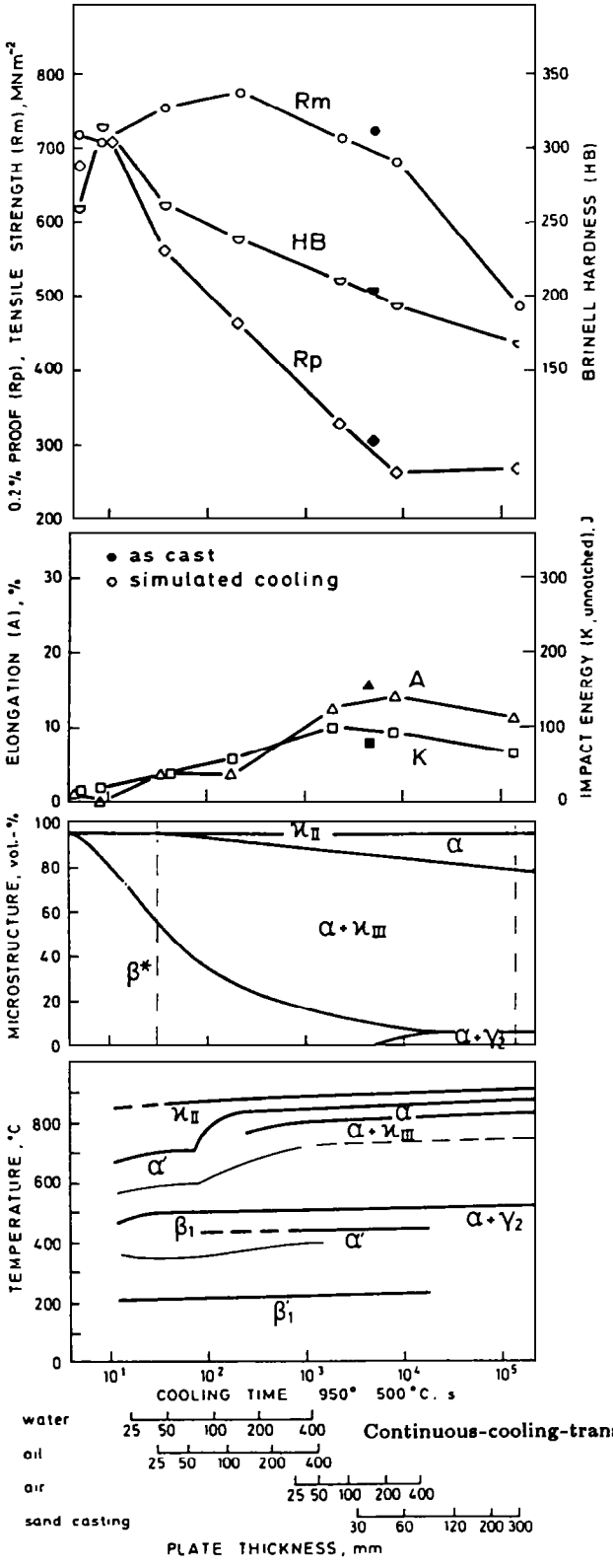
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 10.5% Al - 4.6% Fe - 5.0% Ni
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



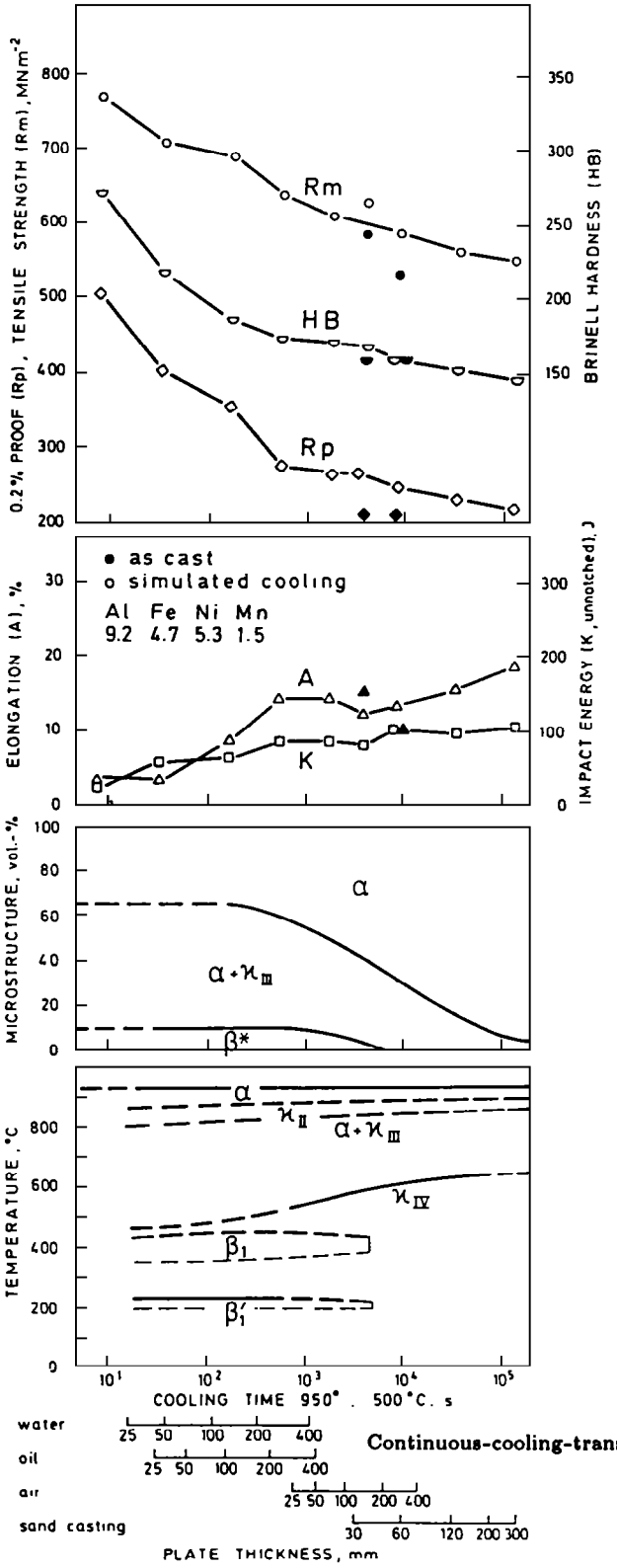
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 8.8% Al - 5.4% Fe - 5% Ni - 0.9% Mn
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



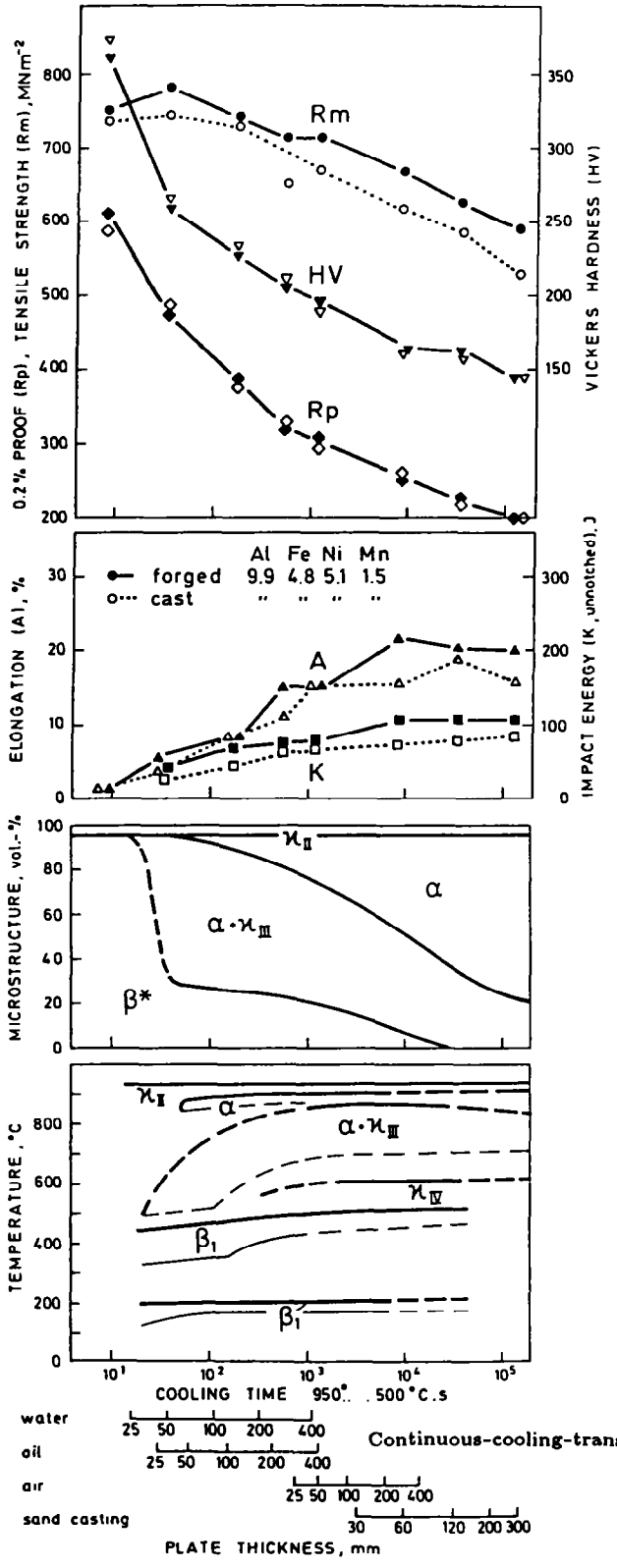
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 9.9% Al - 5.3% Fe - 5.1% Ni - 0.9% Mn
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling

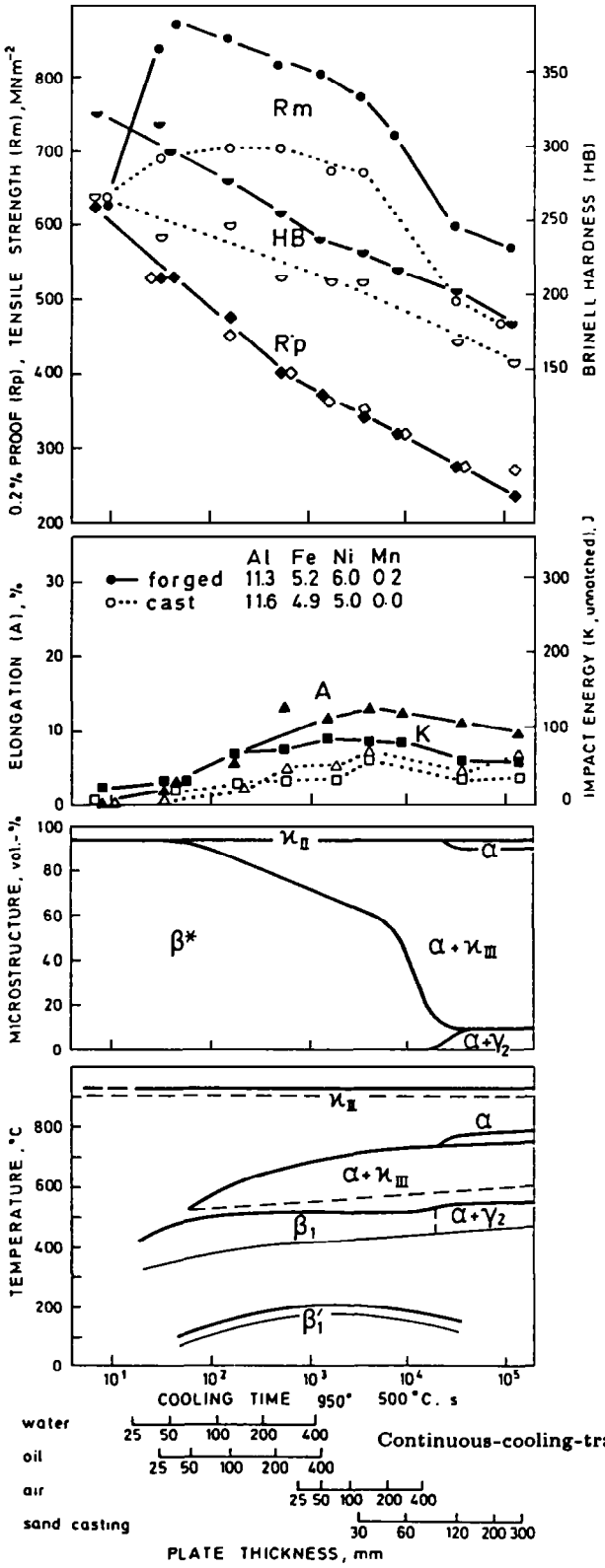


Continuous-cooling-transformation diagram

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 11.5% Al - 5.3% Fe - 5.1% Ni - 0.9% Mn
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



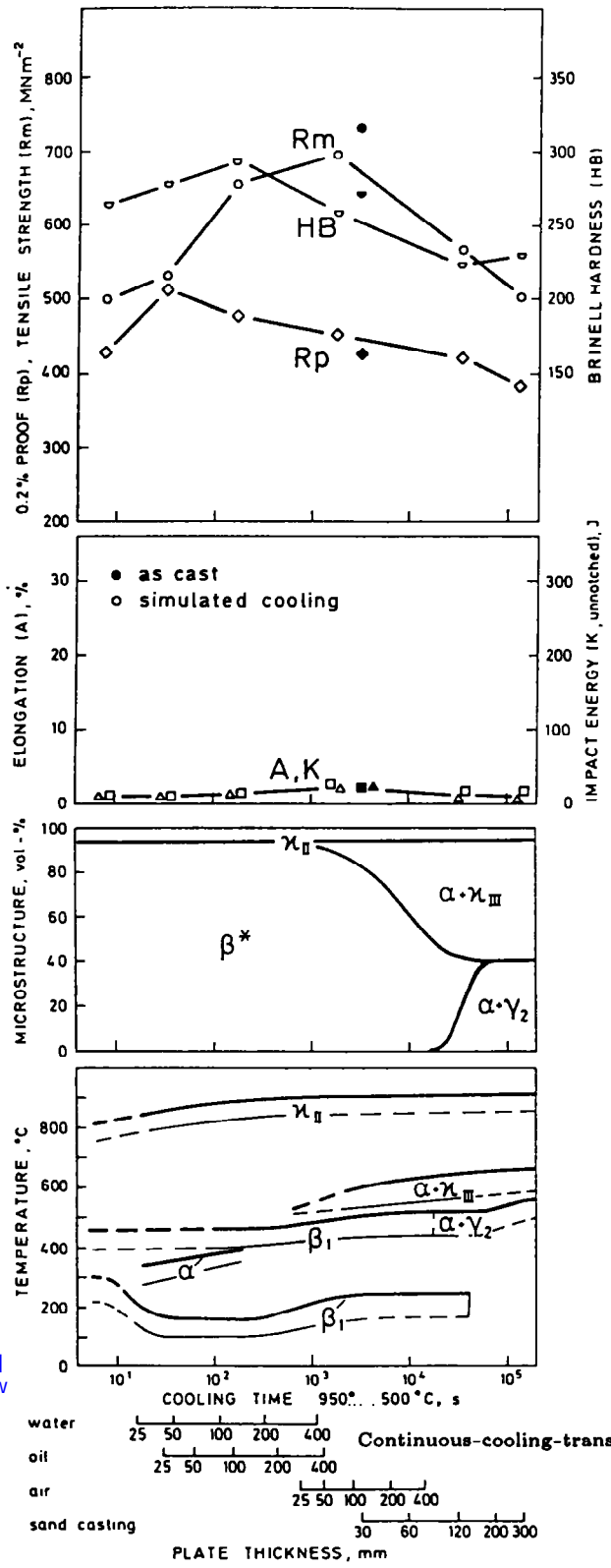
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 12.5% Al - 4.9% Fe - 5.1% Ni
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



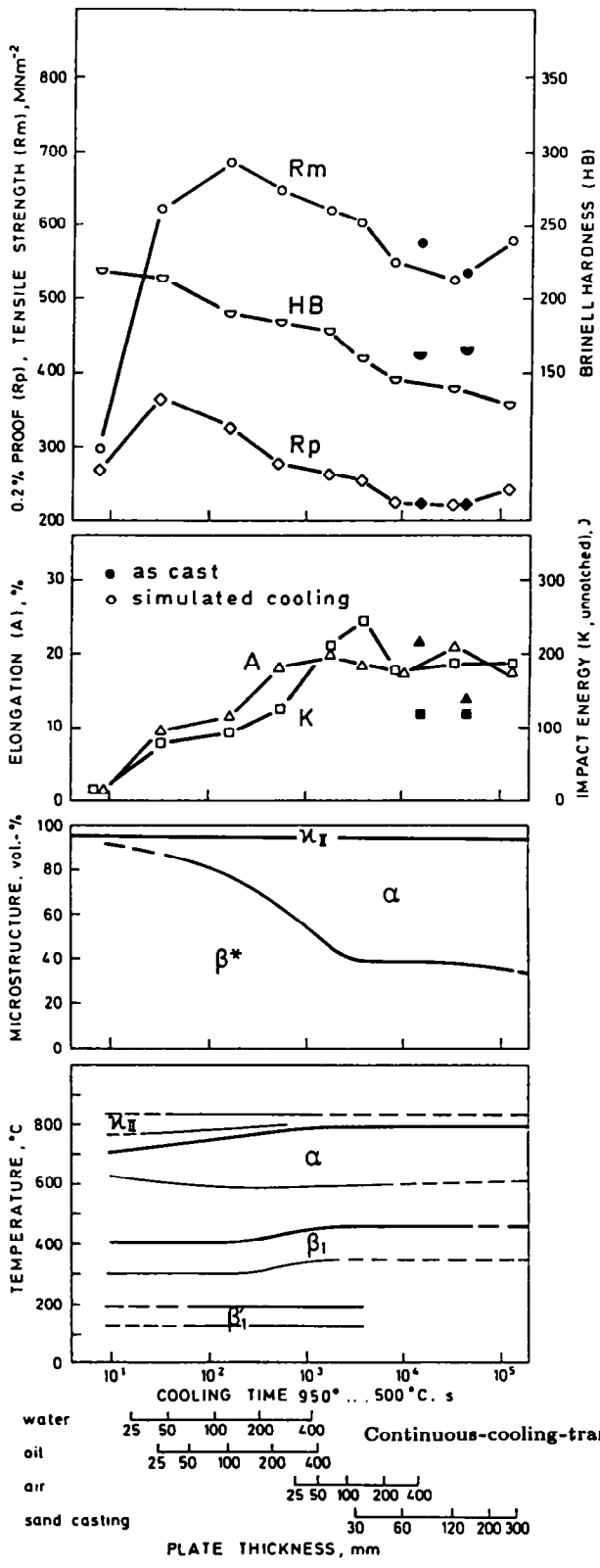
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 8% Al - 6% Mn - 3% Fe - 2% Ni
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



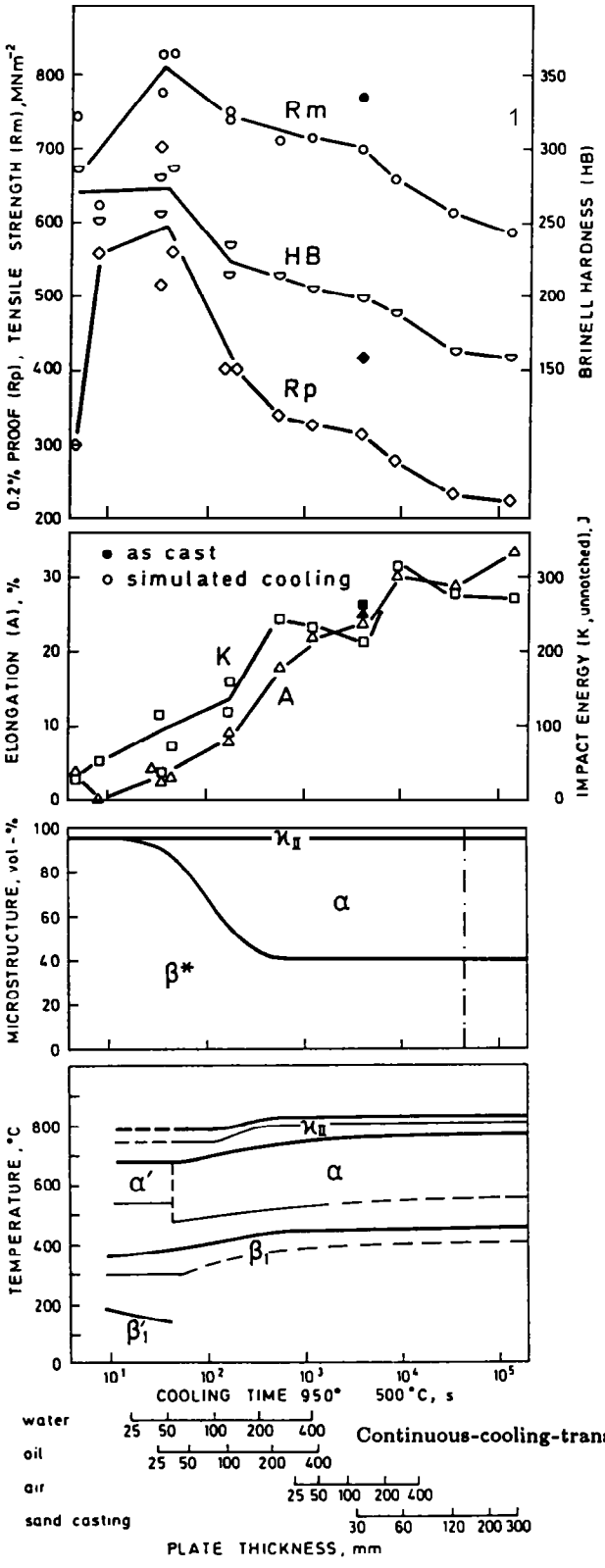
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 12% Mn - 8% Al - 3% Fe - 2% Ni
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



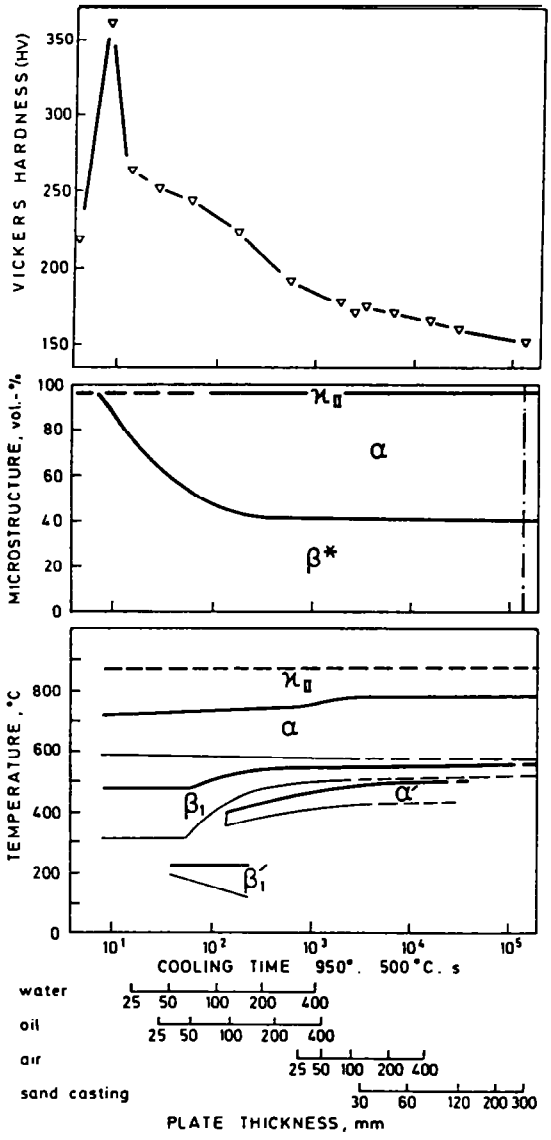
Continuous-cooling-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

Composition: Cu - 8% Al - 1% Be - 0.5% Co
Treatment: Solution treated at 950°C (1742°F) for 1 h, simulated cooling



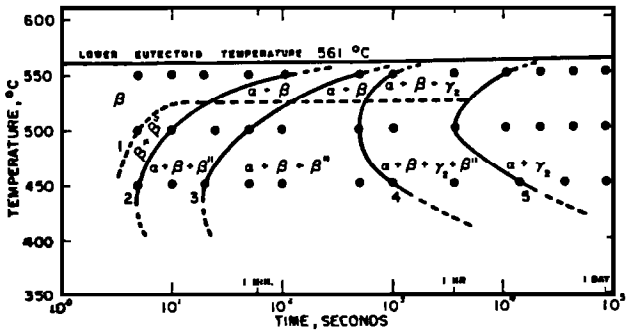
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

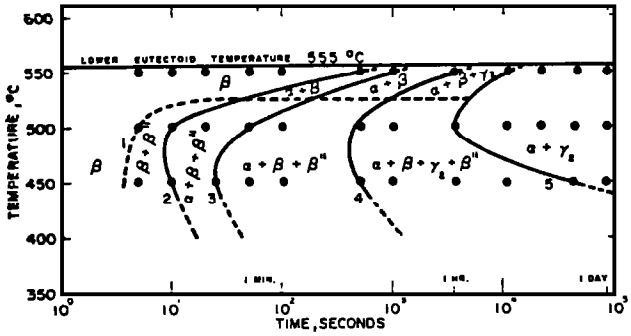
SOURCE: P. Brezina, "Heat Treatment of Complex Aluminium Bronzes," International Metals Reviews, Vol 27, No. 2, 1982, pp 77-120

Copper-Aluminum Alloys

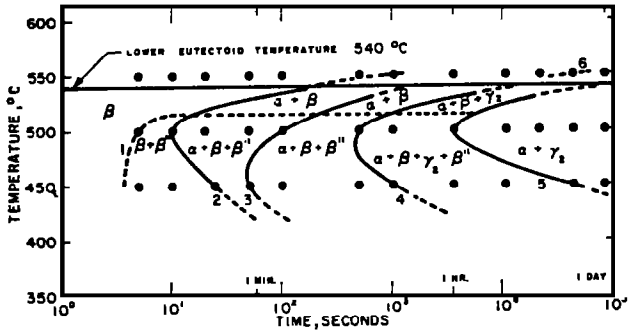
Composition: Cu - 11.54% Al - 0.08% Fe - 0.59% Ag
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.55% Al - 0.08% Fe - 1.08% Ag
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.58% Al - 0.08% Fe - 2.63% Ag
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LIVE GRAPH
Click here to view

LEGEND:

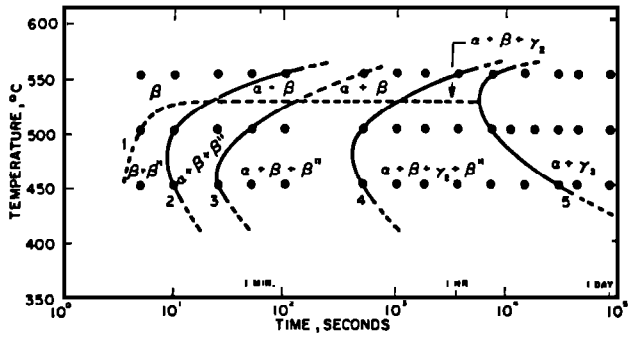
Curve 1: β'' start
Curve 2: α start on grain boundary
Curve 3: α start within grains
Curve 4: eutectoid start
Curve 5: reaction end
Curve 6: γ_2 start

Time-temperature-transformation diagram
Silver bearing eutectoid aluminum bronzes

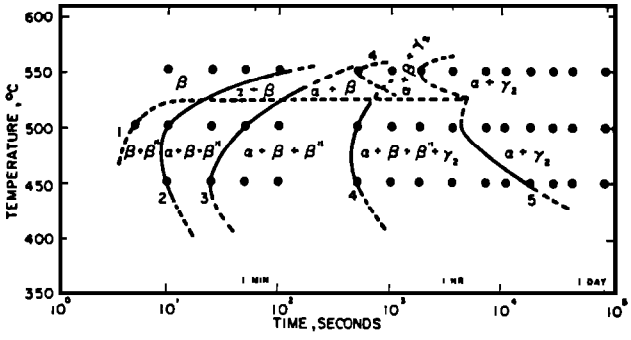
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

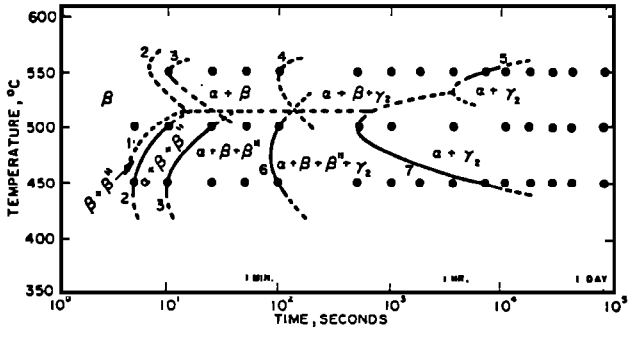
Composition: Cu - 11.83% Al - 0.06% Fe - 0.025% Cd
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.68% Al - 0.05% Fe - 0.43% Cd
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.21% Al - 0.05% Fe - 0.64% Cd
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LIVE GRAPH
Click here to view

LEGEND:

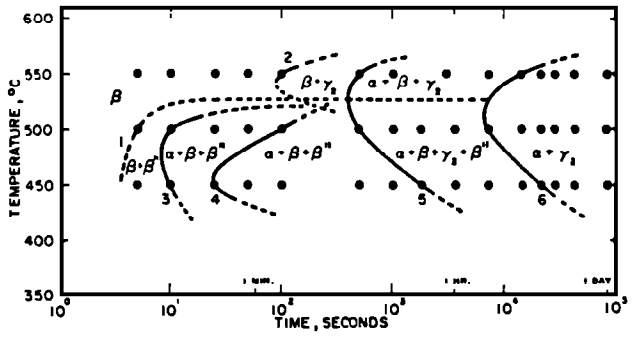
Curve 1: β'' start
Curve 2: α start on grain boundary
Curve 3: α start within grains
Curve 4: eutectoid or pearlite start
Curve 5: eutectoid or pearlite end
Curve 6: α-γ_2 rhythmic precipitation start
Curve 7: α-γ_2 rhythmic precipitation end

Time-temperature-transformation diagram
Cadmium bearing eutectoid aluminum bronzes

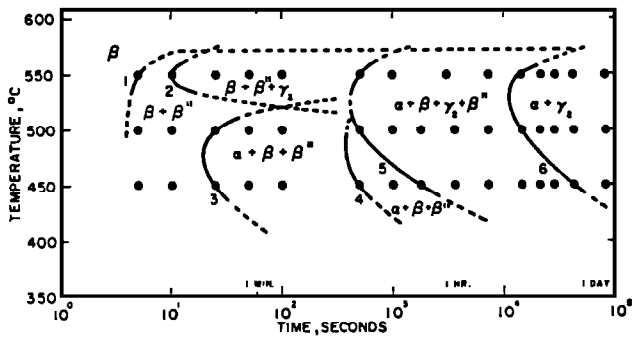
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

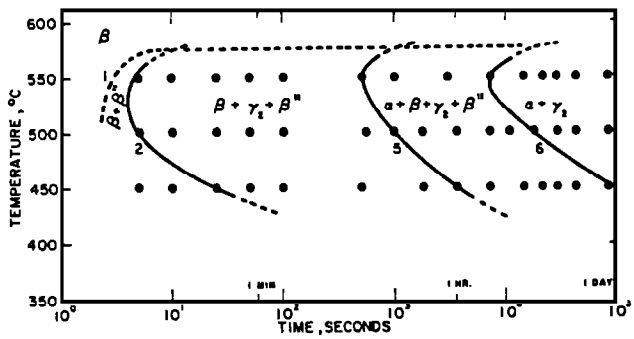
Composition: Cu - 11.73% Al - traces Fe - 0.53% In
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.79% Al - traces Fe - 0.97% In
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.84% Al - traces Fe - 2.44% In
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LIVE GRAPH
Click here to view

LEGEND:

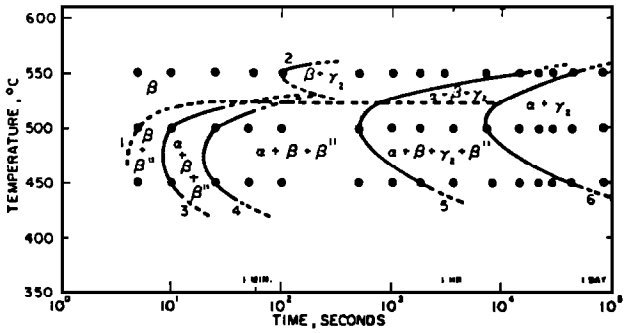
Curve 1: β'' start
Curve 2: γ_2 start
Curve 3: α start on grain boundary
Curve 4: α start within grains
Curve 5: eutectoid or pearlite start
Curve 6: eutectoid or pearlite end

Time-temperature-transformation diagram
Indium bearing eutectoid aluminum bronzes

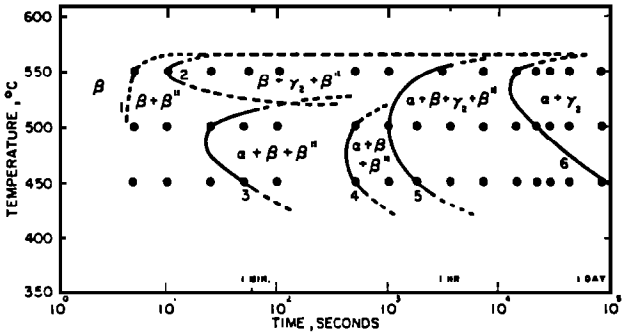
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

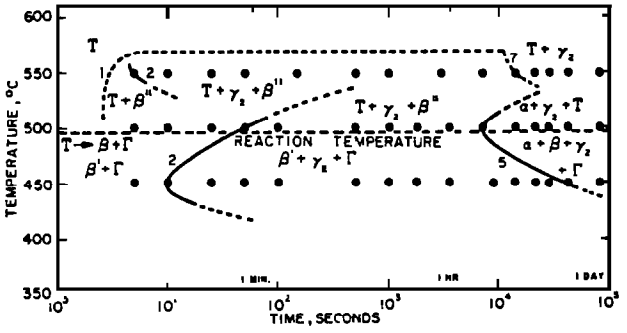
Composition: Cu - 11.74% Al - 0.01% Fe - 0.52% Sn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.84% Al - 0.01% Fe - 1.18% Sn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.56% Al - 0.01% Fe - 2.53% Sn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LIVE GRAPH
Click here to view

LEGEND:

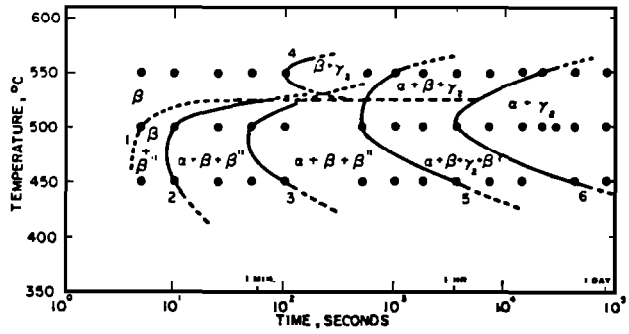
Curve 1: β'' start
Curve 2: γ_2 start
Curve 3: α start on grain boundary
Curve 4: α start within grains
Curve 5: pearlite or eutectoid start
Curve 6: reaction end
Curve 7: γ_2 end

Time-temperature-transformation diagram
Tin bearing eutectoid aluminum bronzes

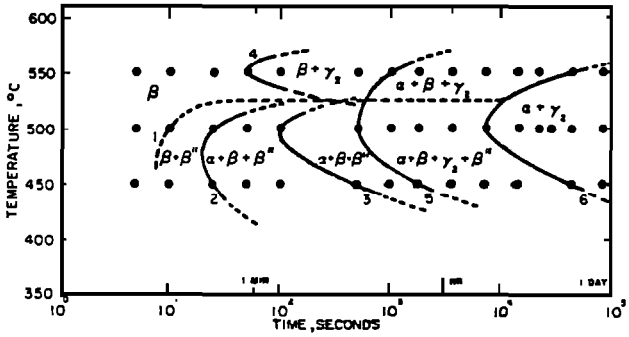
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

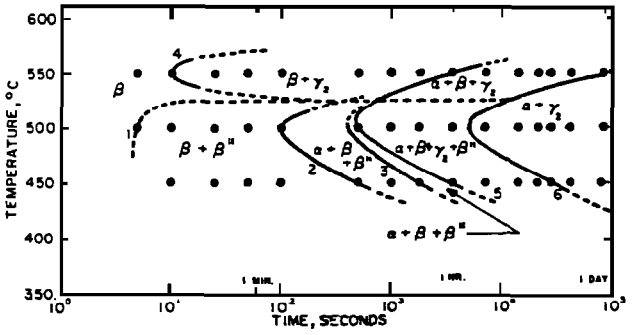
Composition: Cu - 12.06% Al - 0.05% Fe - 0.1% Sb
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.95% Al - 0.05% Fe - 0.45% Sb
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.95% Al - 0.05% Fe - 0.73% Sb
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LIVE GRAPH
Click here to view

LEGEND:

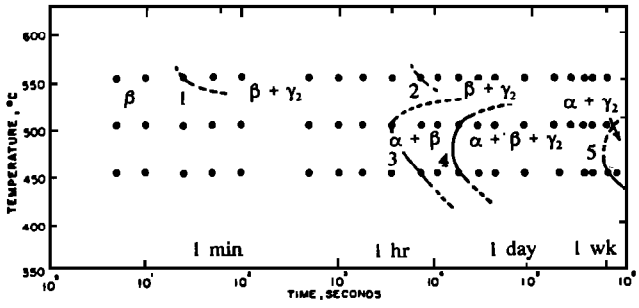
Curve 1: β'' start
Curve 2: α start on grain boundary
Curve 3: α start within grains
Curve 4: γ_2 start
Curve 5: pearlite start
Curve 6: reaction end

Time-temperature-transformation diagram
Antimony bearing eutectoid aluminum bronzes

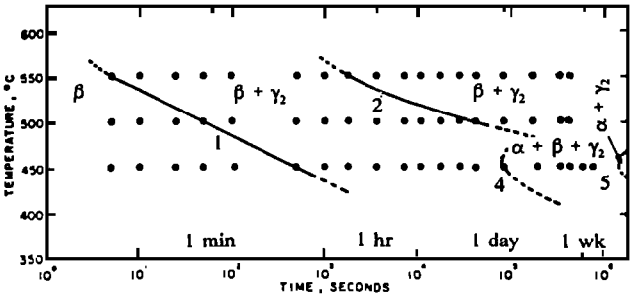
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

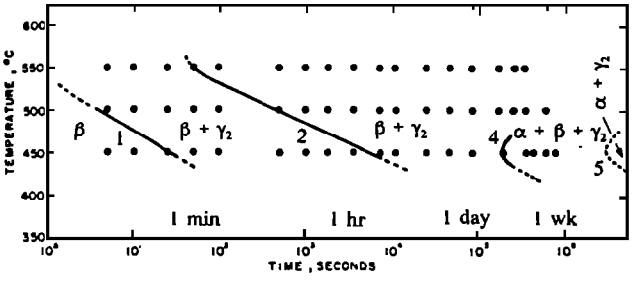
Composition: Cu - 11.75% Al - traces Fe - 0.48% Be
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.71% Al - traces Fe - 0.88% Be
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.42% Al - traces Fe - 2.14% Be
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LEGEND:

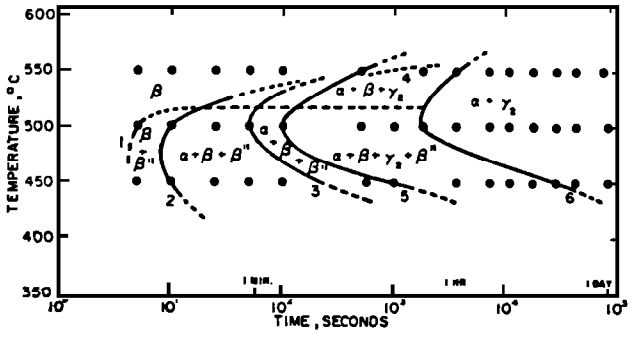
Curve 1: γ_2 start
Curve 2: γ_2 end
Curve 3: α start
Curve 4: eutectoid start
Curve 5: reaction end

Time-temperature-transformation diagram
Beryllium bearing eutectoid aluminum bronzes

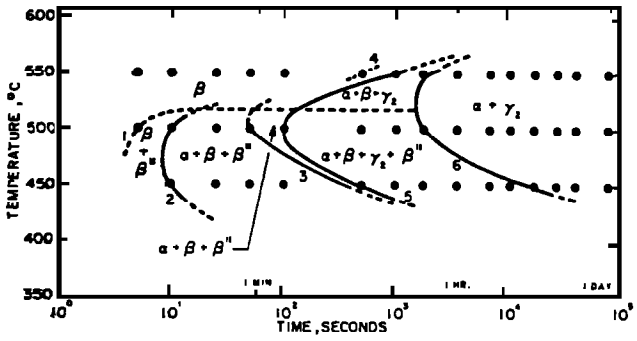
SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

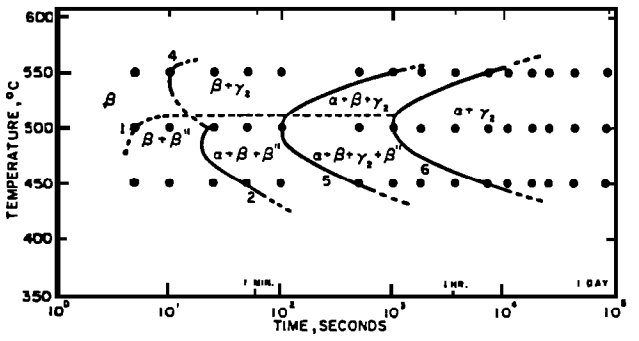
Composition: Cu - 11.65% Al - traces Fe - 0.59% Zn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.58% Al - traces Fe - 1.05% Zn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



Composition: Cu - 11.44% Al - traces Fe - 2.42% Zn
Treatment: Solution treated at 815°C (1500°F) in a tube furnace and subjected to isothermal transformation in a potassium nitrate-sodium nitrite salt bath at 550, 500, or 450°C (1022, 932, or 842°F)



LEGEND:

Curve 1: β'' start
Curve 2: α start on grain boundary
Curve 3: α start within grains
Curve 4: γ_2 start
Curve 5: pearlite start
Curve 6: reaction end

LIVE GRAPH
Click here to view

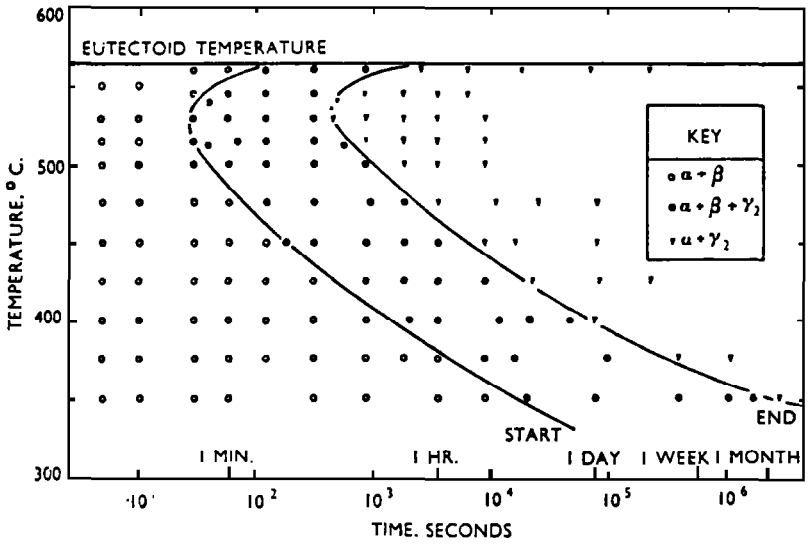
Time-temperature-transformation diagram
Zinc bearing eutectoid aluminum bronzes

SOURCE: T.V. Philip, David J. Mack, "Effect of Ternary Elements on the Eutectoid Transformation in Aluminum Bronze," Trans. AIME, Vol 224, February 1962, pp 34-42

Copper-Aluminum Alloys

Composition: Cu - 11.40% Al - 0.01% Fe
Treatment: Annealed at 890 to 910°C (1634 to 1652°F), and held within 2°, for 1 h in air before immersion in a molten bath containing about 100 lb of pure lead which was held within 2° of the desired transformation temperature, water quenched

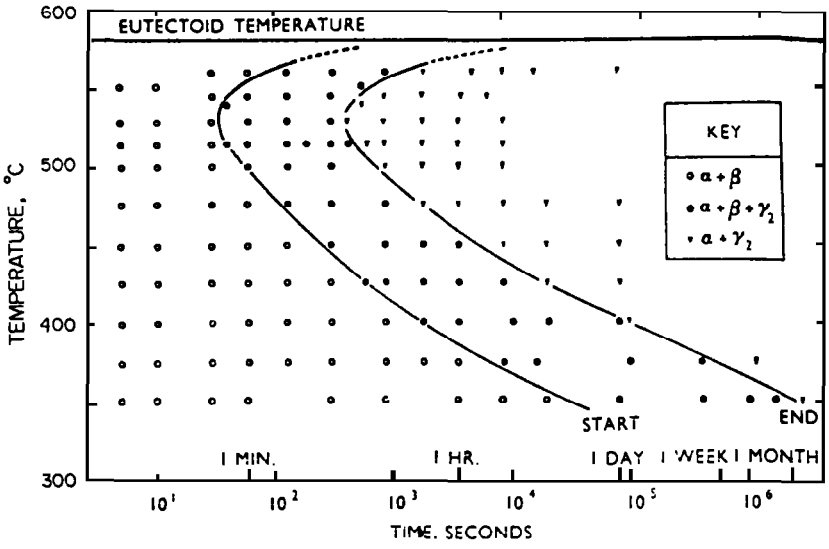
LIVE GRAPH
Click here to view



Time-temperature-transformation diagram

Composition: Cu - 10.57% Al - 0.02% Fe - 1.02% Ni - trace Si
Treatment: Annealed at 890 to 900°C (1634 to 1652°F), and held within 2°, for 1 h in air before immersion in a molten bath containing about 100 lb of pure lead which was held within 2° of the desired transformation temperature, water quenched

LIVE GRAPH
Click here to view

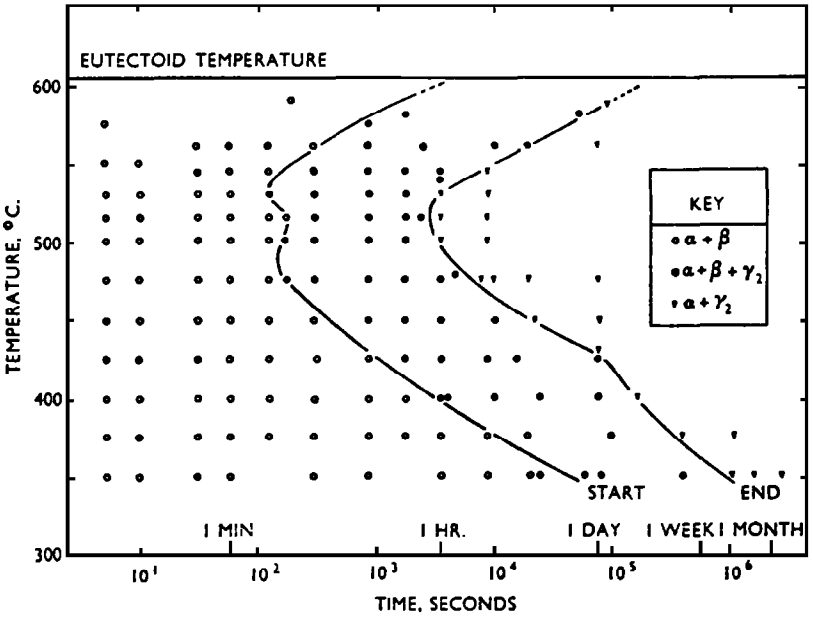


Time-temperature-transformation diagram

SOURCE: R. Haynes, "Isothermal Transformations of Hypo-Eutectoid Aluminium Bronzes," Journal of the Institute of Metals, Vol 82, 1953, pp 493-497

Copper-Aluminum Alloys

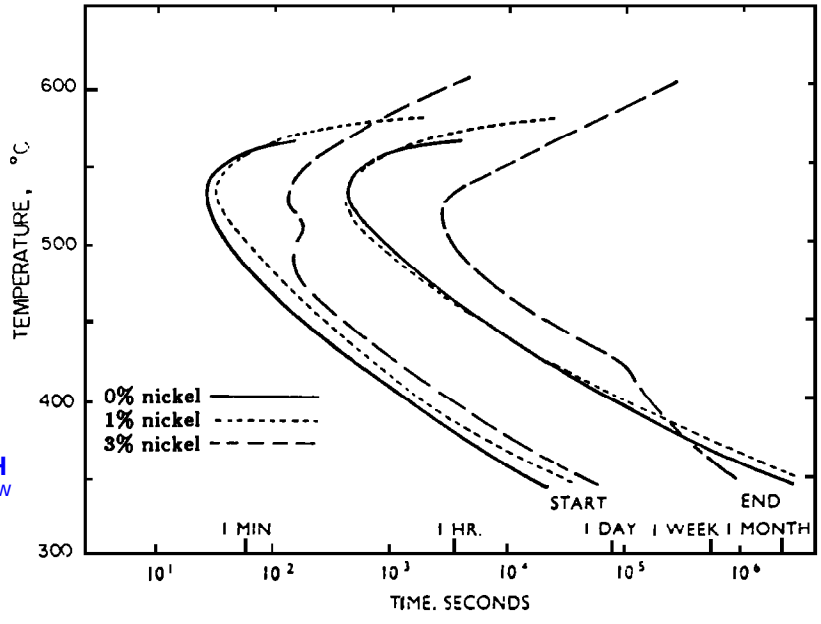
Composition: Cu - 10.54% Al - trace Fe - 3.03% Ni
Treatment: Annealed at 900 to 950°C (1652 to 1742°F), and held within 2°, for 1 h in air before immersion in a molten bath containing about 100 lb of pure lead which was held within 2° of the desired transformation temperature, water quenched



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition time-temperature-transformation diagram of the three preceding alloys



LIVE GRAPH
Click here to view

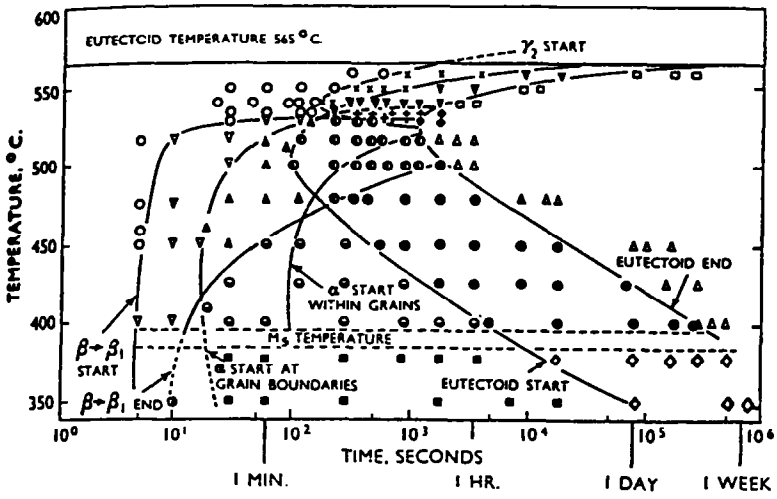
Time-temperature-transformation diagram

SOURCE: R. Haynes, "Isothermal Transformations of Hypo-Eutectoid Aluminium Bronzes," Journal of the Institute of Metals, Vol 82, 1953, pp 493-497

Copper-Aluminum Alloys

Composition: Cu - 12.20% Al - 0.04% Fe - trace Si

Treatment: Annealed at 890 to 900°C (1634 to 1652°F), and held to within 2°, for 1 h before isothermal transformation in a bath of pure molten lead held within 2° of the transformation temperature



LIVE GRAPH
Click here to view

LEGEND:

○ β	▲ $\alpha + \beta + \beta_1$
⊖ $\alpha + \beta$	◇ $\beta + \beta_1 + \gamma_2$
× $\beta + \gamma_2$	◈ $\alpha + \beta + \beta_1 + \gamma_2$
△ α + eutectoid.	◎ $\alpha + \beta + \beta_1$ + eutectoid
□ γ_2 + „ „	● ϕ $\alpha + \beta + \beta_1 + \gamma_2$ + eutectoid *
◆ $\alpha + \gamma_2$ + eutectoid	⊖ $\alpha + \beta_1$
⊸ $\alpha + \beta$ + „ „	● $\alpha + \beta_1$ + eutectoid
▼ $\beta + \gamma_2$ + „ „	◐ $\beta_1 + \beta'$
+ $\alpha + \beta + \gamma_2$ + eutectoid.	■ $\alpha + \beta_1 + \beta'$
▽ $\beta + \beta_1$	◇ $\alpha + \beta_1 + \beta'$ + eutectoid

*** The symbol on the left has been used to enable a curve to be drawn in this figure**

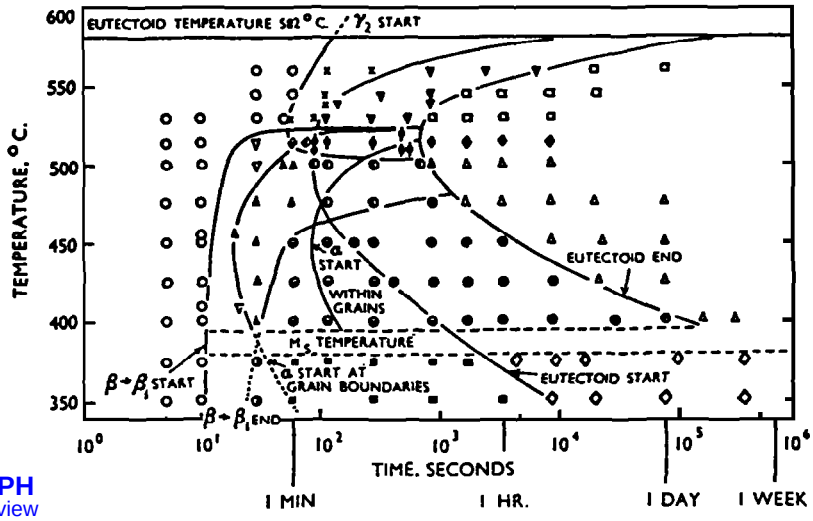
Time-temperature-transformation diagram

SOURCE: R. Haynes, "Isothermal Transformations of Eutectoid Aluminium Bronzes," Journal of the Institute of Metals, Vol 83, 1954, pp 105-115

Copper-Aluminum Alloys

Composition: Cu - 12.45% Al - 0.87% Ni - trace Fe

Treatment: Annealed at 890 to 900°C (1634 to 1652°F), and held within 2°, for 1 h before isothermal transformation in a bath of pure molten lead held within 2° of the transformation temperature



LIVE GRAPH
Click here to view

LEGEND:

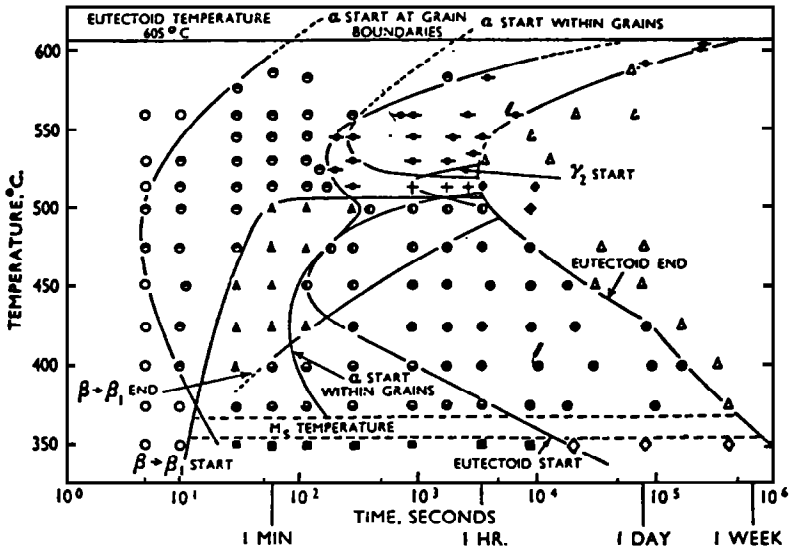
- ○ β
- ⊖ $\alpha + \beta$
- × $\beta + \gamma_2$
- △ α + eutectoid.
- □ γ_2 + „ „
- ◆ $\alpha + \gamma_2$ + eutectoid
- ⊸ $\alpha + \beta$ + „ „
- ▼ $\beta + \gamma_2$ + „ „
- + $\alpha + \beta + \gamma_2$ + eutectoid.
- ▽ $\beta + \beta_1$
- ▲ $\alpha + \beta + \beta_1$
- ◇ $\beta + \beta_1 + \gamma_2$
- ◈ $\alpha + \beta + \beta_1 + \gamma_2$
- ◐ $\alpha + \beta + \beta_1$ + eutectoid
- ⊖ $\alpha + \beta_1$
- ● $\alpha + \beta_1$ + eutectoid
- ◘ $\beta_1 + \beta'$
- ■ $\alpha + \beta_1 + \beta'$
- ◊ $\alpha + \beta_1 + \beta'$ + eutectoid

Time-temperature-transformation diagram

SOURCE: R. Haynes, "Isothermal Transformations of Eutectoid Aluminium Bronzes," Journal of the Institute of Metals, Vol 83, 1954, pp 105-115

Copper-Aluminum Alloys

Composition: Cu - 12.07% Al - 3.08% Ni - trace Fe
Treatment: Annealed at 890 to 900°C (1652°F), and held within 2°, for 1 h before isothermal transformation in a bath of pure molten lead held within 2° of the transformation temperature



LEGEND:

○ β	▲ $\alpha + \beta + \beta_1$
⊖ $\alpha + \beta$	◇ $\beta + \beta_1 + \gamma_2$
× $\beta + \gamma_2$	◈ $\alpha + \beta + \beta_1 + \gamma_2$
△ α + eutectoid.	◎ $\alpha + \beta + \beta_1$ + eutectoid
□ γ_2 + „ „	⊖ $\alpha + \beta_1$
◆ $\alpha + \gamma_2$ + eutectoid	● $\alpha + \beta_1$ + eutectoid
⊷ $\alpha + \beta$ + „ „	◑ $\beta_1 + \beta'$
▼ $\beta + \gamma_2$ + „ „	■ $\alpha + \beta_1 + \beta'$
+ $\alpha + \beta + \gamma_2$ + eutectoid.	◇ $\alpha + \beta_1 + \beta'$ + eutectoid
▽ $\beta + \beta_1$	

LIVE GRAPH
Click here to view

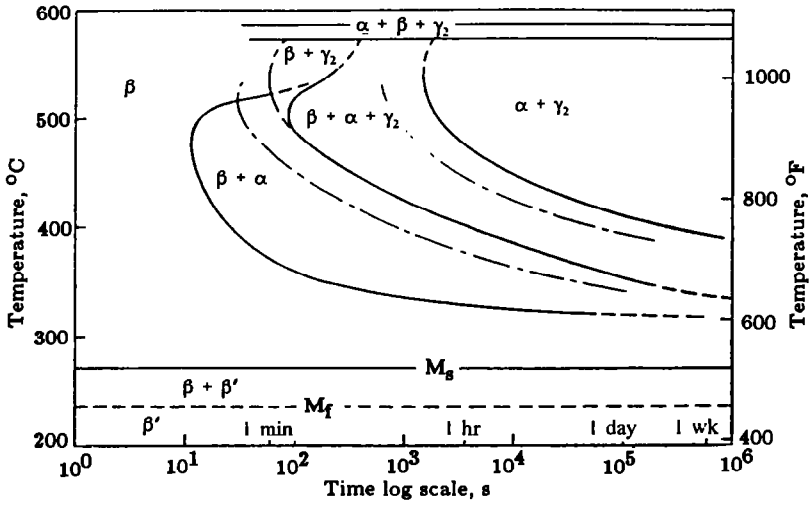
Time-temperature-transformation diagram

SOURCE: R. Haynes, "Isothermal Transformations of Eutectoid Aluminium Bronzes," Journal of the Institute of Metals, Vol 83, 1954, pp 105-115

Aluminum-Bronze Alloys

Composition: Cu - 12.31% Al - 3.68% Fe - 0.28% Ni - 0.03% Mn

Treatment: Soaked at 800°C (1472°F) for 20 min in air and quenched in the isothermal salt bath, and water quenched



LIVE GRAPH
Click here to view

LEGEND
0.090 mm grain size
0.010 mm grain size
uncertain portions

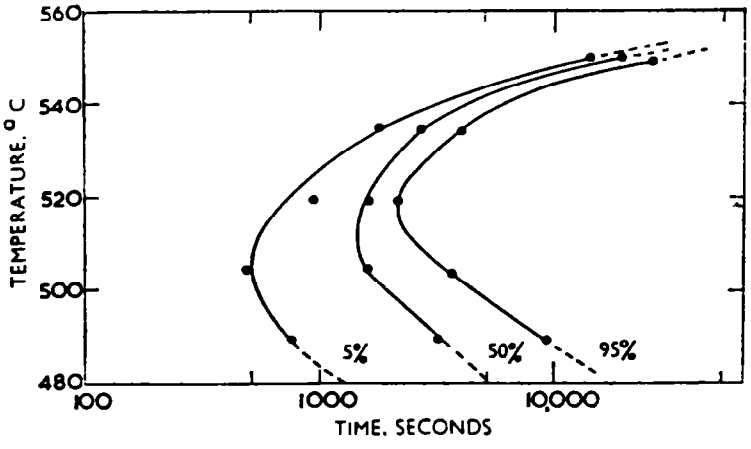
Time-temperature-transformation diagram

SOURCE: A.H. Kasberg, Jr., D.J. Mack, "Isothermal Transformation and Properties of a Commercial Aluminum Bronze," Trans. AIME, October 1951, pp 903-908

Copper-Aluminum Alloys

Composition: Cu - 11.9% Al

Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914°F)



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Binary eutectoid alloy

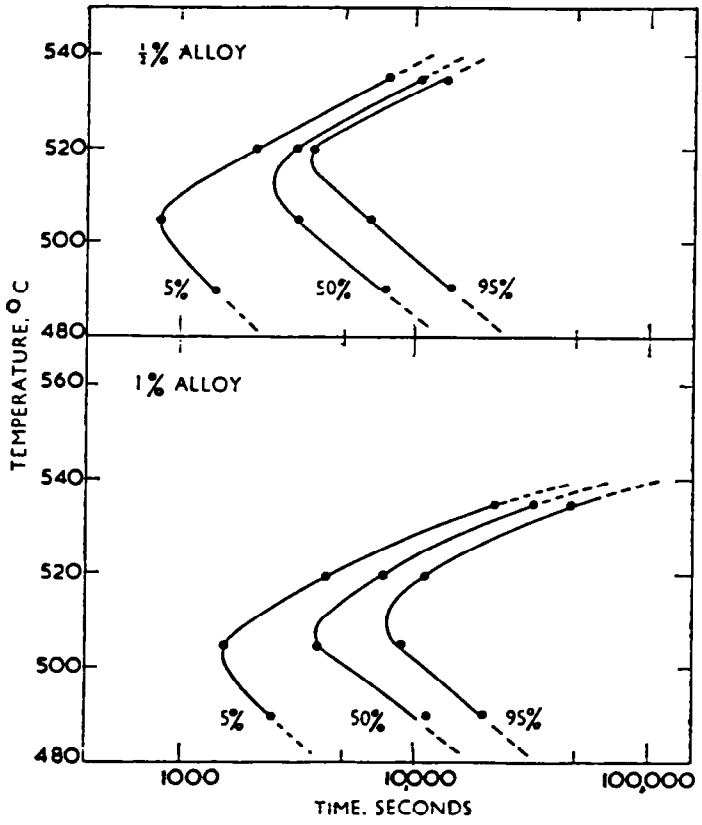
SOURCE: G.V.T. Ranzetta, D.R.F. West, "Kinetics of the Beta to (alpha + gamma$_2$) Transformation in Certain Binary and Ternary Aluminium Bronzes," Journal of the Institute of Metals, Vol 92, 1963, pp 12-17

Copper-Aluminum Alloys

Composition: Cu - 11.7% Al - 0.50% Mn
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914°F)

Composition: Cu - 11.6% Al - 0.96% Mn
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914°F)

LIVE GRAPH
Click here to view



Time-temperature-transformation diagram
Manganese-containing alloys

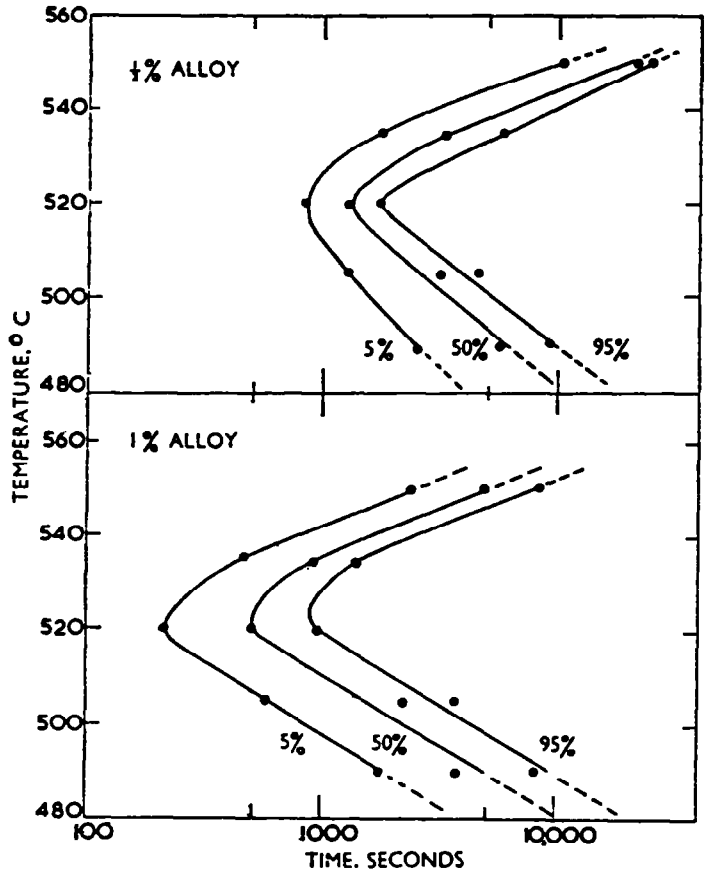
SOURCE: G.V.T. Ranzetta, D.R.F. West, "Kinetics of the Beta to (alpha + gamma$_2$) Transformation in Certain Binary and Ternary Aluminium Bronzes," Journal of the Institute of Metals, Vol 92, 1963, pp 12-17

Copper-Aluminum Alloys

Composition: Cu - 11.7% Al - 0.52% Co
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914°F)

Composition: Cu - 11.8% Al - 1.1% Co
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914°F)

LIVE GRAPH
Click here to view



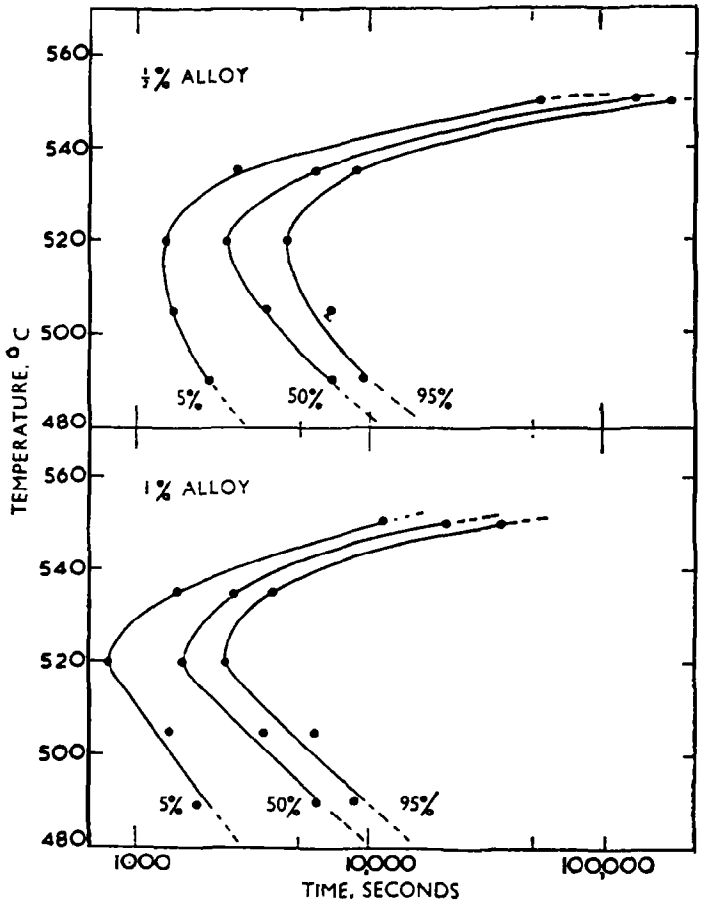
Time-temperature-transformation diagram
Cobalt-containing alloys

SOURCE: G.V.T. Ranzetta, D.R.F. West, "Kinetics of the Beta to (alpha + gamma$_2$) Transformation in Certain Binary and Ternary Aluminium Bronzes," Journal of the Institute of Metals, Vol 92, 1963, pp 12-17

Copper-Aluminum Alloys

Composition: Cu - 11.7% Al - 0.41% Fe
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914+[o]F)

Composition: Cu - 11.6% Al - 0.93% Fe
Treatment: Specimens heated at 800°C (1472°F) for 45 min and quenched into a lead bath maintained at a selected temperature within the range 550-490°C (1022-914+[o]F)



LIVE GRAPH
Click here to view

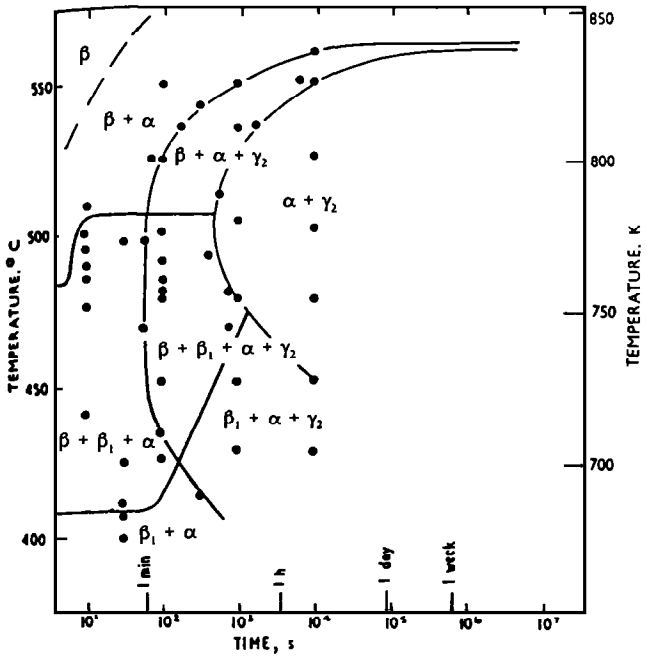
Time-temperature-transformation diagram
Iron-containing alloys

SOURCE: G.V.T. Ranzetta, D.R.F. West, "Kinetics of the Beta to (Alpha + Gamma2) Transformation in Certain Binary and Ternary Aluminium Bronzes," Journal of the Institute of Metals, Vol 92, 1963, pp 12-17

Copper-Aluminum-Zinc Alloys

Composition: Cu - 10.6% Al - 3.0% Zn

Treatment: Solution treated at 800°C (1472°F) for 30 min in air, transferred to a bath of molten salt at selected temperatures below 566°C (1051°F). After isothermal transformation in the salt bath for predetermined times, the specimens were water-quenched



LIVE GRAPH
Click here to view

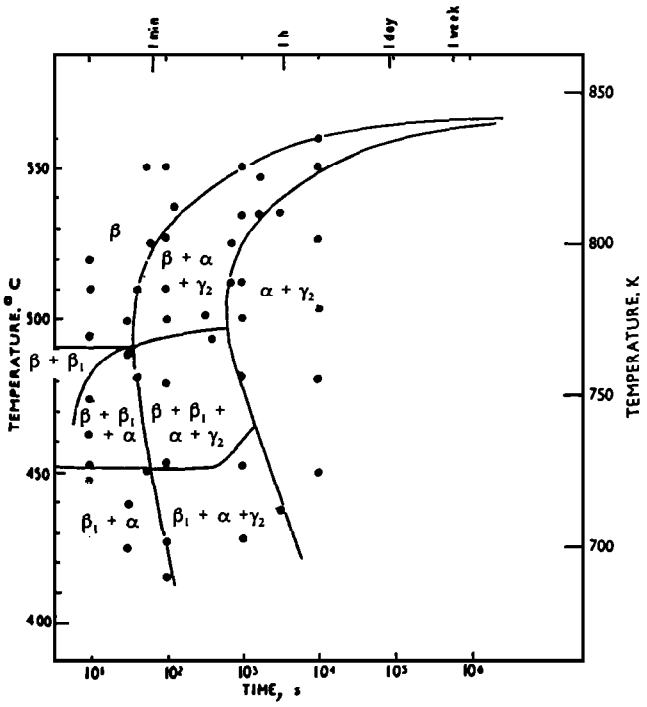
Time-temperature-transformation diagram

SOURCE: A.J. Fletcher, D. Lloyd Thomas, "Solid-State Transformations in Certain Copper-Aluminium-Zinc Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 188-192

Copper-Aluminum-Zinc Alloys

Composition: Cu - 11.0% Al - 3.1% Zn

Treatment: Solution treated at 800°C (1472°F) for 30 min in air, transferred to a bath of molten salt at selected temperatures below 566°C (1051°F). After isothermal transformation in the salt bath for predetermined times, the specimens were water-quenched



LIVE GRAPH
Click here to view

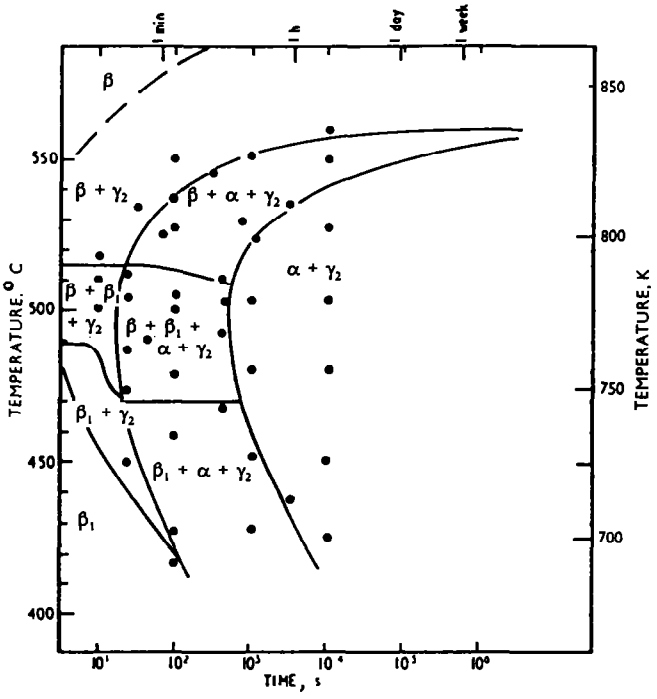
Time-temperature-transformation diagram

SOURCE: A.J. Fletcher, D. Lloyd Thomas, "Solid-State Transformations in Certain Copper-Aluminium-Zinc Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 188-192

Copper-Aluminum-Zinc Alloys

Composition: Cu - 11.5% Al - 3.1% Zn

Treatment: Solution treated at 800°C (1472°F) for 30 min in air, transferred to a bath of molten salt at selected



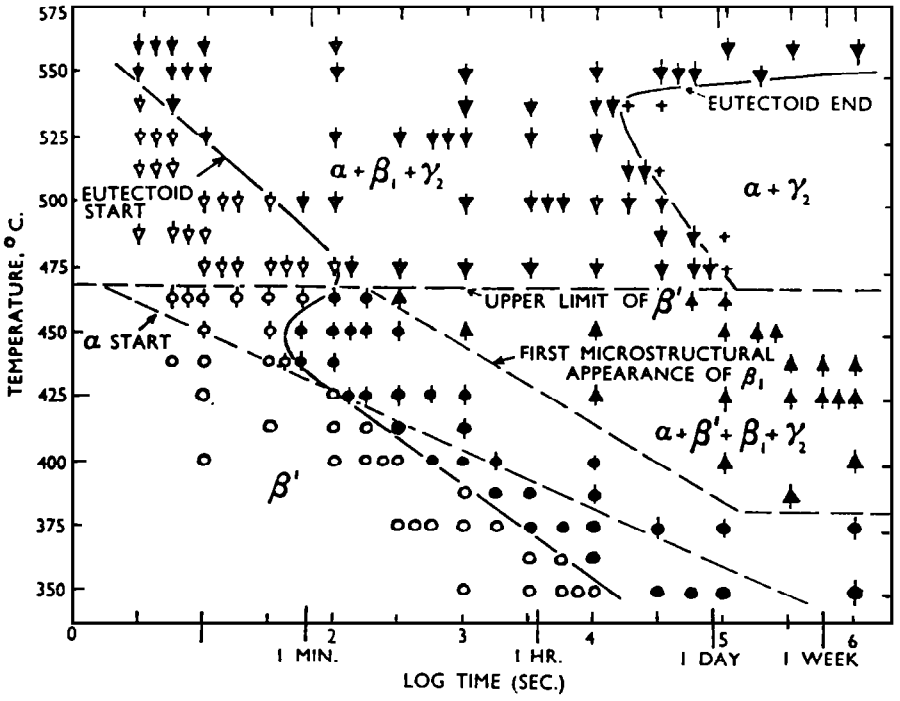
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: A.J. Fletcher, D. Lloyd Thomas, "Solid-State Transformations in Certain Copper-Aluminium-Zinc Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 188-192

Copper-Aluminum Alloys

Composition: Cu - 10.5% Al
Treatment: Martensite formed by water quenching from 950°C (1742°F). Specimens were then tempered in a lead bath and aged at various times and temperatures



LIVE GRAPH
Click here to view

LEGEND:

- β'
- β' + α
- β' + EUTECTOID
- β' + α + EUTECTOID
- β' + γ2 + EUTECTOID
- β' + β1
- β' + β1 + α
- β' + β1 + α + EUTECTOID
- β' + β1 + β + α
- β' + β1 + β + α + EUTECTOID
- β1 + α
- β1 + α + EUTECTOID
- β1 + β
- β1 + β + α
- β1 + β + α + EUTECTOID
- β1 + β + γ2
- β1 + β + γ2 + EUTECTOID
- β + α
- β + γ2
- β + α + EUTECTOID
- β + γ2 + EUTECTOID
- α + γ2
- β' + EUTECTOID + (GRAIN BOUNDARY PHASE + γ2)
- β' + γ2 + EUTECTOID + GRAIN BOUNDARY PHASE + γ2

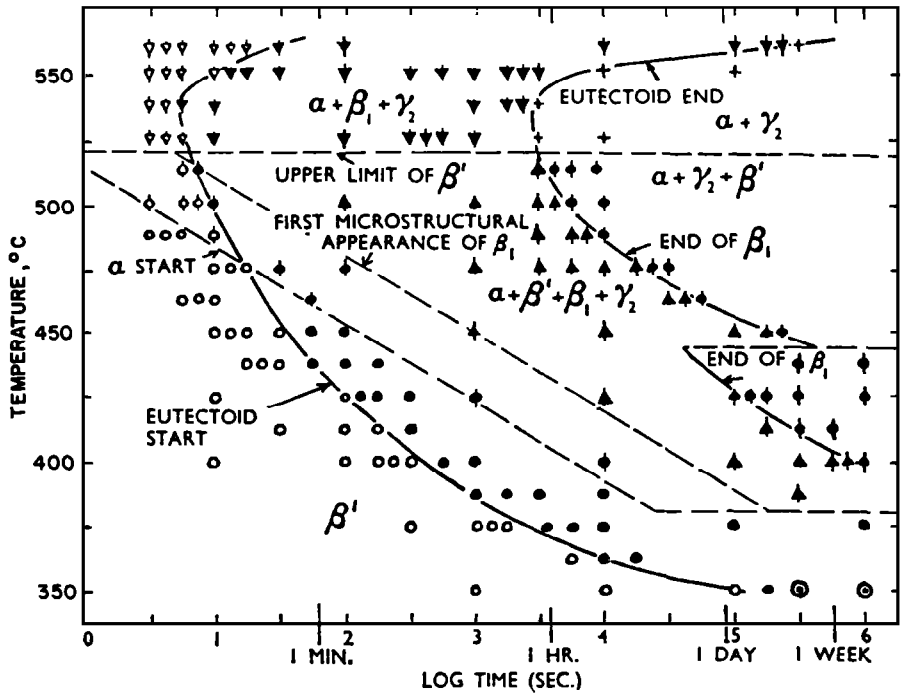
Time-temperature-tempering diagram

SOURCE: R.G. Cope, "The Tempering of Martensite in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 87, 1958, pp 330-336

Copper-Aluminum Alloys

Composition: Cu - 11.3% Al

Treatment: Martensite formed by water quenching from 950°C (1742°F). Specimens were then tempered in a lead bath and aged at various times and temperatures



LIVE GRAPH
Click here to view

LEGEND:

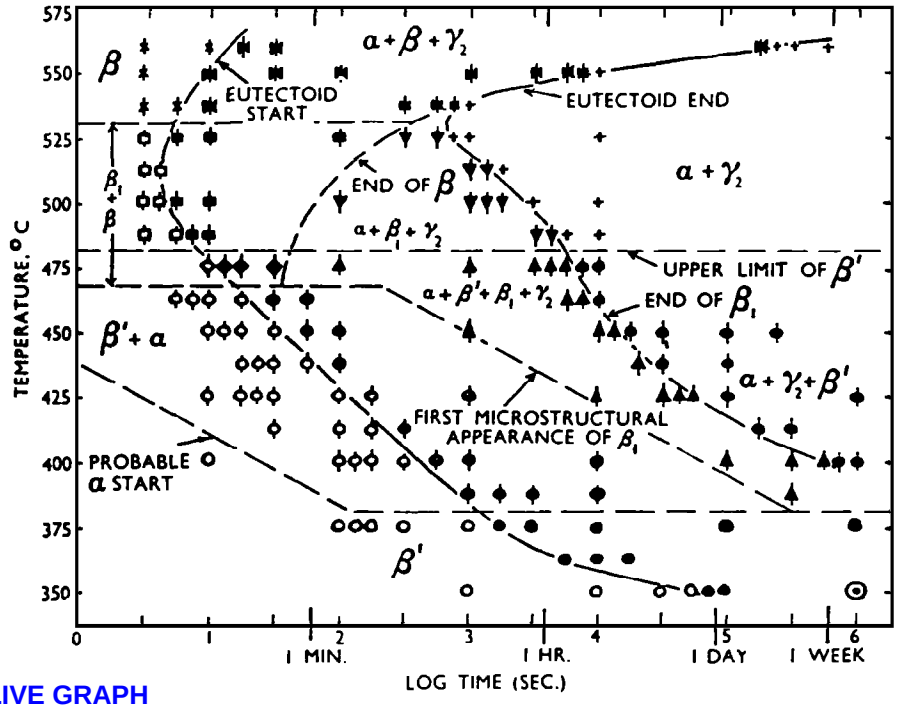
- β'
- $\beta' + \alpha$
- $\beta' +$ EUTECTOID
- $\beta' + \alpha +$ EUTECTOID
- $\beta' + \gamma_2 +$ EUTECTOID
- $\beta' + \beta_1$
- $\beta' + \beta_1 + \alpha$
- $\beta' + \beta_1 + \alpha +$ EUTECTOID
- $\beta' + \beta_1 + \beta + \alpha$
- $\beta' + \beta_1 + \beta + \alpha +$ EUTECTOID
- $\beta_1 + \alpha$
- $\beta_1 + \alpha +$ EUTECTOID
- $\beta_1 + \beta$
- $\beta_1 + \beta + \alpha$
- $\beta_1 + \beta + \alpha +$ EUTECTOID
- $\beta_1 + \beta + \gamma_2$
- $\beta_1 + \beta + \gamma_2 +$ EUTECTOID
- $\beta + \alpha$
- $\beta + \gamma_2$
- $\beta + \alpha +$ EUTECTOID
- $\beta + \gamma_2 +$ EUTECTOID
- $\alpha + \gamma_2$
- $\beta' +$ EUTECTOID + (GRAIN BOUNDARY PRIP PHASE + γ_2)
- $\beta' + \gamma_2 +$ EUTECTOID + GRAIN BOUNDARY PRIP PHASE + γ_2

Time-temperature-tempering diagram

SOURCE: R.G. Cope, "The Tempering of Martensite in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 87, 1958, pp 330-336

Copper-Aluminum Alloys

Composition: Cu - 11.8% Al
Treatment: Martensite formed by water quenching from 950°C (1742°F). Specimens were then tempered in a lead bath and aged at various times and temperatures



LIVE GRAPH
Click here to view

LEGEND:

- β'
- β' + α
- β' + EUTECTOID
- β' + α + EUTECTOID
- β' + γ2 + EUTECTOID
- β' + β1
- β' + β1 + α
- β' + β1 + α + EUTECTOID
- β' + β1 + β + α
- β' + β1 + β + α + EUTECTOID
- β1 + α
- β1 + α + EUTECTOID
- β1 + β
- β1 + β + α
- β1 + β + α + EUTECTOID
- β1 + β + γ2
- β1 + β + γ2 + EUTECTOID
- β + α
- β + γ2
- β + α + EUTECTOID
- β + γ2 + EUTECTOID
- α + γ2
- β' + EUTECTOID + (GRAIN BOUNDARY PRIOR PHASE + γ2)
- β' + γ2 + EUTECTOID + (GRAIN BOUNDARY PRIOR PHASE + γ2)

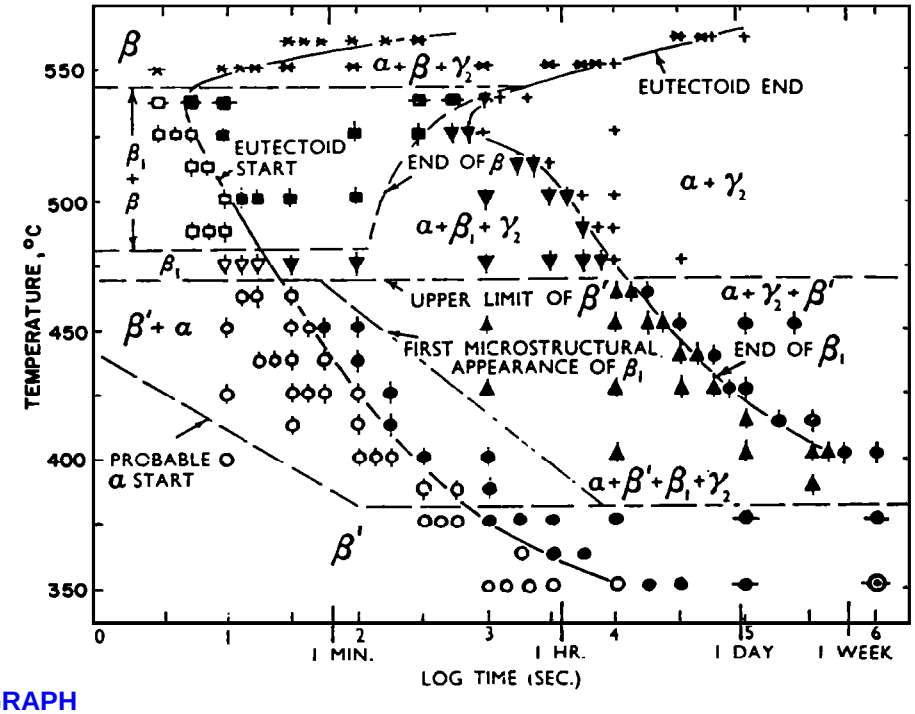
Time-temperature-tempering diagram

SOURCE: R.G. Cope, "The Tempering of Martensite in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 87, 1958, pp 330-336

Copper-Aluminum Alloys

Composition: Cu - 12.0% Al

Treatment: Martensite formed by water quenching from 950°C (1742°F). Specimens were then tempered in a lead bath and aged at various times and temperatures



LIVE GRAPH
Click here to view

LEGEND:

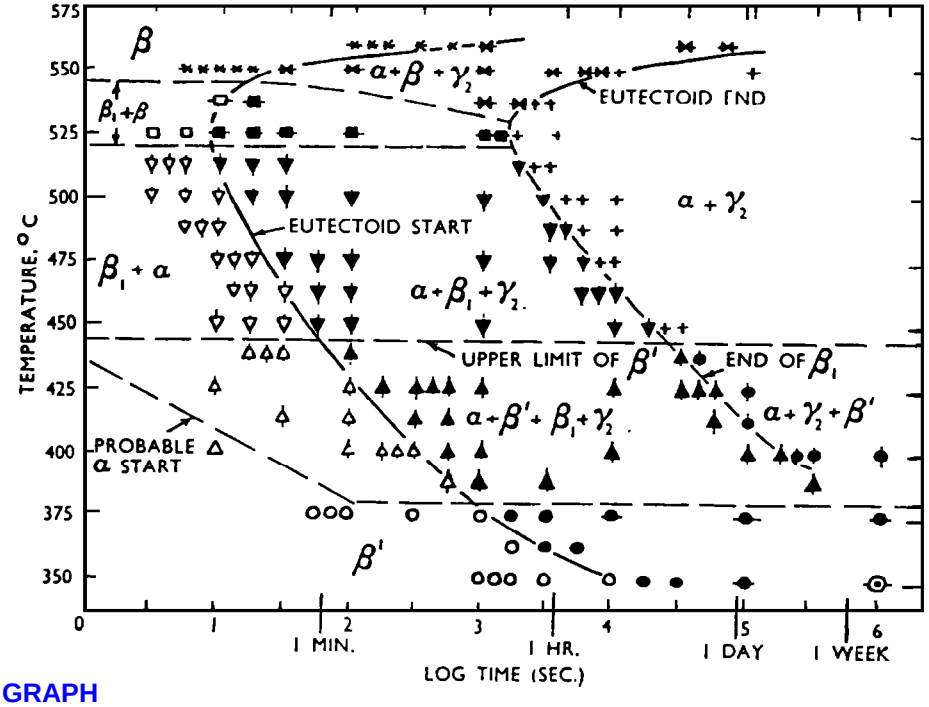
- β'
- β' + α
- β' + EUTECTOID
- β' + α + EUTECTOID
- β' + γ2 + EUTECTOID
- β' + β1
- β' + β1 + α
- β' + β1 + α + EUTECTOID
- β' + β1 + β + α
- β' + β1 + β + α + EUTECTOID
- β1 + α
- β1 + α + EUTECTOID
- β1 + β
- β1 + β + α
- β1 + β + α + EUTECTOID
- β1 + β + γ2
- β1 + β + γ2 + EUTECTOID
- β + α
- β + γ2
- β + α + EUTECTOID
- β + γ2 + EUTECTOID
- α + γ2
- β' + EUTECTOID + (GRAIN BOUNDARY PRE PHASE + γ2)
- β' + γ2 + EUTECTOID + (GRAIN BOUNDARY PRE PHASE + γ2)

Time-temperature-tempering diagram

SOURCE: R.G. Cope, "The Tempering of Martensite in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 87, 1958, pp 330-336

Copper-Aluminum Alloys

Composition: Cu - 12.4% Al
Treatment: Martensite formed by water quenching from 950°C (1742°F). Specimens were then tempered in a lead bath and aged at various times and temperatures



LIVE GRAPH
Click here to view

LEGEND:

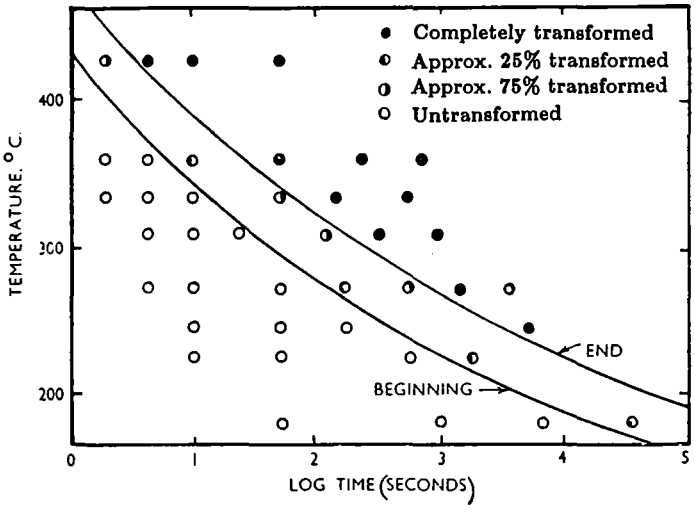
- β'
- β' + α
- β' + EUTECTOID
- β' + α + EUTECTOID
- β' + γ2 + EUTECTOID
- β' + β1
- β' + β1 + α
- β' + β1 + α + EUTECTOID
- β' + β1 + β + α
- β' + β1 + β + α + EUTECTOID
- β1 + α
- β1 + α + EUTECTOID
- β1 + β
- β1 + β + α
- β1 + β + α + EUTECTOID
- β1 + β + γ2
- β1 + β + γ2 + EUTECTOID
- β + α
- β + γ2
- β + α + EUTECTOID
- β + γ2 + EUTECTOID
- α + γ2
- β' + EUTECTOID + (GRAIN BOUNDARY FILM PHASE + γ2)
- β' + γ2 + EUTECTOID + (GRAIN BOUNDARY FILM PHASE + γ2)

Time-temperature-tempering diagram

SOURCE: R.G. Cope, "The Tempering of Martensite in Copper-Aluminium Alloys," Journal of the Institute of Metals, Vol 87, 1958, pp 330-336

Copper-Aluminum-Nickel Alloy

Composition: Cu - 12.8% Al - 7.7% Ni
Treatment: Solution treated at 950°C (1742°F) and quenched drastically into a 10% solution of caustic soda to prevent the decomposition of the body-centered cubic beta phase during cooling. Samples were reheated in a nitrite/nitrate salt bath maintained at constant temperature to within 2°



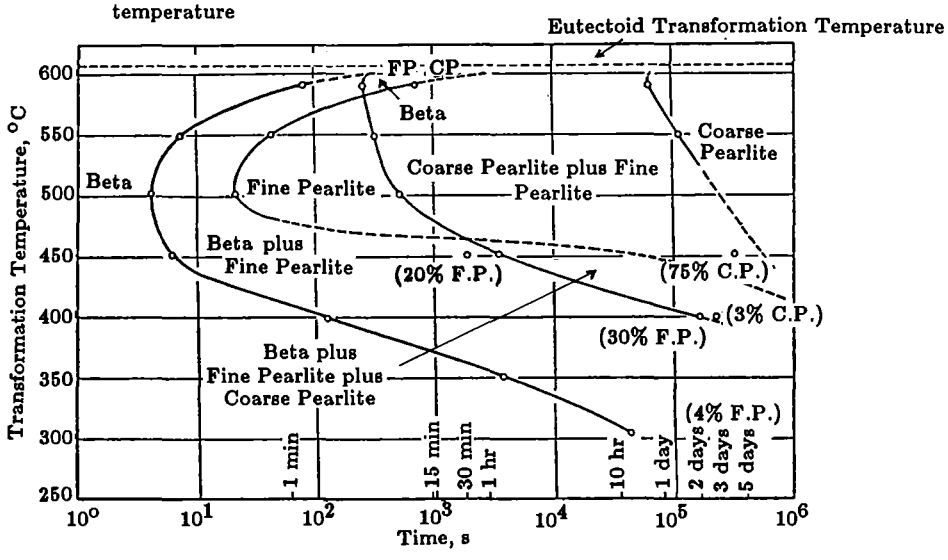
LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Effect of tempering quenched beta-phase alloy and then recooling to room temperature to induce transformation in gamma-prime martensite

SOURCE: D. Hull, R.D. Garwood, "The Martensite Transformations of the Beta Phase in Copper-Aluminium-Nickel Alloys," Journal of the Institute of Metals, Vol 86, 1957, pp 485-492

Beryllium-Bronze Alloy

Composition: Cu - 5.965% Be - trace Fe
Treatment: Solution treated at 788°C (1450°F), in a vertical tube furnace, quenched into an adjacent molten salt bath and held for a definite time, quenched into water at room temperature



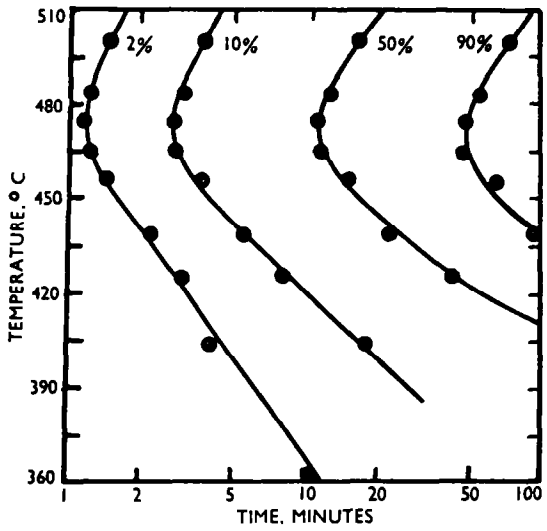
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: R.H. Fillnow, D.J. Mack, "The Isothermal Transformation of a Eutectoid Beryllium Bronze," Trans. AIME, Vol 188, October 1950, pp 1229-1236

Copper-Beryllium Alloys

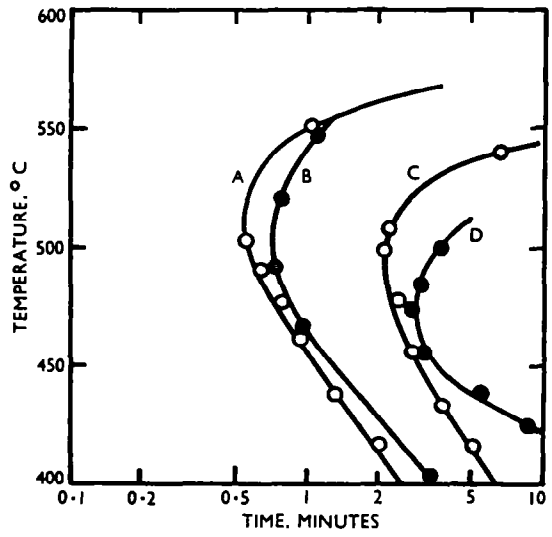
Composition: Cu - 1.77% Be - 0.24% Co
Treatment: Solution treated in the range 760-800°C (1400-1472°F) in a nitrogen atmosphere, then hot quenched into salt baths at suitable temperatures for appropriate times, followed by water quenching



Time-temperature-transformation diagram

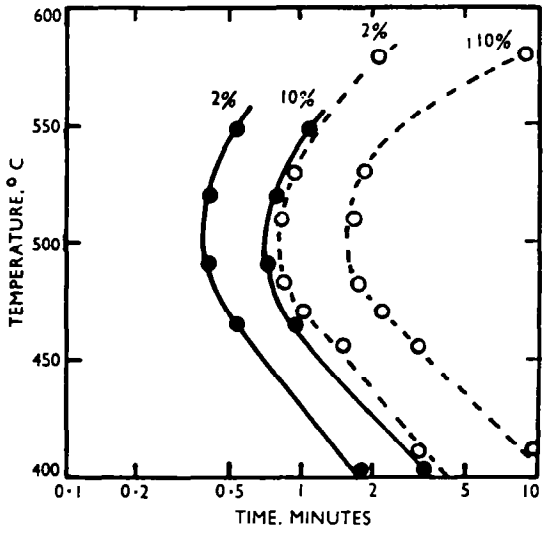
LIVE GRAPH
Click here to view

A - Composition: Cu - 1.99% Be - 0.09% Co
B - Composition: Cu - 1.87% Be - 0.14% Co
C - Composition: Cu - 1.81% Be - 0.20% Co
D - Composition: Cu - 1.77% Be - 0.24% Co
Treatment: Solution treated in the range 760-800°C (1400-1472°F) in a nitrogen atmosphere, then hot quenched into salt baths at suitable temperatures for appropriate times, followed by water quenching



Time-temperature-transformation diagram
At 10% transformation

Composition: Cu - 1.87% Be - 0.14% Co
Treatment: Solution treated in the range 760-800°C (1400-1472°F) in a nitrogen atmosphere, then hot quenched into salt baths at suitable temperatures for appropriate times, followed by water quenching



GRAIN SIZE:
Solid dots = 0.022 mm
Open dots = 0.056 mm

Time-temperature-transformation diagram
The effect of grain size on the TTT curve at 2 and 10% transformation

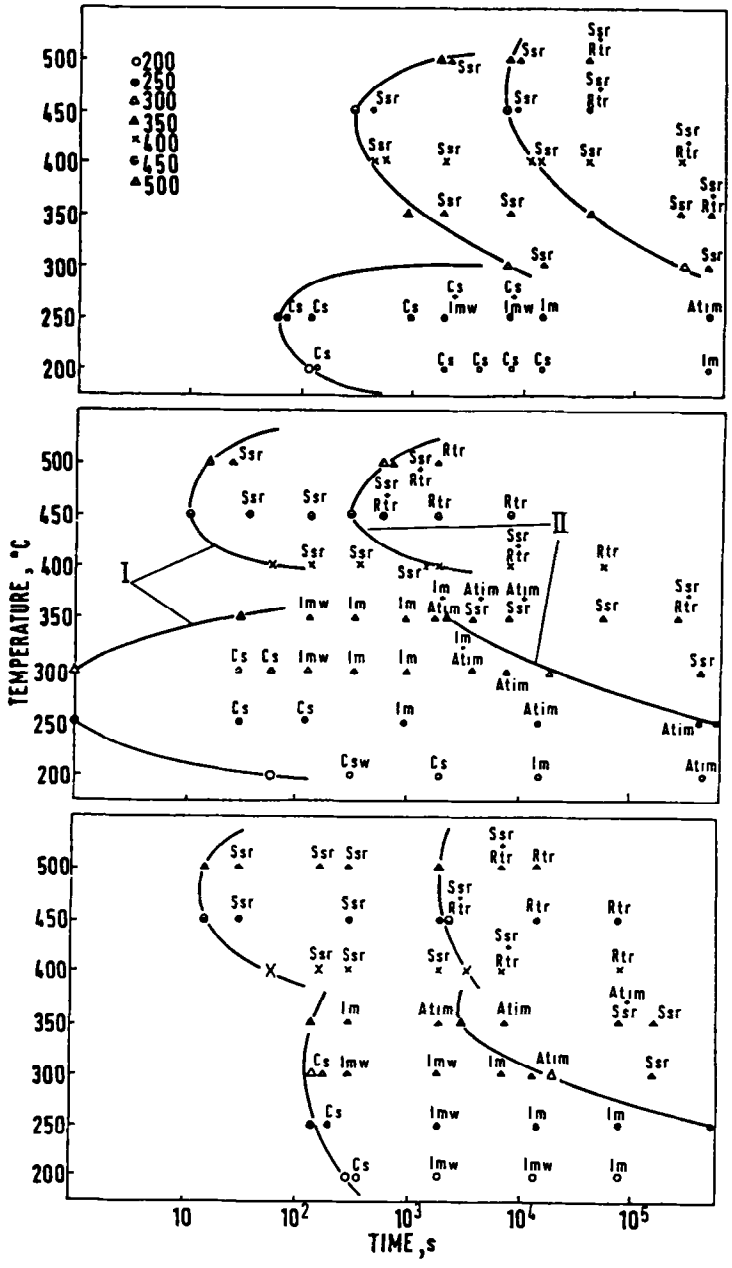
SOURCE: A.R. Entwisle, J.K. Wynn, "Precipitation in Commercial Copper-Beryllium Alloys," Journal of the Institute of Metals, Vol 89, 1960, pp 24-29

Copper-Beryllium Alloys

Composition: Cu - 1.5% Be
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)

Composition: Cu - 2% Be
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)

Composition: Cu - 1.8% Be - 0.2% Co
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)



LIVE GRAPH
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Time-temperature-transformation diagram
Undeformed specimens
Curve I = relationships between aging time and temperature to start hardening
Curve II = and to attain peak hardness

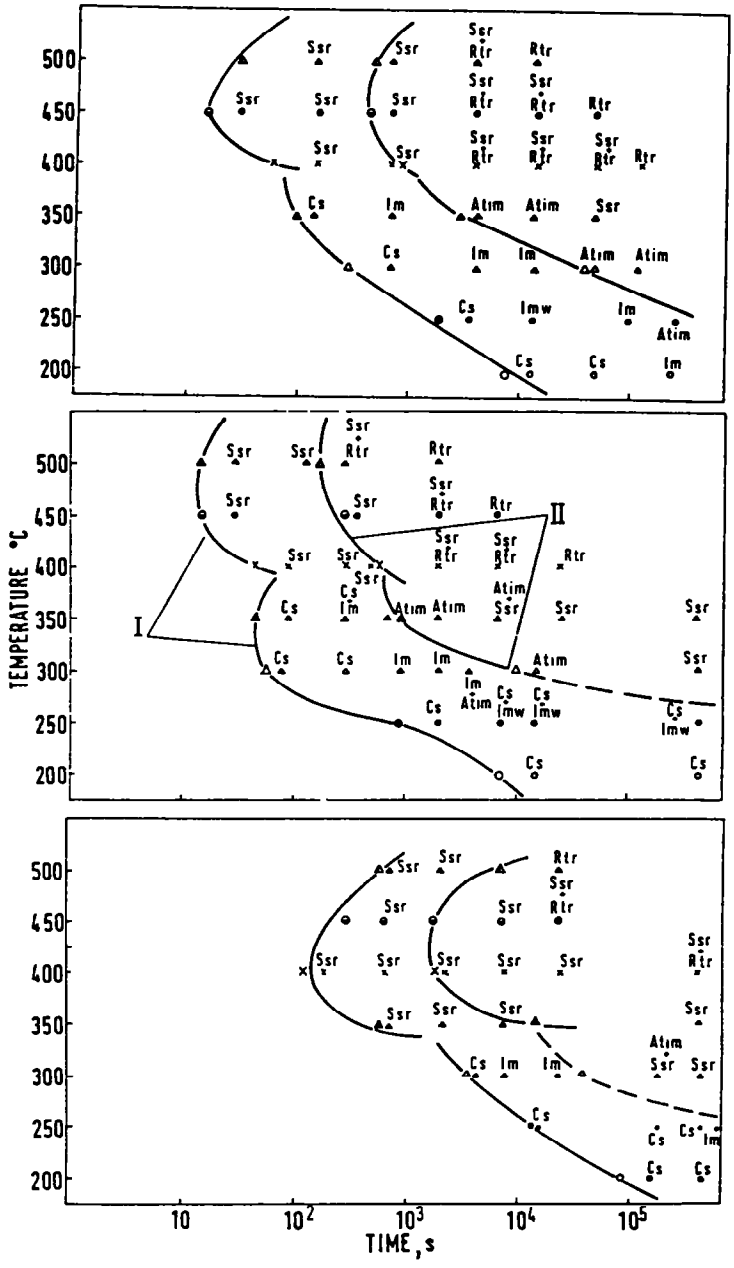
SOURCE: M. Jovanovic, B. Djuric, D. Drobnjak, O. Nesic, R. Kostic, "Aging of Cu-Be Alloys with and without Cobalt Addition," Materials Science and Technology, Vol 2, February 1986, pp 122-128

Copper-Beryllium Alloys

Composition: Cu - 1.5% Be
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)

Composition: Cu - 2% Be
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)

Composition: Cu - 1.8% Be - 0.2% Co
Treatment: Solution treated at 800°C (1472°F) for 20 min under argon and quenched in iced water, then aged from 200-500°C (392-932°F) for 10 to 10^6 s. An oil bath was used for aging at 200 and 250°C (392 and 482°F), and salt mixtures of $NaNO_2$ and $NaNO_3$ for aging over the temperature region from 300 to 500°C (572 to 932°F)



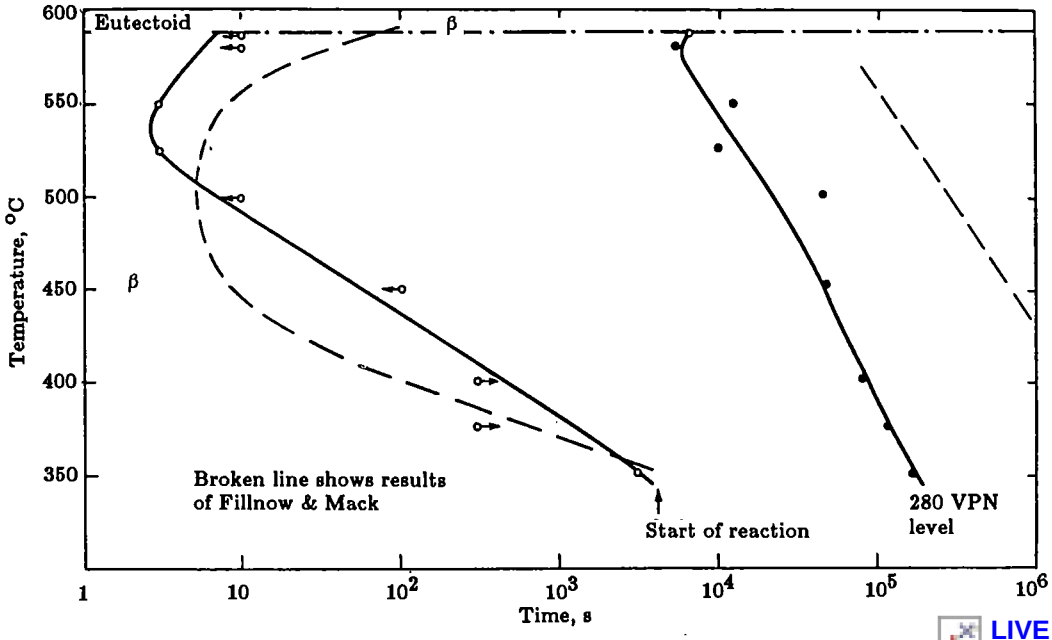
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Deformed specimens
Curve I = relationships between aging time and temperature to start hardening
Curve II = and to attain peak hardness

SOURCE: M. Jovanovic, B. Djuric, D. Drobnjak, O. Nesic, R. Kostic, "Aging of Cu-Be Alloys with and without Cobalt Addition," Materials Science and Technology, Vol 2, February 1986, pp 122-128

Copper-Beryllium Alloys

Composition: Cu - 6.39% Be



LIVE GRAPH Click here to view

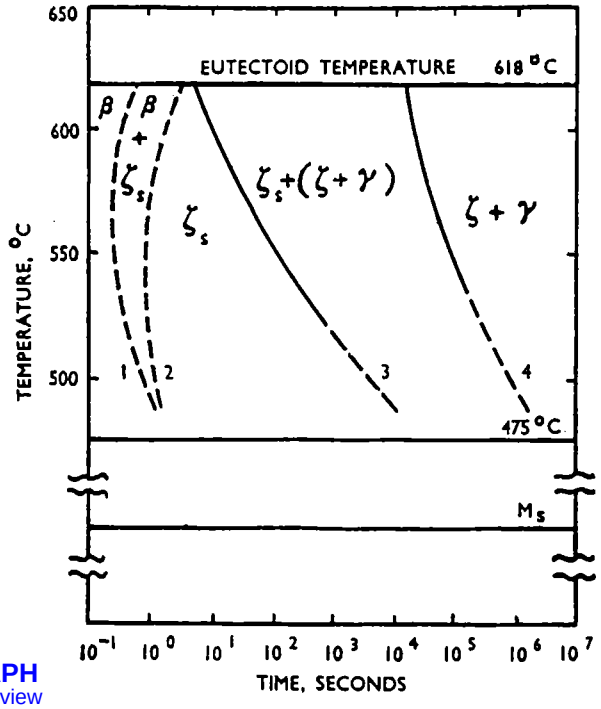
Time-temperature-aging based on hardness

SOURCE: E.R. Petty, H. O'Neill, "Hardness and Structural Transformations in Eutectoid Copper-Aluminium and Copper-Beryllium Alloys," Journal of the Institute of Metals, Vol 89, 1960, pp 281-286

Copper-Gallium Alloy

Composition: Cu - 23.7 at.% Ga

Treatment: Specimens were held at 775°C (1428°F) for 1 h in an air furnace, then transferred to a salt bath for isothermal transformation for the desired length of time, then quenched in water at room temperature or in iced brine



LIVE GRAPH Click here to view

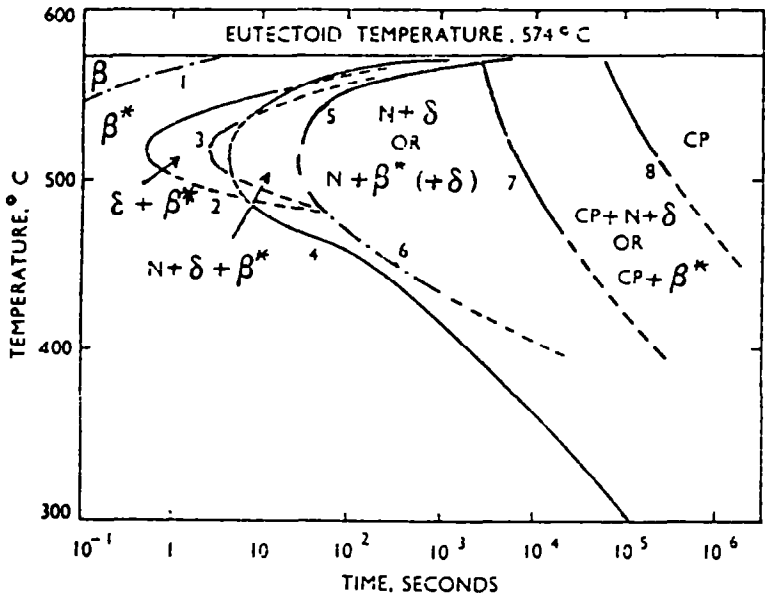
Time-temperature-transformation diagram

SOURCE: C.W. Spencer, D.J. Mack, "Decomposition of the Beta Phase in a Copper-Gallium Eutectoid Alloy," Journal of the Institute of Metals, Vol 84, 1955, pp 461-467

Copper-Indium Alloys

Composition: Cu - 31.36% In

Treatment: Specimens held in an isothermal salt bath of 50:50 potassium nitrate and sodium nitrite for a predetermined period, then quenched into water at 21°C. All specimens were held at 650°C (1202°F) for 2 h before undergoing further heat-treatment, i.e. quenching, isothermal transformation, or continuous cooling



LIVE GRAPH
Click here to view

LEGEND:

β* Cross-hatched β.
δ Pre-eutectoid δ.
N Nodules.
CP Coarse pearlite.
Curve 1 Beginning of cross-hatching of β.†
Curve 2 Beginning of precipitation of pre-eutectoid δ.
Curve 3 End of precipitation of pre-eutectoid δ.
Curve 4 Beginning of formation of nodules.
Curve 5 End of formation of nodules.
Curve 6 (Not an extension of Curve 5) Cross-hatching of β reaches a point where nodules will not grow.
Curve 7 Beginning of formation of coarse pearlite.
Curve 8 End of formation of coarse pearlite.

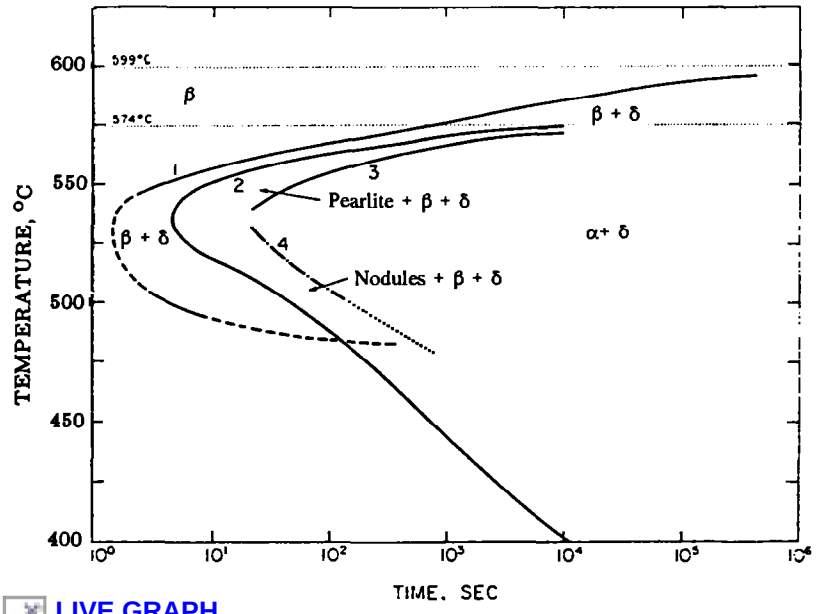
† Since it is not possible completely to retain the β phase to room temperature, this curve indicates the approximate times of transformation at which, after quenching, the cross-hatching of the β becomes appreciably greater.

Time-temperature-transformation diagram

SOURCE: C.W. Spencer, D.J. Mack, "The Copper-Indium Eutectoid at 31.36 wt.% Indium," Jounal of the Institute of Metals, Vol 82, 1953, pp 81-87

Copper-Indium Alloys

Composition: Cu - 32.3% In
Treatment: Homogenized at 626°C (1158°F) for 24 h, then solution annealed at 650°C (1202°F) for 2 h



LIVE GRAPH
Click here to view

LEGEND:

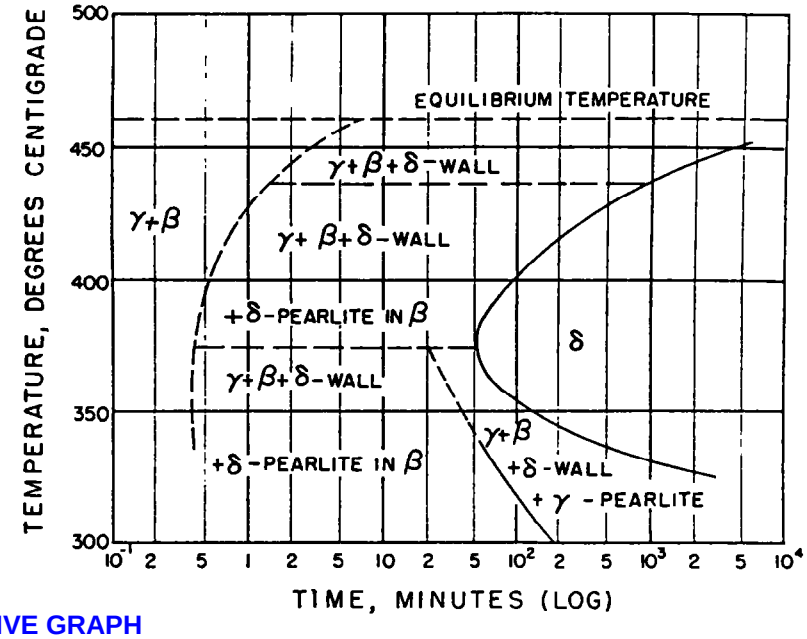
Curve 1: beginning of precipitation of proeutectoid δ.
" 2: beginning of pearlite reaction.
" 3: end of pearlite reaction.
" 4: approximate times at which (α + δ) structure is fully developed throughout areas which have transformed by the low-temperature mechanism of the eutectoid reaction.

Time-temperature-transformation diagram

SOURCE: J.A. Street, H.I. Aaronson, C.W. Spencer, "Formation and Dissolution of Widmanstatten Structures in a Hypereutectoid Copper-Indium Alloy," Journal of the Institute of Metals, Vol 88, 1959, pp 381-384

Copper-Antimony Alloy

Composition: Cu - 30.5% Sb
Treatment: Isothermal transformation studies were carried out in fused-salt media, using the familiar interrupted-quench method. Uniformity of temperature in the salt baths was maintained by continuous stirring with a stainless-steel agitator

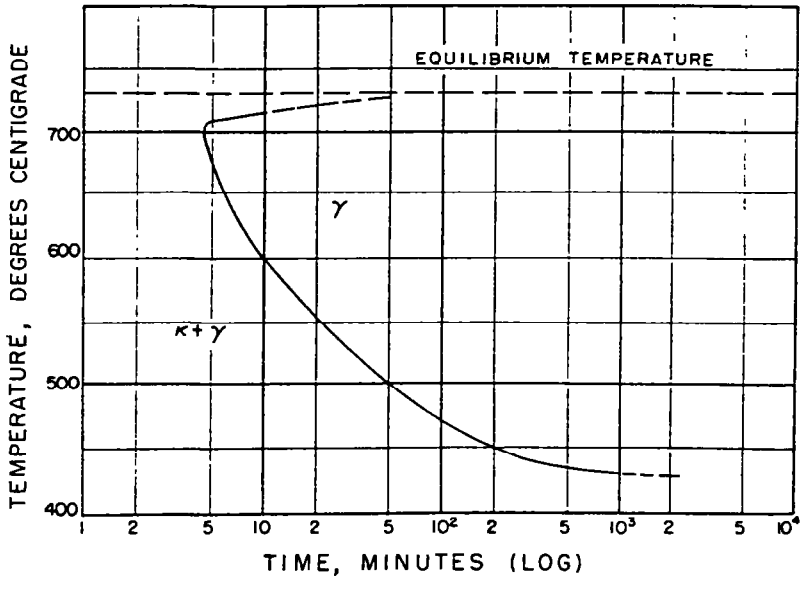


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Copper-Silicon Alloy

Composition: Cu - 8.35% Si
Treatment: Isothermal transformation studies were carried out in fused-salt media, using the familiar interrupted-quench method. Uniformity of temperature in the salt baths was maintained by continuous stirring with a stainless-steel agitator



LIVE GRAPH
Click here to view

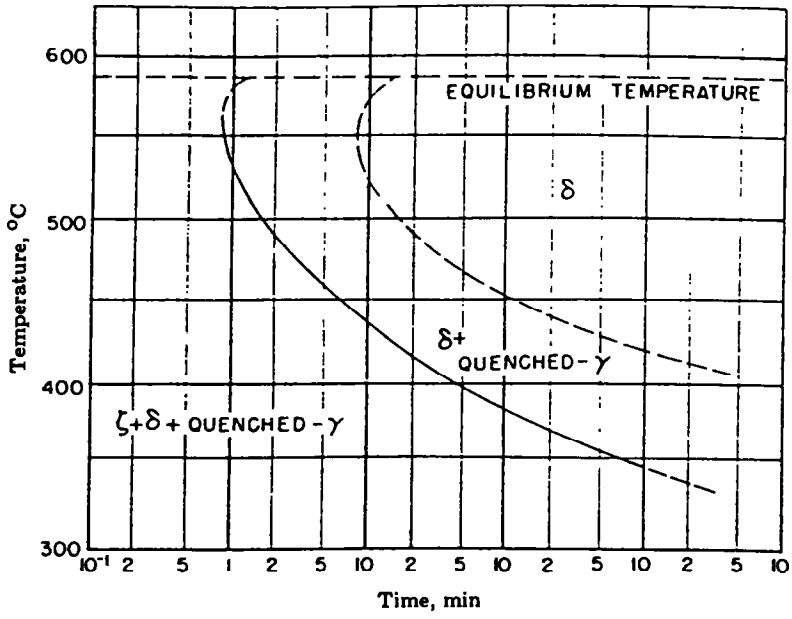
Time-temperature-transformation diagram

SOURCE: R.D. Reiswig, D.J. Mack, "A Study of the Peritectoid Transformation," Trans. AIME, Vol 215, April 1959, pp 301-307

Copper-Tin Alloys

Composition: Cu - 32.3% Sn

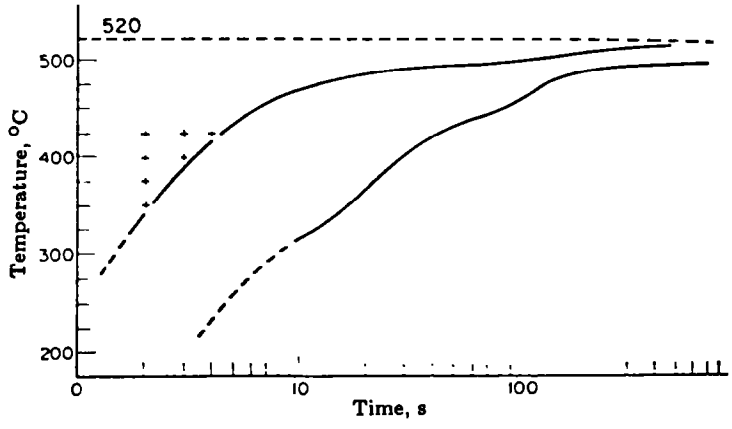
Treatment: Isothermal transformation studies were carried out in fused-salt media, using the familiar interrupted-quench method. Uniformity of temperature in the salt baths was maintained by continuous stirring with a stainless-steel agitator



Time-temperature-transformation diagram

SOURCE: R.D. Reiswig, D.J. Mack, "A Study of the Peritectoid Transformation," Trans. AIME, Vol 215, April 1959, pp 301-307

Composition: Cu - 16.5 at.% Sn

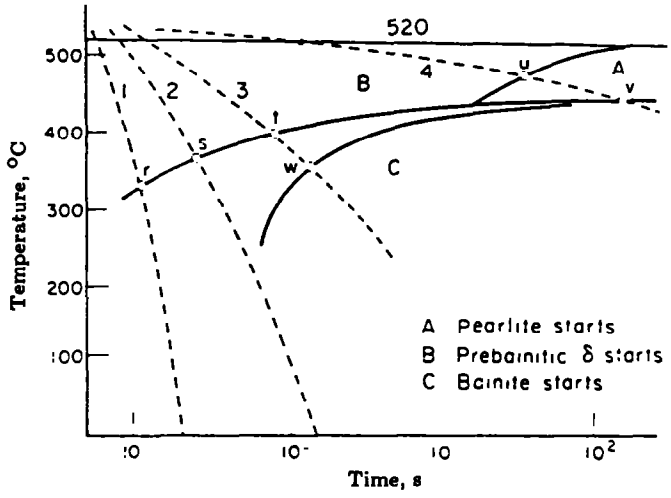


Time-temperature-transformation diagram

SOURCE: M. de Bondt, A. Deruyttere, "Pearlite and Bainite Formation in a Cu-16.5 at.% Sn Alloy," Acta Metallurgica, Vol 15, June 1967, pp 993-1005

Copper-Tin Alloys

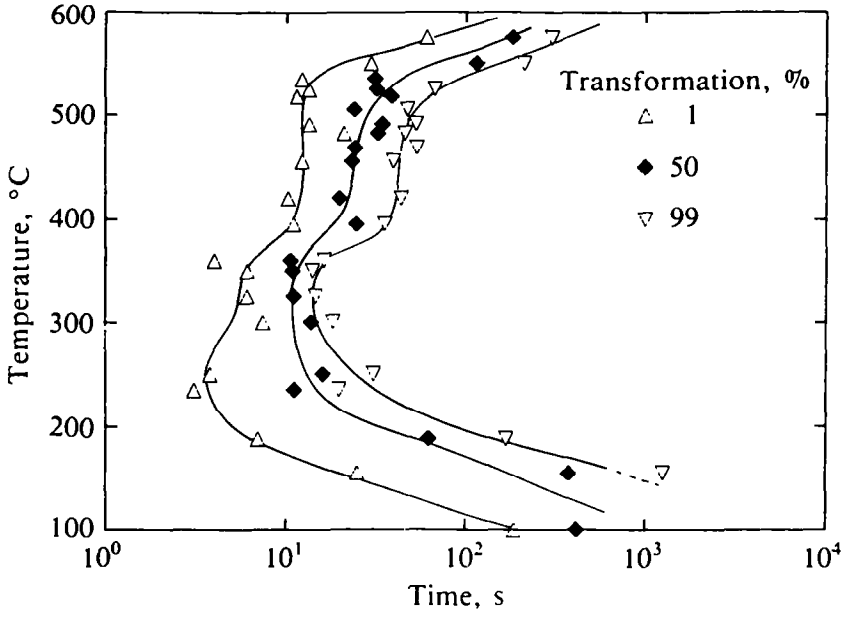
Composition: Cu - 16.5 at.% Sn



Continuous-cooling-transformation diagram

SOURCE: M. de Bondt, A. Deruyttere, "Pearlite and Bainite Formation in a Cu-16.5 at.% Sn Alloy," Acta Metallurgica, Vol 15, June 1967, pp 993-1005

Composition: Cu - 23.6% Sn - 0.02% Pb - 0.01% Fe - 0.01% Ni - 0.02% Zn - <0.01% P
Treatment: Isothermal heat treatments were carried out using a betatizing temperature of 700°C (1292°F) and molten metal baths with temperatures between 145 and 550°C (296 and 1022°F). Specimens were finally quenched into iced brine



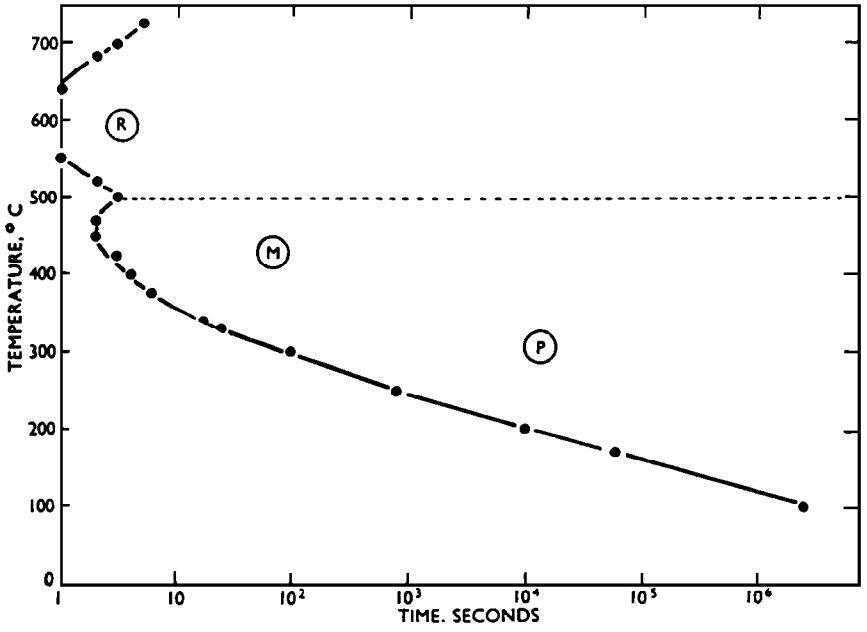
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Statistically derived diagram for the decomposition of the beta phase

SOURCE: M.B. Cortie, C.E. Mavrocordatos, "The Decomposition of the Beta Phase in the Copper-Tin System," Met. Trans. A., Volume 22A, January 1991, pp 11-18

Copper-Zinc Alloys

Composition: Cu - 40.5% Zn
Treatment: Specimens were held within 5° at 830°C (1526°F) for 2 min in a vertical furnace containing an atmosphere of nitrogen, 3% hydrogen, and zinc vapor, then quenched into 10% aqueous sodium hydroxide at 0°C. The quenched structure was entirely metastable beta-prime phase with a grain size of 1-2mm. Subsequent heat-treatment in the range 150-350°C (302-662°F) was in a nitrate-nitrite bath, and above 350°C (662°F) in a lead bath controlled to within 3°C



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

The broken lines indicate the onset of grain-boundary precipitation

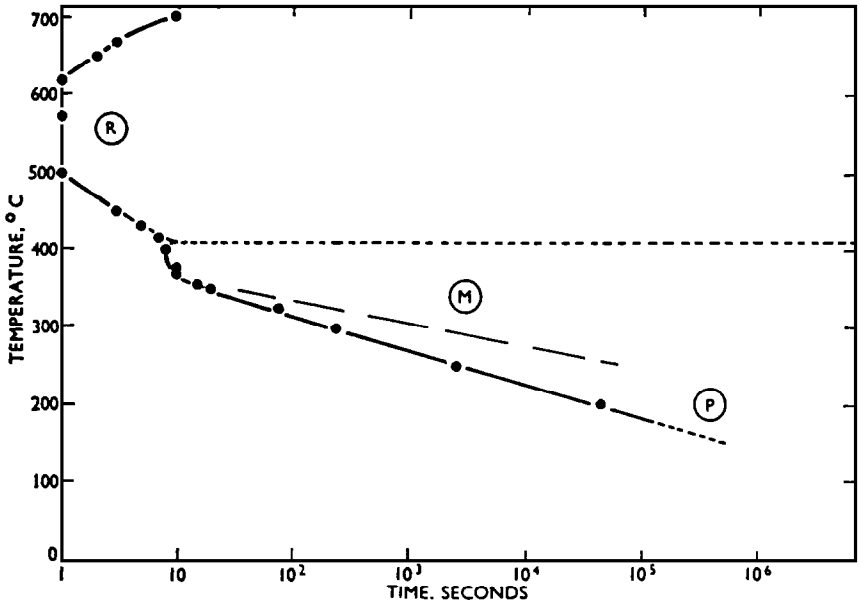
R = alpha rods
M = $alpha_1$ plates + alpha rods
P = $alpha_1$ plates

SOURCE: P.E.J. Flewitt, J.M. Towner, "The Decomposition of Beta Prime in Copper-Zinc Alloys," Journal of the Institute of Metals, Vol 95, 1967, pp 273-280

Copper-Zinc Alloys

Composition: Cu - 41.6% Zn

Treatment: Specimens were held within 5° at 830°C (1526°F) for 2 min in a vertical furnace containing an atmosphere of nitrogen, 3% hydrogen, and zinc vapor, then quenched into 10% aqueous sodium hydroxide at 0°C. The quenched structure was entirely metastable beta-prime phase with a grain size of 1-2mm. Subsequent heat-treatment in the range 150-350°C (302-662°F) was in a nitrate-nitrite bath, and above 350°C (662°F) in a lead bath controlled to within 3°C



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

The broken lines indicate the onset of grain-boundary precipitation

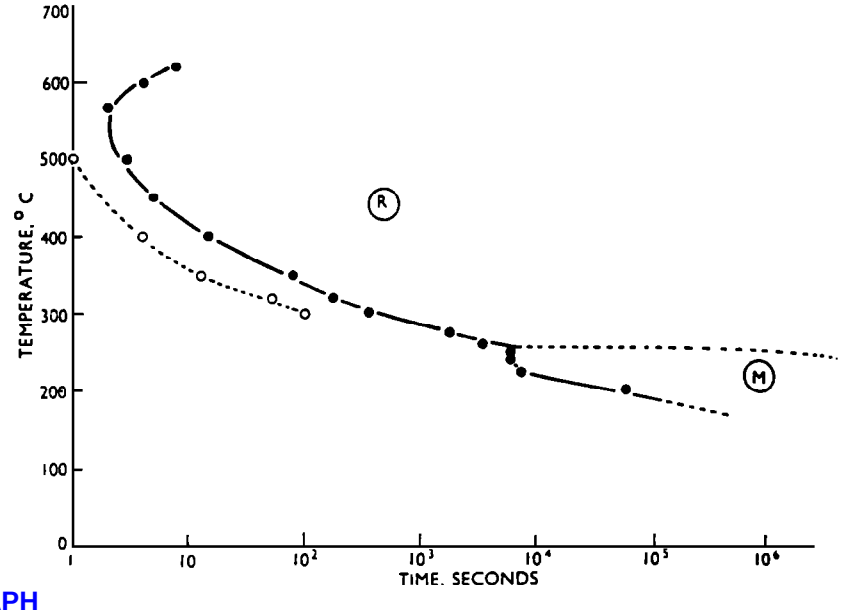
R = alpha rods
M = $alpha_1$ plates + alpha rods
P = $alpha_1$ plates

SOURCE: P.E.J. Flewitt, J.M. Towner, "The Decomposition of Beta Prime in Copper-Zinc Alloys," Journal of the Institute of Metals, Vol 95, 1967, pp 273-280

Copper-Zinc Alloys

Composition: Cu - 43.0% Zn

Treatment: Specimens were held within 5° at 830°C (1526°F) for 2 min in a vertical furnace containing an atmosphere of nitrogen, 3% hydrogen, and zinc vapor, then quenched into 10% aqueous sodium hydroxide at 0°C. The quenched structure was entirely metastable beta-prime phase with a grain size of 1-2mm. Subsequent heat-treatment in the range 150-350°C (302-662°F) was in a nitrate-nitrite bath, and above 350°C (662°F) in a lead bath controlled to within 3°C



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

The broken lines indicate the onset of grain-boundary precipitation

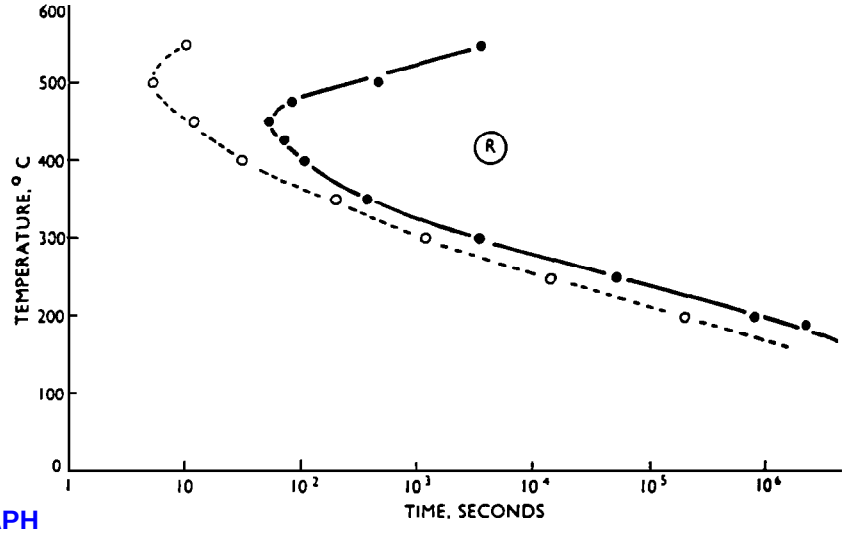
R = alpha rods
M = $alpha_1$ plates + alpha rods

SOURCE: P.E.J. Flewitt, J.M. Towner, "The Decomposition of Beta Prime in Copper-Zinc Alloys," Journal of the Institute of Metals, Vol 95, 1967, pp 273-280

Copper-Zinc Alloys

Composition: Cu - 44.1% Zn

Treatment: Specimens were held within 5° at 830°C (1526°F) for 2 min in a vertical furnace containing an atmosphere of nitrogen, 3% hydrogen, and zinc vapor, then quenched into 10% aqueous sodium hydroxide at 0°C. The quenched structure was entirely metastable beta-prime phase with a grain size of 1-2mm. Subsequent heat-treatment in the range 150-350°C (302-662°F) was in a nitrate-nitrite bath, and above 350°C (662°F) in a lead bath controlled to within 3°C



LIVE GRAPH
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Time-temperature-transformation diagram

The broken lines indicate the onset of grain-boundary precipitation

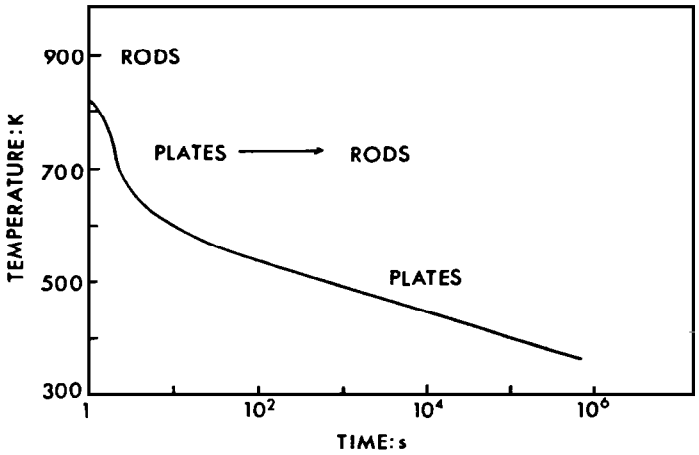
R = alpha rods
M = $alpha_1$ plates + alpha rods

SOURCE: P.E.J. Flewitt, J.M. Towner, "The Decomposition of Beta Prime in Copper-Zinc Alloys," Journal of the Institute of Metals, Vol 95, 1967, pp 273-280

Copper-Zinc Alloys

Composition: Cu - 39.8% Zn

Treatment: Solution treated at 800°C (1472°F) for 2 min in an argon atmosphere furnace and quenched into iced brine. Subsequent isothermal heat treatments were carried out in nitrite-nitrate salt baths controlled to within 1.5°

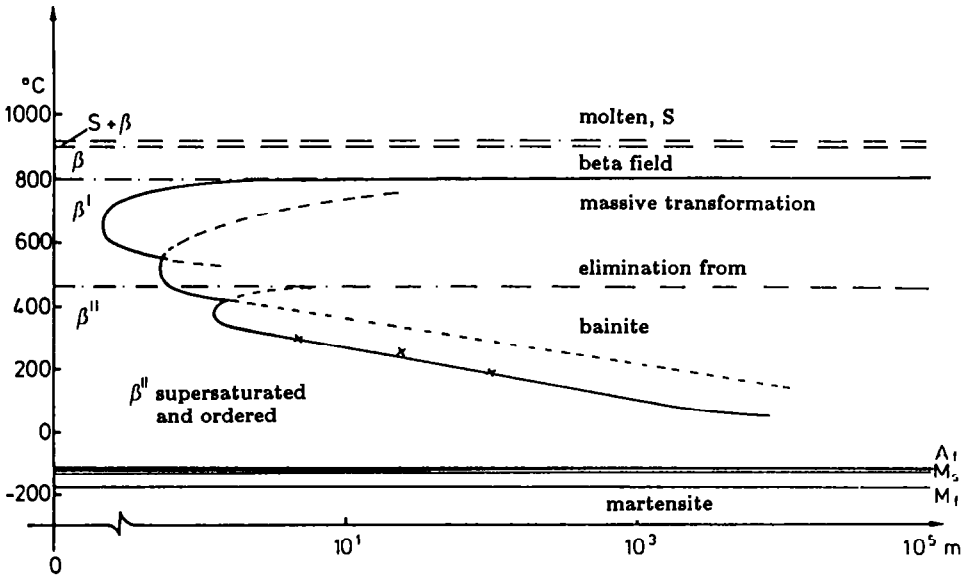


LIVE GRAPH
Click here to view

Time-temperature-aging

SOURCE: P. Doig, P.E.J. Flewitt, "Solute Redistributions Associated with Nucleation and Growth of Alpha$_1$ Plates in Cu-Zn and Au-Cu-Zn Alloys," Metal Science, Vol 17, December 1983, pp 601-608

Composition: Cu - 39.5% Zn



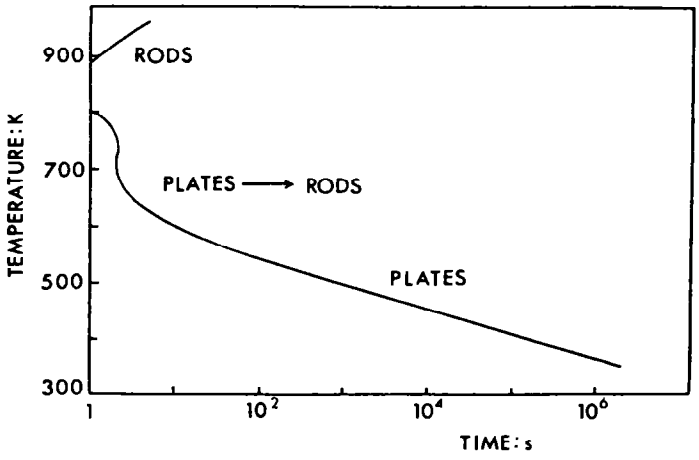
Time-temperature-transformation diagram
Beta phase transformation

LIVE GRAPH
Click here to view

SOURCE: Erhard Hornbogen, "Legierungen mit Formgedachtnis," ("Shape Memory Alloys"), Praktische Metallographie, Vol 26, 1989, pp 279-294

Copper-Gold-Zinc Alloys

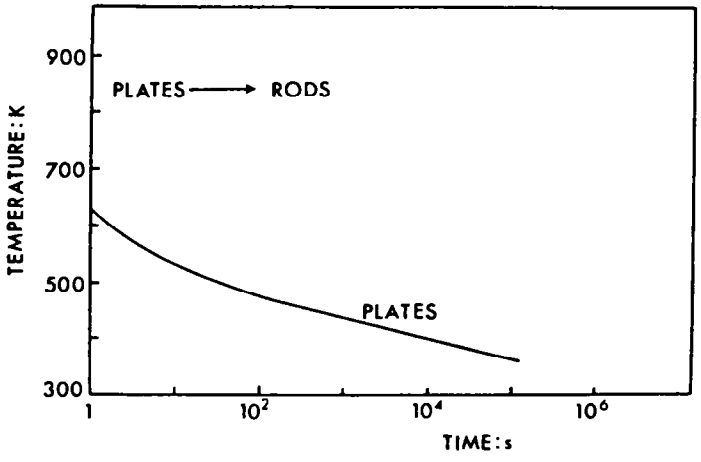
Composition: Cu - 39.9% Zn - 4.2% Au
Treatment: Solution treated at 800°C (1472°F) for 2 min in an argon atmosphere furnace and quenched into iced brine. Subsequent isothermal heat treatments were carried out in nitrite-nitrate salt baths controlled to within 1.5°



LIVE GRAPH
Click here to view

Time-temperature-aging

Composition: Cu - 40.1% Zn - 9.3% Au
Treatment: Solution treated at 800°C (1472°F) for 2 min in an argon atmosphere furnace and quenched into iced brine. Subsequent isothermal heat treatments were carried out in nitrite-nitrate salt baths controlled to within 1.5°



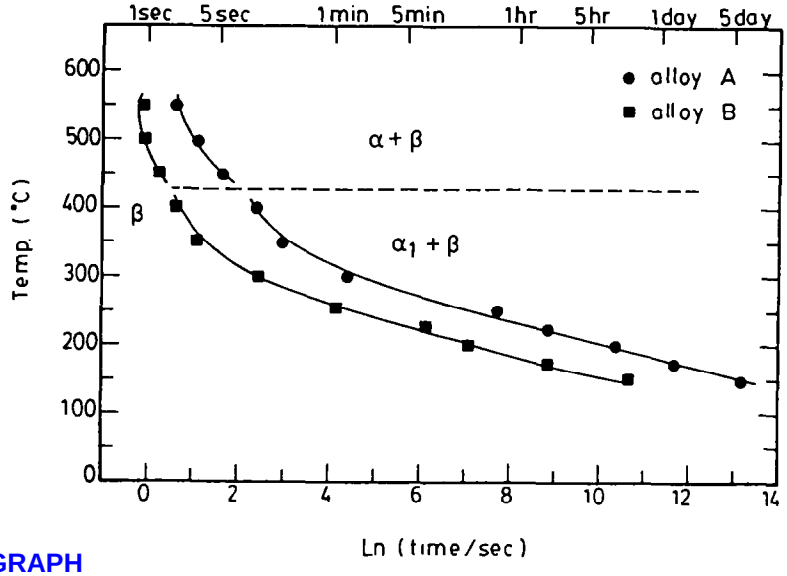
LIVE GRAPH
Click here to view

Time-temperature-aging

SOURCE: P. Doig, P.E.J. Flewitt, "Solute Redistributions Associated with Nucleation and Growth of Alpha$_1$ Plates in Cu-Zn and Au-Cu-Zn Alloys," Metal Science, Vol 17, December 1983, pp 601-608

Copper-Zinc-Aluminum Alloys

Alloy A Composition: Cu - 27.4% Zn - 3.72% Al
Alloy B Composition: Cu - 28.2% Zn - 3.14% Al
Treatment: Specimens were directly quenched into water within 3° at 20°C (68°F) after solution treatment, then immediately up-quenched into an oil bath at 100°C (212°F) for 10 min and quenched again in water within 3° at 20°C (68°F). Isothermally aged at selected temperatures in the range of 150 to 600°C (302 to 1112°F) for various periods of aging



LIVE GRAPH
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Time-temperature-transformation diagram
Start of transformation of beta to alpha or alpha$_1$

SOURCE: S.S. Leu, C.T. Hu, "The Aging Effect on Cu-Zn-Al Shape Memory Alloys with Low Contents of Aluminum," Met. Trans. A, Vol 22A, January 1991, pp 25-33

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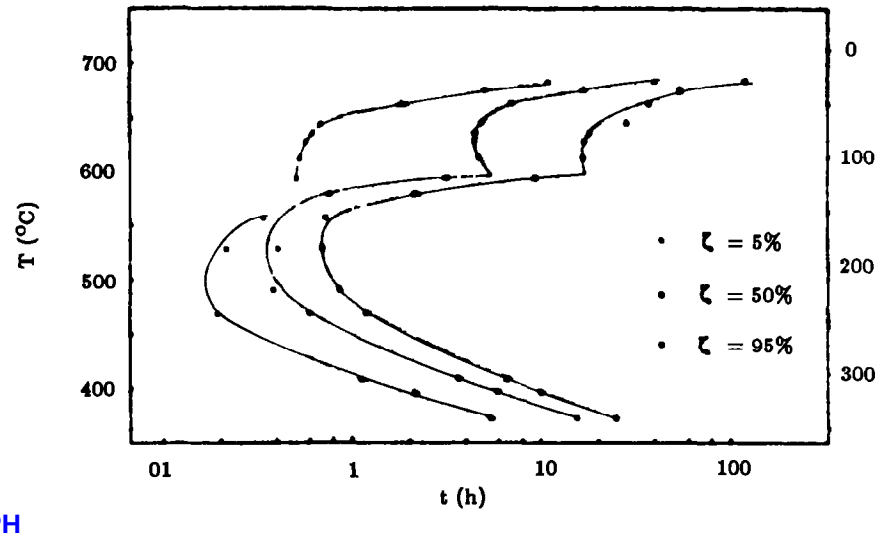
Gold-Base Alloys

Au-Co Alloy

Composition: Au - 4.8 at.% Co



LIVE GRAPH
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Time-temperature-precipitation diagram
Curves show the degree of precipitation at 5%, 50% and 95%

Zeta = fraction of solute precipitate

SOURCE: F. Schlawne, H. Alexander, "A Study of the Precipitation Kinetics of a Gold-Cobalt-Alloy," Z. Metallkd., Vol 72, No. 2, February 1981, pp 105-108

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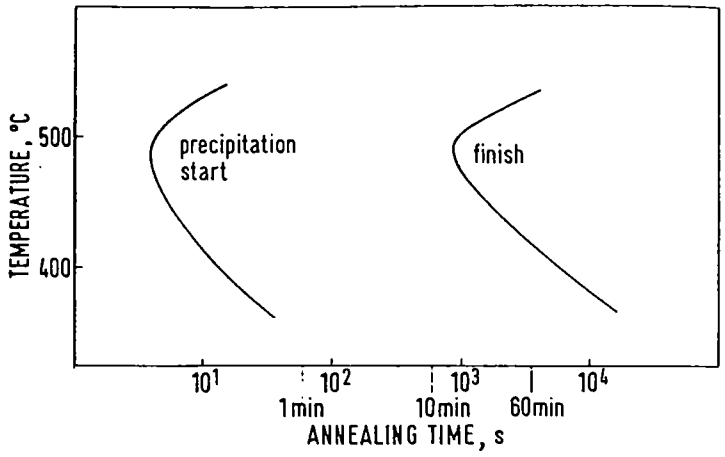
Magnesium-Base Alloys

Magnesium-Manganese Alloy

Composition: Mg - 1.58% Mn
Treatment: Samples were aged at temperatures between 390 and 530°C (734 and 986°F) in a salt bath furnace and subsequently water quenched. The bath temperature was controlled within 2°



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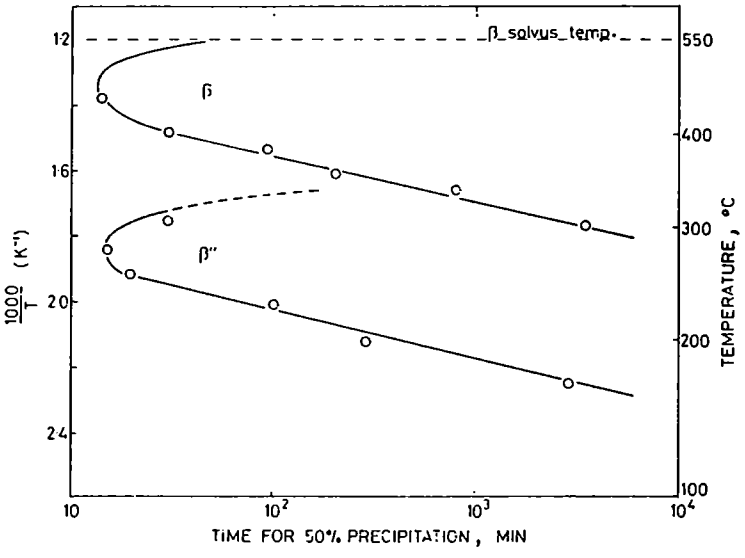
Time-temperature-precipitation diagram
The precipitation of Mn is a rapid transformation, starting after only 7 s and being complete after 10 min aging at 500°C (932°F)

SOURCE: P.M. Skjerpe, C.J. Simensen, "Precipitation in Mg-Mn Alloys," Metal Science, Vol 17, August 1983, pp 403-407

Magnesium-Thorium Alloy

Composition: Mg - 3.1% Th
Treatment: Solution treatment consisted of heating the alloy at 575°C (1065°F) for 1 h and quenching into water at 20°C (68°F)



LIVE GRAPH
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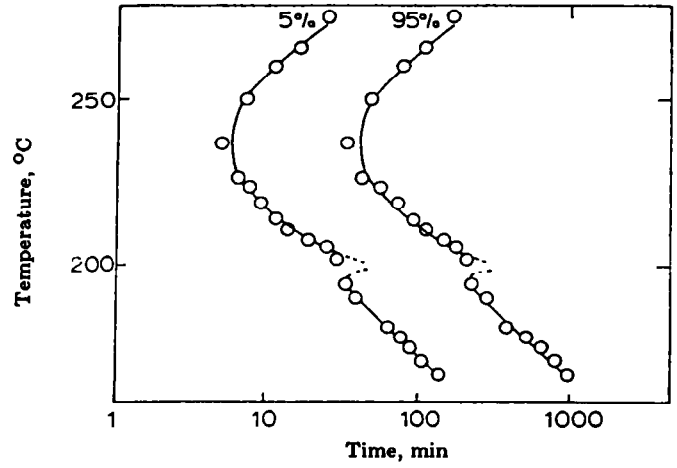
Time-temperature-precipitation on aging
Precipitation of beta double prime Mg_3Th and beta $Mg_{23}Th_6$

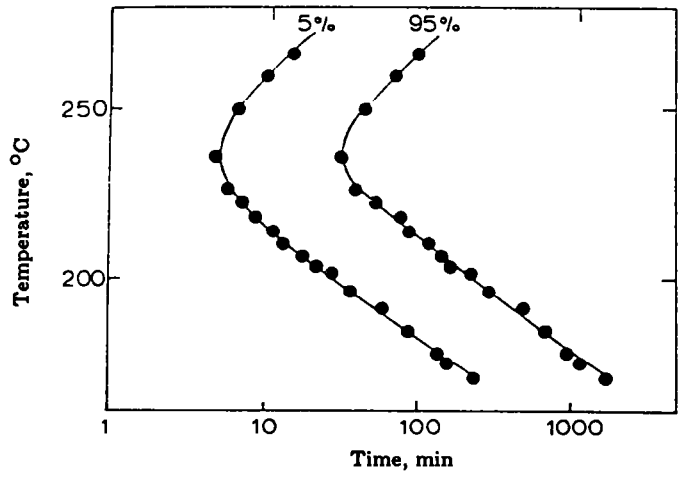
SOURCE: B. Noble, A. Crook, "A Kinetic and Electron-Microscope Study of Precipitation in Magnesium-Thorium Alloys," Journal of the Institute of Metals, Vol 98, 1970, pp 375-380

Magnesium-Zinc Alloys

Composition: Mg - 52% Zn and Mg - 55% Zn

Treatment: Specimens were heat treated at 335°C (635°F) to convert them to Mg_7Zn_3 throughout, and quenched into iced water to retain this structure. A lead-tin eutectic bath was used for isothermal transformations above 200°C (392°F) and a silicone oil bath for transformations below this temperature. The bath temperature was controlled to within 5°





LIVE GRAPH
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Time-temperature-precipitation on aging
o = decomposition of Mg_7Zn_3 in the presence of excess magnesium solid solution
• = decomposition of Mg_7Zn_3 in the presence of excess MgZn

SOURCE: W.J. Kitchingman, I.M. Vesey, "The Mechanism and Kinetics of Transformation of the Eutectoidal Decomposition of Mg_7Zn_3," Journal of the Institute of Metals, Vol 98, 1970, pp 52-54

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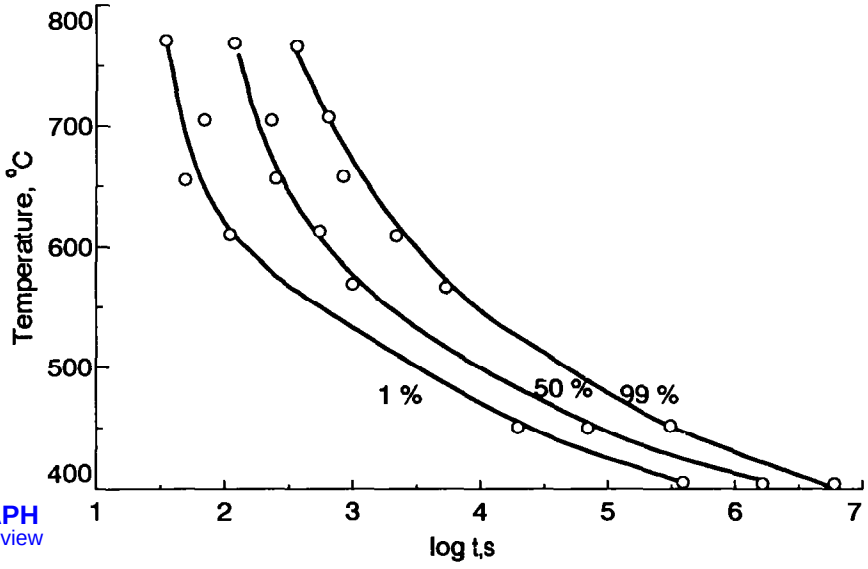
Nickel-Base Alloys

Nickel-Indium Alloys

Composition: Ni - 5.52 at.% In

Treatment: Aging treatments were carried out in a vertical tube furnace with a tin bath placed in it. The temperature of the bath was maintained constant within 5° by stabilized voltage supply. After isothermal arrests for definite time intervals, the specimens were quenched into cold water



LIVE GRAPH
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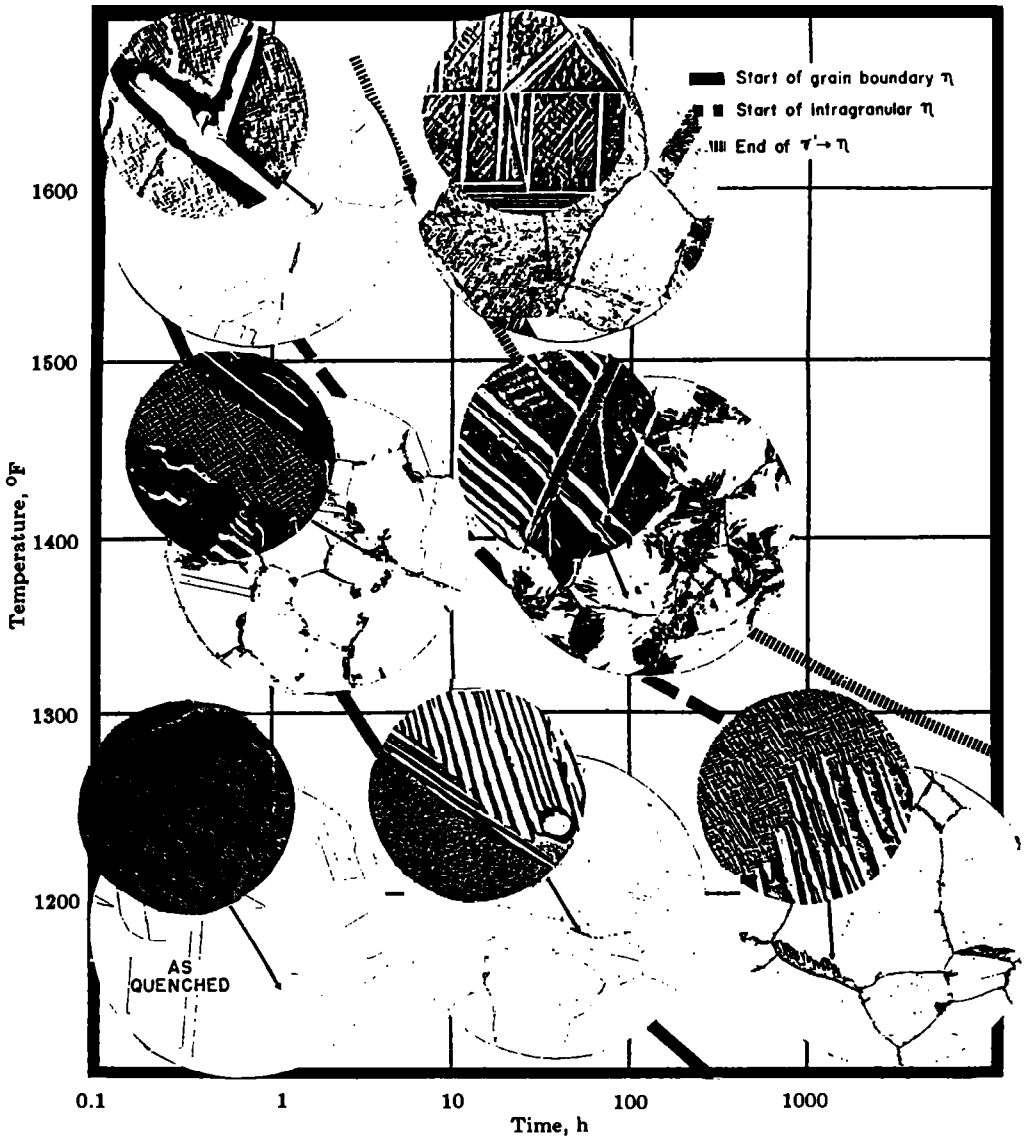
TTT diagram
Showing the time of reaching 1%, 50% and 99% of volume transformation as a function of the temperature of aging

SOURCE: S. Budurov, V. Bojinov, Kr. Russew, "On the Volume Transformation Kinetics of Cellular Precipitation in f.c.c. Nickel-Indium Alloys," Crystal Research and Technology, Vol 13, No. 4, 1978, pp 435-440

Nickel-Titanium Alloys

Composition: Ni - 12.2 at.% Ti - <0.02 at.% Al - <10 ppm B - 0.02 wt.% Si - 0.03 wt.% Fe - 0.01-0.02 wt.% C - <0.01 wt.% Co - <0.005 wt.% Mn - <0.001 wt.% Mg - <0.001 wt.% Cu
Treatment: Solution treated at 1204°C (2200°F) for 2 h in tank argon, water quenched, and aged isothermally at 649 to 871°C (1200 to 1600°F) for times up to 1000 h



Time-temperature-precipitation diagram

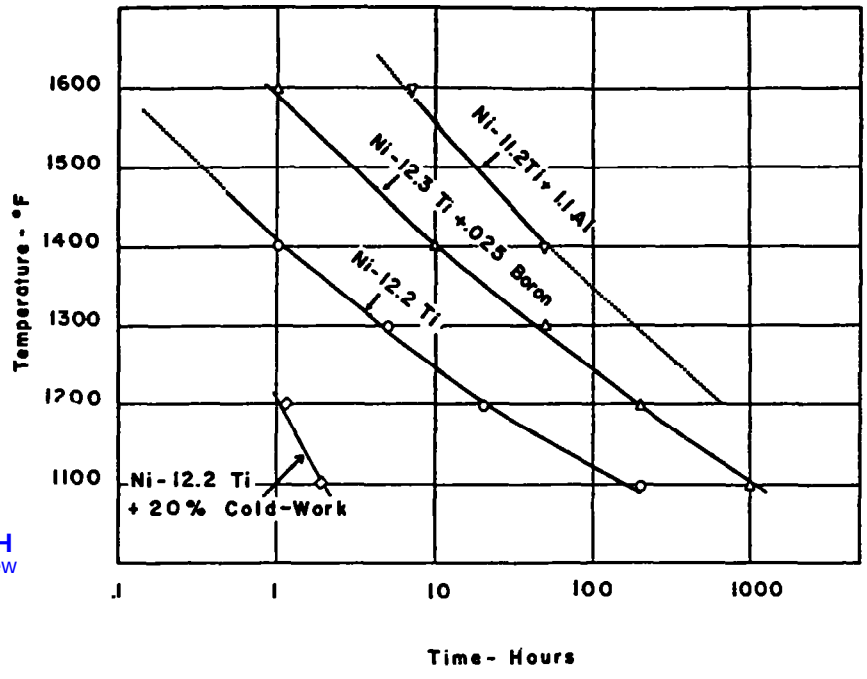
Electron and optical micrographs superimposed on TTT diagram
Aging times are marked on each set of micrographs

SOURCE: J.R. Mihalisin, R.F. Decker, "Phase Transformations in Nickel-Rich Nickel-Titanium-Aluminum Alloys," Trans. AIME, Vol 218, June 1960, pp 507-515

Nickel-Titanium Alloys

Composition: Ni - 12.2 at.% Ti - <0.02 at.% Al - <10 ppm B - 0.02 wt.% Si - 0.03 wt.% Fe - 0.01-0.02 wt.% C - <0.01 wt.% Co - <0.005 wt.% Mn - <0.001 wt.% Mg - <0.001 wt.% Cu

Treatment: Solution treated at 1204°C (2200°F) for 2 h in tank argon, water quenched, and aged isothermally at 649 to 871°C (1200 to 1600°F) for times up to 1000 h



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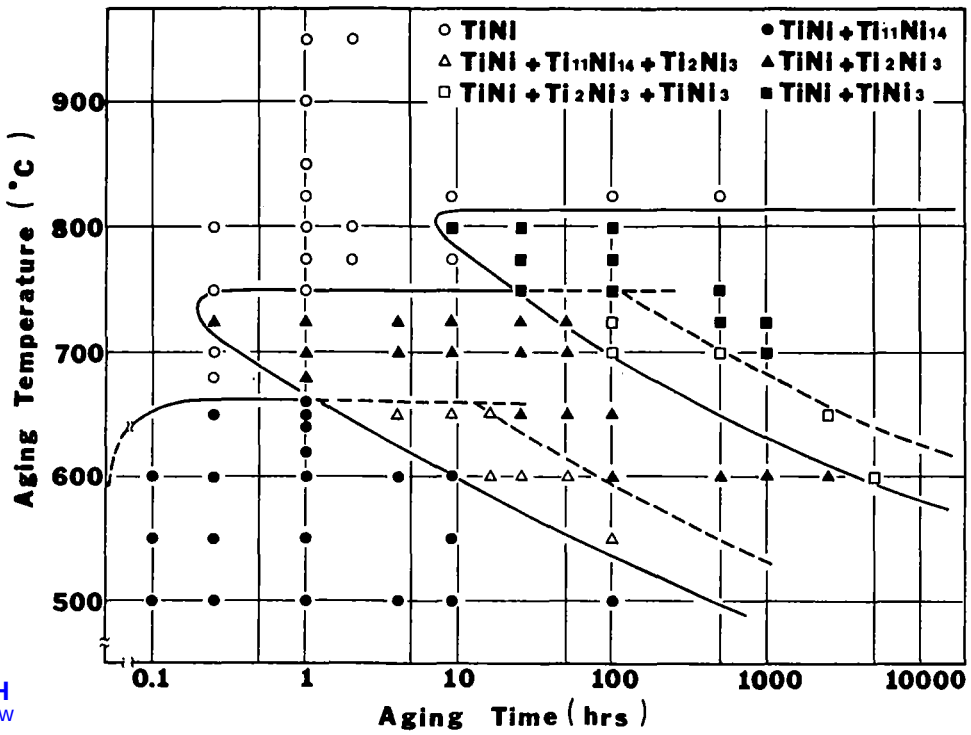
Time-temperature-precipitation diagram

Aluminum and boron additions and cold work had the effect of changing the rates of the transformations, but not the transformations themselves

SOURCE: J.R. Mihalisin, R.F. Decker, "Phase Transformations in Nickel-Rich Nickel-Titanium-Aluminum Alloys," Trans. AIME, Vol 218, June 1960, pp 507-515

Nickel-Titanium Alloys

Composition: Ni - 48 at.% Ti
Treatment: Specimens were annealed at 1000°C (1832°F) for 1 h in evacuated quartz capsules, quenched into ice water without breaking the capsules, and aged under several conditions



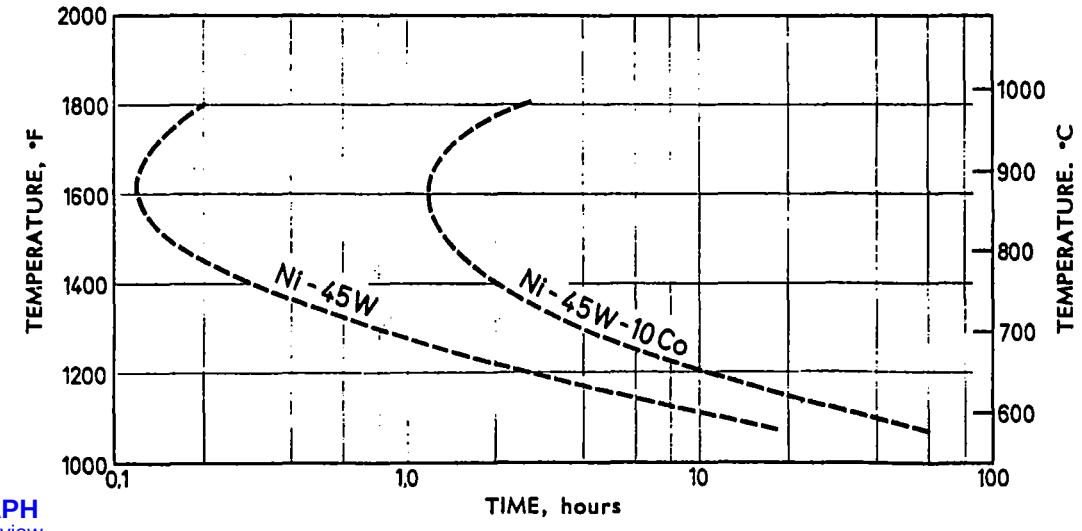
LIVE GRAPH
Click here to view

Time-temperature-aging diagram

SOURCE: M. Nishida, C.M. Wayman, T. Honma, "Precipitation Processes in Near-Equiatomic TiNi Shape Memory Alloys," Met. Trans. A, Vol 17A, September 1986, pp 1505-1515

Nickel-Tungsten Alloys

Composition: Ni - 45% W
Composition: Ni - 45% W - 10% Co
Treatment: Annealed and cold worked



LIVE GRAPH
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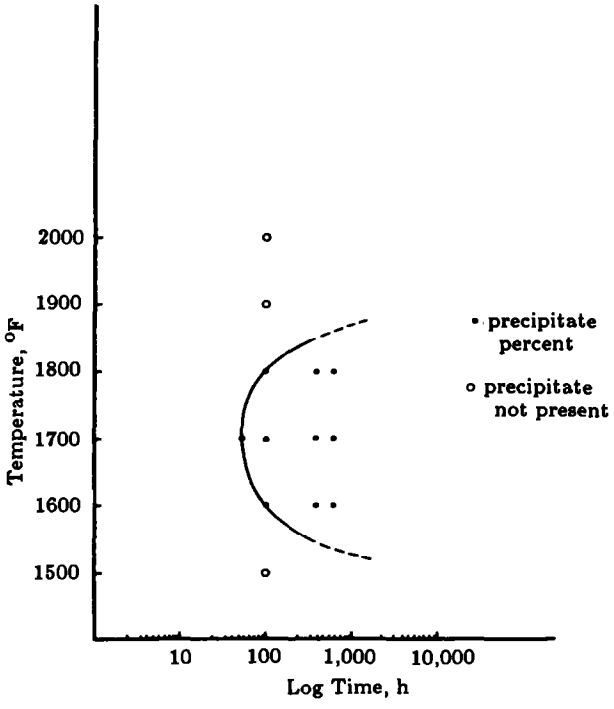
TTT diagram
Initiation of precipitation upon aging

SOURCE: F.F. Schmidt, D.N. Williams, H.R. Ogden, "Effects of Cobalt on Nickel-Tungsten Alloys," Cobalt, No. 45, Development Association, Slough UK, 1969, pp 171-176

Nickel-Aluminum-Molybdenum Alloys

Composition: Ni - 6.8% Al - 14.4% Mo - 6.1% W - 0.04% C
Treatment: Materials were prepared from rapidly solidified powders. Stainless steel cans were filled with powder, sealed, outgassed, and extruded at a temperature just below the gamma prime solvus. Slices 1 to 2 mm thick were cut from the as-extruded bars and sealed in quartz in vacuum. Specimens were cycled twice above and then below the gamma prime solvus before being exposed at 3092°C (1700°F) for 500 h and air cooled



LIVE GRAPH
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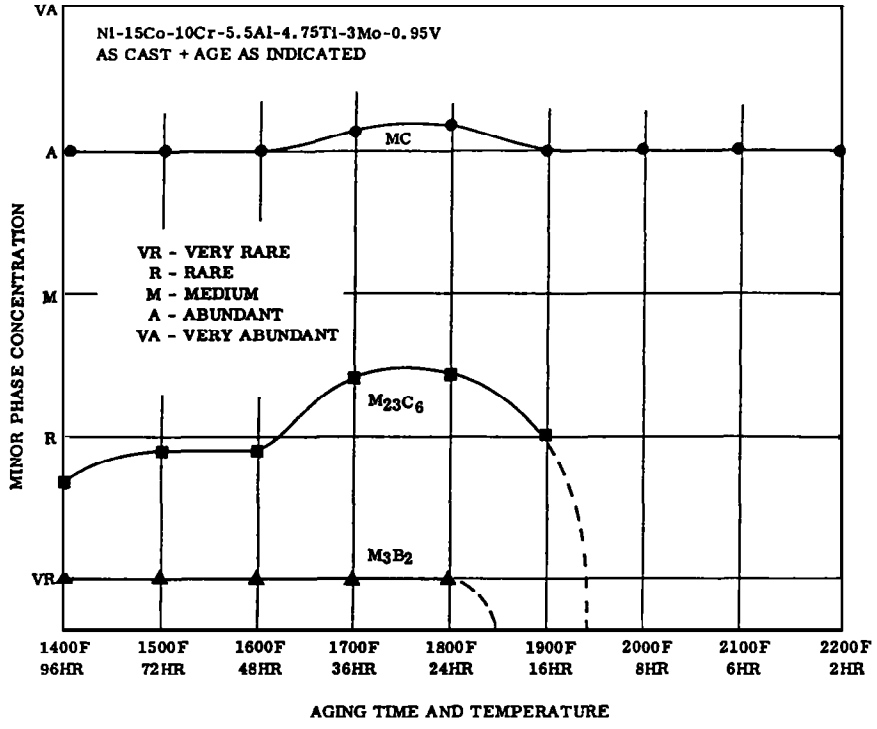
Time-temperature-precipitation diagram
Needle-like phase from a rapidly solidified Ni-Al-Mo alloy

SOURCE: K.A. Williams, D.B. Miracle, H.A. Lipsitt, "Partitioning and Precipitation of TCP Phases in Rapidly Solidified Alloys," Rapid Solidification Processing. Principles and Technologies, II, R. Mehrabian, B.H. Kear, M. Cohen, Eds., Claitor's Publications Division, Baton Rouge, 1980, pp 129-134

IN-100

Composition: Ni - 0.17% C - 10.30% Cr - 14.30% Co - 2.89% Mo - 4.73% Ti - 5.79% Al - 0.016% B - 0.076% Zr - 0.93% V
Treatment: Solution treated as cast, aged at 760 to 1204°C (1400 to 2200°) for varying times

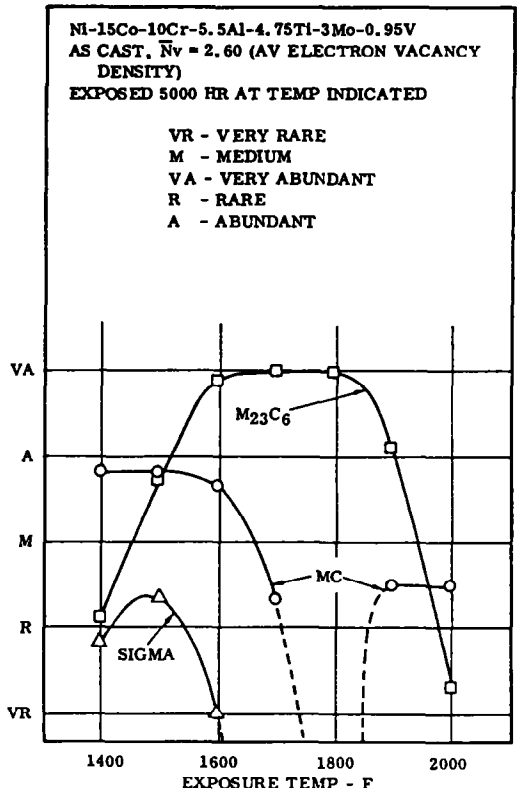


Minor phase concentration as a function of aging temperature

SOURCE: H.E. Collins, R.J. Quigg, "Carbide and Intermetallic Instability in Advanced Nickel-Base Superalloys," Trans. ASM, Vol 61, 1968, pp 139-148

IN-100

Composition: Ni - 0.17% C - 10.30% Cr - 15.00% Co - 2.93% Mo - 4.68% Ti - 5.53% Al - 0.016% B - 0.082% Zr - 0.94% V
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

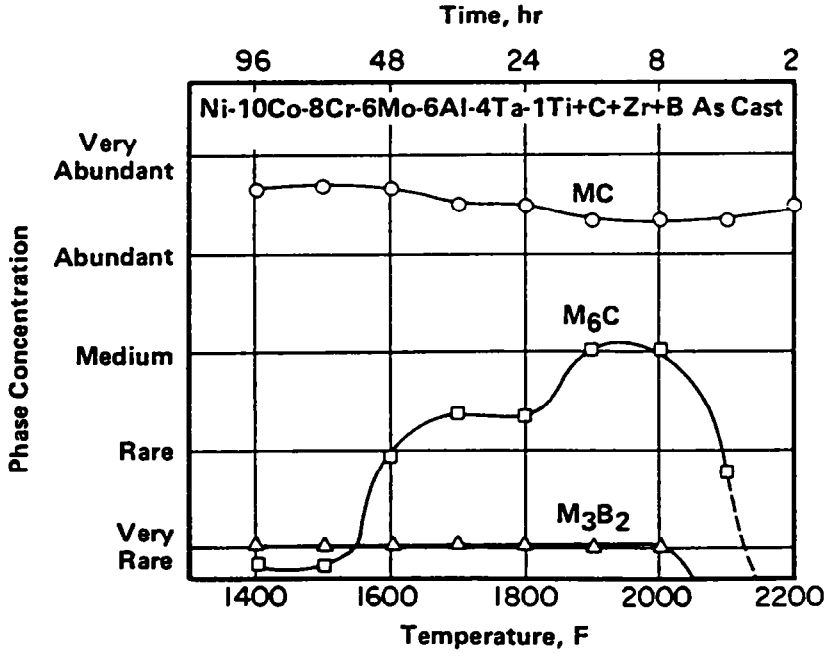


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

B-1900

Composition: Ni - 0.10% C - 7.96% Cr - 9.70% Co - 5.89% Mo - 1.08% Ti - 6.06% Al - 0.015% B - 0.084% Zr - 4.25% Ta
Treatment: Solution treated as cast, aged at 760 to 1204°C (1400 to 2200°) for varying times

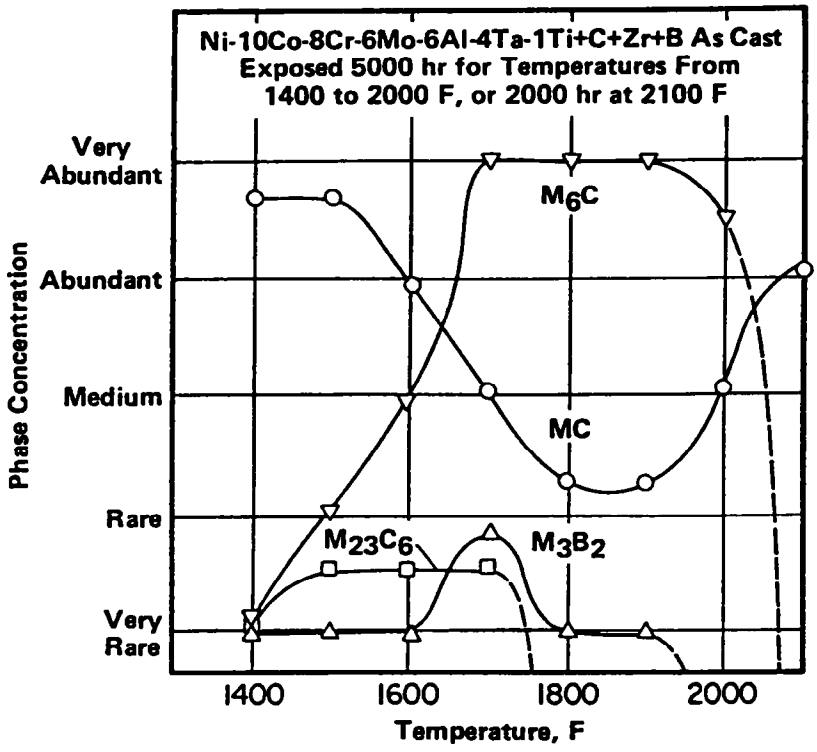


Minor phase concentration as a function of aging temperature

SOURCE: H.E. Collins, R.J. Quigg, "Carbide and Intermetallic Instability in Advanced Nickel-Base Superalloys," Trans. ASM, Vol 61, 1968, pp 139-148

B-1900

Composition: Ni - 0.10% C - 8.25% Cr - 9.50% Co - 5.89% Mo - 1.07% Ti - 5.98% Al - 0.016% B - 0.10% Zr - 4.19% Ta
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

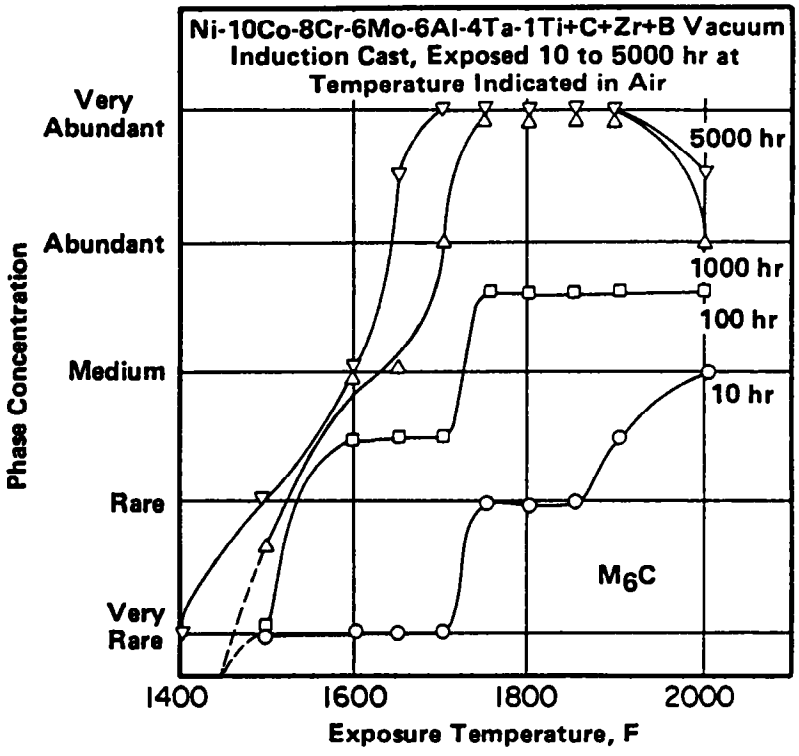


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

B-1900

Composition: Ni - 10% Co - 8% Cr - 6% Mo - 6% Al - 4% Ta - 1% Ti + C + Zr + B
Treatment: Vacuum induction cast, exposed at temperature indicated 10 to 5000 h in air

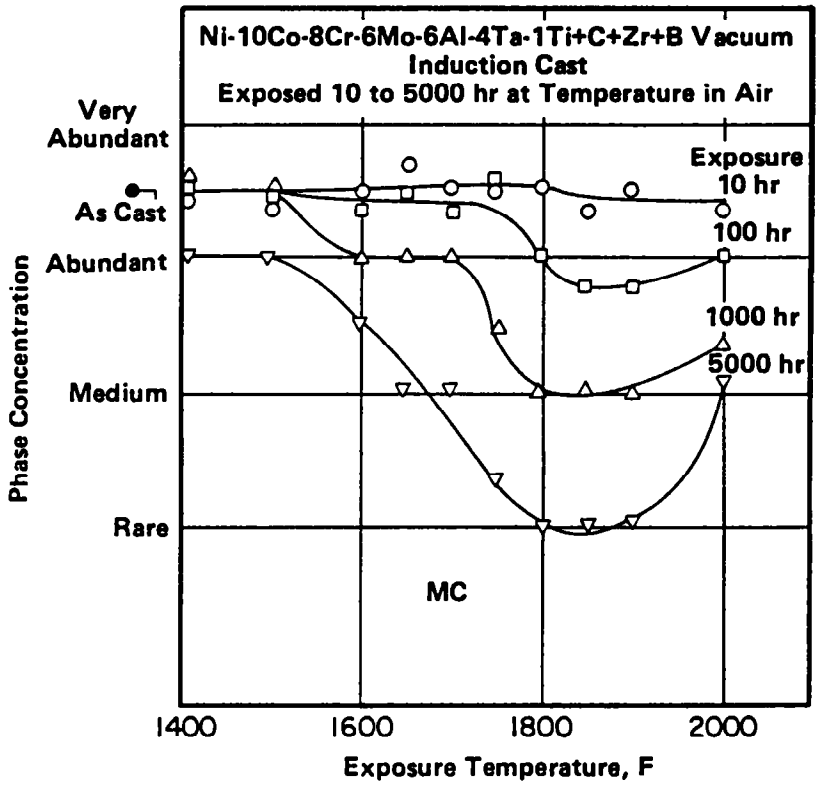


Effect of exposure time and temperature on M_6C carbide phase

SOURCE: H.E. Collins, "The Effect of Simulated Jet Engine Thermal Conditions on the Microstructure and Mechanical Properties of the Nickel-Base Superalloy B-1900," as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, March 1985, Code 4213, p 7

B-1900

Composition: Ni - 10% Co - 8% Cr - 6% Mo - 6% Al - 4% Ta - 1% Ti + C + Zr + B
Treatment: Vacuum induction cast, exposed at temperature indicated 10 to 5000 h in air

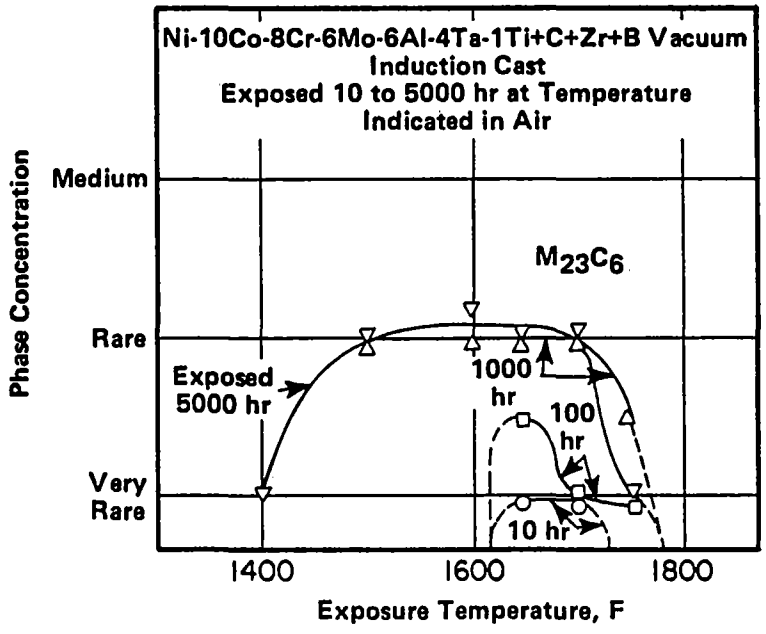


Effect of exposure time and temperature on MC carbide phase

SOURCE: H.E. Collins, "The Effect of Simulated Jet Engine Thermal Conditions on the Microstructure and Mechanical Properties of the Nickel-Base Superalloy B-1900," as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, March 1985, Code 4213, p 7

B-1900

Composition: Ni - 10% Co - 8% Cr - 6% Mo - 6% Al - 4% Ta - 1% Ti + C + Zr + B
Treatment: Vacuum induction cast, exposed at temperature indicated 10 to 5000 h in air

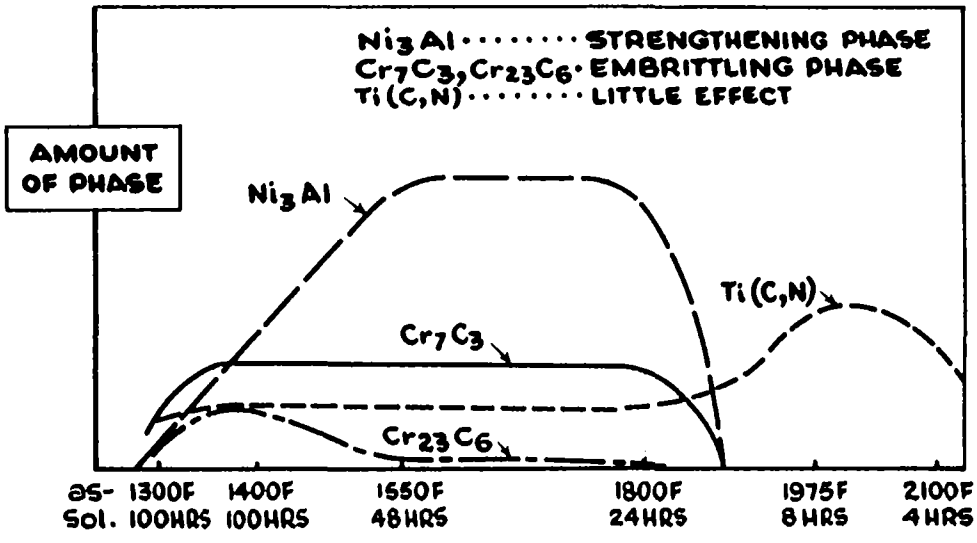


Effect of exposure time and temperature on $M_{23}C_6$ carbide phase

SOURCE: H.E. Collins, "The Effect of Simulated Jet Engine Thermal Conditions on the Microstructure and Mechanical Properties of the Nickel-Base Superalloy B-1900," as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, March 1985, Code 4213, p 7

Inconel 702

Nominal composition: Ni - 0.08% C - 0.6% Ti - 3.2% Al - 15.5% Cr - 1.0% max Fe
Treatment: Specimens were heated treated at 2200°F) for 2 h, ice brine quenched, aged as noted on diagram, water quenched



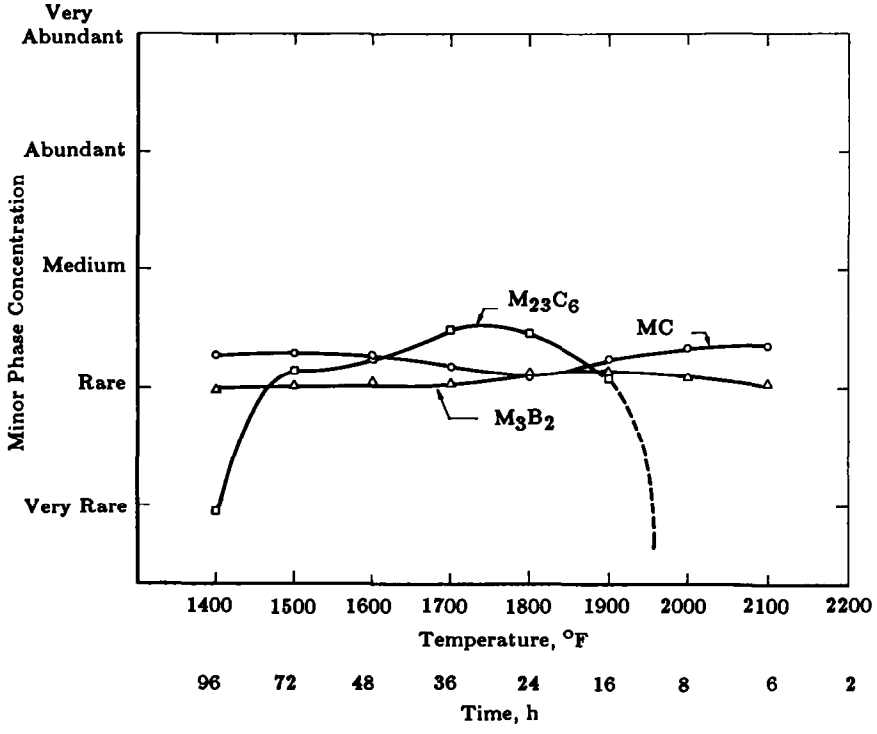
Precipitation of phases and relative amounts

SOURCE: M. Kaufman, A.E. Palty, "The Phase Structure of Inconel 718 and 702 Alloys," Trans. AIME, Vol 221, December 1961, pp 1253-1262

Udimet-700

Nominal Composition: Ni - 0.08% C - 15.0% Cr - 18.5% Co - 5.2% Mo - 3.5% Ti - 4.3% Al - 0.030% B

Treatment: Bar stock specimens were solution treated at 1177°C (2150°F) for 6 hr, aged at 760 to 1149°C (1400 to 2100°F) for varying times

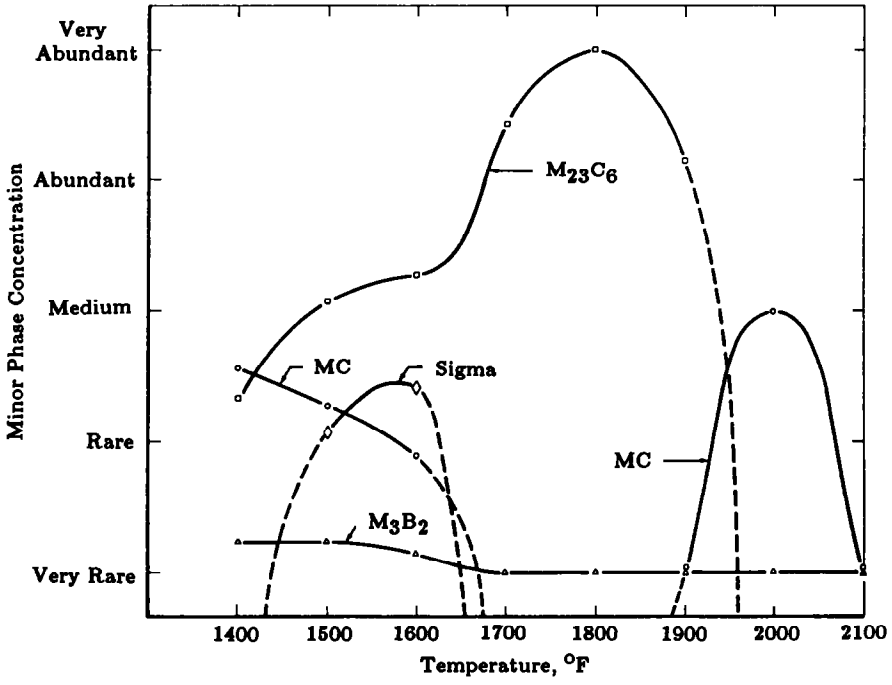


Minor phase concentration as a function of aging temperature

SOURCE: H.E. Collins, R.J. Quigg, "Carbide and Intermetallic Instability in Advanced Nickel-Base Superalloys," Trans. ASM, Vol 61, 1968, pp 139-148

Udimet-700

Composition: Ni - 0.07% C - 15.10% Cr - 18.30% Co - 5.33% Mo - 3.34% Ti - 4.29% Al - 0.024% B
Treatment: Solution treated at 1177°C (2150°F) for 4 h, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

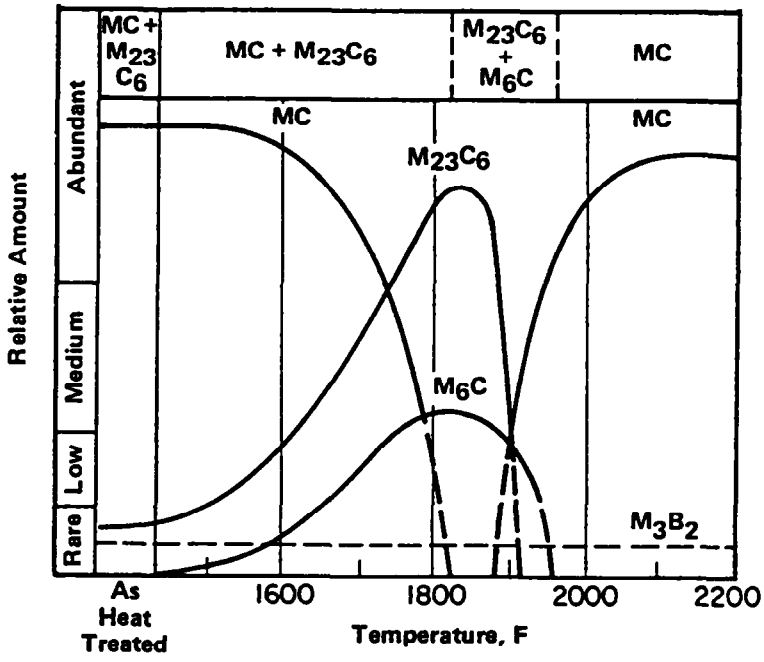


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

Rene'80

Nominal composition: Ni - 14% Cr - 9.5% Co - 4% Mo - 4% W - 5% Ti - 3% Al



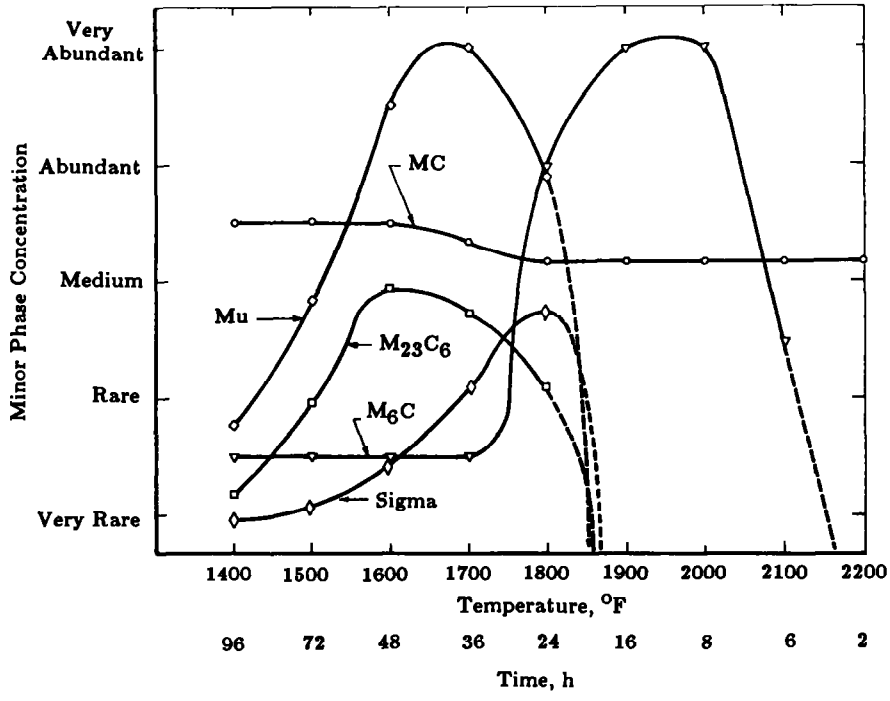
Precipitation of phases as a function of temperature

W.H. Chang, "Tensile Embrittlement of Turbine Blade Alloys after High Temperature Exposure," General Electric Company, MCIC Report 72-10, September 1972, as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, September 1986, Code 4214, p 6

Rene' 41

Composition: Ni - 0.08% C - 19.31% Cr - 10.82% Co - 9.77% Mo - 2.34% Fe - 3.23% Ti - 1.51% Al - 0.006% B

Treatment: Bar stock specimens were solution treated at 1204°C (2200°F) for 2 h, aged at 760 to 1204°C (1400 to 2200°) at varying times



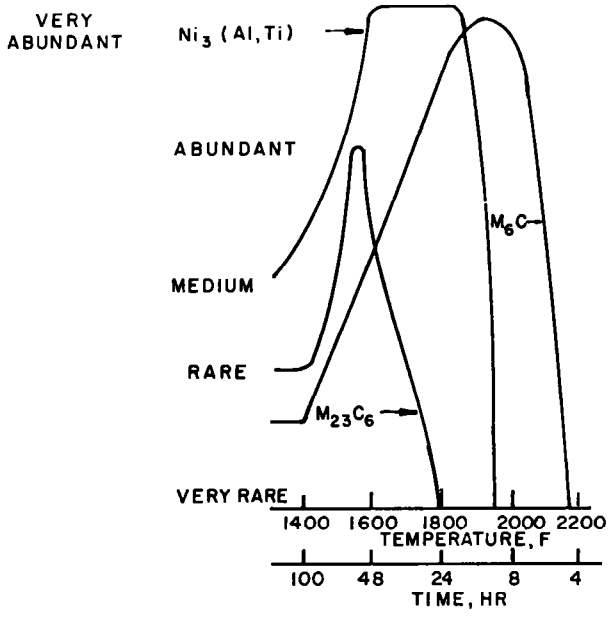
Minor phase concentration as a function of aging temperature

SOURCE: H.E. Collins, R.J. Quigg, "Carbide and Intermetallic Instability in Advanced Nickel-Base Superalloys," Trans. ASM, Vol 61, 1968, pp 139-148

Rene' 41

Typical composition: Ni - 0.08% C - 0.50% Fe - 19.00% Cr - 11.00% Co - 9.75% Mo - 3.15% Ti - 1.50% Al - 0.006% B

Treatment: Bar stock specimens were initially treated at 1204°C (2200°F), water quenched, and aged



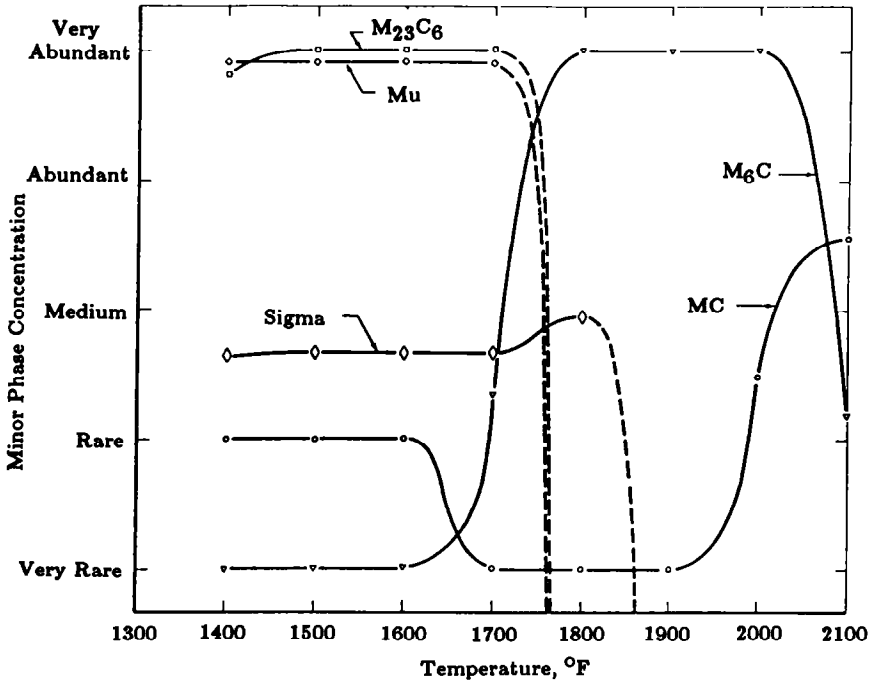
Time-temperature precipitation of phases
Isothermal phase reactions after aging at the times and temperatures indicated

SOURCE: L.A. Weisenberg, R.J. Morris, "How to Fabricate Rene 41," Metal Progress, Vol 78, November 1960, pp 70-74

Rene' 41

Composition: Ni - 0.08% C - 19.31% Cr - 10.82% Co - 9.77% Mo - 3.23% Ti - 1.51% Al - 0.006% B - 2.34% Fe

Treatment: Solution treated at 1177°C (2150°F) for 2 h, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h



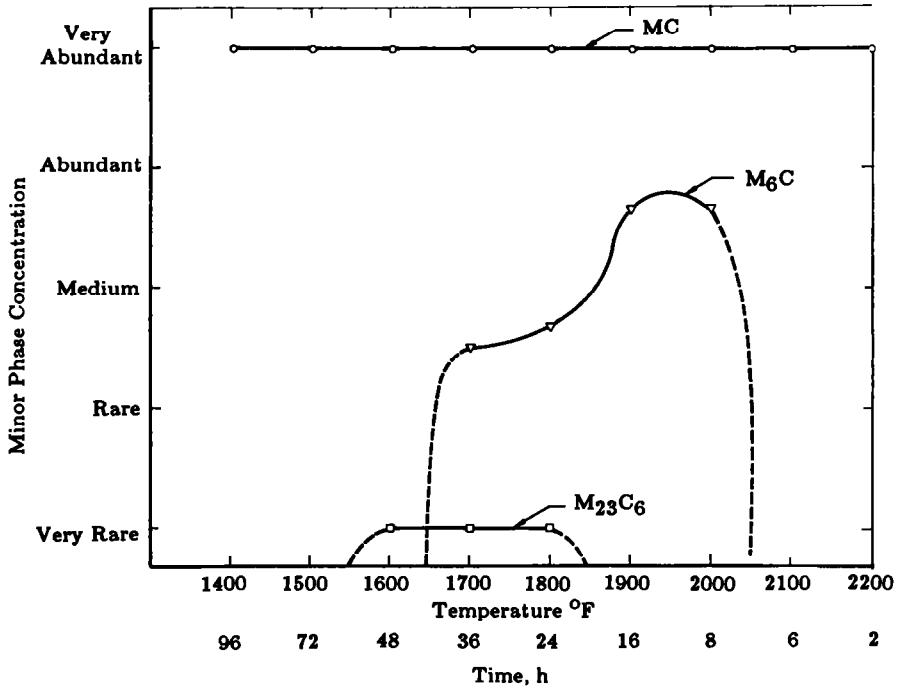
Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

Unitemp AF2-1D

Composition: Ni - 0.35% C - 11.92% Cr - 14.05% Co - 4.94% Mo - 4.87% W - 3.02% Ti - 4.60% Al - 0.013% B - 0.10% Zr - 1.56% Ta

Treatment: Bar stock specimens were solution treated at 1232°C (2250°F) for 2 h, aged at 760 to 1204°C (1400 to 2200°) at varying times



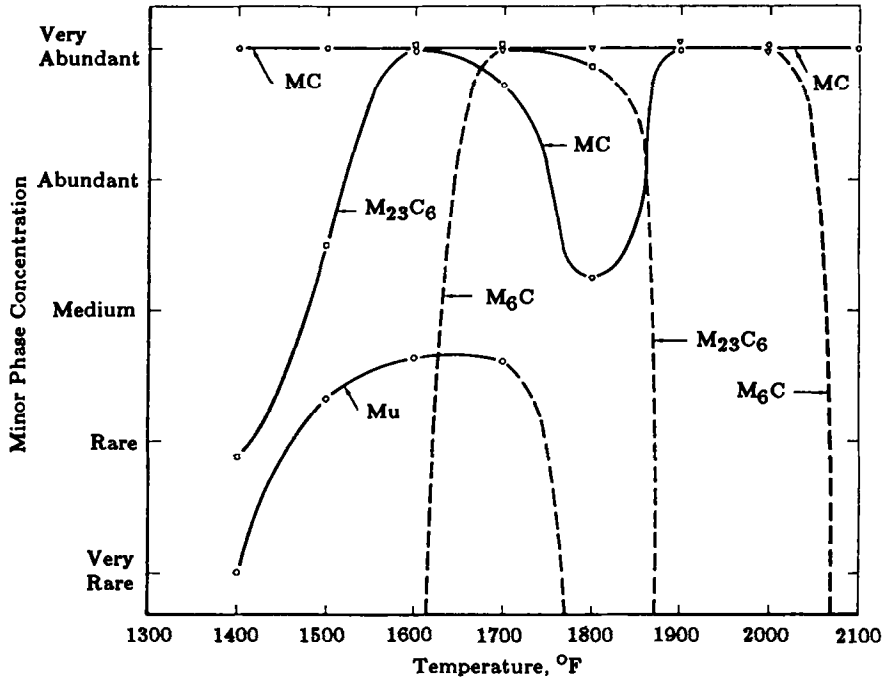
Minor phase concentration as a function of aging temperature

SOURCE: H.E. Collins, R.J. Quigg, "Carbide and Intermetallic Instability in Advanced Nickel-Base Superalloys," Trans. ASM, Vol 61, 1968, pp 139-148

Unitemp AF2-ID

Composition: Ni - 0.33% C - 11.93% Cr - 14.20% Co - 5.05% Mo - 3.04% Ti - 4.60% Al - 4.93% W - 0.014% B - 0.10% Zr - 1.48% Ta

Treatment: Solution treated at 1232°C (2250°F) for 2 h, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

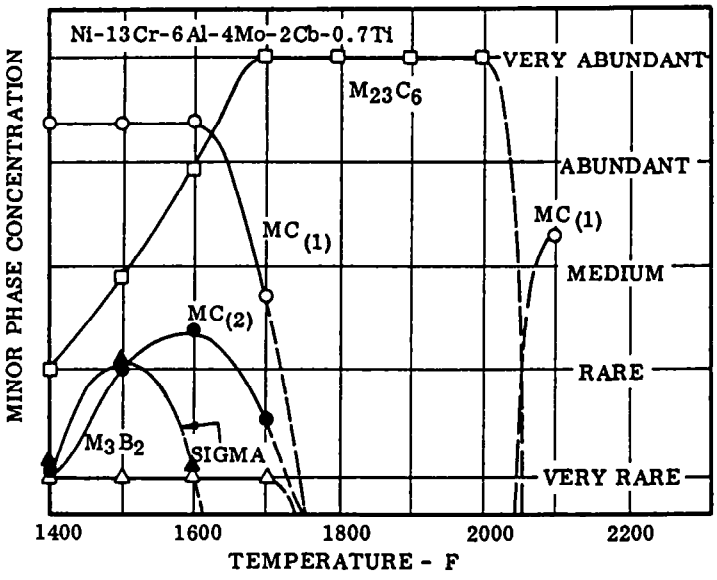


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

Inco 713C

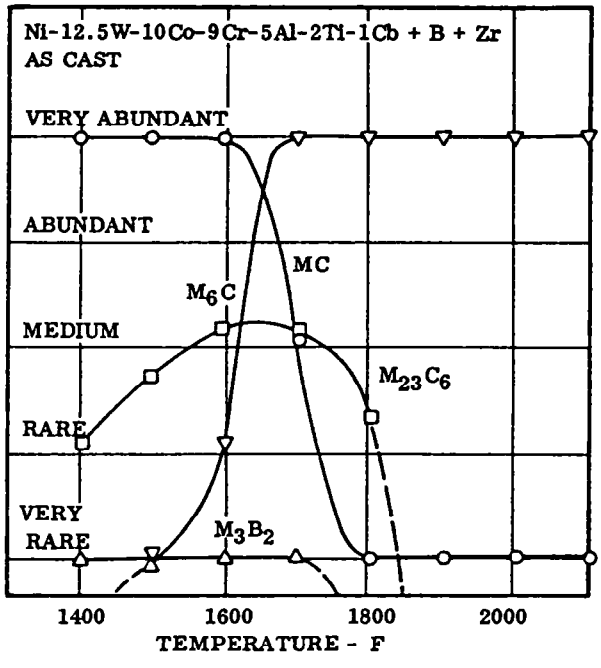
Composition: Ni - 0.12% C - 13.25% Cr - 4.28% Mo - 0.81% Ti - 6.40% Al - 0.009% B - 0.05% Zr - 2.66% Nb
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h



Minor phase concentration as a function of temperature for long exposure times

MAR-M200

Composition: Ni - 0.14% C - 9.51% Cr - 10.3% Co - 2.06% Ti - 5.05% Al - 12.15% W - 0.010% B - 0.048% Zr - 0.99% Nb
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h



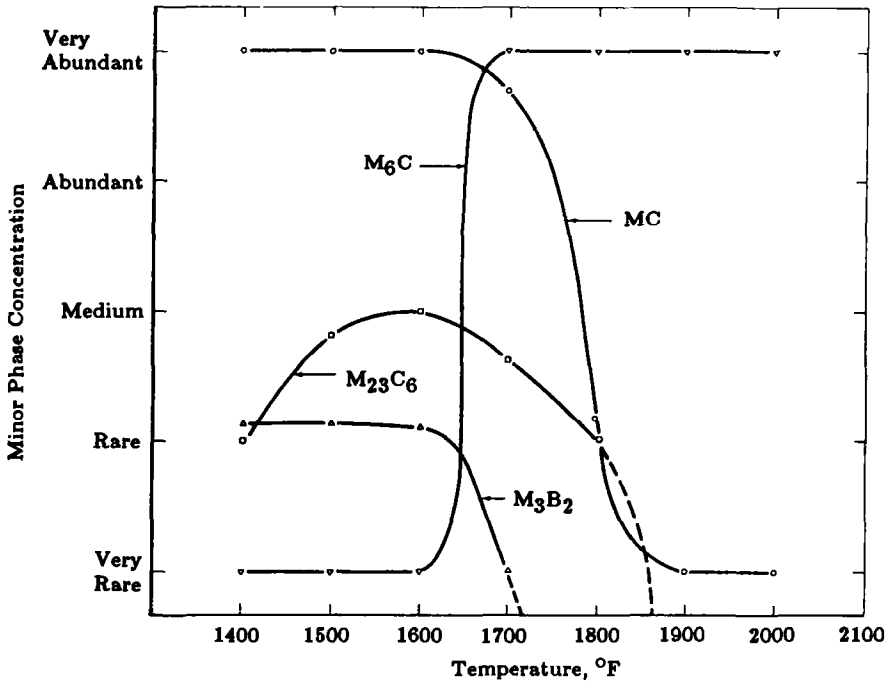
Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

MAR-M246

Nominal Composition: Ni - 0.15% C - 9.00% Cr - 10.0% Co - 2.50% Mo - 1.50% Ti - 5.50% Al - 10.0% W - 0.010% B - 0.05% Zr - 1.5% Ta

Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

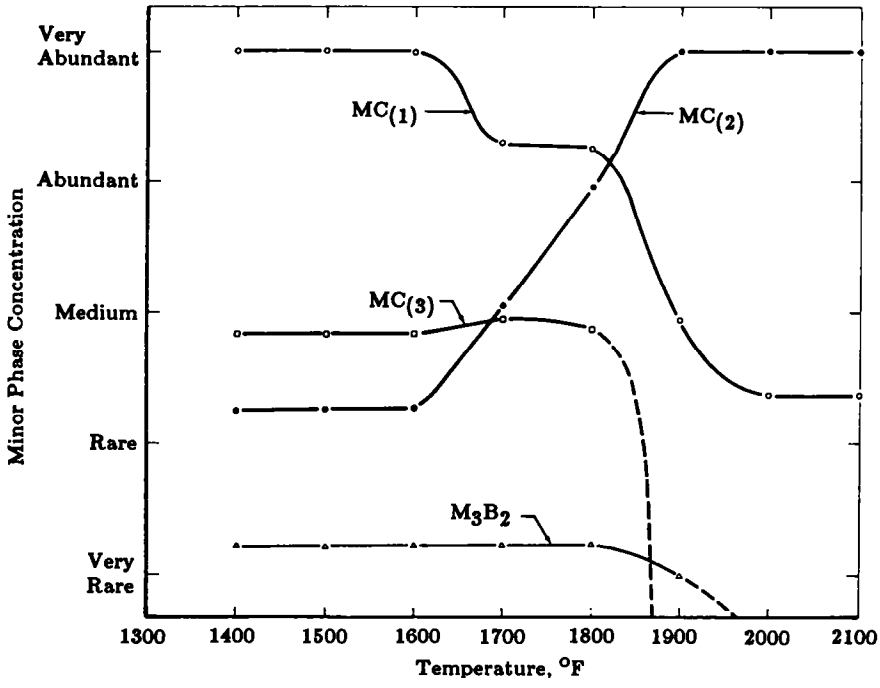


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

TRW-NASA IVY

Composition: Ni - 0.15% C - 5.85% Cr - 4.82% Co - 2.04% Mo - 1.08% Ti - 5.25% Al - 5.36% W - 0.023% B - 0.039% Zr - 8.17% Ta - 0.89% Nb - 2.01% Hf - 0.90% Re
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

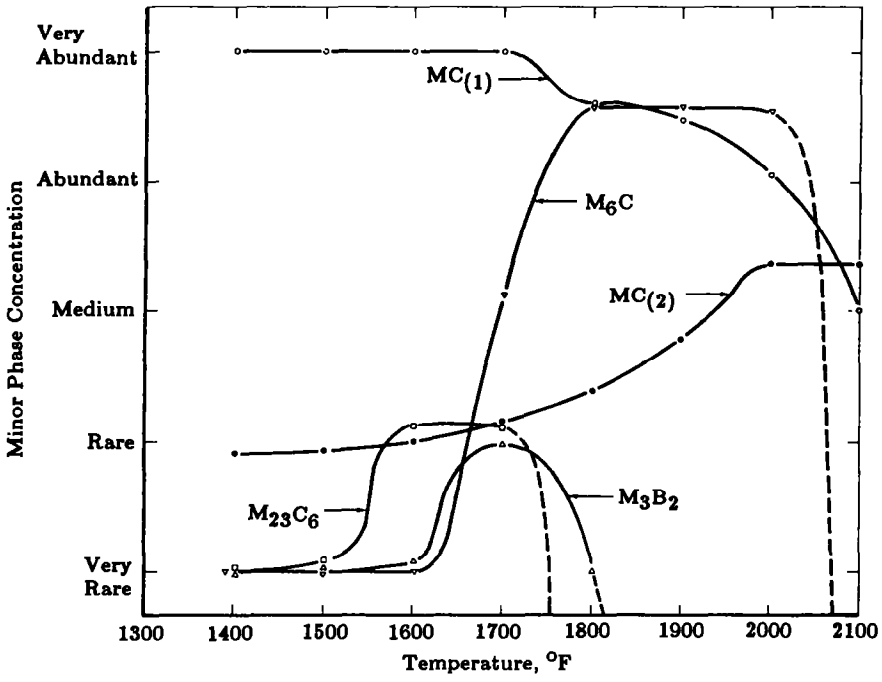


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

TRW-NASA VIA

Composition: Ni - 0.16% C - 6.03% Cr - 7.19% Co - 2.24% Mo - 0.98% Ti - 5.26% Al - 5.78% W - 0.018% B - 0.12% Zr - 8.32% Ta - 0.34% Nb - 0.46% Hf - 0.57% Re
Treatment: Solution treated as cast, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h



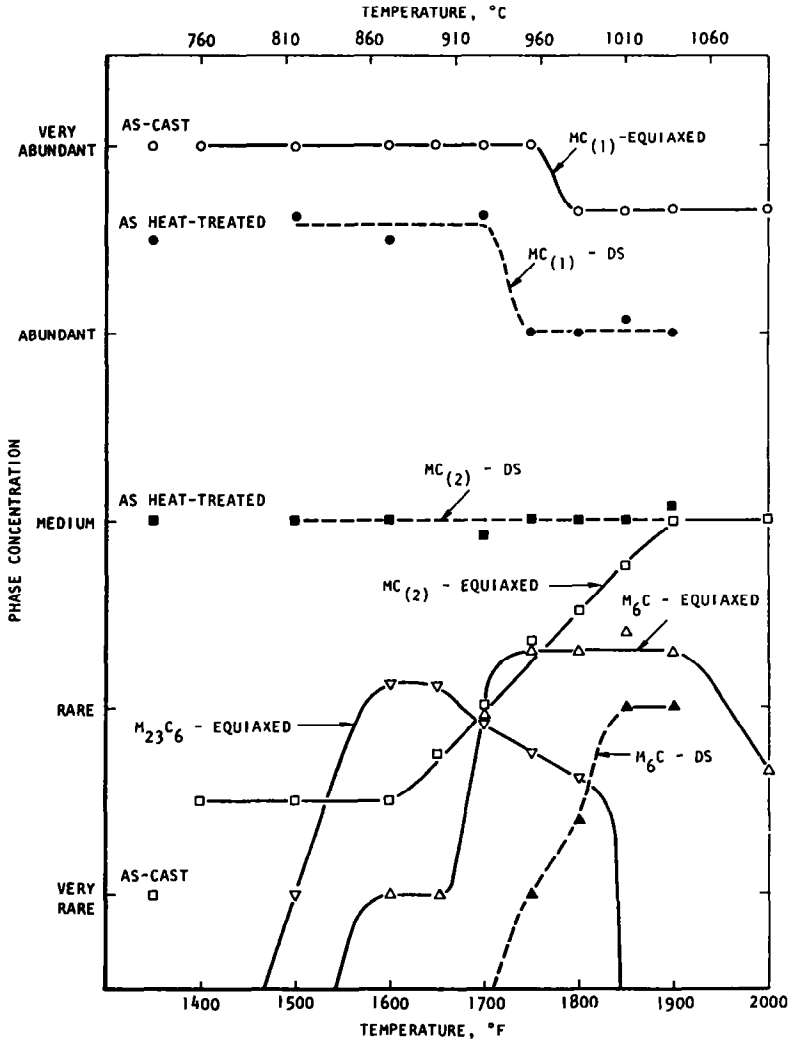
Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

TRW-NASA VIA

Composition: Ni - 0.13% C - 5.92% Cr - 2.05% Mo - 1.01% Ti - 5.27% Al - 7.46% Co - 0.38% Hf - 8.97% Ta - 5.92% W - 0.32% Re - 0.10% Zr - 0.020% B - 0.47% Nb

Treatment: Directionally solidified specimens were heat treated at 1232°C (2250°F) for 4 h and 871°C (1600°F) for 65 h, and aged at 816 to 1038°C (1500 to 1900°F) at 28°C (50°F) intervals for 1000 h in air



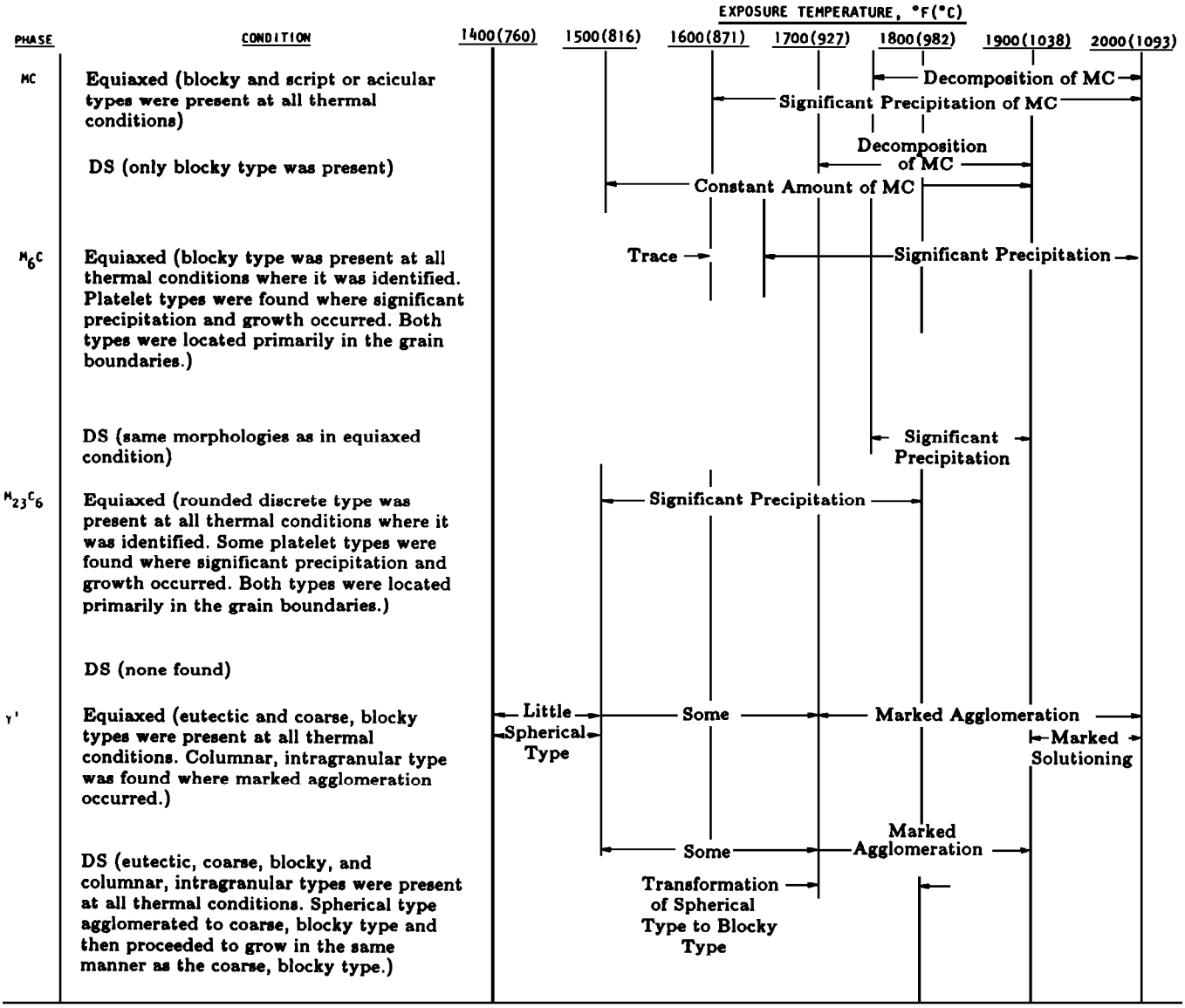
Effect of temperature on the carbide minor phases

SOURCE: H.E. Collins, "The Effect of Thermal Exposure on the Mechanical Properties of the Directionally Solidified Superalloy TRW-NASA VIA," Met. Trans. A, Vol 6A, March 1975, pp 515-530

TRW-NASA VIA

Composition: Ni - 0.13% C - 5.92% Cr - 2.05% Mo - 1.01% Ti - 5.27% Al - 7.46% Co - 0.38% Hf - 8.97% Ta - 5.92% W - 0.32% Re - 0.10% Zr - 0.020% B - 0.47% Nb

Treatment: Directionally solidified specimens were heat treated at 1232°C (2250°F) for 4 h and 871°C (1600°F) for 65 h, and aged at 816 to 1038°C (1500 to 1900°F) at 28°C (50°F) intervals for 1000 h in air



Equiaxed material was evaluated in the 760 to 1093°C (1400 to 2000°F) temperature range, while the DS material was evaluated in the 816 to 1038°C (1500 to 1900°F) temperature range

DS = Directional solidification

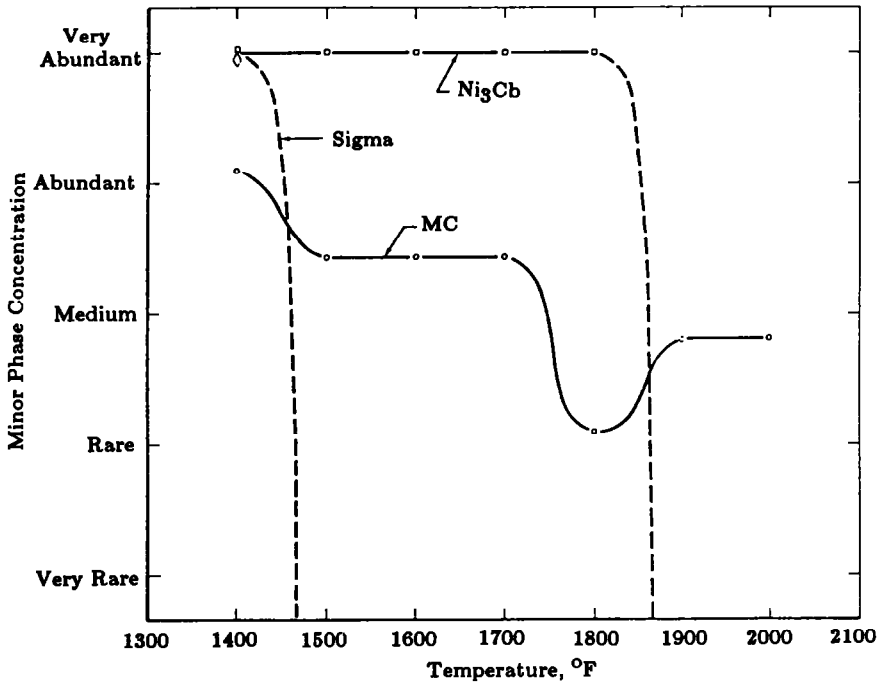
Significant variations in the microstructure after thermal exposure

SOURCE: H.E. Collins, "The Effect of Thermal Exposure on the Mechanical Properties of the Directionally Solidified Superalloy TRW-NASA VIA," Met. Trans. A, Vol 6A, March 1975, pp 515-530

Inconel 718

Composition: Ni - 0.06% C - 18.86% Cr - 2.99% Mo - 0.93% Ti - 0.57% Al - 5.25% Nb - 17.48% Fe

Treatment: Solution treated at 982°C (1800°F) for 1 h, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h



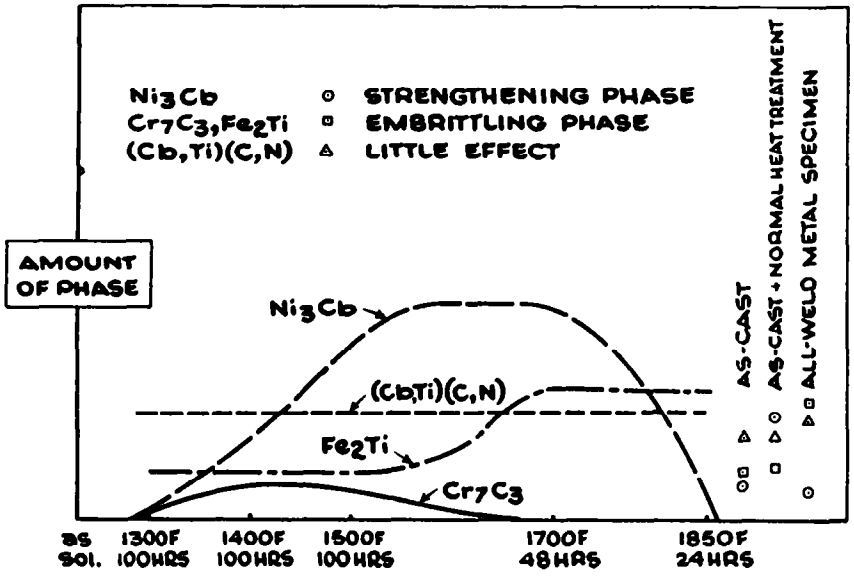
Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

Inconel 718

Composition: Fe - 53% Ni - 0.05% C - 1.0% Ti - 0.7% Al - 19.0% Cr - 3.0% Mo - 5.3% Nb+Ta - 0.006% B - 0.03% Zr - 0.2% Mn - 0.3% Si

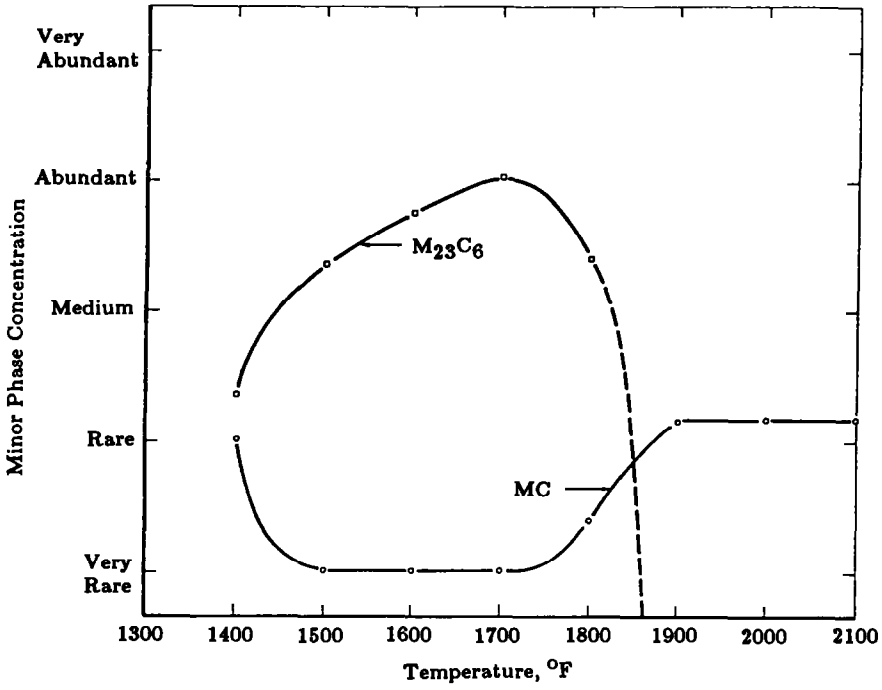
Treatment: 1232°C (2250°F) for 2 h, ice brine quench + 704°C (1300°F) for 100 h, water quench, aged at temperatures and times indicated



Precipitation of phases in Inconel 718

SOURCE: M. Kaufman, A.E. Palty, "The Phase Structure of Inconel 718 and 702 Alloys," Trans. AIME, Vol 221, December 1961, pp 1253

Waspaloy
Composition: Ni - 0.06% C - 19.30% Cr - 14.60% Co - 4.39% Mo - 3.08% Ti - 1.42% Al - 0.051% Zr
Treatment: Solution treated at 1079°C (1975°F) for 4 h, aged in air at 760 to 1093°C (1400 to 2000°F) at 38°C (100°F) intervals for 5000 h, and at 1149°C (2100°F) for 2000 h

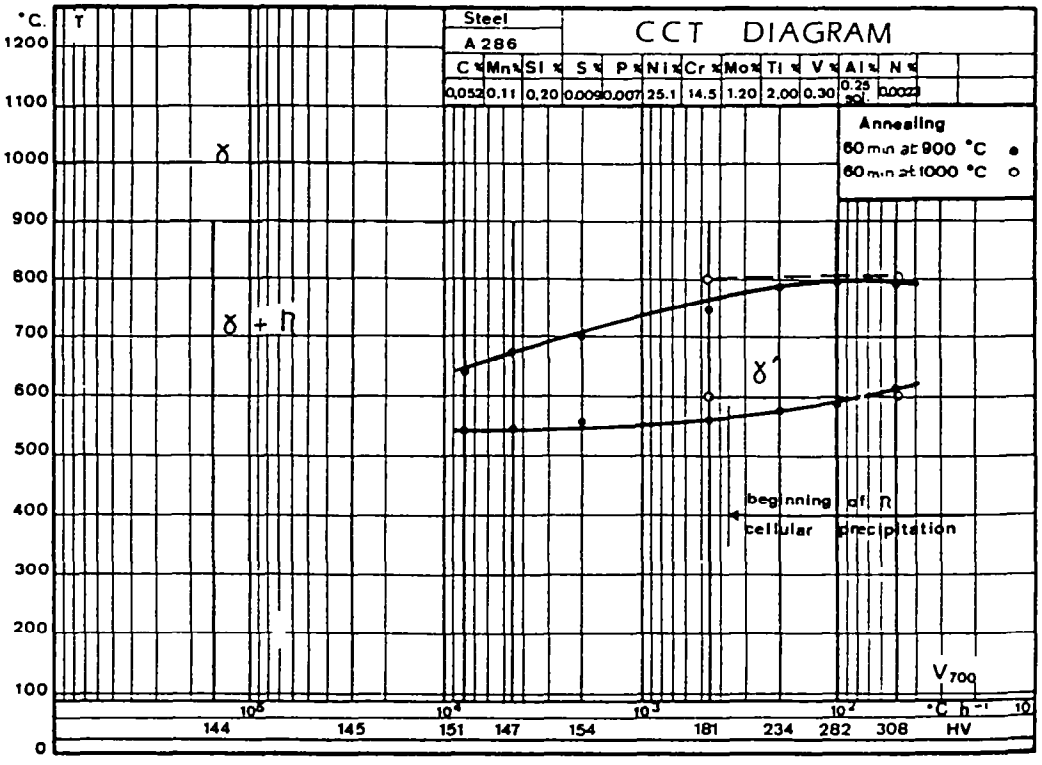


Minor phase concentration as a function of temperature for long exposure times

SOURCE: H.E. Collins, "Relative Long-Time Stability of Carbide and Intermetallic Phases in Nickel-Base Superalloys," Trans. ASM, Vol 62, 1969, pp 82-104

A-286

Composition: 25.1% Ni - 14.5% Cr - 1.20% Mo - 2.00% Ti - 0.30% V - 0.25% sol. Al - 0.052% C - 0.11% Mn - 0.20% Si - 0.009% S - 0.007% P - 0.0023% N



LIVE GRAPH
Click here to view

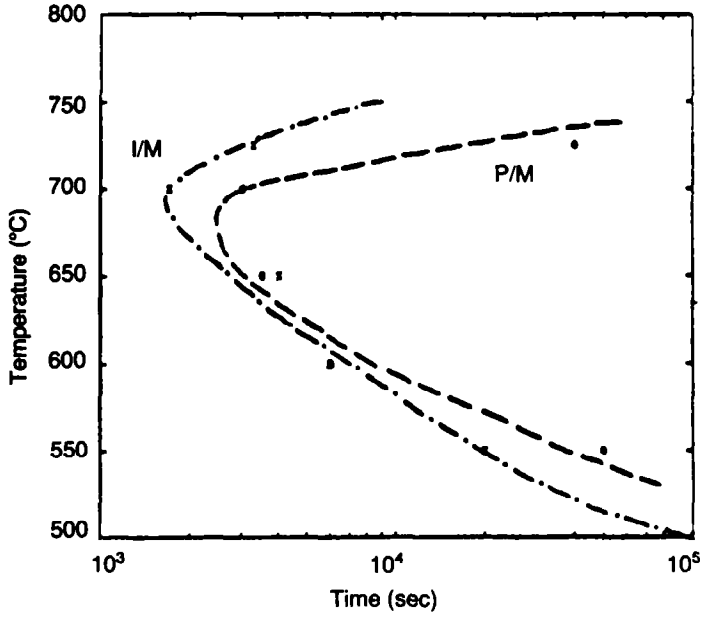
CCT diagram

Note: Cooling rate at °C/h, and resultant hardness, HV

SOURCE: C. Loier, M.C. Ottman, "Influence of Thermal Treatments on the Determination of Manufacturing Processes for A 286 Steel Courses," Bulletin du Cercle d'Etudes des Metaux, Vol 15, No. 3, September 1983

A-286

Composition: Fe - 24.7% Ni - 14.4% Cr - 2.2% Ti - 1.1% Mo - 0.26% Al
Treatment: Powder samples were produced by Inert Gas Atomization and the properties of conventional Ingot Metallurgy material were used as a baseline for determination of the effects of IGA powder metallurgy processing
I/M material was solution treated at 900°C (1652°F) for 2 h and water quenched
P/M material was held at 1100°C (2012°F) for 1 h and water quenched



LIVE GRAPH
Click here to view

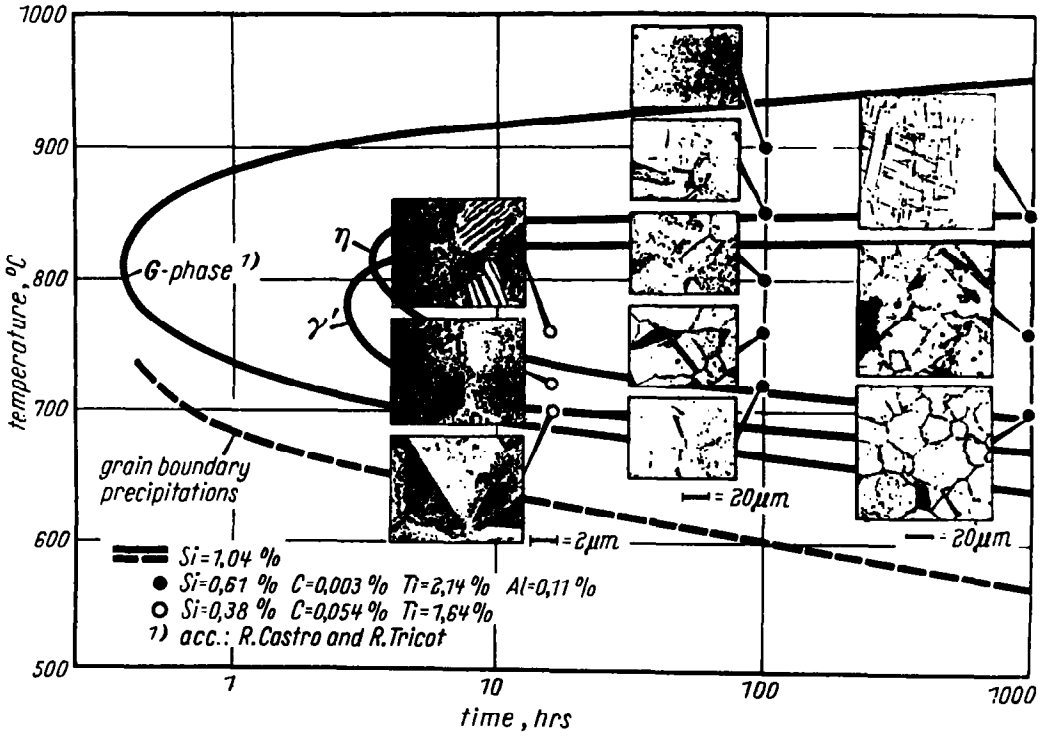
Time-temperature-precipitation diagram
I/M vs P/M, near start of precipitation
Transformation to 1 nm precipitates as derived from peak resistance changes

SOURCE: C.H. Sellers, J.E. Flinn, "Characterization of Microstructural Stability of Dispersion Strengthened P/M A-286 Alloy," Industrial Heating, November 1990, p 39

ATS 28 - X-5NiCrTi 26 15
(similar to A-286)

Composition: Fe - 26% Ni - -15% Cr - 1.3% Mo - 1.8% Ti - 0.03% Ca - 0.3% V

Treatment: Subjected to heats of 400 to 1000°C (752 to 1832°F) for up to 1000 h



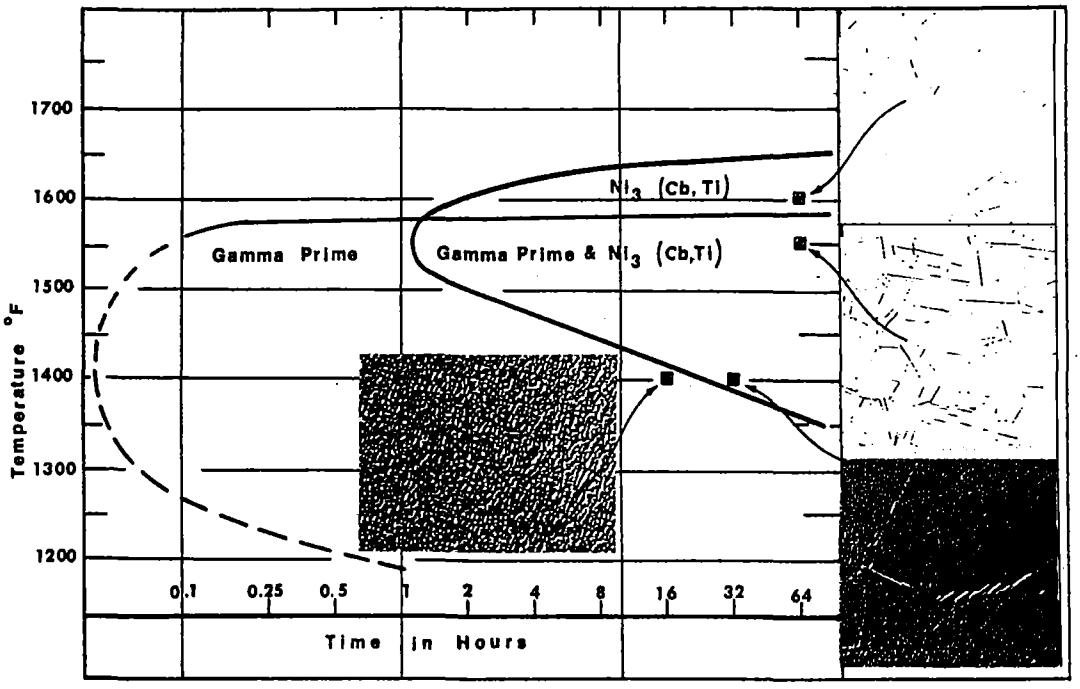
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram

R. Castro, R. Tricot, "Precipitation Hardening of Austenitic Stainless Steel of Type Chromium 15% and Nickel 25% with Titanium. I. Hardening Through Isothermal Treatment," Mem. Sci. Rev. Met., Vol 61, 1964, pp 573-591

Pyromet CTX-1

Composition: Fe - 37.7% Ni - 16.0% Co - 3.0% Nb - 1.75% Ti - 1.0% Al - 0.008% B - 0.03% C
Treatment: Annealed at 913°C (1675°F) for 1 h, oil quenched



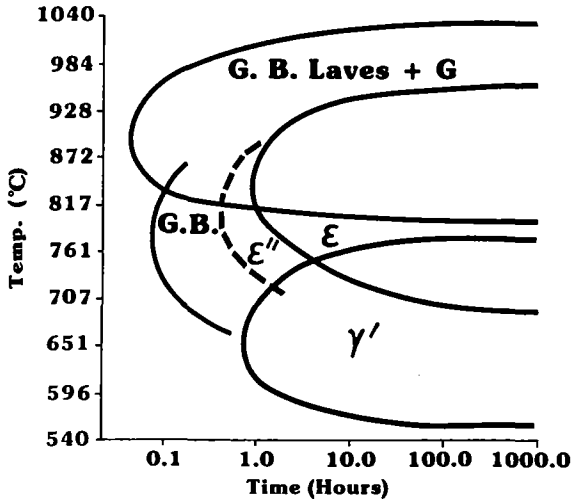
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram

SOURCE: D.R. Muzyka, C.R. Whitney, D.K. Schlosser, "Physical Metallurgy and Properties of a New Controlled-Expansion Superalloy," Journal of Metals, Vol 27, July 1975, pp 11-15

Incoloy 909

Composition: Fe - 38.3% Ni - 12.9% Co - 4.70% Nb - 1.58% Ti - 0.35% Si - 0.04% Al - 0.01% C - 0.01% Cr
Treatment: Solution annealed at 1038°C (1900°F) for 1 h, air cooled, and isothermally aged between 538 and 1038°C (1000 and 1900°F) for 0.1 to 1000 h



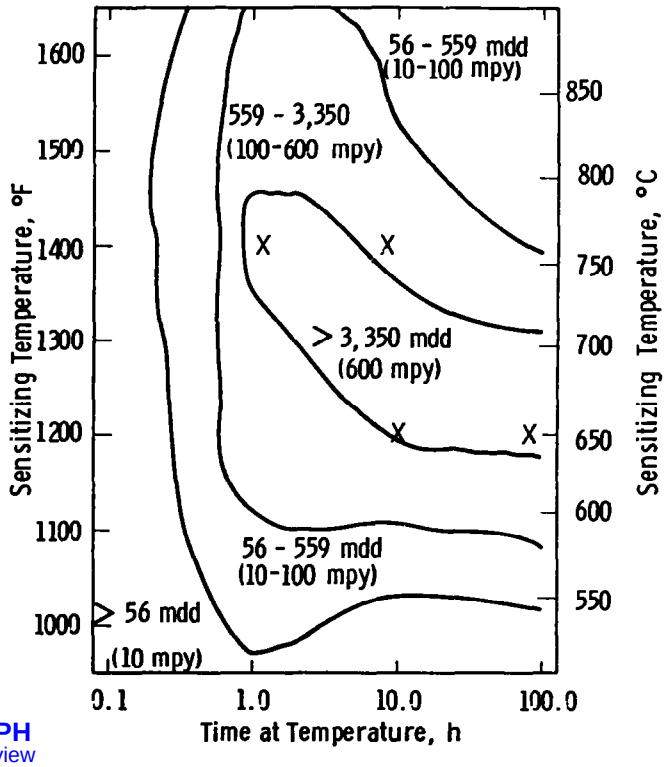
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram

SOURCE: K.A. Heck, D.F. Smith, J.S. Smith, D.A. Wells, M.A. Holderby, "The Physical Metallurgy of a Silicon-Containing Low Expansion Superalloy," Superalloys 1988, S. Reichman, et al., Eds., TMS, 1988 pp 151-160

Incoloy 800

Composition: Fe - 31.85% Ni - 0.23% Cu - 0.06% C - 0.81% Mn - 0.007% S - 0.32% Si - 21.81% Cr
Treatment: Solution heat treated in argon at 1093°C (2000°F) for 1 h, water quenched, aged, and rapidly water cooled



LIVE GRAPH
Click here to view

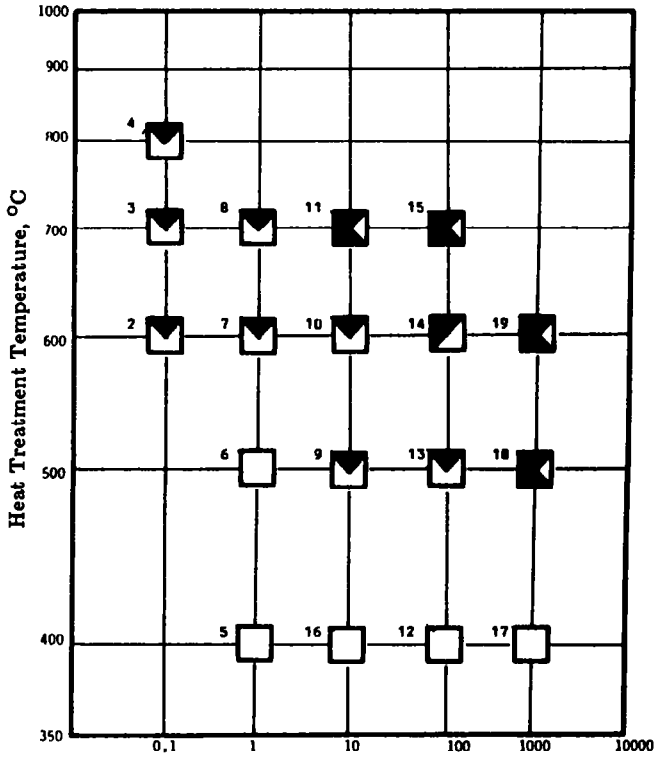
Time-temperature-sensitization diagram

Contour lines = corrosion rates in milligrams/dm^2/day, mils per year in boiling 65% nitric acid
X = specimens which failed the copper-copper sulfate-sulfuric acid tests (ASTM A262-68)

SOURCE: R.G. Aspden, G. Economy, F.W. Pement, I.L. Wilson, "Relationship Between Magnetic Properties, Sensitization, and Corrosion of Incoloy Alloy 800 and Inconel Alloy 600," Met. Trans., Vol 3, October 1972, pp 2691-2697

Incoloy-800

Composition: Fe - 31.1% Ni - 21.4% Cr - 0.90% Mn - 0.28% Si - 0.037% C - 0.02% N - 0.01% P - 0.007% S - 0.5% Al - 0.3% Ti
Grain size: ASTM 7-8
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)
Etchant: 10% Br-CH_3OH



LEGEND:

- No precipitate
- Fine GB particles
- Massive GB particles
- Specimen identification
- GB and ITB particles
- GB, ITB ad TB particles

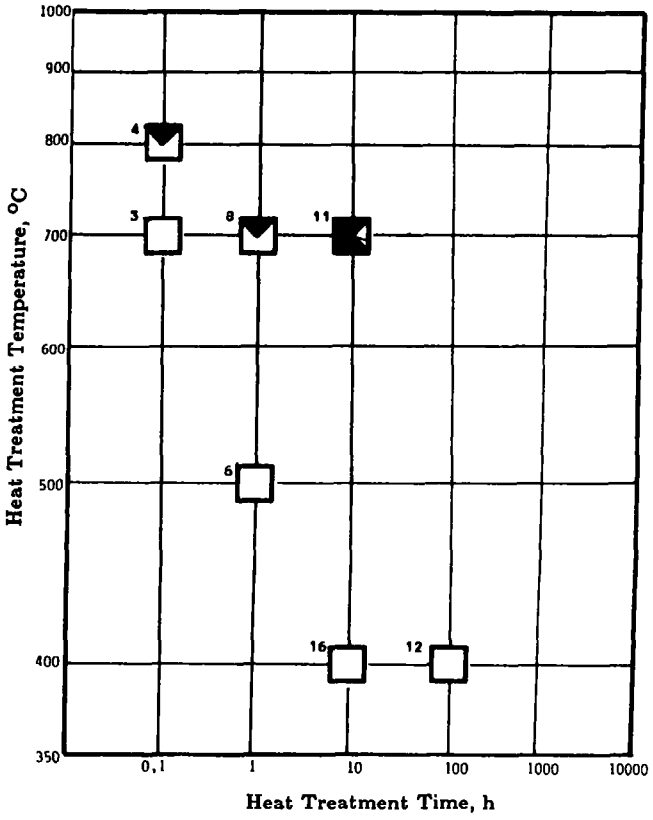
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Light microscope evaluation of heat treated specimens

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Incoloy-800

Composition: Fe - 31.1% Ni - 21.4% Cr - 0.90% Mn - 0.28% Si - 0.037% C - 0.02% N - 0.01% P - 0.007% S - 0.5% Al - 0.3% Ti
Grain size: ASTM 7-8
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)
Etchant: 10% Br-CH_3OH



LEGEND:

- No precipitate
- Fine GB particles
- Massive GB particles
- GB and ITB particles
- GB, ITB ad TB particles

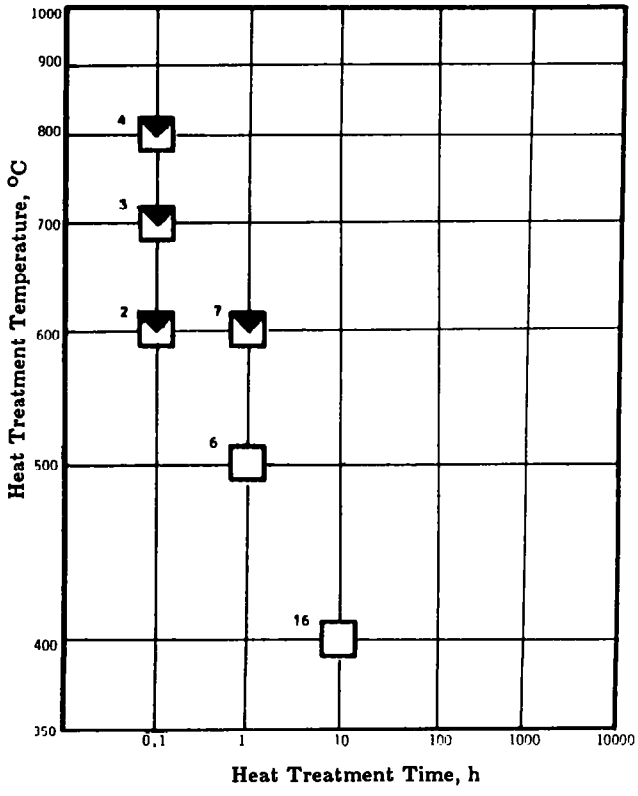
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Scanning electron microscope evaluation of heat treated specimens

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Incoloy-800

Composition: Fe - 31.1% Ni - 21.4% Cr - 0.90% Mn - 0.28% Si - 0.037% C - 0.02% N - 0.01% P - 0.007% S - 0.5% Al - 0.3% Ti
Grain size: ASTM 7-8
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)
Carbon-extraction replicas of Br-methanol etched transverse cross sections of tube specimens



LEGEND:
□ No precipitate, except globular HC or M(C, N) particles
▣ Very fine GB particles

GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Transmission electron microscope evaluation of heat treated specimens

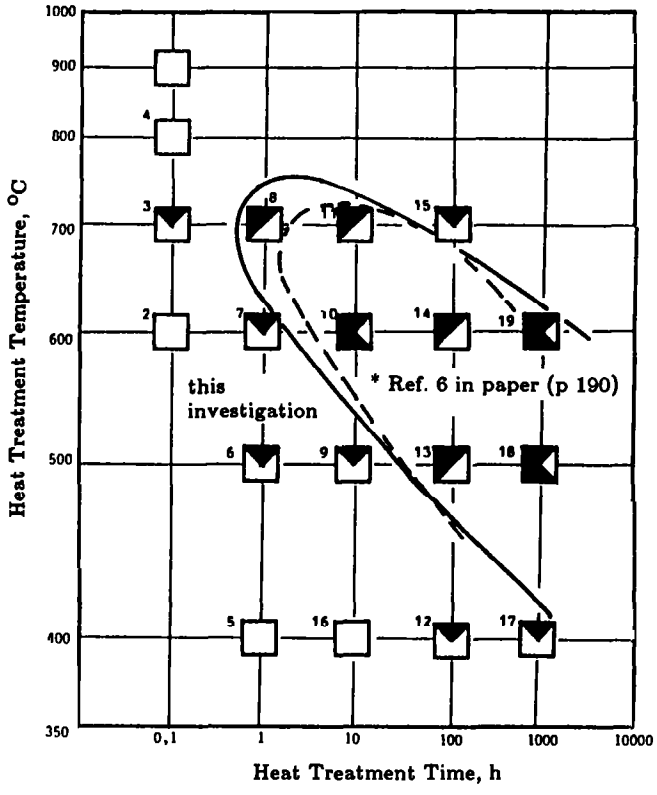
SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Incoloy-800

Composition: Fe - 31.1% Ni - 21.4% Cr - 0.90% Mn - 0.28% Si - 0.037% C - 0.02% N - 0.01% P - 0.007% S - 0.5% Al - 0.3% Ti

Grain size: ASTM 7-8

Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)



* W. Debray et al Nickel Power Conference, Lausanne, Paper No. 3, 1972

LEGEND:

- No attack
- GB etching
- GB fissuring
- GB cracking
- Disintegration

GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

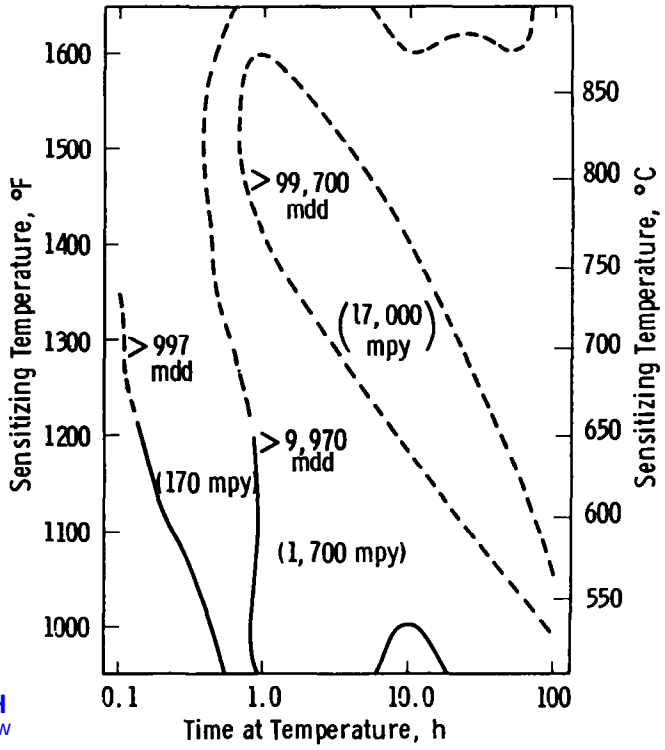
Intercrystalline corrosion susceptibility
Test conditions: 45 h boiling in solution of 250 ml H_2SO_4 + 100 g $CuSO_4$ + 750 ml H_2O, followed by bend test and SEM evaluation

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Inconel 600

Composition: Ni - 7.92% Fe - 0.15% Cu - 0.06% C - 0.17% Mn - 0.007% S - 0.22% Si - 15.40% Cr

Treatment: Solution heat treated in argon at 1121°C (2050°F) for 2 h, water quenched, aged, and rapidly water cooled



LIVE GRAPH
Click here to view

Time-temperature-sensitization diagram

Contour lines = corrosion rates in milligrams/dm^2/day, mils per year in boiling 65% nitric acid
No specimens failed the copper-copper sulfate-sulfuric acid test

SOURCE: R.G. Aspden, G. Economy, F.W. Pement, I.L. Wilson, "Relationship Between Magnetic Properties, Sensitization, and Corrosion of Incoloy Alloy 800 and Inconel Alloy 600," Met. Trans., Vol 3, October 1972, pp 2691-2697

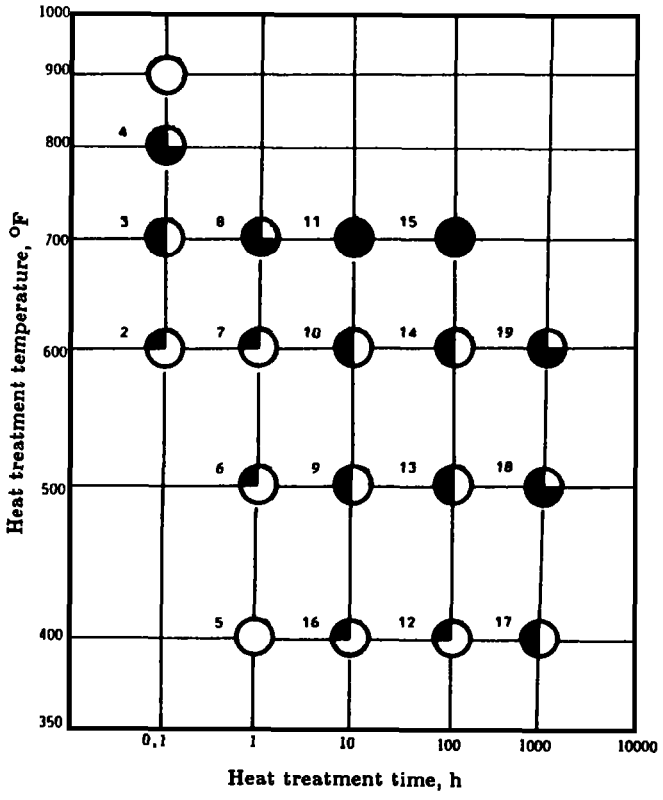
Inconel 600

Composition: Ni - 15.6% Cr - 8.1% Fe - 0.2% Ti - 0.03% Mo - 0.03% N - 0.03% Cu - 0.16% Al - 0.040% C - 0.27% Si - 0.13% Mn

Grain size: ASTM 6-7

Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)

Etchant: 10% Br-Ch_3OH



LEGEND:
- ○ No precipitate
- ◔ Fine GB particles
- ◐ Massive GB particles
- ○ Specimen identification
- ◕ GB and ITB particles
- ● GB, ITB and TB particles

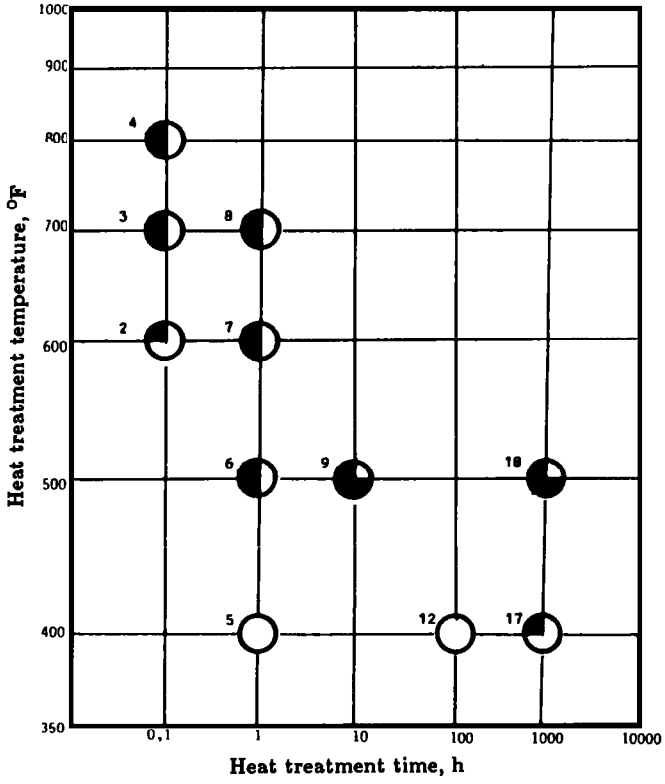
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Light microscope evaluation of heat treated specimens

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Inconel 600

Composition: Ni - 15.6% Cr - 8.1% Fe - 0.2% Ti - 0.03% Mo - 0.03% N - 0.03% Cu - 0.16% Al - 0.040% C - 0.27% Si - 0.13% Mn
Grain size: ASTM 6-7
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)
Etchant: 10% Br-Ch_3OH



LEGEND:
- ○ No precipitate
- ◔ Fine GB particles
- ◐ Massive GB particles
- ◕ GB and ITB particles
- ● GB, ITB and TB particles

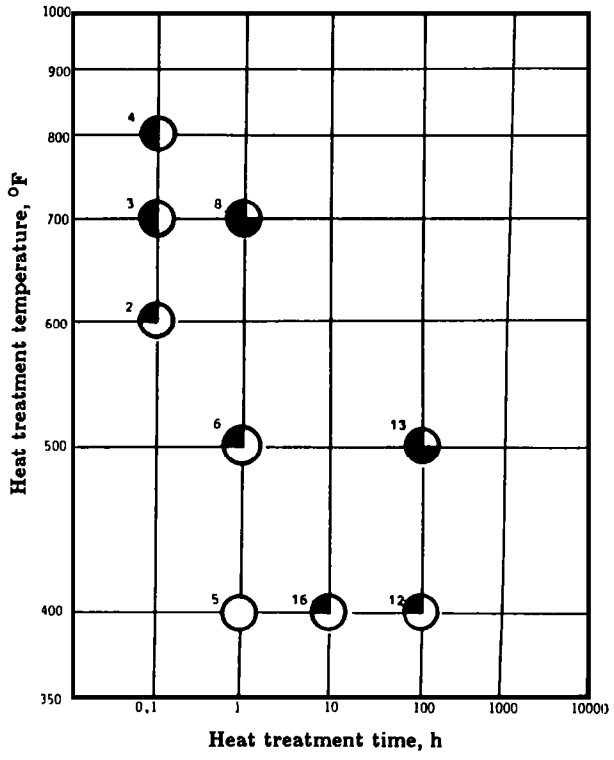
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Scanning electron microscope evaluation of heat treated specimens

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Inconel 600

Composition: Ni - 15.6% Cr - 8.1% Fe - 0.2% Ti - 0.03% Mo - 0.03% N - 0.03% Cu - 0.16% Al - 0.040% C - 0.27% Si - 0.13% Mn
Grain size: ASTM 6-7
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)
Carbon-extraction replicas of Br-methanol etched transverse cross sections of tube specimens



LEGEND:

- Very fine GB particles
- Coarse or dendritic GB particles
- No precipitate except globular MC_X or M(C, N) particles
- GB and ITB particles

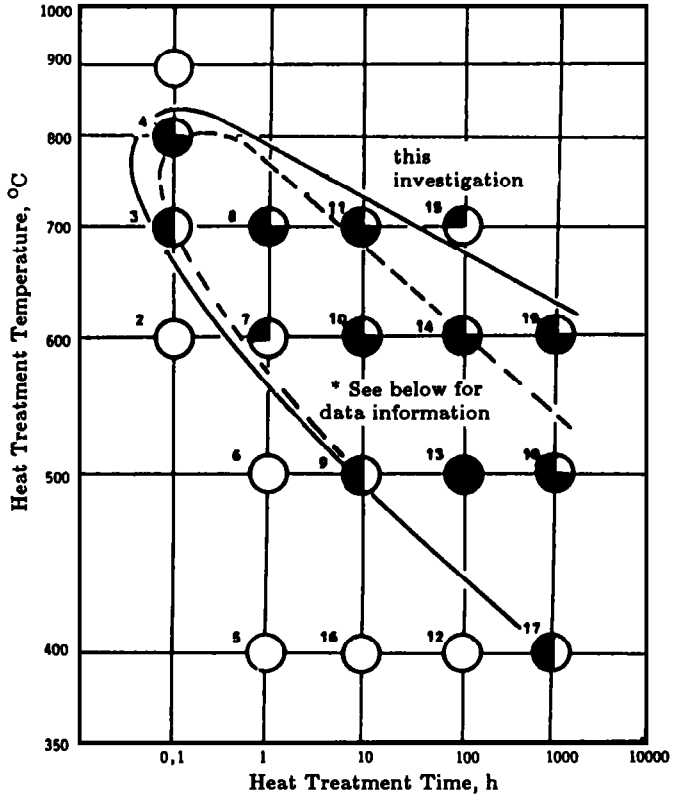
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Transmission electron microscope evaluation of heat treated specimens

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Inconel 600

Composition: Ni - 15.6% Cr - 8.1% Fe - 0.2% Ti - 0.03% Mo - 0.03% N - 0.03% Cu - 0.16% Al - 0.040% C - 0.27% Si - 0.13% Mn
Grain size: ASTM 6-7
Treatment: Mill annealed specimens aged at 400 to 800°C (752 to 1472°F)



* G. Herbsleb, Mitteilungen des VGB, Vol 50, April 1970, p 138

LEGEND:

- ○ No attack
- ◕ GB etching
- ◐ GB fissuring
- ◔ GB cracking
- ● Disintegration

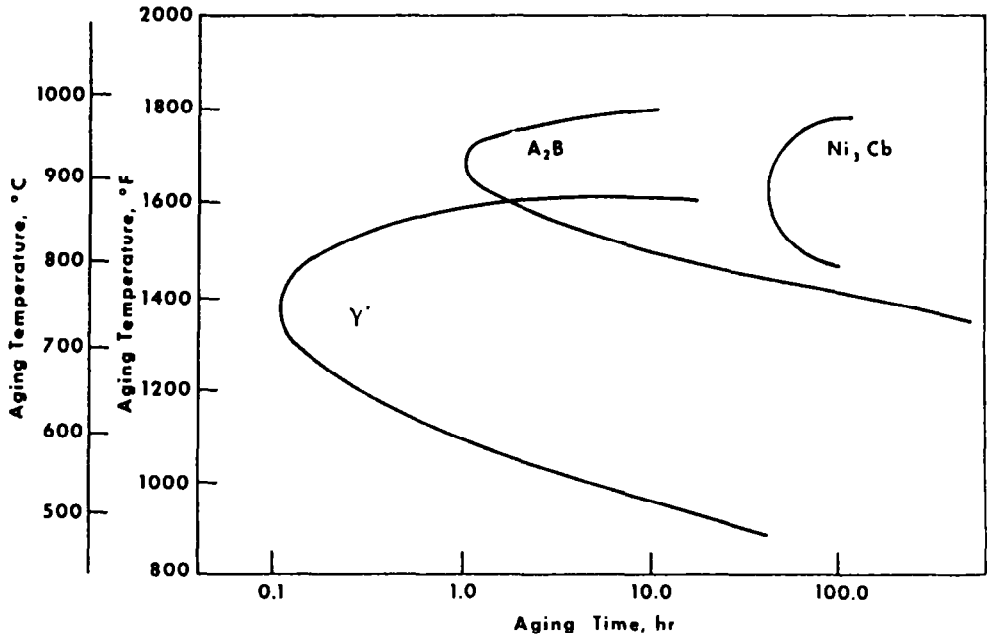
GB = Grain boundary
ITB = Incoherent twin boundary
TB = Coherent twin boundary

Intercrystalline corrosion susceptibility
Test conditions: 45 h boiling in solution of 21 g $Fe_2(SO_4)_3$ + 100 ml H_2SO_4 + 400 ml H_2O, followed by bend test and SEM evaluation

SOURCE: R. Stickler, G. Weidlich, "Microstructure and Intergranular Corrosion of Inconel-600 and Incoloy-800 Tubes," Prakt. Met. Vol 20, April 1983, pp 174-193

Inconel 706

Nominal composition: Ni - 37% Fe - 16% Cr - 2.9% Nb - 1.8% Ti
Treatment: Solution annealed at 1093°C (2000°F) 1 h, air cooled and aged at various times and temperatures



LIVE GRAPH
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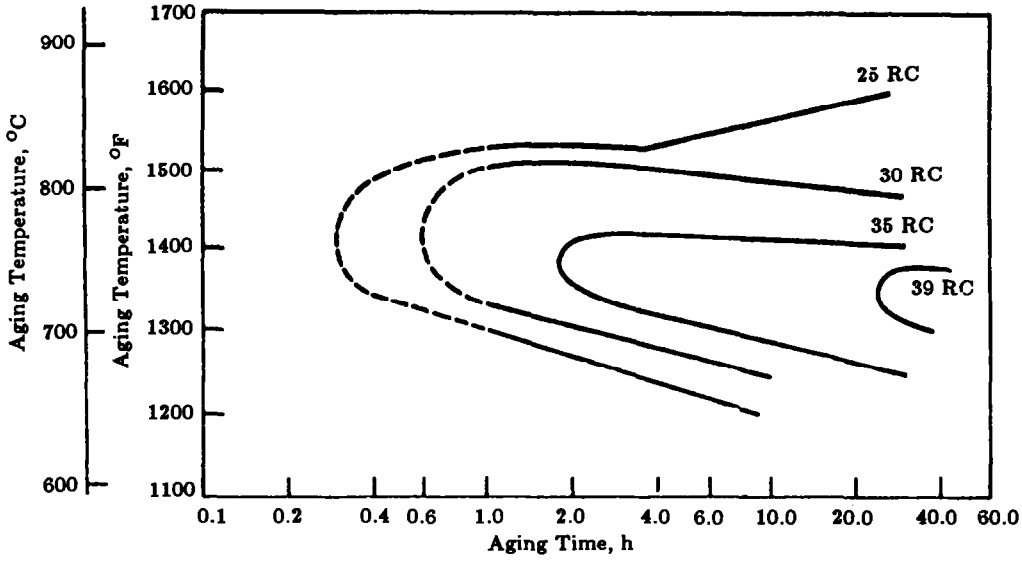
Time-temperature precipitation diagram
A_2B = Laves

Nominal composition: Ni - 37% Fe - 16% Cr - 2.9% Nb - 1.8% Ti
Treatment: Annealed at 1038°C (1900°F) for 30 min, air cooled



LIVE GRAPH
Click here to view

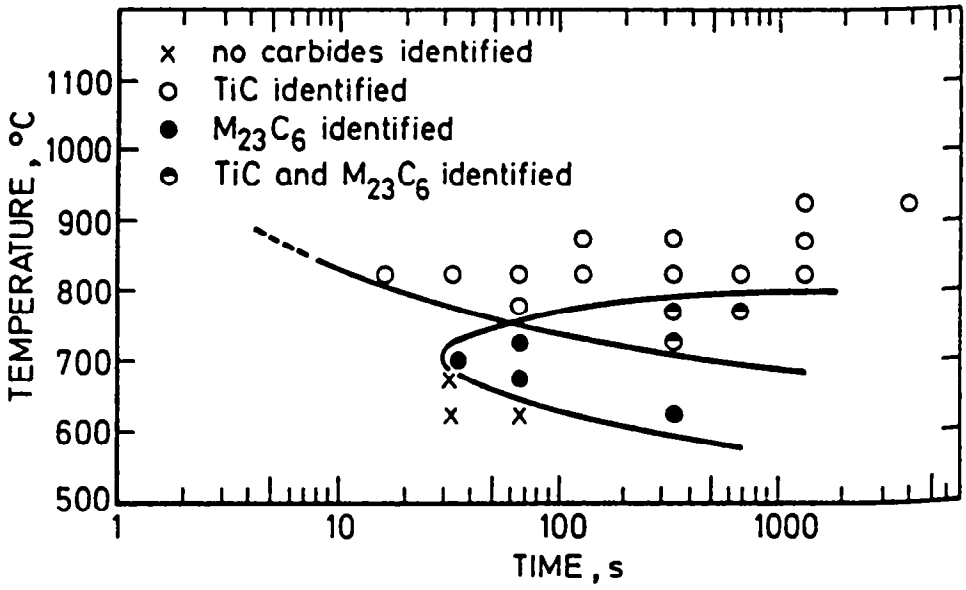
Time-temperature-hardness diagram

SOURCE: H.L. Eiselstein, "Properties of Inconel Alloy 706," Technical Report No. C 70-9.5, ASM, 1970

Nimonic PE16

Composition: Fe - 17.1% Cr - 42.5% Ni - 3.1% Mo - 1.2% Ti - 1.3% Al - 0.03% Zr - 0.05% Mn - 0.0003% B - 0.08% C

Treatment: Specimens were rapidly heated to 1100°C (2012°F) and maintained at temperature for 1 h, then rapidly cooled to an aging temperature between 625 and 950°C (1157 and 1742°F) and maintained at the desired aging temperature for times varying between 15 and 3600 s, followed by rapid cooling to ambient temperatures



LIVE GRAPH
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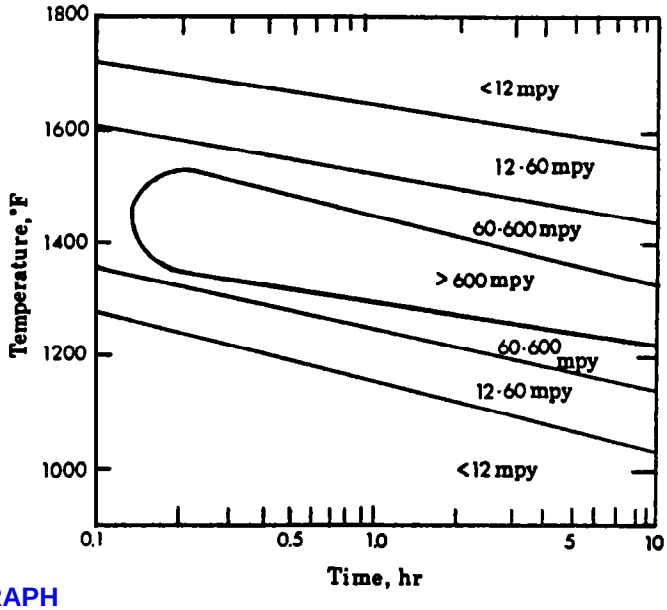
Time-temperature-precipitation diagram for carbides

SOURCE: R.G. Faulkner, J. Caisley, "The Kinetics of Grain Boundary Carbide Precipitation in Nimonic PE16," Metal Science, Vol 11, June 1977, pp 200-207

Incoloy 825

Composition: Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo
Treatment: Solution treated at 1204°C (2200°F) for 1 h, and sensitized at various temperatures and times



LIVE GRAPH
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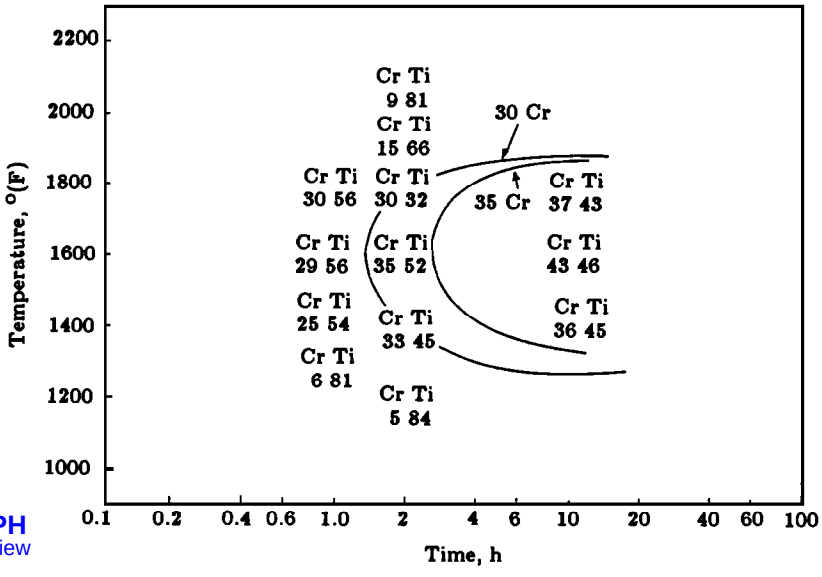
Time-temperature-sensitization diagram

Composition: Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo
Treatment: Solution annealed at 1204°C (2200°F) for 1 h, then aged



LIVE GRAPH
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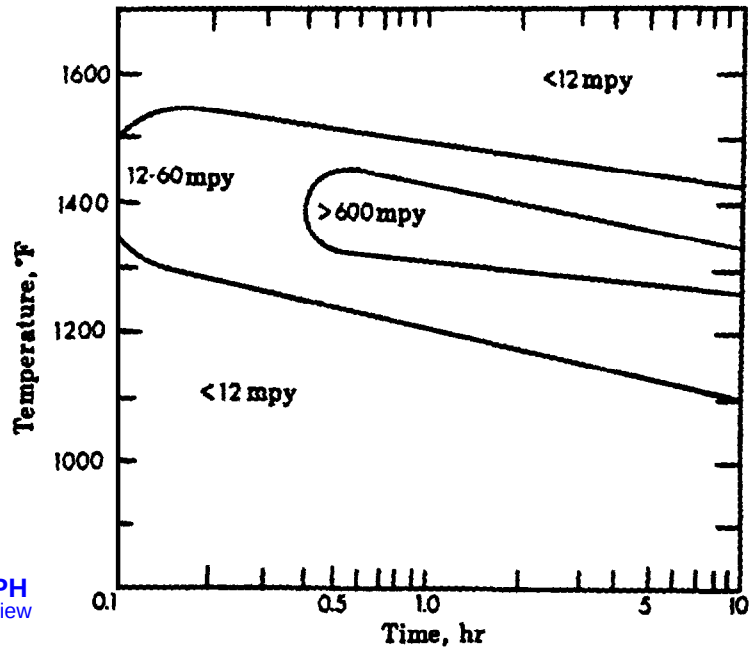
Time-temperature-precipitation diagram for $M_{23}C_6$
The amount of $M_{23}C_6$ is indicated by the chromium content of the residue (3Cr, 87Ti for as-annealed material)

SOURCE: E.L. Raymond, "Mechanisms of Sensitization and Stabilization of Incoloy Nickel-Iron-Chromium Alloy 825," Corrosion, Vol 24, No. 6, June 1968, pp 180-188

Incoloy 825

Composition: Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo

Treatment: Annealed at 1093°C (2000°F) for 1 h prior to aging

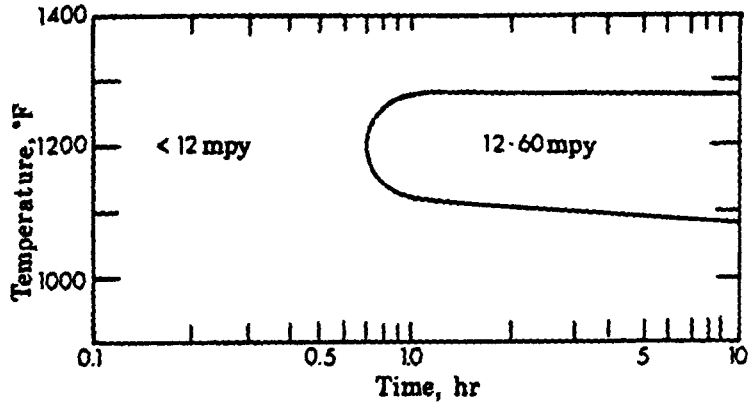


LIVE GRAPH
Click here to view

Time-temperature-sensitization diagram

Composition: Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo

Treatment: Annealed at 941°C (1725°F) for 1 h prior to aging



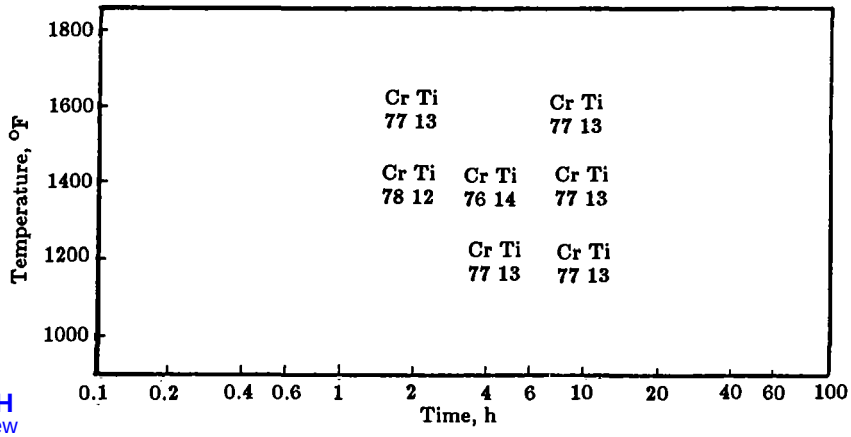
LIVE GRAPH
Click here to view

Time-temperature-sensitization diagram

SOURCE: E.L. Raymond, "Mechanisms of Sensitization and Stabilization of Incoloy Nickel-Iron-Chromium Alloy 825," Corrosion, Vol 24, No. 6, June 1968, pp 180-188

Incoloy 825

Composition: Ni - 0.03% C - 0.65% Mn - 29.59% Fe - 0.27% Si - 1.71% Cu - 21.18% Cr - 0.11% Al - 0.99% Ti - 2.61% Mo
Treatment: Annealed at 941°C (1725°F) for 1 h



LIVE GRAPH
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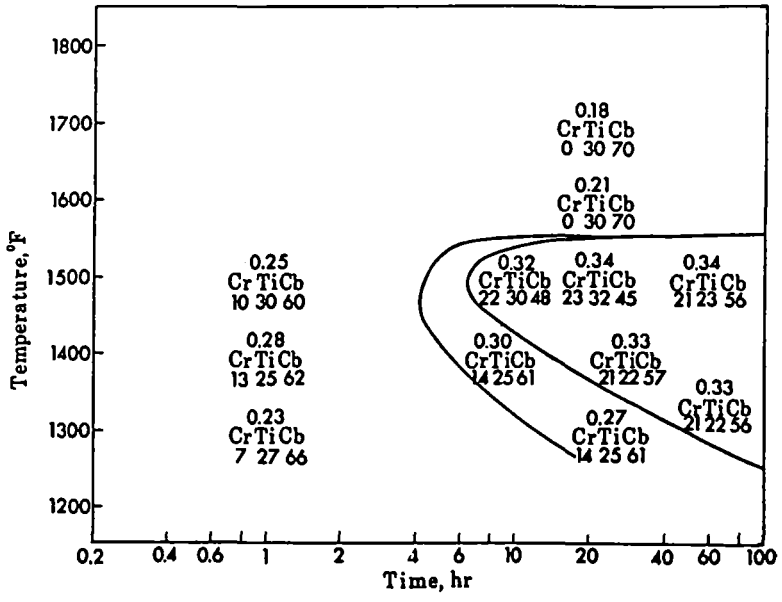
Time-temperature-precipitation diagram for $M_{23}C_6$
Numbers show the Cr and Ti contents of the residue (77Cr, 13Ti for as-annealed material)

Inconel X-750

Composition: Ni - 0.05% C - 0.57% Mn - 6.56% Fe - 0.25% Si - 0.05% Cu - 15.66% Cr - 0.70% Al - 2.35% Ti - 0.92% Nb



LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram for $M_{23}C_6$
The amount of $M_{23}C_6$ is indicated by the chromium content of the carbide residue

SOURCE: E.L. Raymond, "Mechanisms of Sensitization and Stabilization of Incoloy Nickel-Iron-Chromium Alloy 825," Corrosion, Vol 24, No. 6, June 1968, pp 180-188

IN 939

Nominal Composition: Ni - 0.15% C - 22.5% Cr - 19.0% Co - 2.0% W - 1.0% Nb - 1.4% Ta - 3.7% Ti - 1.9% Al - 0.1% Zr - 0.01% B

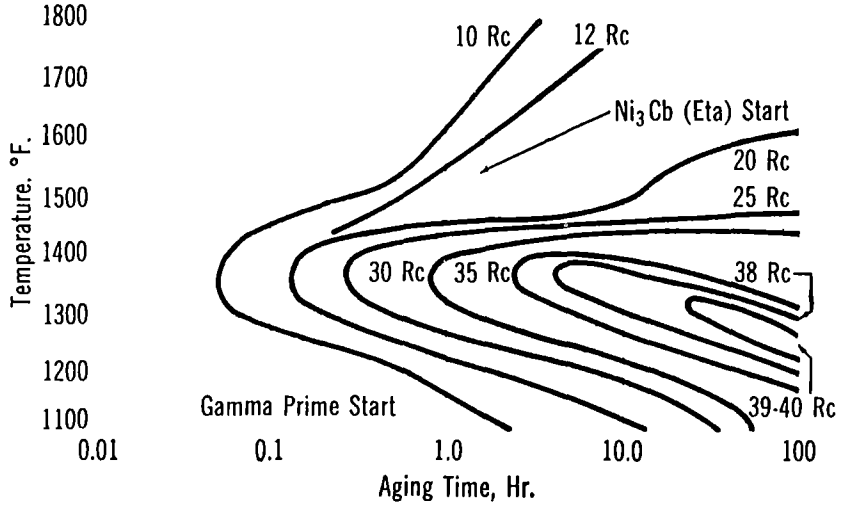
Temperature °C	Temperature (°F)	Phase Reaction
1340	(2444)	Liquidus temperature
~1300	(~2372)	Formation of primary MC
1235	(2255)	Solidus temperature
1145	(2093)	Solvus temperature of eta
1080 to 1100	(1976 to 2012)	Solvus temperature of gamma prime
~1000	(~1832)	Solvus temperature of $M_{23}C_6$
~950	(~1742)	Solvus temperature of sigma
~850	(~1562)	Maximum rate of sigma formation

Information for time-temperature-precipitation diagram

SOURCE: T.B. Gibbons, R. Stickler, "IN939: Metallurgy, Properties and Performance," High Temperature Alloys for Gas Turbines, 1982, D. Reidel Publishing Co., Dordrecht, Holland, 1982, pp 369-393

Inconel 718

Nominal composition: Fe - 52% Ni - 19% Cr - 3% Mo - 5% Nb+Ta - 0.8% Ti - 0.6% Al - 0.05% C
Treatment: Mill annealed, heated at 927°C (1700°F) for 1 h, air cooled, aged at 718°C (1325°F) for 16 h, air cooled

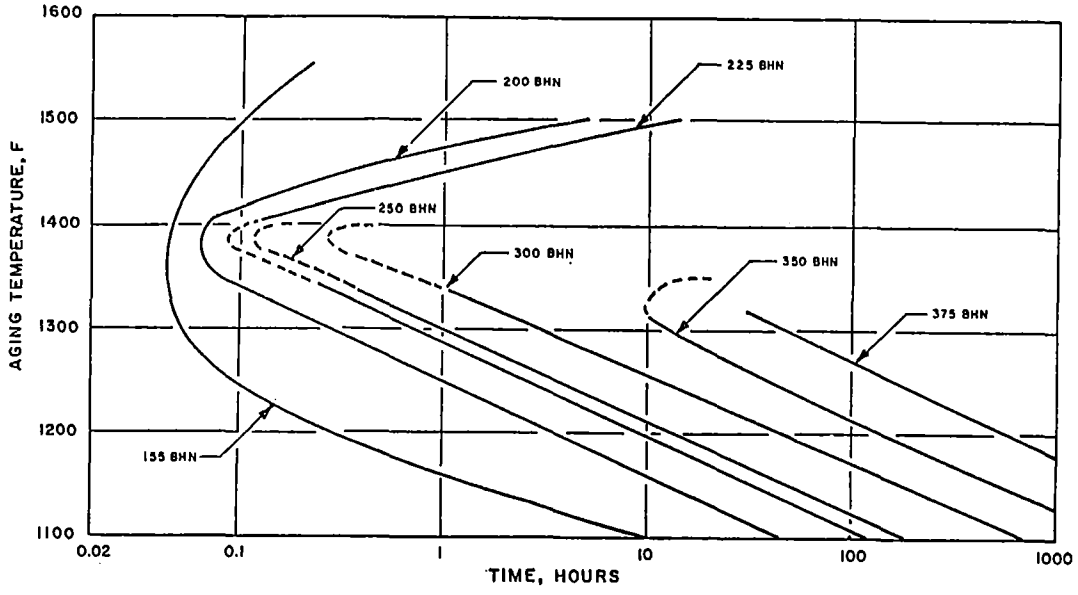


Time-temperature hardness
At this time the strengthening phase was thought to be gamma prime, and later found to be gamma double prime

SOURCE: J.F. Barker, "A Superalloy for Medium Temperatures," Metal Progress, May 1962, pp 72-76

Inconel 718

Composition: Ni - 18.49% Cr - 16.79% Fe - 5.07% Nb+Ta - 3.11% Mo - 0.95% Ti - 0.51% Al - 0.30% Si - 0.28% Mn - 0.05% Cu - 0.04% C - 0.011% P - 0.007% S - 0.0023% B
Treatment: Solution treated at 1038°C (1900°F) for 30 min, water quenched to room temperature within 1 min



LIVE GRAPH
Click here to view

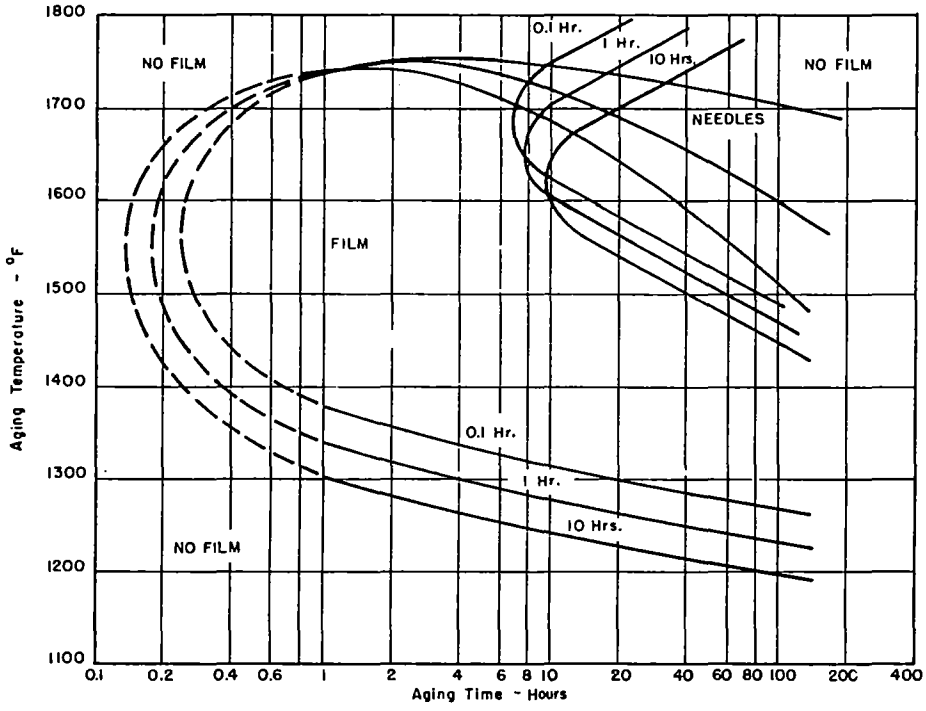
Time-temperature-hardness diagram
Strengthening phase still thought to be gamma prime

SOURCE: B.G. Koepke, R.J. Zeto, W.E. Hensley, "Mechanism and Kinetics of Aging in Inconel 718," NASA Tech. Bulletin 70-1021, June 1970, p 34

Inconel 718

Nominal composition: Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti - 0.4% Al - 0.04% C - 0.007% S

Treatment: Solution annealed at 1149°C (2100°F), aged at various times and temperatures indicated



LIVE GRAPH
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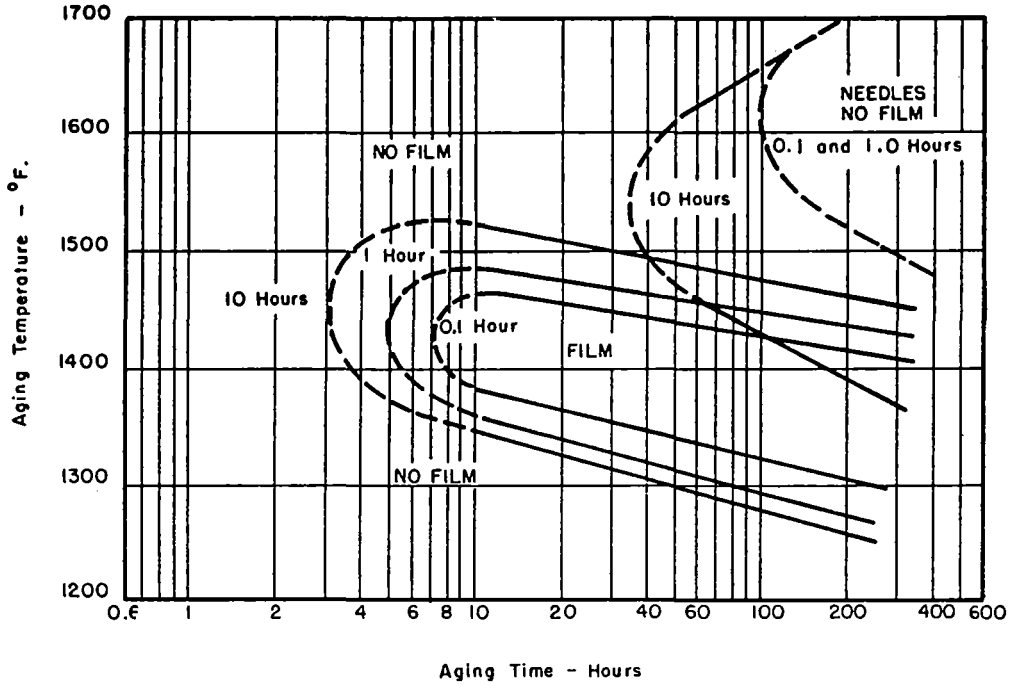
Time-temperature-precipitation diagram
Occurrence of grain boundary carbide film and needles

SOURCE: H.L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," Advances in The Technology of Stainless Steels and Related Alloys, ASTM STP No. 369, 1965 pp 62-79

Inconel 718

Nominal composition: Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti - 0.4% Al - 0.04% C - 0.007% S

Treatment: Solution annealed at 1038°C (1900°F), aged at various times and temperatures indicated



LIVE GRAPH
Click here to view

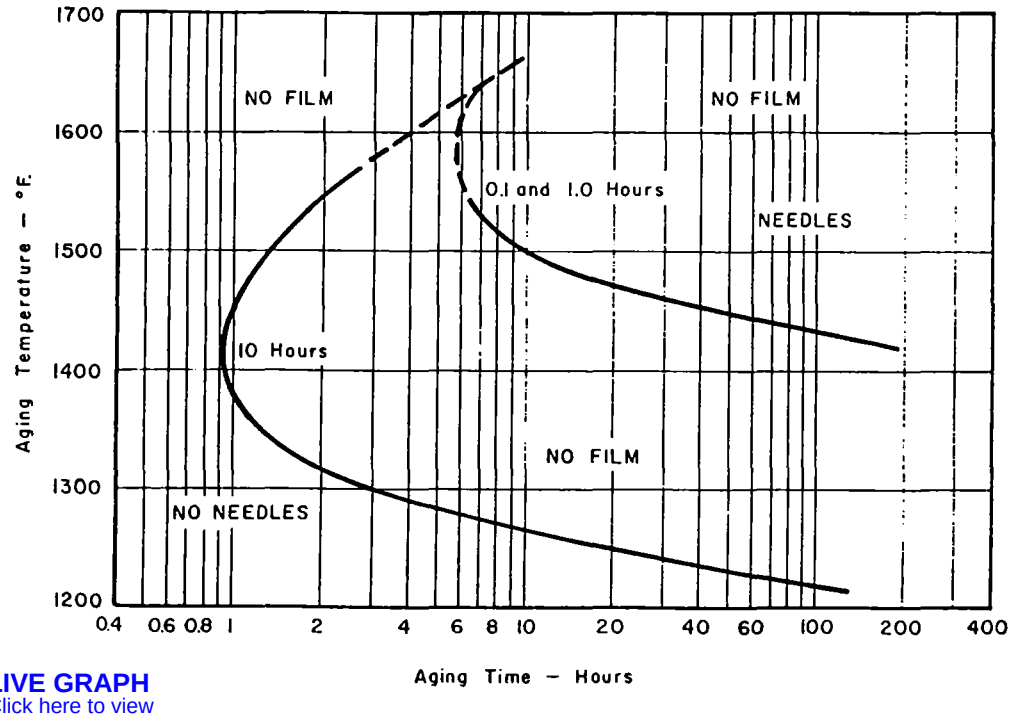
Time-temperature-precipitation diagram
Occurrence of grain boundary carbide film and needles

SOURCE: H.L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," Advances in The Technology of Stainless Steels and Related Alloys, ASTM STP No. 369, 1965 pp 62-79

Inconel 718

Nominal composition: Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti - 0.4% Al - 0.04% C - 0.007% S

Treatment: Solution annealed at 927°C (1700°F), aged at various times and temperatures indicated



LIVE GRAPH
Click here to view

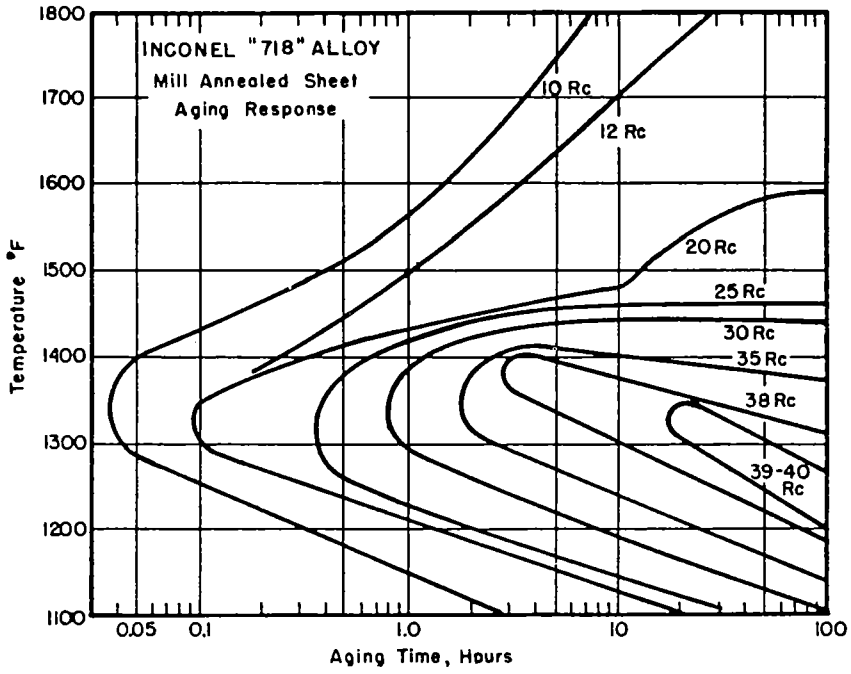
Time-temperature-precipitation diagram
Occurrence of grain boundary carbide film and needles

SOURCE: H.L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," Advances in The Technology of Stainless Steels and Related Alloys, ASTM STP No. 369, 1965 pp 62-79

Inconel 718

Nominal composition: Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti - 0.4% Al - 0.04% C - 0.007% S

Treatment: Solution annealed at 1038°C (1900°F) for 1 h



LIVE GRAPH
Click here to view

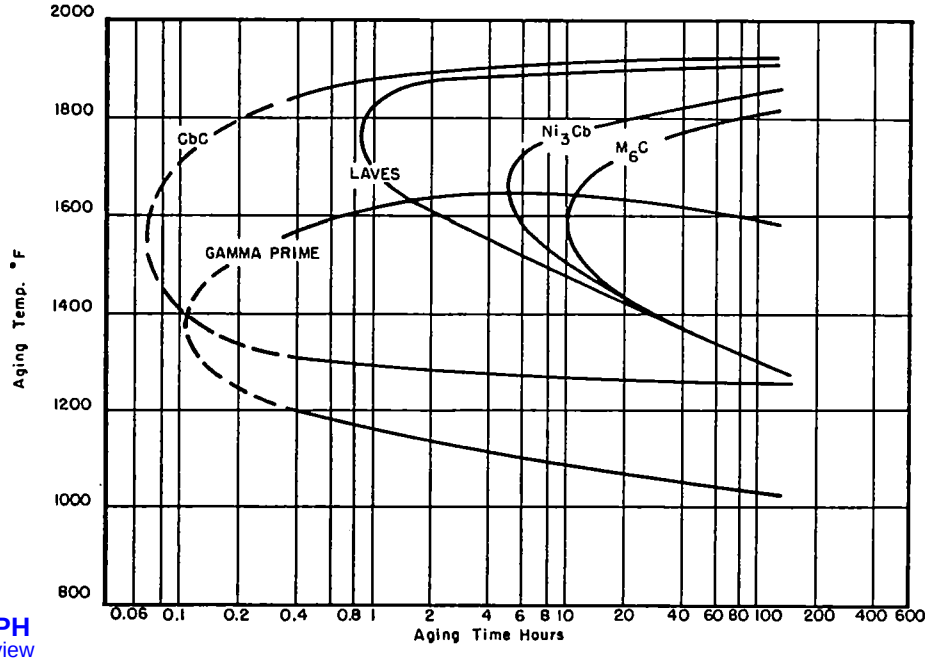
Time-temperature-hardness diagram

SOURCE: H.L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," Advances in The Technology of Stainless Steels and Related Alloys, ASTM STP No. 369, 1965 pp 62-79

Inconel 718

Nominal composition: Ni - 19% Cr - 18% Fe - 5% Nb - 3% Mo - 0.15% Si - 0.10% Cu - 0.20% Mn - 1.0% Ti - 0.4% Al - 0.04% C - 0.007% S

Treatment: Solution annealed at 1149°C (2100°F) for 1 h, and water quenched



LIVE GRAPH
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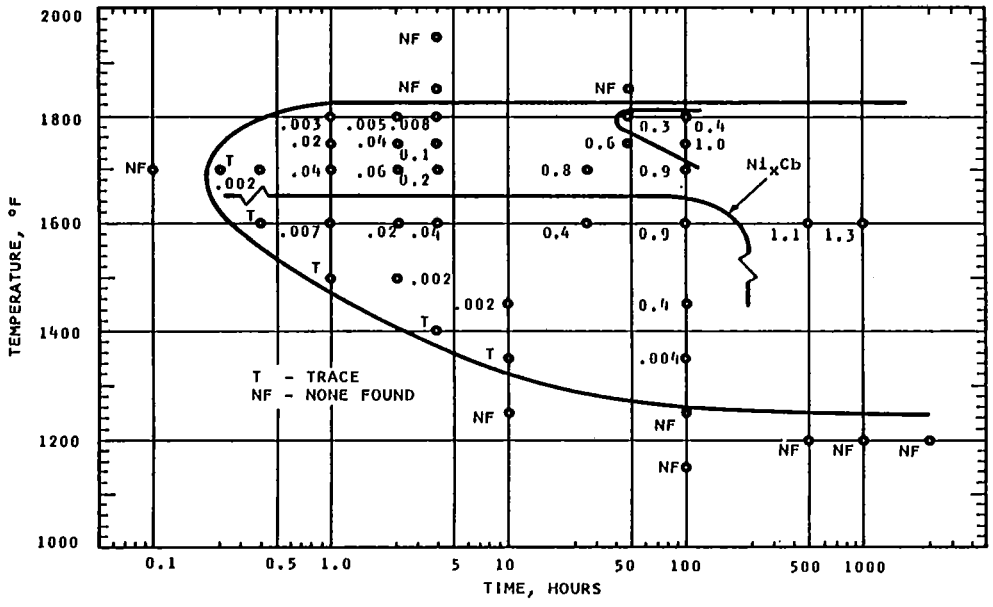
Time-temperature-precipitation diagram
At this time the strengthening phase was thought to be gamma prime, later it was shown to be gamma double prime

SOURCE: H.L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy," Advances in The Technology of Stainless Steels and Related Alloys, ASTM STP No. 369, 1965 pp 62-79

Inconel 718

Composition: Fe - 53.8% Ni - 18.0% Cr - 3.00% Mo - 5.24% Nb+Ta - 1.00% Ti - 0.59% Al - 0.05% C - 0.003% S - 0.004% B
Treatment: Solution treated at 1066°C (1950°F) for 4 h, air cooled



LIVE GRAPH
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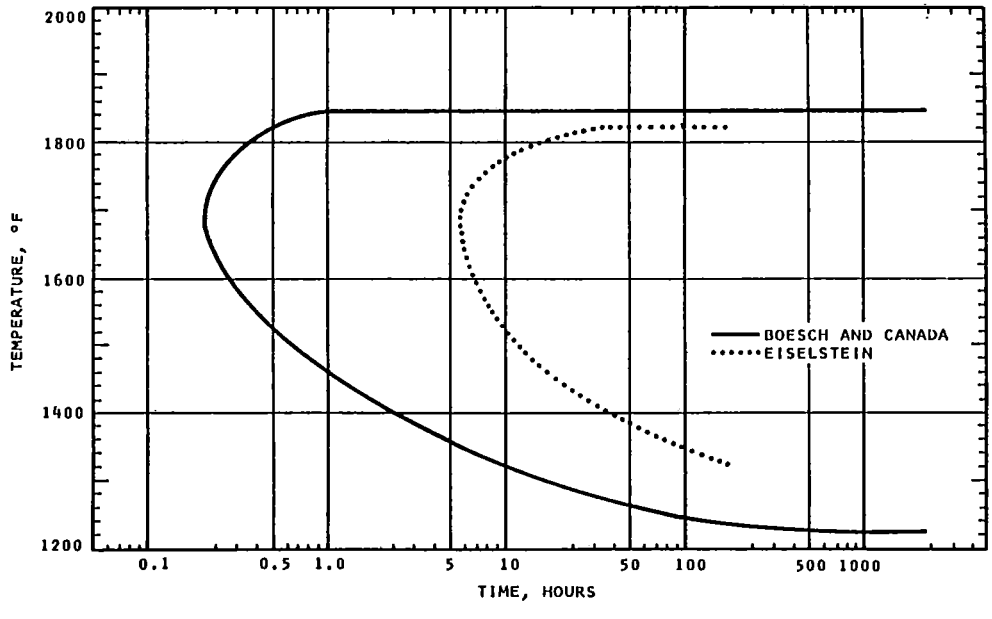
Time-temperature-precipitation diagram of Ni_3Nb

Composition: Fe - 53.8% Ni - 18.0% Cr - 3.00% Mo - 5.24% Nb+Ta - 1.00% Ti - 0.59% Al - 0.05% C - 0.003% S - 0.004% B
Treatment: Solution treated at 1066°C (1950°F) for 4 h, air cooled



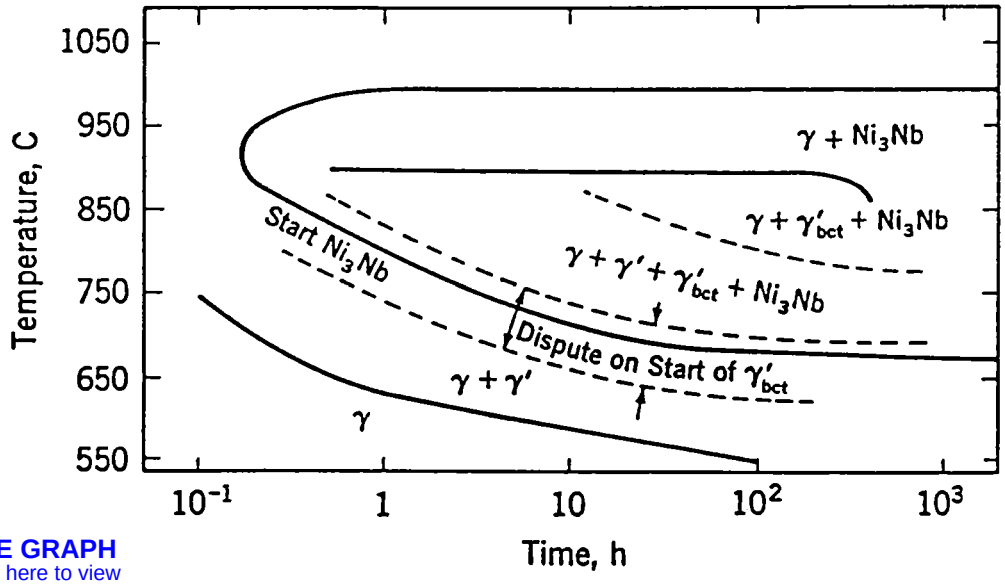
Time-temperature-precipitation diagram for Ni_3Nb compared to Eiselstein data

LIVE GRAPH
Click here to view

SOURCE: W.J. Boesch, H.B. Canada, "Precipitation Reactions and Stability of NI_3Nb in Inconel Alloy 718," International Symposium on Structural Stability in Superalloys, Seven Springs PA, 4-6 September, 1968; and, Journal of Metals, Vol 22, October 1969, pp 34-38

Inconel 718

Composition: Ni - 0.04% C - 0.20% Mn - 0.30% Si - 18.6% Cr - 3.1% Mo - 5.0% Nb - 18.5% Fe - 0.9% Ti - 0.4% Al



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Composite time-temperature-precipitation diagram
Data from E.L. Raymond (1967); H.L. Eiselstein (1965); W.J. Boesch, H.B. Canada (1968); F.J. Rizzo, J.D. Buzzanell, (1968)

SOURCE: R.F. Decker, "Strengthening Mechanisms in Nickel-Base Superalloys," Steel-Strengthening Mechanisms, 5-6 May, 1969, Zurich, pp 147-170

Inconel 718

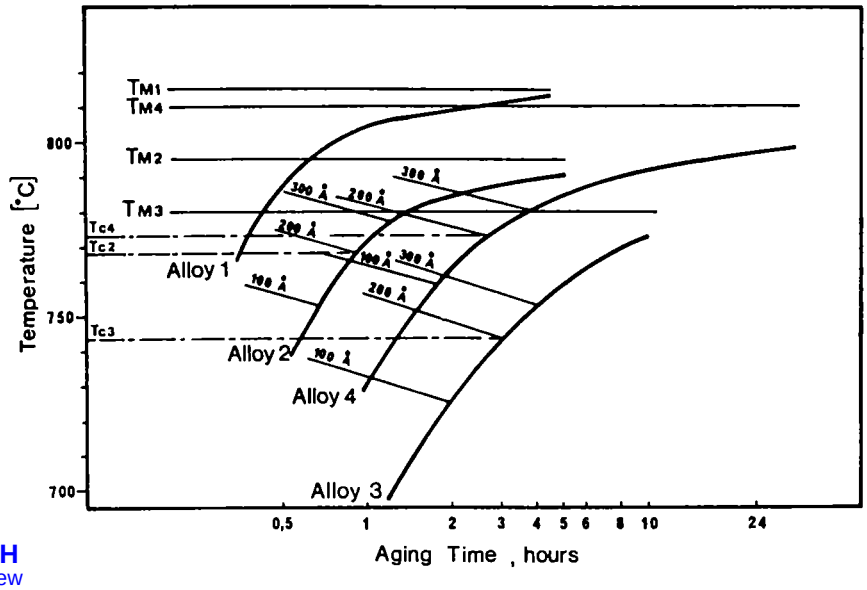
Alloy 1 composition: 52.51% Ni - 18.16% Cr - 19.5% Fe - 2.96% Mo - 0.82% Ti - 0.70% Al - 5.18% Nb

Alloy 2 composition: 51.98% Ni - 18.59% Cr - 21% Fe - 2.85% Mo - 0.72% Ti - 0.63% Al - 3.99% Nb

Alloy 3 composition: 51.98% Ni - 18.97% Cr - 17% Fe - 7.03% Mo - 0.59% Ti - 0.63% Al - 3.41% Nb

Alloy 4 composition: 52.09% Ni - 18.90% Cr - 16.4% Fe - 7.00% Mo - 0.90% Ti - 0.74% Al - 3.85% Nb

Treatment: Annealed at 1200°C (2192°F) for 30 min, water quenched, aged at 650 to 820°C (1202 to 1508°F) under vacuum in vycor capsules



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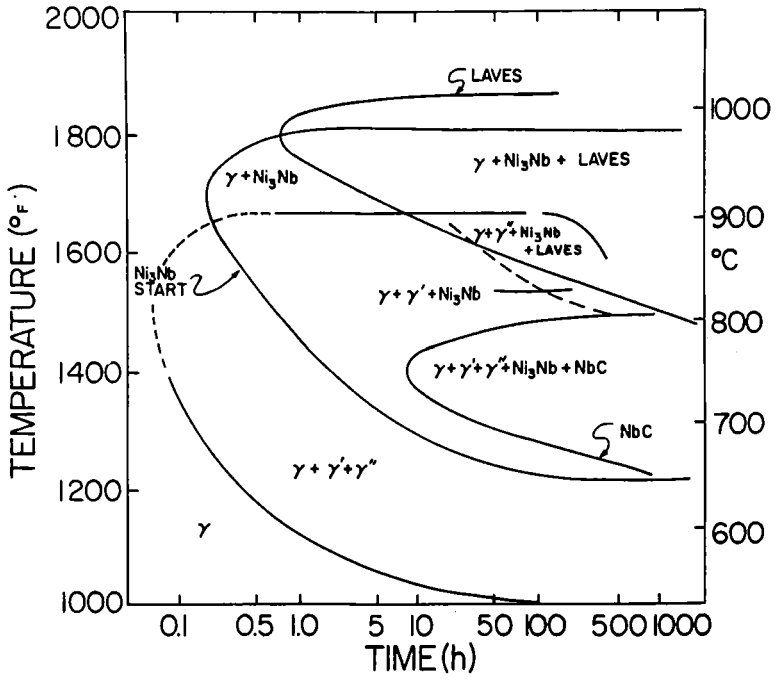
Time-temperature-precipitation diagram
For appearance of gamma double prime phase and highest temperatures T_M for homogeneous precipitation in alloys 1, 2, 3, and 4. On this diagram curves showing the gamma prime size before appearance of gamma double prime are indicated for alloys 2, 3, and 4

SOURCE: R. Cozar, A. Pineau, "Morphology of Y' and Y" Precipitates and Thermal Stability of Inconel 718 Type Alloys," Met. Trans., Vol 4, January 1973, pp 47-59

Inconel 718



LIVE GRAPH
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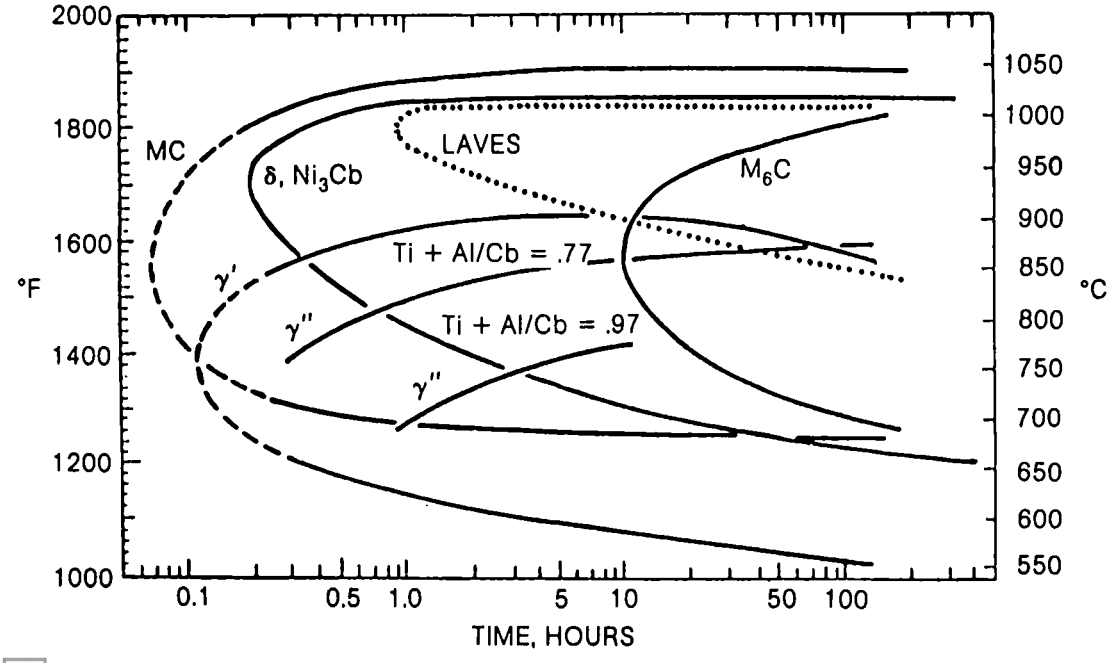
Time-temperature-precipitation diagram

SOURCE: E.R. Vincent, "The Microstructure of Welds in Inconel 718," Department of Physics, University of Bristol, UK, 1980

Composition: Fe - 52.5% Ni - 0.04% C - 19.0% Cr - 0.90% Ti - 0.50% Al - 0.005% B - 3.05% Mo - 5.30% Nb
Treatment: Annealed in the range 1149 to 1093°C (2100 to 2000°F) for 1 hr, water quenched



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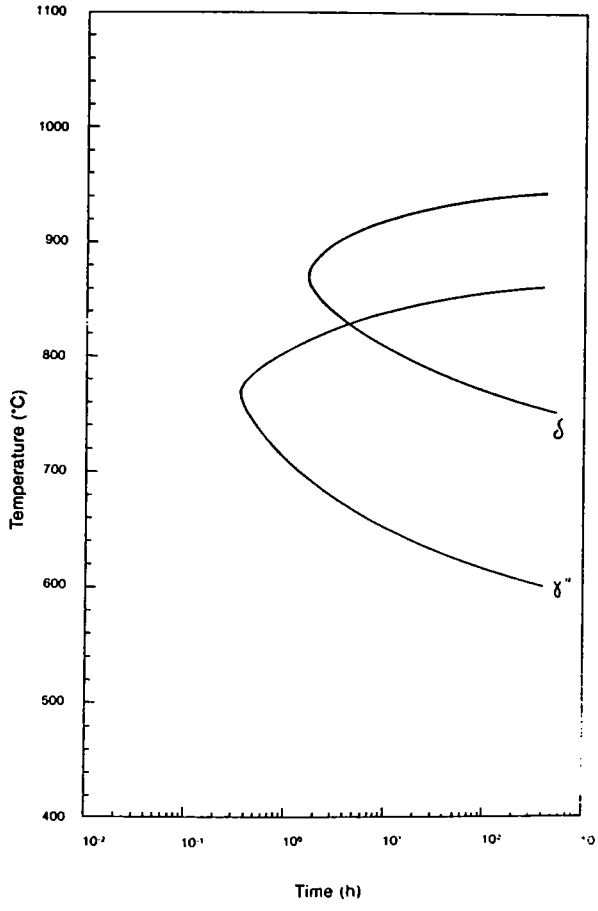
TTT diagram
A composite of past work

SOURCE: C.T. Sims, "A Perspective of Niobium in Superalloys," International Symposium of Niobium Processing, H. Stuart, ed., 8-11 November 1981, San Francisco, AIME, 1984, pp 1169-1220

Inconel 718

Nominal composition: Fe - 0.08% max C - 0.35% max Mn - 0.35% max Si - 0.015% max P - 0.015% max S - 17.0-21.0% Cr - 1.0% max Co - 2.80-3.30% Mo - 4.75-5.50% Nb+Ta - 0.65-1.15% Ti - 0.20-0.80% Al - 0.30% max Cu - 50.0-55.0 Ni+Co - 0.006% max B

Treatment: Solution treated at 1090°C (1994°F), isothermally aged at temperatures between 500 and 1050°C (932 and 1922°F) for times varying from 15 min to 250 h



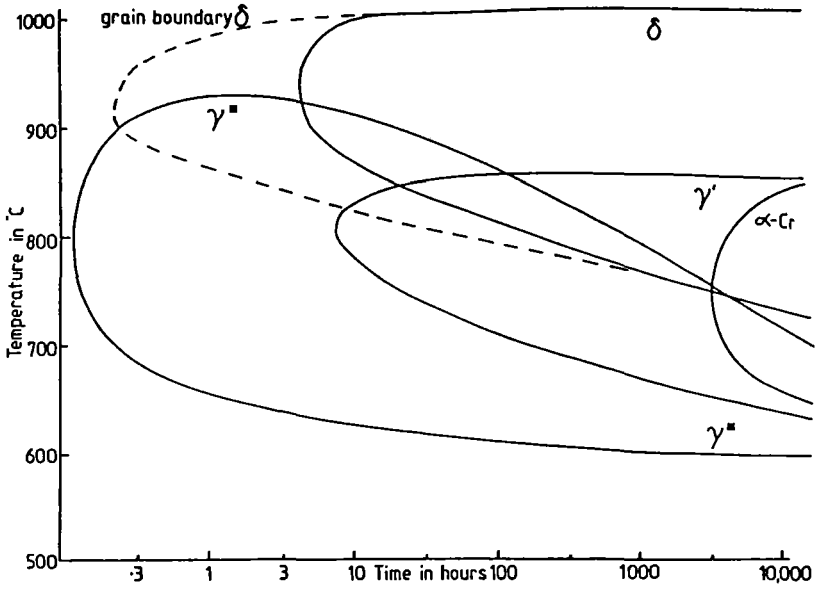
Time-temperature-precipitation diagram for delta and gamma double prime

SOURCE: E. Campo, C. Turco, V. Catena, "The Correlation Between Heat Treatment, Structure and mechanical Characteristics in Inconel 718," Metallurgical Science and Technology, Vol 3, No. 1, April 1985, pp 16-21

Inconel 718

Composition: Ni - 17.58% Fe - 18.83% Cr - 0.98% Ti - 2.97% Mo - 5.13% Nb - 0.53% Al - 0.05% Ta - 0.30% Co - 0.09% Mn - 0.04% C - 0.004% S - 0.01% P - 0.17% Si - 0.09% Cu

Treatment: Solution treated between 955 and 1200°C (1751 and 2192°F) followed by either water quench, air cool, or furnace cool



LIVE GRAPH
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Time-temperature-precipitation diagram
For Ni_3Nb (bct) = gamma *, gamma prime, delta, and alpha-chromium

SOURCE: J.W. Brooks, P.J. Bridges, "Long Term Stability of Inconel Alloy 718 for Turbine Disc Applications," High Temperature Alloys for Gas Turbines and Other Applications, 1986, Part II, D. Reidel Publishing Co., Dordrecht, 1986, pp 1431-1440

Inconel 718

Composition 718 (solid line): Ni - 0.95% Ti - 0.46% Al - 5.26% Nb - 18.25% Fe - 3.05% Mo - 18.00% Cr - 0.031% C - 0.003% B - 0.001% Mg
Composition alloy 4 (dashed line): Ni - 1.34% Ti - 0.63% Al - 5.28% Nb - 18.30% Fe - 3.05% Mo - 17.80% Cr - 0.028% C - 0.004% B - 0.001% Mg
Treatment: Solutionized at 1110°C (2030°F) for 6 h and quenched

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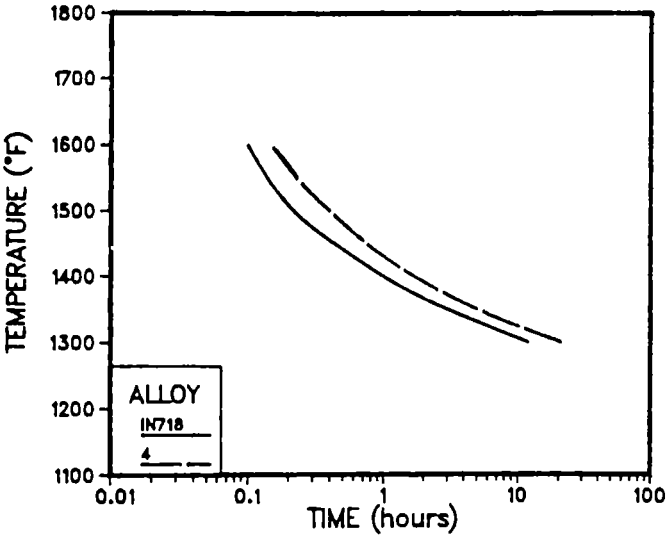

Time-temperature-precipitation diagram
Delta phase start only

Composition alloy 9 (solid line): Ni - 0.96% Ti - 0.53% Al - 4.32% Nb - 18.30% Fe - 3.02% Mo - 18.15% Cr - 0.031% C - 0.003% B - 0.004% Mg
Composition alloy 11 (dashed line): Ni - 0.96% Ti - 0.87% Al - 5.42% Nb - 18.00% Fe - 3.02% Mo - 17.80% Cr - 0.031% C - 0.004% B - 0.001% Mg
Treatment: Solutionized at 1110°C (2030°F) for 6 h and quenched

LIVE GRAPH
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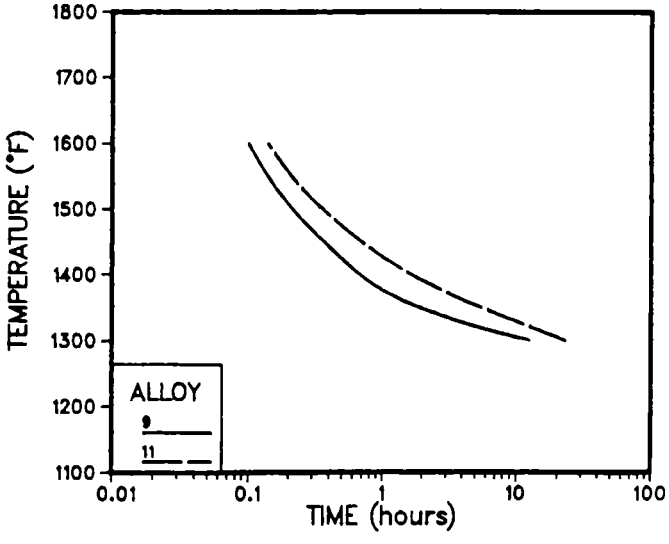


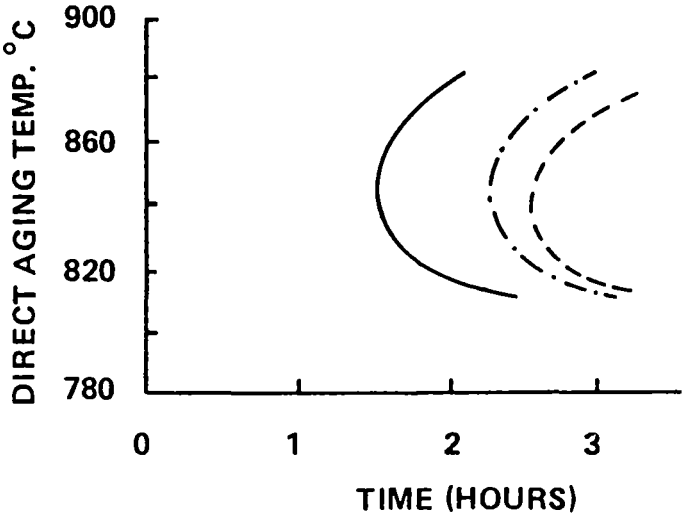
Time-temperature-precipitation diagram
Delta phase start only

SOURCE: J.P. Collier, Song How Wong, J.C. Phillips, J.K. Tien, "The Effect of Varying Al, Ti, and Nb Content on the Phase Stability of Inconel 718," Met. Trans. A, Vol 19A, July 1988, pp 1657-1666

Inconel 718

Composition: 53.1-53.2% Ni - 17.8-19.1% Fe - 0.03-0.05% C - 0.21-1.12% Si - 17.9-18.3% Cr - 3.0-3.06% Mo - 5.11-5.17% Nb+Ta - 0.96-1.0% Ti - 0.42-0.47% Al

Treatment: Solution treated at 1032, 1066, and 1080°C (1900, 1950, and 1976°F)



LEGEND:

——— 1032°C ST
—·— 1066°C ST
– – – 1080°C ST

LIVE GRAPH
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Time-temperature-precipitation diagram
Delta phase Ni_3Nb start only

SOURCE: A.K. Koul, et. al., "Development of a Damage Tolerant Microstructure for Inconel 718 Turbine Disc Material," Superalloys 1988, S. Reichman, et al., Eds., TMS, 1988, pp 3-12

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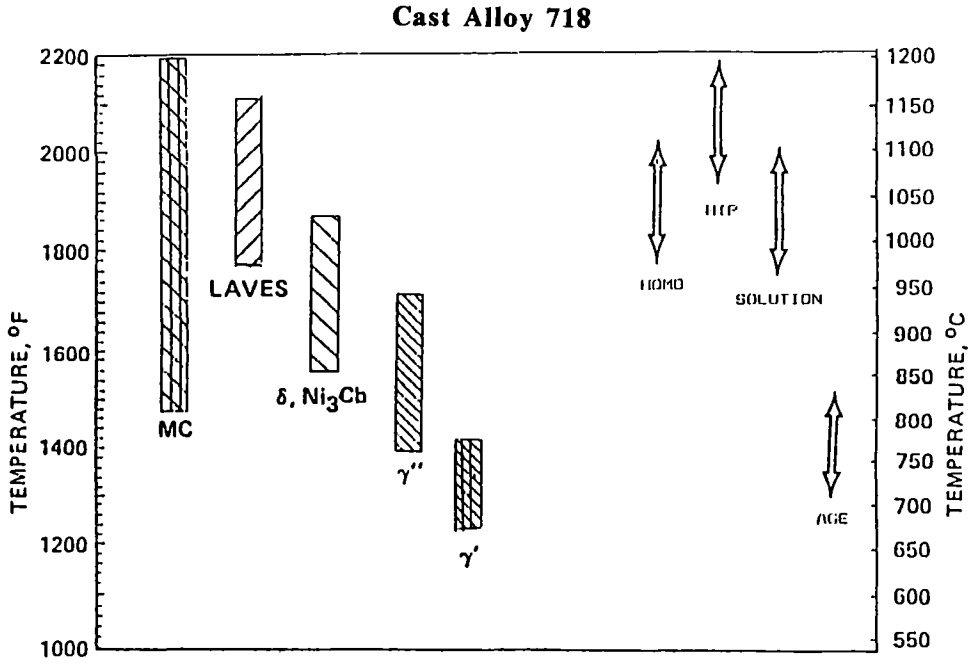

Temperature-phase stability diagram for cast 718 showing temperature for homogenization and HIP heat treat cycle
The range of temperatures in which the various phases can be found is only valid if the cast material has been originally homogenized and then heat treated

LIVE GRAPH
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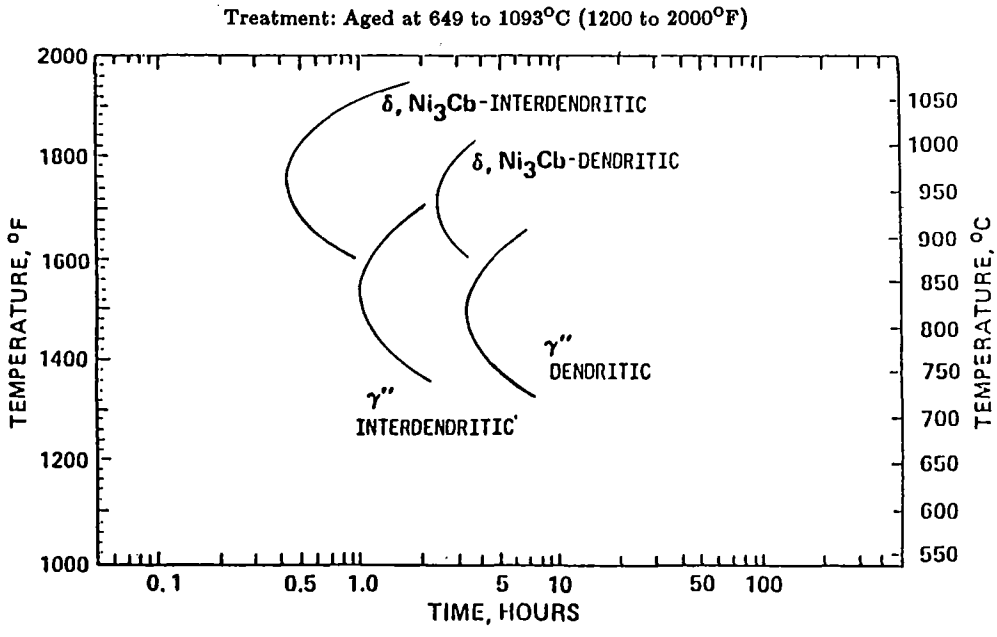

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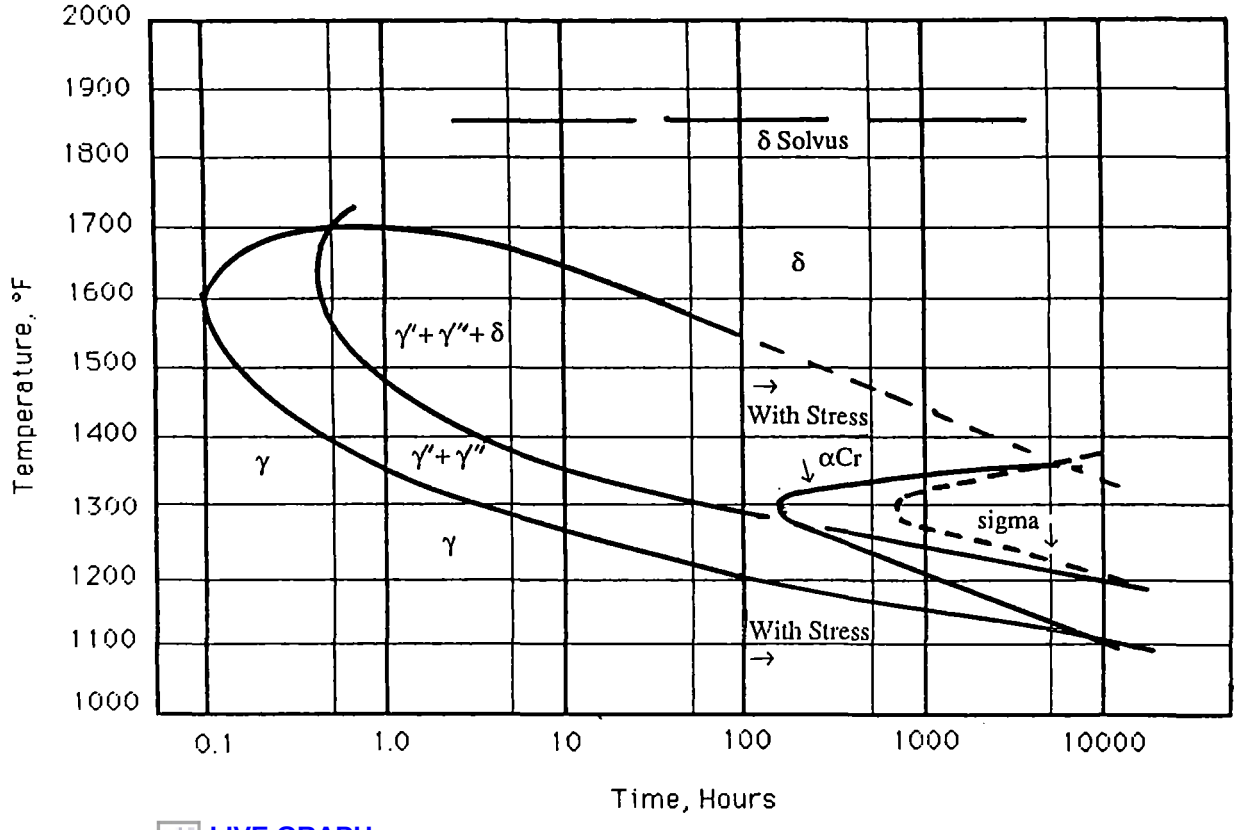
Time-temperature-precipitation diagram for cast 718
The temperature ranges of phase precipitation change as the chemistries vary and/or if the material initially is not totally homogenized

SOURCE: R.G. Carlson, J.F. Radavich, "Microstructural Characterization of Cast 718," Superalloy 718 - Metallurgy and Applications, E.A. Loria, ed., TMS, 1989, pp 79-95

Alloy 718

Composition: A nominal 718 composition with 5.38% Nb and 0.07% Si
Treatment: Heat treated at 1002°C (1835°F) for 15 min, samples were exposed at 649 to 927°C (1200 to 1700°F) for 0.1 to 50 h, and water quenched



LIVE GRAPH
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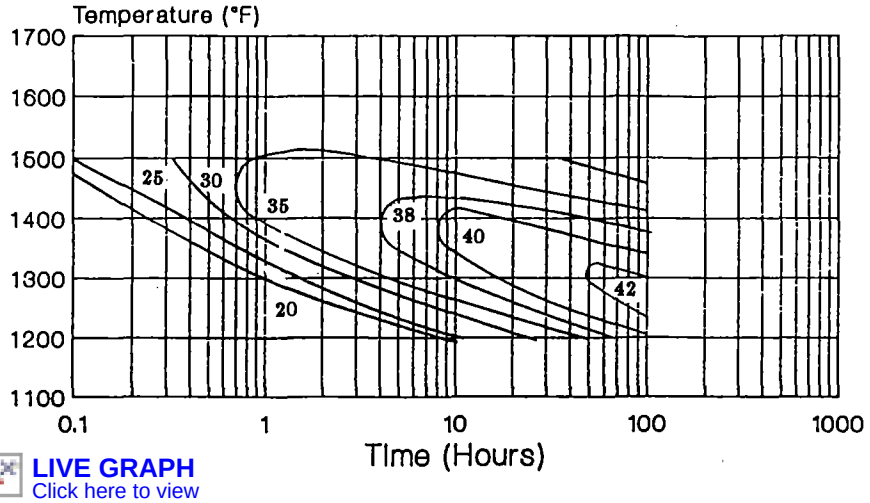
Time-temperature-aging diagram

SOURCE: A. Oradei-Basile, J.F. Radavich, "A Current T-T-T Diagram for Wrought Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 325-335

Alloy 718

Composition: 51.6% Ni - 20.2% Fe - <0.05% Co - 3.20% Mo - 5.28% Nb+Ta - 0.94% Ti - 0.46% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.007% S - 0.004% P - <0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30 μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h



LIVE GRAPH
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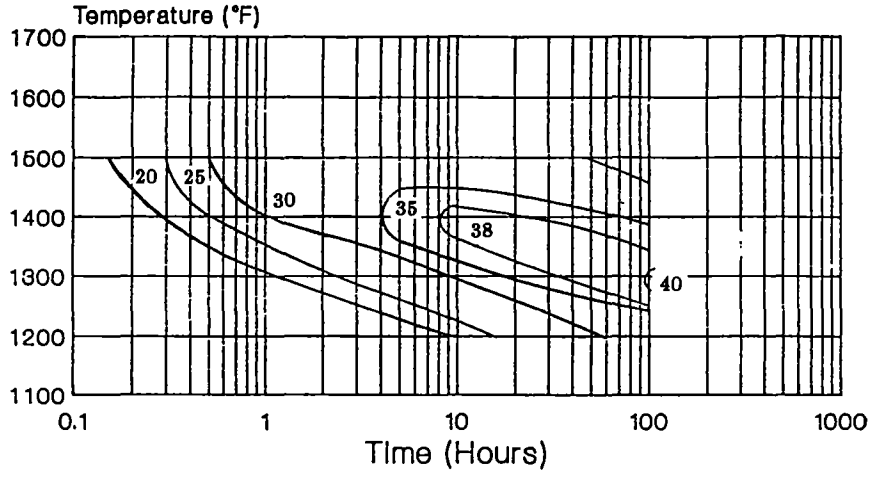
Time-temperature-hardness HRC diagram

Alloy 718 (Modified)

Composition: 61.6% Ni - 9.8% Fe - <0.05% Co - 3.20% Mo - 5.13% Nb+Ta - 0.96% Ti - 0.58% Al - 0.04% Mn - 0.06% Si - 0.02% C - 0.001% B - 0.006% S - 0.002% P - <0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30 μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h



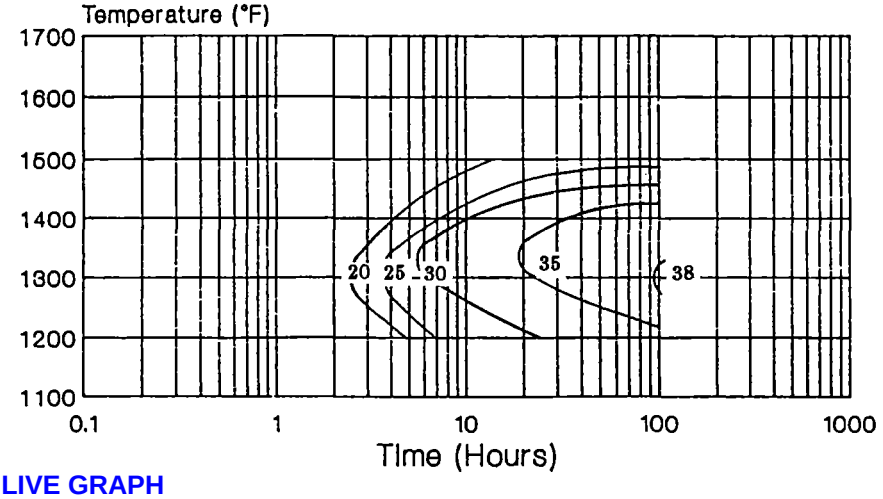
LIVE GRAPH
Click here to view

Time-temperature-hardness HRC diagram

SOURCE: J.R. Groh, J.F. Radavich, "Effects of Iron, Nickel, and Cobalt on Precipitation Hardening of Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 351-361

Alloy 718 (Modified)

Composition: 69.8% Ni - <0.05% Fe - <0.05% Co - 3.02% Mo - 5.14% Nb+Ta - 0.93% Ti - 0.53% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.003% B - 0.008% S - 0.004% P - <0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30 μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h



LIVE GRAPH
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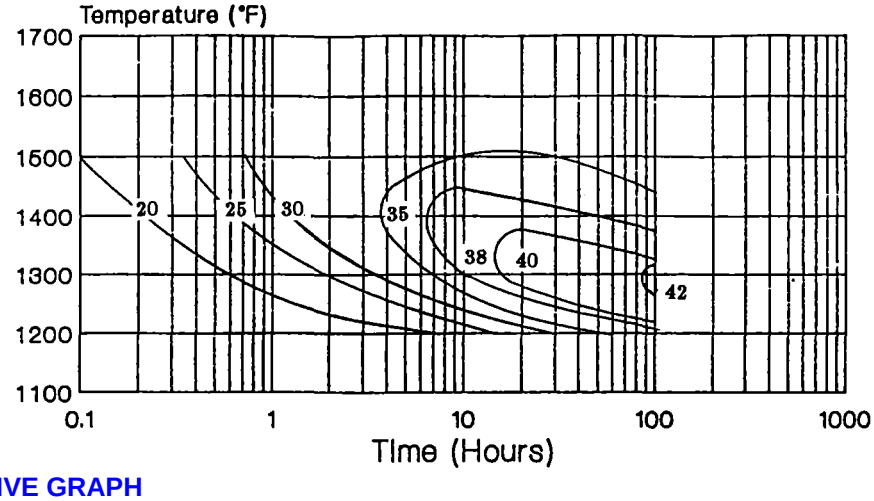
Time-temperature-hardness HRC diagram

Composition: 52.9% Ni - 10.1% Fe - 8.6% Co - 3.10% Mo - 5.05% Nb+Ta - 0.90% Ti - 0.48% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.006% S - 0.005% P - 0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30 μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h



LIVE GRAPH
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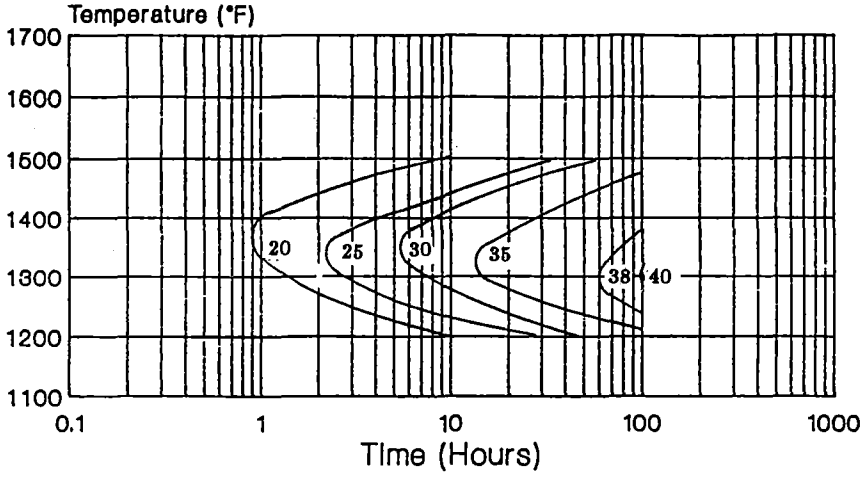
Time-temperature-hardness HRC diagram

SOURCE: J.R. Groh, J.F. Radavich, "Effects of Iron, Nickel, and Cobalt on Precipitation Hardening of Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 351-361

Alloy 718 (Modified)

Composition: 54.2% Ni - 0.25% Fe - 17.6% Co - 3.19% Mo - 5.31% Nb+Ta - 0.92% Ti - 0.48% Al - 0.03% Mn - 0.04% Si - 0.04% C - 0.003% C - 0.006% S - 0.005% P - 0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h



LIVE GRAPH
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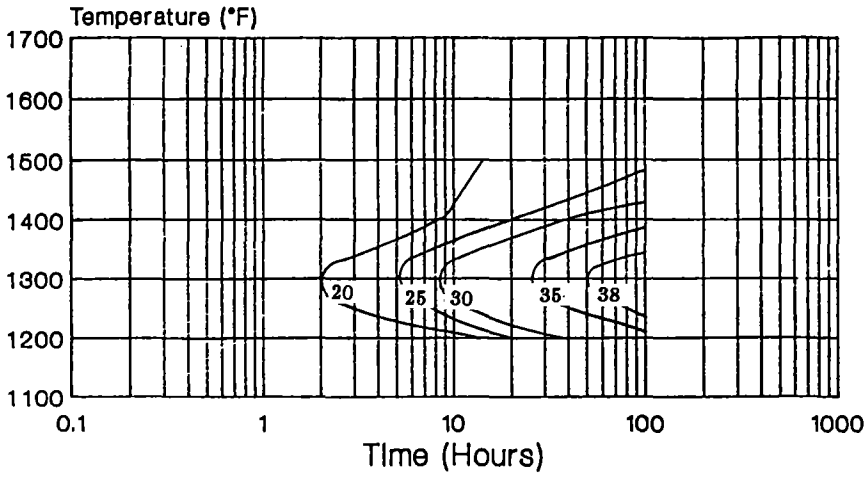
Time-temperature-hardness HRC diagram

SOURCE: J.R. Groh, J.F. Radavich, "Effects of Iron, Nickel, and Cobalt on Precipitation Hardening of Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 351-361

Alloy 718 (Modified)

Composition: 62.8% Ni - <0.05% Fe - 8.8% Co - 3.0% Mo - 5.09% Nb+Ta - 0.86% Ti - 0.47% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.002% B - 0.006% S - 0.004% P - 0.01% Cu
Treatment: Samples solution annealed at temperature to produce a 30μm grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h

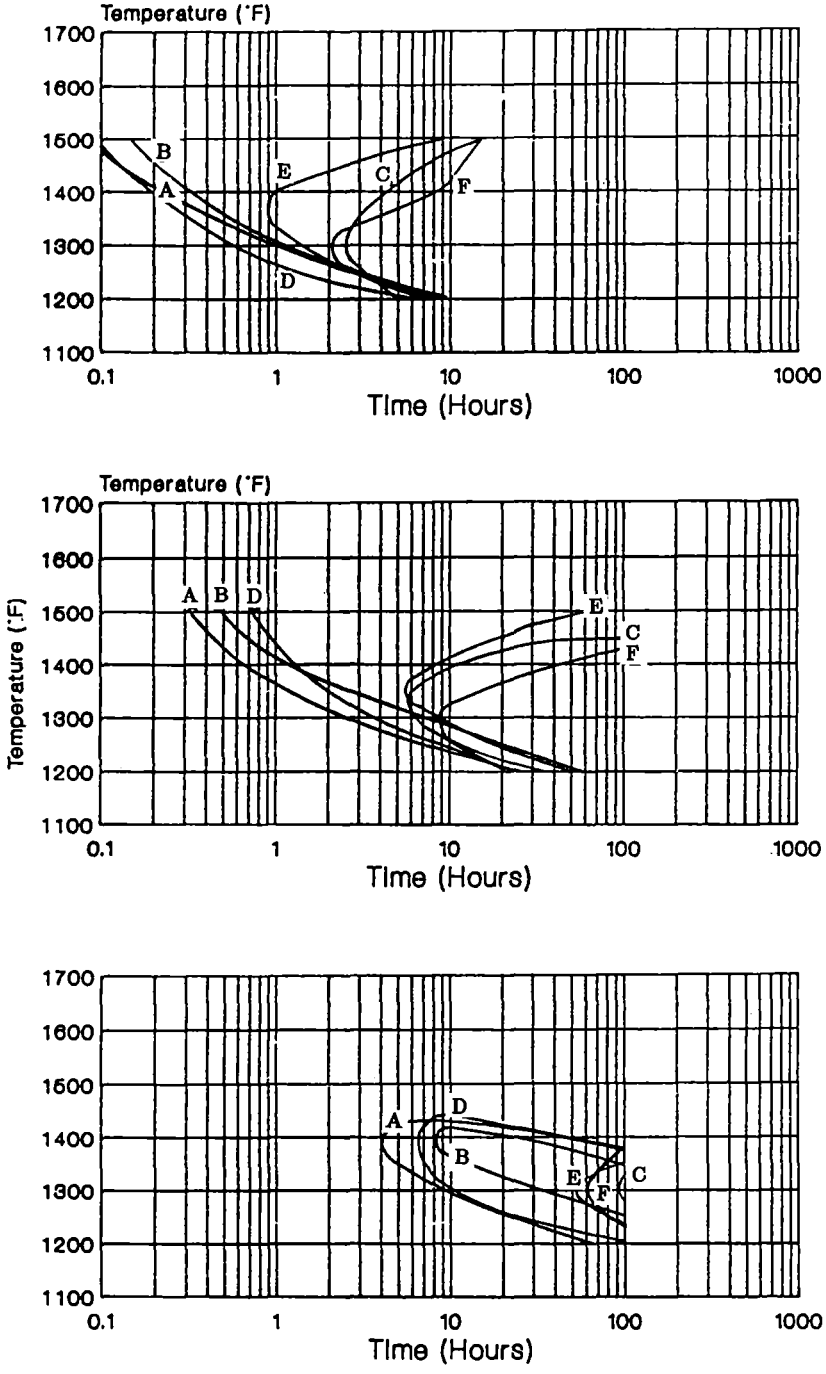


LIVE GRAPH
Click here to view

Time-temperature-hardness HRC diagram

SOURCE: J.R. Groh, J.F. Radavich, "Effects of Iron, Nickel, and Cobalt on Precipitation Hardening of Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 351-361

Alloy 718 (and Modifications)



Alloy A Composition: 51.6% Ni - 20.2% Fe - <0.05% Co - 3.20% Mo - 5.28% Nb+Ta - 0.94% Ti - 0.46% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.007% S - 0.004% P - <0.01% Cu

Alloy B Composition: 61.6% Ni - 9.8% Fe - <0.05% Co - 3.20% Mo - 5.13% Nb+Ta - 0.96% Ti - 0.58% Al - 0.04% Mn - 0.06% Si - 0.02% C - 0.001% B - 0.006% S - 0.002% P - <0.01% Cu

Alloy C Composition: 69.8% Ni - <0.05% Fe - <0.05% Co - 3.02% Mo - 5.14% Nb+Ta - 0.93% Ti - 0.53% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.003% B - 0.008% S - 0.004% P - <0.01% Cu

Alloy D Composition: 52.9% Ni - 10.1% Fe - 8.6% Co - 3.10% Mo - 5.05% Nb+Ta - 0.90% Ti - 0.48% Al - 0.04% Mn - 0.06% Si - 0.03% C - 0.003% B - 0.006% S - 0.005% P - 0.01% Cu

Alloy E Composition: 54.2% Ni - 0.25% Fe - 17.6% Co - 3.19% Mo - 5.31% Nb+Ta - 0.92% Ti - 0.48% Al - 0.03% Mn - 0.04% Si - 0.04% C - 0.003% C - 0.006% S - 0.005% P - 0.01% Cu

Alloy F Composition: 62.8% Ni - <0.05% Fe - 8.8% Co - 3.0% Mo - 5.09% Nb+Ta - 0.86% Ti - 0.47% Al - 0.04% Mn - 0.05% Si - 0.03% C - 0.002% B - 0.006% S - 0.004% P - 0.01% Cu

Treatment: Samples solution annealed at temperature produce a 30μ m grain size. Specimens were aged at 649, 704, 760 and 816°C (1200, 1300, 1400 and 1500°F) for 0.1 to 96 h; also at 871°C (1600°F) for 1 and 4 h; and at 593°C (1100°F) for 4 h

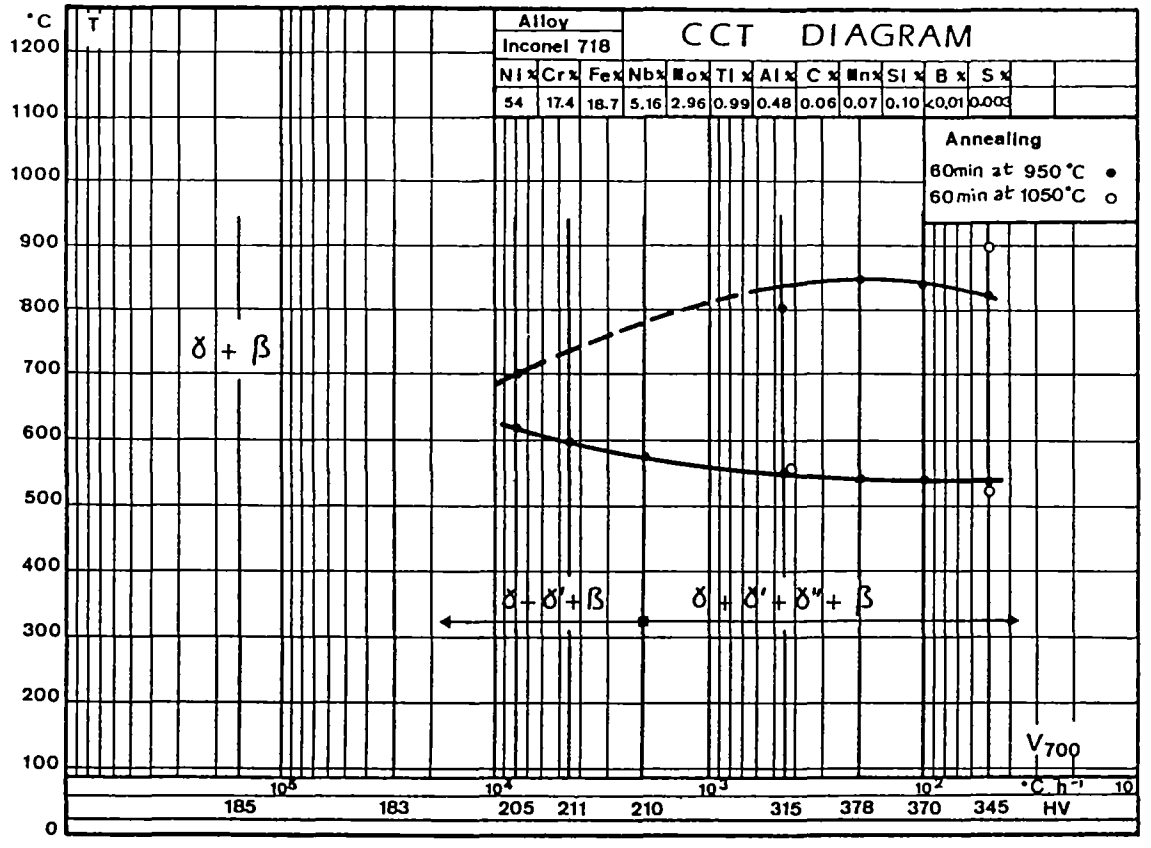
LIVE GRAPH
Click here to view

Time-temperature-hardness HRC diagrams

SOURCE: J.R. Groh, J.F. Radavich, "Effects of Iron, Nickel, and Cobalt on Precipitation Hardening of Alloy 718," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 351-361

Inconel 718

Composition: Ni - 17.4% Cr - 18.7% Fe - 5.16% Nb - 2.96% Mo - 0.99% Ti - 0.48% Al - 0.06% C - 0.07% Mn - 0.10% Si - <0.01% B - 0.003% S
Treatment - solid circle: Annealed at 950°C (1742°F) for 1 h
Treatment - open circle: Annealed at 1050°C (1922°F) for 1 h



LIVE GRAPH
Click here to view

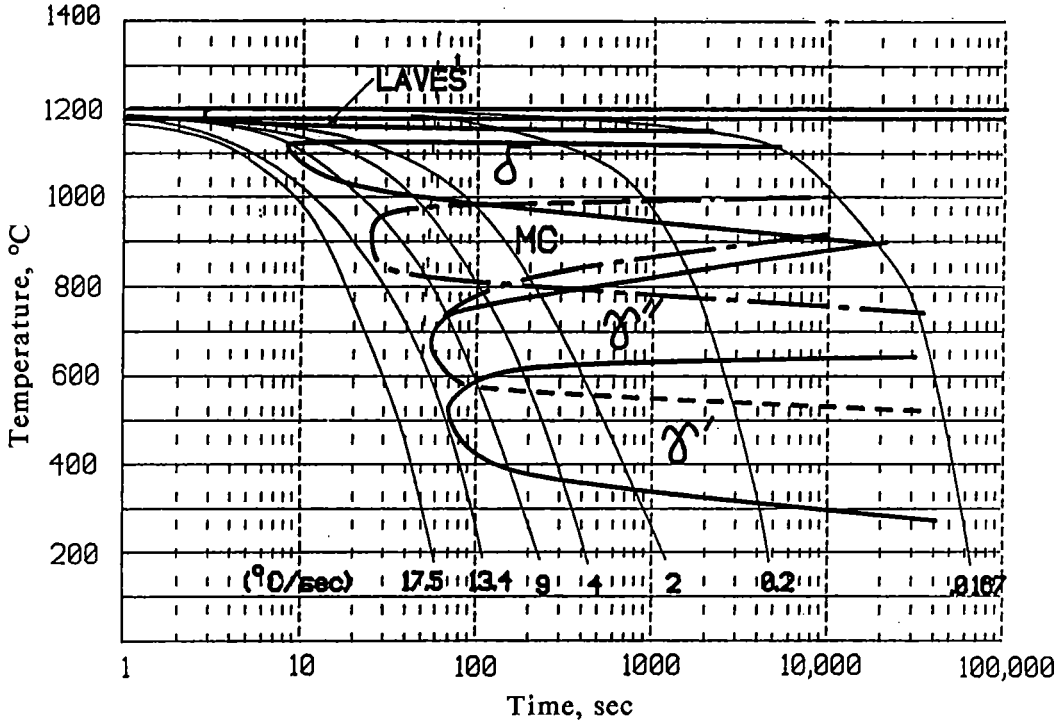
CCT diagram
Note: Cooling rate °C/h, and resultant hardness, HV

SOURCE: C. Loier, M.C. Ottman, C. Leymonie, "Structural Transformations and Mechanical Properties of Two Non-Magnetic Alloys (Inconel 718 and ASM A 286)," Materials Science and Engineering, Vol 63, 1984, pp 91-100

As Cast Alloy 718

Composition: 51.5% Ni - 19.9% Fe - 18.2% Cr - 5.1% Nb - 2.9% Mo - 1.15% Ti - 0.57% Al - 0.035% Cr

Treatment: Homogenized at 1180°C (2156°F) for 24 h



LEGEND:

Laves $(Fe, Ni, Cr)_2$ (Nb, Ti, Mo)

δ Ni_3 Nb (orthorhombic crystal structure)

MC (Nb, Ti)C

γ'' Ni_3 (Nb, Ti, Al) (body-centered tetragonal crystal structure)

γ' Ni_3 (Ti, Al, Nb) (face-centered cubic)

LIVE GRAPH
Click here to view

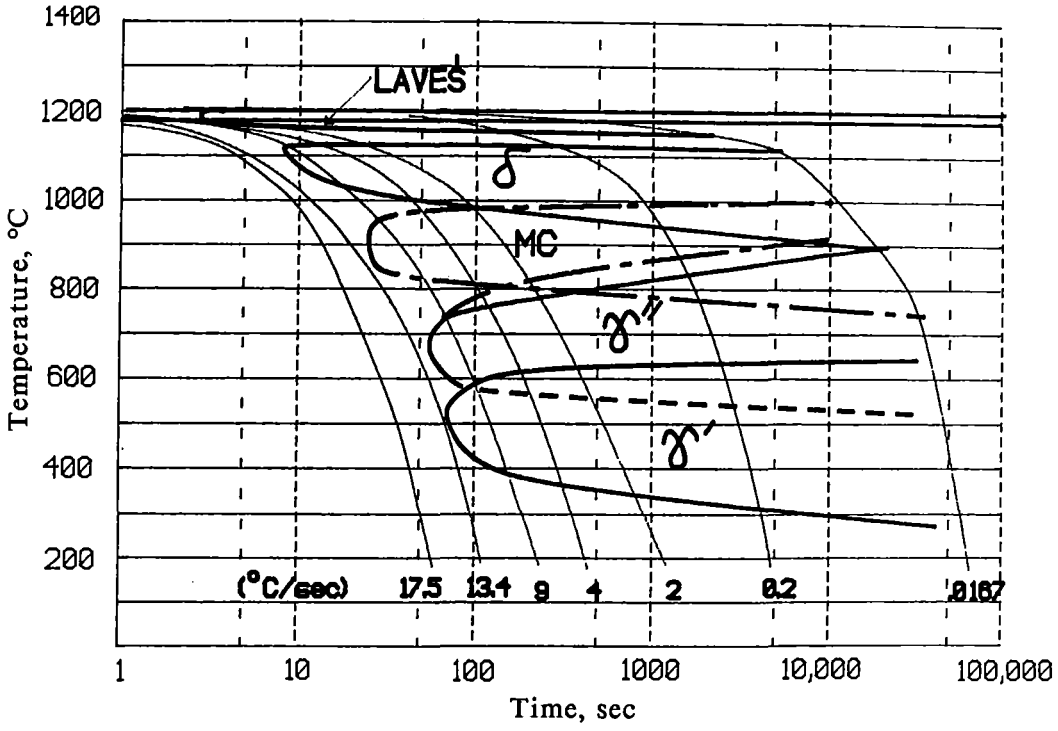
CCT diagram

SOURCE: C.I. Garcia, D.E. Camus, E.A. Loria, A.J. DeArdo, "Microstructural Refinement of As-Cast Alloy 718 Via Thermomechanical Processing," Superalloys 718, 625 and Various Derivatives, E.A. Loria, ed., TMS, 1991, pp 925-941

Alloy 718

Composition: Ni - 19.9% Fe - 18.2% Cr - 5.1% Nb - 2.9% Mo - 1.15% Ti - 0.2% Mn

Treatment: Cylinders 40 mm long x 10 mm diam were vacuum sealed in quartz and homogenized at 1180°C (2156°F) for 24 h, water quenched. Dilatometer specimens were machined from the cylinders. The dilatometer specimens were heated to 1180°C (2156°F) at 0.5°C/s, held for 30 min and then cooled at various rates. Companion specimens were treated identically but water quenched from different temperatures and examined metallographically



LIVE GRAPH
Click here to view

LEGEND:
Laves (Fe, Ni, Cr)$_2$ (Nb, Ti, Mo)
δ Ni_3 Nb (orthorhombic crystal structure)
MC (Nb, Ti)C
γ'' Ni_3 (Nb, Ti, Al) (body-centered tetragonal crystal structure)
γ' Ni_3 (Ti, Al, Nb) (face-centered cubic)

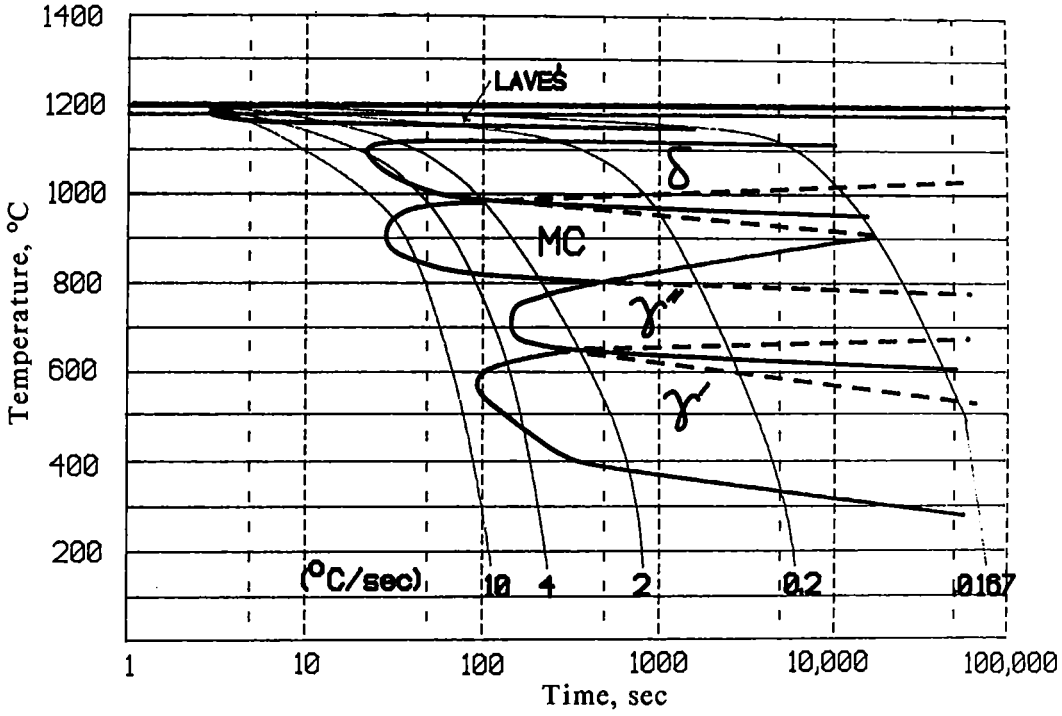
CCT diagram

SOURCE: A.K. Lis, G.I. Garcia, A.J. DeArdo, "The Effect of Homogenization Treatment and Cooling Rate on the Transformation Characteristics of Alloy 718," to be presented at the International Symposium on Superalloys, 20-24 September 1992, Seven Springs Mountain Resort, Champion, PA (and published in proceedings)

Alloy 718

Composition: Ni - 19.9% Fe - 18.2% Cr - 5.1% Nb - 2.9% Mo - 1.15% Ti - 0.2% Mn

Treatment: Cylinders 40 mm long x 10 mm diam were vacuum sealed in quartz and homogenized at 1180°C (2156°F) for 72 h, water quenched. Dilatometer specimens were machined from the cylinders. The dilatometer specimens were heated to 1180°C (2156°F) at 0.5°C/s, held for 30 min and then cooled at various rates. Companion specimens were treated identically but water quenched from different temperatures and examined metallographically



LIVE GRAPH
Click here to view

LEGEND:
Laves $(Fe, Ni, Cr)_2$ (Nb, Ti, Mo)
δ Ni_3 Nb (orthorhombic crystal structure)
MC (Nb, Ti)C
γ'' Ni_3 (Nb, Ti, Al) (body-centered tetragonal crystal structure)
γ' Ni_3 (Ti, Al, Nb) (face-centered cubic)

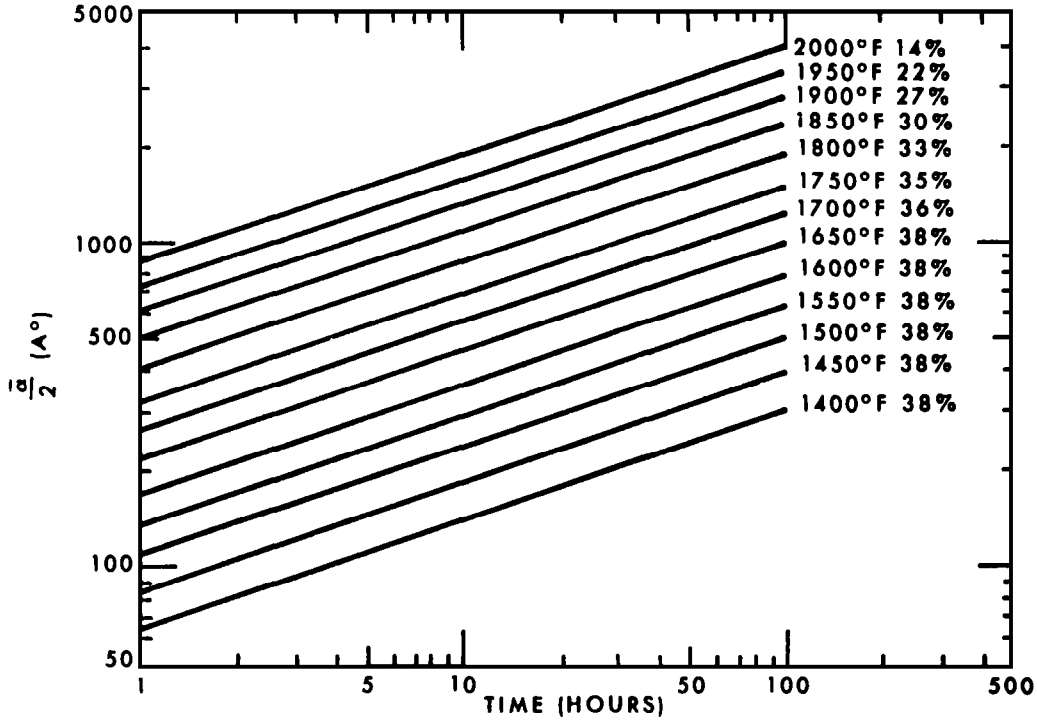
CCT diagram

SOURCE: A.K. Lis, G.I. Garcia, A.J. DeArdo, "The Effect of Homogenization Treatment and Cooling Rate on the Transformation Characteristics of Alloy 718," to be presented at the International Symposium on Superalloys, 20-24 September 1992, Seven Springs Mountain Resort, Champion, PA (and published in proceedings)

Udimet 700

Composition: Ni - 14.5% Cr - 17.5% Co - 5.1% Mo - 3.7% Ti - 4.1% Al - 0.015% B - 0.08% C

Treatment: Specimens were annealed above the gamma prime solvus temperature at 1177°C (2150°F) for 4 h, followed by a fast air cool



LIVE GRAPH
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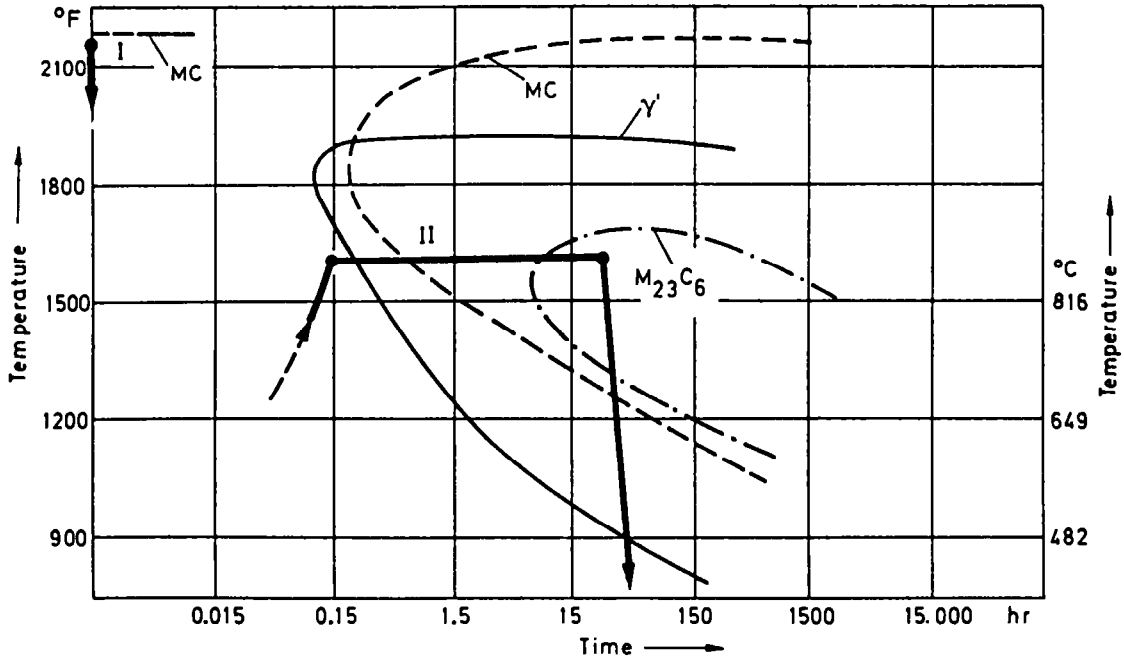
Gamma prime particle size vs temperature and time
From 760 to 1093°C (1400 to 2000°F)
Volume fraction of gamma prime from 38 to 14%

SOURCE: E.H. Van Der Molen, J.M. Oblak, O.H. Kriege, "Control of Gamma Prime Particle Size and Volume Fraction in the High Temperature Superalloy Udimet 700," Met. Trans., Vol 2, June 1971, pp 1627-1633

IN-700

Composition: 44.0% Ni - 16.0% Cr - 0.1% C - 3.0% Mo - 29.5% Co - 2.5% Ti - 3.0% Al

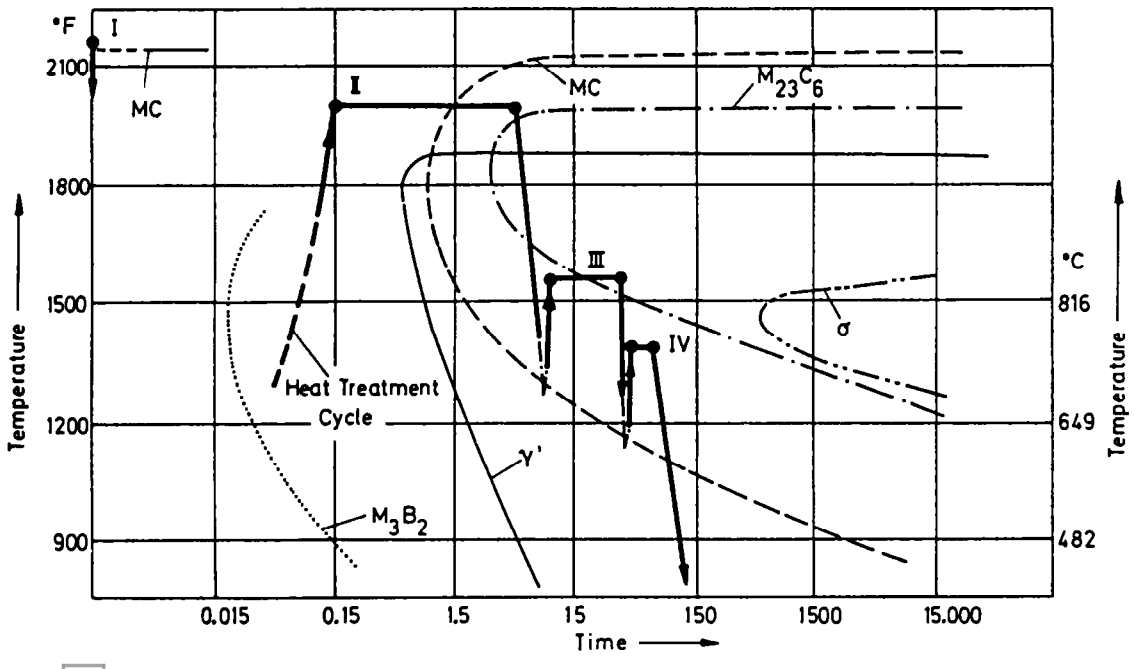


LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram Showing heat treatment cycle

Udimet-700

Composition: 52.7% Ni - 15.0% Cr - 0.07% C - 5.3% Mo - 18.5% Co - 3.5% Ti - 4.3% Al - 0.03% B



LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram Showing heat treatment cycle

SOURCE: D.M. Moon unpublished work, as cited by Roland Stickler, "Phase Stability in Superalloys," High Temperature Materials in Gas Turbines, P.R. Sahn, M.O. Speidel, Eds., Elsevier Science Publications, Amsterdam, 1974, pp 116-149

Udimet-520 *and* Udimet-710

U-520 composition: Ni - 0.03% C - 18.8% Cr - 11.8 Co - 6.0% Mo - 0.9% W - 2.9% Ti - 2.1% Al - 0.02% B

U-710 composition: Ni - 0.06% C - 17.7% Cr - 15.1% Co - 3.0% Mo - 1.4% W - 4.8% Ti - 2.4% Al - 0.02% B

LIVE GRAPH
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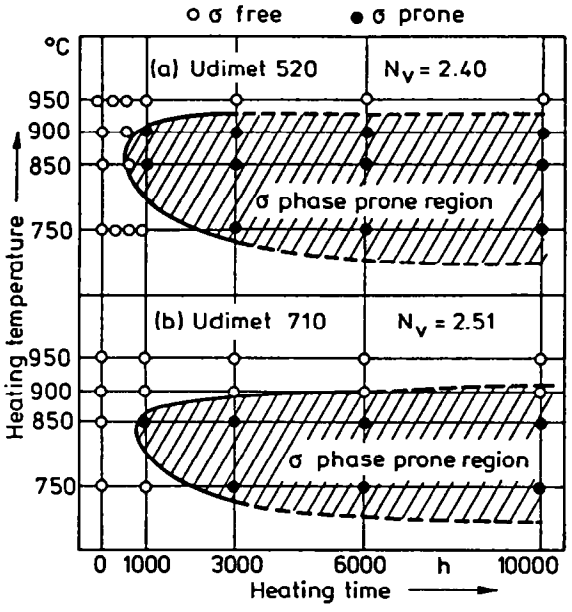
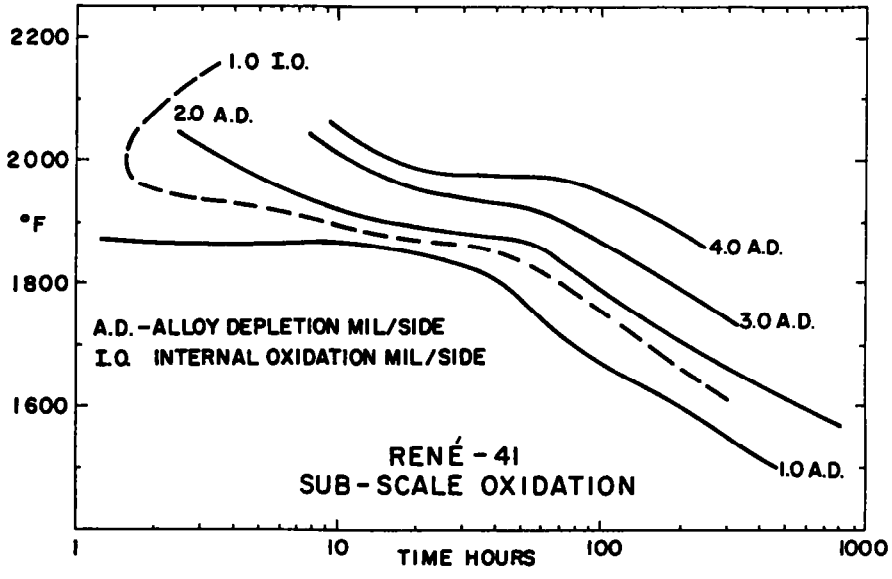


Time-temperature-precipitation diagram Showing sigma phase formation

SOURCE: H. Susukida, Y. Sakumoto, I. Tsuji, H. Kawai, "Strength and Microstructure of Ni-Base Superalloys After Long Term Heating," Kobe Technical Institute, Akashi, Japan, 1972

Rene' 41
Composition: Ni - 19.05% Cr - 0.71% Fe - 10.93% Co - 9.91% Mo - 3.10% Ti - 1.48% Al - 0.06% Si - 0.06% Mn - 0.004% B - 0.11% C - 0.008% S
Treatment: 0.5-in-diam rod, solution annealed at 1177°C (2150°F) for 30 min, aged at 871°C (1600°F) for 4 h



LIVE GRAPH
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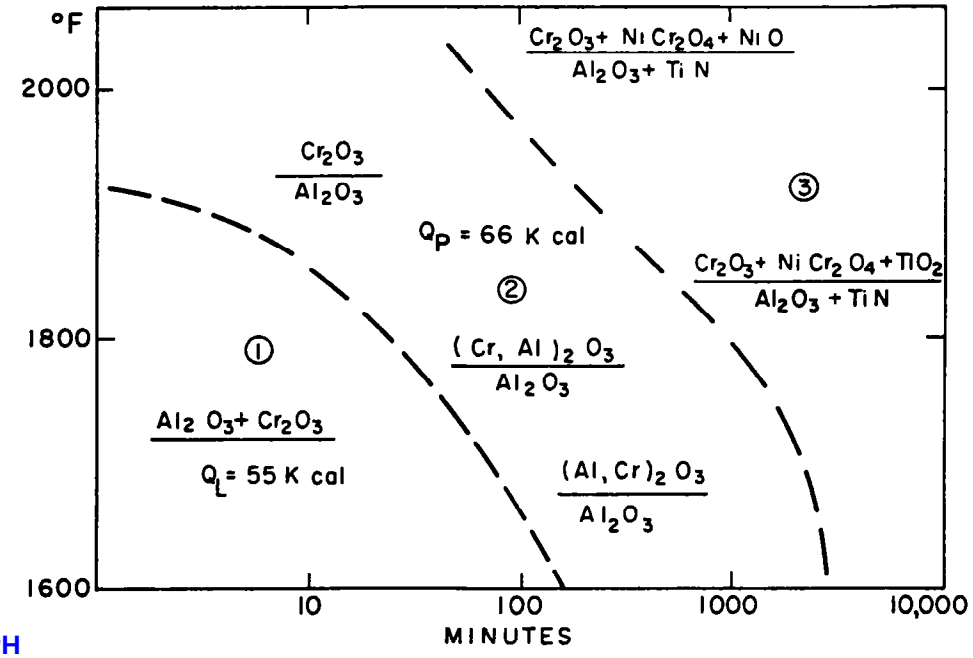
Time-temperature-oxidation diagram
Qualitative portrayal of time and temperature conditions required to produce 1.0 mil (25.4 μm) per side of internal oxidation and 1, 2, 3, and 4 mils (25.4, 50.8, 76.2 and 101.6 μm) per side of alloy depletion

SOURCE: S.T. Wlodek, "The Oxidation of Rene 41 and Udimet 700," Trans. AIME, Vol 230, August 1964, pp 1078-1090

Rene'41

Composition: Ni - 19.05% Cr - 0.71% Fe - 10.93% Co - 9.91% Mo - 3.10% Ti - 1.48% Al - 0.06% Si - 0.06% Mn - 0.004% B - 0.11% C - 0.008% S

Treatment: 0.5-in-diam rod, solution annealed at 1177°C (2150°F) for 30 min, aged at 871°C (1600°F) for 4 h



LIVE GRAPH
Click here to view

LEGEND:
(1) = linear growth rate
(2) and (3) = parabolic growth rate
Phases present in the numerator = the scale constituents present
Phases present in the denominator = the products of internal oxidation

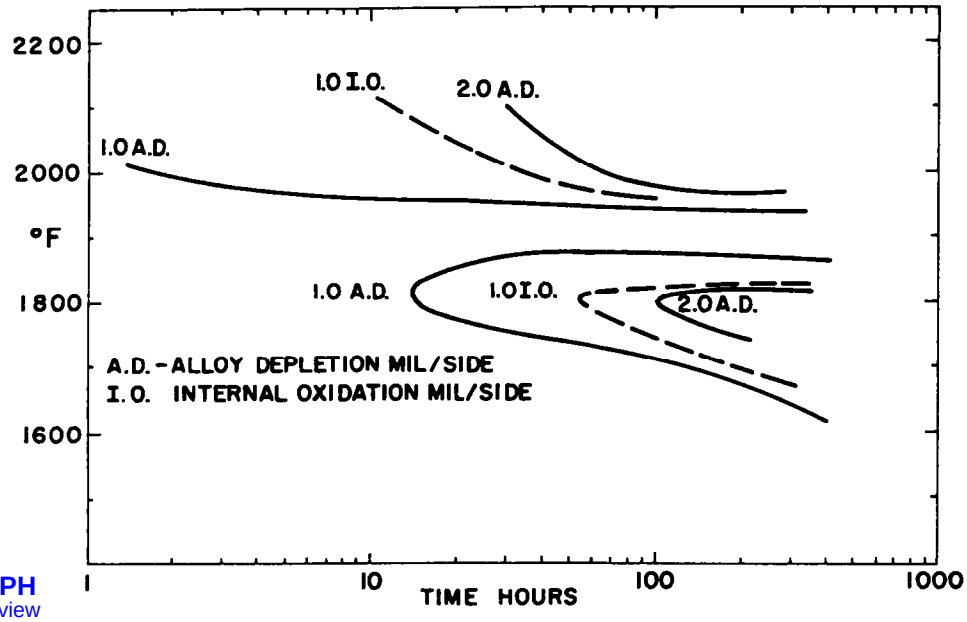
Time-temperature-oxidation diagram
Schematic presentation of the major reaction products that can form during oxidation

SOURCE: S.T. Wlodek, "The Oxidation of Rene 41 and Udimet 700," Trans. AIME, Vol 230, August 1964, pp 1078-1090

Udimet 700

Composition: Ni - 15.0% Cr - 0.15% Fe - 19.0% Co - 5.15% Mo - 3.49% Ti - 4.45% Al - 0.10% Si - 0.10% Mn - 0.028% B - 0.06% C

Treatment: 0.5-in-diam rod, solution annealed at 1177°C (2150°F) for 4 h, aged at 1080°C (1975°F) for 4 h + at 843°C (1550°F) for 24 h and at 871°C (1600°F) for 16 h



LIVE GRAPH
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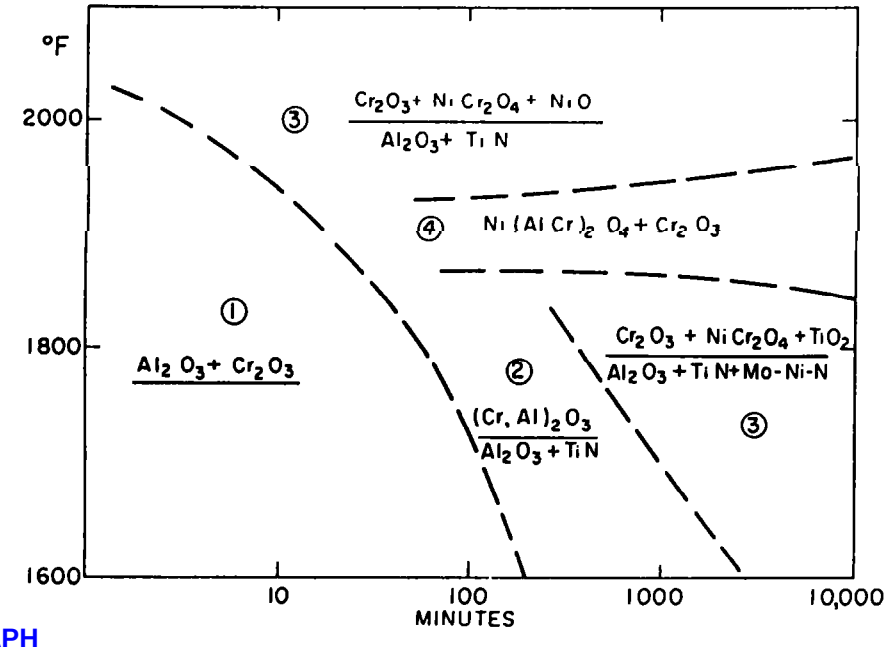
Time-temperature-oxidation diagram
Isoreactivity plots for constant amount of subscale damage
Note: complete reversal of behavior at 1038°C (1900°F) and absence of internal oxidation at this temperature

SOURCE: S.T. Wlodek, "The Oxidation of Rene 41 and Udimet 700," Trans. AIME, Vol 230, August 1964, pp 1078-1090

Udimet 700

Composition: Ni - 15.0% Cr - 0.15% Fe - 19.0% Co - 5.15% Mo - 3.49% Ti - 4.45% Al - 0.10% Si - 0.10% Mn - 0.028% B - 0.06% C

Treatment: 0.5-in-diam rod, solution annealed at 1177°C (2150°F) for 4 h, aged at 1080°C (1975°F) for 4 h + at 843°C (1550°F) for 24 h and at 871°C (1600°F) for 16 h



LIVE GRAPH
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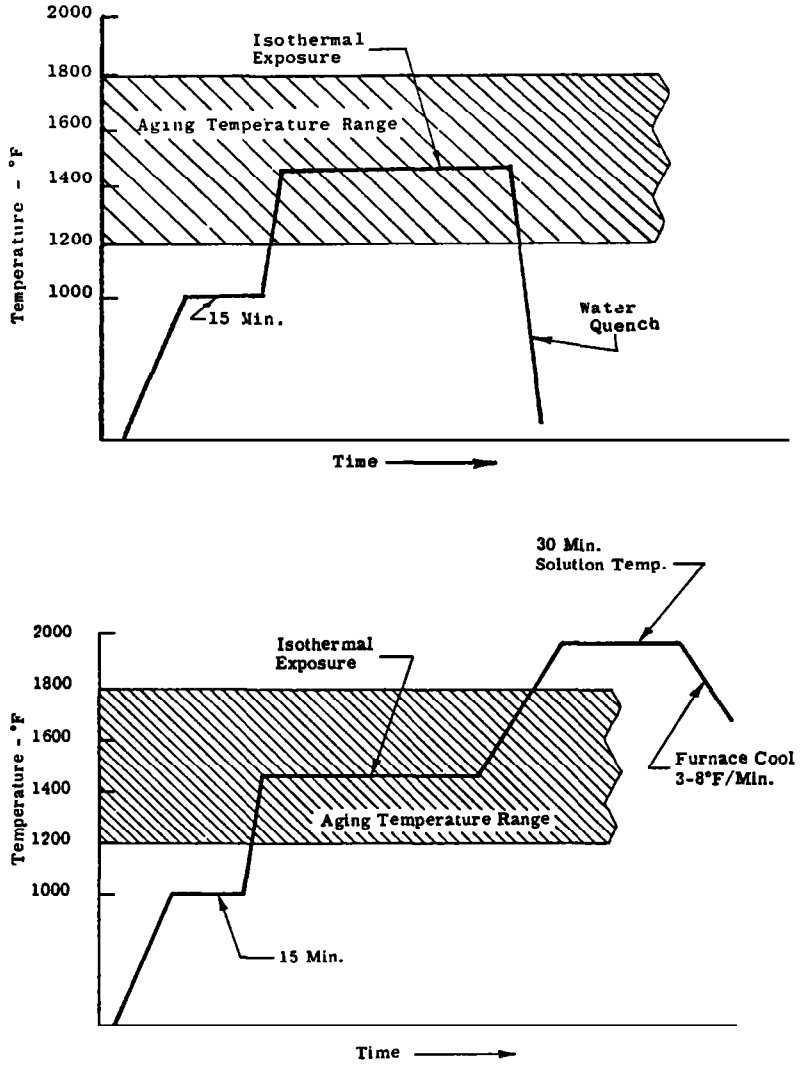
LEGEND:
(1) = linear growth rate
(2) and (3) = parabolic growth rate
(4) = where weight gain reaches a constant value in some 1000 min
Numerator = the scale constituents present
Denominator = the products of internal oxidation

Time-temperature-oxidation diagram
Simplified summary of the four main stages of oxidation

SOURCE: S.T. Wlodek, "The Oxidation of Rene 41 and Udimet 700," Trans. AIME, Vol 230, August 1964, pp 1078-1090

Rene' 41

Composition: Ni - 20.10% Cr - 2.03% Fe - 0.089% C - 0.25% Si - 11.55% Co - 0.05% Mn - 10.17% Mo - 1.60% Al - 3.17% Ti - 0.0056% B - 0.016% S

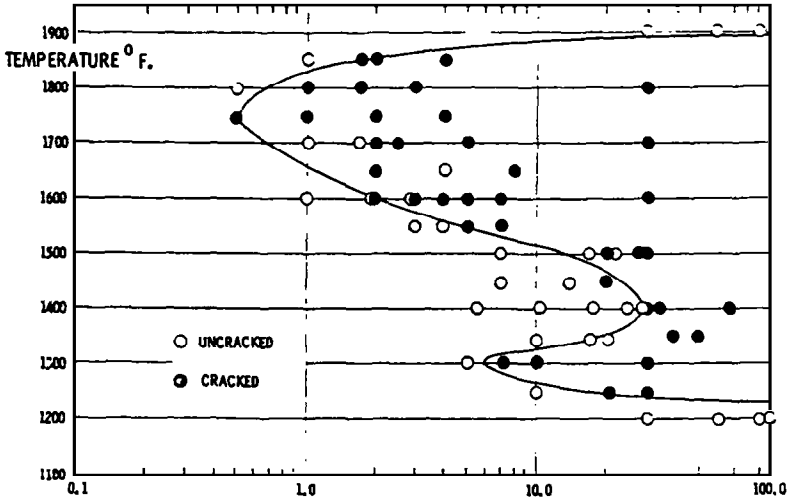


Postweld thermal cycles used for developing strain-age cracking C-curves in next 5 diagrams

SOURCE: T.F. Berry, W.P. Hughes, "A Study of the Strain-Age Cracking Characteristics in Welded Rene 41 - Phase II," Welding Research Supplement, November 1969, pp 505s-513s

Rene' 41

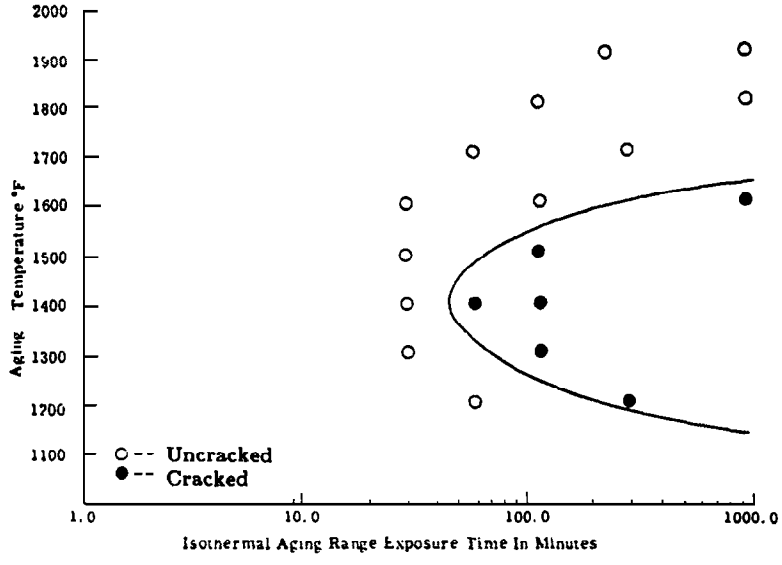
Composition: Ni - 20.10% Cr - 2.03% Fe - 0.089% C - 0.25% Si - 11.55% Co - 0.05% Mn - 10.17% Mo - 1.60% Al - 3.17% Ti - 0.0056% B - 0.016% S
Treatment: Mill annealed prior to welding



LIVE GRAPH
Click here to view

Time-temperature-cracking diagram
Crack susceptibility C-curve as generated using the postweld heat treating procedure in prior figure
Indicated cracking occurred either during isothermal aging, or during cooling

Composition: Ni - 18.64% Cr - 0.20% Fe - 0.075% C - 0.05% Si - 10.76% Co - 0.05% Mn - 9.76% Mo - 1.62% Al - 3.13% Ti - 0.009% B - 0.008% P - 0.007% S
Treatment: Mill annealed prior to welding

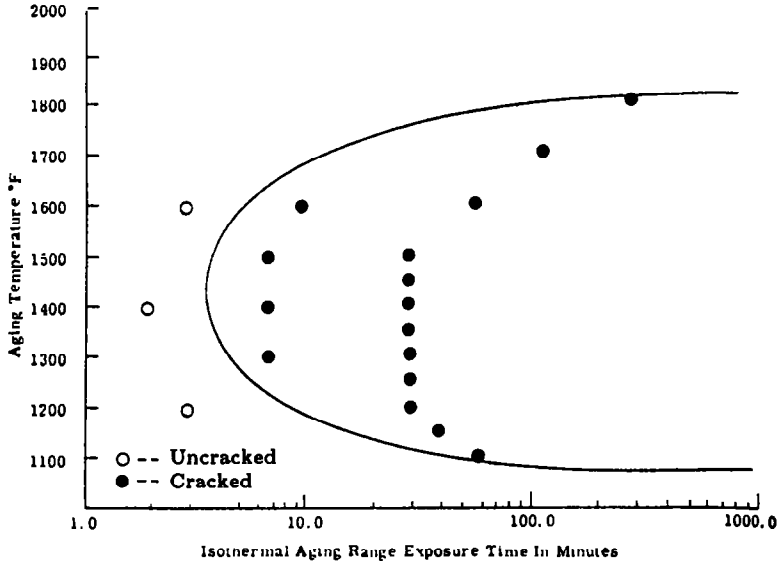


LIVE GRAPH
Click here to view

Time-temperature-cracking diagram
Crack susceptibility C-curve

SOURCE: T.F. Berry, W.P. Hughes, "A Study of the Strain-Age Cracking Characteristics in Welded Rene 41 - Phase II," Welding Research Supplement, November 1969, pp 505s-513s

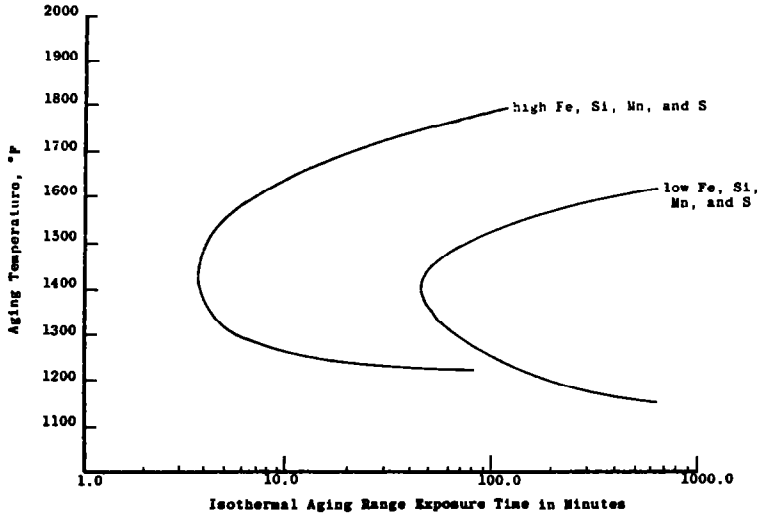
Rene' 41
Composition: Ni - 19.02% Cr - 0.30% Fe - 0.07% C - 0.06% Si - 10.84% Co - 0.04% Mn - 9.84% Mo - 1.45% Al - 3.18% Ti - 0.0056% B - 0.005% P - 0.005% S
Treatment: Mill annealed prior to welding



LIVE GRAPH
Click here to view

Time-temperature-cracking diagram
Crack susceptibility C-curve

High Fe-Si-Mn-S composition: Ni - 19.73% Cr - 2.03% Fe - 0.067% C - 0.18% Si - 11.12% Co - 0.05% Mn - 10.09% Mo - 1.60% Al - 3.10% Ti - 0.0045% B - 0.020% S
Low Fe-Si-Mn-S composition: Composition: Ni - 18.64% Cr - 0.20% Fe - 0.075% C - 0.05% Si - 10.76% Co - 0.05% Mn -



Time-temperature-cracking diagram
Comparison of the crack susceptibilities of high Fe-Si-Mn-S and low Fe-Si-Mn-S heats

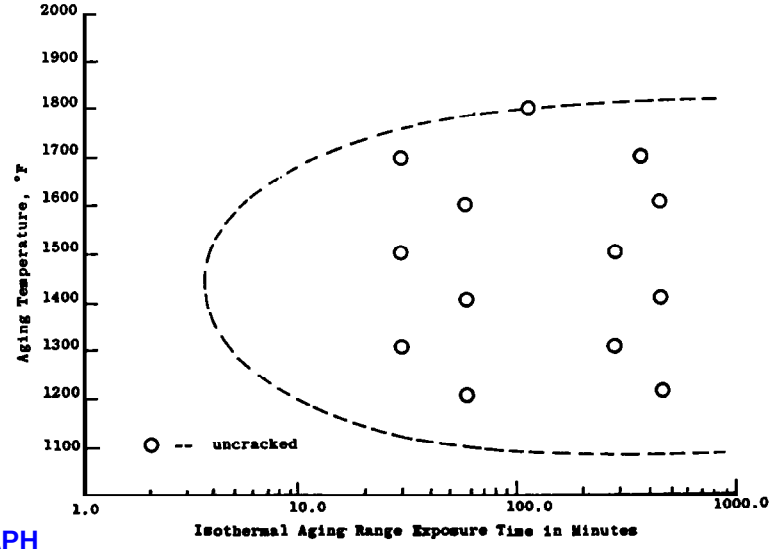
LIVE GRAPH
Click here to view

SOURCE: T.F. Berry, W.P. Hughes, "A Study of the Strain-Age Cracking Characteristics in Welded Rene 41 - Phase II," Welding Research Supplement, November 1969, pp 505s-513s

Rene' 41

Composition: Ni - 19.02% Cr - 0.30% Fe - 0.07% C - 0.06% Si - 10.84% Co - 0.04% Mn - 9.84% Mo - 1.45% Al - 3.18% Ti - 0.0056% B - 0.005% P - 0.005% S

Overage treatment: Aged at 1080°C (1975°F) for 30 min, cool at ~2 to 5°C/min to 962°C (1800°F), hold for 4 h, cool at ~2 to 5°C/min to 871°C (1600°F), hold for 4 h, cool at ~2 to 5°C/min to 760°C (1400°F) hold for 16 h, air cool to room temperature



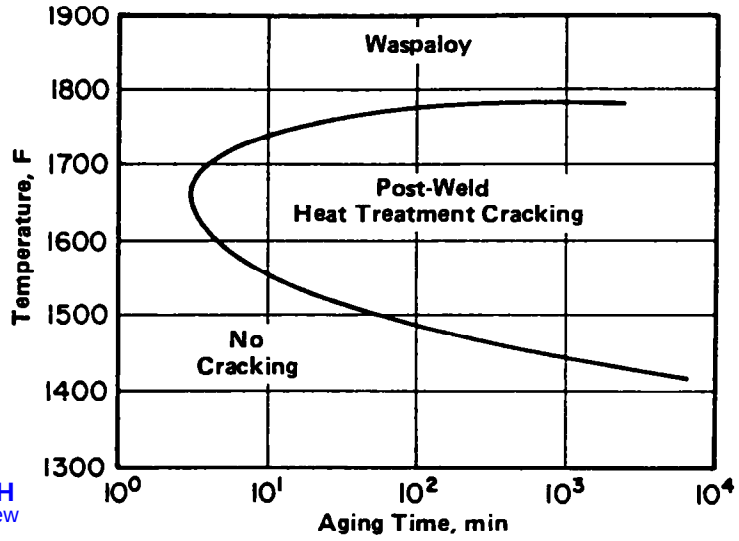
LIVE GRAPH
Click here to view

Time-temperature-cracking diagram
Annealed vs overaged crack susceptibility C-curve
The dotted curve, shown for comparison, is for the mill annealed alloy
The test data are for the overaged specimens

SOURCE: T.F. Berry, W.P. Hughes, "A Study of the Strain-Age Cracking Characteristics in Welded Rene 41 - Phase II," Welding Research Supplement, November 1969, pp 505s-513s

Waspaloy

Nominal composition: Ni - 20% Cr - 14% Co - 4% Mo - 3% Ti - 1% Al

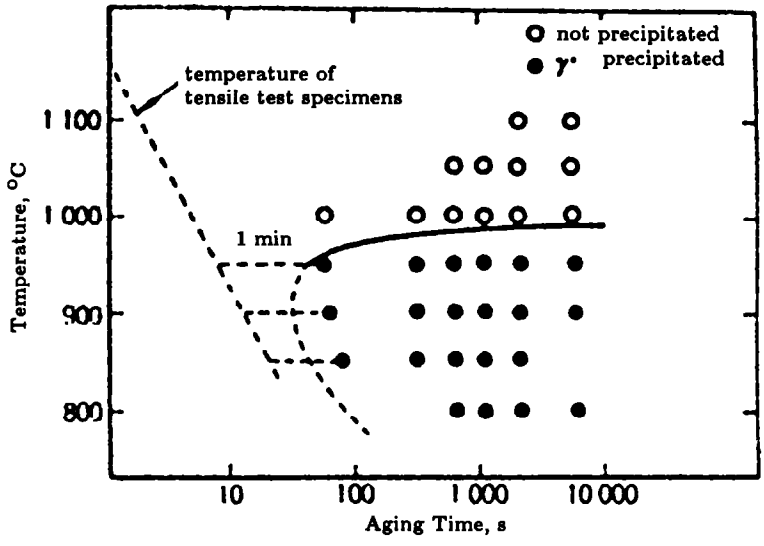


LIVE GRAPH
Click here to view

Time-temperature cracking diagram
Post-weld heat treatment cracking tendency as a function of aging time and temperature

SOURCE: W.A. Owczarski, "Process and Metallurgical Factors in Joining Superalloys and Other High Service Temperature Materials," 1977 as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, September 1986, Code 4208, p 36

Composition: Ni - 0.071% C - 0.004$ Si - 0.062% Mn - 0.002% P - 0.004% S - 19.36% Cr - 13.9% Co - 0.20% Fe - 4.40% Mo - 1.55% Al - 3.03% Ti - 0.062% Zr



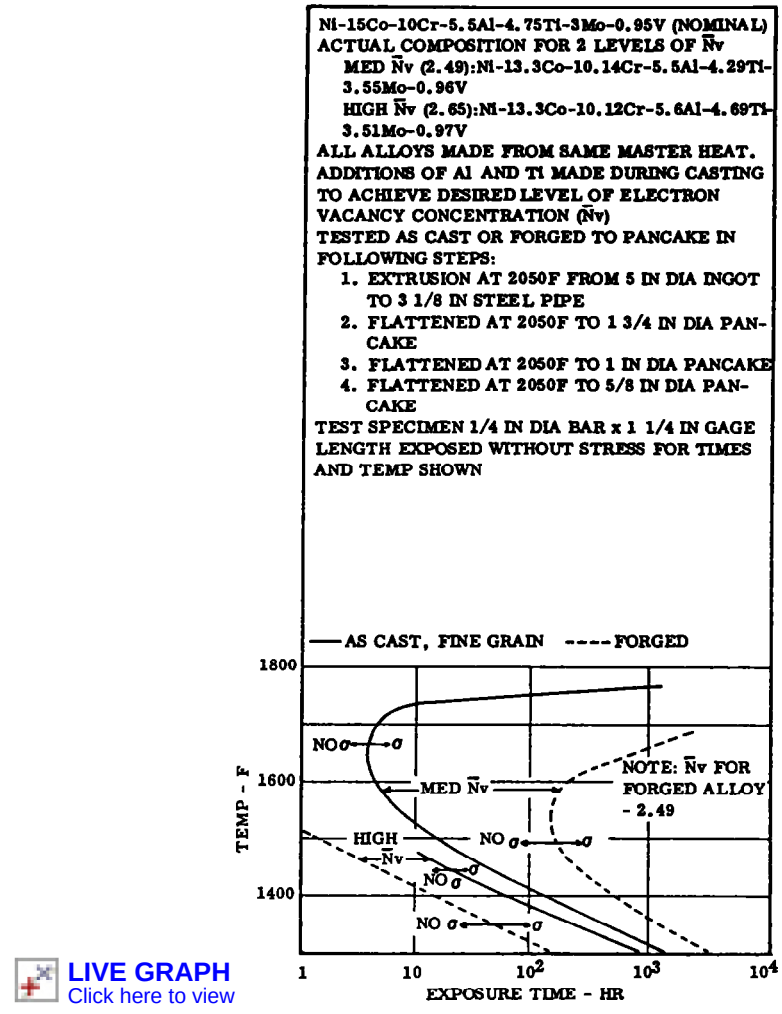
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
Gamma prime phase only

SOURCE: Sadao Ohta, Ken-ichi Aota, Takemitsu Honjo, Toshiya Moriyama, "Hot Workability of Several Fe, Ni and Co-Based Alloys," Kobe Res. Dev., Vol 32, No. 3, July 1982, p 14

IN-100

Nominal composition: Ni - 15% Co - 10% Cr - 5.5% Al - 4.7% Ti - 3% Mo - 0.95% V



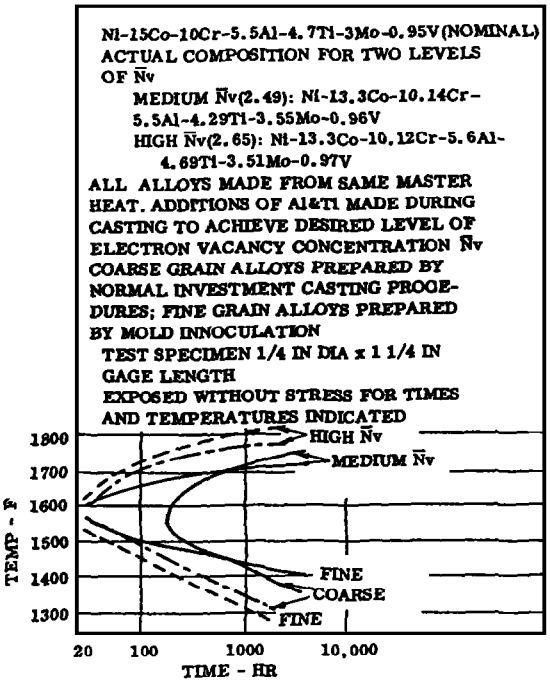
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Transformation to sigma phase for as-cast and forged alloy for two levels of electron vacancy concentration

SOURCE: Robert L. Dreshfield, Richard L. Ashbrook, "Further Observations on the Formation of Sigma Phase in a Nickel Base Superalloy (IN-100)," NASA TN D-6015, September 1970, as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, December 1978, Code 4212, p 8

IN-100

Nominal composition: Ni - 15% Co - 10% Cr - 5.5% Al - 4.7% Ti - 3% Mo - 0.95% V



LIVE GRAPH
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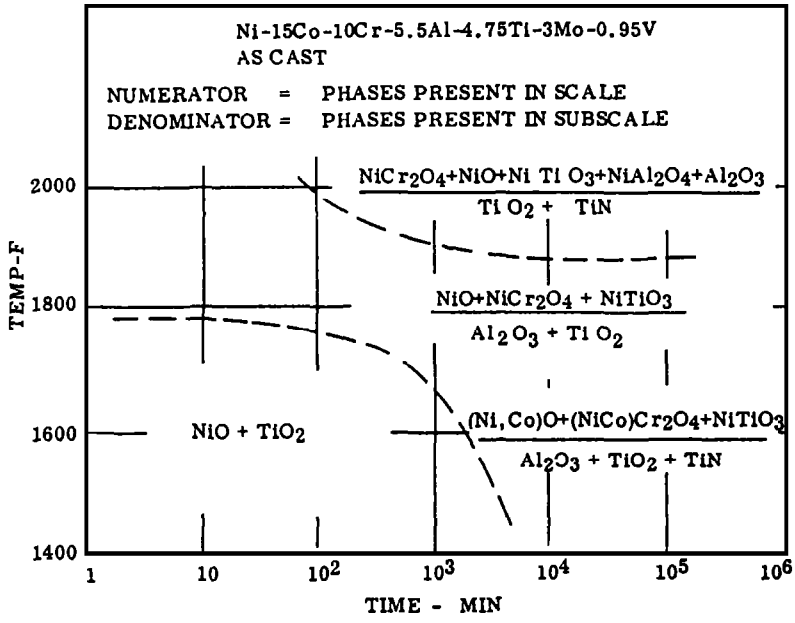
Time-temperature-precipitation diagram
Relation for the onset of sigma phase precipitation for medium and high electron vacancy compositions, and in fine and coarse grain size structure

SOURCE: Robert L. Dreshfield, Richard L. Ashbrook, "Sigma Phase Formation and Its Effect on Stress-Rupture Properties of IN-100," NASA TN D-5185, September 1970, as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, December 1978, Code 4212, p 8

IN-100

Nominal composition: Ni - 15% Co - 10% Cr - 5.5% Al - 4.7% Ti - 3% Mo - 0.95% V



Time-temperature-oxidation diagram
Summary of main stages of oxidation

SOURCE: G.E. Wasielewski, "Nickel-Base Superalloy Oxidation," AFML-TR-67-30, January 1967, as published in Aerospace Structural Metals Handbook, Nonferrous Alloys, December 1978, Code 4212, p 9

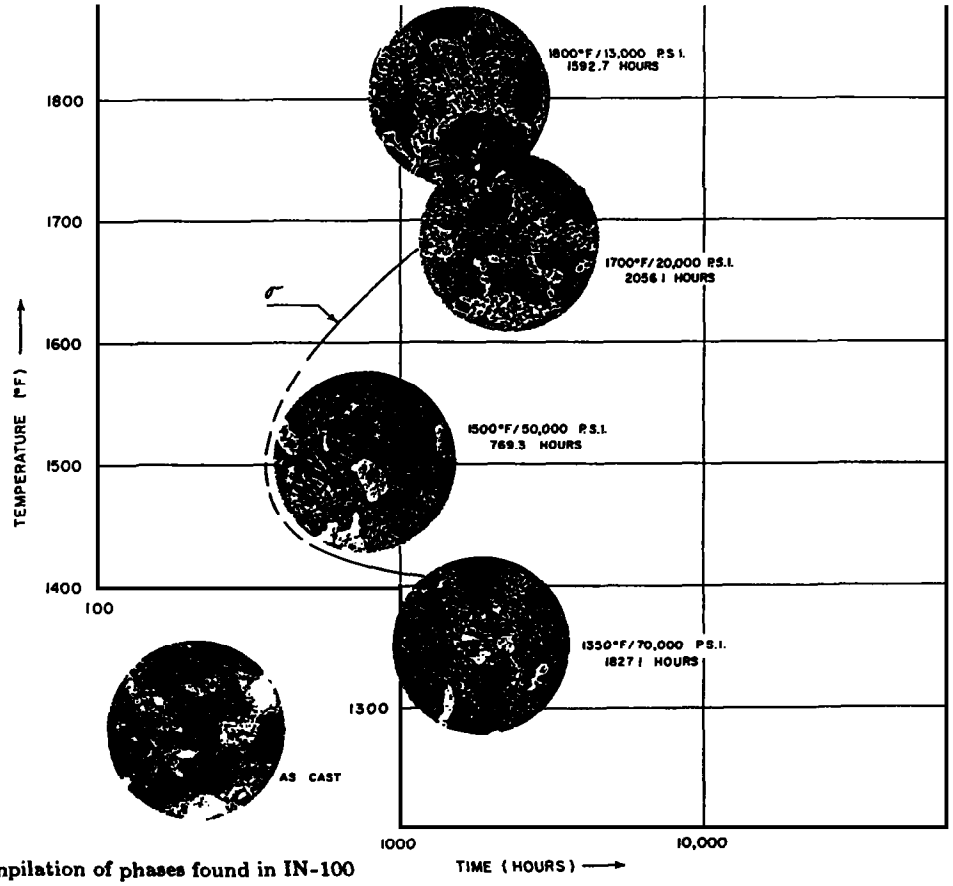
IN-100

Composition: Ni - 0.18% C - 14.26% Co - 10.26% Cr - 2.97% Mo - 5.35% Ti - 5.60% Al - 0.30% Fe - 0.92% V - 0.012% B - 0.05% Zr

Phases Present	As-Cast	As-Cast + 1800°F/13,000 psi, 1592.7 hr	As-Cast + 1700°F/20,000 psi 2056.1 hr	As-Cast + 1500°F/50,000 psi, 769.3 hr	As-Cast + 1350°F/70,000 psi, 1827.1 hr
TiC	4.30Å Strong	4.31Å Weak to moderate weak	4.31Å Moderate	4.31Å Strong	4.31Å Strong
σ	N. D.*	c = 4.62Å a = 8.84Å c/a = 0.52 Very weak	c = 4.60Å a = 8.85Å c/a = 0.52 Weak	c = 4.59Å a = 8.85Å c/a = 0.52 Moderate Strong	c = 4.58Å a = 8.83Å c/a = 0.52 Moderate
$M_{23}C_6$	10.67Å Very weak	10.71Å Strong	10.71Å Strong	10.71Å Moderate strong	10.68Å Moderate
M_6C	11.01Å Very weak	N. D.	N. D.	11.06Å Very weak	?
M_6C'	10.92Å Very weak	?†	?	10.98Å Weak	?

*Not detected.
†Presence or absence questionable.

Time-temperature-transformation diagram
Shows start of sigma phase formation



Compilation of phases found in IN-100

SOURCE: J.R. Mihalisin, C.G. Bieber, R.T. Grant, "Sigma - Its Occurrence, Effect, and Control in Nickel-Base Superalloys," Trans. AIME, Vol 242, December 1968, pp 2399-2414

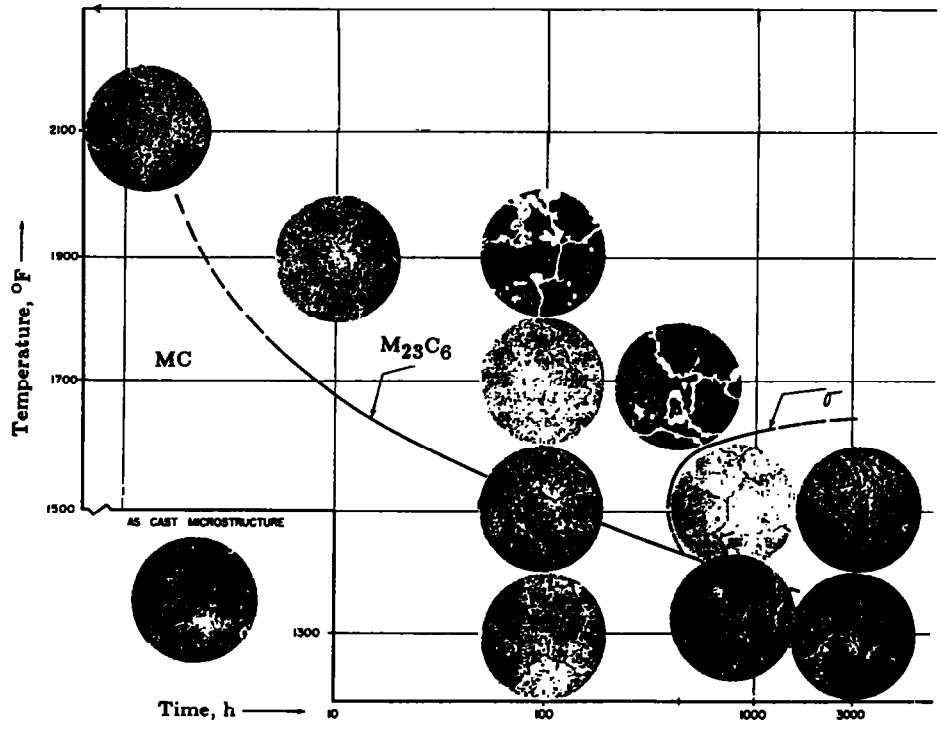
Alloy 713C

Composition: Ni - 12.77% Cr - 0.07% Fe - 0.10% C - 0.22% Si - 0.012% B - 4.52% Mo - 5.94% Al - 0.80% Ti - 2.08% Nb+Ta - 0.12% Zr

Phases Present and Relative Abundances from Electrolytic Extractions (d spacing in A)

Phases Present	As-Cast	2100F/ 10 hr	1900F/ 500 hr	1700F/ 10 hr	1700F 1000 hr	1500F/ 500 hr	1500F/ 1000 hr	1500F/ 3000 hr
(Cb, Ti)C	4.40Å Strong	4.40Å Strong	4.40Å Weak	4.40Å Strong	4.40Å Moderate	4.40Å Strong	4.40Å Strong	4.40Å Strong
σ	–	–	–	–	–	a = 8.96Å c = 4.63Å c/a = 0.52 Mod. W → Mod	a = 8.96Å c = 4.63Å c/a = 0.52 Moderate	a = 8.95Å c = 4.64Å c/a = 0.52 Mod. → Mod. St
$M_{23}C_6$	–	10.60Å Weak ?	10.73Å Strong	10.68Å Weak to Mod. weak	10.72Å Mod. strong	10.72Å Mod. W → Mod	10.72Å Mod. W → Mod	10.73Å Moderate
M_6C	11.27Å Weak 11.15Å Weak 10.99Å Weak	10.95Å Mod. weak	11.00Å Mod. weak	11.15Å Weak 11.00Å Weak	10.95Å Weak	11.00Å Weak	11.06Å Weak → MW	11.00Å Weak
M_6C'	10.87Å Weak	–	–	10.93Å Weak 10.86Å Weak	10.87Å Weak	–	10.85Å Weak → MW	10.86Å Weak
M_3B_2	a = 5.80Å c = 3.14Å a = 5.73Å c = 3.11Å c/a = 0.54 Weak	a = 5.82Å c = 3.15Å c/a = 0.54 Weak	– – *	a = 5.80Å c = 3.15Å a = 5.76Å c = 3.12Å c/a = 0.54 Weak	a = 5.77Å c = 3.13Å c/a = 0.54 Weak	a = 5.74Å c = 3.11Å c/a = 0.54 Weak	a = 5.81Å c = 3.15Å a = 5.73Å c = 3.11Å c/a = 0.54	a = 5.76Å c = 3.12Å c/a = 0.54 Weak (?)

Time-temperature-precipitation diagram
Start of $M_{23}C_6$ and sigma phase formation



Compilation of phases present and relative abundances from electrolytic extractions

SOURCE: J.R. Mihalisin, C.G. Bieber, R.T. Grant, "Sigma - Its Occurrence, Effect, and Control in Nickel-Base Superalloys," Trans. AIME, Vol 242, December 1968, pp 2399-2414

IN-100 (Modified) *and* AF-2-1DA (Modified)

IN-100 Nb-modified (PM) - composition: Ni - 11.9% Cr - 17.7% Co - 3.3% Mo - 5.2% Al - 4.2% Ti - 1.4% Nb - 0.024% B - 0.06% Zr - 0.09% C

IN-100 Nb-modified (CE) - composition: Ni - 12.1% Cr - 17.4% Co - 3.2% Mo - 5.3% Al - 4.4% Ti - 1.5% Nb - 0.028% B - 0.06% Zr - 0.08% C

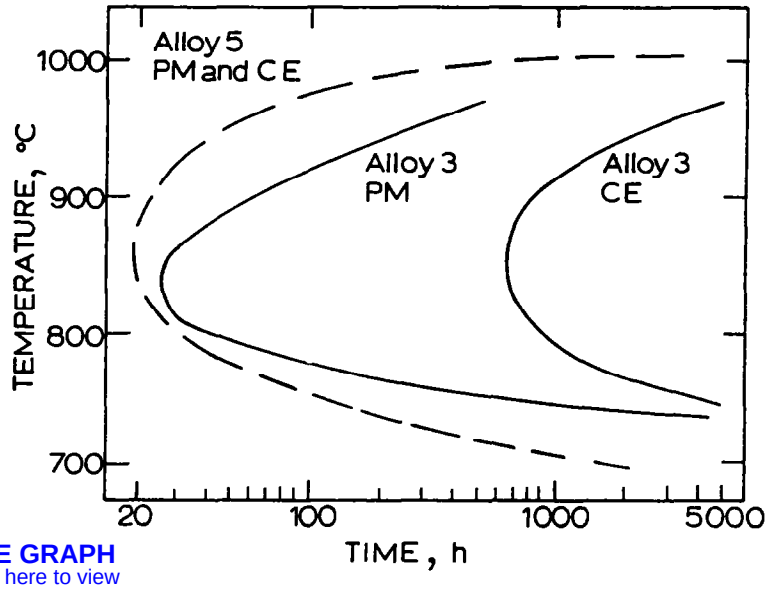
AF-2-1DA Nb-C-modified (PM) - composition: Ni - 12.1% Cr - 10.0% Co - 5.7% W - 2.9% Mo - 4.8% Al - 3.1% Ti - 1.5% Nb - 1.5% Ta - 0.018% B - 0.08% Zr - 0.09% C

AF-2-1DA Nb-C-modified (CE) - composition: Ni - 12.0% Cr - 10.3% Co - 5.5% W - 2.9% Mo - 4.7% Al - 2.9% Ti - 1.4% Nb - 1.6% Ta - 0.020% B - 0.11% Zr - 0.09% C

PM = powder metallurgy

CE = case and extruded

Treatment: Both PM and CE materials were given identical heat treatments, which consisted of a partial gamma prime solution treatment at temperatures 20°C (68°F) below the gamma prime solvus for 2 h, followed by cooling in air, a carbide-stabilizing heat treatment at 980°C (1796°F) for 8 h, followed by an air cool, and a gamma prime precipitation cycle of 760°C (1400°F) for 8 h. To observe the formation of sigma phase the heat-treated specimens were exposed to temperatures from 708 to 980°C (1300 to 1800°F) for various times in argon



LIVE GRAPH
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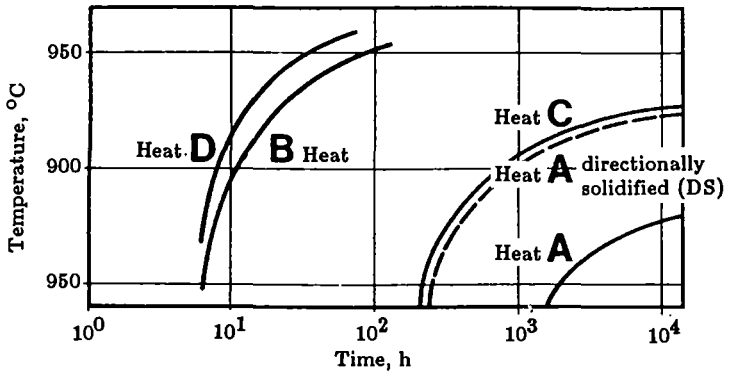
Time-temperature-precipitation diagram
Start of sigma phase

PM modified versions of IN-100 (Alloy 3) and AF-2-IDA (Alloy 5) vs conventional wrought

SOURCE: C.C. Law, W. Wallace, C.P. Ashdown, D.A. Grey, "Sigma Phase Formation in Conventional and PM Nickel-Base Superalloys," Metal Science, Vol 13, November 1979, pp 627-634

IN-738

Heat A, nominal composition: Ni - 0.12% C - 15.86% Cr - 8.40% Co - 1.93% Mo - 2.60% W - 3.42% Al - 3.50% Ti - 0.92% Nb - 1.80% Ta - 0.070% Zr - 0.0105% B
Heat B, high Cr: Ni - 0.086% C - 18.57% Cr - 7.88% Co - 1.80% Mo - 2.53% W - 3.35% Al - 3.43% Ti - 0.92% Nb - 1.72% Ta - 0.048% Zr - 0.0115% B
Heat C, high Mo+W: Ni - 0.078% C - 16.61% Cr - 8.39% Co - 1.99% Mo - 3.32% W - 3.32% Al - 3.42% Ti - 0.89% Nb - 1.75% Ta - 0.048% Zr - 0.0118% B
Heat D, high hardness: Ni - 0.077% C - 16.60% Cr - 8.40% Co - 1.75% Mo - 2.55% W - 3.56% Al - 3.70% Ti - 1.15% Nb - 1.86% Ta - 0.05% Zr - 0.0115% B

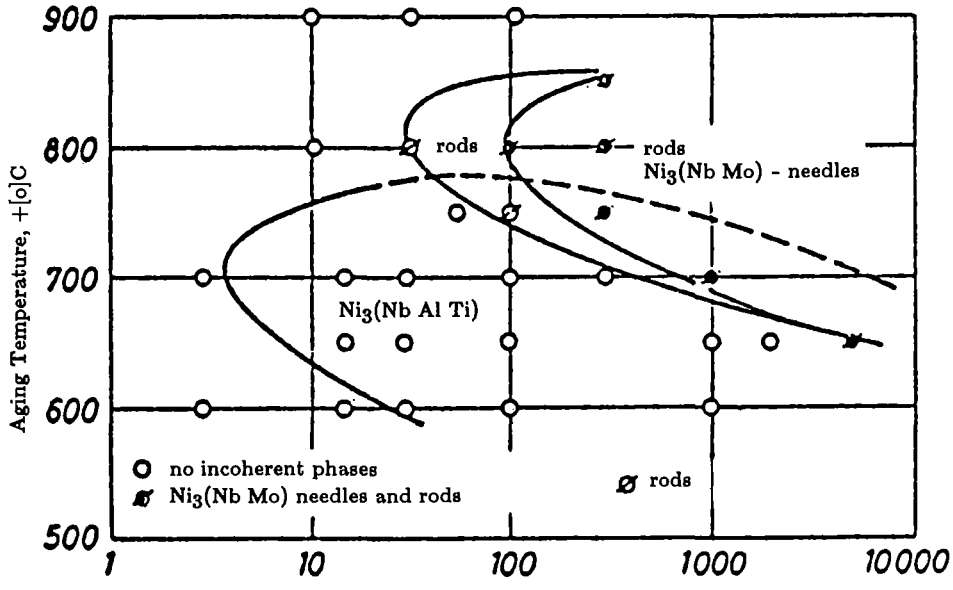


Time-temperature-precipitation diagram
Effect of composition on sigma phase formation

SOURCE: E. Erdis, et al., Final Report, Sulzer Bros., July 1977, as cited by T. Geiger, R. Stickler, G.H. White, "The Structural Stability of Ni-Cr Base Superalloys during Long-Time Exposure at Elevated Temperatures," High-Temperature Alloys for Gas Turbines, Applied Science Publishers Ltd., London, 1978, pp 317-333

Inconel 625

Composition: Ni - 0.03% C - 0.10% Mn - 0.25% Si - 0.008% S - 0.011% P - 22.1% Cr - 1.89% Fe - 0.20% Al - 0.22% Ti - 9.1% Mo - 3.35% Nb+Ta - 0.20% W - 40 ppm B - 50 ppm O - 480 ppm N



LIVE GRAPH
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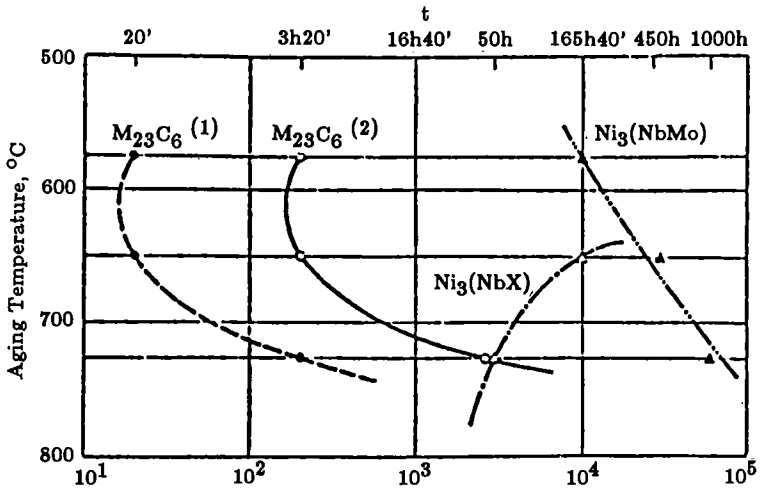
Time-temperature-precipitation diagram

SOURCE: F. Gazarolli, A. Gerscha, K.P. Francke, "Studies of the Precipitation Behaviour and Mechanical Properties of Inconel Alloy 625," Z. Metallkunde, Vol 60, 1969, pp 643-652

Inconel 625

Composition: Ni - 0.016% C - 0.3% Si - 0.05% Mn - 0.005% P - 0.006% S - 21.8% Cr - 0.027% Co - 9.05% Mo - 0.2% Ti - 0.1% Al - 2.4% Fe - 0.023% Cu - 3.7% Nb+Ta - 1 ppm B

Treatment: Solution annealed 1150°C (2102°F) for 3 h, water quenched. Aging done in a vacuum



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(1) = For short aging times, $M_{23}C_6$ is precipitated at grain boundaries, dislocations and twin boundaries

(2) = $M_{23}C_6$ precipitates within the grains and grow slowly (for t >50 h, needle and plate-shaped carbides are formed)

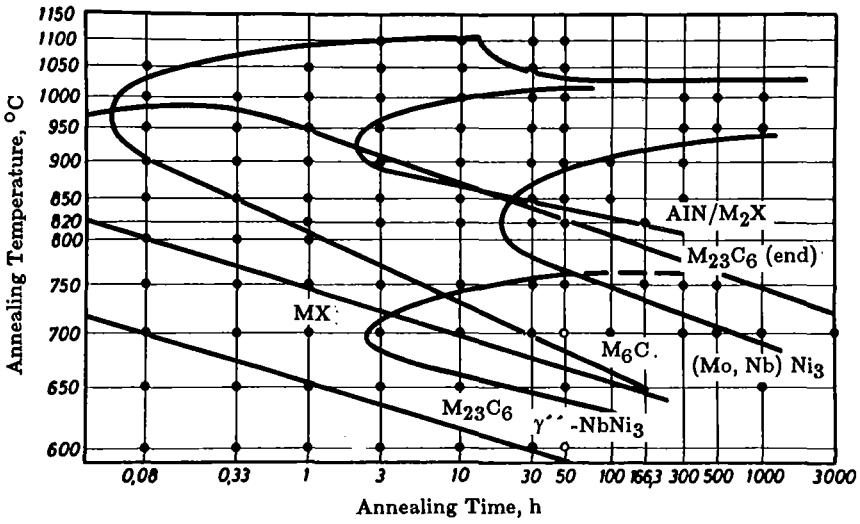
Time-temperature-precipitation diagram

SOURCE: H. Bohm, K. Erlich, K.H. Kramer, "The Precipitation Behaviour of the Nickel-Base Alloy Inconel 625," Metall., Vol 24, 1970, pp 139-144

Inconel 625

Composition: Ni - 0.029% C - 0.34% Si - 0.38% Mn - 0.009% P - 0.004% S - 22.67% Cr - 1.33% Fe - 8.75% Mo - 0.17% Ti - 3.72% Nb - 0.15% Al - 0.0071% N

Treatment: Solution treated at 1150°C)2102°F) for 3 h, water quenched, followed by a precipitation anneal at temperatures between 600 and 1100°C (1112 and 2012°F) for 5 min to 3000 h



Time-temperature-precipitation diagram

Gamma double prime - Ni_3Nb is tetragonal = gamma double prime
$Ni_3(Nb,Mo)$ - orthorhombic = delta phase

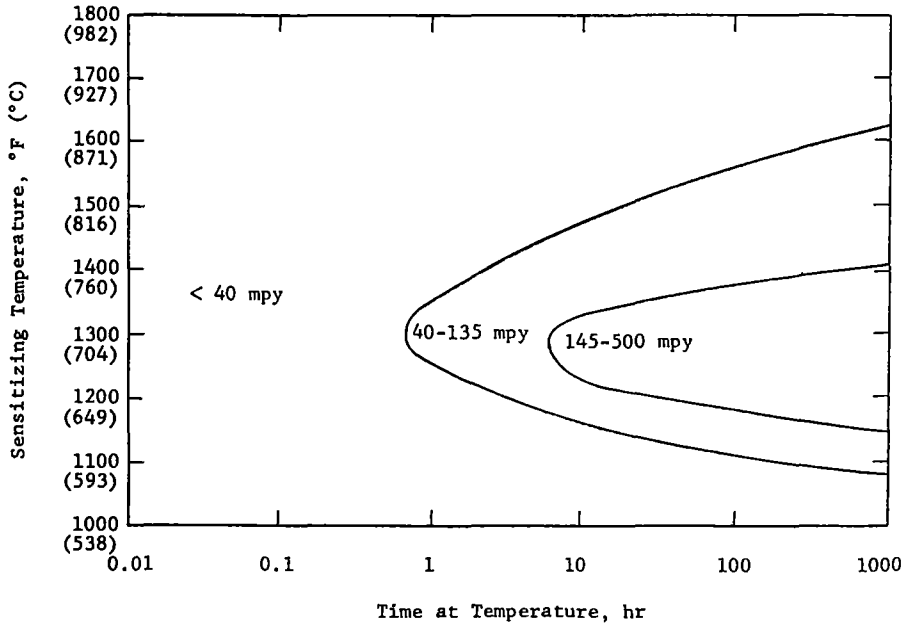
NOTE: During aging, carbides $M_{23}C_6$ and M_6C, carbonitrides of type MX, the intermetallic phase gamma$^+$-$NbNi_3$, $(Mo,Nb)Ni_3$ and, to a small extent, eta-Ni_3Ti precipitated out. A phase was also observed, which could not be identified exactly. It is presumably a niobium carbonitride of type M_2X but could also possibly be AlN

SOURCE: Ekkehard Schnabel, Hans-Jurgen Schuller, Paul Schwaab, "The Precipitation and Recrystallization Behaviour of the Nickel-Base-Alloy Inconel 625," Practical Metallography, Vol 8, September 1971, pp 521-527

Inconel 625

Nominal composition: 61.0% Ni+Co - 21.5% Cr - 9.0% Mo - 3.65% Nb+Ta - 2.5% Fe - 0.05% C - 0.25% Mn - 0.008% S - 0.25% Si - 0.2% Al - 0.2% Ti

Treatment: Annealed at 982°C (1800°F) for 30 min, water quenched, subjected to sensitizing heat treatments of 538 to 871°C (1000 to 1600°F) for 1 h, and air cooled. Specimens were then subjected to the ASTM A262 boiling 65% nitric acid test



LIVE GRAPH
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Time-temperature-sensitization diagram

SOURCE: J.A. Harris, R.C. Scarberry, "Effect of Metallurgical Reactions in Inconel Nickel-Chromium-Molybdenum Alloy 625 on Corrosion Resistance in Nitric Acid," Journal of Metals, Vol 23, September 1971, pp 45-49

Inconel 625

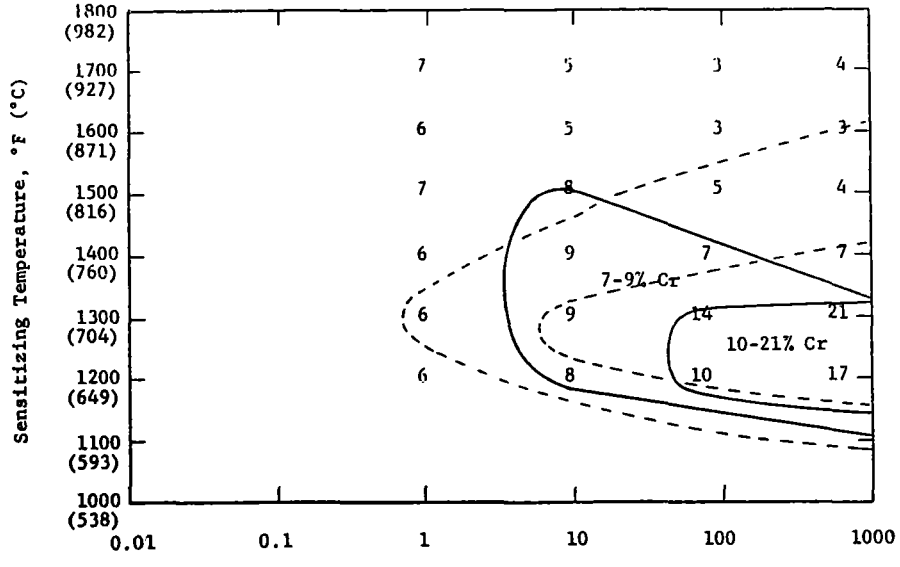
Nominal composition: 61.0% Ni+Co - 21.5% Cr - 9.0% Mo - 3.65% Nb+Ta - 2.5% Fe - 0.05% C - 0.25% Mn - 0.008% S - 0.25% Si - 0.2% Al - 0.2% Ti

Treatment: Annealed at 982°C (1800°F) for 30 min, water quenched, subjected to sensitizing heat treatments of 538 to 871°C (1000 to 1600°F) for 1 h, and air cooled. Specimens were then subjected to the ASTM A262 boiling 65% nitric acid test

Relative amounts and compositions of phases present after anneal at 982°C (1800°F) for 1 h, water quench and age treatments listed below

Temperature, °F (°C)	Time at Temperature, hr	Phases Present*				Residue Analysis, %				
		Cb (C, N)	M_6C	M_6C^I	M_6C^{II}	Ni	Cr	Cb	Mo	Other**
1200 (649)	1	M	A	—	—	18	6	40	30	6
	10	M	A	—	—	17	8	38	29	8
	100	M	A	—	—	25	10	32	26	7
	1000	M	A	—	R	40	17	19	19	5
1300 (704)	1	M	A	—	—	18	6	40	30	6
	10	M	A	—	—	21	9	35	27	9
	100	—	A	—	R	40	14	19	21	6
	1000	—	MR	—	A	26	21	18	31	4
1400 (760)	1	M	A	—	—	19	6	40	29	6
	10	M	A	—	—	23	9	32	30	6
	100	—	A	—	A	28	7	23	40	2
	1000	—	—	—	VA	31	7	17	43	2
1500 (816)	1	M	A	—	—	21	7	37	30	5
	10	MR	A	—	M	24	8	30	33	5
	100	—	MR	M	A	38	5	21	33	3
	1000	—	MR	—	A	39	4	21	34	2
1600 (871)	1	M	A	—	—	17	6	39	30	8
	10	R	A	R	MR	38	5	31	27	4
	100	—	MR	A	—	36	3	27	32	2
	1000	—	R	A	—	36	3	31	27	3
1700 (927)	1	M	A	—	—	18	7	39	29	7
	10	—	A	R	—	29	5	34	28	4
	100	—	—	R	—	40	3	32	23	2
	1000	—	A	—	—	35	4	30	26	5

* A = abundant; R = rare; M = medium; VA = very abundant.
** Iron and titanium.



LIVE GRAPH
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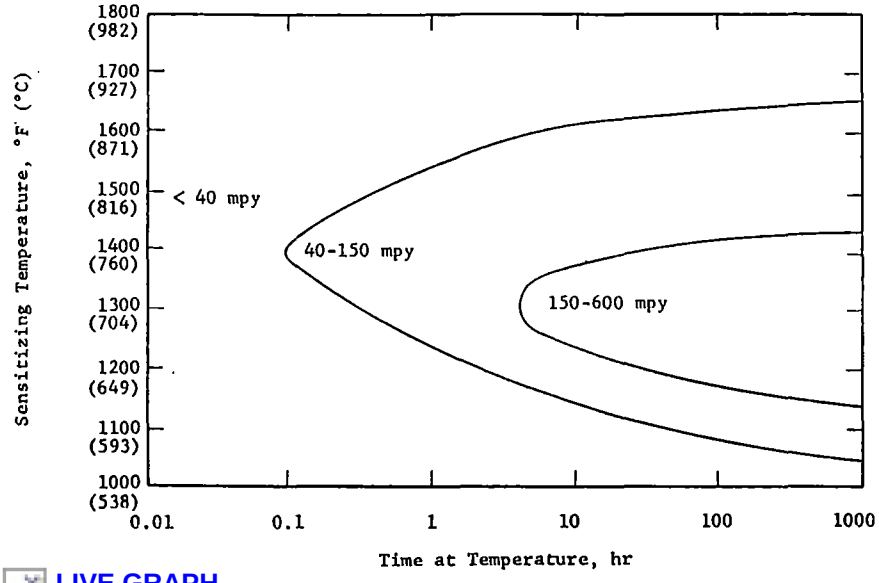
LEGEND:
Labels = %Cr in extracted carbide residues
Broken-line curves enclose areas of moderate sensitization and excessive sensitization from prior diagram
Time-temperature-sensitization diagram
Correlation of sensitization with carbide precipitation
M_6C is the predominant carbide

SOURCE: J.A. Harris, R.C. Scarberry, "Effect of Metallurgical Reactions in Inconel Nickel-Chromium-Molybdenum Alloy 625 on Corrosion Resistance in Nitric Acid," Journal of Metals, Vol 23, September 1971, pp 45-49

Inconel 625

Nominal composition: 61.0% Ni+Co - 21.5% Cr - 9.0% Mo - 3.65% Nb+Ta - 2.5% Fe - 0.05% C - 0.25% Mn - 0.008% S - 0.25% Si - 0.2% Al - 0.2% Ti

Treatment: Annealed at 1149°C (2100°F) for 30 min, water quenched, subjected to sensitizing heat treatments of 538 to 871°C (1000 to 1600°F) for 1 h, and air cooled. Specimens were then subjected to the ASTM A262 boiling 65% nitric acid test



LIVE GRAPH
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Time-temperature-sensitization diagram

SOURCE: J.A. Harris, R.C. Scarberry, "Effect of Metallurgical Reactions in Inconel Nickel-Chromium-Molybdenum Alloy 625 on Corrosion Resistance in Nitric Acid," Journal of Metals, Vol 23, September 1971, pp 45-49

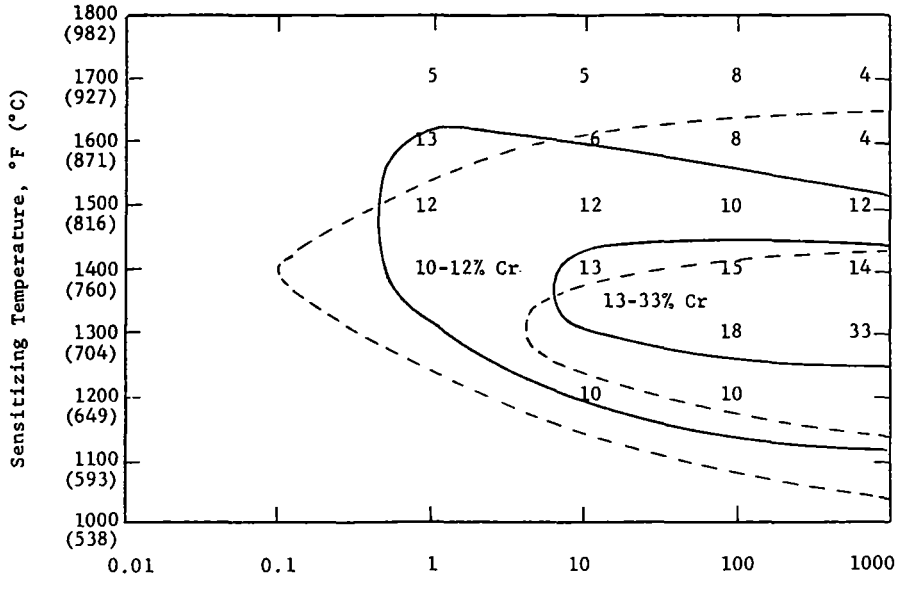
Inconel 625

Nominal composition: 61.0% Ni+Co - 21.5% Cr - 9.0% Mo - 3.65% Nb+Ta - 2.5% Fe - 0.05% C - 0.25% Mn - 0.008% S - 0.25% Si - 0.2% Al - 0.2% Ti
Treatment: Annealed at 1204°C (2200°F) for 1 h, water quenched, subjected to sensitizing heat treatments of 538 to 871°C (1000 to 1600°F) for 1 h, and air cooled. Specimens were then subjected to the ASTM A262 boiling 65% nitric acid test

Relative amounts and compositions of phases present after anneal at 1204°C (2200°F) for 1 h, water quench and age treatments listed below

Temperature, °F (°C)	Time at Temperature, hr	Cb (C, N)	Phases Present*				Residue Analysis, %				
			M_6C	M_6C^1	M_6C^{11}	$M_{28}C_6$	Ni	Cr	Cb	Mo	Other**
1200 (649)	100	A	R	—	—	R	12	10	49	13	16
1300 (704)	100	A	R	—	—	M	7	18	48	9	18
	1000	A	R	—	—	A	10	33	27	13	17
1400 (760)	10	A	R	—	—	—	9	13	44	9	25
	100	A	R	—	—	M	7	18	48	9	18
	1000	A	R	—	A	R	13	14	32	29	12
1500 (816)	10	A	R	—	—	—	9	12	48	12	19
	100	M	A	—	—	R	16	10	41	20	13
	1000	—	R	—	A	—	21	12	24	34	7
1600 (871)	1	A	M	—	—	—	10	13	52	11	14
	10	A	A	—	—	—	11	6	54	19	10
	100	—	A	R	—	—	21	8	37	28	6
	1000	—	A	A	—	—	19	4	33	39	4
1700 (927)	1	A	A	—	—	—	7	5	61	15	13
	10	M	A	—	—	—	15	5	47	23	10
	100	—	A	—	—	—	19	8	36	32	5
	1000	—	A	—	—	—	16	4	44	32	4

* A = abundant; R = rare; M = medium; VA = very abundant,
** Iron and titanium.



LIVE GRAPH
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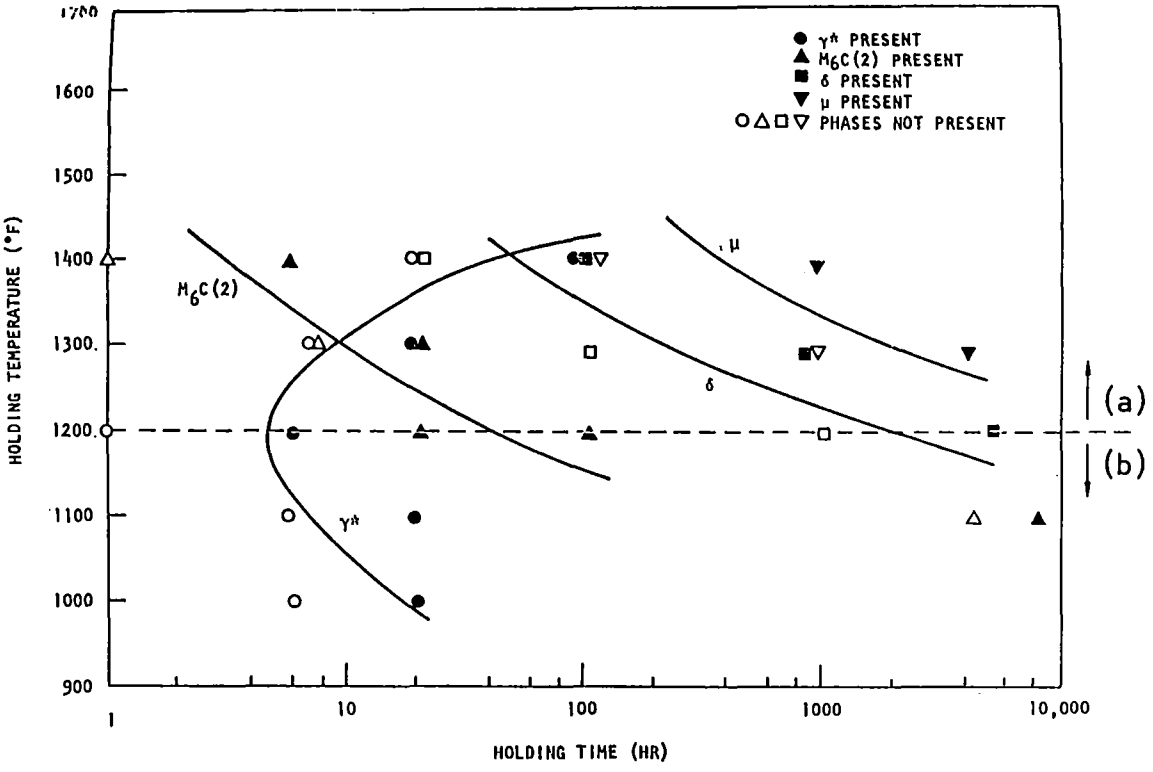
Legend:
Labels = %Cr in extracted carbide residues
Broken-line curves enclose areas of moderate sensitization and excessive sensitization from prior diagram
Time-temperature-sensitization diagram
Correlation of sensitization with carbide precipitation

SOURCE: J.A. Harris, R.C. Scarberry, "Effect of Metallurgical Reactions in Inconel Nickel-Chromium-Molybdenum Alloy 625 on Corrosion Resistance in Nitric Acid," Journal of Metals, Vol 23, September 1971, pp 45-49

Inconel 625

Composition: 60.95% Ni - 22.21% Cr - 3.61% Fe - 8.97% Mo - 3.50% Nb+Ta - 0.19% Al - 0.27% Ti - 0.26% Si - 0.05% Mn - 0.006% P - 0.004% S - 0.08% Cu - 0.03% C
Treatment: Solution annealed material obtained by heat treating mill annealed material at 1149°C (2100°F) for 1 h, air cooled



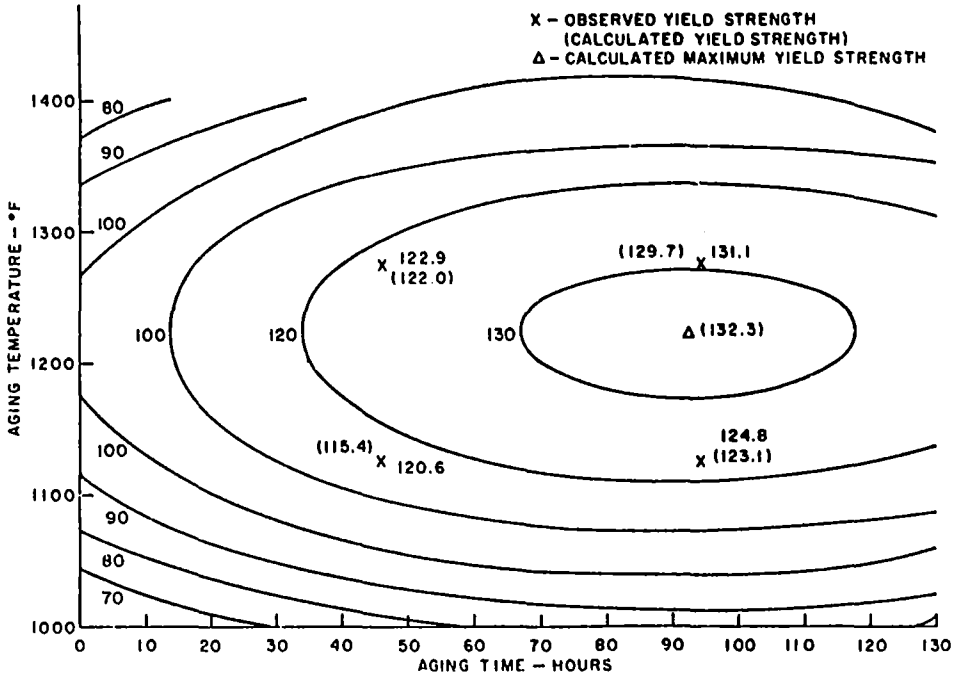
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram
(a) data based on solution-annealed material
(b) data based on mill-annealed material

SOURCE: O.F. Kimball, P.K. Gantzel, Thermal Stability of Inconel 625 - Principal Metallurgy," Gulf-GA-A12683, October 1973

Inconel 625

Composition: 60.64% Ni - 0.02% C - 0.09% Mn - 0.19% Si - 22.14% Cr - 4.06% Fe - 9.0% Mo - 3.39% Nb+Ta - 0.22% Al - 0.24% Ti - 0.001% B - 0.05% Co
Treatment: Hot-rolled, nucleated at 649°C (1200°F) for 10 h, then aged as shown



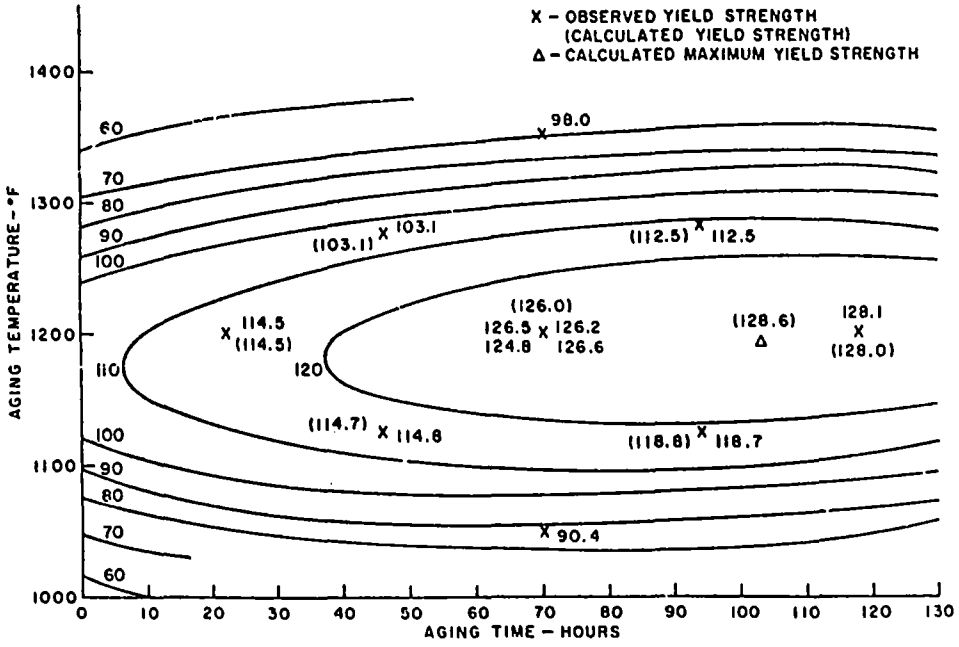
LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Contours of equal yield strength (ksi)

SOURCE: S.C. Hayes, "Heat-Treatment Parameters for the Aging of Alloy 625," General Electric Company, Knolls Atomic Power Laboratory, Schenectady NY, Contract DE-AC12-76SN00052, September 1981

Inconel 625

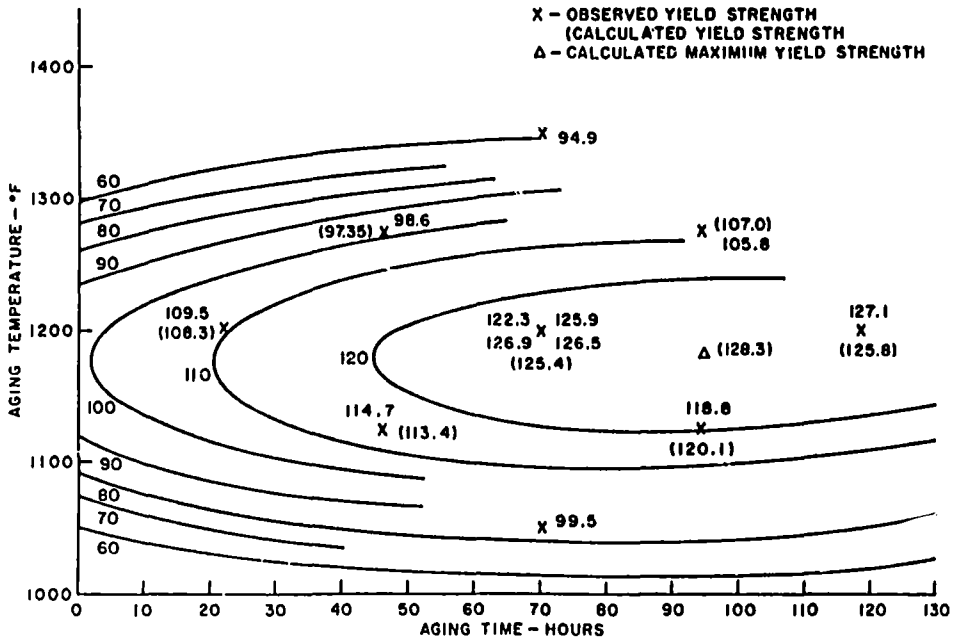
Composition: 60.64% Ni - 0.02% C - 0.09% Mn - 0.19% Si - 22.14% Cr - 4.06% Fe - 9.0% Mo - 3.39% Nb+Ta - 0.22% Al - 0.24% Ti - 0.001% B - 0.05% Co
Treatment: Hot-rolled, then aged as shown



LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Contours of equal yield strength (ksi)

Composition: 60.64% Ni - 0.02% C - 0.09% Mn - 0.19% Si - 22.14% Cr - 4.06% Fe - 9.0% Mo - 3.39% Nb+Ta - 0.22% Al - 0.24% Ti - 0.001% B - 0.05% Co
Treatment: Hot-rolled, mill-annealed, then aged as shown



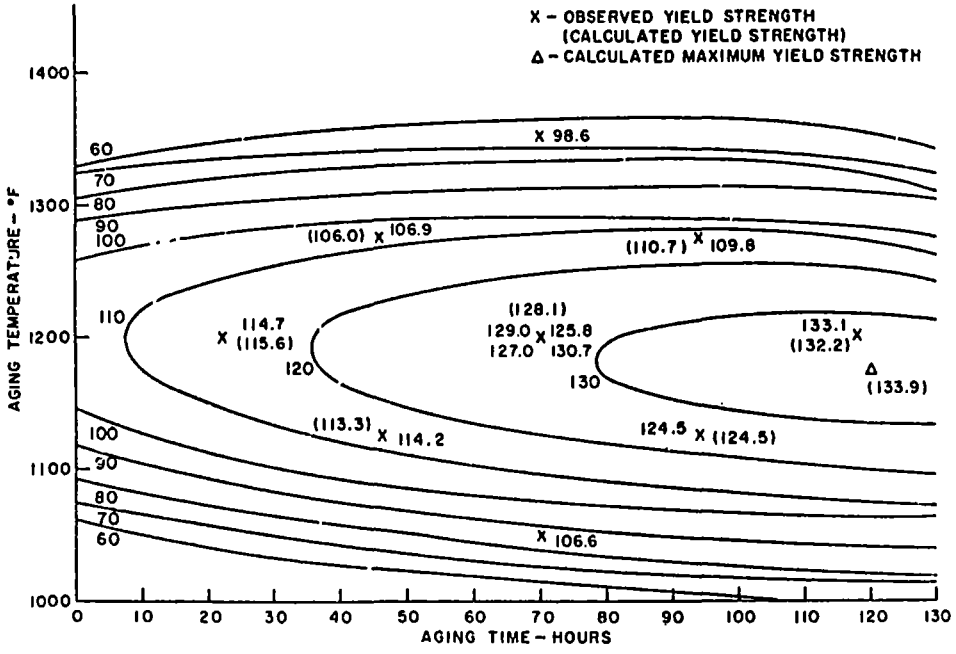
LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Contours of equal yield strength (ksi)

SOURCE: S.C. Hayes, "Heat-Treatment Parameters for the Aging of Alloy 625," General Electric Company, Knolls Atomic Power Laboratory, Schenectady NY, Contract DE-AC12-76SN00052, September 1981

Inconel 625

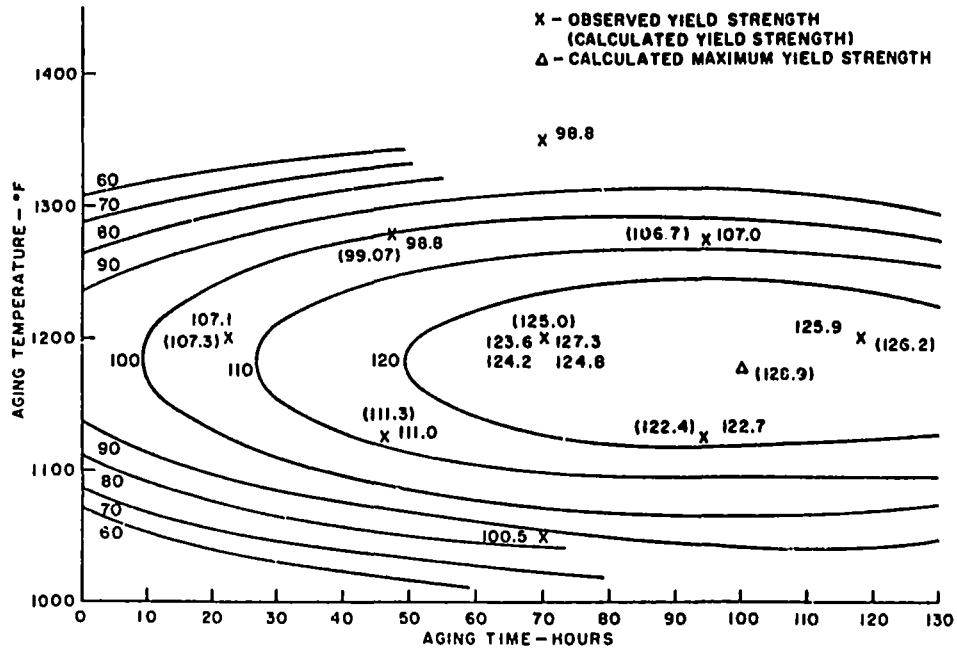
Composition: 60.96% Ni - 0.02% C - 0.12% Mn - 0.31% Si - 21.94% Cr - 3.82% Fe - 8.94% Mo - 3.47% Nb+Ta - 0.21% Al - 0.20% Ti - 0.06% Co - 0.001% B
Treatment: Hot-rolled, aged as shown



LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Contours of equal yield strength (ksi)

Composition: 60.96% Ni - 0.02% C - 0.12% Mn - 0.31% Si - 21.94% Cr - 3.82% Fe - 8.94% Mo - 3.47% Nb+Ta - 0.21% Al - 0.20% Ti - 0.06% Co - 0.001% B
Treatment: Hot-rolled, aged as shown



LIVE GRAPH
Click here to view

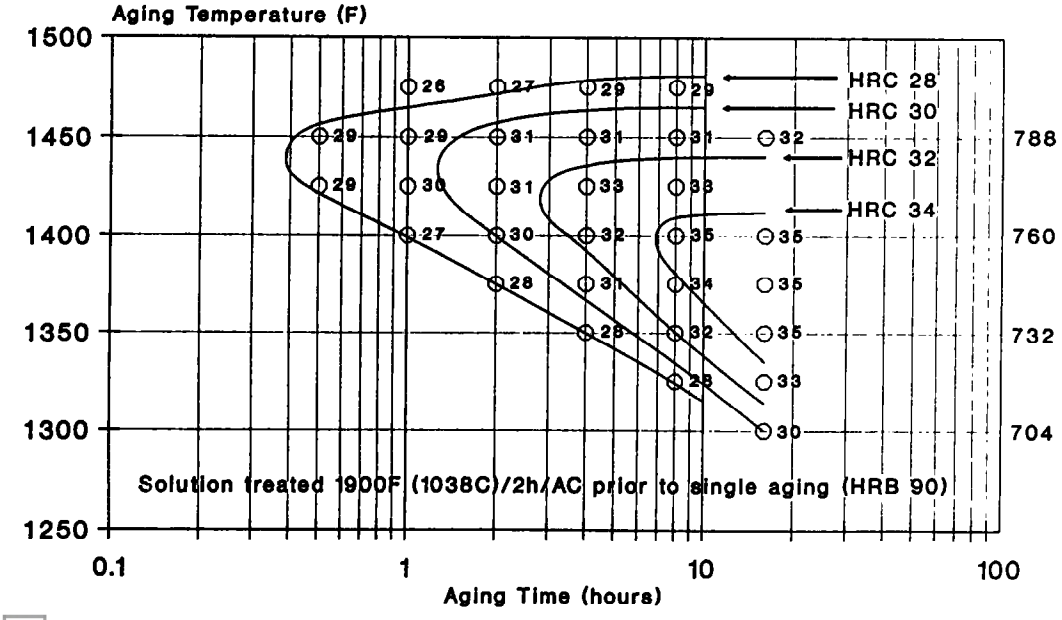
Time-temperature-aging diagram
Contours of equal yield strength (ksi)

SOURCE: S.C. Hayes, "Heat-Treatment Parameters for the Aging of Alloy 625," General Electric Company, Knolls Atomic Power Laboratory, Schenectady NY, Contract DE-AC12-76SN00052, September 1981

Custom Age 625 PLUS

Nominal composition: 61% Ni - 0.01% C - 21% Cr - 8% Mo - 3.4% Nb - 1.3% Ti - 0.2% Al - 5% Fe

Treatment: Solution treated at 1038°C (1900°C) for 2 h, air cooled prior to single aging



LIVE GRAPH
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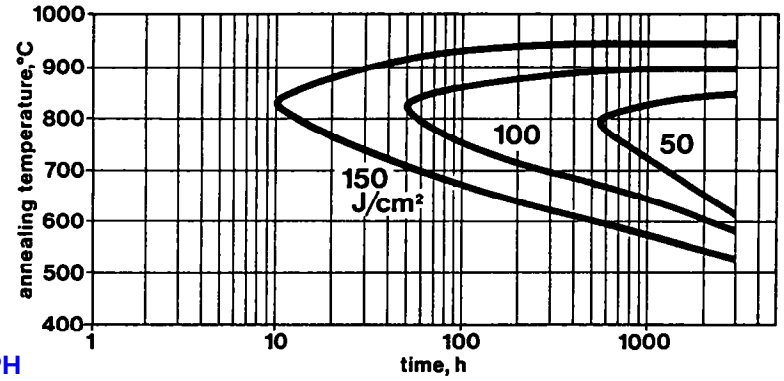
Time-temperature-hardness on aging diagram

SOURCE: R.B. Frank, T.A. DeBold, "Heat Treatment of an Age-Hardenable, Corrosion-Resistant Alloy - UNS N07716," Corrosion 90, NACE, 23-27 April 1990, Las Vegas NV

Alloy 625 (Nicrofer 6020 hMo)

Composition: Ni - 22.25% Cr - 9.27% Mo - 2.05% Fe - 0.1% Mn - 0.04% Si - 0.3% Ti - 3.42% Nb+Ta - 0.14% Al - 0.011% C
Treatment: Annealed at 1120°C (2048°F) for 50 min and aged as shown



LIVE GRAPH
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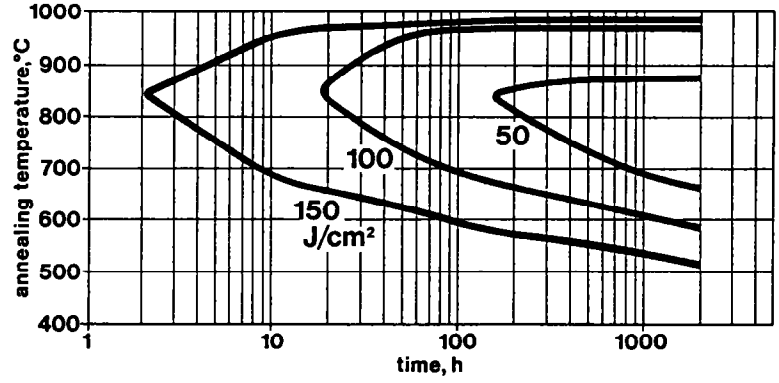
Time-temperature-toughness diagram
Iso-notched impacts tests (iso-impact strength curves) at room temperature

Alloy 625 (Nicrofer 6022 hMo)

Composition: Ni - 21.9% Cr - 8.94% Mo - 1.4% Fe - 0.03% Mn - 0.04% Si - 0.18% Ti - 3.74% Nb+Ta - 0.16% Al - 0.03% C
Treatment: Annealed at 980°C (1796°F) for 50 min and aged as shown



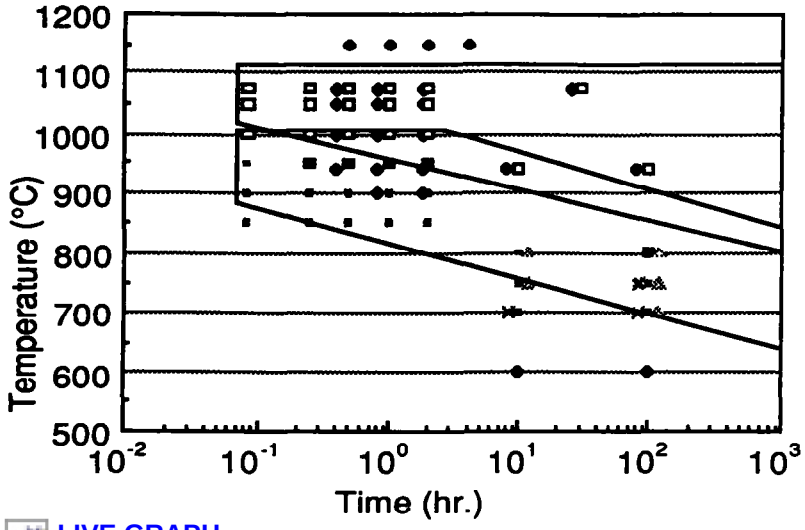
Time-temperature-toughness diagram
Iso-notched impacts tests (iso-impact strength curves) at room temperature

LIVE GRAPH
Click here to view

SOURCE: M. Kohler, "Effect of the Elevated-Temperature-Precipitation in Alloy 625 Properties and Microstructure," Superalloys 718, 625 and Various Derivatives, Edward A. Loria, ed., TMS, 1991, pp 363-374

Alloy 625

Composition: Ni - 20.5% Cr - 8.2% Mo - 4.3% Fe - 3.6% Nb - 0.1% Co - 0.1% Al - 0.1% Ti - 0.1% Si - 0.1% Mn - 0.03% C
Treatment: solution annealed at 1150°C (2102°F), then aged at 600 to 1075°C (1112 to 1967°F)



LIVE GRAPH
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LEGEND:

- ● MC
- ▫ M_6C
- ▪ $M_{23}C_6$
- × gamma double prime
- ▲ delta

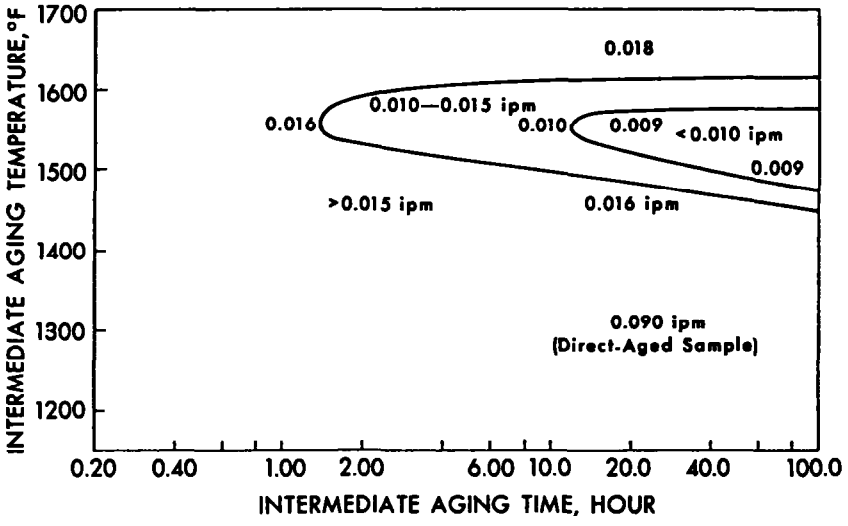
Time-temperature-precipitation diagram

SOURCE: L. Ferrer, B. Pieraggi, J.F. Uginet, "Microstructural Evolution During Thermomechanical Processing of Alloy 625," Superalloys 718, 625 and Various Derivatives, Edward A. Loria, ed., TMS, 1991, pp 217-228

Inconel X-750

Composition: 73.19% Ni - 0.03% C - 0.56% Mn - 6.51% Fe - 0.007% S - 0.27% Si - 0.06% Cu - 15.24% Cr - 0.76% Al - 2.50% Ti - 0.85% Nb+Ta

Treatment: All but one specimen were solution treated at 1150°C (2100°F), aged for temperatures and times shown in the diagram, then aged at 704°C (1300°F) for 20 h. The one other specimen was direct-aged at 704°C (1300°F) for 20 h



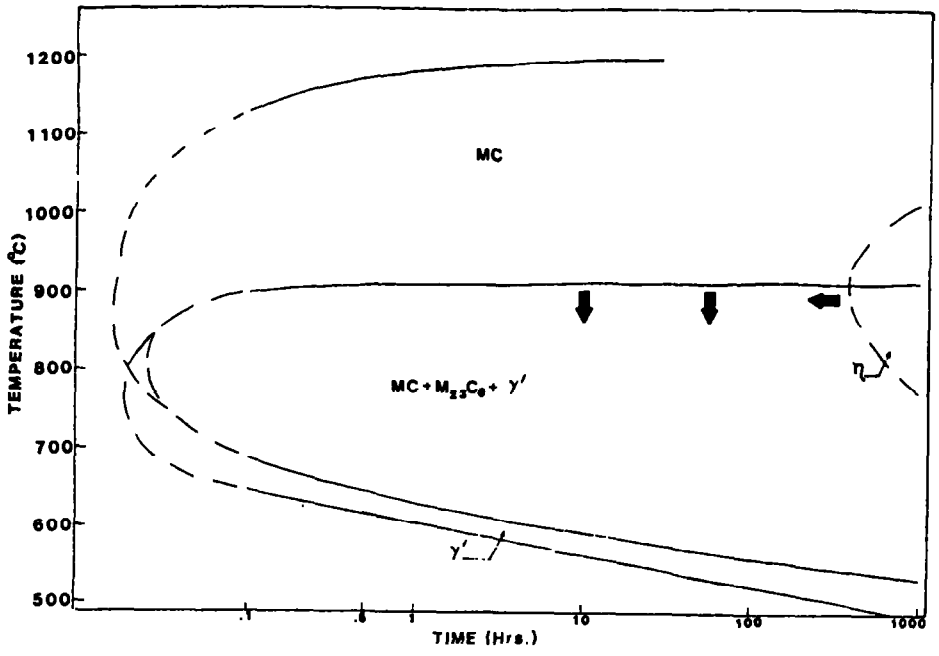
LIVE GRAPH
Click here to view

Time-temperature sensitization diagram
Indicated by corrosion rate in inches per month (ipm)

SOURCE: E.L. Raymond, "Effect of Grain Boundary Denudation of Gamma Prime on Notch-Rupture Ductility of Inconel Nickel-Chromium Alloys X-750 and 718," Trans. AIME, Vol 239, September 1967, pp 1415-1422

Inconel X-750

Composition: 72.02% Ni - 0.06% C - 0.19% Mn - 7.82% Fe - 0.001% S - 0.40% Si - 0.37% Cu - 14.82% Cr - 0.85% Al - 2.49% Ti - 0.98% Nb+Ta
Treatment: Solution annealed at 1075°C (1967°F) for 2 h, water quenched, and aged



Time-temperature-precipitation diagram

LIVE GRAPH
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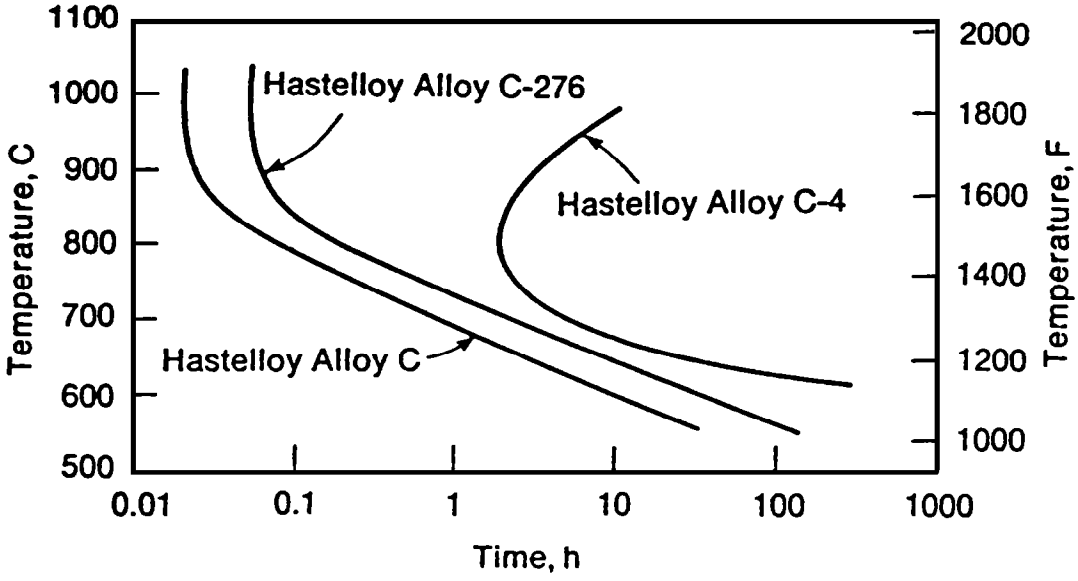
SOURCE: INCONEL Alloy X-750, 4th edition, Huntington Alloys, Inc., 1979

Hastelloy Alloys

Nominal compositions:
Hastelloy Alloy C: Ni - 17% Mo - 15% Cr - 4.5% W - 6% Fe
Hastelloy Alloy C-4: Ni - <0.015% C - <2% Co - 16% Cr - 15.5% Mo - <0.7% Ti - <3% Fe - <1% Mn - <0.08% Si
Hastelloy Alloy C-276: Ni - 13% Cr - 16% Mo - <2.5% Co - 3.75% W - 5.5% Fe - <0.02% C - <1% Mn



LIVE GRAPH
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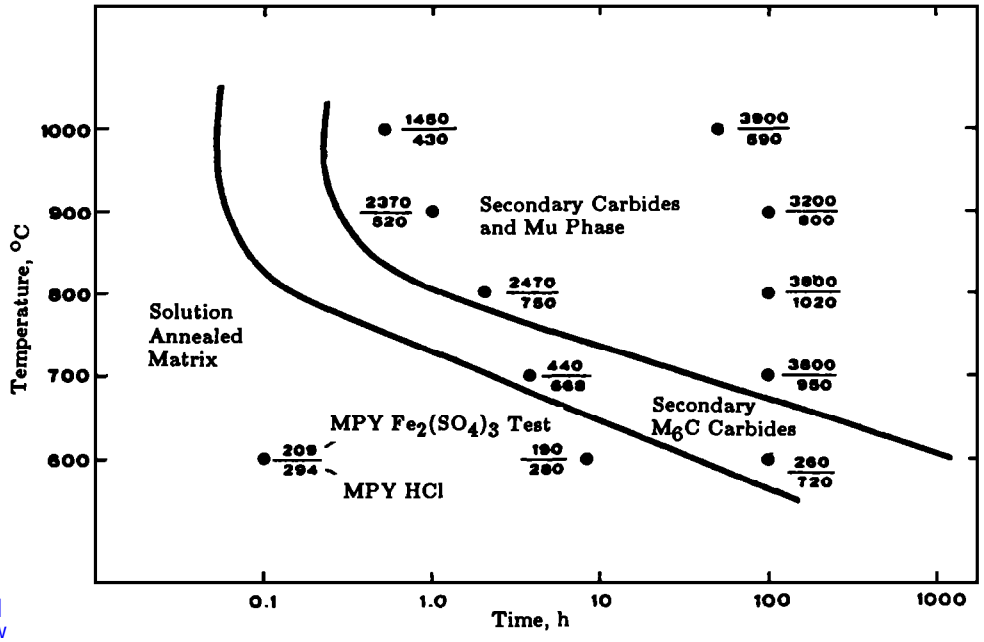
Time-temperature-transformation diagram
Beginning of carbide precipitation

SOURCE: Heins Spahn, "Performance Requirements for Stainless Steels in the Chemical Process Industry," Stainless Steel '77, Climax Molybdenum Co., 1978

Hastelloy C-276

Nominal composition: Ni - 16% Cr - 3.4% W - 6% Fe - 0.01% C - 0.02% Si - 1% Co - 0.45% Mn - 0.2% V - 16% Mo
Treatment: Solution annealed at 1123°C (2045°F)



LIVE GRAPH
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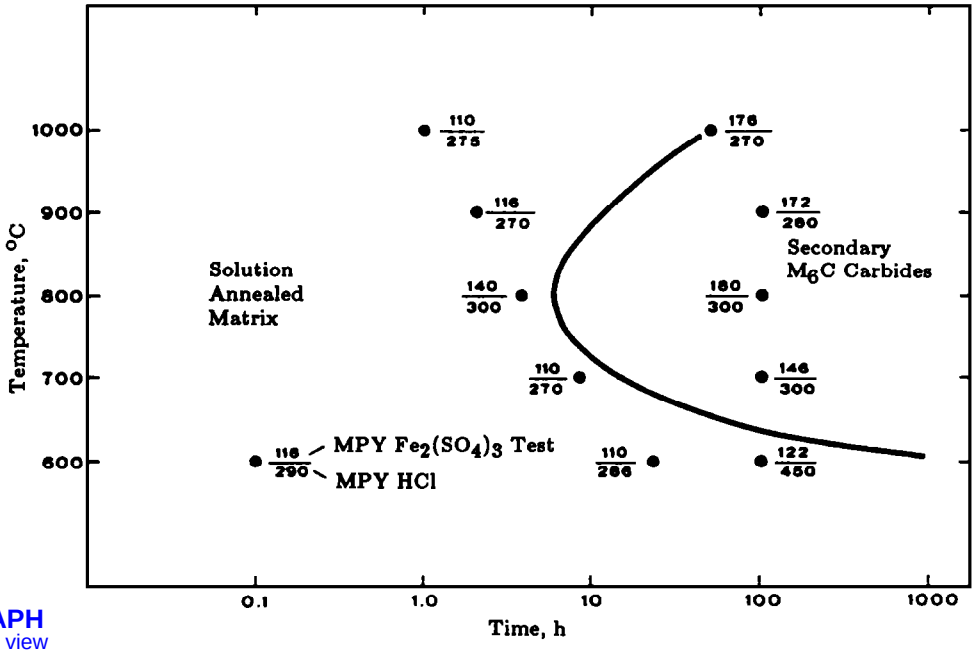
Time-temperature-precipitation-corrosion diagram
Corrosion test solution: 10% HCl test and the ferric sulfate test (50% sulfuric acid plus 42 g/L ferric sulfate)

SOURCE: F.G. Hodge, R.W. Kirchner, "An Improved Ni-Cr-Mo Alloy for Corrosion Service," Corrosion 74, NACE, 4-8 March 1974, Chicago IL

Hastelloy C-4

Nominal composition: Ni - 16% Cr - 0.15% W - 0.3% Fe - <0.01% C - 0.03% Si - 0.1% Co - 0.05% Mn - 0.03% V - 15% Mo - 0.45% Ti

Treatment: Solution annealed at 1065°C (1950°F)



LIVE GRAPH
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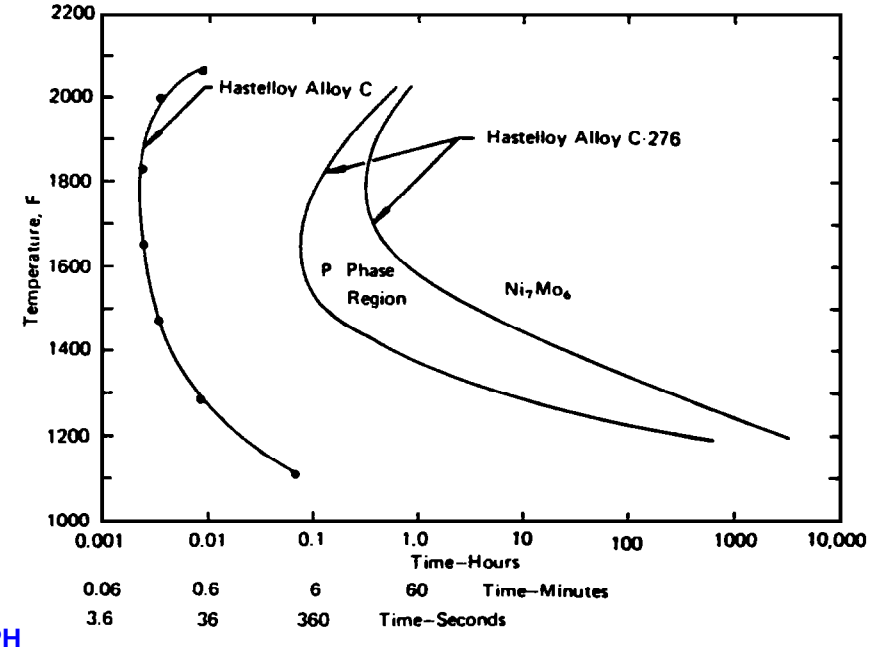
Time-temperature-precipitation-corrosion diagram
Corrosion test solution: 10% HCl test and the ferric sulfate test (50% sulfuric acid plus 42 g/L ferric sulfate)

SOURCE: F.G. Hodge, R.W. Kirchner, "An Improved Ni-Cr-Mo Alloy for Corrosion Service," Corrosion 74, NACE, 4-8 March 1974, Chicago IL

Hastelloy Alloys

Composition Hastelloy C: Ni - 0.04% C - 0.50% Si - 0.010% P - 0.010% S - 16.00% Mo - 4.00% W - 1.00% Co - 5.00% Fe - 0.35% Mn - 16.00% Cr - 0.20% V

Composition Hastelloy C-276: Ni - 0.004% C - <0.01% Si - 0.010% P - 0.003% S - 0.22% Al - 16.25% Mo - <0.01% Zr - 3.70% W - 0.04% Cu - 1.08% Co - 5.98% Fe - 0.34% Mn - 16.38% Cr - 0.21% V - 0.026% Mg



LIVE GRAPH
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Precipitate Formation in Hastelloy Alloy C-276

Temperature									
1200 F		1400 F		1600 F		1800 F		2000 F	
Time	Form	Time	Form	Time	Form	Time	Form	Time	Form
Min.		Min.		Min.		Min.		Min.	
5	none	5	none	5	P	5	none	5	none
15	none	15	none	15	P	15	P	15	none
30	none	30	P	30	P	30	Ni_7Mo_6	30	P
Hrs.		Hrs.		Hrs.		Hrs.		Hrs.	
1	none	1	P	1	Ni_7Mo_6	1	Ni_7Mo_6	1	Ni_7Mo_6
2	none	2	P	2	Ni_7Mo_6	2	Ni_7Mo_6	2	Ni_7Mo_6
4	none	4	P	4	Ni_7Mo_6	4	Ni_7Mo_6	4	Ni_7Mo_6
8	none	8	Ni_7Mo_6	8	Ni_7Mo_6	8	Ni_7Mo_6	8	Ni_7Mo_6
41.7	P	9.7	P	12.5	Ni_7Mo_6	10.9	Ni_7Mo_6		
70.2	none	117.7	Ni_7Mo_6	62.0	Ni_7Mo_6	630.4	Ni_7Mo_6		
161.9	none	341.9	Ni_7Mo_6	160.6	Ni_7Mo_6	2369.5	Ni_7Mo_6		
292.6	M_6C Type			1000	Ni_7Mo_6				
560.5	M_6C Type			1417	Ni_7Mo_6				
763.5	none								
1000	P								

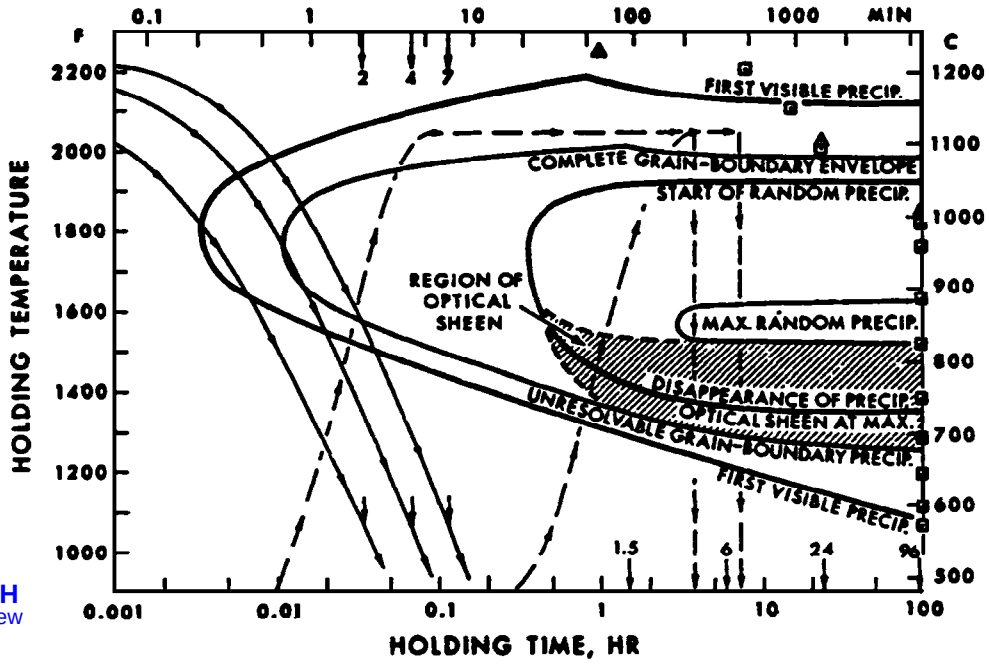
Time-temperature-precipitation diagram
Comparison of Hastelloy Alloys C and C-276

SOURCE: R.B. Leonard, "Thermal Stability of Hastelloy Alloy C-276," Corrosion, Vol 25, No. 5, May 1969, pp 222-228

Hastelloy C

Composition: Ni - 14.94-16.46% Cr - 15.47-16.47% Mo - 3.38-4.02% W - 5.05-6.77% Fe - 0.74-1.86% Co - 0.42-0.69% Mn - 0.42-0.73% Si - 0.22-0.32% V - 0.04-0.08% C - 0.004-0.012% P - 0.005-0.011% S

Treatment: Aged from 540 to 1230°C (1000 to 2250°F) for 1.5 to 96 h



LIVE GRAPH
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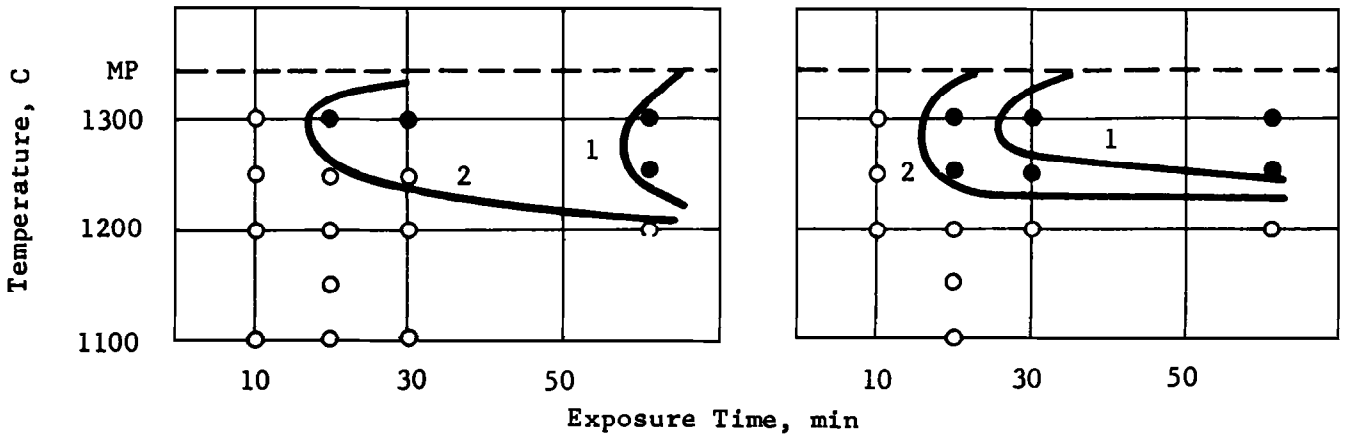
Time-temperature-precipitation diagram

SOURCE: C.H. Samans, A.R. Meyer, G.F. Tisinai, "Sensitization and Thermal Stabilization of Ni-Cr-Mo-Fe-W Alloy," Corrosion, Vol 22, December 1966, pp 336-345

Hastelloy B-2

Composition: Ni - 1.00% max Co - 1.00% max Cr - 26.00%-30.00% Mo - 2.00% max Fe - 0.10% max Si - 1.00% max Mn - 0.02% max C - 0.040% max P - 0.030% max S



LIVE GRAPH
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LEGEND:
1 = 0.015-0.02% C
2 = 0.04% C
o = No intergranular corrosion
● = Intergranular corrosion ov 20 μ deep

Time-temperature-intergranular-corrosion diagram

Left: Ni - 27% Mo - 0.2% Fe and 0.015-0.02% C vs 0.04% C

Right: Ni - 27% Mo - 3.5% Fe and 0.015-0.02% C vs 0.04% C

SOURCE: T.V. Svistunova, "Molybdenum in Nickel-Base Corrosion-Resistant Alloys," presented at a Soviet-American Symposium held at the Central Scientific Research Institute for Ferrous Metals (TsNIChM) in Moscow, 17-18 January 1973, on the theme: New Developments in the Field of Molybdenum-Alloyed Cast Iron and Steel

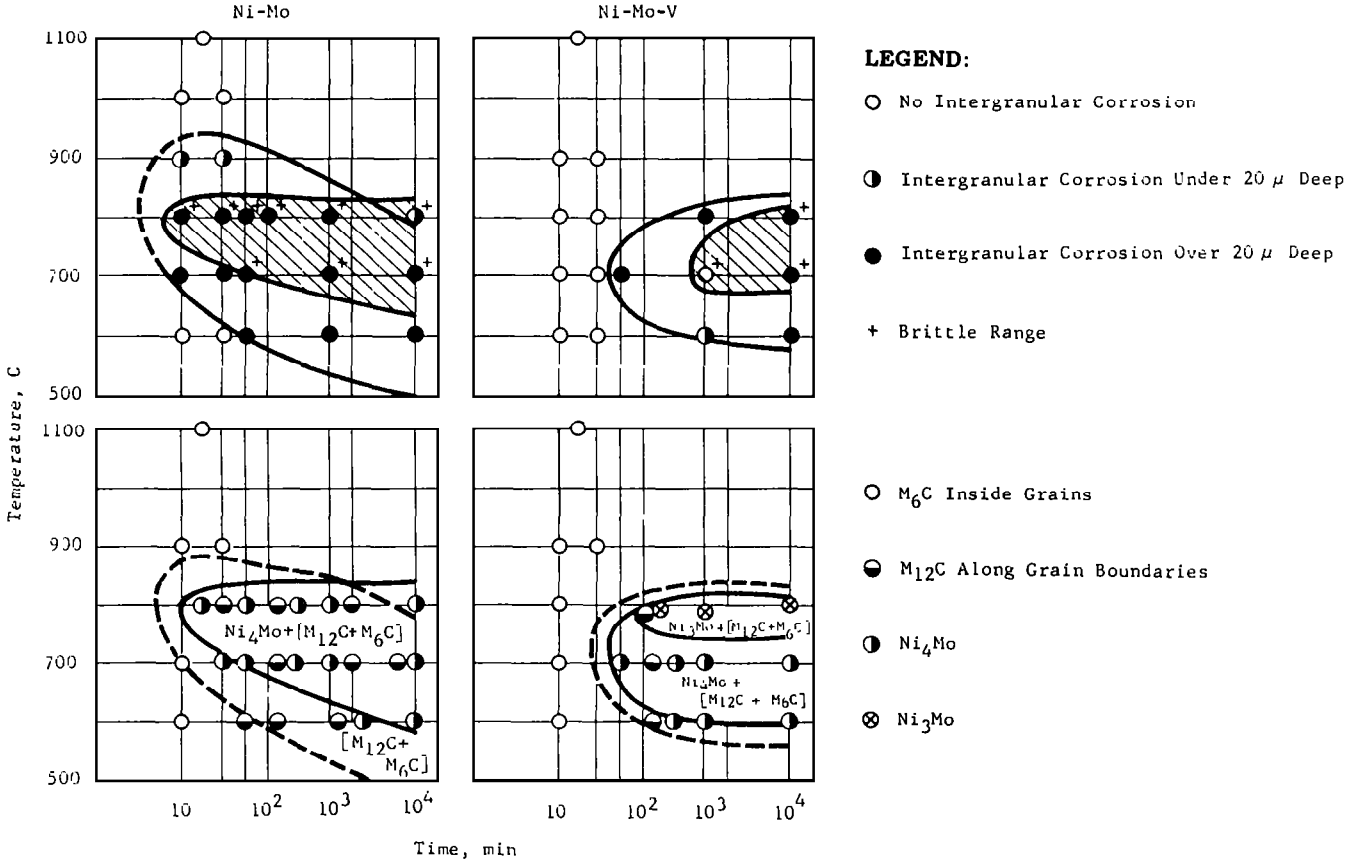
Hastelloy B-2

Nominal composition: Ni - 1.00% max Co - 1.00% max Cr - 26.00%-30.00% Mo - 2.00% max Fe - 0.10% max Si - 1.00% max Mn - 0.02% max C - 0.040% max P - 0.030% max S

vs

Hastelloy B-282

Nominal composition: Ni - 0.40% Cr - 4.80% Fe - 0.02% C - 0.31% Si - 0.52% Mn - 37.50% Mo - 0.33% V



Time-temperature-intergranular-corrosion diagrams (top)

Time-temperature-precipitation diagrams (bottom)

Corrosion tests in boiling 21% HCl, or at 185°C (365°F)

SOURCE: T.V. Svistunova, "Molybdenum in Nickel-Base Corrosion-Resistant Alloys," presented at a Soviet-American Symposium held at the Central Scientific Research Institute for Ferrous Metals (TsNIChM) in Moscow, 17-18 January 1973, on the theme: New Developments in the Field of Molybdenum-Alloyed Cast Iron and Steel

Single Crystal Alloy 800

Composition: 63.6% Ni - 8.0% Cr - 7.5% Co - 1.5% Mo - 4.0% W - 5.0% Ta - 1.5% Ti - 5.8% Al - 3.0% Re

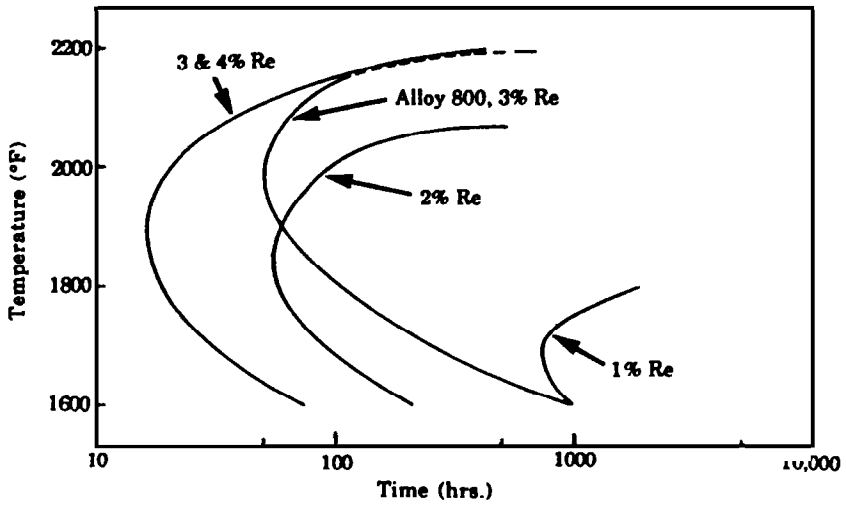
1% Re composition: 63.5% Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 3.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 1.0% Re

2% Re composition: 63.5% Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 2.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 2.0% Re

3% Re composition: 63.5% Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 1.0% W - 12.0% Ta - 1.0% Ti - 5.0% Al - 3.0% Re

4% Re composition: 63.5% Ni - 7.5% Cr - 5.0% Co - 2.0% Mo - 12.0% Ta - 1.0% Ti - 5.0% Al - 4.0% Re

Treatment: Fully solutioned and aged specimens were exposed at 871, 982, 1093, 1149, and 1204°C (1600, 1800, 2000, 2100 and 2200°F) for times up to 1000 h to determine the occurrence of topologically close packed (TCP) phases



LIVE GRAPH
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Time for Start of TCP Phases at Various Temperatures of Exposure for Alloy 800

Time Hours	Temperature 1600°F	1800°F	2000°F	2100°F	2200°F
20	N	N	N	N	N
35	N	N	T	N	N
50	N	N	T	N	N
75	N	N	TCP	T	N
100	N	T	TCP	T	N
500	N	TCP	TCP	-	-
1000	T	TCP	TCP	-	-

N = None, T = Trace Amounts of TCP, TCP = minor to moderate amounts of TCP

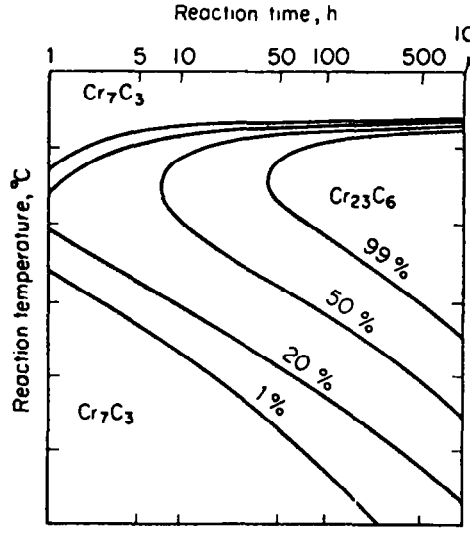
Time-temperature-precipitation diagram
Single Crystal Alloy 800 vs 4 similar compositions

SOURCE: R. Darolia, D.F. Lahrman, R.D. Field, R. Sisson, "Formation of Topologically Closed Packed Phases in Nickel Base Single Crystal Superalloys," Superalloys 1988, S. Reichman, et al., Eds., TMS, 1988, pp 255-264

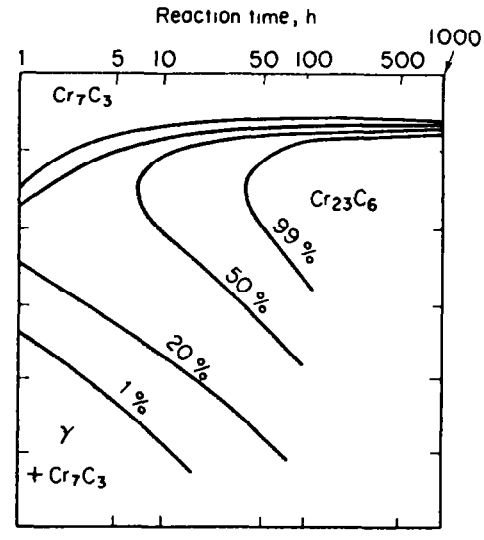
Nimonic 80A

Nominal composition: Ni - 0.08% C - 20% Cr - 2.4% Ti - 1.4% Al

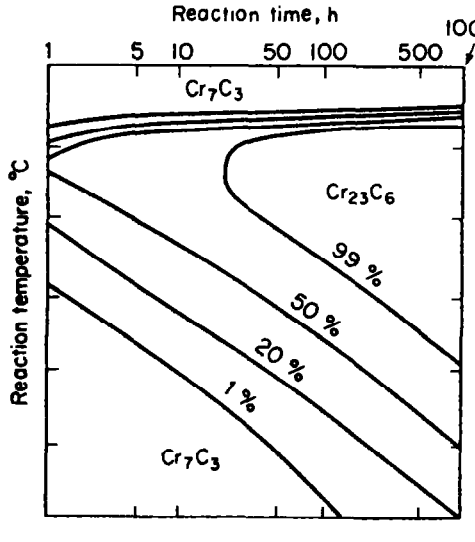
Treatment: Heat treated at 1080°C (1976°F) for 8 h, air cool



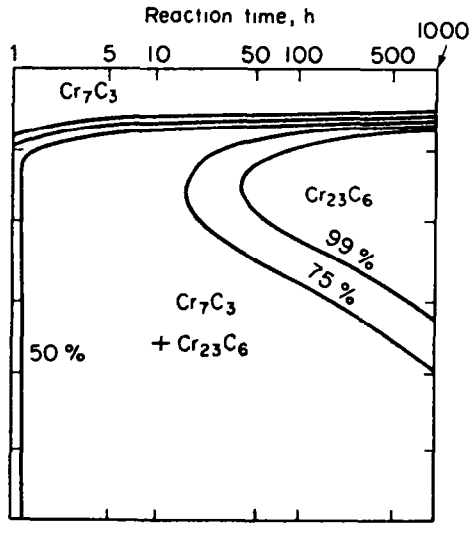
Treatment: Heat treated at 1080°C (1976°F) for 8 h, water quench



Treatment: Heat treated at 1200°C (2192°F) for 2 h, air cool



Treatment: Heat treated at 1080°C (1976°F) for 8 h, air cool + 850°C (1562°F) for 24 h, air cool



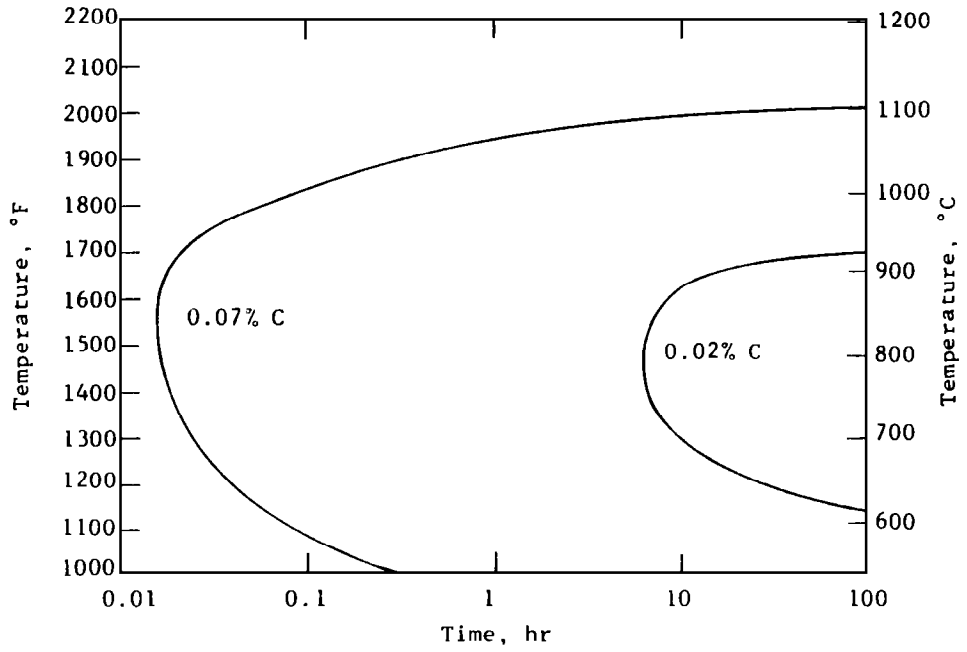
LIVE GRAPH
Click here to view

Time-temperature-precipitation diagram for carbides after various heat treatments

SOURCE: E.A. Fell, Metallurgia, Vol 63, 1961, pp 157-166

Inconel 600

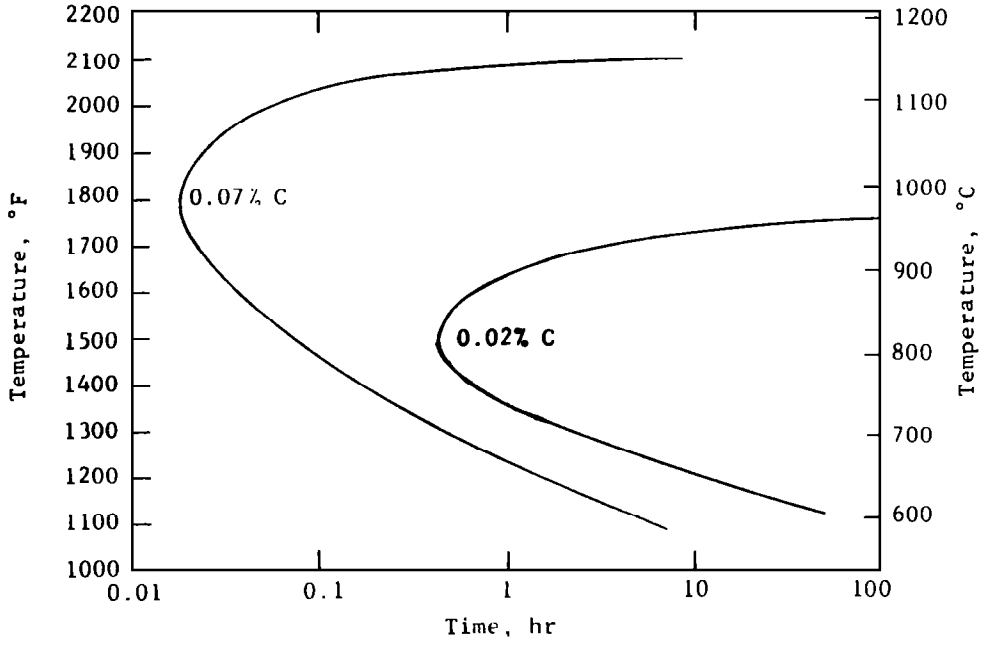
Nominal composition: Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr
Treatment: Solution treated at 1150°C (2100°F) for 30 min, before exposure to precipitation temperatures



LIVE GRAPH
Click here to view

Time-temperature-carbide-precipitation diagram

Nominal composition: Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr
Treatment: Solution treated at 1150°C (2100°F) for 30 min, and cold worked 25% before exposure to precipitation temperatures

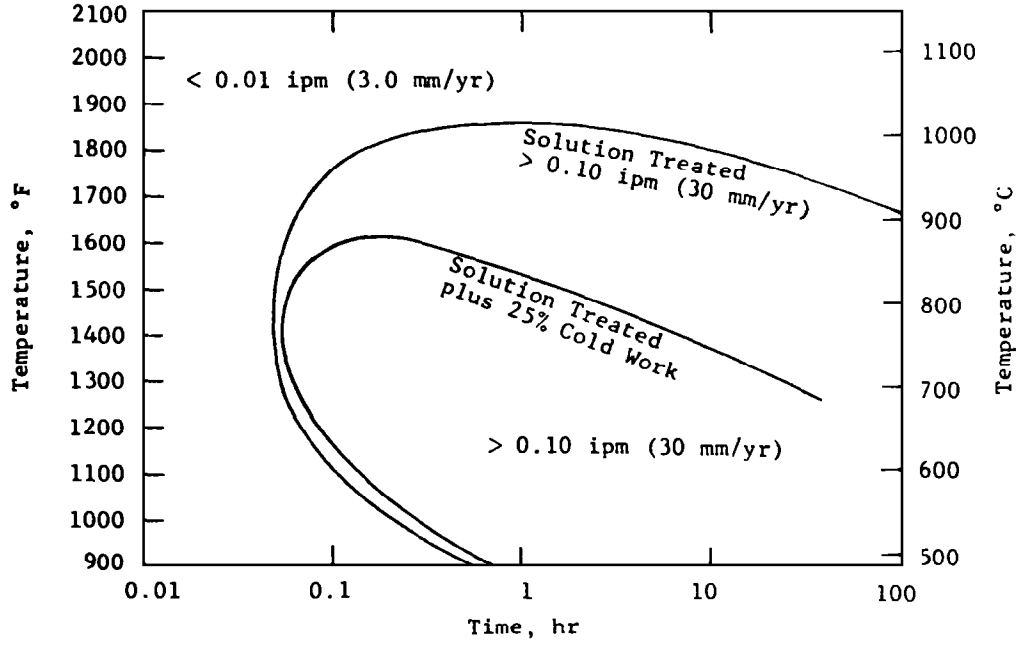


LIVE GRAPH
Click here to view

Time-temperature-carbide-precipitation diagram

SOURCE: R.C. Scarberry, S.C. Pearman, J.R. Crum, "Precipitation Reactions in Inconel Alloy 600 and Their Effect on Corrosion Behavior," Corrosion, Vol 32, No. 10, October 1976, pp 401-406

Inconel 600
Nominal composition: Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr
Treatment: Solution treated at 1093°C (2000°F)



LIVE GRAPH
Click here to view

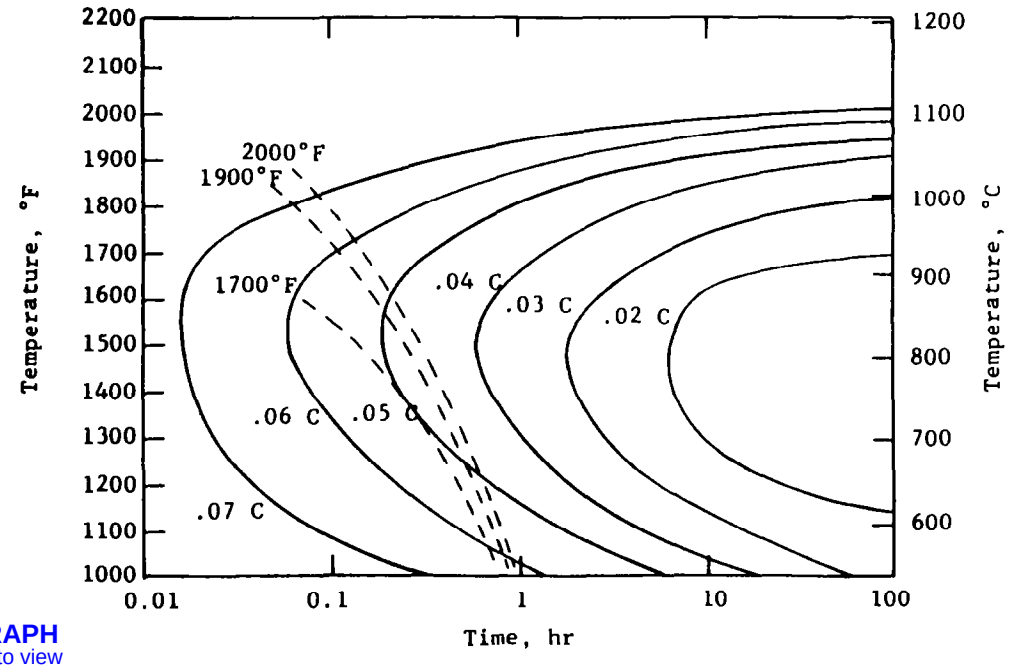
Time-temperature-sensitization diagram in two conditions
The curves enclose areas of high corrosion rates in boiling 70% nitric acid

SOURCE: R.C. Scarberry, S.C. Pearman, J.R. Crum, "Precipitation Reactions in Inconel Alloy 600 and Their Effect on Corrosion Behavior," Corrosion, Vol 32, No. 10, October 1976, pp 401-406

Inconel 600

Nominal composition: Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr

Treatment: Solution treated at 1150°C (2100°F) for 30 min, before exposure to precipitation temperatures



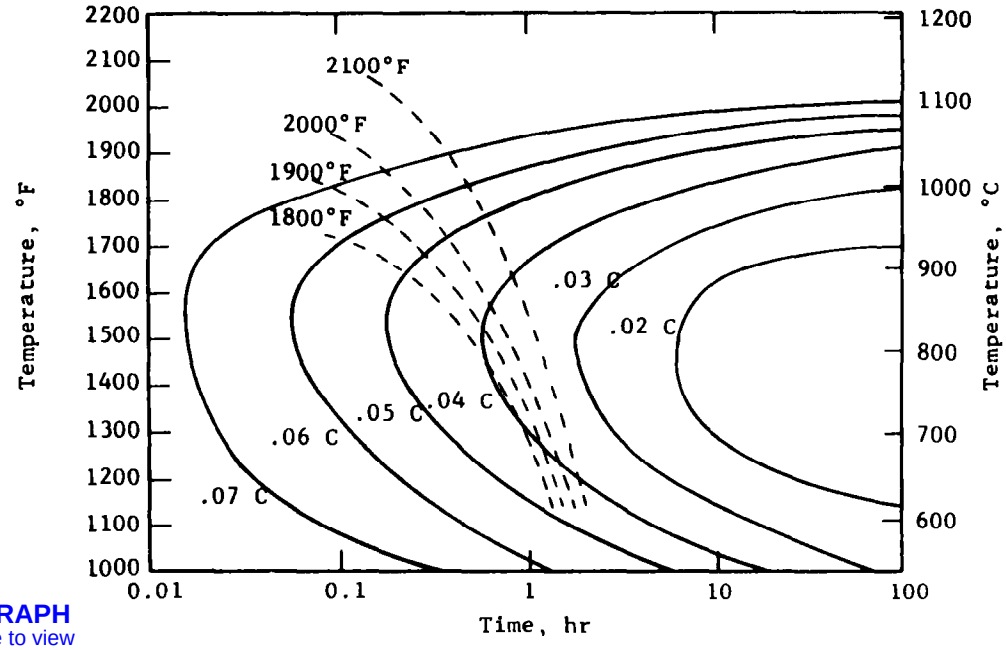
LIVE GRAPH
Click here to view

Time-temperature -carbide-precipitation diagram for material having various carbon contents
Broken line curves show time below solution temperature at the center of a 250 mm (10 in) diameter round during air cooling from the indicated temperatures

SOURCE: R.C. Scarberry, S.C. Pearman, J.R. Crum, "Precipitation Reactions in Inconel Alloy 600 and Their Effect on Corrosion Behavior," Corrosion, Vol 32, No. 10, October 1976, pp 401-406

Inconel 600

Nominal composition: Ni - 0.08% C - 0.5% Mn - 8% Fe - 0.25% Cu - 15.5% Cr
Treatment: Solution treated at 1150°C (2100°F) for 30 min, before exposure to precipitation temperatures



LIVE GRAPH
Click here to view

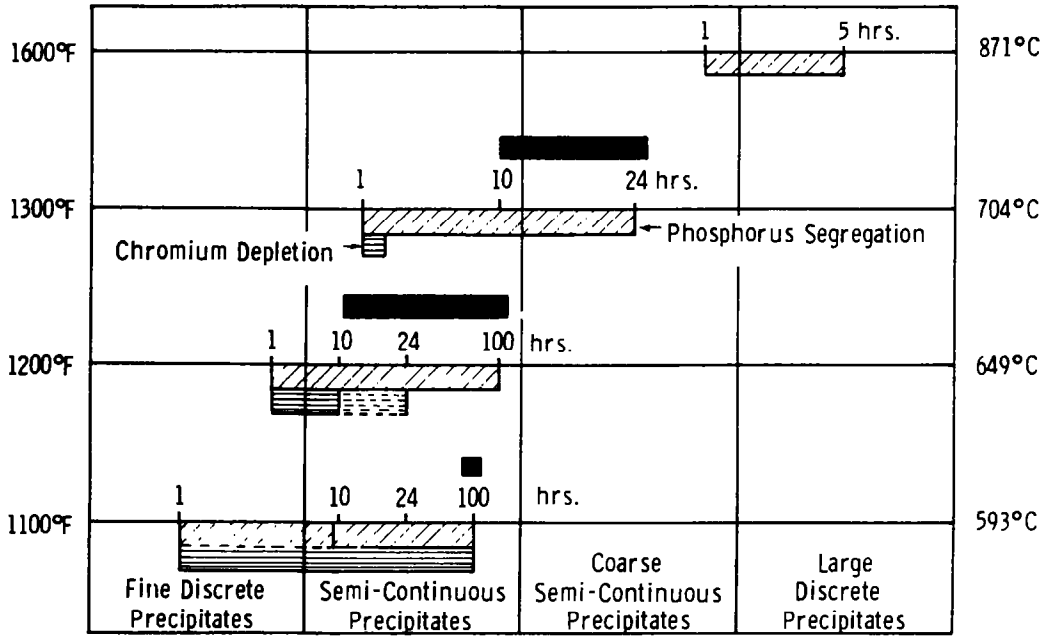
Time-temperature-carbide-precipitation diagram for material having various carbon contents
Broken line curves show time below solution temperature at the center of a 510 mm (20 in) diameter round during air cooling from the indicated temperatures

SOURCE: R.C. Scarberry, S.C. Pearman, J.R. Crum, "Precipitation Reactions in Inconel Alloy 600 and Their Effect on Corrosion Behavior," Corrosion, Vol 32, No. 10, October 1976, pp 401-406

Inconel 600

Composition: 73.66% Ni - 0.04% C - 15.36% Cr - 9.98% Fe - 0.40% Mn - 0.17% Si - 0.38% Cu - 0.17% Al - 0.20% Ti - 0.05% Co - 0.011% S

Treatment: Annealed in a flowing hydrogen environment, followed by a thermal treatment in the temperature range 593 to 871°C (1100 to 1600°F)



Time-temperature grain boundary microstructure

LEGEND:
Dotted lines = minor grain boundary segregation or chromium depletion
Solid bars = maximum improvement in caustic SCC resistance

NOTE:

The grain-boundary carbide precipitate morphology was divided into four classes: fine discrete particles, semicontinuous precipitate, coarse semicontinuous precipitate, and large discrete precipitates

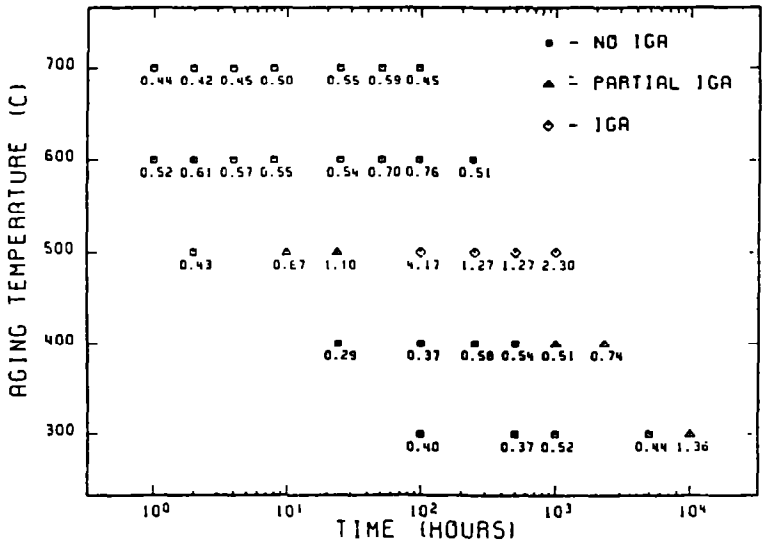
A floating time scale was used for each thermal treatment temperature so that a precipitate morphology could be assigned to each thermal treatment

The presence of a chromium-depleted layer and grain-boundary phosphorus segregation are also represented

SOURCE: G.O. Airey, "Microstructural Aspects of the Thermal Treatment of Inconel Alloy 600," Metallography, Vol 13, 1980, pp 21-41

Alloy 600

Composition: 74.5% Ni - 0.029% C - 0.211% Mn - 8.05% Fe - 0.003% S - 0.180% Si - 0.219% Cu - 14.09% Cr - 0.464% Al - 0.259%Ti - 0.034% Co - 0.007% P - 0.002% B - 0.026% Mg
Treatment: Mill annealed and thermally aged at temperatures ranging from 300 to 600°C (572 to 1112°F) for times ranging from 1 to 10,000 h



Time-temperature-sensitization diagram

Corrosion Tests were conducted in accordance with a modification of ASTM A-262 Practice C (Huey) Samples were immersed in a boiling 25% nitric acid solution for 48 h

Corrosion values in mg/cm^2/day are listed below each symbol

Partial IGA = attack which is 1 grain or less deep

SOURCE: R.G. Ballinger, R.M. Latanision, W.C. Moshier, K.N. Siebein, "A Study of the Thermal Aging Behavior of Alloy-600," proceedings of the International Congress on Metallic Corrosion, Toronto, 3-7 June 1984, Vol 3, National Research Council of Canada, pp 265-273

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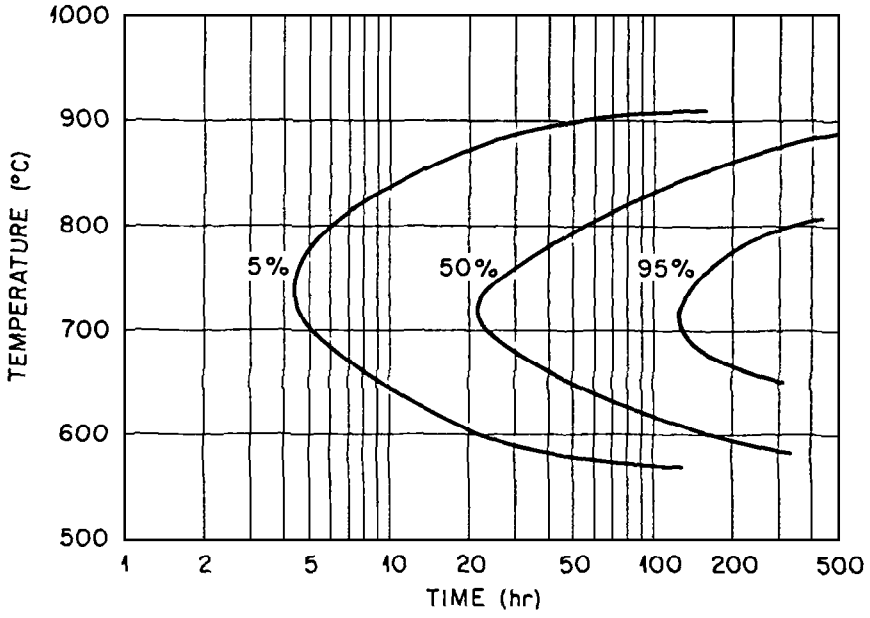
Niobium-Base Alloys

Niobium-Zirconium Alloys

Composition: Nb - 33 at.% Zr

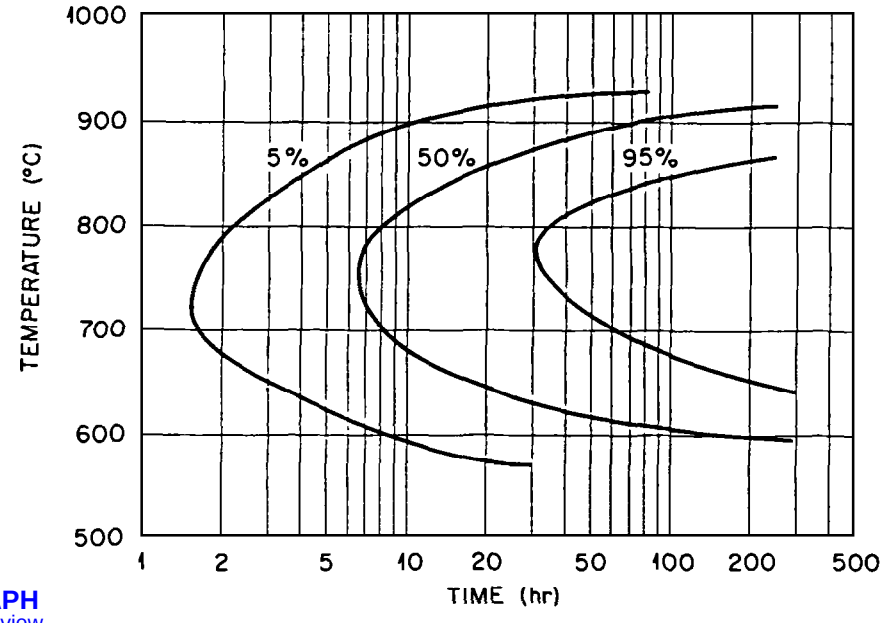


LIVE GRAPH
Click here to view

Time-temperature-precipitation on aging

For the reaction β to β_1 + β_2 annealed, in oxygen-free fine-grained alloy (3μm grain size)

Composition: Nb - 25 at.% Zr



LIVE GRAPH
Click here to view

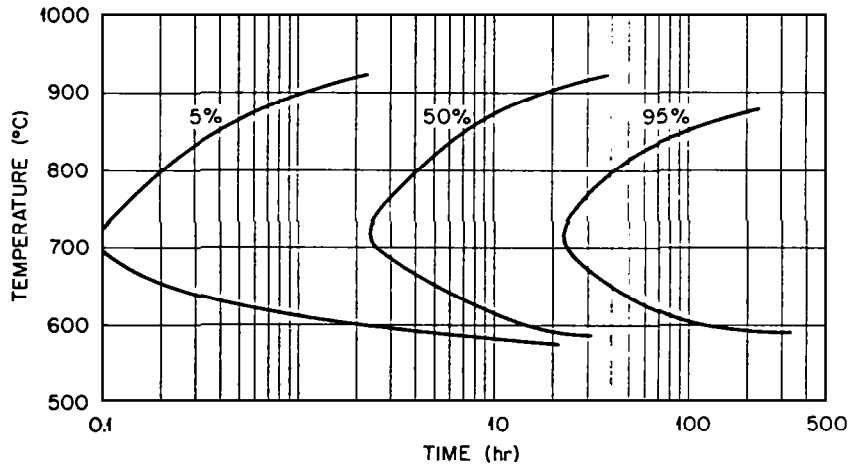
Time-temperature-precipitation on aging

For the reaction β to β_1 + β_2 annealed, oxygen-free fine-grained alloy (4μm grain size)

SOURCE: G.R. Love, M.L. Picklesimer, "The Kinetics of Beta-Phase Decomposition in Niobium (Columbium)-Zirconium," Trans. AIME, Vol 236, April 1966, pp 430-435

Niobium-Zirconium Alloys

Composition: Nb - 33 at.% Zr



LIVE GRAPH
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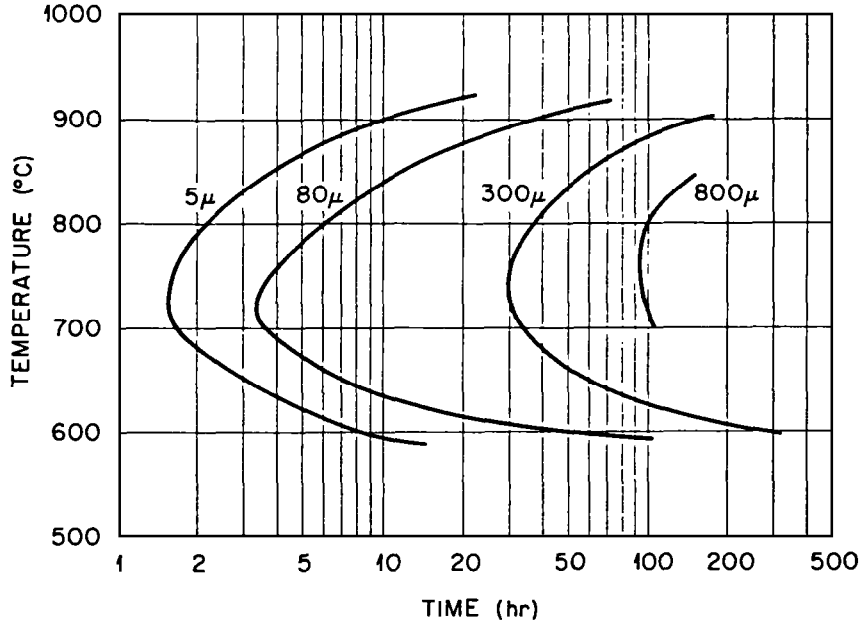
Time-temperature-precipitation on aging

For the reaction β to β_1 + β_2 in cold-worked, oxygen-free alloy

Composition: Nb - 33 at.% Zr



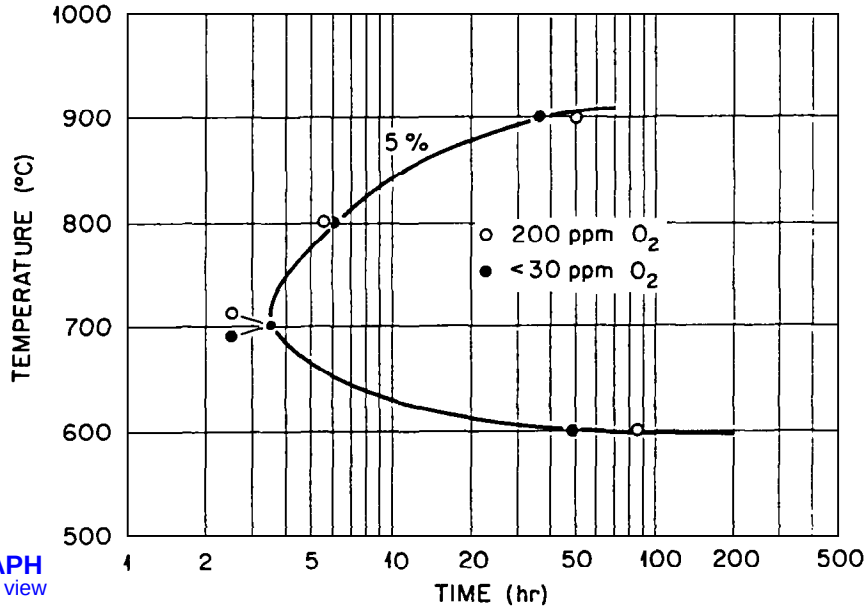
LIVE GRAPH
Click here to view

Time-temperature-precipitation on aging
Nominal reaction-start lines (5% transformation) for various grain sizes

SOURCE: G.R. Love, M.L. Picklesimer, "The Kinetics of Beta-Phase Decomposition in Niobium (Columbium)-Zirconium," Trans. AIME, Vol 236, April 1966, pp 430-435

Niobium-Zirconium Alloys

Composition: Nb - 33 at.% Zr



LIVE GRAPH
Click here to view

Time-temperature-precipitation on aging
Nominal reaction-start lines (5% transformation) in alloy with and without oxygen contamination

SOURCE: G.R. Love, M.L. Picklesimer, "The Kinetics of Beta-Phase Decomposition in Niobium (Columbium)-Zirconium," Trans. AIME, Vol 236, April 1966, pp 430-435

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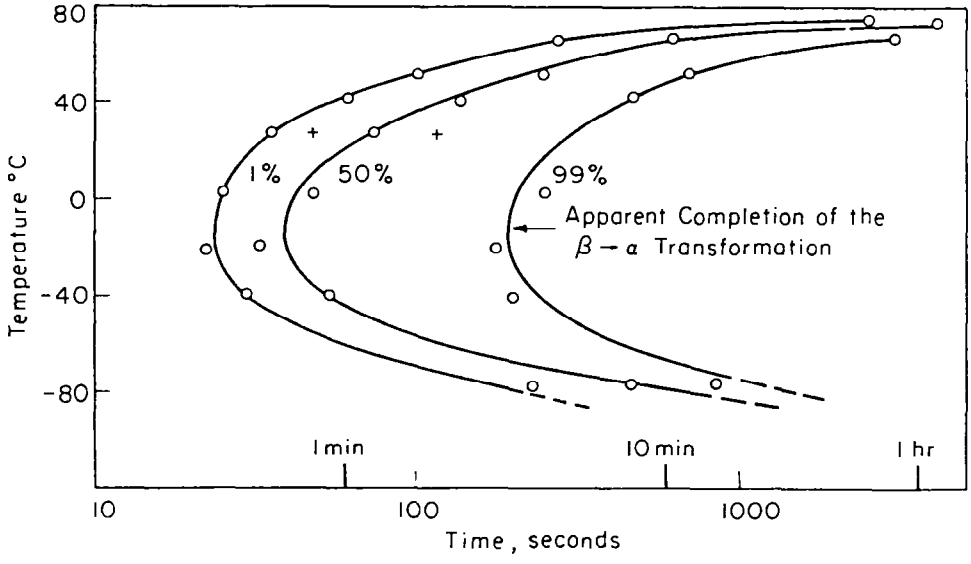
Plutonium-Base Alloys

Beta Plutonium

Composition: Pure plutonium (500-1000 ppm total impurities)
Treatment: Isothermal reaction curves of the beta to alpha transformation were obtained by solution heat treating at 175°C (347°F) for 1 h, quenching to temperatures between -80 and +90°C (-112 and 194°F), holding isothermally until there was no further apparent transformation, then quickly taking the sample from the high temperature bath and quenching into the low temperature bath



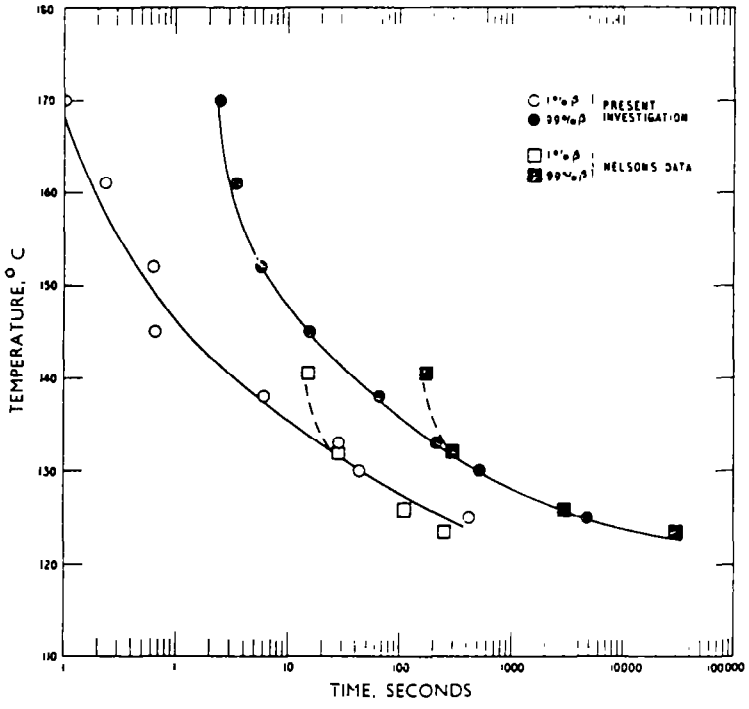
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beta to alpha transformation

SOURCE: R.D. Nelson, "Transformation Kinetics of Beta Plutonium," Trans. ASM, Vol 51, 1959, pp 677-682

Electrorefined Plutonium

Composition: Pure plutonium (79 ppm total impurities)
Treatment: Wire specimens were produced by extrusion, transformed, cut into specimen lengths and individually electropolished to remove surface oxide. Any retained high-temperature phases were eliminated by thermally cycling the wire 10 times between +80 and -80°C (176 and -112°F)



LIVE GRAPH
Click here to view

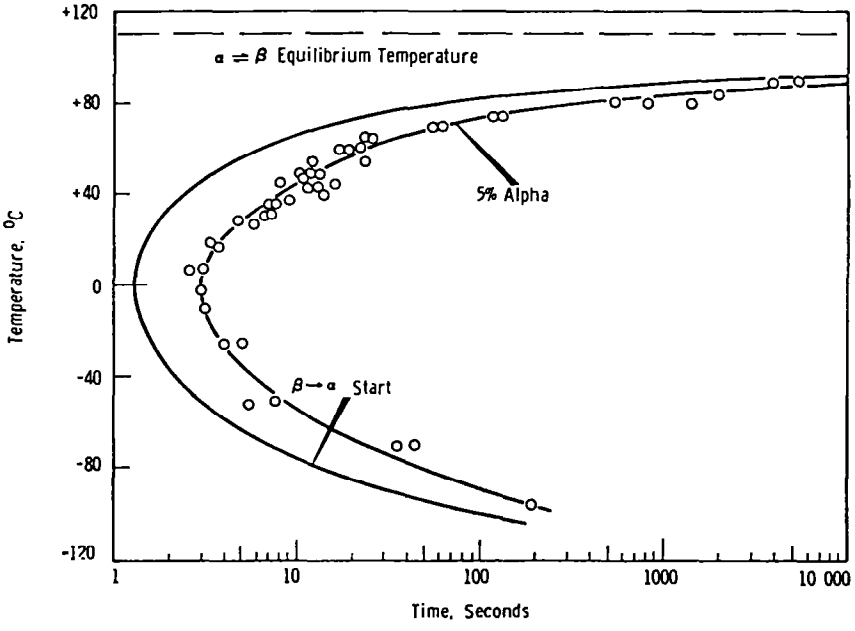
Time-temperature-transformation diagram
Isothermal reaction curves for the alpha to beta transformation

SOURCE: M.E. Faiers, J.S. White, "The Alpha to Beta Transformation in Electrorefined Plutonium," Journal of the Institute of Metals, Vol 93, 1964-65, p 405

Pure plutonium

Composition: ~300 ppm total impurities

Treatment: Specimens were heat treated at 160°C (320°F) for 1 h in an inert atmosphere, cooled to 110°C (230°F), held 1 min and quenched to the isothermal transformation temperature



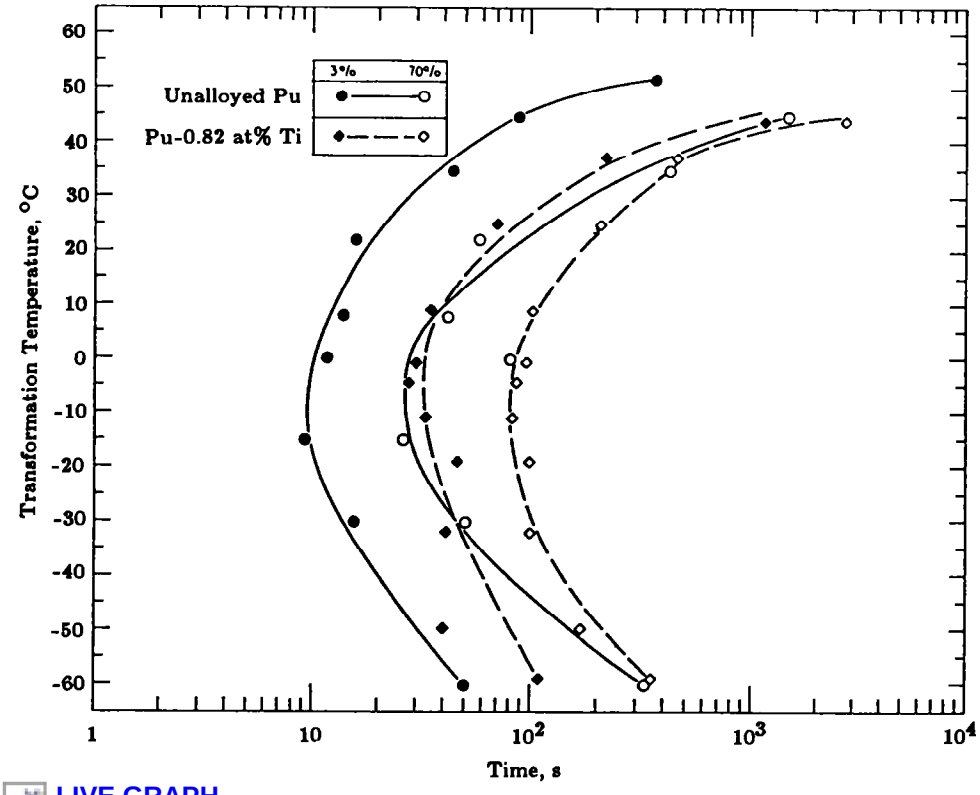
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Data points are only for 5% transformation

SOURCE: R.D. Nelson, "The Plutonium Beta to Alpha TTT Curve," Journal of Nuclear Materials, Vol 93, 1967, pp 238-240

Dilute Plutonium Alloys

Composition: Unalloyed Pu and Pu - 0.82 at.% Ti
Treatment: Specimens were heat-treated in a silicone oil bath at 160°C (320°F) for 30 min to ensure completion of transformation



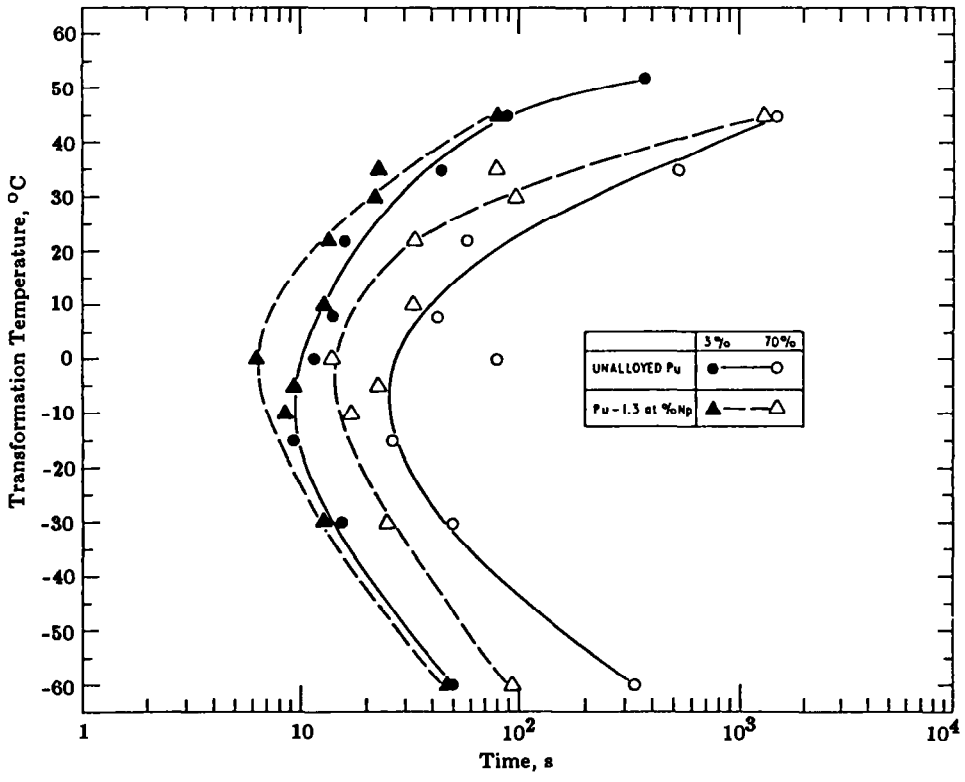
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beta to alpha transformation

SOURCE: L.G.T. Davy, M.E. Faiers, J.S. White, "The Kinetics of the α ⇌ β Transformations in Some Dilute Plutonium Alloys," Journal of Nuclear Materials, Vol 22, 1967, pp 197-204

Dilute Plutonium Alloys

Composition: Unalloyed Pu and Pu - 1.3 at.% Np
Treatment: Specimens were heat-treated in a silicone oil bath at 160°C (320°F) for 30 min to ensure completion of transformation



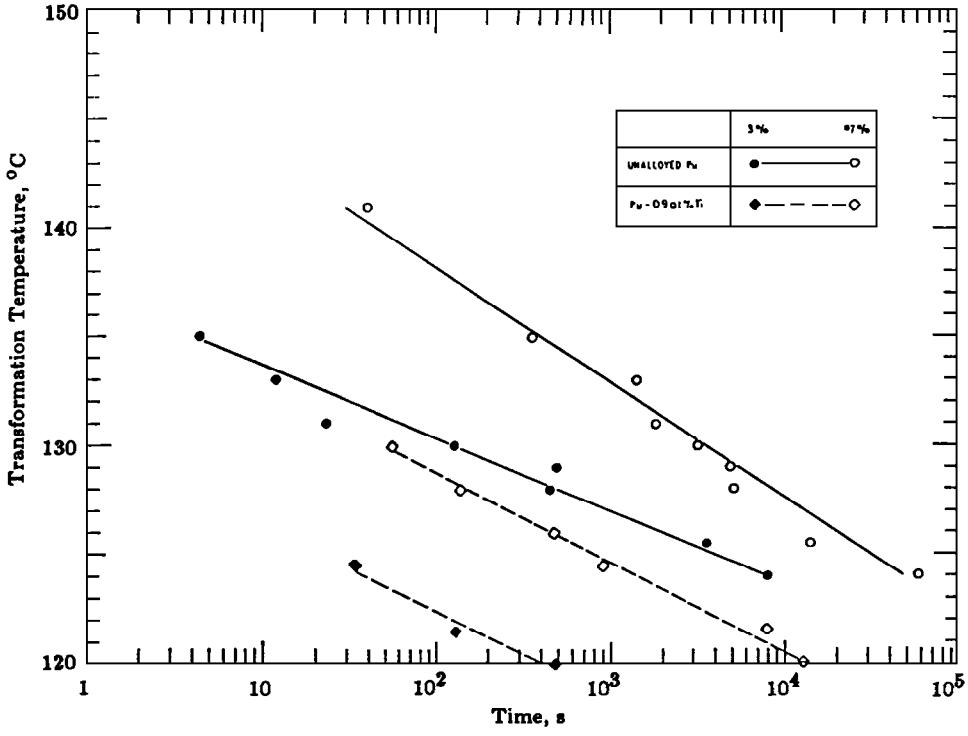
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beta to alpha transformation

SOURCE: L.G.T. Davy, M.E. Faiers, J.S. White, "The Kinetics of the α ⇌ β Transformations in Some Dilute Plutonium Alloys," Journal of Nuclear Materials, Vol 22, 1967, pp 197-204

Dilute Plutonium Alloys

Composition: Unalloyed Pu and Pu - 0.90% Ti
Treatment: Specimens were heat-treated in a silicone oil bath at the appropriate transformation temperature



LIVE GRAPH
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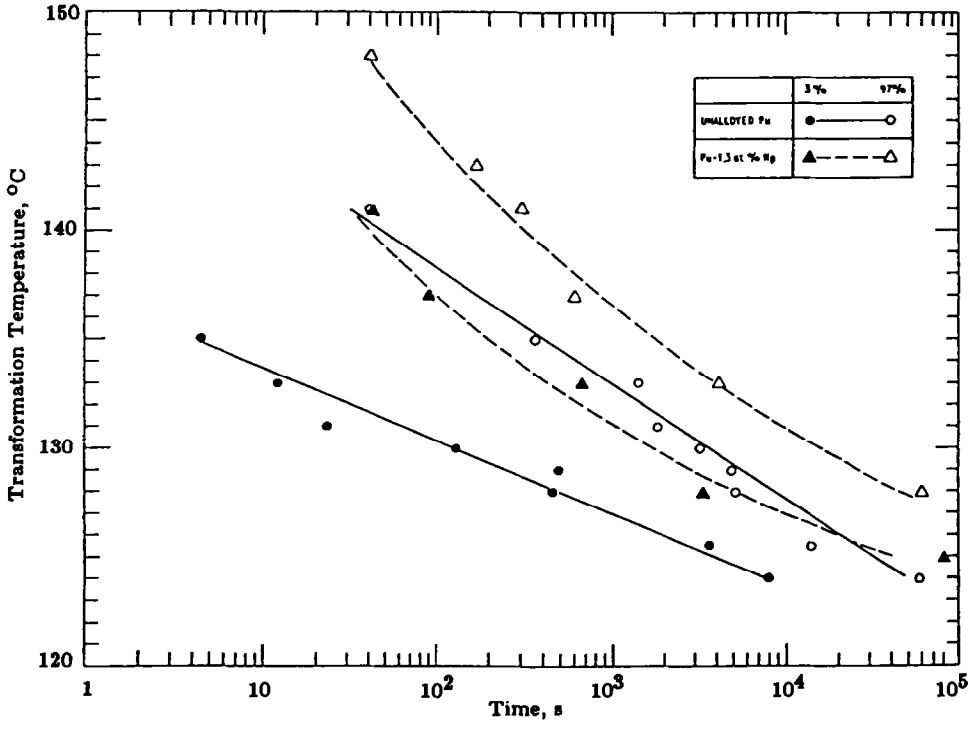
Time-temperature-transformation diagram
Alpha to beta transformation

SOURCE: L.G.T. Davy, M.E. Faiers, J.S. White, "The Kinetics of the α ⇌ β Transformations in Some Dilute Plutonium Alloys," Journal of Nuclear Materials, Vol 22, 1967, pp 197-204

Dilute Plutonium Alloys

Composition: Unalloyed Pu and Pu - 1.3% Np
Treatment: Specimens were heat-treated in a silicone oil bath at the appropriate transformation temperature



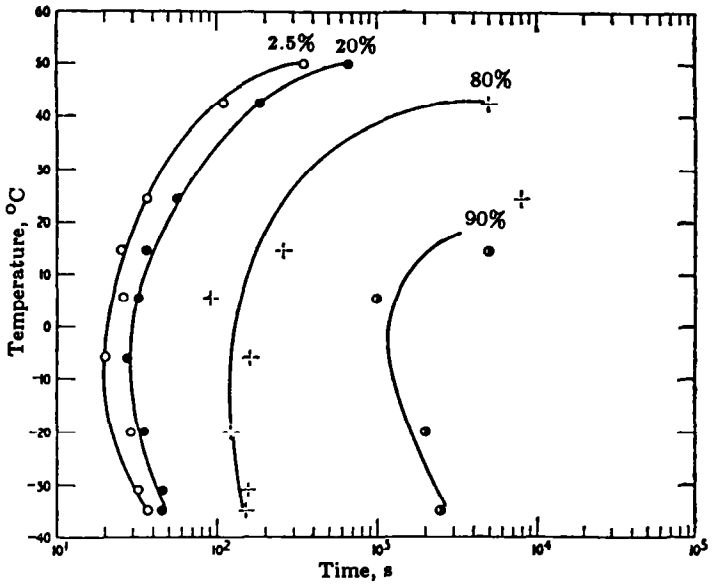
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Alpha to beta transformation

SOURCE: L.G.T. Davy, M.E. Faiers, J.S. White, "The Kinetics of the α ⇌ β Transformations in Some Dilute Plutonium Alloys," Journal of Nuclear Materials, Vol 22, 1967, pp 197-204

Plutonium-Titanium Alloys

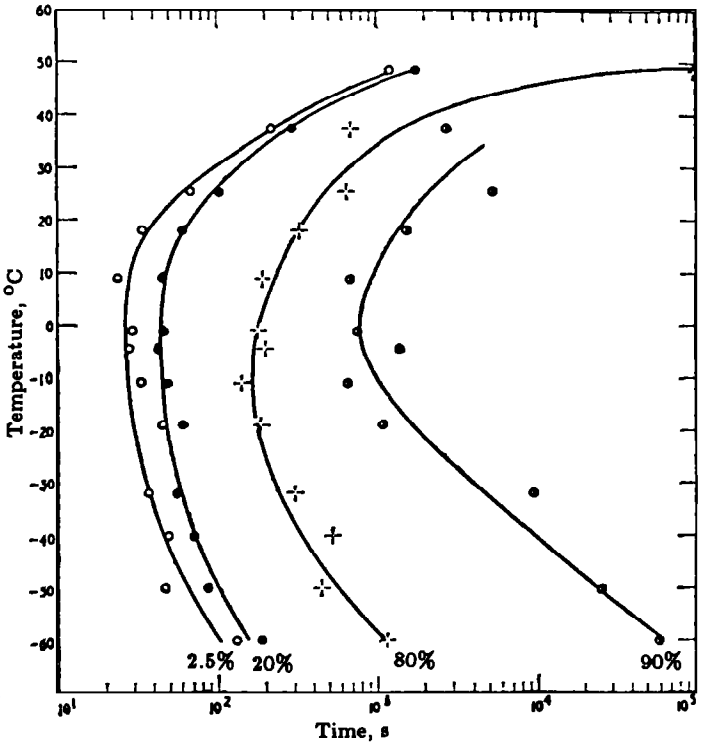
Composition: Pu - 0.23 at.% Ti
Treatment: Specimens were beta heat treated in a silicone oil bath at 160°C (320°F) for 30 min



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beta to alpha transformation

Composition: Pu - 0.82 at.% Ti
Treatment: Specimens were beta heat treated in a silicone oil bath at 160°C (320°F) for 30 min



LIVE GRAPH
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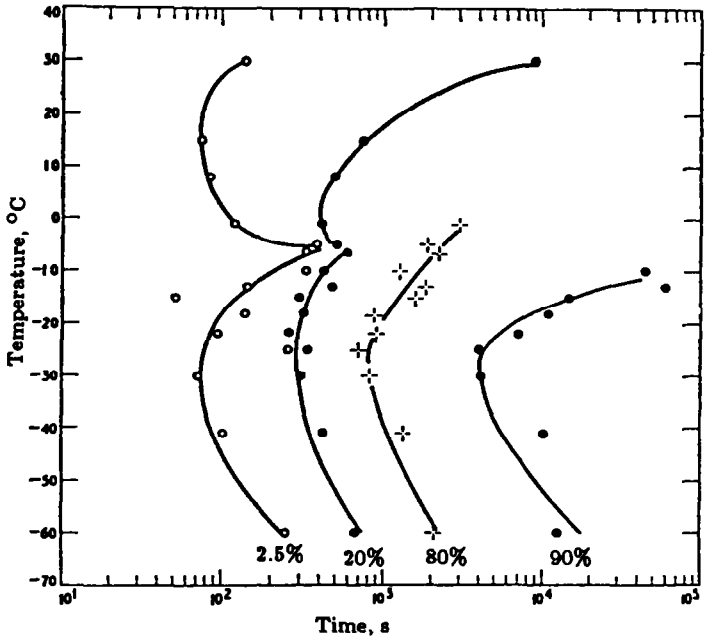
Time-temperature-transformation diagram
Beta to alpha transformation

SOURCE: L.G.T. Davy, J.S. White, "The Kinetics of the Beta to Alpha Transformation in Plutonium-Titanium Alloys," Journal of Nuclear Materials, Vol 12, No. 2, 1964, pp 221-225

Plutonium-Titanium Alloys

Composition: Pu - 1.05 at.% Ti

Treatment: Specimens were beta heat treated in a silicone oil bath at 160°C (320°F) for 30 min



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Beta to alpha transformation

SOURCE: L.G.T. Davy, J.S. White, "The Kinetics of the Beta to Alpha Transformation in Plutonium-Titanium Alloys," Journal of Nuclear Materials, Vol 12, No. 2, 1964, pp 221-225

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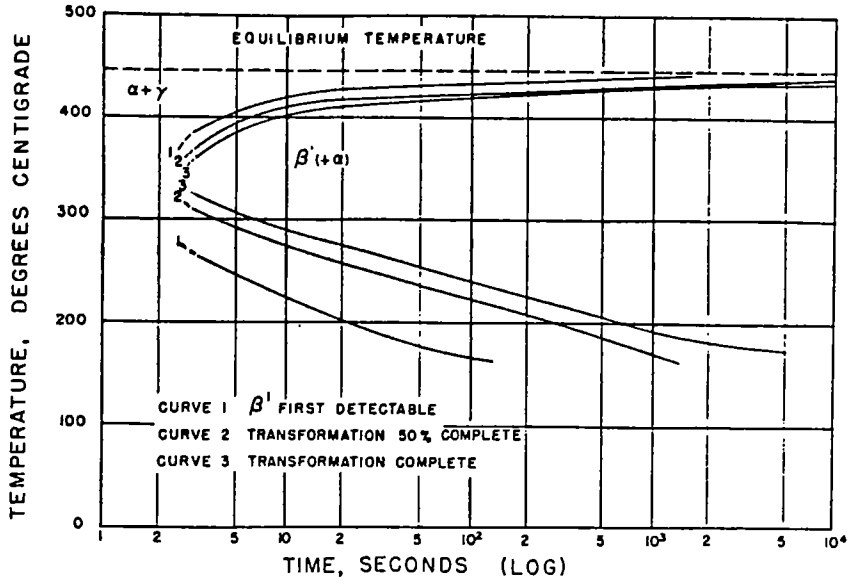
Silver-Base Alloys

Ag-Al Alloy

Composition: Ag - 7.02% Al



LIVE GRAPH
Click here to view

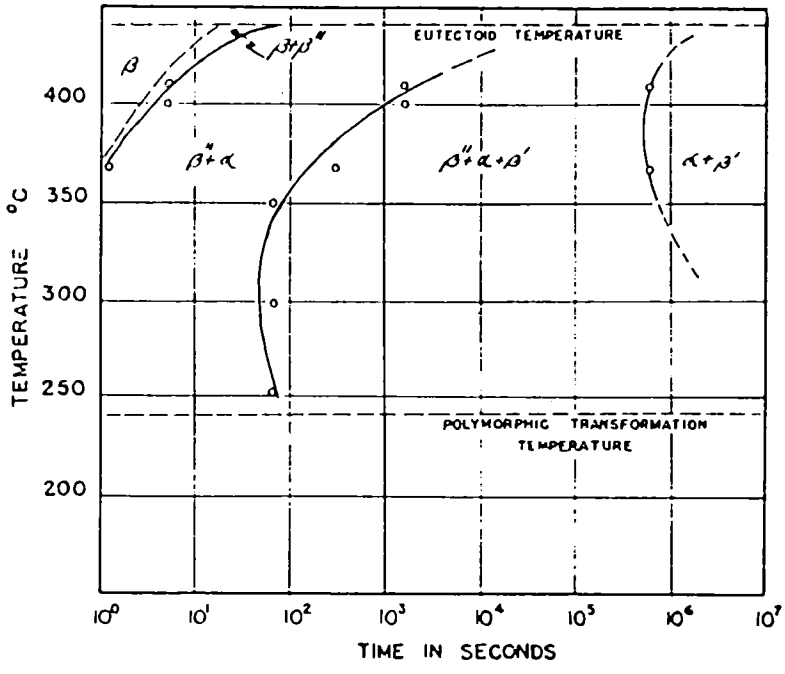
Time-temperature-transformation diagram

SOURCE: R.D. Reiswig, D.J. Mack, "A Study of the Peritectoid Transformation," Trans. AIME, Vol 215, April 1959, pp 301-307

Ag-Cd Alloy

Composition: Ag - 49.2% Cd

Treatment: Specimens were heated to form beta at 650°C (1202°F) held for 3 h, then transferred to a salt bath at the desired transformation temperature, held, then water quenched



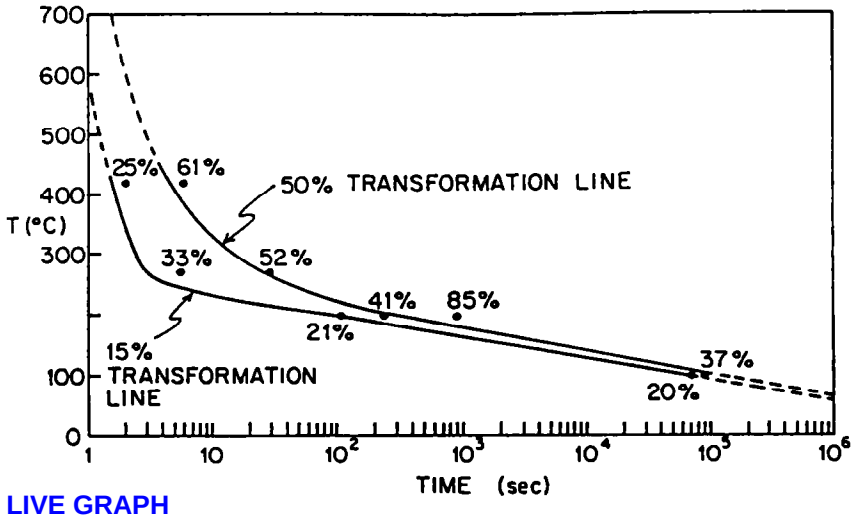
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
For a eutectoid alloy

SOURCE: G.R. Speich, David J. Mack, "Silver-Cadmium Eutectoid," Vol 197, Trans. AIME, Vol 197, April 1953, pp 549-553

Ag-Cu Alloys

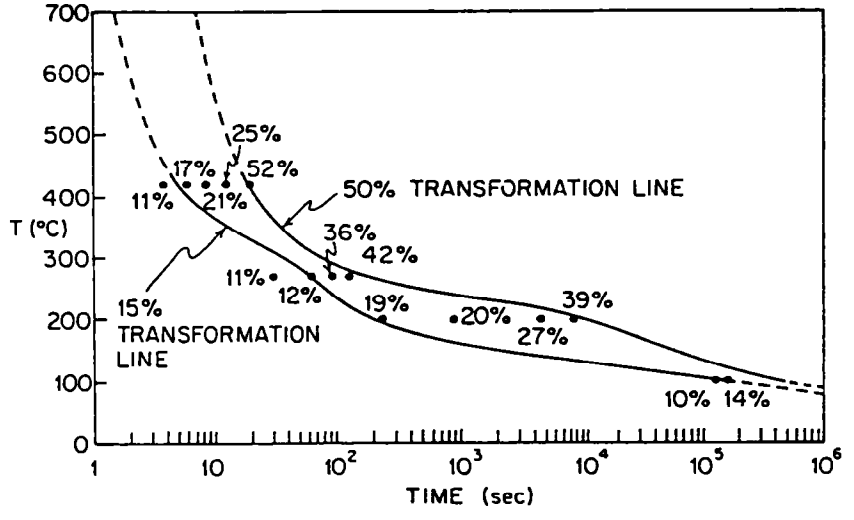
Composition: Ag - 38.3 at.% Cu
Treatment: Samples were placed in a quartz tube inside a vertical furnace, held at a temperature appox. 45°C (113°F) above melting point in an argon atmosphere for 2 h, then drop quenched into a water bath to obtain a fine initial microstructure. Salt baths and boiling distilled water were used for the isothermal aging treatments



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Gamma transformation

Composition: Ag - 38.3 at.% Cu
Treatment: Samples were placed in a quartz tube inside a vertical furnace, held at a temperature appox. 45°C (113°F) above melting point in an argon atmosphere for 2 h, then drop quenched into a water bath to obtain a fine initial microstructure. Salt baths and boiling distilled water were used for the isothermal aging treatments



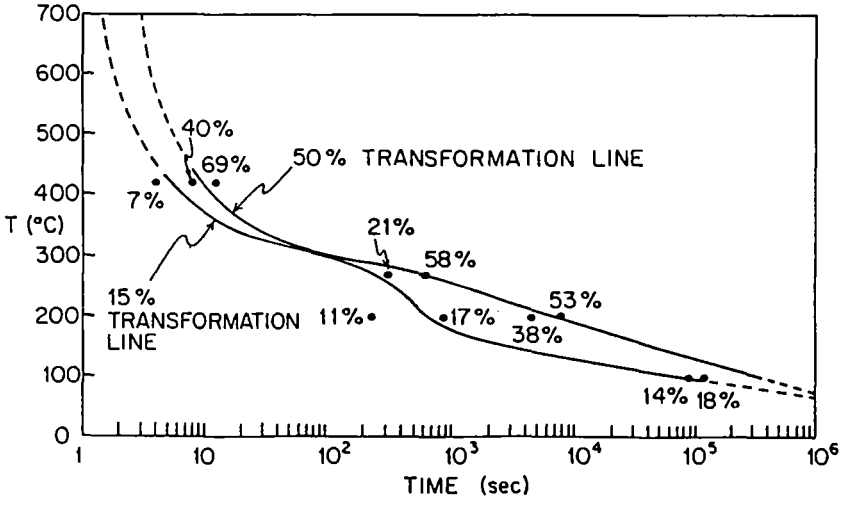
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Alpha prime transformation

SOURCE: D.G. Beck, S.M. Copley, M. Bass, "The Constitution and Phase Stability of Overlapping Melt Trails in Ag-Cu Alloys Produced by Continuous Laser Melt Quenching," Met. Trans. A, Vol 13A, November 1982, pp 1879-1889

Ag-Cu Alloys

Composition: Ag - 28.2 at.% Cu
Treatment: Samples were placed in a quartz tube inside a vertical furnace, held at a temperature appox. 45°C (113°F) above melting point in an argon atmosphere for 2 h, then drop quenched into a water bath to obtain a fine initial microstructure. Salt baths and boiling distilled water were used for the isothermal aging treatments



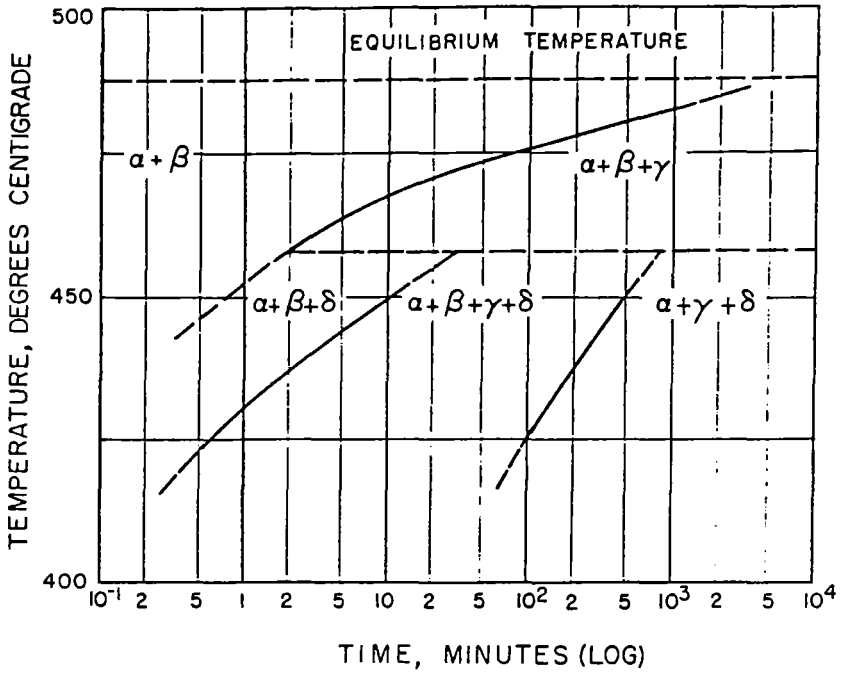
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Gamma transformation

SOURCE: D.G. Beck, S.M. Copley, M. Bass, "The Constitution and Phase Stability of Overlapping Melt Trails in Ag-Cu Alloys Produced by Continuous Laser Melt Quenching," Met. Trans. A, Vol 13A, November 1982, pp 1879-1889

Ag-Sb Alloy

Composition: Ag - 26.0% Sb



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: R.D. Reiswig, D.J. Mack, "A Study of the Peritectoid Transformation," Trans. AIME, Vol 215, April 1959, pp 301-307

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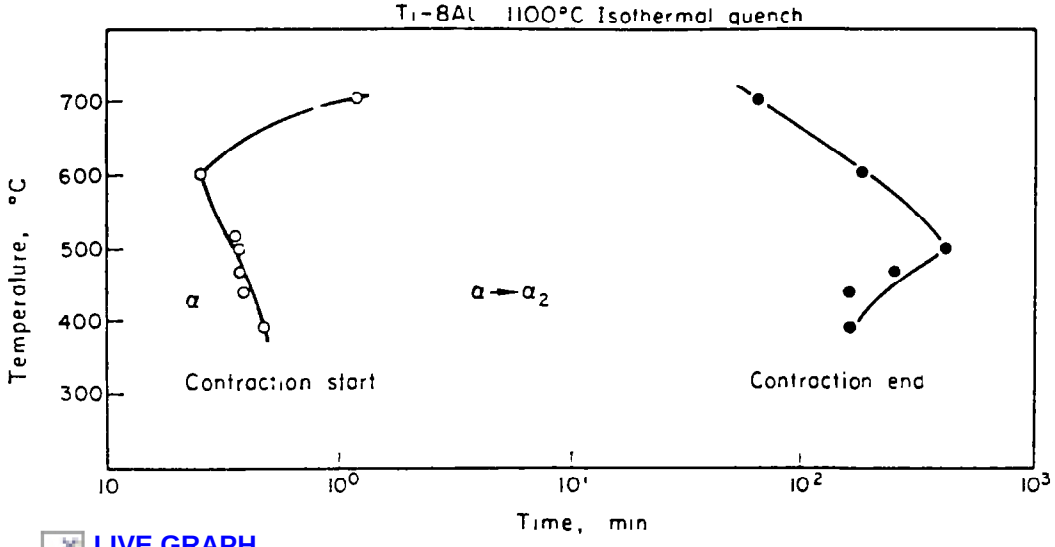
Titanium-Base Alloys

Ti-Al Alloy

Composition: Ti - 8% Al

Treatment: Solution treated at 1000°C (1832°F) for 30 min in vacuum by high-frequency induction heating and isothermal quenched to a temperature in the range from 300 to 700°C (572 to 1292°F) by argon or helium gas cooling. The quenching rate was 100-150°C/s



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: T. Yukawa, S. Ohtani, T. Nishimura, T. Sakai, "Phase Transformation of Titanium Alloys by Means of Automatic Transformation Apparatus," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, eds., Pergamon Press, Oxford, 1970, pp 699-710

Titanium Alloys

(Amounts in atomic percent)

(a) Composition: Ti - 3.1% Bi

(b) Composition: Ti - 3.2% Co

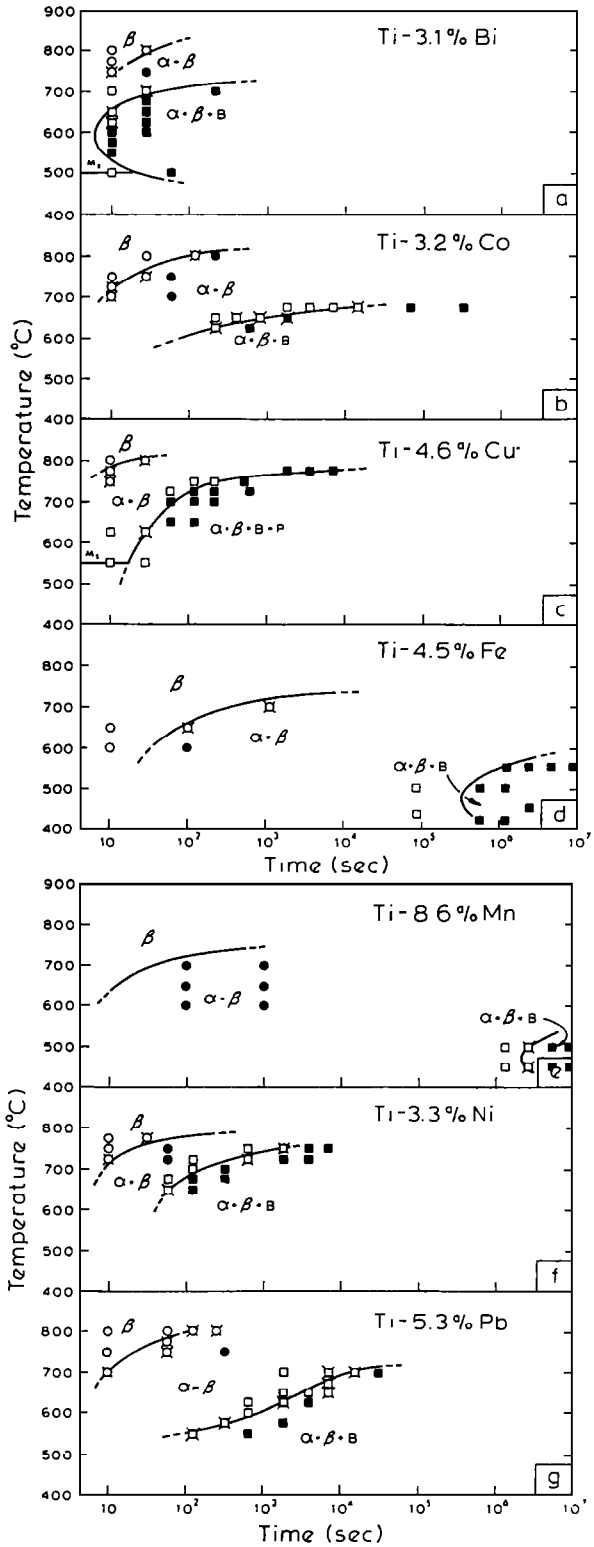
(c) Composition: Ti - 4.6% Cu

(d) Composition: Ti - 4.5% Fe

(e) Composition: Ti - 8.6% Mn

(f) Composition: Ti - 3.3% Ni

(g) Composition: Ti - 5.3% Pb



LIVE GRAPH
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TTT diagrams for the initiation of the proeutectoid alpha reaction and the beginning of the bainite and/or pearlite reaction in the hypoeutectoid alloys. beta = bcc, alpha = hcp, B = bainite, P = pearlite. The hollow, "rayed" and filled data points indicate reaction times prior to, at the beginning of, and subsequent to initiation of the proeutectoid alpha reaction (circles) and compound precipitation in either the bainitic or pearlitic modes (squares).

SOURCE: G.W. Franti et al., "A Survey of Eutectoid Decomposition in Ten Ti-X Systems," Met. Trans., Vol 9A, November 1978, pp 1641-1649

Titanium Alloys

(Amounts in atomic percent)

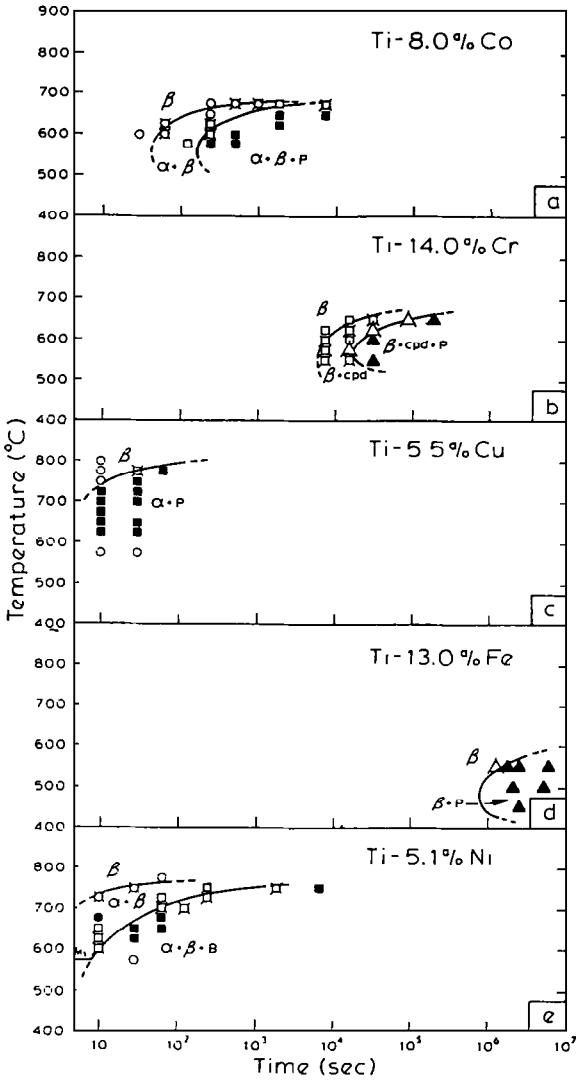
(a) Composition: Ti - 8.0% Co

(b) Composition: Ti - 14.0% Cr

(c) Composition: Ti - 5.5% Cu

(d) Composition: Ti - 13.0% Fe

(e) Composition: Ti - 5.1% Ni



LIVE GRAPH
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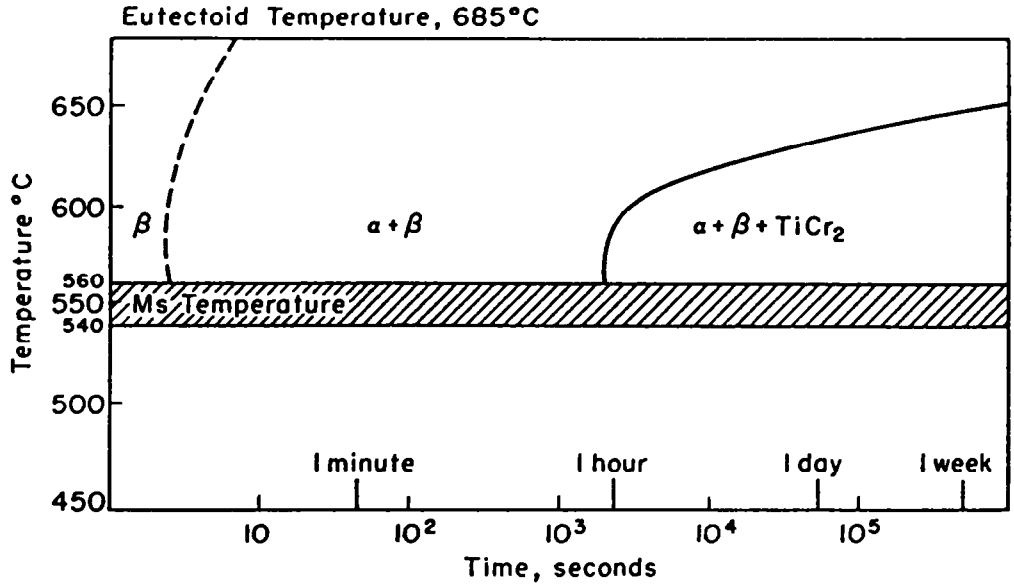
TTT diagrams for the initiation of the proeutectoid alpha or proeutectoid compound reaction and the beginning of the pearlite or bainite reaction in the near-eutectoid alloys. Beta = bcc, alpha = hcp, B = bainite, P = pearlite, cpd = intermetallic compound. The hollow, "rayed" and filled data points indicate reaction times prior to, at the beginning of, and subsequent to initiation of the proeutectoid alpha reaction (circles) and compound precipitation in either the bainitic or pearlitic modes (squares).

SOURCE: G.W. Franti et al., "A Survey of Eutectoid Decomposition in Ten Ti-X Systems," Met. Trans., Vol 9A, November 1978, pp 1641-1649

Ti-Cr Alloys

Composition: Ti - 2.35% Cr



LIVE GRAPH
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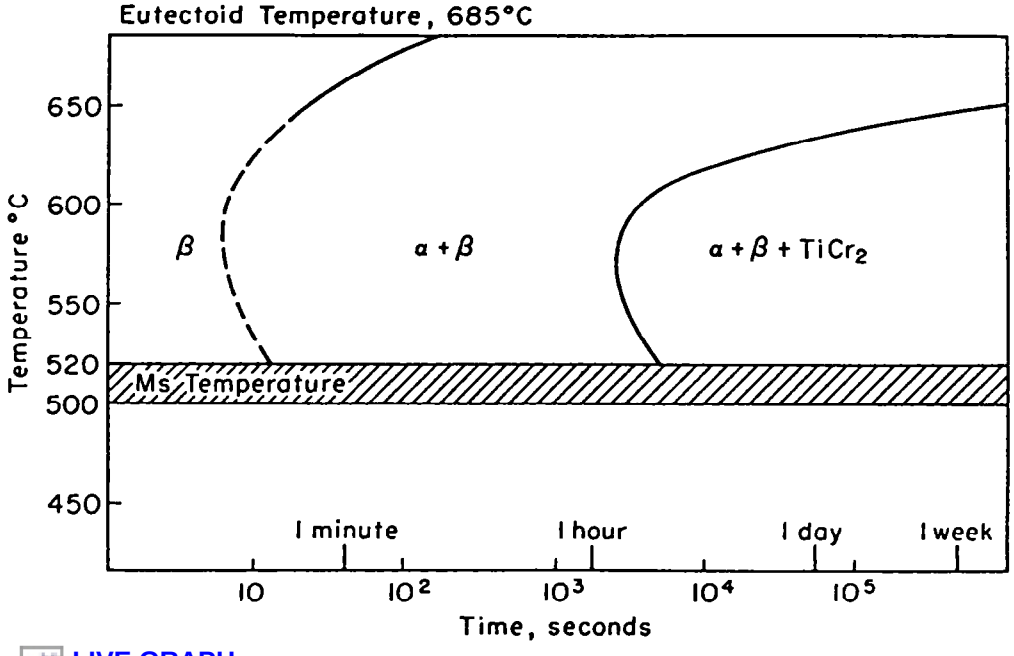
Time-temperature-transformation diagram

Composition: Ti - 4.64% Cr



LIVE GRAPH
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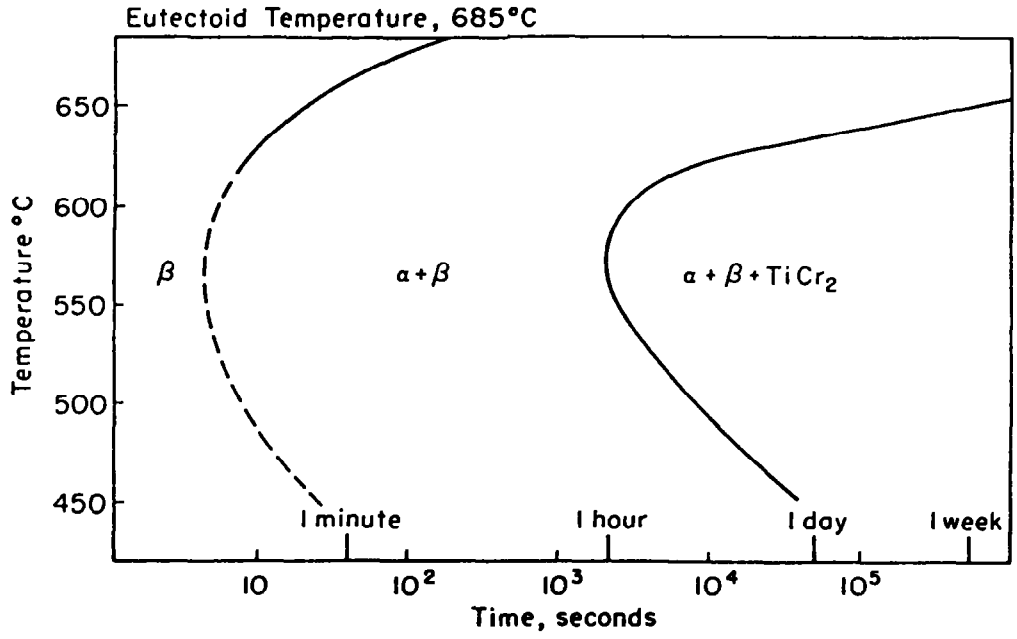
Time-temperature-transformation diagram

SOURCE: P.D. Frost et al., "Isothermal Transformation of Titanium-Chromium Alloys," Trans. ASM, Vol 46, 1954, pp 231-256

Ti-Cr Alloys

Composition: Ti - 7.54% Cr



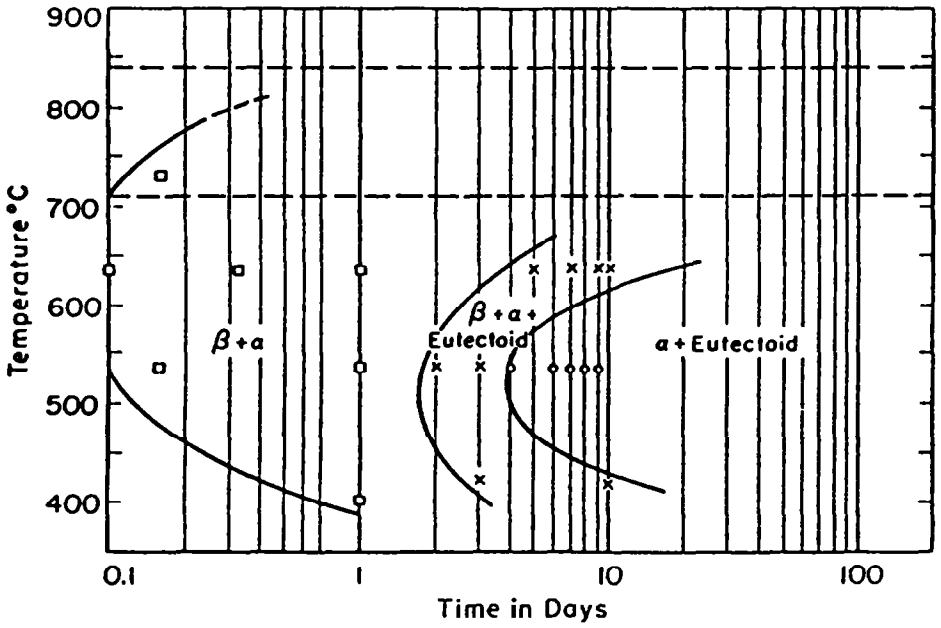
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: P.D. Frost et al., "Isothermal Transformation of Titanium-Chromium Alloys," Trans. ASM, Vol 46, 1954, pp 231-256

Ti-Cr Alloys

Composition: Ti - 5.0% Cr



LIVE GRAPH
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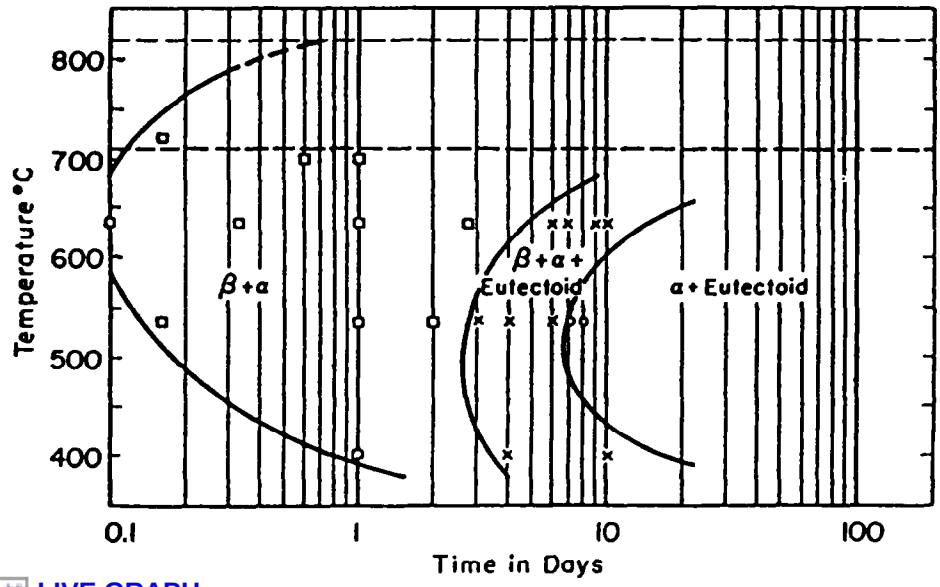
Time-temperature-transformation diagram

Composition: Ti - 7.0% Cr



LIVE GRAPH
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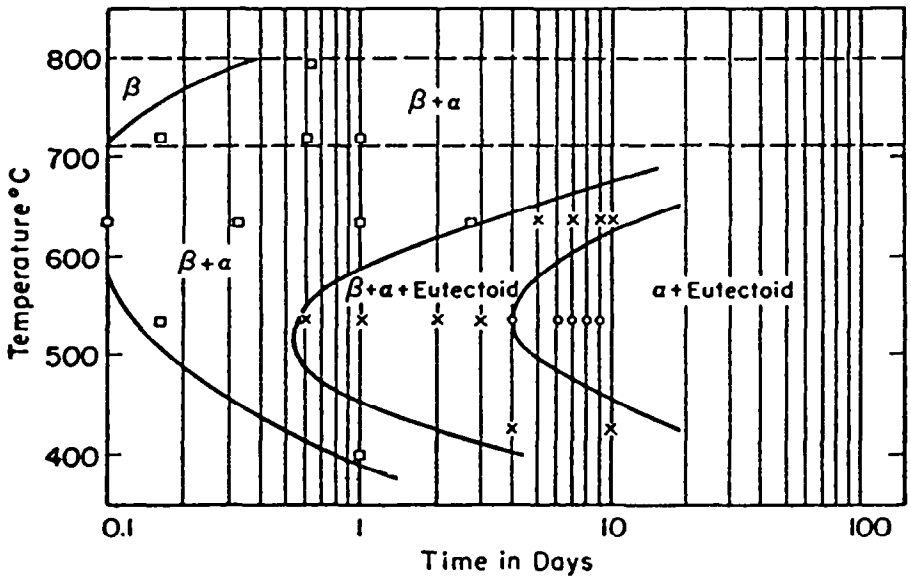
Time-temperature-transformation diagram

SOURCE: W. Rostoker, discussion of "Isothermal Transformation of Titanium-Chromium Alloys," by P.D. Frost et al., Trans. ASM, Vol 46, 1954, pp 231-256

Ti-Cr Alloys

Composition: Ti - 9.0% Cr



LIVE GRAPH
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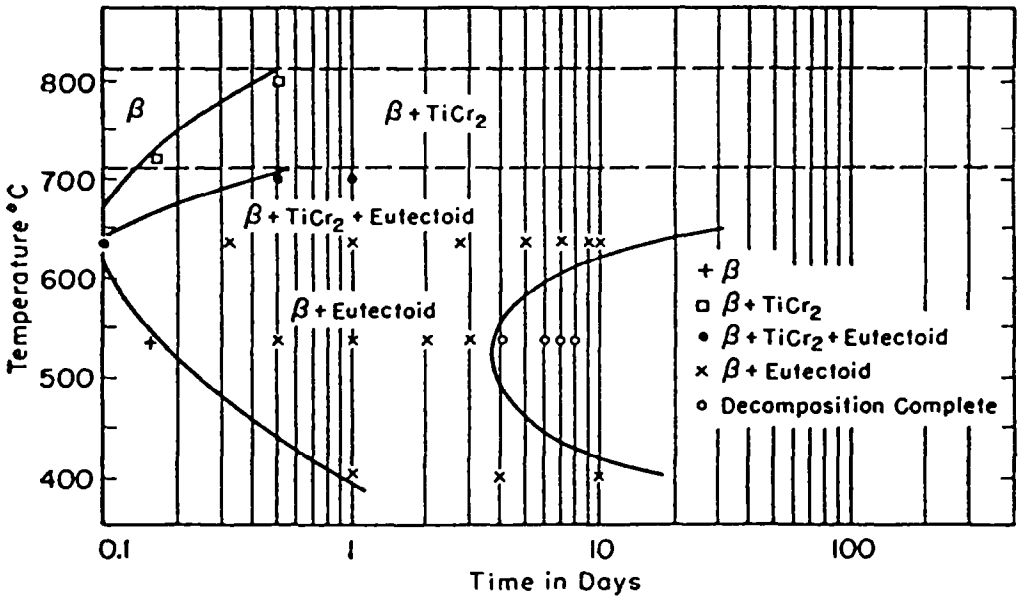
Time-temperature-transformation diagram

Composition: Ti - 17.0% Cr



LIVE GRAPH
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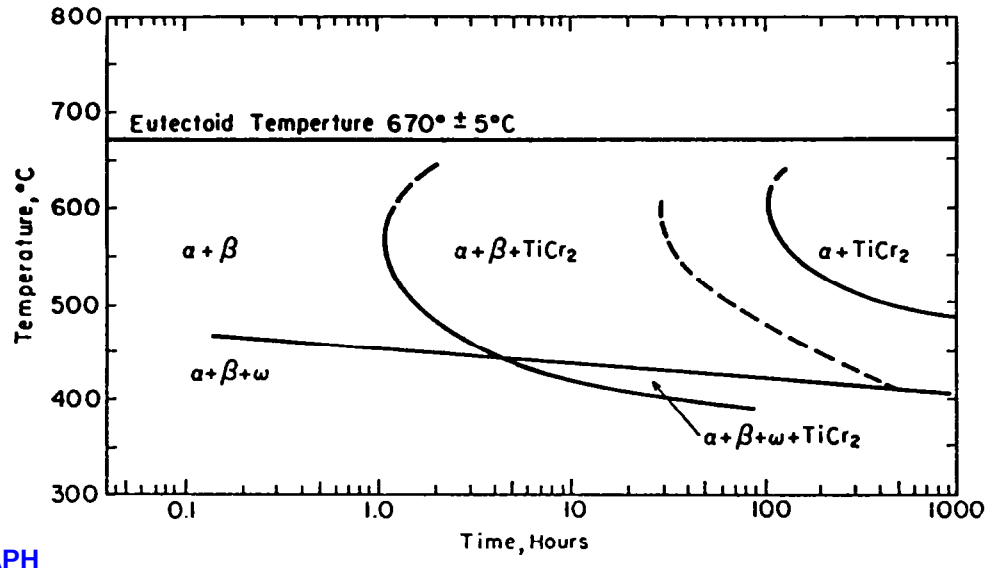
Time-temperature-transformation diagram

SOURCE: W. Rostoker, discussion of "Isothermal Transformation of Titanium-Chromium Alloys," by P.D. Frost et al., Trans. ASM, Vol 46, 1954, pp 231-256

Ti-Cr Alloys

Composition: Ti - 3.0% Cr



LIVE GRAPH
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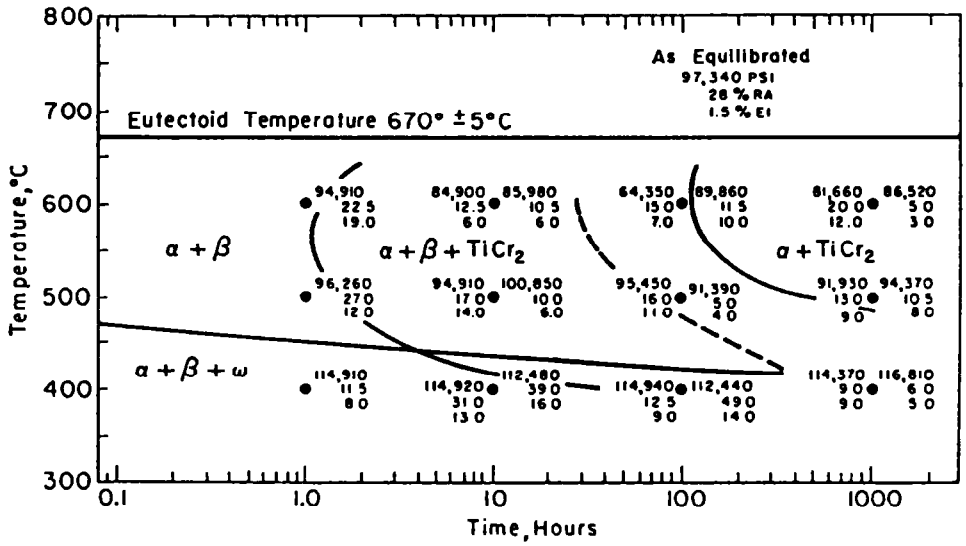
Time-temperature-transformation diagram
Equilibrated at 685°C (1265°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 3.0% Cr



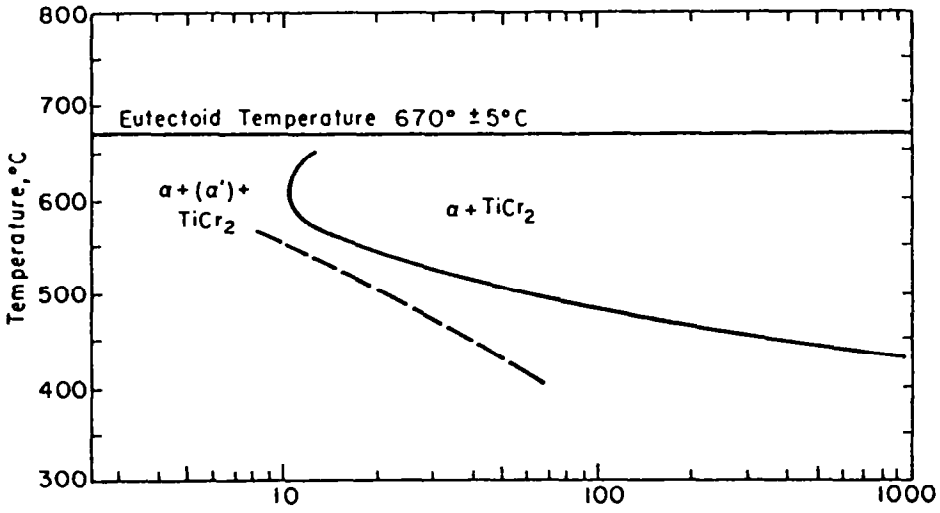
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties for the alloy
Data to the left of each point are for stressed transformation
Data to the right are for unstressed transformation

SOURCE: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

Composition: Ti - 3.0% Cr



LIVE GRAPH
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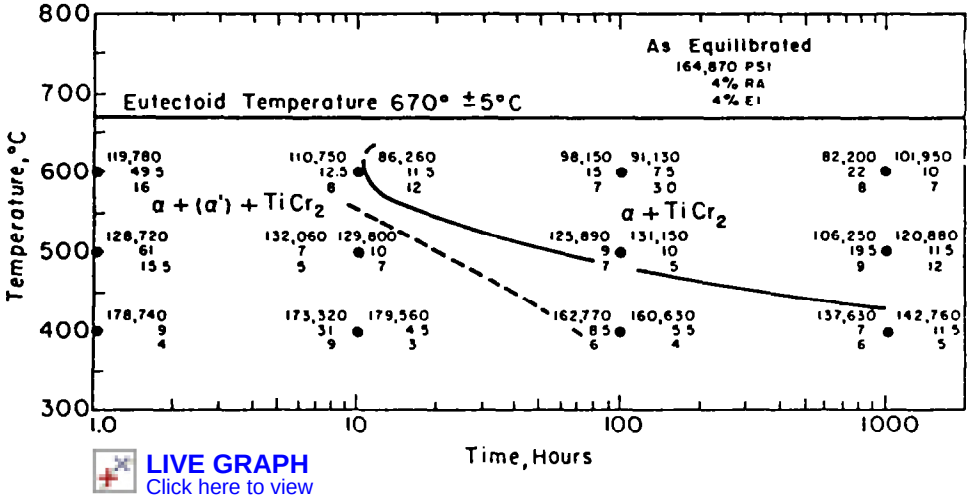
Time-temperature-transformation diagram
Equilibrated at 810°C (1490°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 3.0% Cr



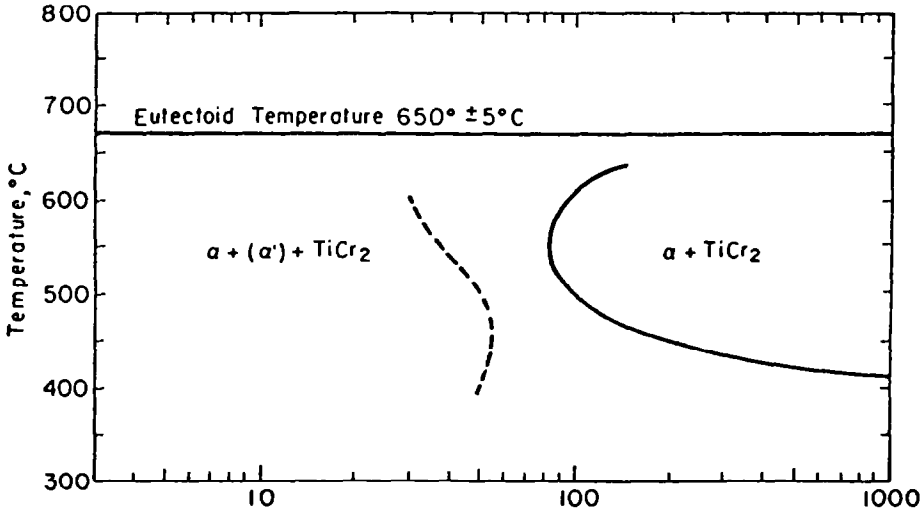
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties for the alloy
Data to the left of each point are for stressed transformation
Data to the right are for unstressed transformation

SOURCE: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

Composition: Ti - 3.0% Cr



LIVE GRAPH
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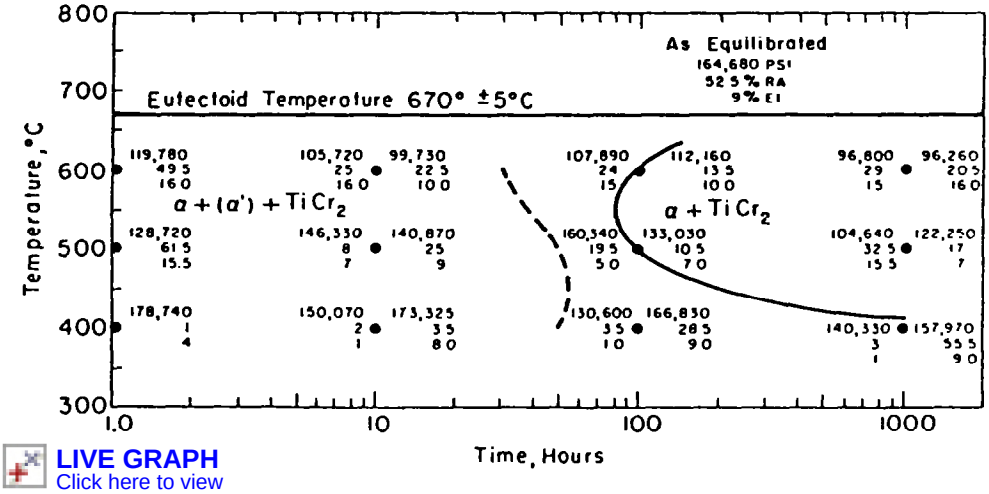
Time-temperature-transformation diagram
Equilibrated at 840°C (1545°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 3.0% Cr



LIVE GRAPH
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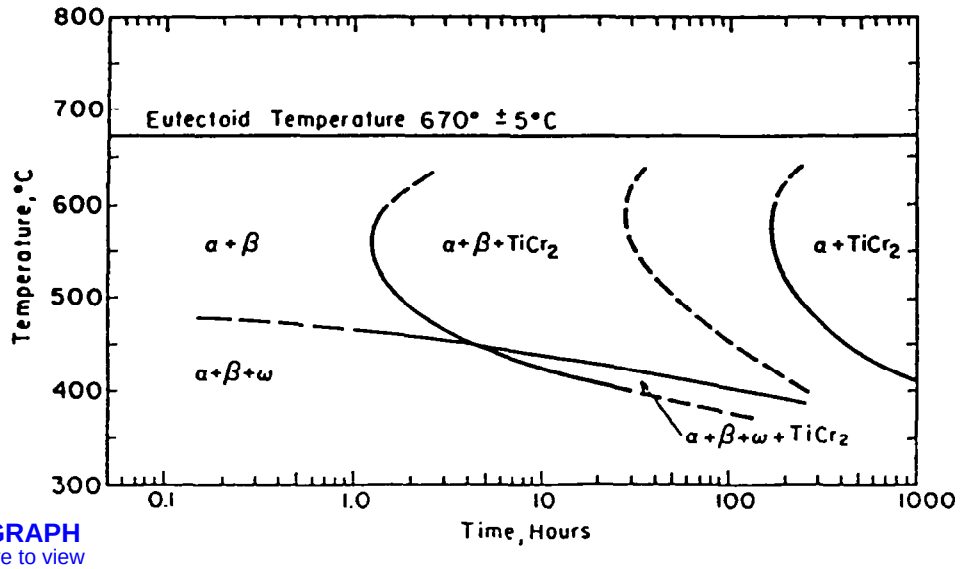
Time-temperature-transformation diagram
Tensile properties for the alloy
Data to the left of each point are for stressed transformation
Data to the right are for unstressed transformation

SOURCE: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

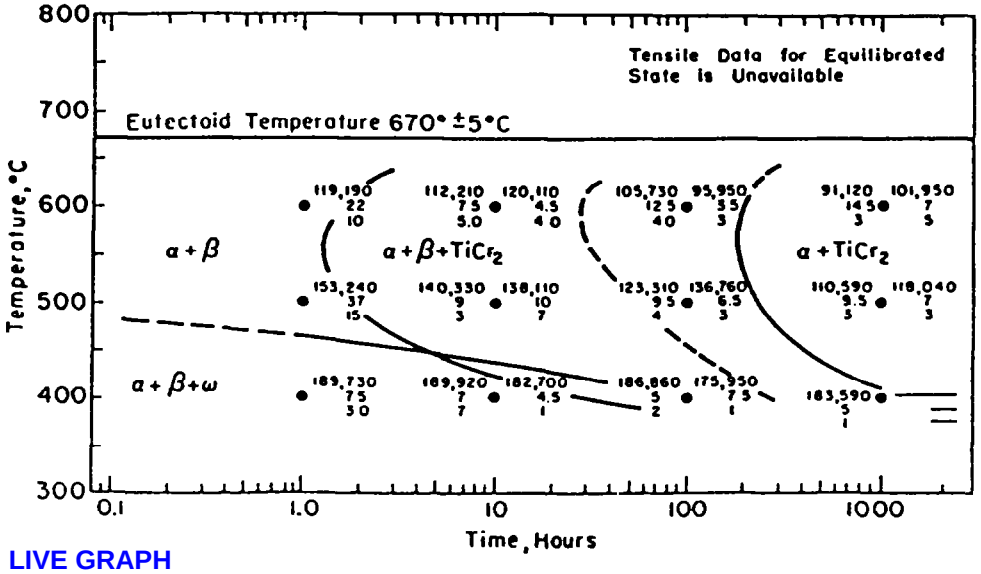
Composition: Ti - 7.5% Cr



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Alloy equilibrated at 685°C (1265°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 7.5% Cr



LIVE GRAPH
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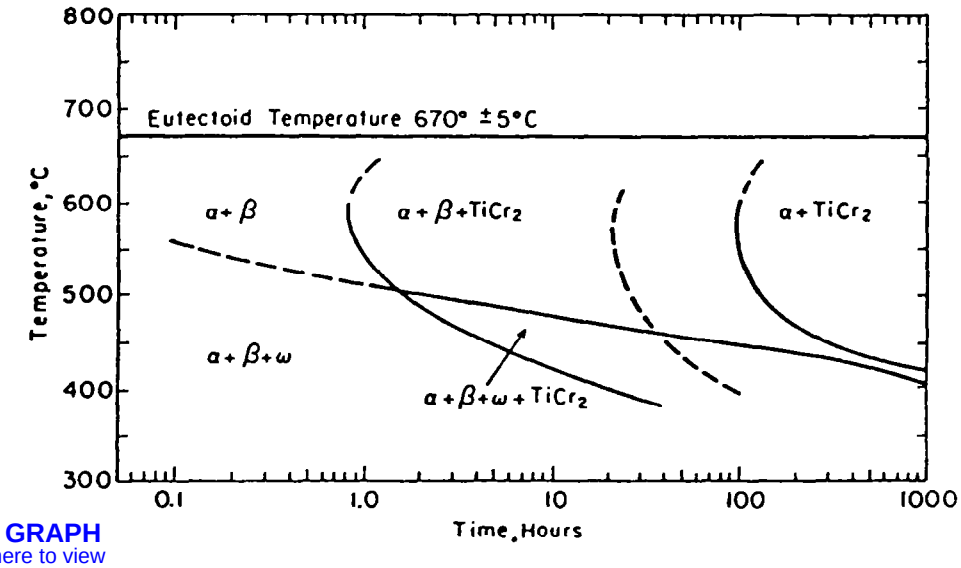
Time-temperature-transformation diagram
Tensile properties for the alloy
Data to the left of each point are for the stressed transformation
Data to the right are for the unstressed transformation.

Source: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

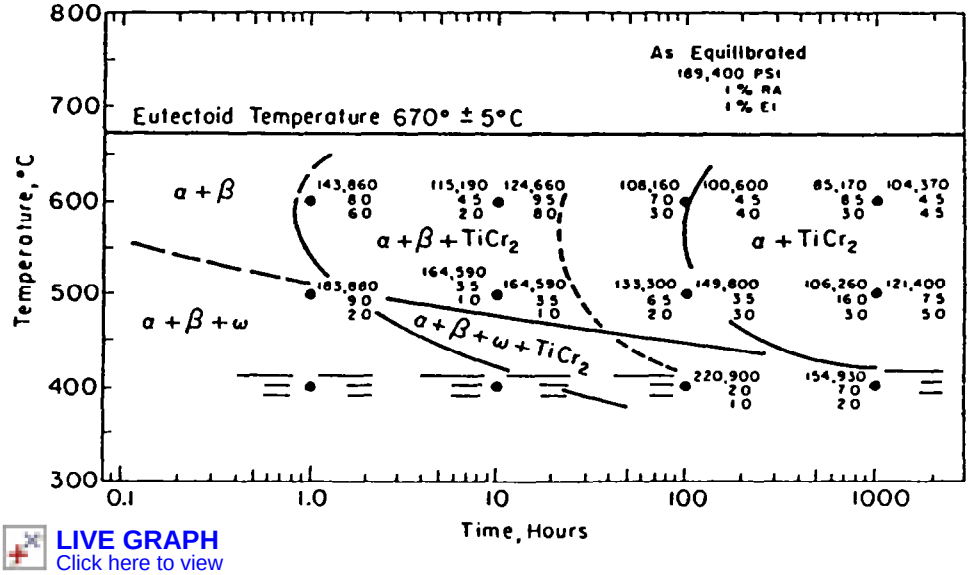
Composition: Ti - 7.5% Cr



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Alloy equilibrated at 750°C (1380°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 7.5% Cr



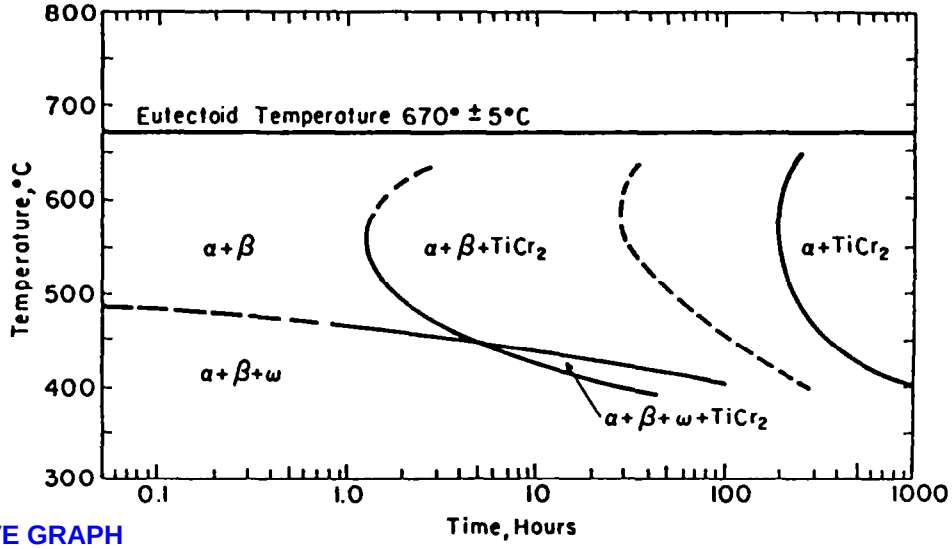
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties for the alloy
Data to the left of each point are for stressed transformation.
Data to the right are for unstressed transformation

Source: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

Composition: Ti - 12.0% Cr



LIVE GRAPH
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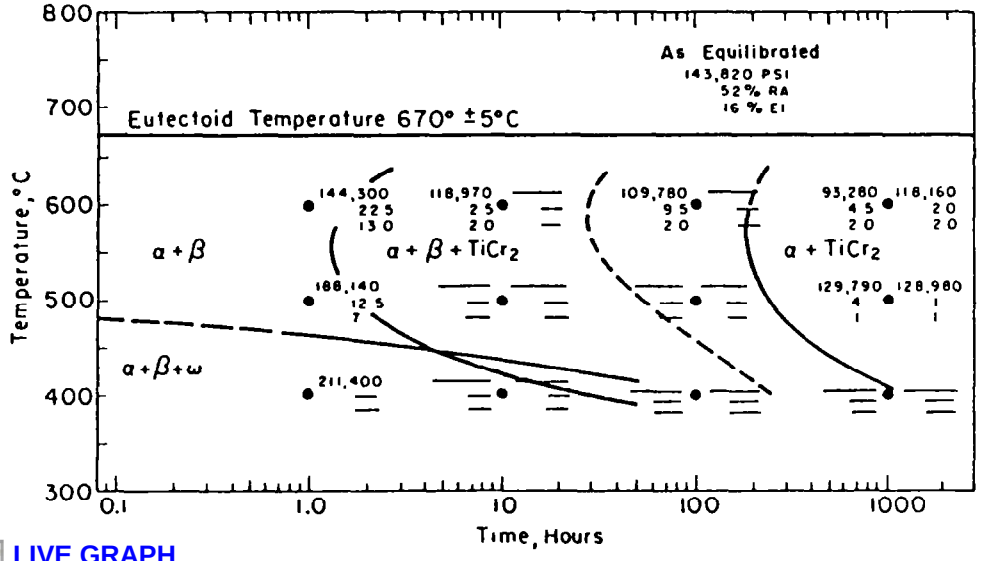
Time-temperature-transformation diagram
Alloy equilibrated at 685°C (1265°F)
The dashed line represents the displacement of the end of transformation due to stress

Composition: Ti - 12.0% Cr



LIVE GRAPH
Click here to view

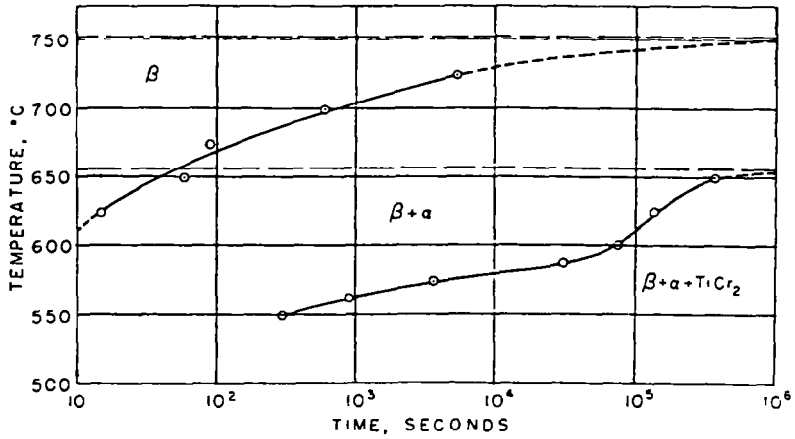
Time-temperature-transformation diagram
Mechanical properties for the alloy
Data to the left of each point are for stressed transformation
Data to the right are for unstressed transformation

SOURCE: A.W. Goldenstein et al., "The Effect of Stress on the Eutectoid Decomposition of Titanium-Chromium Alloys," Trans. ASM, Vol 51, 1959, pp 1036-1054

Ti-Cr Alloys

Composition: Ti - 7.22% Cr

Treatment: Solution annealed at 1000°C (1832°F) for 40 min



LIVE GRAPH
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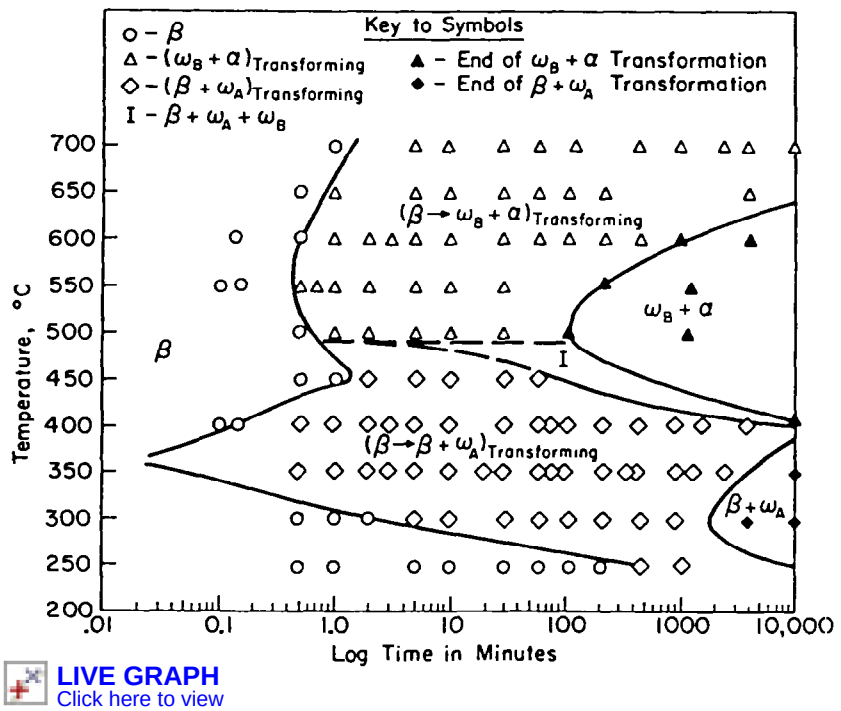
Time-temperature transformation diagram

SOURCE: H.I. Aaronson et al., "Phase Transformations in Hypoeutectoid Ti - Cr Alloys," Trans. AIME, Vol 209, October 1957, pp 1227-1235

Composition: Ti - 8.0% Cr



LIVE GRAPH
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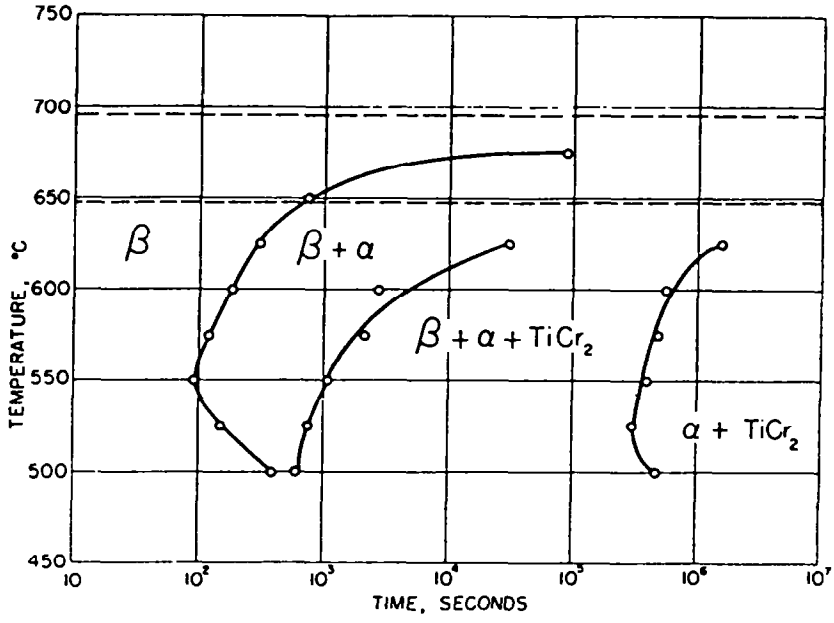
Time-temperature-transformation diagram

SOURCE: S.A. Spachner and W. Rostoker, "Transformation Kinetics of Two Titanium Alloys in the Transition Phase Region," Trans. AIME, Vol 212, December 1958, pp 765-768

Ti-Cr Alloys

Composition: Ti - 10.8% Cr

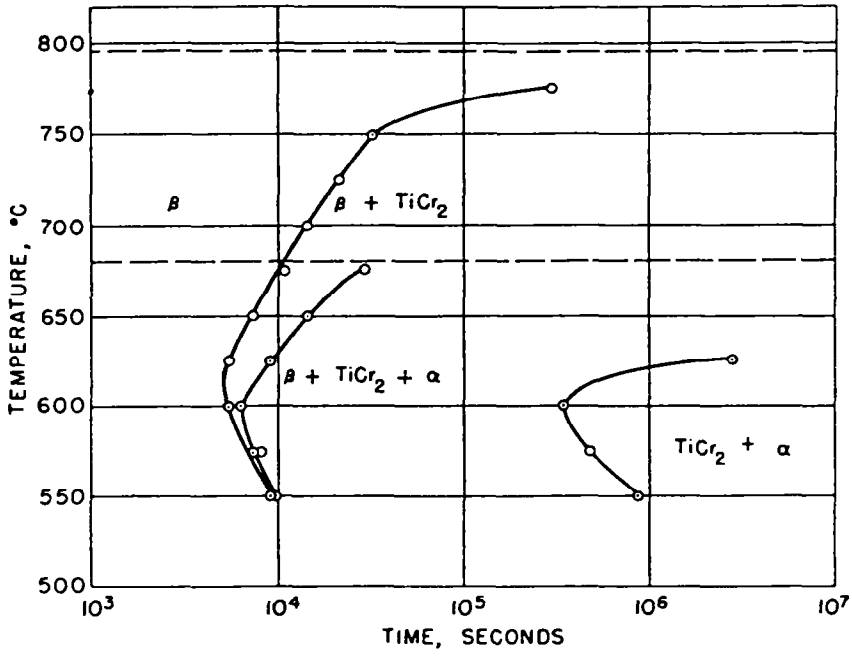


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: H.I. Aaronson et al., "Effects of Composition on Transformations in Titanium-Chromium Alloys," Trans. AIME, Vol 212, October 1958, pp 624-626

Composition: Ti - 17.42% Cr



LIVE GRAPH
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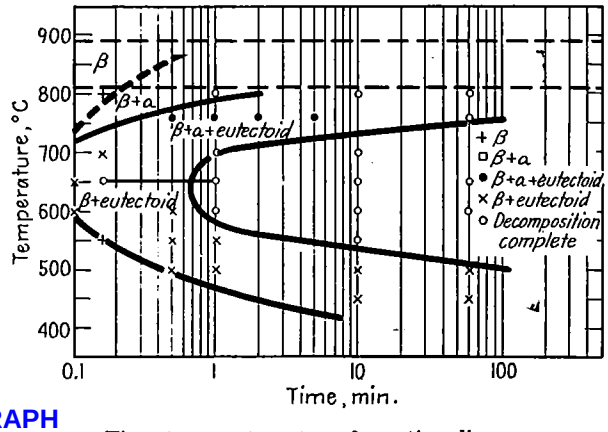
Time-temperature-transformation diagram

SOURCE: H.I. Aaronson et al., "Transformation Mechanisms in a Hypereutectoid Titanium-Chromium Alloy," Trans. AIME, Vol 218, April 1960, pp 331-339

Ti-Cu Alloy

Composition: Ti - 5.0% Cu



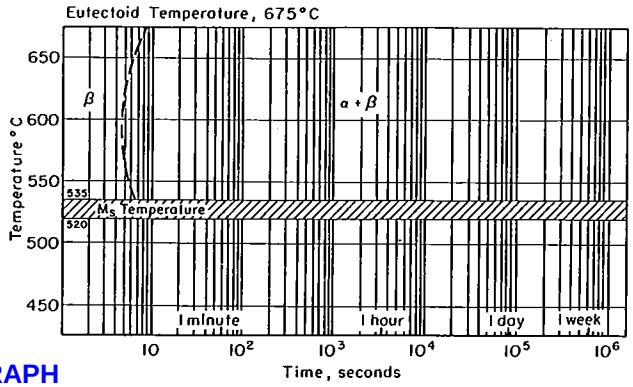
LIVE GRAPH Click here to view

Time-temperature-transformation diagram

SOURCE: W. Rostoker and H.D. Kessler, "Titanium Alloy Development Mapped," The Iron Age, Vol 169, No. 25, 19 June 1952, pp 136-142

Ti-Mn Alloys

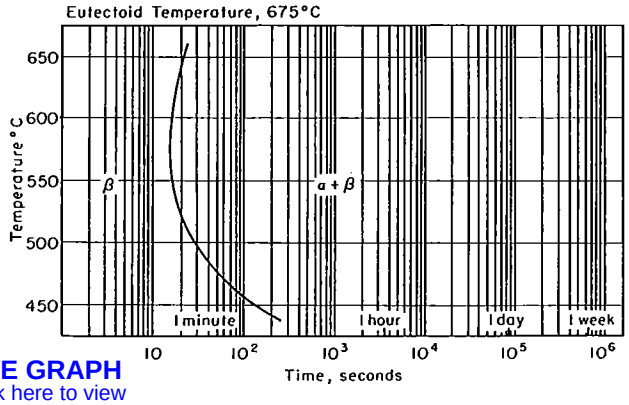
Composition: Ti - 2.91% Mn
Treatment: Solution annealed at 950°C (1740°F)



LIVE GRAPH Click here to view

Time-temperature-transformation diagram

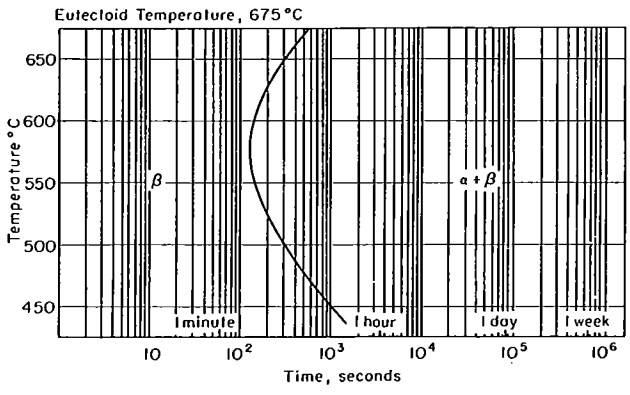
Composition: Ti - 7.72% Mn
Treatment: Solution annealed at 950°C (1740°F) before transformation



LIVE GRAPH Click here to view

Time-temperature-transformation diagram

Composition: Ti - 12.3% Mn
Treatment: Solution annealed at 950°C (1740°F) before transformation



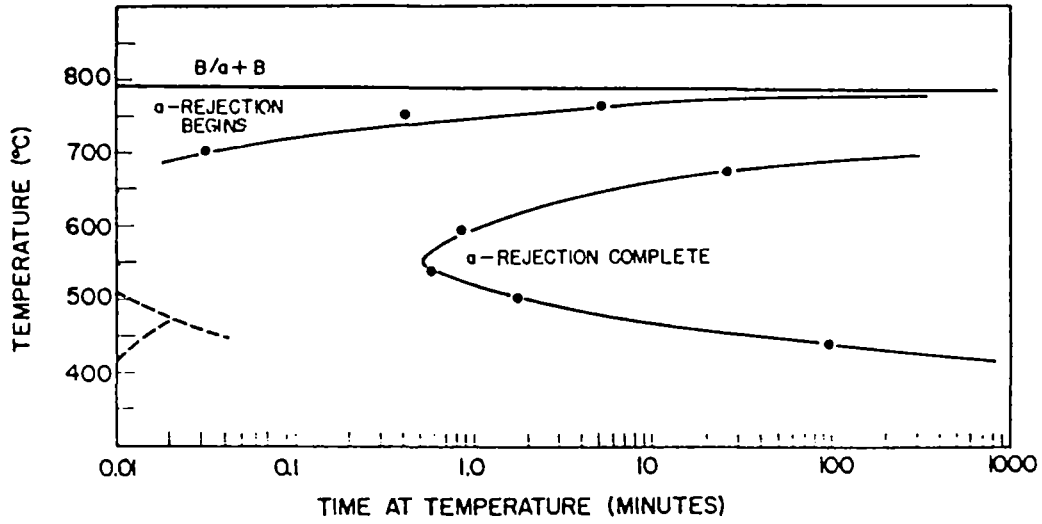
Time-temperature-transformation diagram

SOURCE: P.D. Frost et al., "Isothermal Transformation of Titanium-Manganese Alloys," Trans. ASM, Vol 46, 1954, pp 1056-1074

LIVE GRAPH Click here to view

Ti-Mn Alloys

Composition: Ti - 6.0% Mn
Treatment: Solution treated at 1000°C (1832°F) for 20 min



LIVE GRAPH
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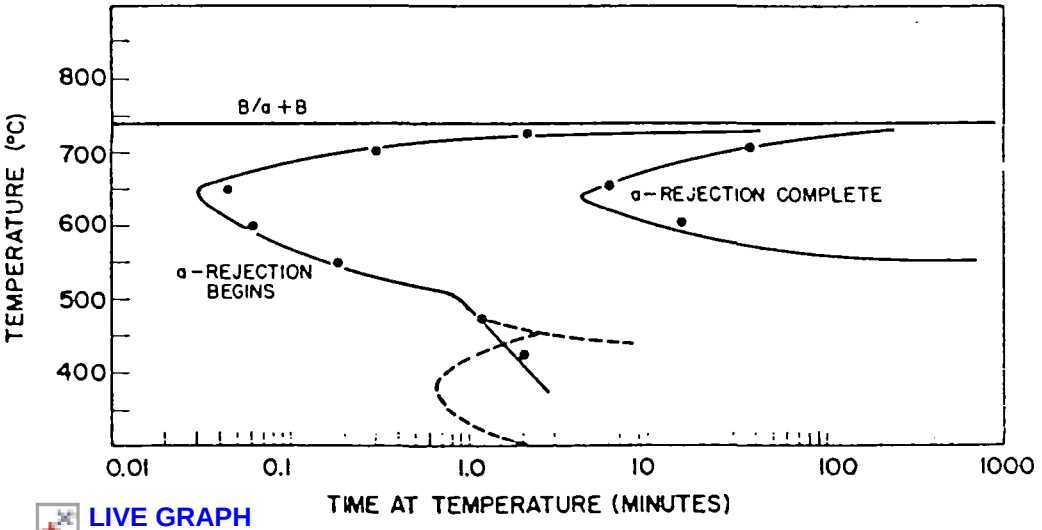
Time-temperature-transformation

Composition: Ti - 10.0% Mn
Treatment: Solution treated at 1000° (1832°F) for 20 min



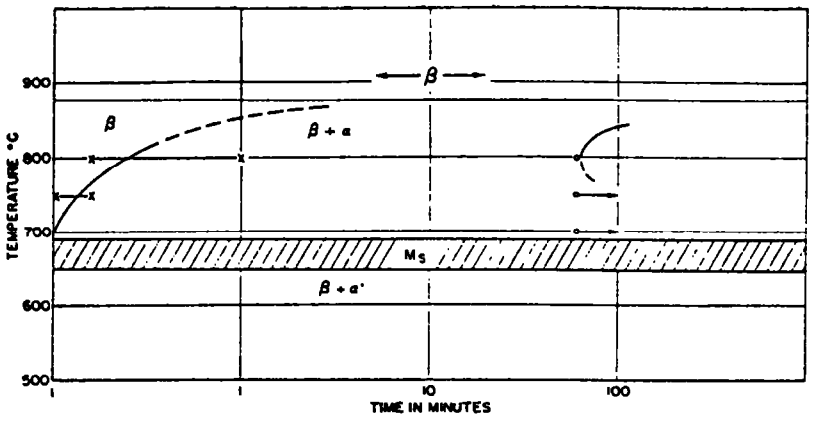
LIVE GRAPH
Click here to view

Time-temperature-transformation

SOURCE: H.D. Kessler and Harold Margolin discussion of "Correlation Between Microstructure and Resistivity of Transforming Ti - Mn Alloys," by D.J. DeLazaro and D.W. Levinson, Trans. AIME, Vol 201, May 1955, pp 715-717

Ti-Mo Alloys

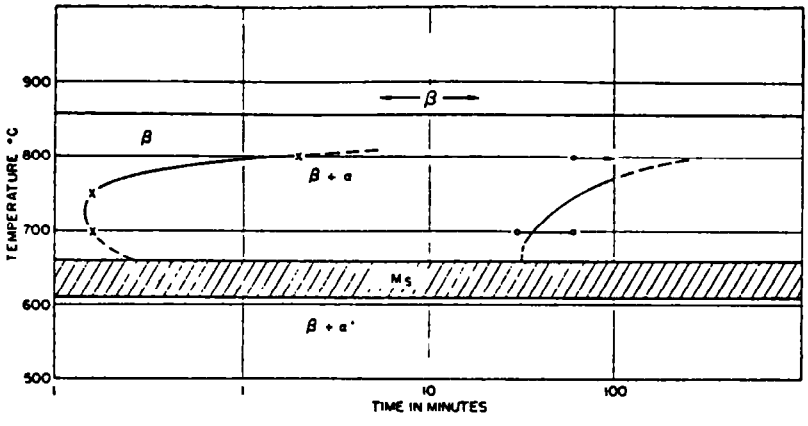
Composition: Ti - 1.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Ti - 3.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



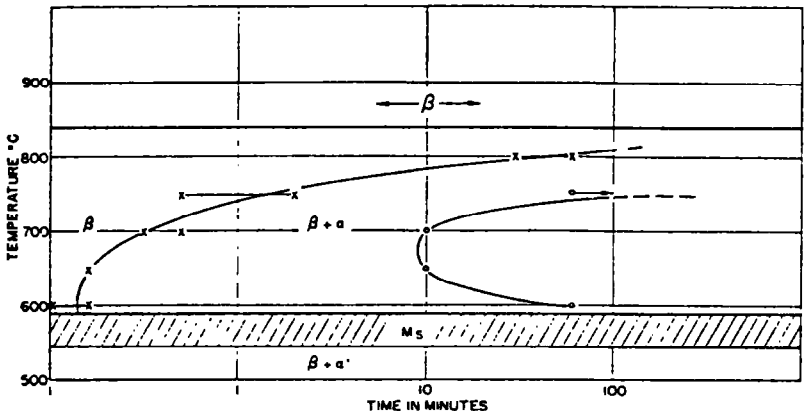
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D.J. DeLazaro et al., "Time-Temperature-Transformation Characteristics of Titanium-Molybdenum Alloys," Trans. AIME, Vol 194, March 1952, pp 265-269

Ti-Mo Alloys

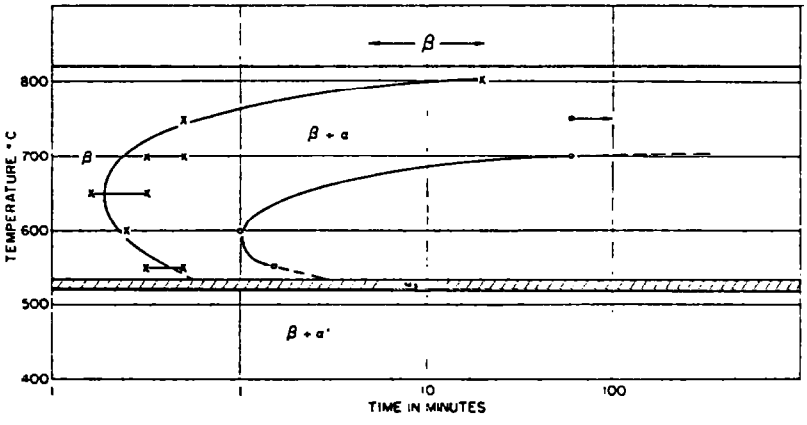
Composition: Ti - 5.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Ti - 7.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



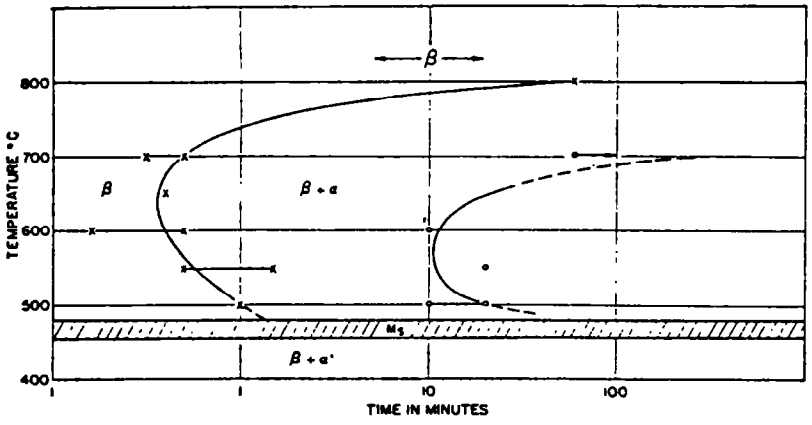
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D.J. DeLazaro et al., "Time-Temperature-Transformation Characteristics of Titanium-Molybdenum Alloys," Trans. AIME, Vol 194, March 1952, pp 265-269

Ti-Mo Alloys

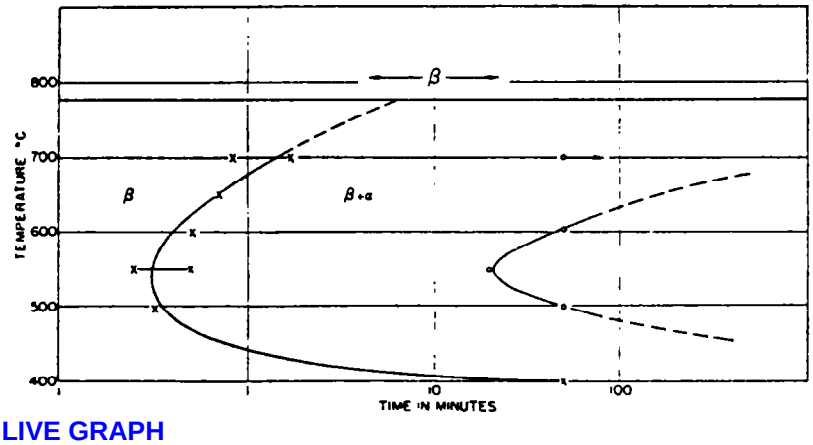
Composition: Ti - 9.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Ti - 11.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min prior to transformation



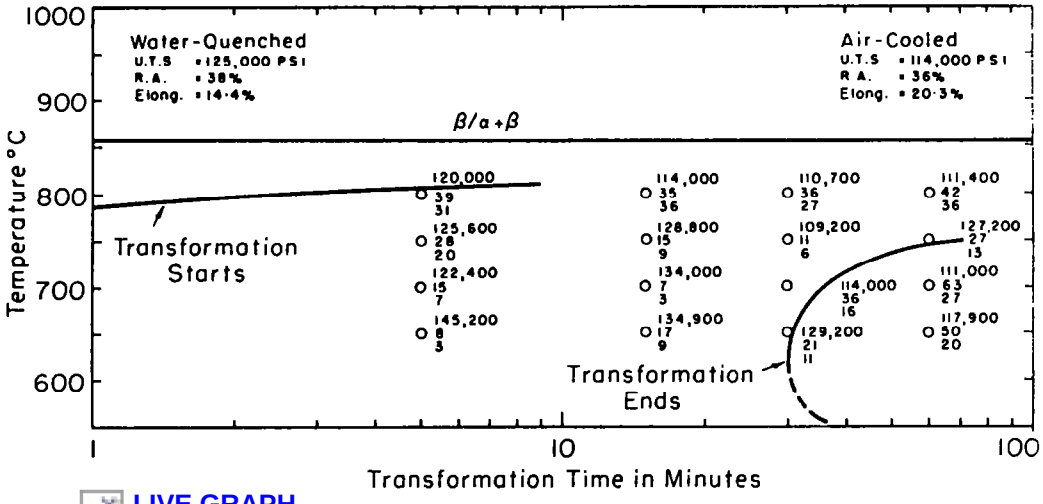
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D.J. DeLazaro et al., "Time-Temperature-Transformation Characteristics of Titanium-Molybdenum Alloys," Trans. AIME, Vol 194, March 1952, pp 265-269

Ti-Mo Alloys

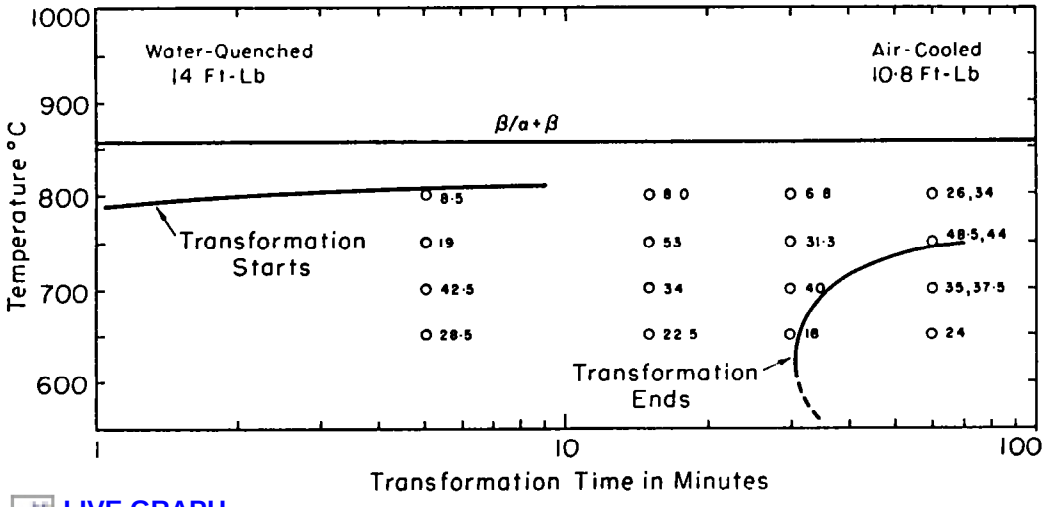
Composition: Ti - 3.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties

Composition: Ti - 3.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



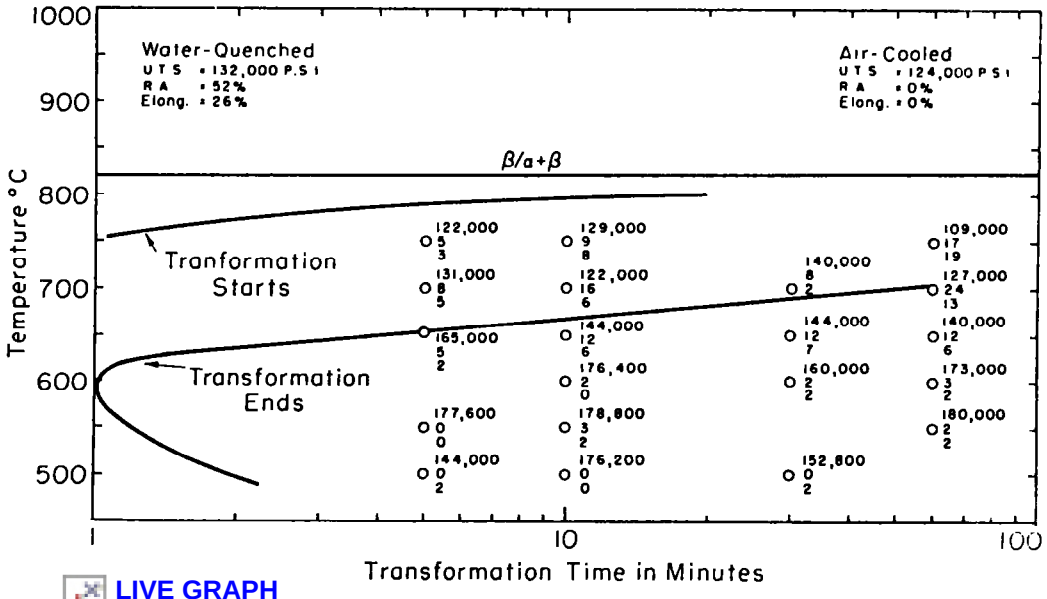
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Charpy impact properties

SOURCE: D.J. DeLazaro and W. Rostoker, "Correlation Between Heat Treatment, Microstructure and Mechanical Properties of Titanium-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 292-311

Ti-Mo Alloys

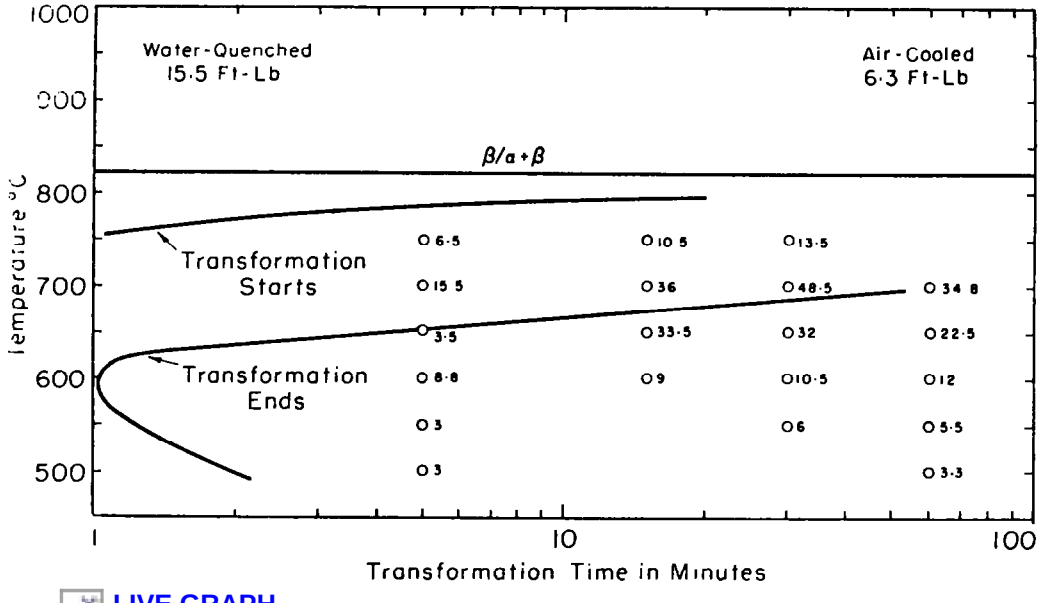
Composition: Ti - 7.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties

Composition: Ti - 7.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



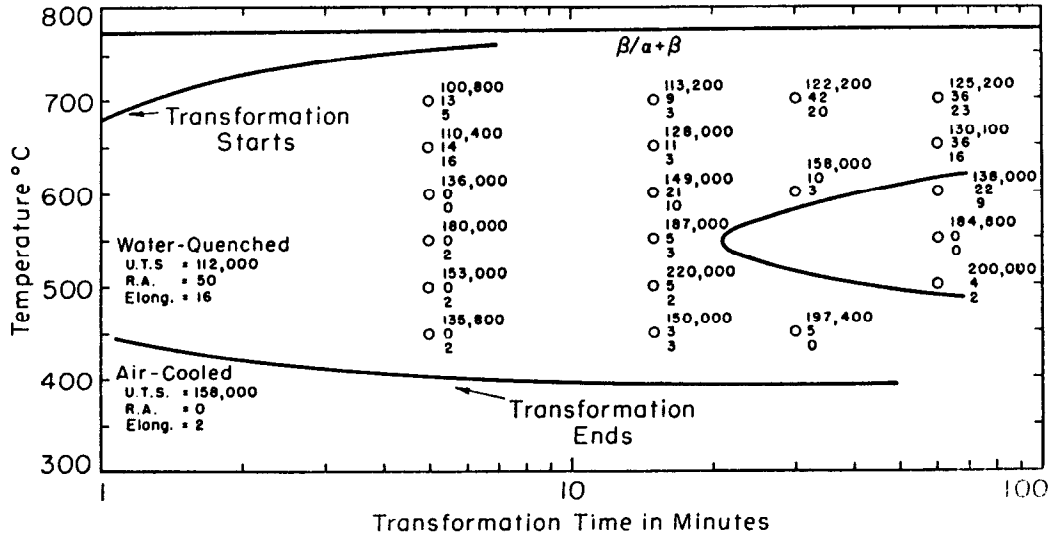
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Charpy impact properties

SOURCE: D.J. DeLazaro and W. Rostoker, "Correlation Between Heat Treatment, Microstructure and Mechanical Properties of Titanium-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 292-311

Ti-Mo Alloys

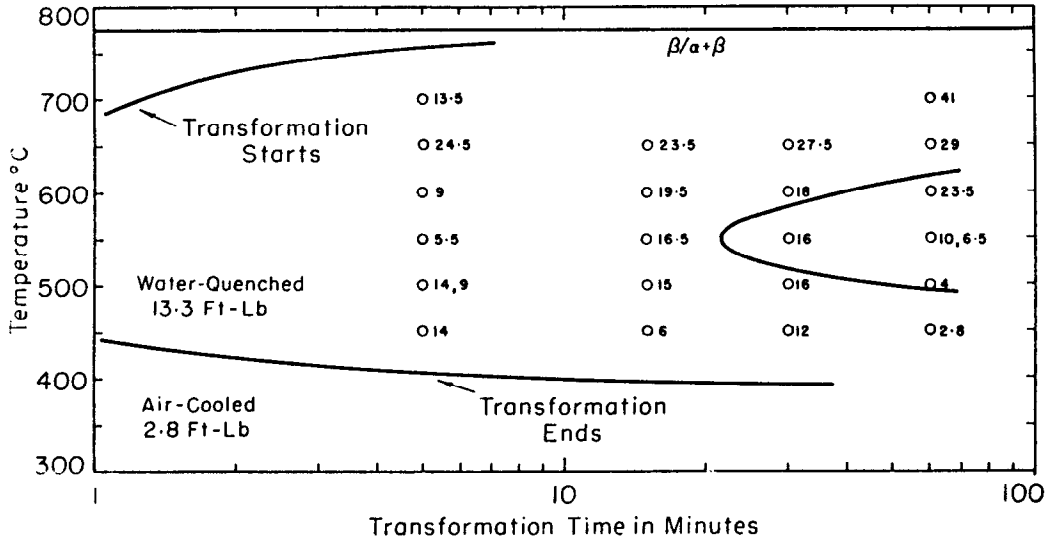
Composition: Ti - 11.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Tensile properties

Composition: Ti - 11.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



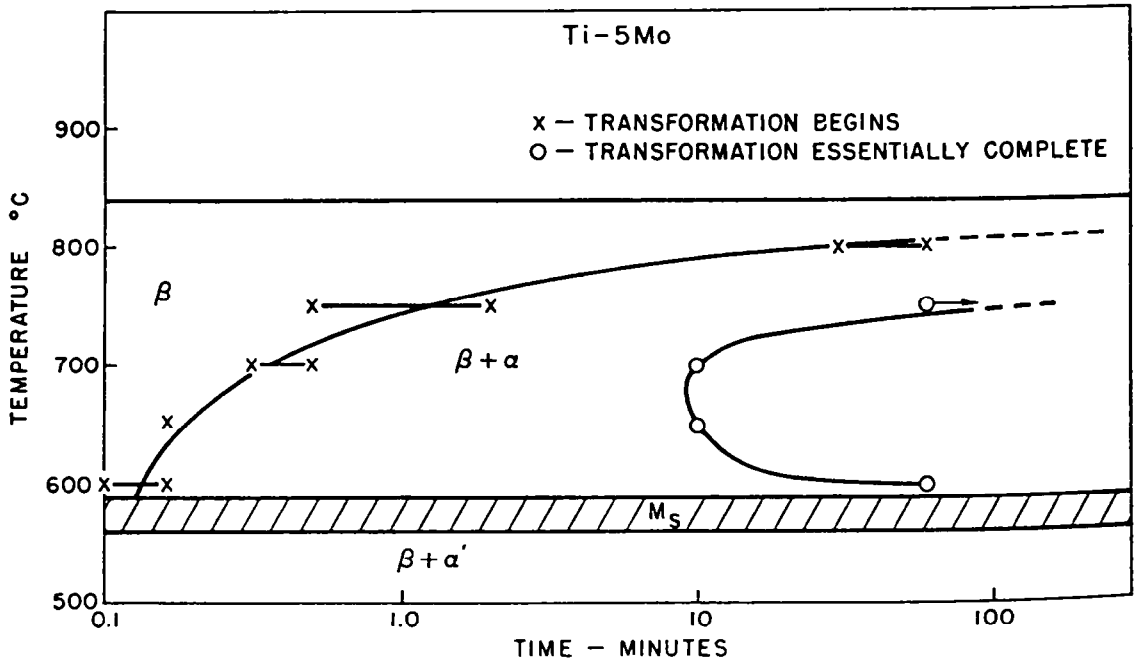
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Charpy impact properties

SOURCE: D.J. DeLazaro and W. Rostoker, "Correlation Between Heat Treatment, Microstructure and Mechanical Properties of Titanium-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 292-311

Ti-Mo Alloys

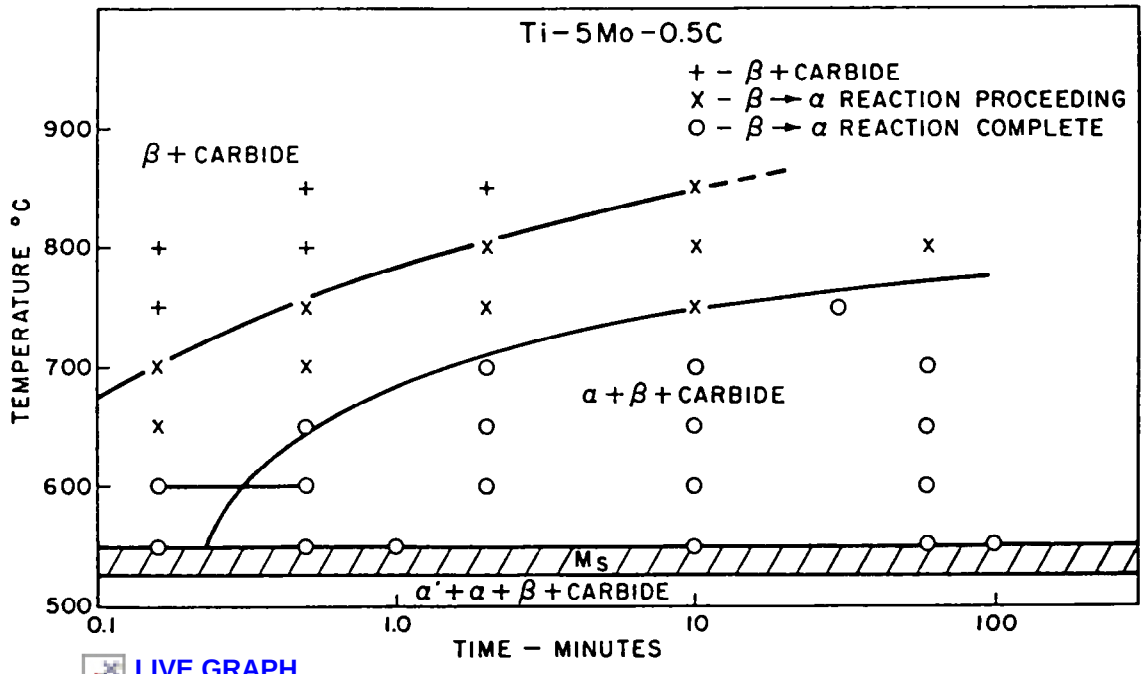
Composition: Ti - 5.16% Mo
Treatment: Solution treated at 1000°C (1832°F) for 30 min before transformation



LIVE GRAPH Click here to view

Time-temperature-transformation diagram

Composition: Ti - 5.21% Mo - 0.46% C
Treatment: Solution treated at 1000°C (1832°F) for 30 min before transformation



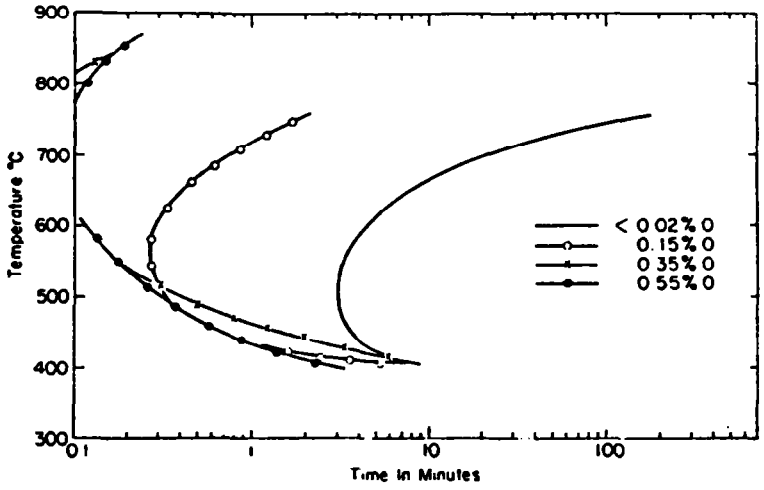
LIVE GRAPH Click here to view

Time-temperature-transformation diagram

SOURCE: D.W. Levinson et al., "Effect of Carbon on Some Properties of Ti - Mo Alloys," Trans. AIME, Vol 206, June 1956, pp 790-793

Ti-Mo Alloys

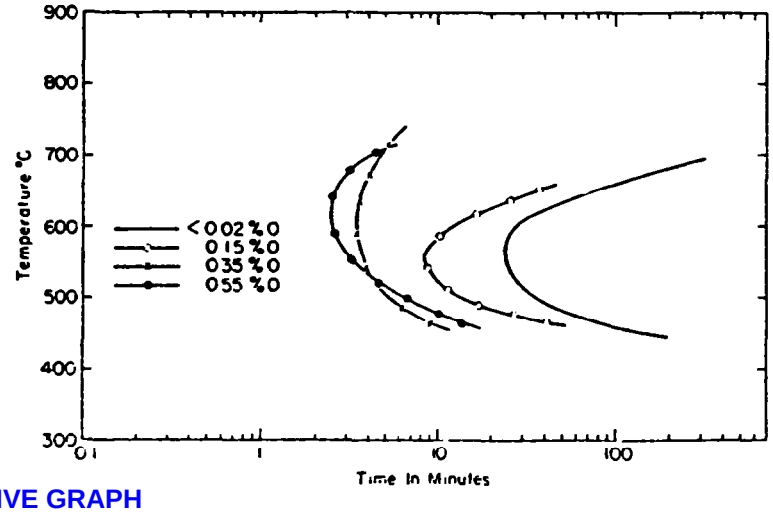
Composition: Ti - 11.0% Mo vs O



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Initiation of transformation

Composition: Ti - 11.0% Mo vs O



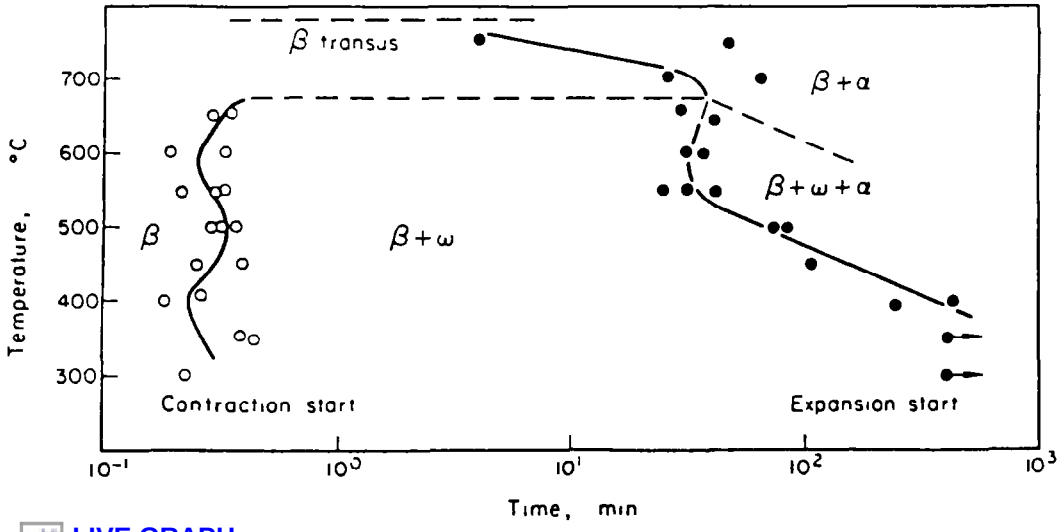
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Completion of transformation

SOURCE: D.J. DeLazaro and W. Rostoker, "The Influence of Oxygen Contents on Transformations in a Titanium Alloy Containing 11 Per Cent Molybdenum," Acta Met., Vol 1, 1953, pp 674-677

Ti-Mo Alloy

Composition: Ti - 12% Mo
Treatment: Solution treated at 1000°C (1832°F) for 30 min in vacuum by high-frequency induction heating and isothermal quenched to a temperature in the range from 300 to 700°C (572 to 1292°F) by argon or helium gas cooling. The quenching rate was 100-150°C/s

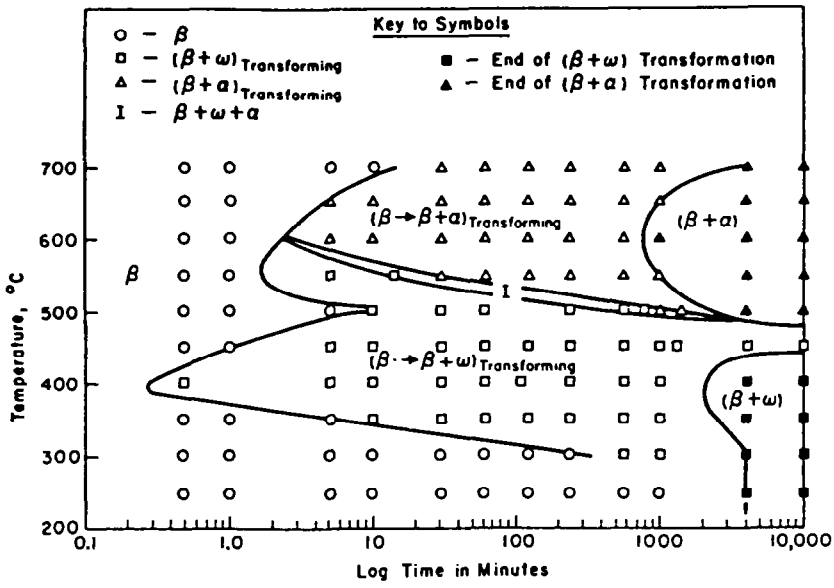


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: T. Yukawa, S. Ohtani, T. Nishimura, T. Sakai, "Phase Transformation of Titanium Alloys by Means of Automatic Transformation Apparatus," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, eds., Pergamon Press, Oxford, 1970, pp 699-710

Composition: Ti - 13.0% Mo
Treatment: Solution treated at 900°C (1652°F) for 30 min



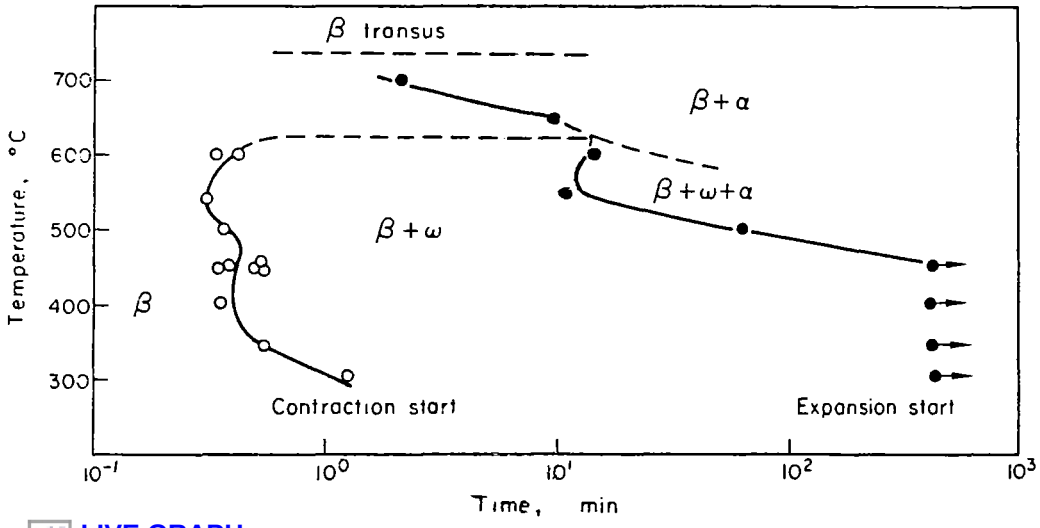
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: S.A. Spachner and W. Rostoker, "Transformation Kinetics of Two Titanium Alloys in the Transition Phase Region," Trans. AIME, Vol 212, December 1958, pp 765-767

Ti-Mo Alloy

Composition: Ti - 15% Mo
Treatment: Solution treated at 1000°C (1832°F) for 30 min in vacuum by high-frequency induction heating and isothermal quenched to a temperature in the range from 300 to 700°C (572 to 1292°F) by argon or helium gas cooling. The quenching rate was 100-150°C/s

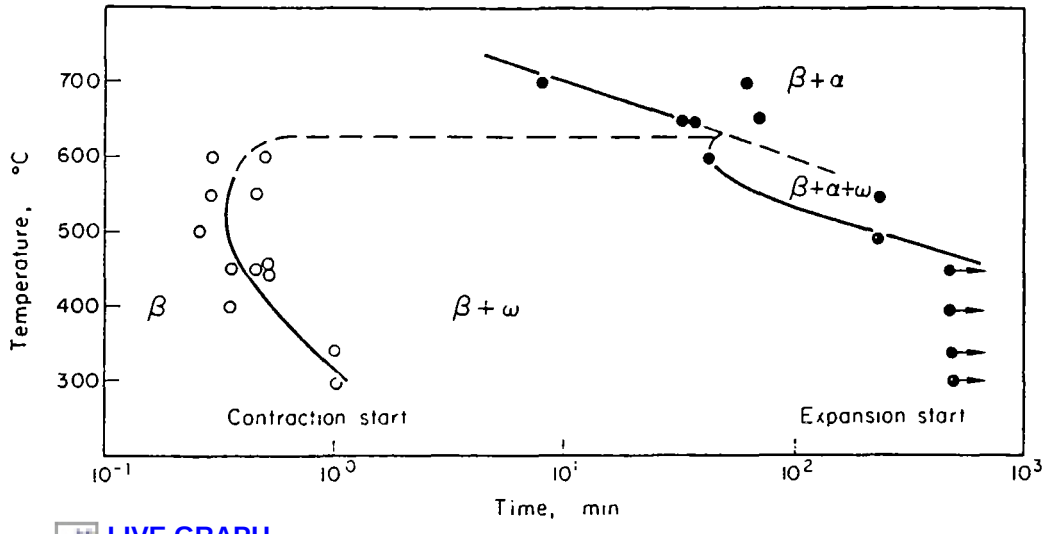


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Ti-Mo-Pd Alloy

Composition: Ti - 15% Mo - 0.2% Pd
Treatment: Solution treated at 1000°C (1832°F) for 30 min in vacuum by high-frequency induction heating and isothermal quenched to a temperature in the range from 300 to 700°C (572 to 1292°F) by argon or helium gas cooling. The quenching rate was 100-150°C/s



LIVE GRAPH
Click here to view

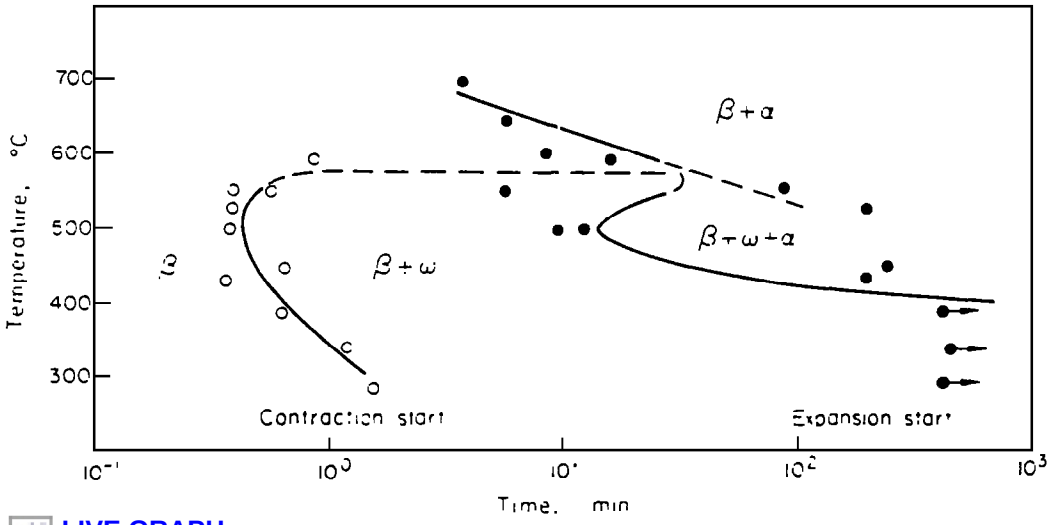
Time-temperature-transformation diagram

SOURCE: T. Yukawa, S. Ohtani, T. Nishimura, T. Sakai, "Phase Transformation of Titanium Alloys by Means of Automatic Transformation Apparatus," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, eds., Pergamon Press, Oxford, 1970, pp 699-710

Ti-Mo-Zr Alloy

Composition: Ti - 15% Mo - 5% Zr

Treatment: Solution treated at 1000°C (1832°F) for 30 min in vacuum by high-frequency induction heating and isothermal quenched to a temperature in the range from 300 to 700°C (572 to 1292°F) by argon or helium gas cooling. The quenching rate was 100-150°C/s



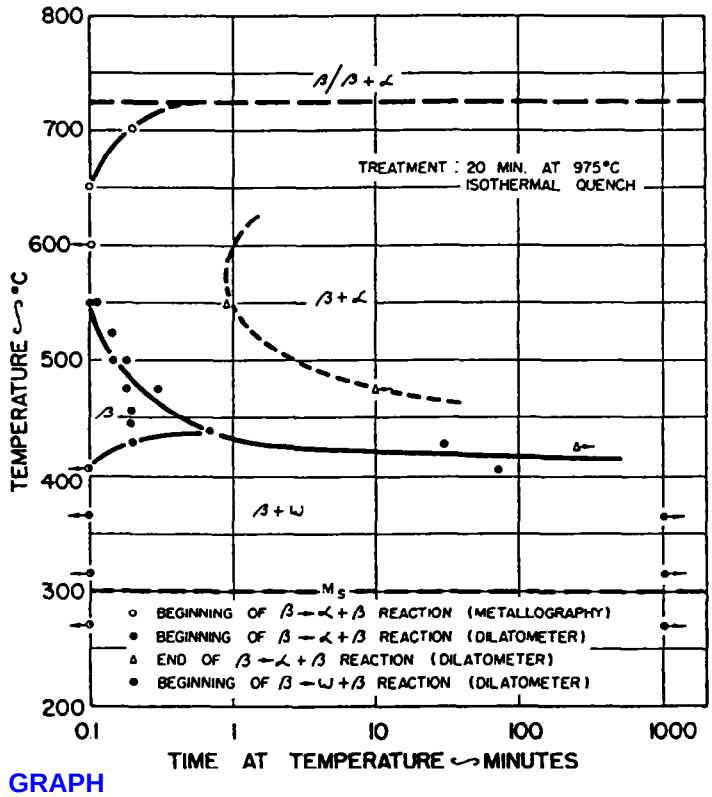
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: T. Yukawa, S. Ohtani, T. Nishimura, T. Sakai, "Phase Transformation of Titanium Alloys by Means of Automatic Transformation Apparatus," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, eds., Pergamon Press, Oxford, 1970, pp 699-710

Ti-V Alloys

Composition: Ti - 12.5% V



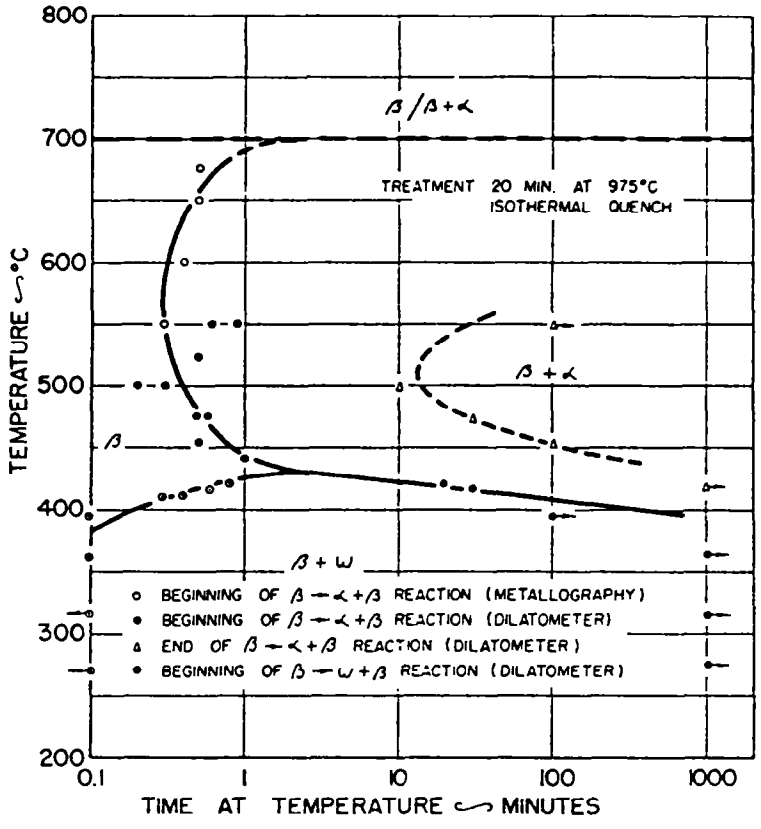
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: F.R. Brotzen et al., "Decomposition of Beta Titanium," Trans. AIME, Vol 203, February 1955, pp 413-419

Ti-V Alloys

Composition: Ti - 15.0% V



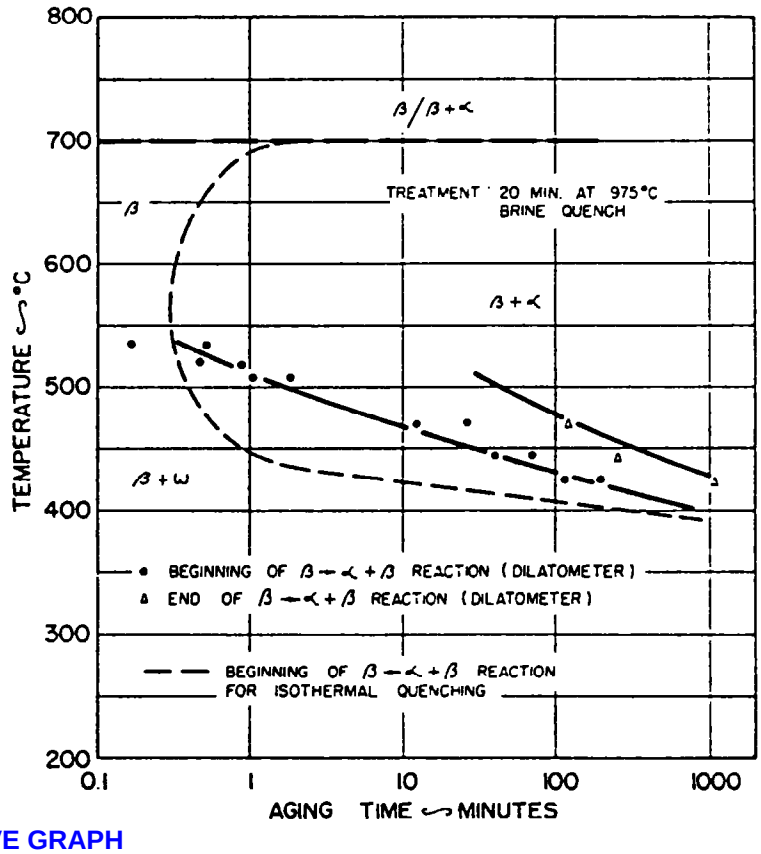
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Isothermal quenching

SOURCE: F.R. Brotzen et al., "Decomposition of Beta Titanium," Trans. AIME, Vol 203, February 1955, pp 413-419

Ti-V Alloys

Composition: Ti - 15.0% V



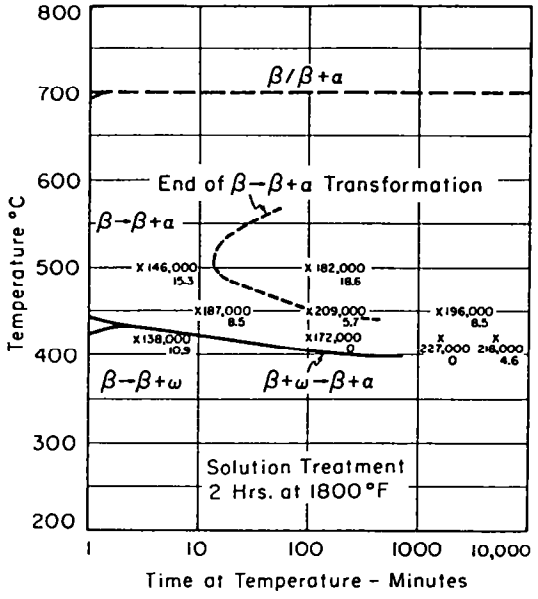
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Aging a quenched alloy

SOURCE: F.R. Brotzen et al., "Decomposition of Beta Titanium," Trans. AIME, Vol 203, February 1955, pp 413-419

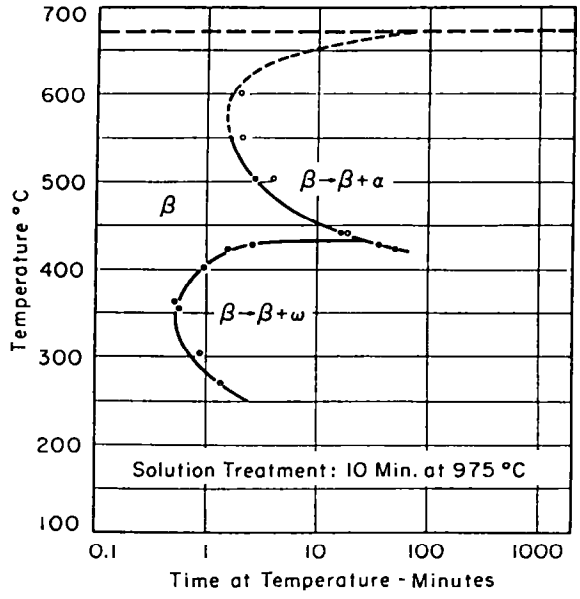
Ti-V Alloys

Composition: Ti - 15.0% V
Treatment: Solution treated at 982°C (1800°F) for 2 h



Time-temperature-transformation diagram
Tensile strength and reduction of area of specimens quenched from the beta region and isothermally transformed

Composition: Ti - 20.0% V
Treatment: Solution treated at 975°C (1787°F) for 10 min



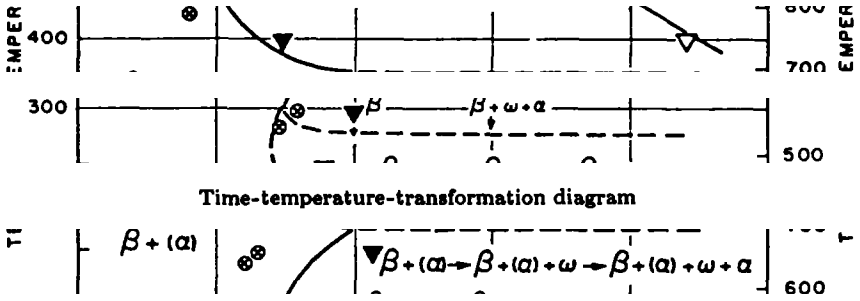
Time-temperature-transformation diagram

LIVE GRAPH
Click here to view

LEGEND:

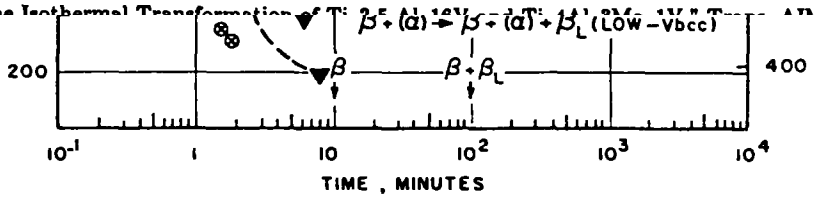
- ○ Beginning of β→β+α Reaction (Metallography)
- ● Beginning of β→β+α Reaction (Dilatometer)
- ◦ Beginning of β→β+ω Reaction (Dilatometer)

SOURCE: E.L. Harmon et al., "Mechanical Properties Correlated with Transformation Characteristics of Titanium-Vanadium Alloys," Trans. ASM, Vol 50, 1958, pp 418-437



Time-temperature-transformation diagram

SOURCE: L.E. Tanner, "The Isothermal Transformation of Ti-2.5 Al-16V and Ti-6Al-3Mo-1V," Trans. AIME, Vol 221, pp 74-83



SOURCE: L.E. Tanner, "The Isothermal Transformation of Ti-2.5 Al-16V and Ti-6Al-3Mo-1V," Trans. AIME, Vol 221, pp 74-83

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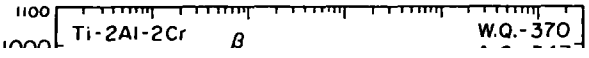
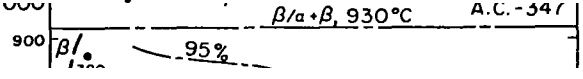
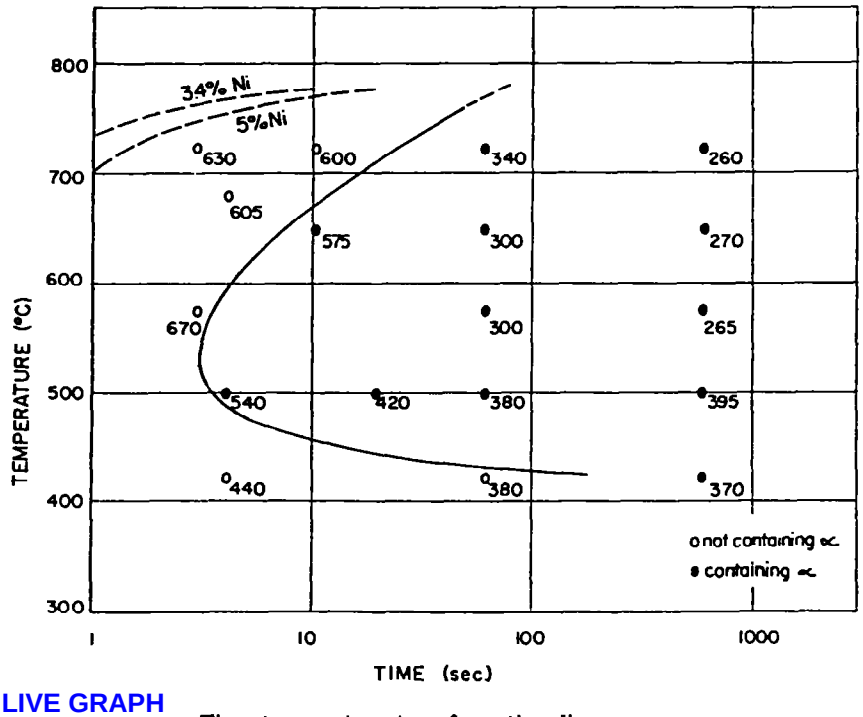


Ti-Al-Cr Alloys



Ti-Ni Alloys

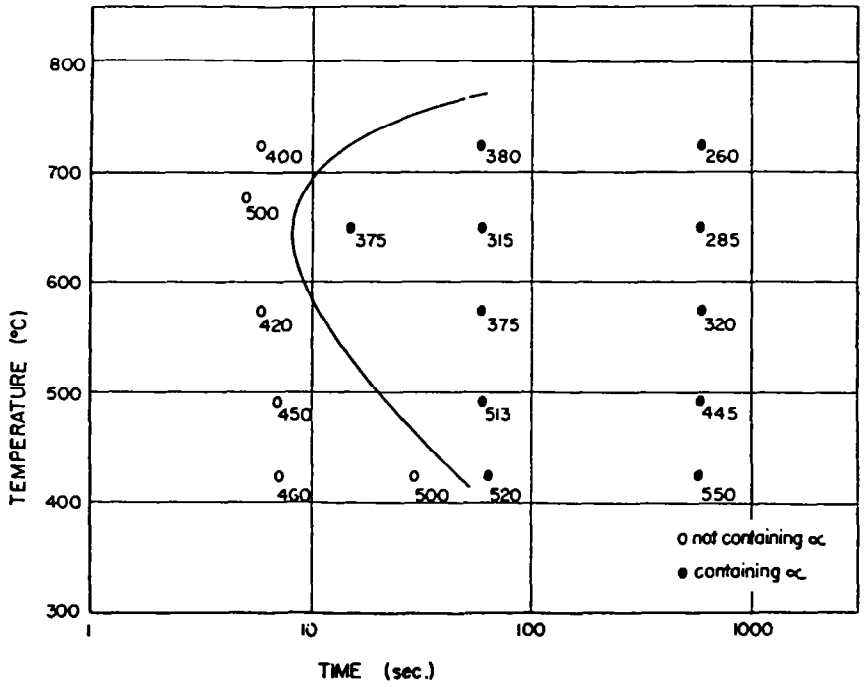
Composition: Ti - 7 at.% Ni



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Values on diagram are hardnesses, HV (1 kgf)

Composition: Ti - 10 at.% Ni



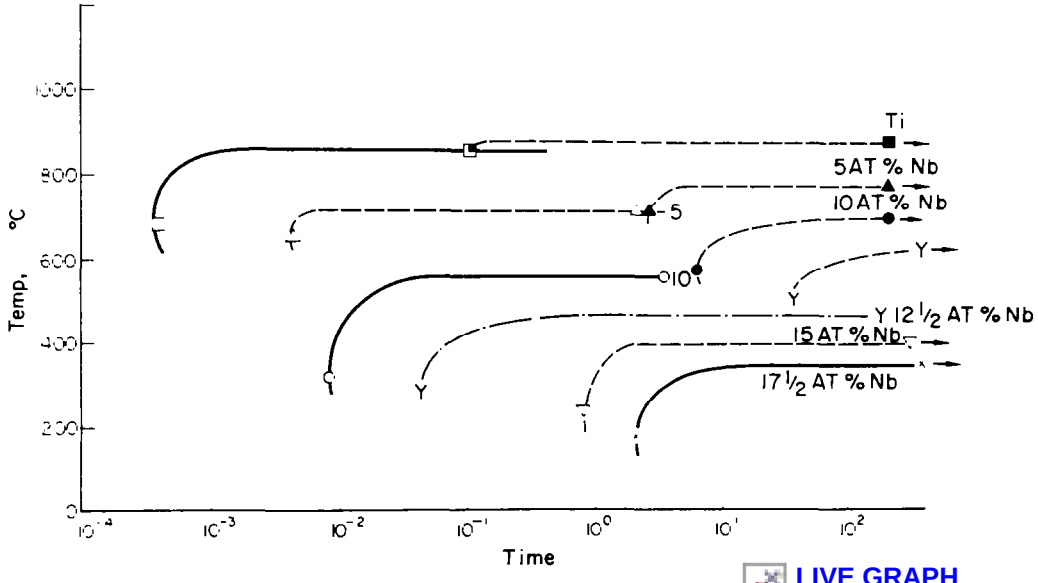
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Values on diagram are hardnesses, HV (1kgf)

SOURCE: J.W. Barton et al., "Structure and Properties of Titanium-Rich Titanium-Nickel Alloys," Trans. AIME, Vol 218, October 1960, pp 844-849

Ti-Nb Alloy

Composition: The alloys were made from high purity (90 B.H.N.) Japanese sponge titanium, reactor grade Nb sheet
Treatment: Homogenized for 24 h at 1000°C (1832°F) in vacuo, furnace cooled, annealed and cold rolled



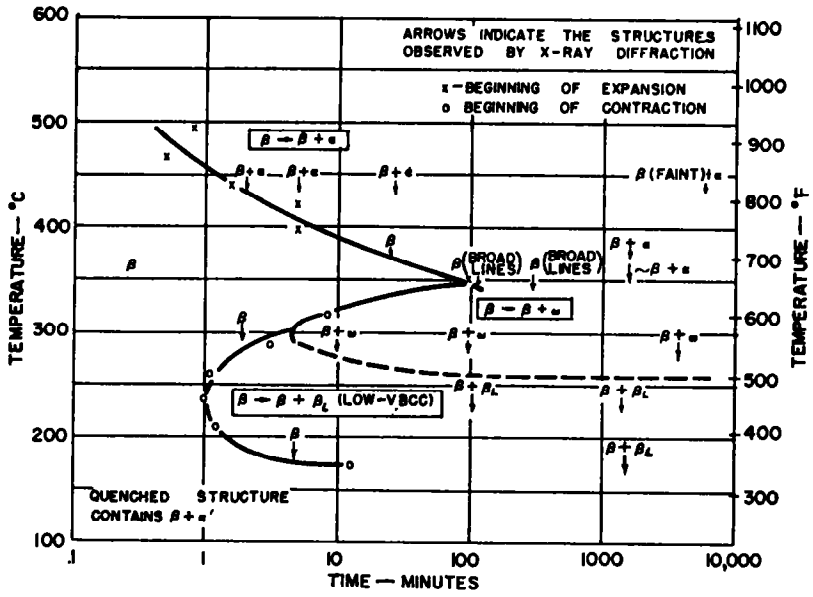
LIVE GRAPH
Click here to view

Time-temperature-transformation diagrams
Martensite formation in Ti-Nb alloys: Pure Ti, 5%, 10%, 12.5, 15% and 17.5% (atomic %) Nb

SOURCE: K.S. Jepson, A.R.G. Brown, J.A. Gray, "The Effect of Cooling Rate on the Beta Transformation in Titanium-Niobium and Titanium-Aluminium Alloys," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, eds., Pergamon Press, Oxford, 1970, pp 677-690

Ti-V-Al Alloys

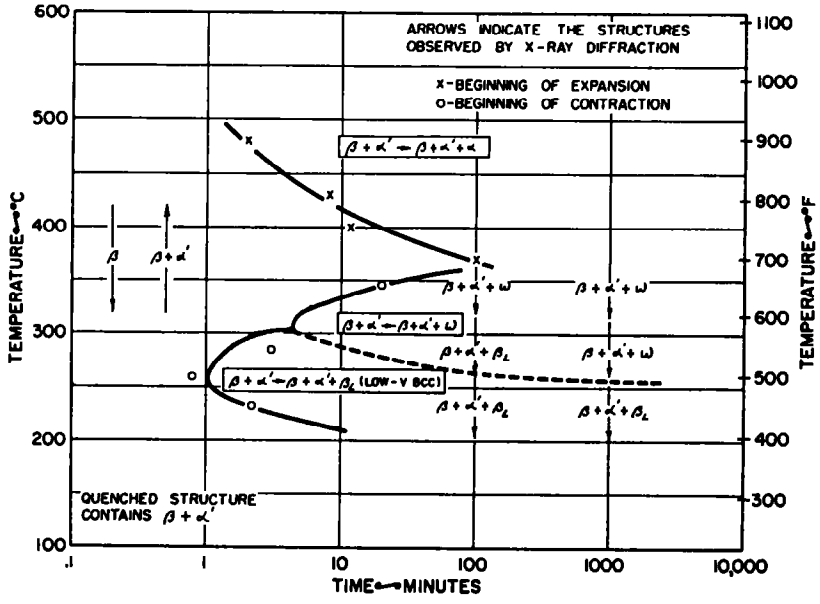
Composition: Ti - 16.0% V - 2.5% Al
Treatment: Solution treated at 830°C (1526°F) for 20 min



Time-temperature-transformation diagram
Quenched to isothermal transformation temperature

LIVE GRAPH
Click here to view

Composition: Ti - 16.0% V - 2.5% Al
Treatment: Solution treated at 830°C (1526°F) for 20 min



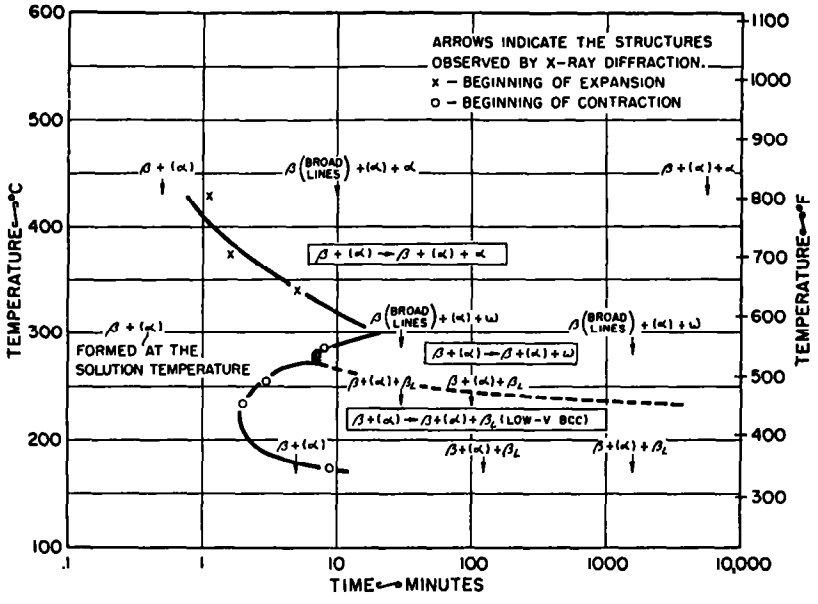
Time-temperature-transformation diagram
Quenched in water, reheated and aged

LIVE GRAPH
Click here to view

SOURCE: E.L. Harmon and A.R. Troiano, "Beta Transformation Characteristics of Titanium Alloyed with Vanadium and Aluminum," Trans. ASM, Vol 53, 1961, pp 43-53

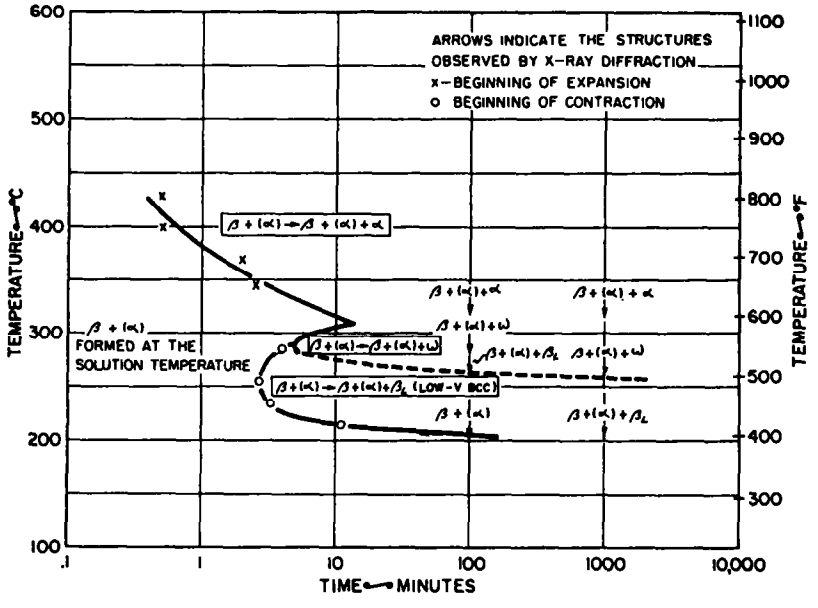
Ti-V-Al Alloys

Composition: Ti - 16.0% V - 2.5% Al
Treatment: Solution treated at 740°C (1364°F) for 20 min



Time-temperature-transformation diagram
Quenched to isothermal transformation temperature

Composition: Ti - 16.0% V - 2.5% Al
Treatment: Solution treated at 740°C (1364°F) for 20 min



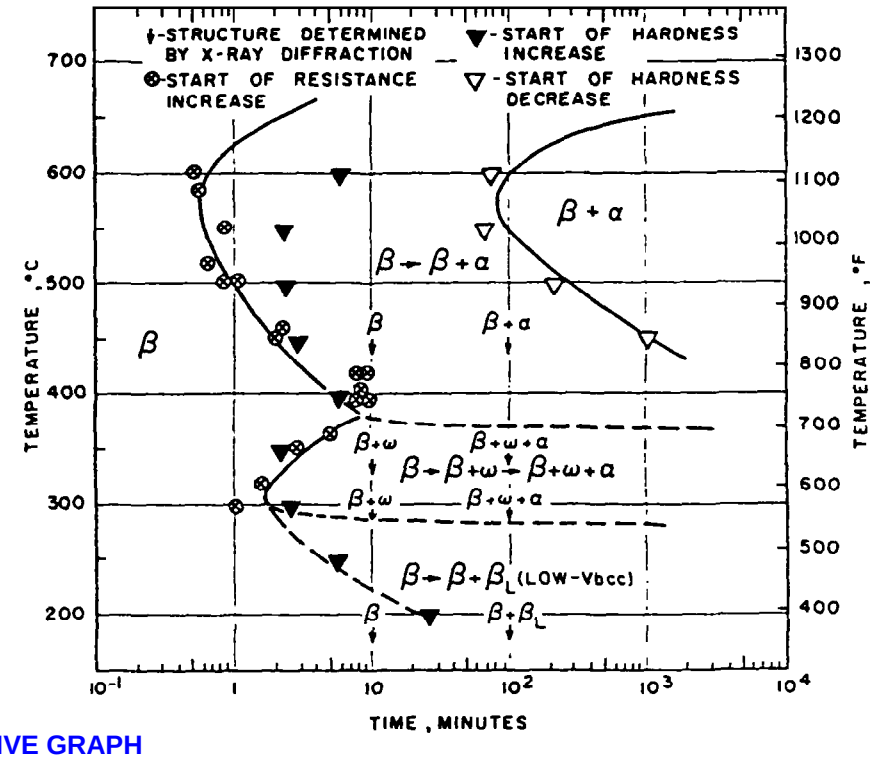
Time-temperature-transfomation diagram
Quenched in water, reheated and aged

SOURCE: E.L. Harmon and A.R. Troiano, "Beta Transformation Characteristics of Titanium Alloyed with Vanadium and Aluminum," Trans. ASM, Vol 53, 1961, pp 43-53

Ti-V-Al Alloys

Composition: Ti - 16.0% V - 2.5% Al

Treatment: Solution annealed at 900°C (1652°F) for 20 min before isothermal transformation



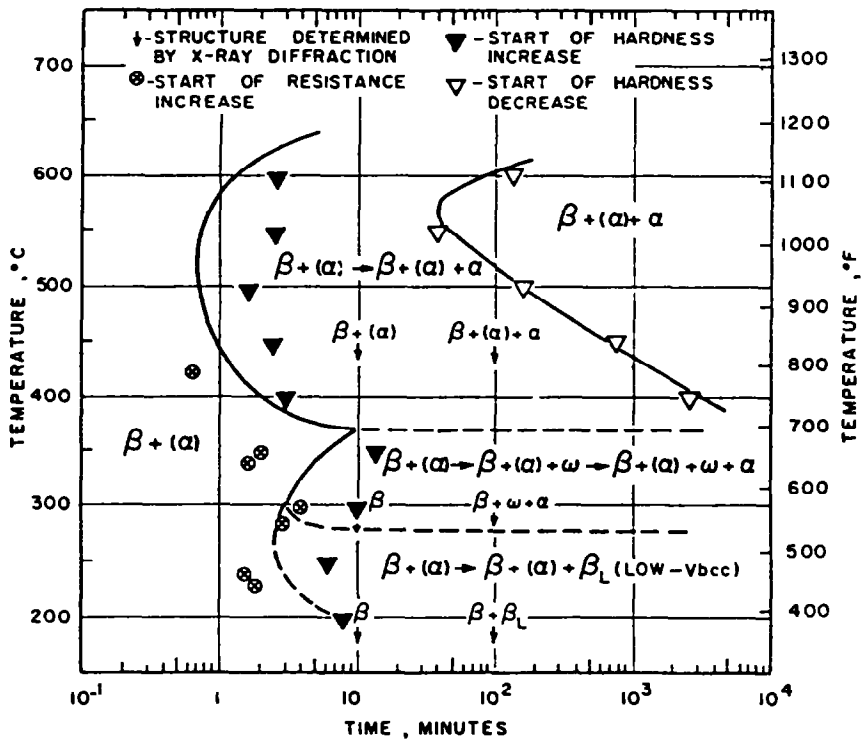
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: L.E. Tanner, "The Isothermal Transformation of Ti-2.5 Al-16V and Ti-4Al-3Mo-1V," Trans. AIME, Vol 221, pp 74-83

Ti-V-Al Alloys

Composition: Ti - 16.0% V - 2.5% Al
Treatment: Solution annealed at 740°C (1364°F) for 1 h, water quenched and reheated to aging temperatures



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

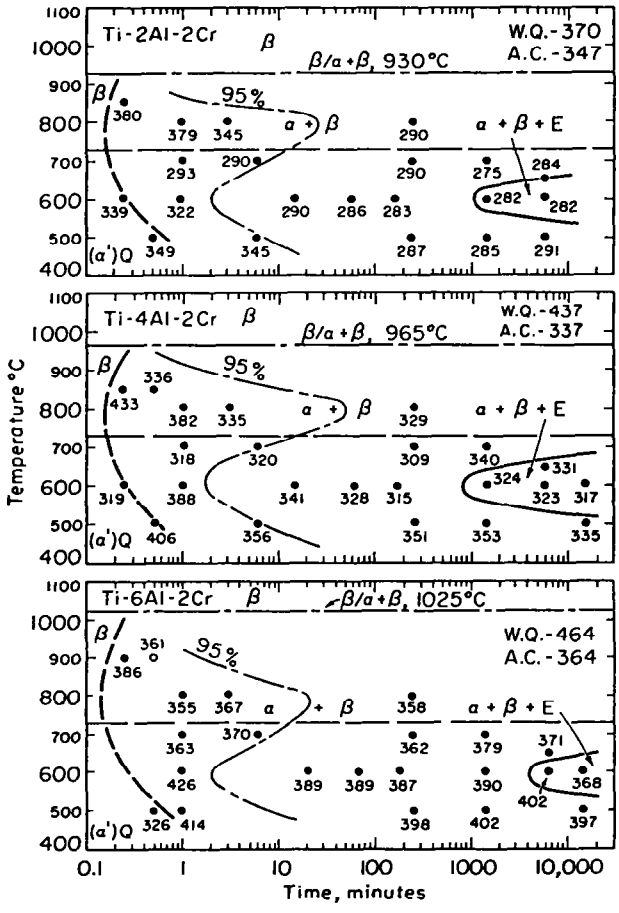
SOURCE: L.E. Tanner, "The Isothermal Transformation of Ti-2.5 Al-16V and Ti-4Al-3Mo-1V," Trans. AIME, Vol 221, pp 74-83

Ti-Al-Cr Alloys

Composition: Ti - 2.0% Al - 2.0% Cr

Composition: Ti - 4.0% Al - 2.0% Cr

Composition: Ti - 6.0% Al - 2.0% Cr



LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the diagrams
Time-temperature-transformation diagrams

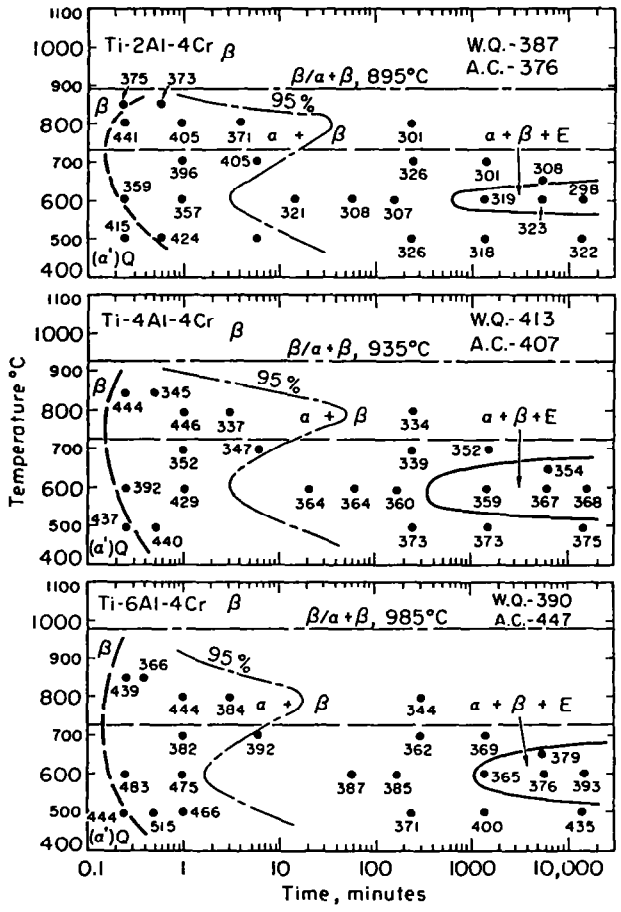
SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Chromium Alloys," Trans. ASM, Vol 46, 1954, pp 609-639

Ti-Al-Cr Alloys

Composition: Ti - 2.0% Al - 4.0% Cr

Composition: Ti - 4.0% Al - 4.0% Cr

Composition: Ti - 6.0% Al - 4.0% Cr



LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the diagrams
Time-temperature-transformation diagrams

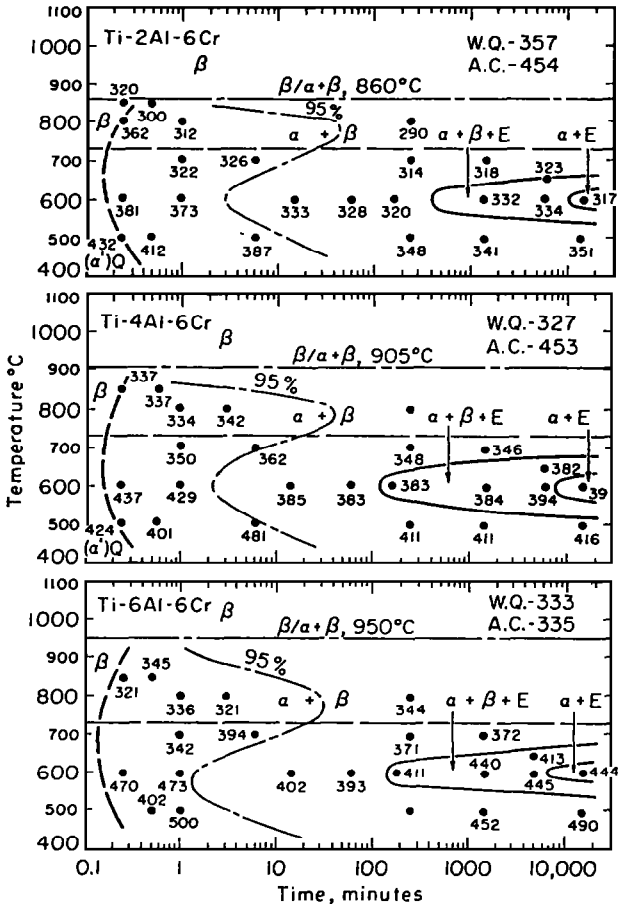
SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Chromium Alloys," Trans. ASM, Vol 46, 1954, pp 609-639

Ti-Al-Cr Alloys

Composition: Ti - 2.0% Al - 6.0% Cr

Composition: Ti - 4.0% Al - 6.0% Cr

Composition: Ti - 6.0% Al - 6.0% Cr



LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the diagrams
Time-temperature-transformation diagrams

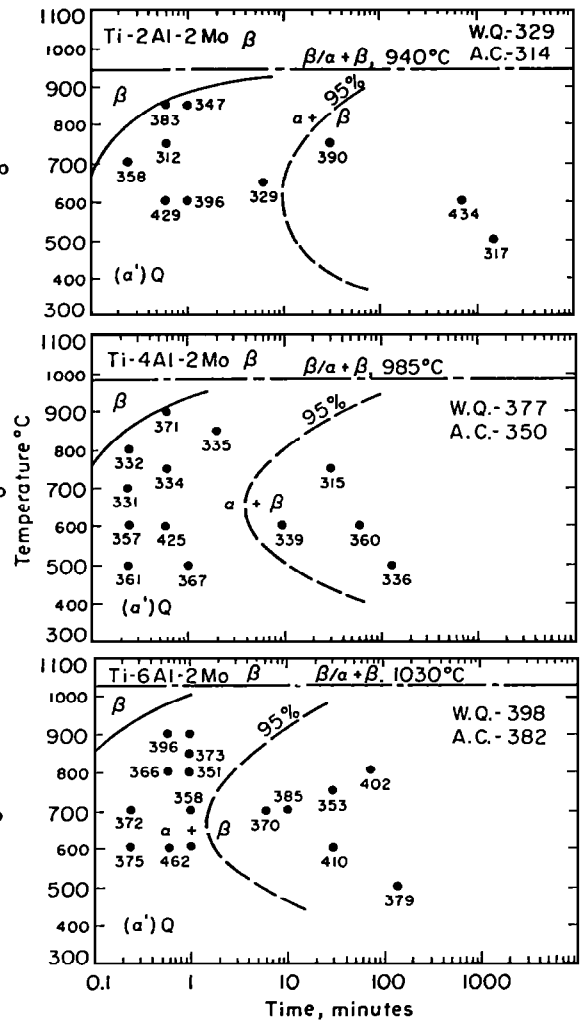
SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Chromium Alloys," Trans. ASM, Vol 46, 1954, pp 609-639

Ti-Al-Mo Alloys

Composition: Ti - 2.0% Al - 2.0% Mo

Composition: Ti - 4.0% Al - 2.0% Mo

Composition: Ti - 6.0% Al - 2.0% Mo



LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the diagrams
Time-temperature-transformation diagrams

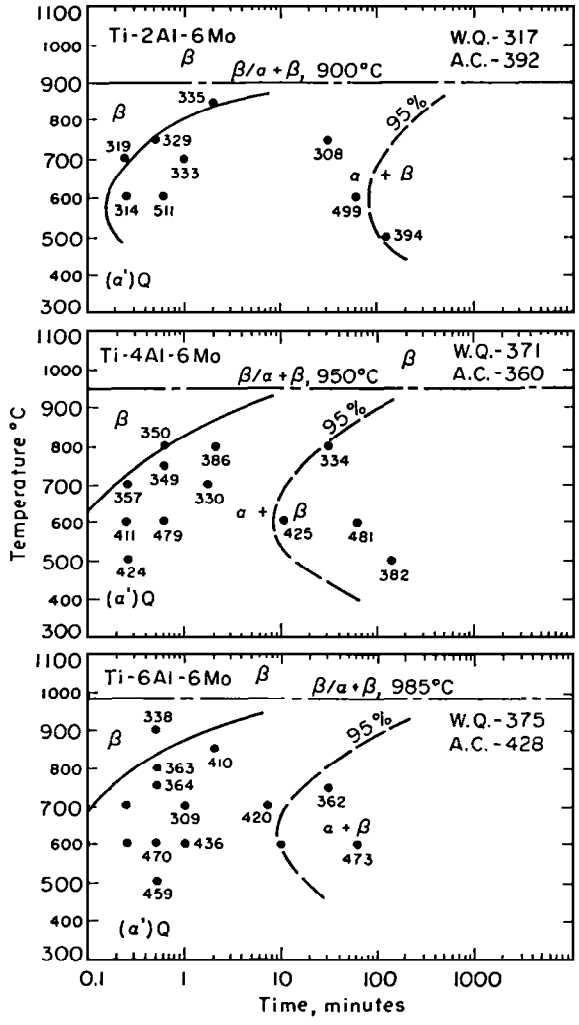
SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 587-608

Ti-Al-Mo Alloys

Composition: Ti - 2.0% Al - 6.0% Mo

Composition: Ti - 4.0% Al - 6.0% Mo

Composition: Ti - 6.0% Al - 6.0% Mo



LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the Time-temperature-transformation diagrams

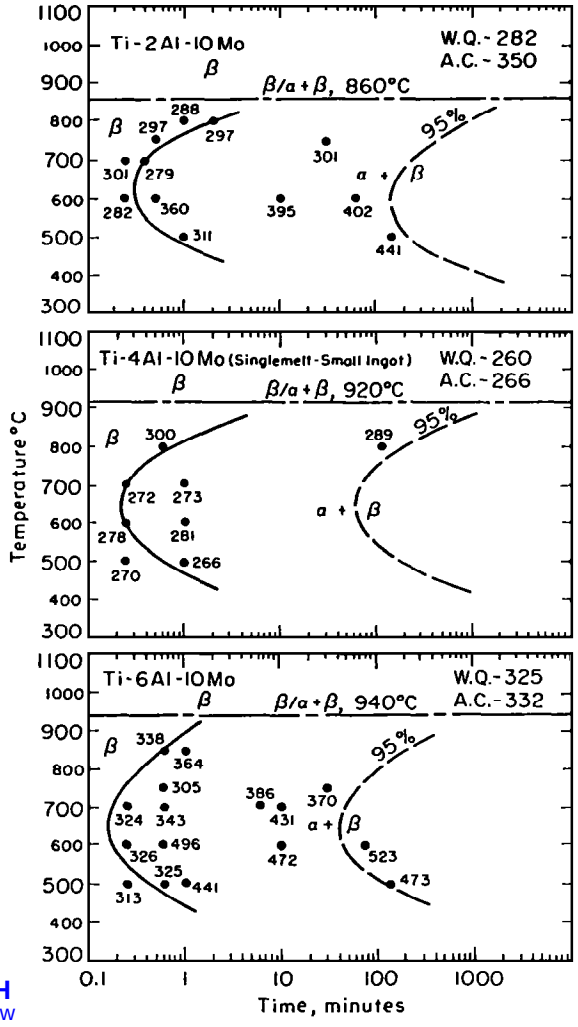
SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 587-608

Ti-Al-Mo Alloys

Composition: Ti - 2.0% Al - 10.0% Mo

Composition: Ti - 4.0% Al - 10.0% Mo
Single melt, small ingot

Composition: Ti - 6.0% Al - 10.0% Mo



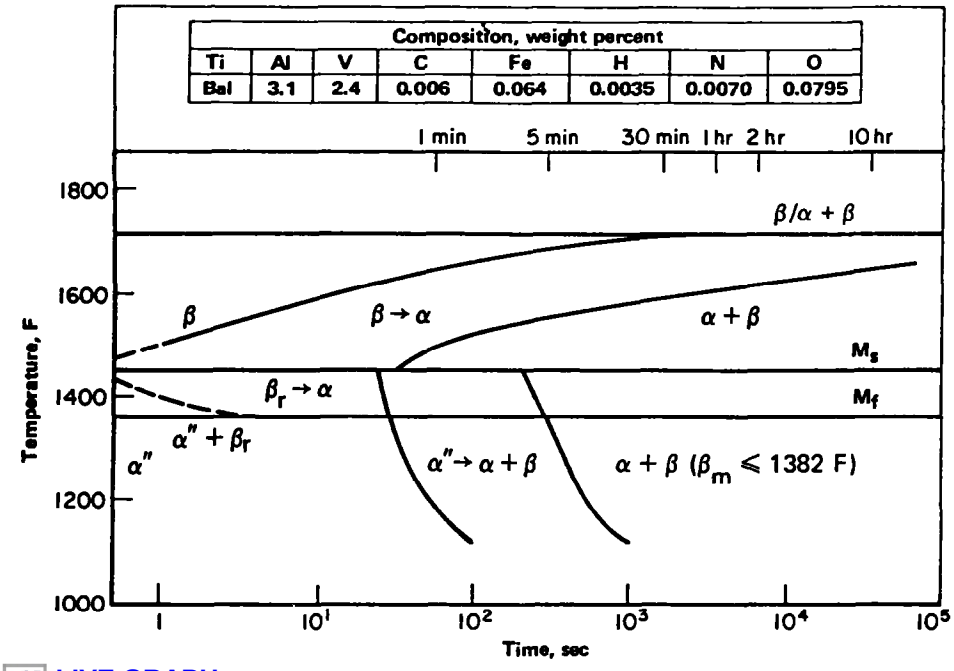
LIVE GRAPH
Click here to view

Vickers hardness (30 kg load) numbers are shown on the diagrams
Time-temperature-transformation diagrams

SOURCE: H.D. Kessler and M. Hansen, "Transformation Kinetics and Mechanical Properties of Titanium-Aluminum-Molybdenum Alloys," Trans. ASM, Vol 46, 1954, pp 587-608

Ti-3Al-2.5V

Composition: Ti - 3.1% Al - 2.4% V - 0.006% C - 0.064% Fe



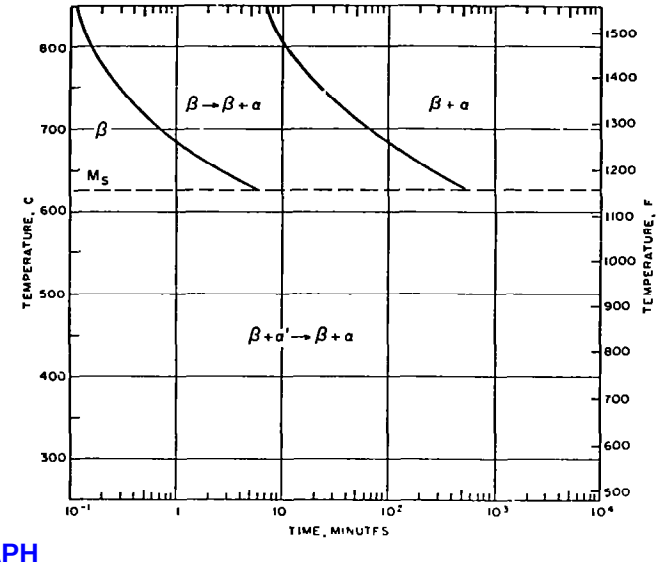
LIVE GRAPH
Click here to view

Isothermal transformation diagram

SOURCE: T. Anderson, "Isothermal and Continuous Cooling Transformations of Beta Phase in the Titanium Alloy Ti-3Al-2.5V," Scandinavian Journal of Metallurgy 2, 1973, pp 251-256, as published in Aerospace Structural Metals Handbook for Titanium, March 1980

Ti-Al-V Alloys

Composition: Ti-6.0% Al - 4.0% V
Solution annealed at 1020°C (1868°F), and quenched directly to reaction temperatures



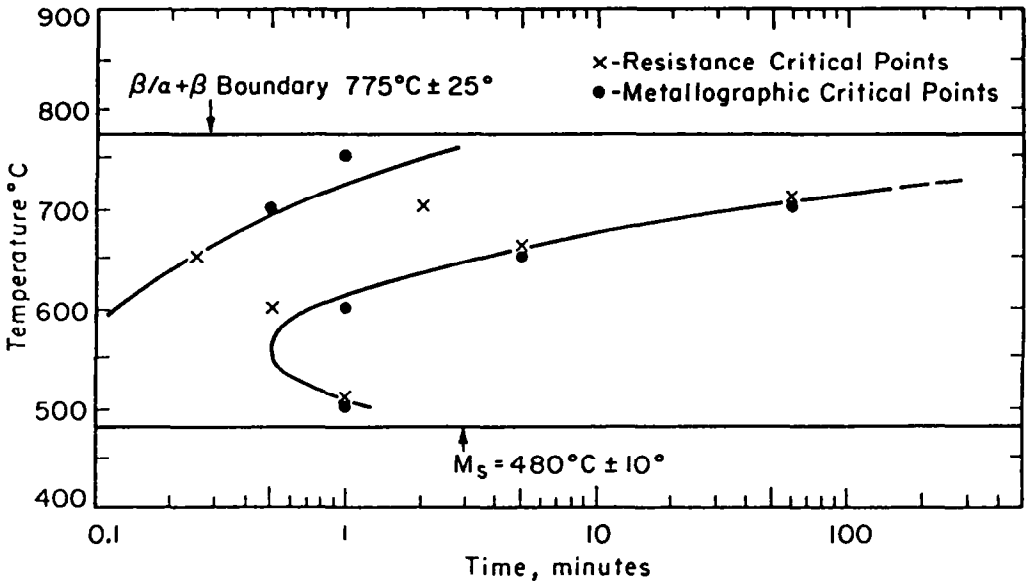
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: L.E. Tanner, "Time-Temperature-Transformation Diagrams of the Titanium Sheet-Rolling-Program Alloys," DMIC Report 46G, Battelle Memorial Institute, Columbus OH, October 1959

Ti-Cr-Mo Alloys

Composition: Ti - 4.0% Cr - 2.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



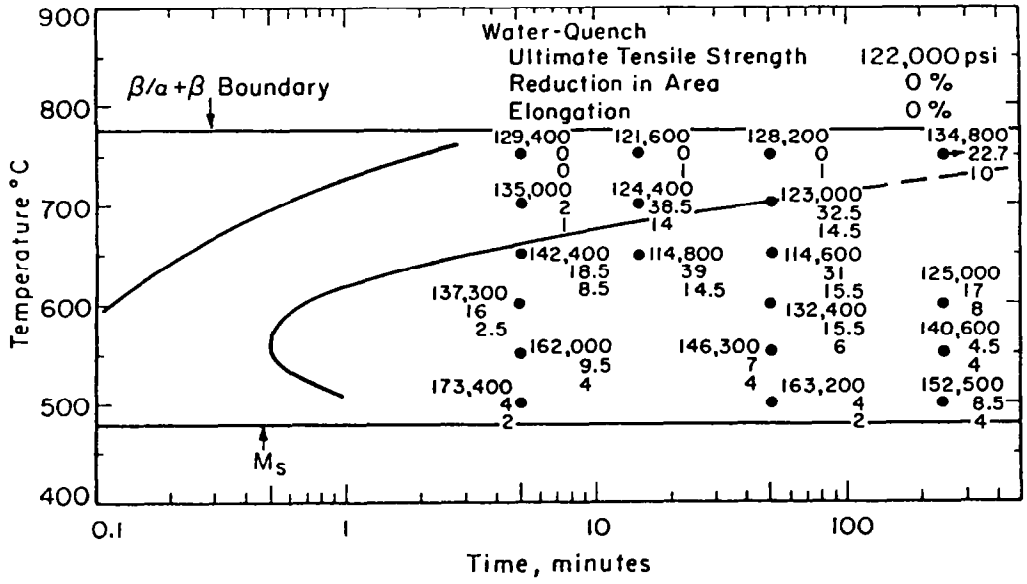
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: A.W. Goldenstein and W. Rostoker, "Relationship Between Heat Treatment, Structure, and Mechanical Properties of a Titanium Alloy Containing 4% Cr and 2% Mo," Trans. ASM, Vol 49, 1957, pp 315-327

Ti-Cr-Mo Alloys

Composition: Ti - 4.0% Cr - 2.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



LIVE GRAPH
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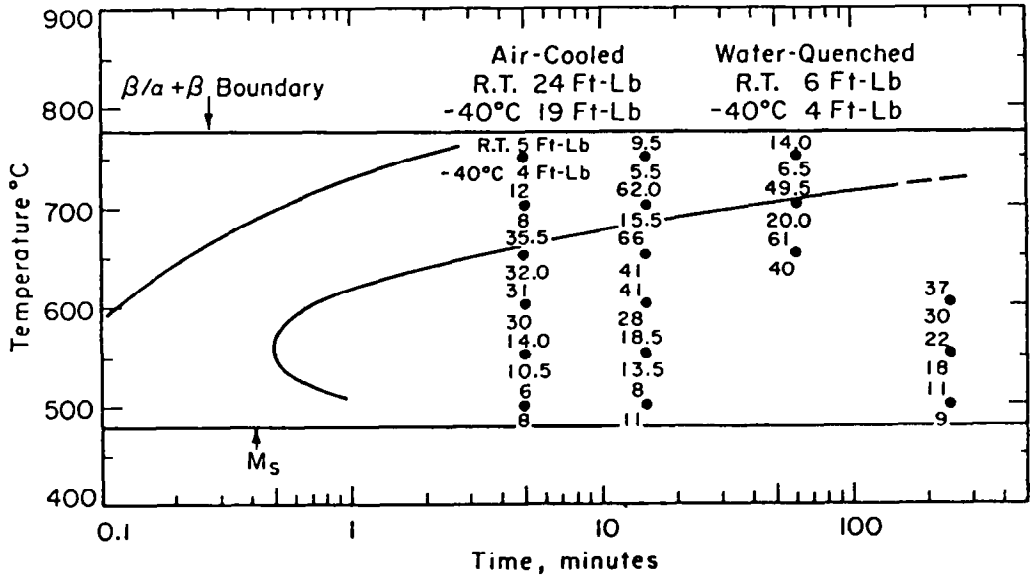
Time-temperature-transformation diagram
Tensile properties

Composition: Ti - 4.0% Cr - 2.0% Mo
Treatment: Solution treated at 1000°C (1832°F) for 20 min



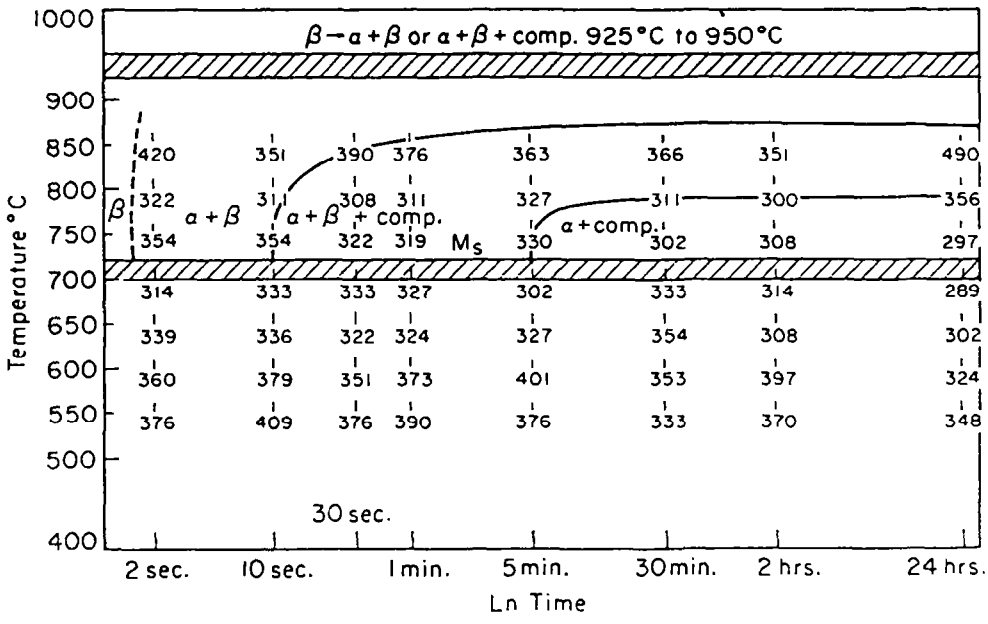
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Charpy V-notch impact strength at -40°C (-4°F)

SOURCE: A.W. Goldenstein and W. Rostoker, "Relationship Between Heat Treatment, Structure, and Mechanical Properties of a Titanium Alloy Containing 4% Cr and 2% Mo," Trans. ASM, Vol 49, 1957, pp 315-327

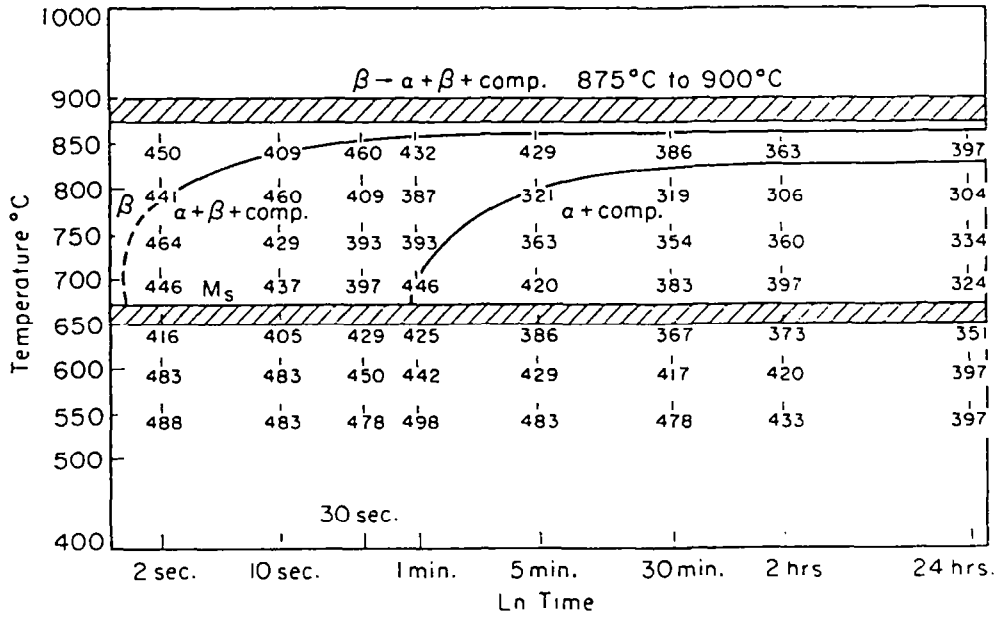
Ti-Cu-Al Alloys

Composition: Ti - 5.0% Cu - 3.0% Al



Time-temperature-transformation diagram

Composition: Ti - 8.0% Cu - 3.0% Al

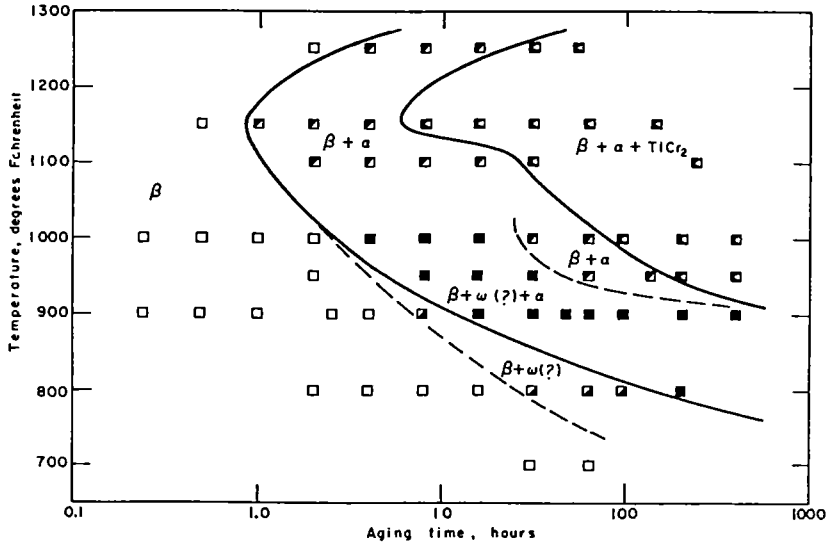


Time-temperature-transformation diagram

SOURCE: R.F. Bunshah and H. Margolin, "Microstructure and Mechanical Properties of Ti-Cu-Al and Ti-Cu-Al-Sn Alloys," Trans. ASM, Vol 51, 1959, pp 961-980

Ti-V-Cr-Al Alloys

Composition: Ti - 12.8% V - 11.1% Cr - 4.1% Al
Treatment: Solution treated at 760°C (1400°F) for 1 h, air cooled, reheated and aged isothermally



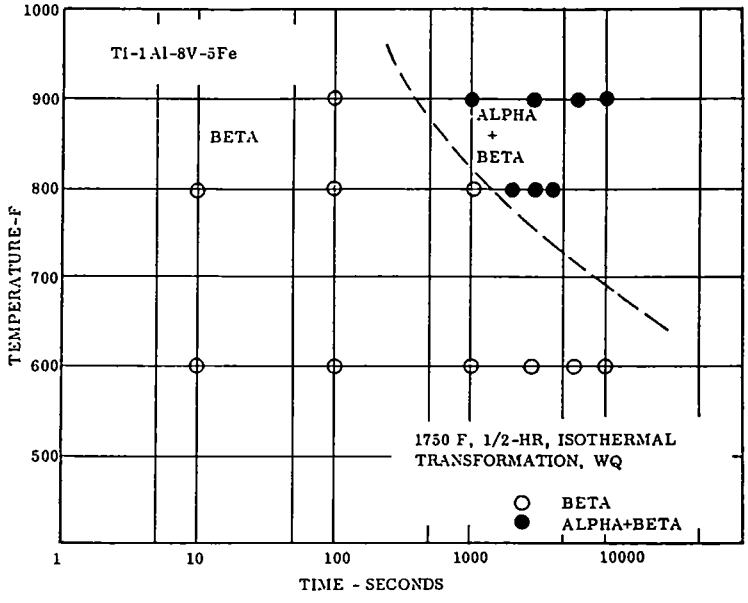
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: R.A. Rawe et al., "The Aging Characteristics of the Ti-13V-11Cr-4Al Allloy, Trans. AIME, Vol 218, 1960, pp 821-825

Ti-1Al-8V-5Fe

Composition: Ti - 0.8-1.8% Al - 7.5-8.5% V - 4.0-6.0% Fe - max 0.05% C



LIVE GRAPH
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Isothermal transformation diagram

SOURCE: S.R. Seagle, "Initial Work on Isothermal Transformation Studies of MST 185," Mallory-Sharon Titanium Corp., Research Report No. 1000R261, Project No. 25004, February 1958, as published in Aerospace Structural Metals Handbook for Titanium, March 1968

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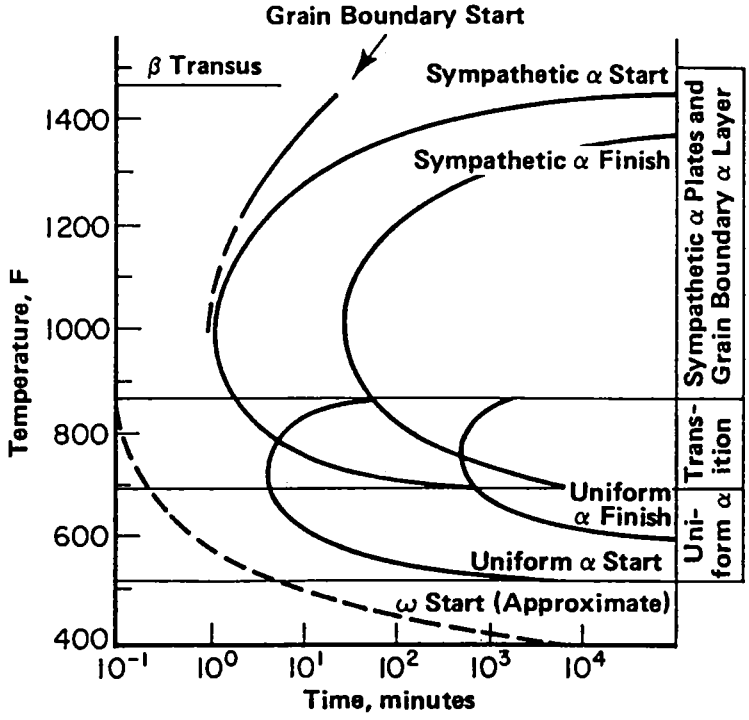
Ti-10-2-3
Composition: Ti - 10% V - 2% Fe- 3% Al
Treatment: Beta solution treated, quenched, and rapidly heated to the aging temperature

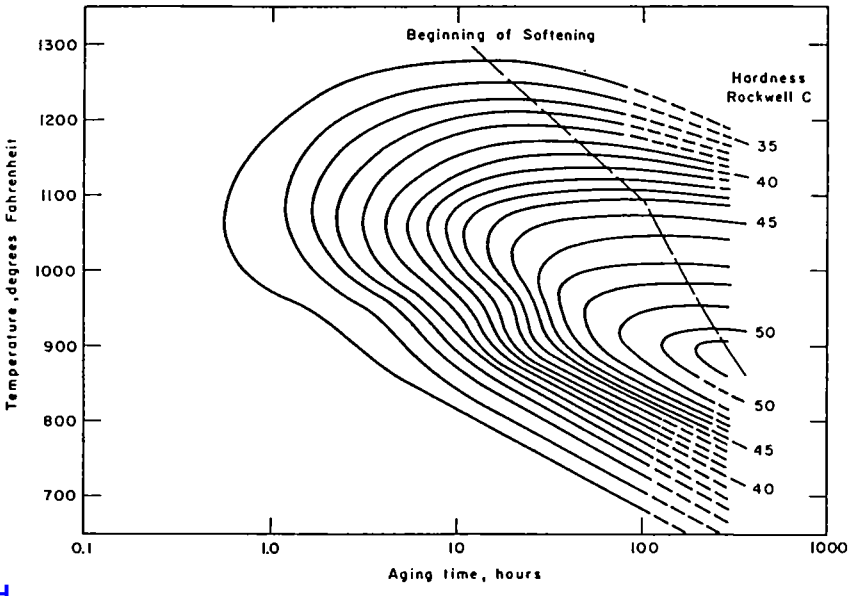


LIVE GRAPH
Click here to view

Schematic time-temperature-aging diagram

SOURCE: T.W. Duerig, "Phase Transformations and properties of Ti-10V-2Fe-3Al," PhD Thesis, Department of Metallurgy and Materials Science, Carnegie-Mellon University, Pittsburgh PA, as published in Aerospace Structural Metals Handbook for Nonferrous Alloys, December 1981

Ti-V-Cr-Al Alloys
Composition: Ti - 12.8% V - 11.1% Cr - 4.1% Al
Treatment: Solution treated at 760°C (1400°F) for 1 h, air cooled, reheated and aged isothermally



LIVE GRAPH
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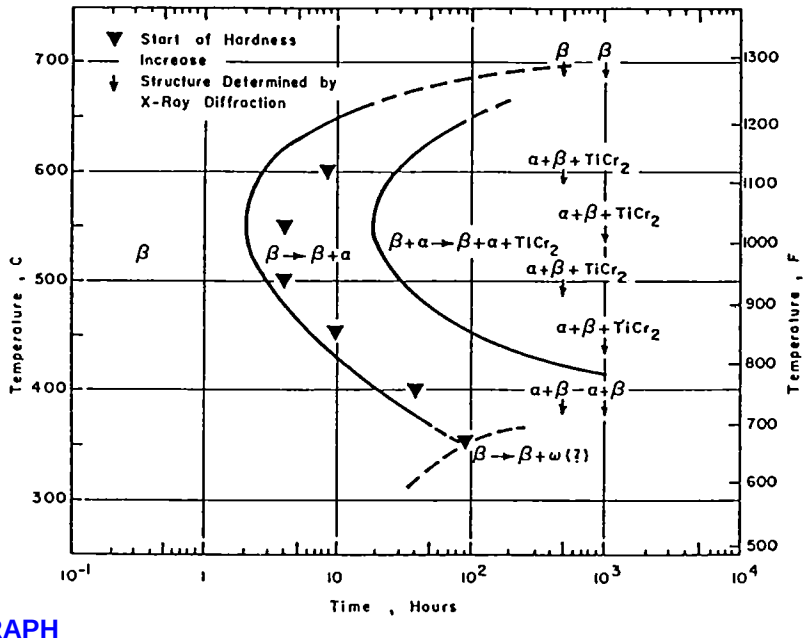
Time-temperature-transformation diagram
Iso-hardness

SOURCE: R.A. Rawe et al., "The Aging Characteristics of the Ti-13V-11Cr-4Al Alloy, Trans. AIME, Vol 218, 1960, pp 821-825

Ti-V-Cr-Al Alloys

Composition: Ti - 13.6% V - 10.5% Cr - 2.9% Al
Treatment: Solution treated at 788°C (1450°F) for 30 min, water quenched and reheated to the aging temperature



LIVE GRAPH
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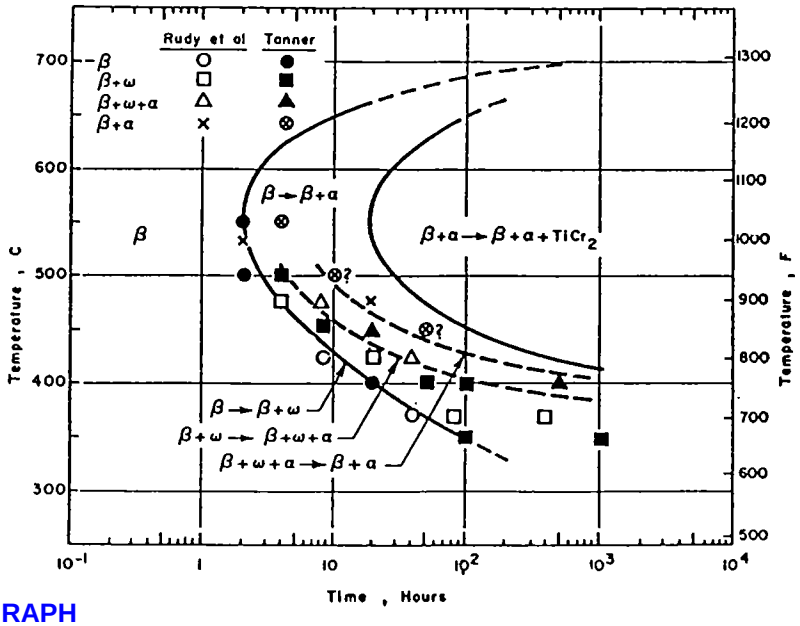
Time-temperature-transformation diagram by Tanner

Composition: Ti - 13.6% V - 10.5% Cr - 2.9% Al
Treatment: Solution treated at 788°C (1450°F) for 30 min, water quenched and reheated to the aging temperature



LIVE GRAPH
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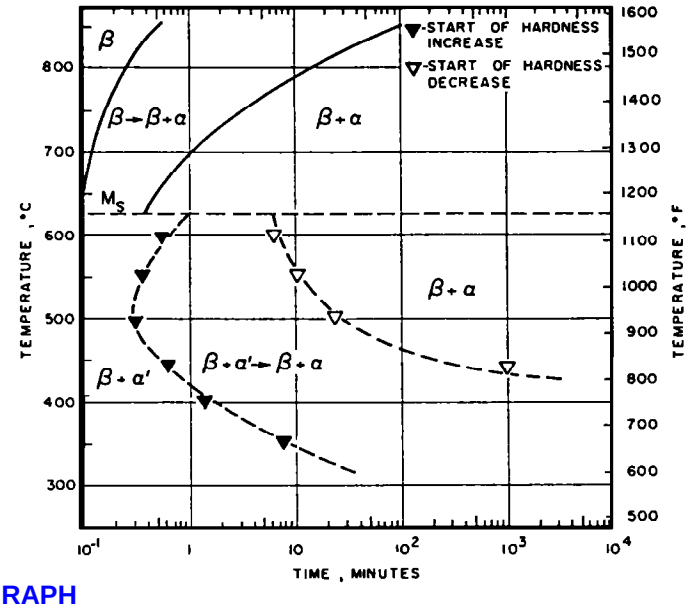
Time-temperature-transformation diagram
Modified Tanner diagram based on work by Rudy et al.

SOURCE: L.E. Tanner, "The Isothermal Transformation of Ti-13V-11Cr-3Al," Trans. ASM, Vol 53, 1961, pp 407-414 and discussion, pp 930-933

Ti-Al-Mo-V Alloys

Composition: Ti - 4.1% Al - 2.9% Mo - 1.0% V

Treatment: Solution annealed at 1020°C (1868°F) for 20 min, quenched to the reaction temperatures



LIVE GRAPH
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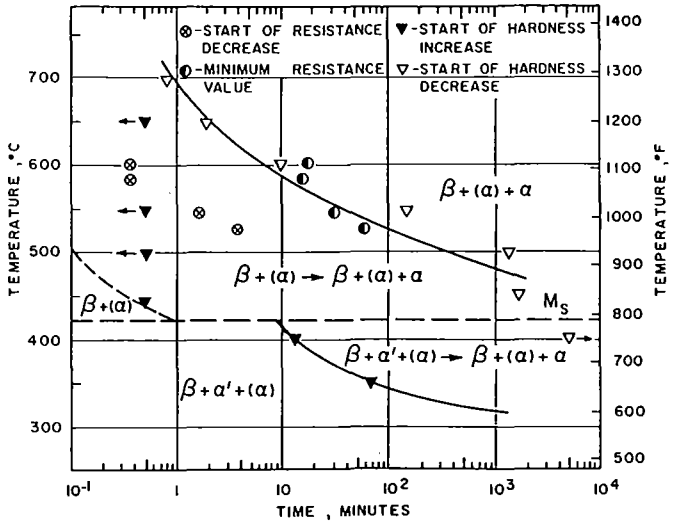
Time-temperature-transformation diagram

SOURCE: L.E. Tanner, "The Isothermal Transformations of Ti-2.5Al-16V and Ti-4Al-3Mo-1V," Trans. AIME, Vol 221, 1961, pp 74-83

Ti-Al-Mo-V Alloys

Composition: Ti - 4.1% Al - 2.9% Mo - 1.0% V
Treatmen: Solution annealed at 890°C (1634°F), water quenched and reheated to the aging temperature



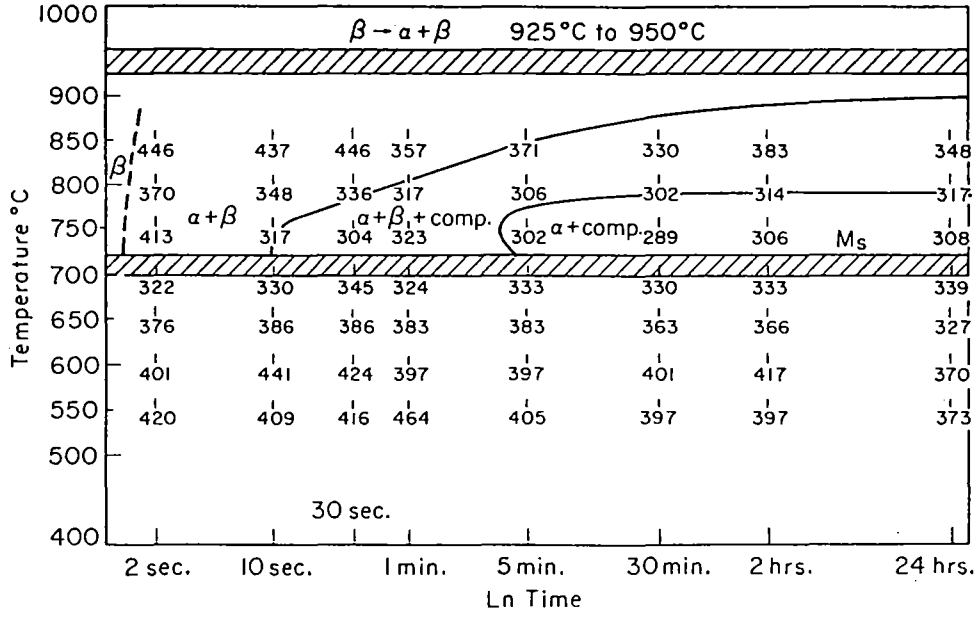
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: L.E. Tanner, "The Isothermal Transformations of Ti-2.5Al-16V and Ti-4Al-3Mo-1V," Trans. AIME, Vol 221, 1961, pp 74-83

Ti-Cu-Al-Sn Alloys

Composition: Ti - 5.0% Cu - 3.0% Al - 2.0% Sn

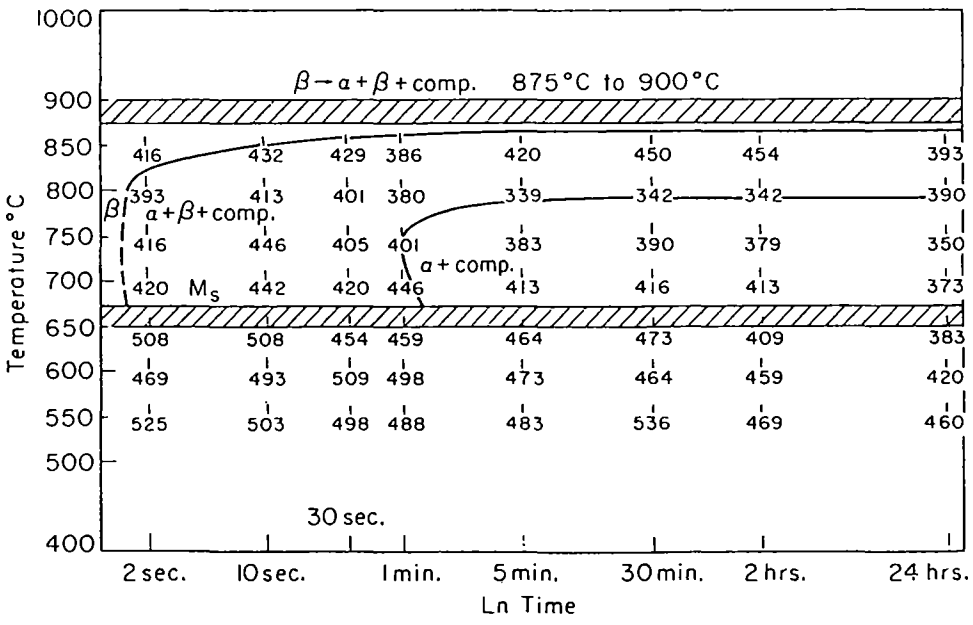


Time-temperture-transformation diagram

SOURCE: R.F. Bunshah and H. Margolin, "Microstructure and Mechanical Properties of Ti-Cu-Al and Ti-Cu-Al-Sn Alloys," Trans. ASM, Vol 51, 1959, pp 961-980

Ti-Cu-Al-Sn Alloys

Composition: Ti - 8.0% Cu - 3.0% Al - 2.0% Sn

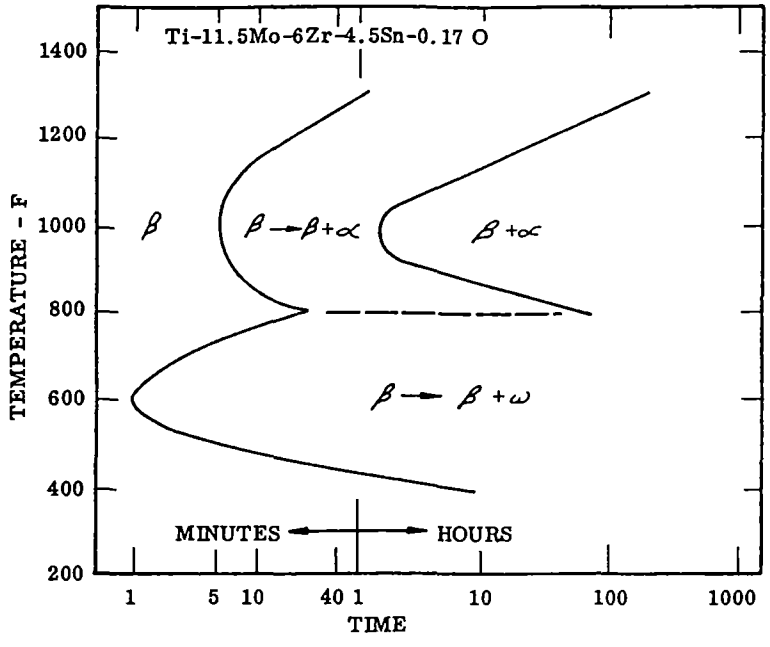


Time-temperature-transformation diagram

SOURCE: R.F. Bunshah and H. Margolin, "Microstructure and Mechanical Properties of Ti-Cu-Al and Ti-Cu-Al-Sn Alloys," Trans. ASM, Vol 51, 1959, pp 961-980

Ti-Mo-Zr-Sn Alloy : Beta III

Composition: Ti - 11.5% Mo - 6% Zr - 4.5% Sn - 0.17% O



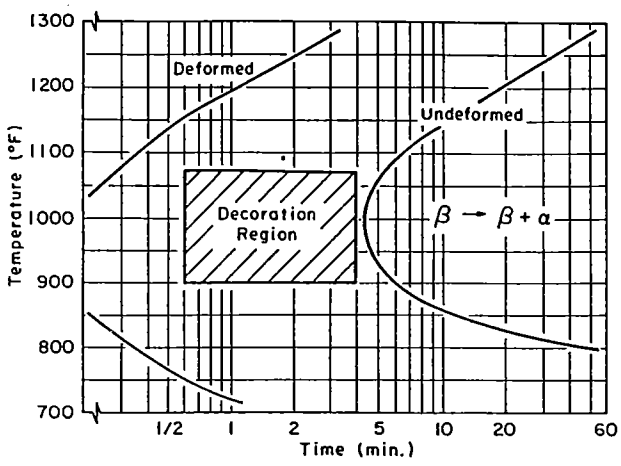
Time-temperature-transformation diagram

LIVE GRAPH
Click here to view

SOURCE: C.F. Yolton, "Time-Temperature-Transformation Characteristics of the Ti-11.5Mo-6Zr-4.5Sn Alloy," B.Sc. Thesis, School of Engineering, University of Pittsburgh, 1968, as published in Aerospace Structural Metals Handbook for Titanium, 1972

Ti-Mo-Zr-Sn Alloy : Beta III

Composition: Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn

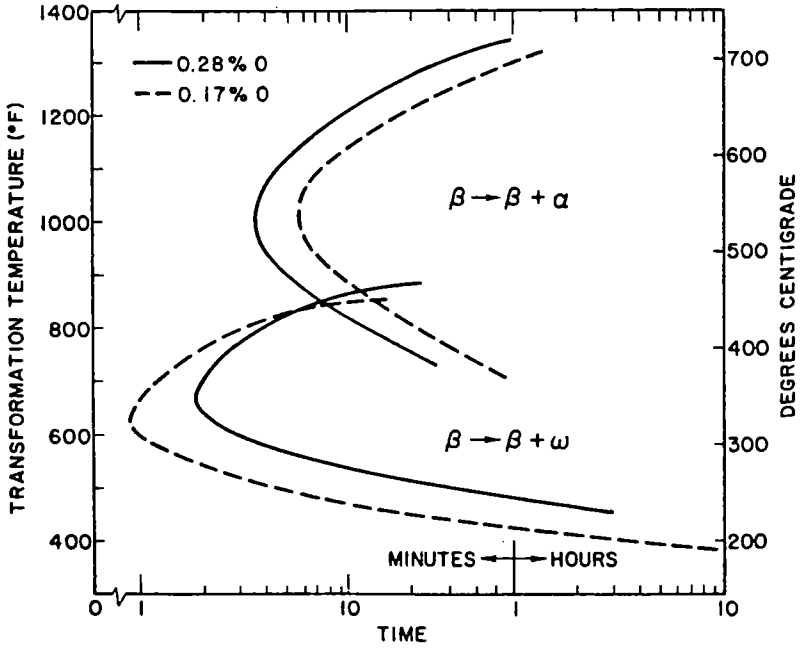


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Transformation start curves for deformed and undeformed specimens, transformation after solution treating in the beta field

SOURCE: F.H. Froes et al., "Decoration of Plastically Strained Regions in Metallic Systems," Metallography, Vol 9, 1976, pp 535-537

Composition: Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn
Treatment: Material quenched from 900°C (1650°F)



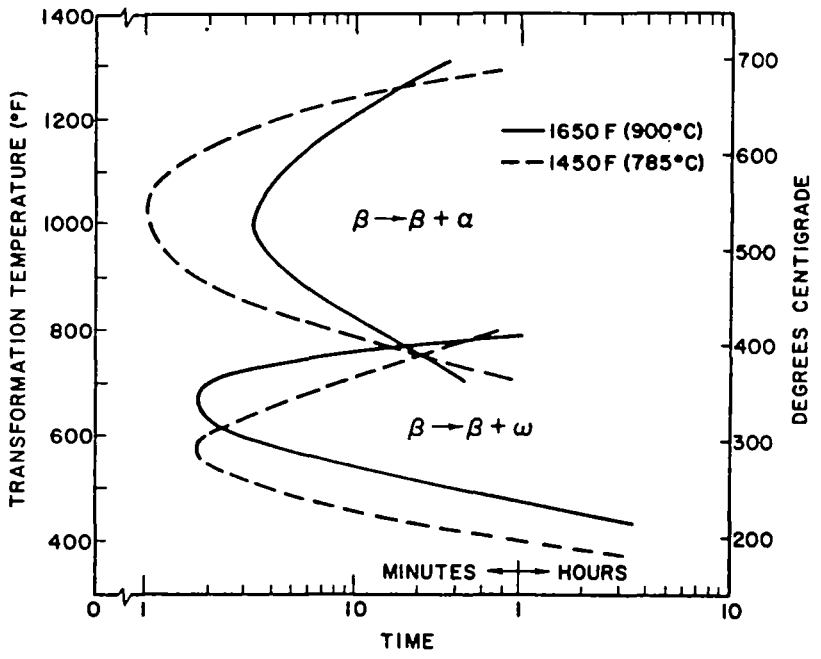
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Showing effect of oxygen on the beta - omega and beta - alpha reactions

SOURCE: F.H. Froes, et al., "The Relationship Between Microstructure and Age Hardening Response in the Metastable Beta Titanium Alloy Ti-11.5 Mo-6 Zr-4.5 Sn (Beta III)," Met. Trans. ASM, Vol 11A, January 1980, pp 21-30

Ti-Mo-Zr-Sn Alloy : Beta III

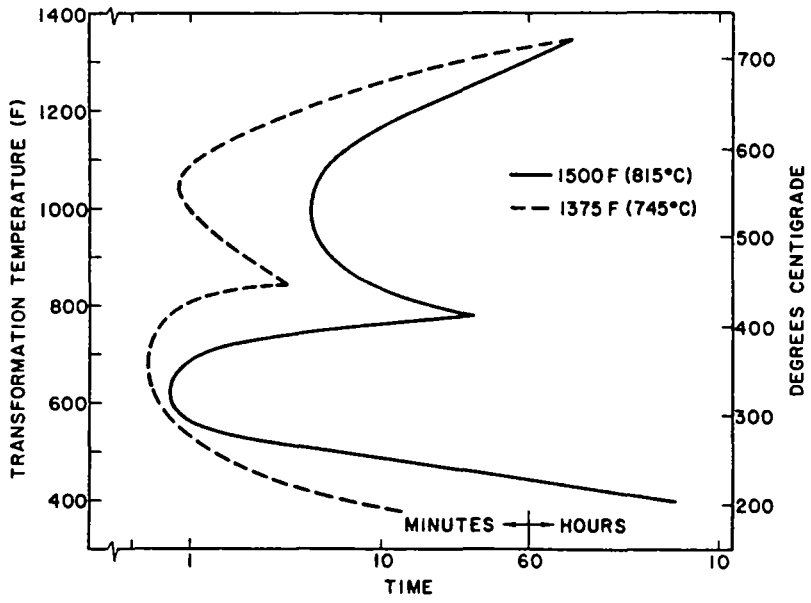
Composition: Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn - 0.28% O_2
Treatment: Solution annealed then reheated to aging temperature



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Ti - 11.5% Mo - 6.0% Zr - 4.5% Sn - 0.17% O_2
Treatment: Solution annealed, then reheated to aging temperature



LIVE GRAPH
Click here to view

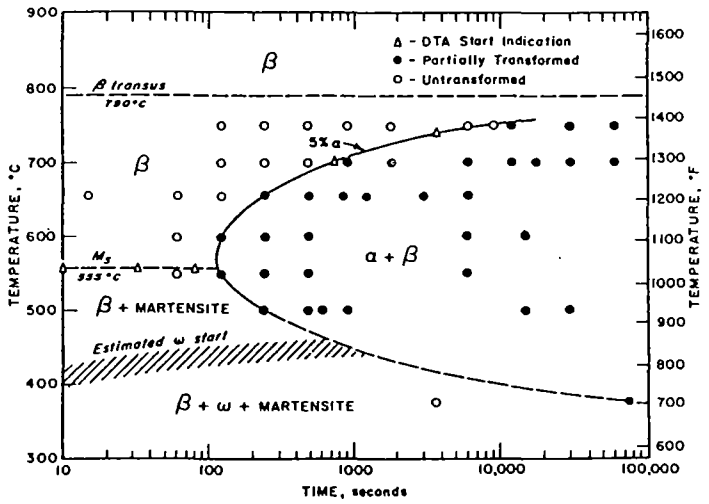
Time-temperature-transformation diagram

SOURCE: F.H. Froes, et al., "The Relationship Between Microstructure and Age Hardening Response in the Metastable Beta Titanium Alloy Ti-11.5 Mo-6 Zr-4.5 Sn (Beta III)," Met. Trans. ASM, Vol 11A, January 1980, pp 21-30

Ti-V-Fe-Al Alloy

Composition: Ti - 9.70% V - 2.08% Fe - 2.98% Al

Solutioned at 860°C (1580°F) for 240 s



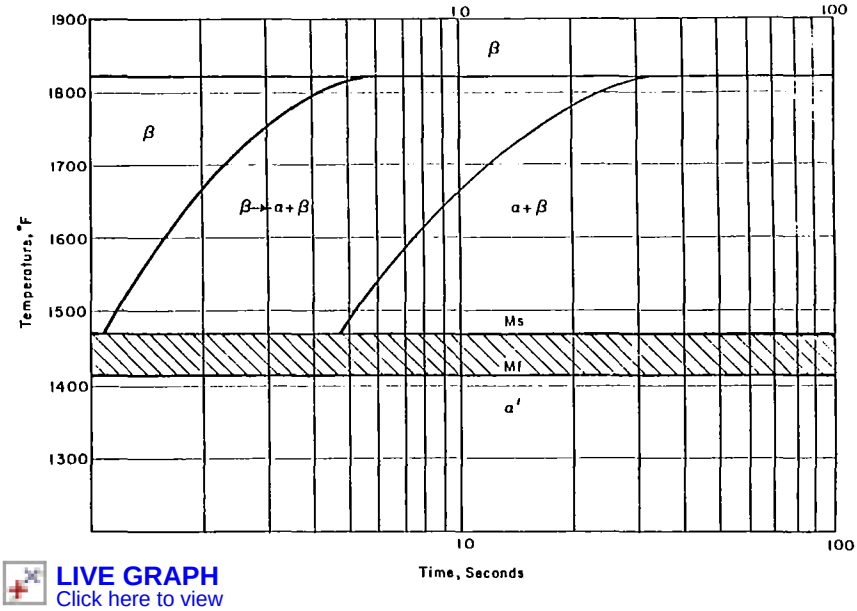
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: J.R. Toran and R.R. Biederman, "Phase Transformation Study of Ti-10V-2Fe-3Al," Titanium '80, TMS, Warrendale, 1980, pp 1491-1501

Ti-6242

Composition: Ti - 6% Al - 2% Sn - 4% Zr - 2% Mo



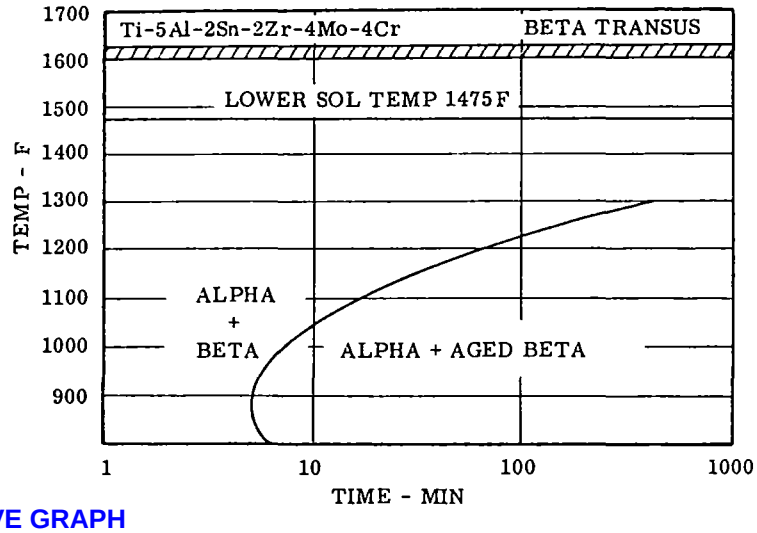
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: H.W. Rosenberg, M.B. Vordahl, D.B. Hunter, Project No. 48-8, Technical Report No. 17, TIMET, Henderson NV, January 1966

Ti-5Al-2Sn-2Zr-4Mo-4Cr : Ti-17

Composition: Ti - 4.5-5.5% Al - 1.5-2.5% Sn - 1.5-2.5% Zr - 3.5-4.5% Mo - 3.5-4.5% Cr - 0.08-0.13% O - max 0.30% Fe



LIVE GRAPH
Click here to view

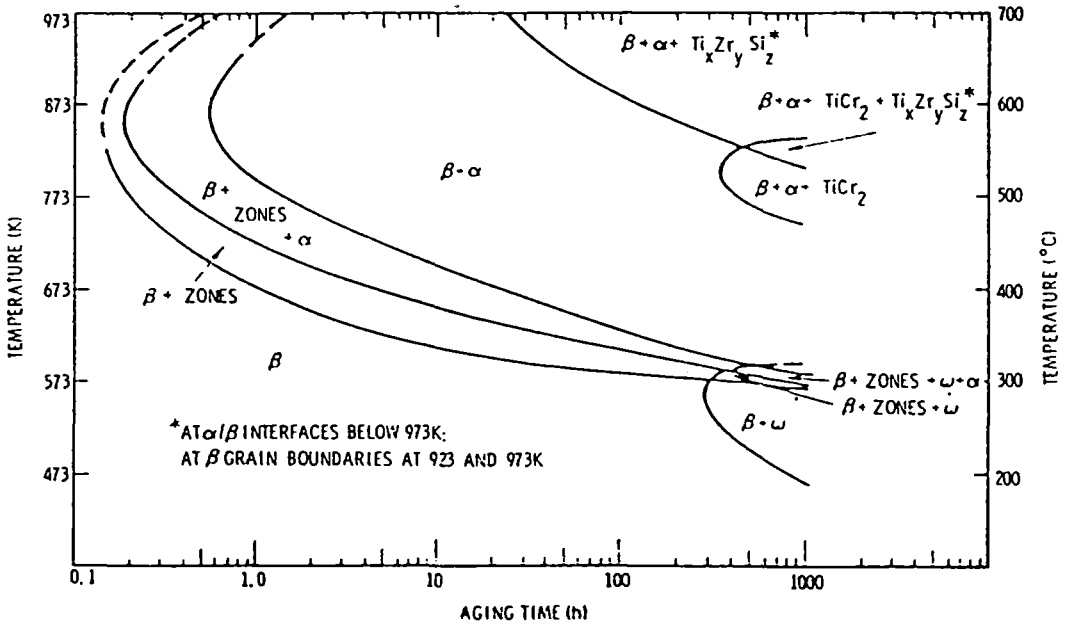
Isothermal transformation diagram

SOURCE: General Electric Co., "Ti-17 Alloy Processing and Properties," AEG-700, January 1973, as published in Aerospace Structural Metals Handbook for Titanium, September 1976

Ti-Al-V-Cr-Mo-Zr Alloys

Composition: Ti - 3.4% Al - 8.3% V - 5.8% Cr - 4.2% Mo - 3.9% Zr

Treatment: Solution treated, air quenched and aged



LIVE GRAPH
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Time-temperature-transformation diagram

SOURCE: T.J. Headley and H.J. Rack, "Phase Transformations in Ti-3Al-8V-6Cr-4Zr-4Mo," Met. Trans. ASM, Vol 10A, 1979, pp 909-920

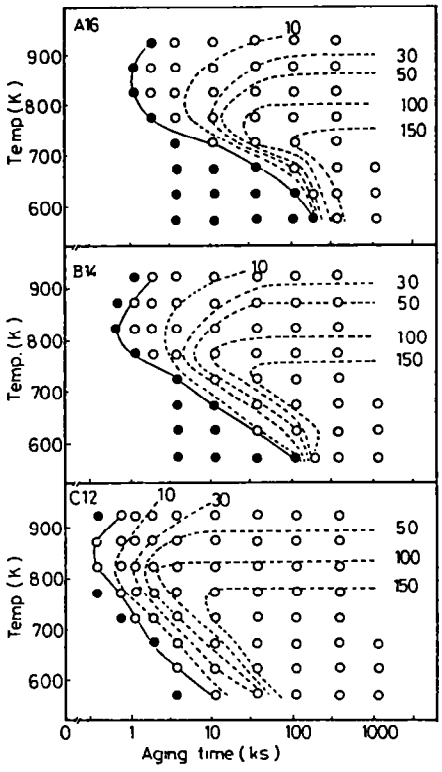
Ti-V-Cr-Sn-Al Alloys

Treatment: Alloys solutioned after beta recrystallization

Composition: Ti - 14.52% V - 3.04% Cr - 2.90% Sn - 3.04% Al

Composition: Ti - 13.23% V - 2.47% Cr - 3.05% Sn - 3.19% Al

Composition: Ti - 11.76% V - 2.28% Cr - 3.03% Sn - 3.49% Al



(●), (○): Alpha precipitation was observed and not observed through optical microscope, respectively.

(——): Alpha phase was detected through X-ray diffraction analysis.

(- - - -): Dotted line shows equal hardness increase with aging from solution-treated condition.

Figures beside lines indicate the amount of hardness increase, respectively.

LIVE GRAPH
Click here to view

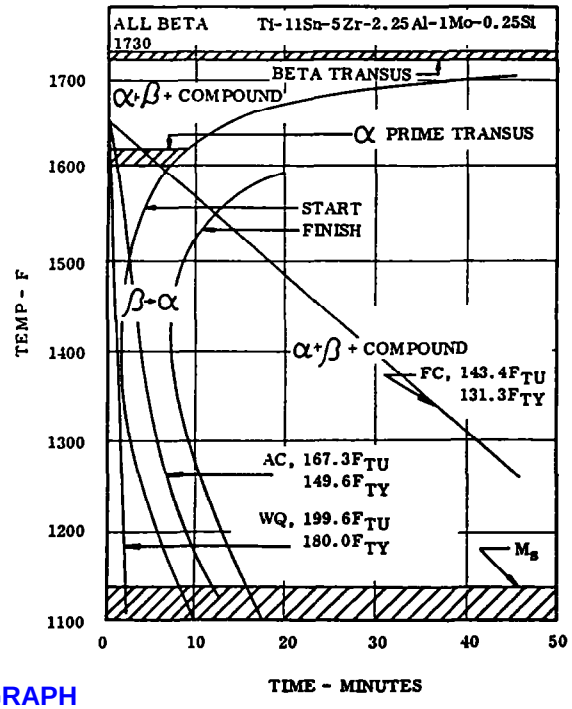
Time-temperature-transformation diagram
Lines show the increase in Vickers hardness with aging

SOURCE: N. Niwa et al., "Effects of Chemical Composition on the Heat-Treatment Response of Ti-15V-3Cr-3Sn-3Al Based Beta Titanium Alloys," ISIJ International, Vol 30, 1990, pp 773-779

Ti-11Sn-5Zr-2.5Al-1Mo-0.25Si : Ti-679

Composition: Ti - 10.50-11.50% Sn - 4.00-6.00% Zr - 2.00-2.50% Al - 0.80-1.20% Mo - 0.15-0.27% Si - max 0.12% Fe - max 0.04% C

Treatment: Solution treated, and aged at 499°C (930°F) for 24 h, air cooled (for test data listed)



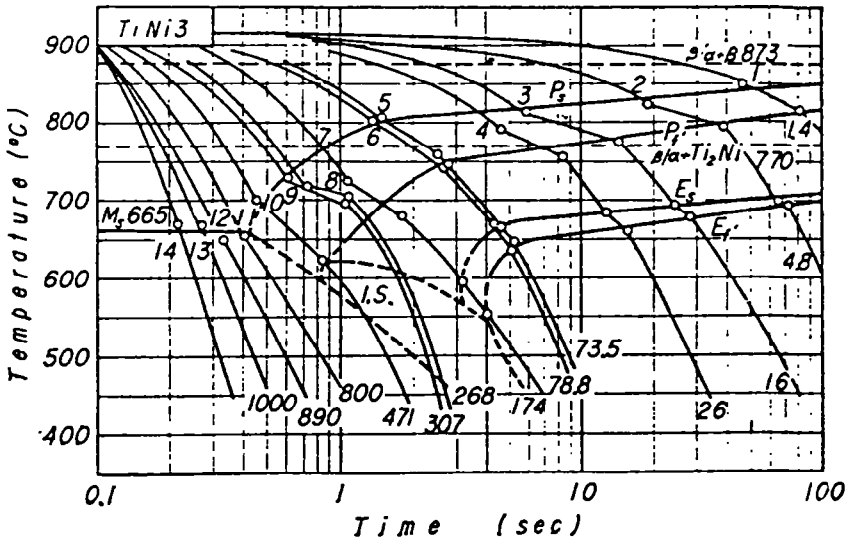
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram (Strength values are ksi)

SOURCE: "Metallurgical and Mechanical Properties of Titanium Alloy Ti-679," Technical Service Department, TMCA, August 1965, as published in Aerospace Structural Metals Handbook for Titanium, June 1969

Ti-Ni Alloy

Composition: Ti - 3.03% Ni
Treatment: Sponge titanium with a Brinell hardness of 112-116, prepared by an argon-arc furnace, hot rolled into sheets, surface cleaned and homogenized at 900°C (1652°F) for 20 days



LIVE GRAPH
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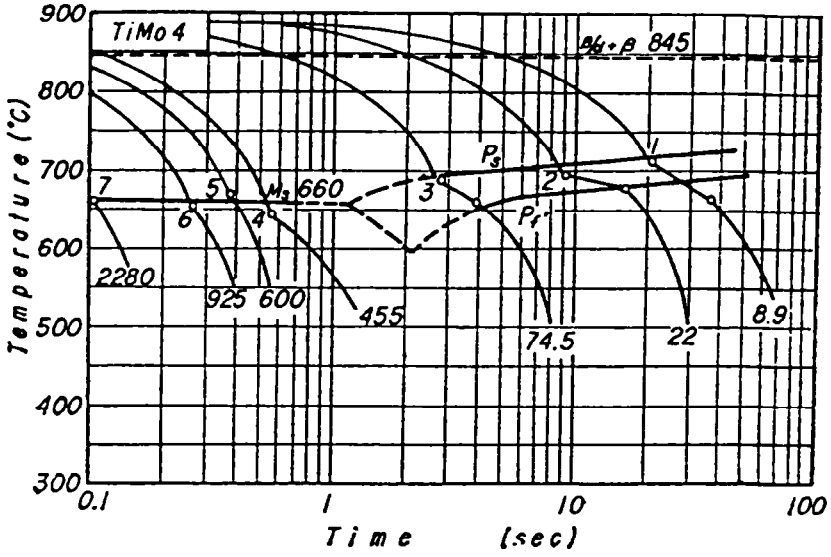
Continuous-cooling-transformation diagram

Ti-Mo Alloy

Composition: Ti - 4.57% Mo
Treatment: Sponge titanium with a Brinell hardness of 112-116, prepared by an argon-arc furnace, hot rolled into sheets, surface cleaned and homogenized at 900°C (1652°F) for 20 days



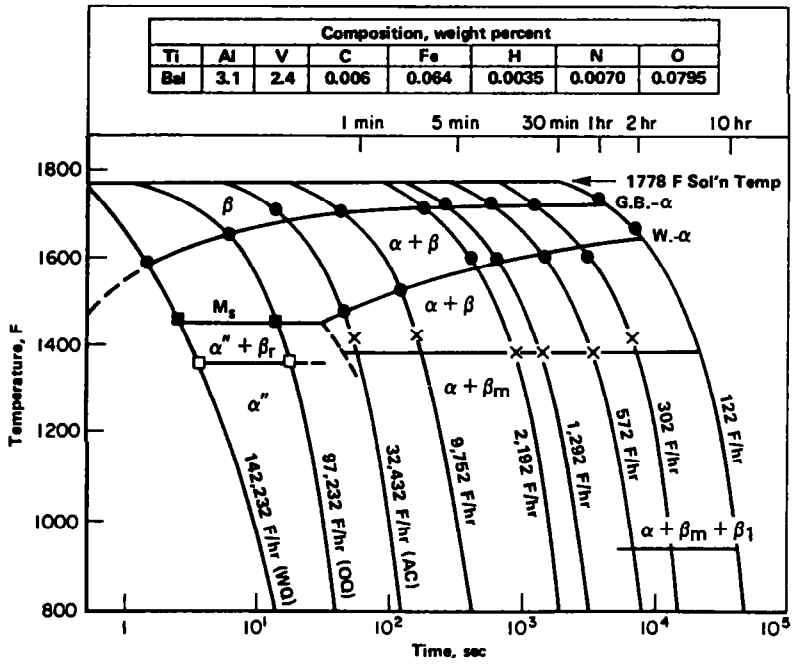
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: Y.C. Huang, S. Suzuki, H. Kaneko, T. Sato, "Continuous Cooling-Transformation of Beta-Phase in Binary Titanium Alloys," proceedings of an International Conference held at the Royal Festival Hall, London, 21-24 May, 1968, The Science, Technology and Application of Titanium, R.I. Jaffee, N.E. Promisel, Eds., Pergamon Press, Oxford, 1970, pp 695-698

Ti-3Al-2.5V

Composition: Ti - 3.1% Al - 2.4% V - 0.006% C - 0.064% Fe



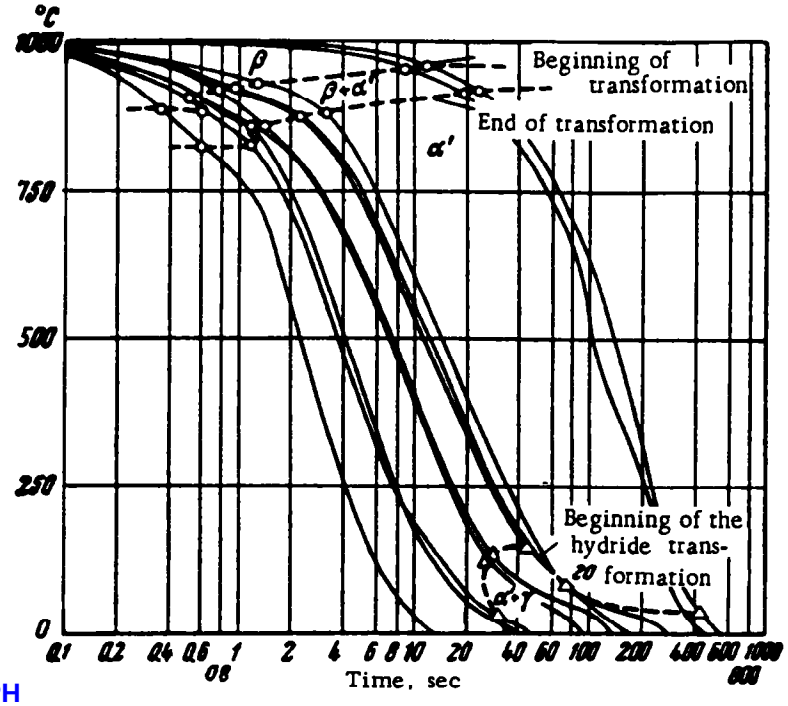
LIVE GRAPH
Click here to view

Continuous cooling transformation diagram

SOURCE: T. Anderson, "Isothermal and Continuous Cooling Transformations of Beta Phase in the Titanium Alloy Ti-3Al-2.5V," Scandinavian Journal of Metallurgy 2, 1973, pp 251-256, as published in Aerospace Structural Metals Handbook for Titanium, March 1980

Ti-Al-Sn Alloy

Composition: Ti - 4.75% Al - 2.5% Sn
Thermal cycles: Heating at a rate of 200°C/s to 1200°C (392°F/s to 2192°F) and cooling at different cooling rates (4.5 to 260°C/s) between 1000 and 900°C (1832 and 1652°F)
Content of gases in the alloys: 0.33-0.35% O, 0.07% N, 0.045-0.068% H



LIVE GRAPH
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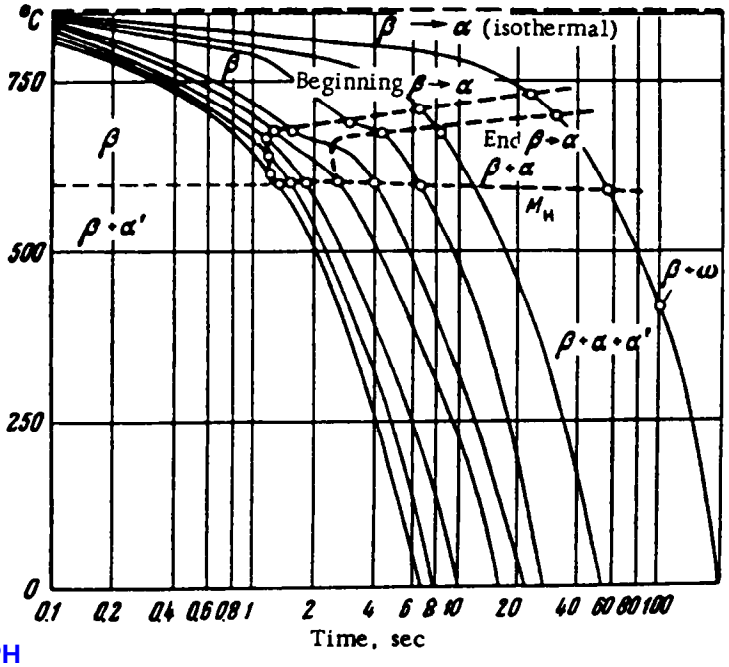
Continuous-cooling-transformation diagram
Anisothermal transformation in alloys under conditions of welding

SOURCE: M. Kh. Shorshorov, G.V. Nazarov, "Phase Transformations in the Heat-Affected Zone of Alpha and Alpha+Beta Titanium Alloys and the Criteria for Choosing the Welding Processes," Titanium and Its Alloys, Publication No. 10, I.I. Kornilov, ed., Israel Program for Scientific Translations, 1966, pp 297-302

Ti-Al-Mo Alloy

Composition: Ti - 2.6% Al - 7.5% Mo
Thermal cycles: Heating at a rate of 200°C/s to 1200°C (392°F/s to 2192°F) and cooling at different cooling rates (4.5 to 260°C/s) between 1000 and 900°C (1832 and 1652°F)
Content of gases in the alloys: 0.33-0.35% O, 0.07% N, 0.045-0.068% H



LIVE GRAPH
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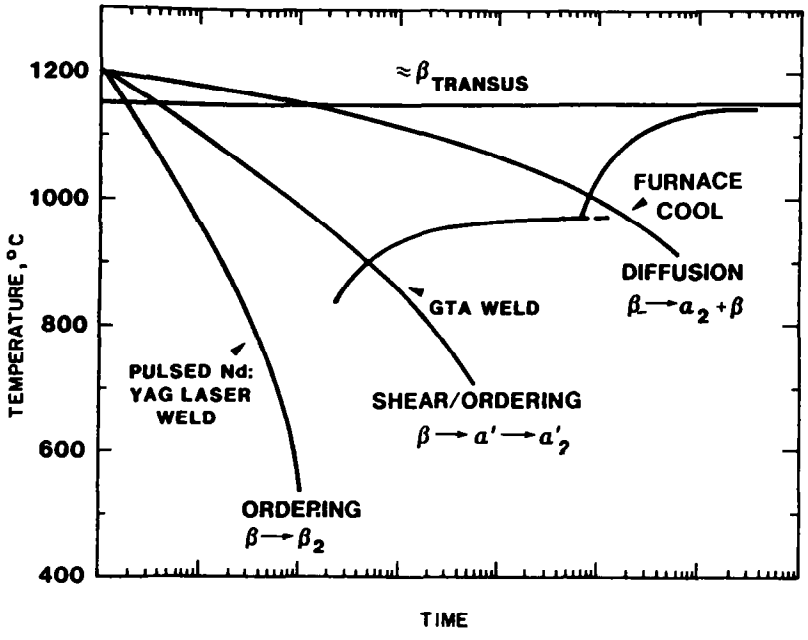
Continuous-cooling-transformation diagram
Anisothermal transformation in alloys under conditions of welding

SOURCE: M. Kh. Shorshorov, G.V. Nazarov, "Phase Transformations in the Heat-Affected Zone of Alpha and Alpha+Beta Titanium Alloys and the Criteria for Choosing the Welding Processes," Titanium and Its Alloys, Publication No. 10, I.I. Kornilov, ed., Israel Program for Scientific Translations, 1966, pp 297-302

Ti-15Al-21Nb

Composition: Ti - 14.80% Al - 21.30% Nb - 0.065% Fe - 0.058% O - 0.006% N

Treatment: Samples were heated at the rate of 100°C/s to 1200°C (212°F/s to 2192°F) and held for 90 s. Cooling rates of 60° to 0.1°C/s were run, terminated at a temperature of 850°C 1562°F) and free cooled to room temperature

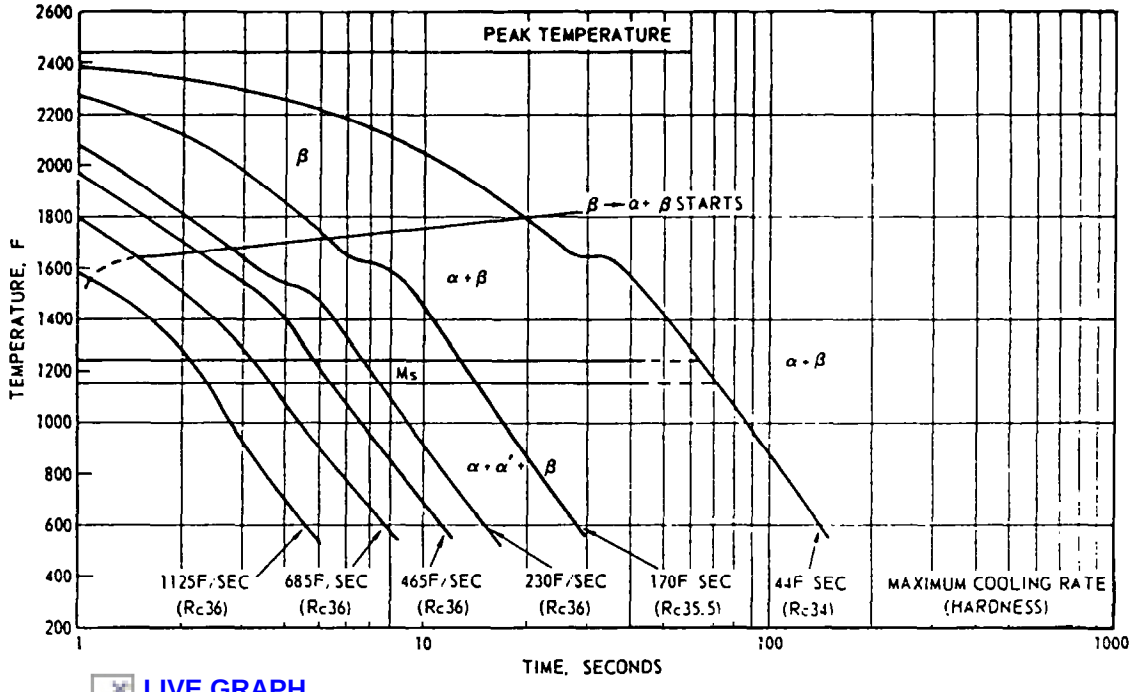


Schematic continuous-cooling-transformation diagram
Approximate cooling rates for various industrial processes are indicated

SOURCE: M.J. Cieslak, T.J. Headley, W.A. Baeelack III, "Effect of Thermal Processing on the Microstructure of Ti-26Al-11Nb: Applications to Fusion Welding," Met. Trans. A, Vol21A, May 1990, pp 1273-1286

Ti - Al - V - Mo Alloys

Composition: Ti - 7.6% Al - 1.0% V - 1.0% Mo
Solution treated and cooling began from 1338°C (2440°F)



LIVE GRAPH
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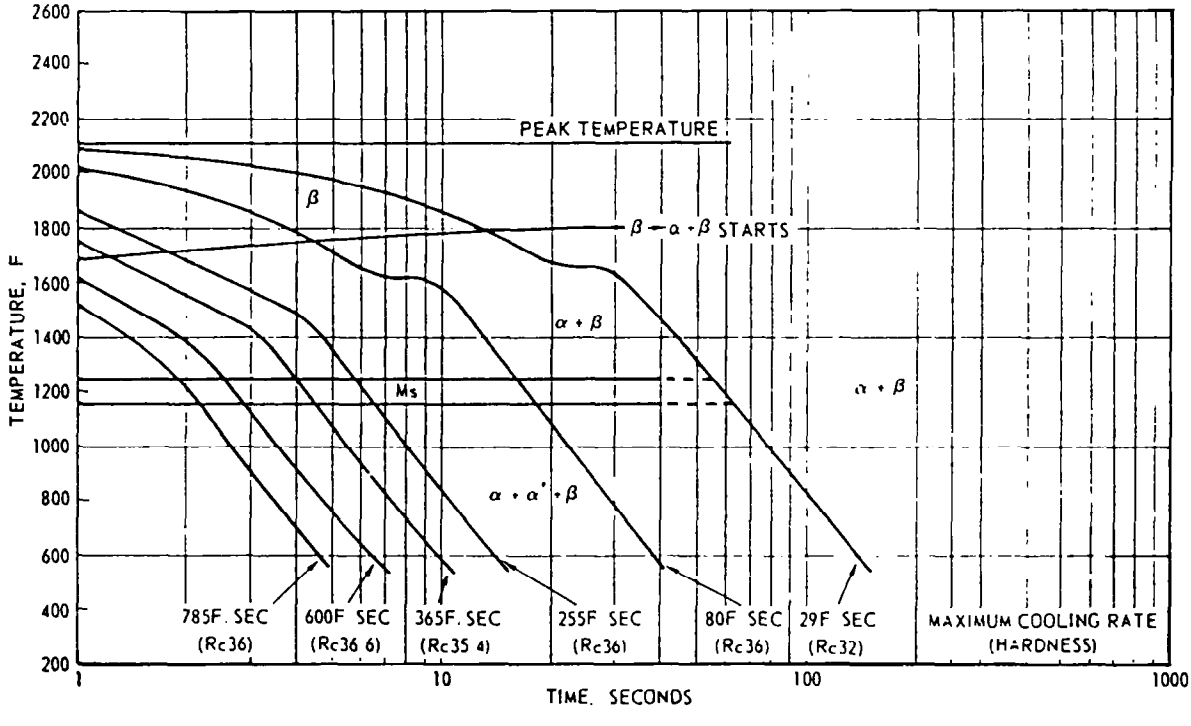
Continuous-cooling-transformation diagram

Composition: Ti - 7.6% Al - 1.0% V - 1.0% Mo
Solution treated and cooling began from 1149°C (2100°F)



LIVE GRAPH
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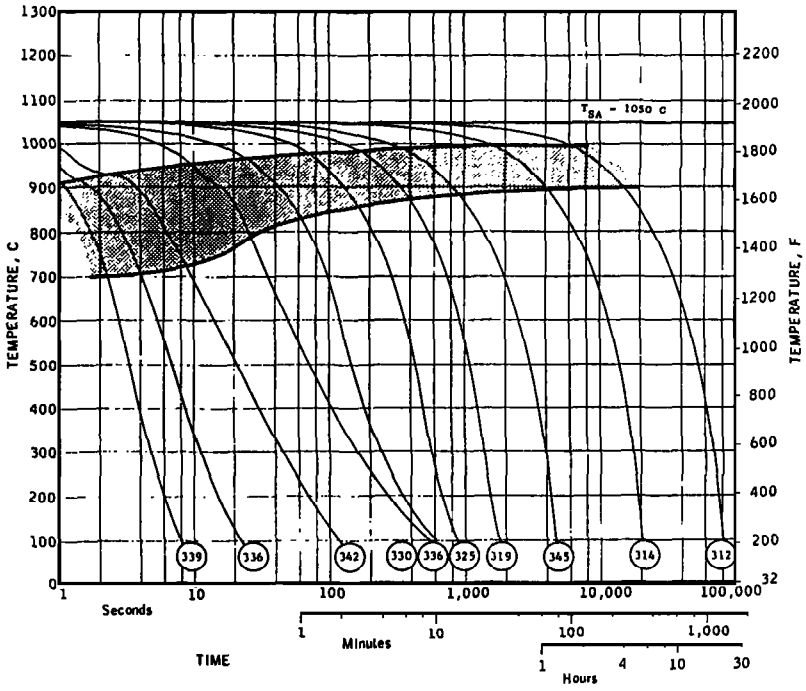
Continuous-cooling-transformation diagram

SOURCE: K.C. Wu, "Continuous-Cooling Transformation Diagrams of Ti-8Al-1Mo-1V," Trans. ASM, Vol 61, 1968, pp 621-625

IMI 685 Titanium Alloy

Composition: Ti - 6.17% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N

Treatment: Solution annealed at 1050°C (1920°F) for 20 min



LIVE GRAPH
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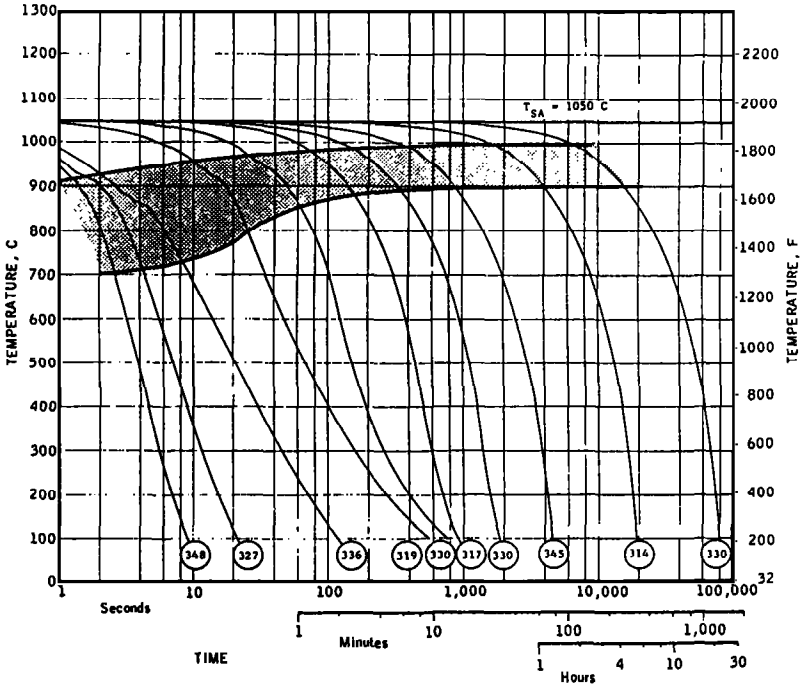
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 685 Titanium Alloy

Composition: Ti - 6.17% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N
Treatment: Solution annealed at 1050°C (1920°F) for 20 min, hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



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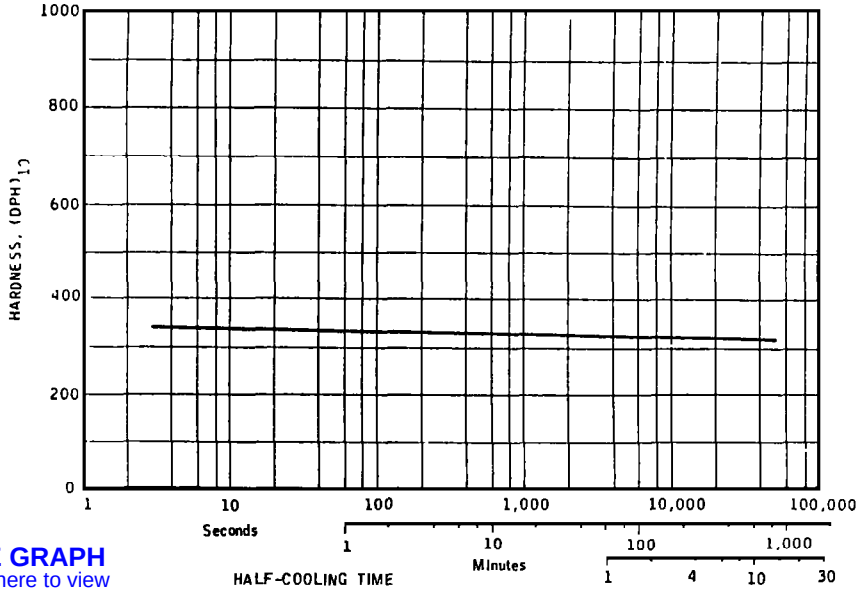
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 685 Titanium Alloy

Composition: Ti - 6.17% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N

Treatment: Solution annealed at 1050°C (1920°F) for 20 min, cooled to room temperature at various rates, and optionally aged by heating up to 650°C (1200°F)at a rate of about 10°C/min



LIVE GRAPH
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Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

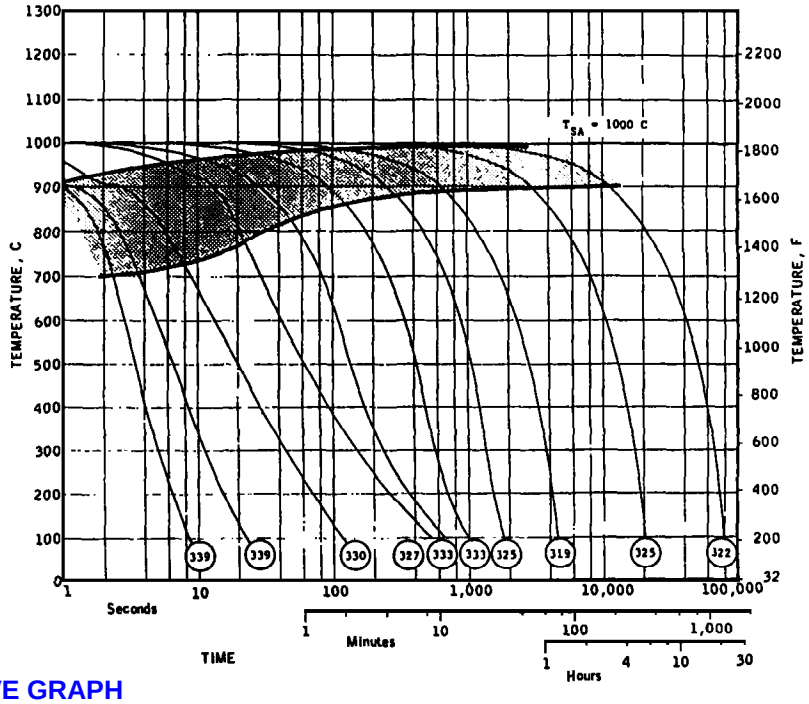
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 685 Titanium Alloy

Composition: Ti - 6.17% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N

Treatment: Solution annealed at 1000°C (1830°F) for 20 min



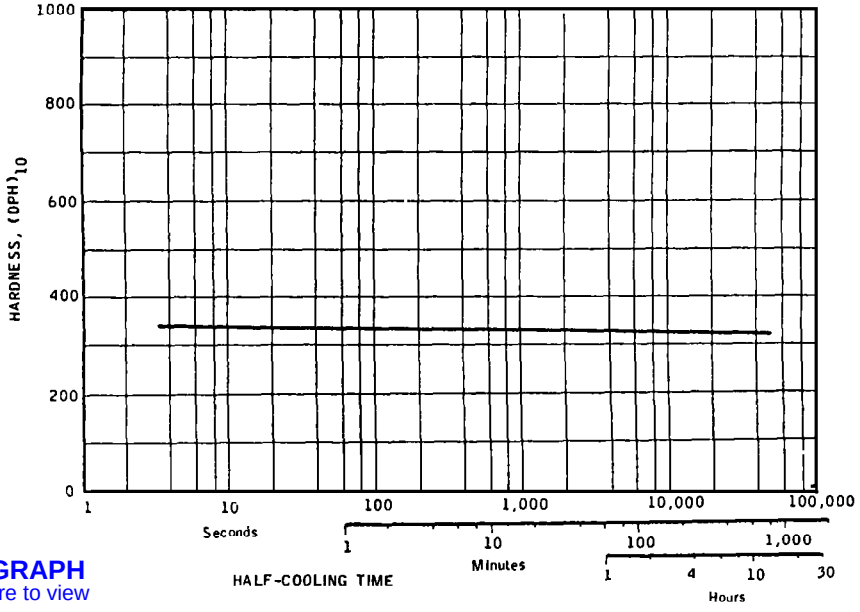
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 685 Titanium Alloy

Composition: Ti - 6.17% Al - 4.97% Zr - 0.49% Mo - 0.22% Si - 0.10% O - 0.029% N
Treatment: Solution annealed at 1000°C (1830°F) for 20 min, and continuously cooled at various rates



LIVE GRAPH
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Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

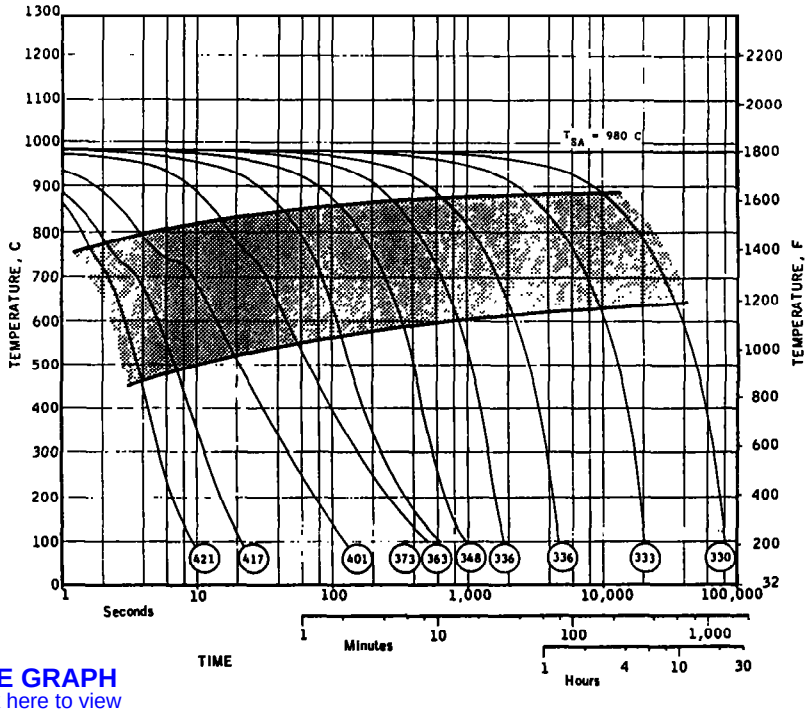
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 550 Titanium Alloy

Composition: Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N

Treatment: Solution annealed at 980°C (1795°F) for 20 min



LIVE GRAPH
Click here to view

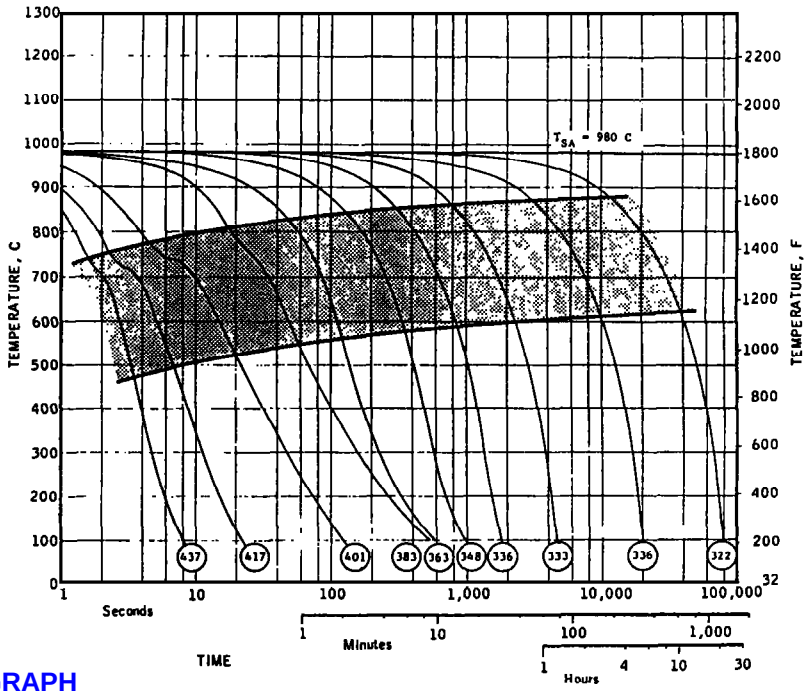
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 550 Titanium Alloy

Composition: Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N

Treatment: Solution annealed at 980°C (1795°F) for 20 min, hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
Click here to view

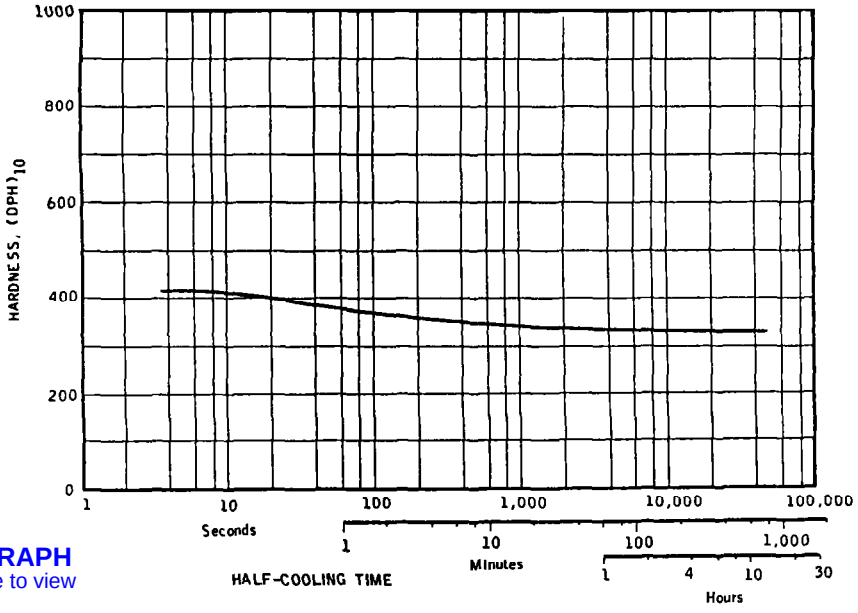
Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 550 Titanium Alloy

Composition: Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N

Treatment: Solution annealed at 980°C (1795°F) for 20 min, continuously cooled to room temperature at various rates, and optionally aged by heating up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
Click here to view

Hardness vs half cooling time *

*** NOTE:** In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:

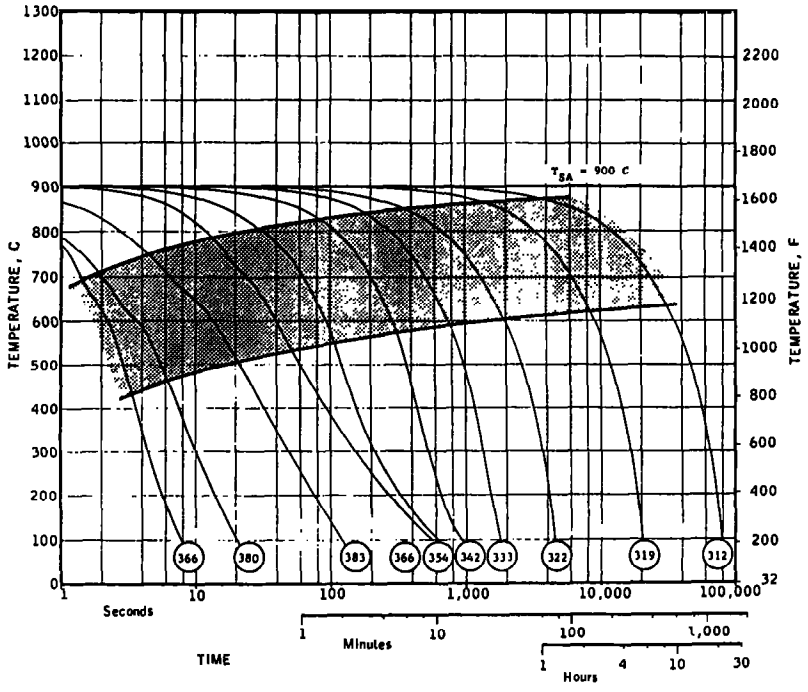
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 550 Titanium Alloy

Composition: Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N

Treatment: Solution annealed at 900°C (1650°F) for 20 min



LIVE GRAPH
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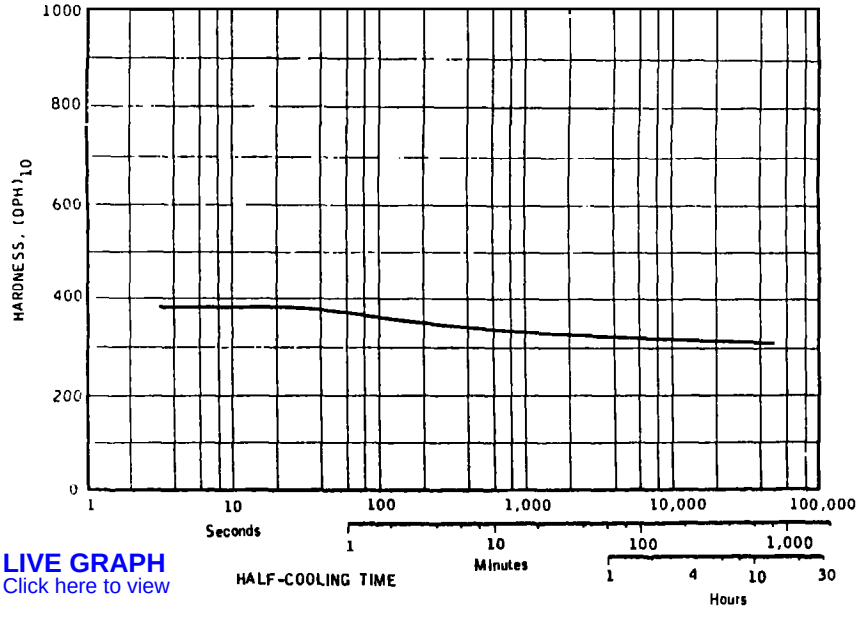
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

IMI 550 Titanium Alloy

Composition: Ti - 3.93% Al - 3.18% Sn - 3.97% Mo - 0.50% Si - 0.22% O - 0.022% N

Treatment: Solution annealed at 900°C (1650°F) for 20 min, continuously cooled at various rates



LIVE GRAPH
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Continuous-cooling-transformation and aging diagram
Hardness vs half cooling time *

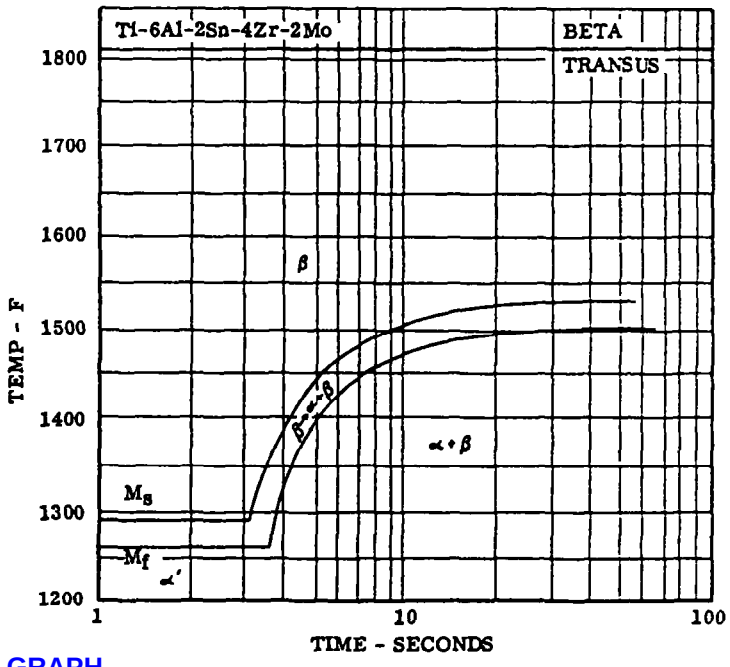
*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Continuous Cooling Transformation Kinetics of the IMI 685 and IMI 550 Titanium Alloys," Rp-27-72-08, Climax Molybdenum, 1 March 1973

Ti-6242

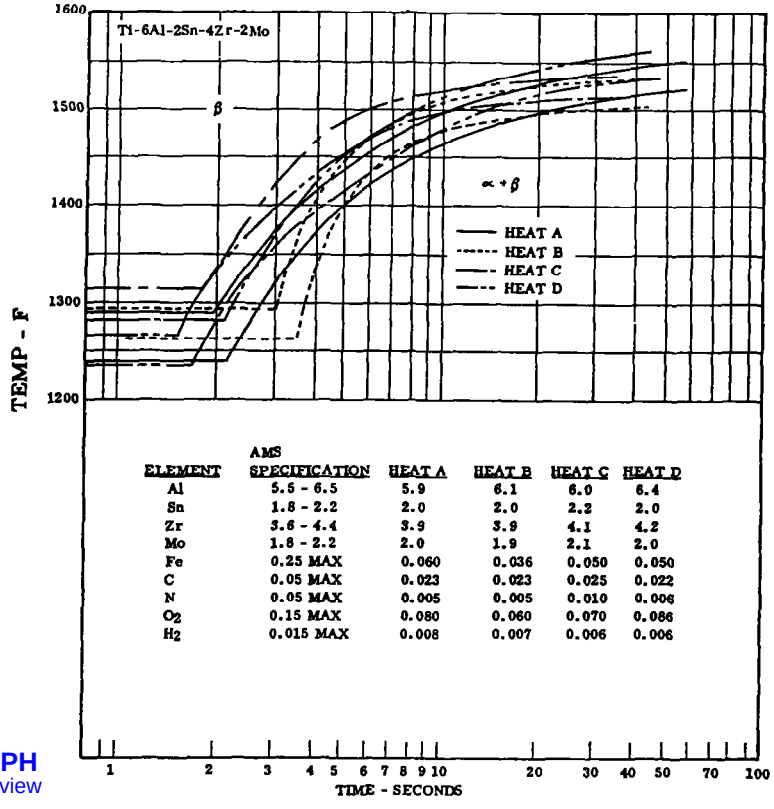
Composition: Ti - 6% Al - 2% Sn - 4% Zr - 2% Mo



LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

Composition: Ti - 6% Al - 2% Sn - 4% Zr - 2% Mo



ELEMENT	AMS SPECIFICATION	HEAT A	HEAT B	HEAT C	HEAT D
Al	5.5 - 6.5	5.9	6.1	6.0	6.4
Sn	1.8 - 2.2	2.0	2.0	2.2	2.0
Zr	3.6 - 4.4	3.9	3.9	4.1	4.2
Mo	1.8 - 2.2	2.0	1.9	2.1	2.0
Fe	0.25 MAX	0.060	0.036	0.050	0.050
C	0.05 MAX	0.023	0.023	0.025	0.022
N	0.05 MAX	0.005	0.005	0.010	0.006
O_2	0.15 MAX	0.080	0.060	0.070	0.086
H_2	0.015 MAX	0.008	0.007	0.006	0.006

LIVE GRAPH
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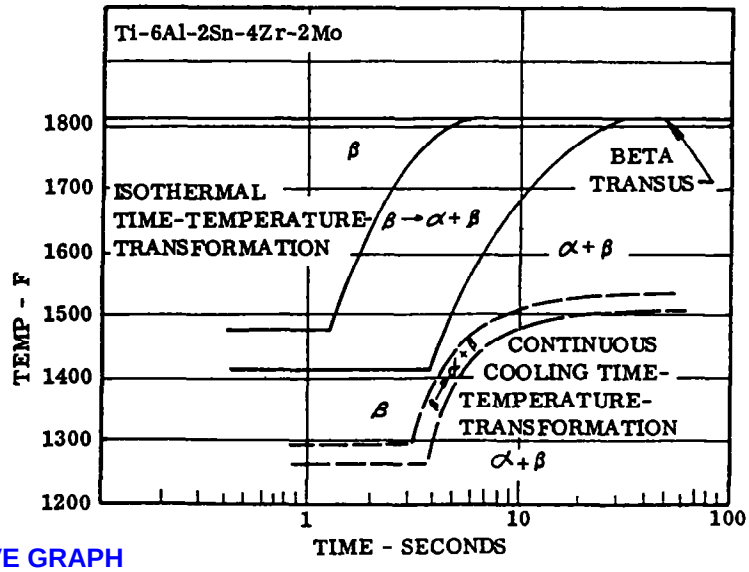
Continuous-cooling-transformation diagram
Effect of compositional variations within specification on continuous-cooling-transformation

SOURCE: D.R. Mitchell, "Welding Evaluation of Ti-6Al-2Sn-4Zr-2Mo Sheet," TMCA Project BW-10-1, Final Report, June 1968, as published in Aerospace Structural Metals Handbook for Titanium, June 1978

Ti-6242

Composition: Ti - 6% Al - 2% Sn - 4% Zr - 2% Mo



LIVE GRAPH
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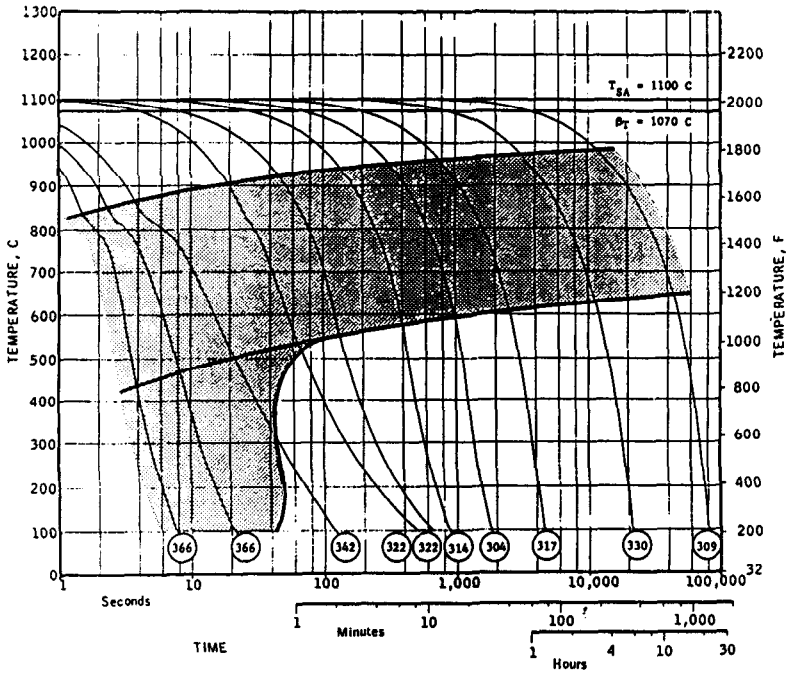
Comparison of CCT diagram and I-T diagram

SOURCE: D.R. Mitchell, "Welding Evaluation of Ti-6Al-2Sn-4Zr-2Mo Sheet," TMCA Project BW-10-1, Final Report, June 1968, as published in Aerospace Structural Metals Handbook for Titanium, June 1978

Ti-6242

Composition: Ti - 6.63% Al - 2.08% Sn - 3.91% Zr - 1.99% Mo - 0.066% O_2

Treatment: Solution annealed at 1100°C (2012°F) for 20 min



LIVE GRAPH
Click here to view

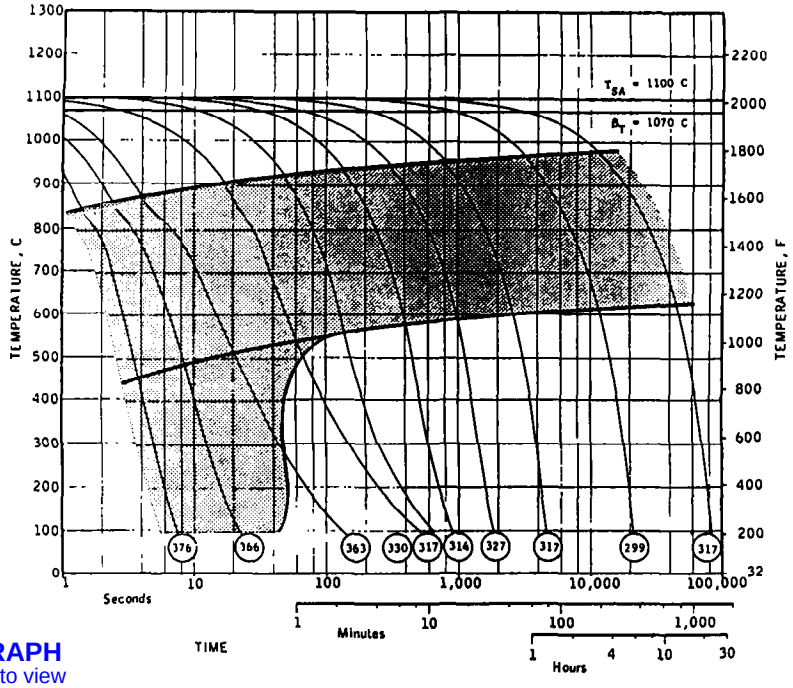
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-2Mo Titanium Alloy," Rp-27-72-03, Climax Molybdenum, 7 June 1972

Ti-6242

Composition: Ti - 6.63% Al - 2.08% Sn - 3.91% Zr - 1.99% Mo - 0.066% O_2

Treatment: Solution annealed at 1100°C (2012°F) for 20 min, hardness values determined after additional aging by heating from room temperature to 650°C (1200°F)



LIVE GRAPH
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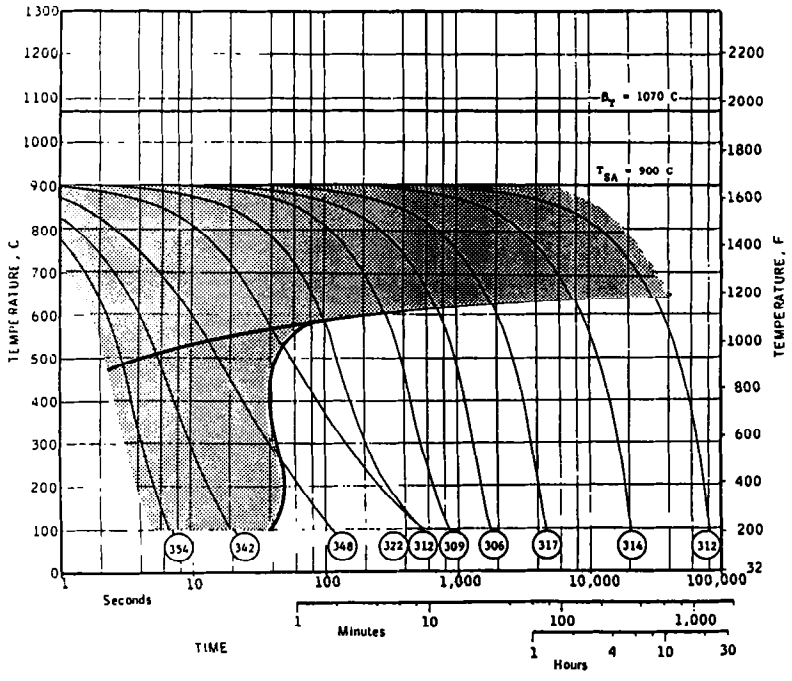
Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-2Mo Titanium Alloy," Rp-27-72-03, Climax Molybdenum, 7 June 1972

Ti-6242

Composition: Ti - 6.63% Al - 2.08% Sn - 3.91% Zr - 1.99% Mo - 0.066% O_2

Treatment: Solution annealed at 900°C (1650°F) for 20 min



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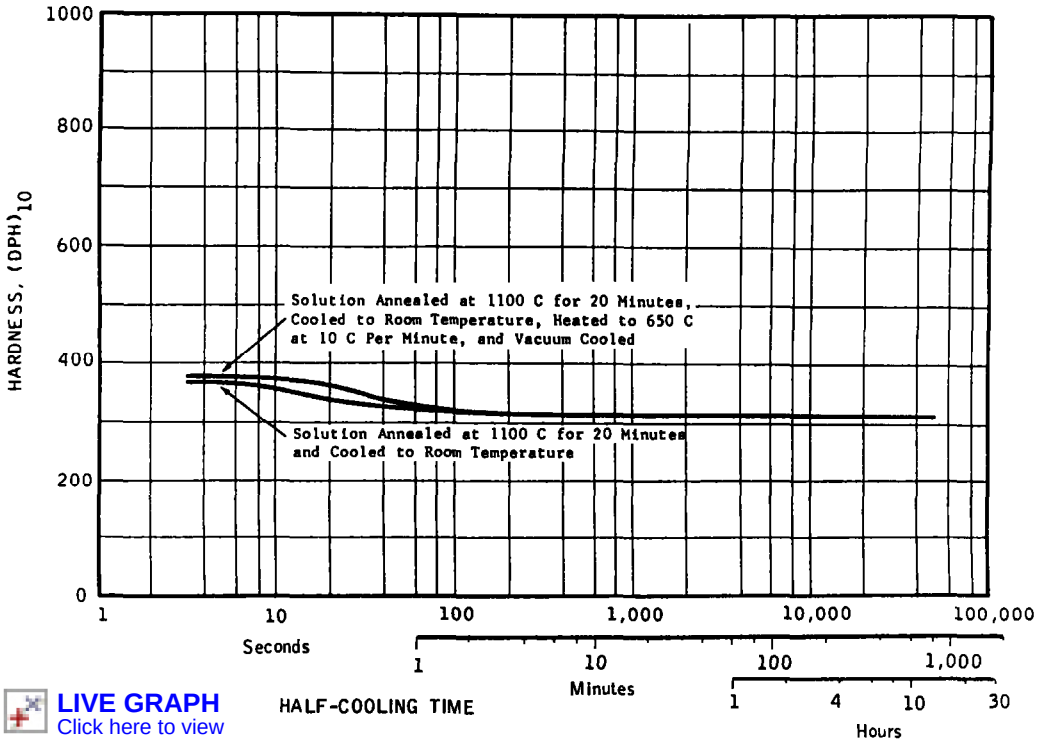
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-2Mo Titanium Alloy," Rp-27-72-03, Climax Molybdenum, 7 June 1972

Ti-6242

Composition: Ti - 6.63% Al - 2.08% Sn - 3.91% Zr - 1.99% Mo - 0.066% O_2
Treatment: Solution annealed at 1100°C (2012°F) for 20 min, cooled to room temperature at various rates, and optionally aged by heating up to 650°C (1200°F) at a rate of about 10°C /min, followed by vacuum cooling



Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-2Mo Titanium Alloy," Rp-27-72-03, Climax Molybdenum, 7 June 1972

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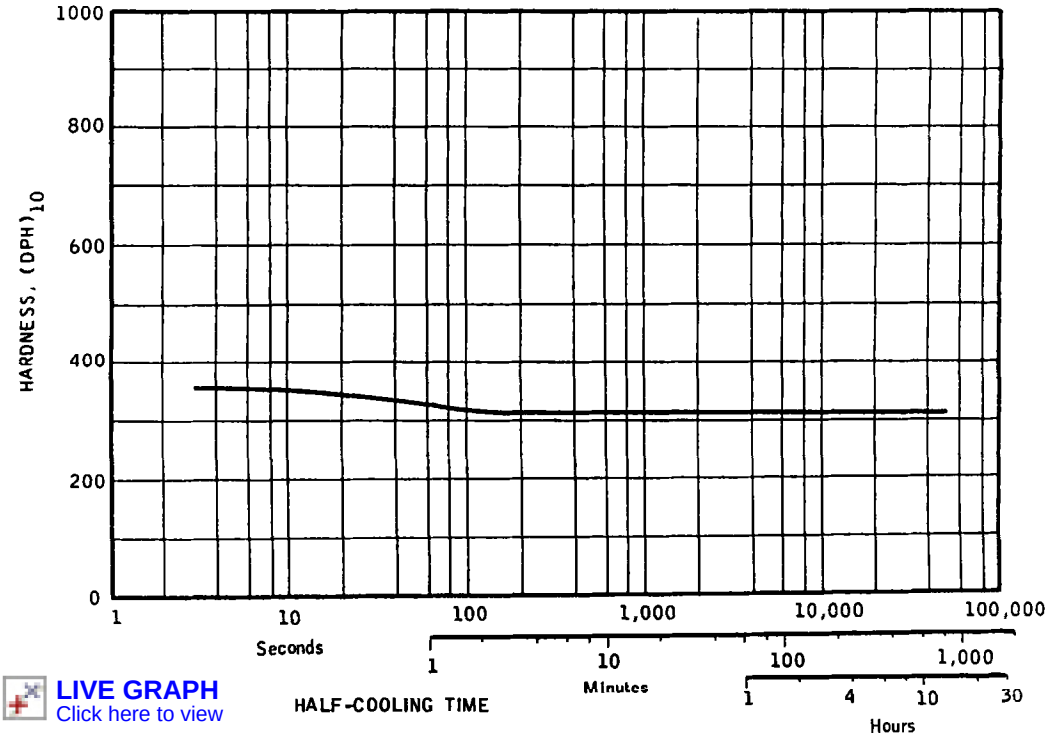
Treatment: Solution annealed at 900°C (1650°F) for 20 min, and cooled at various rates



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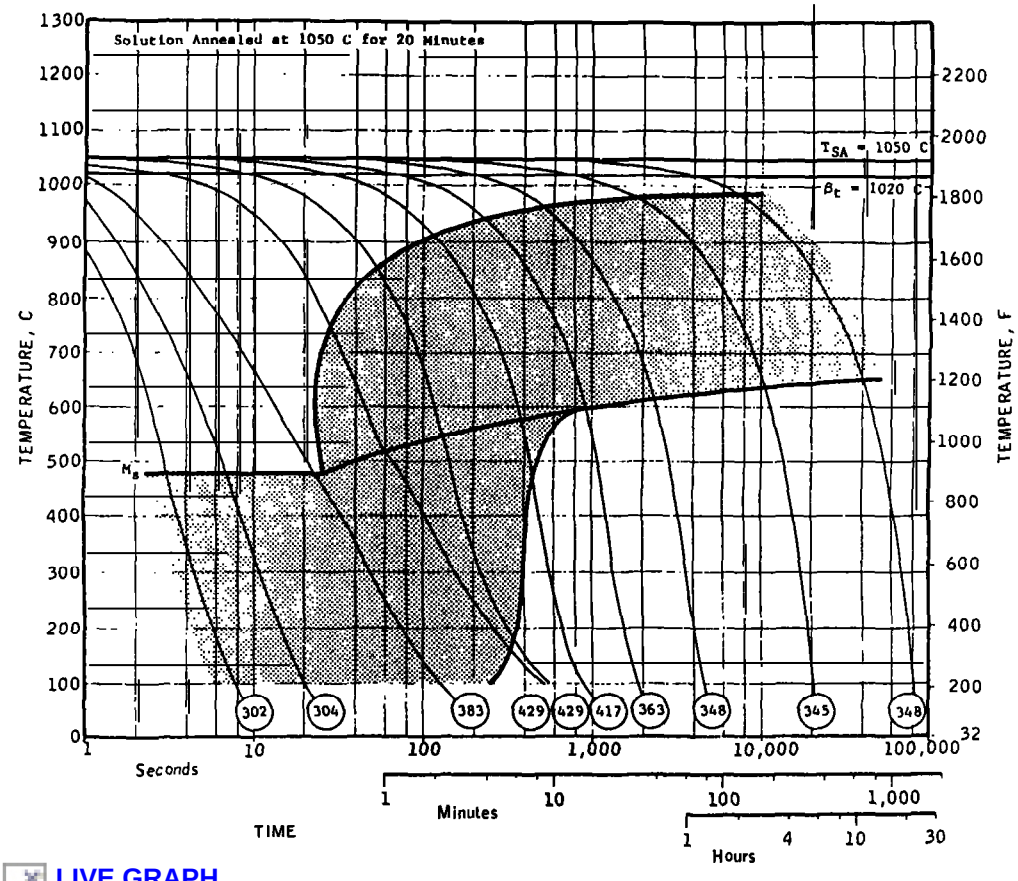
SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-2Mo Titanium Alloy," Rp-27-72-03, Climax Molybdenum, 7 June 1972

Ti-6246

Composition: Ti - 6.1% Al - 2.1% Sn - 4.0% Zr - 6.3% Mo - 0.10% O_2

Treatment: Solution annealed at 1050°C (1922°F) for 20 min



LIVE GRAPH
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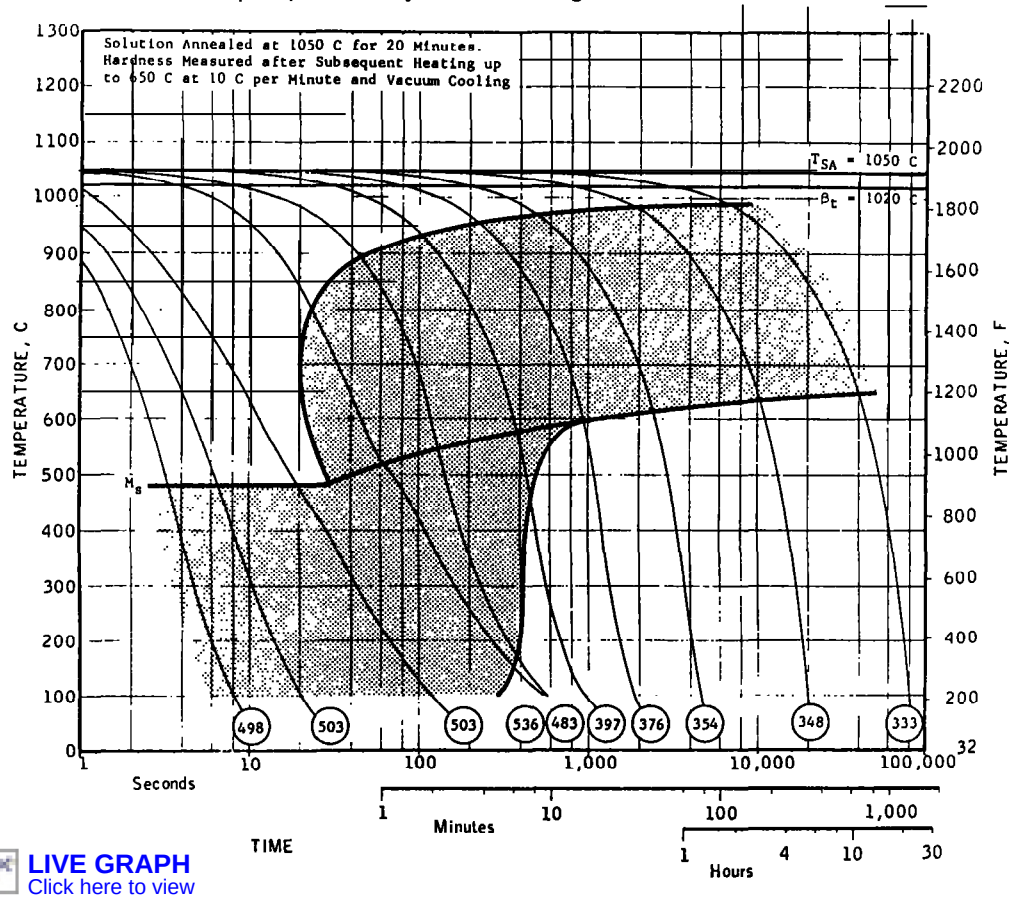
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformational Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-6Mo Titanium Alloy," Rp-27-71-02, Climax Molybdenum, 2 March 1972

Ti-6246

Composition: Ti - 6.1% Al - 2.1% Sn - 4.0% Zr - 6.3% Mo - 0.10% O_2

Treatment: Solution annealed at 1050°C (1922°F) for 20 min, hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
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Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Phase Transformational Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-6Mo Titanium Alloy," Rp-27-71-02, Climax Molybdenum, 2 March 1972

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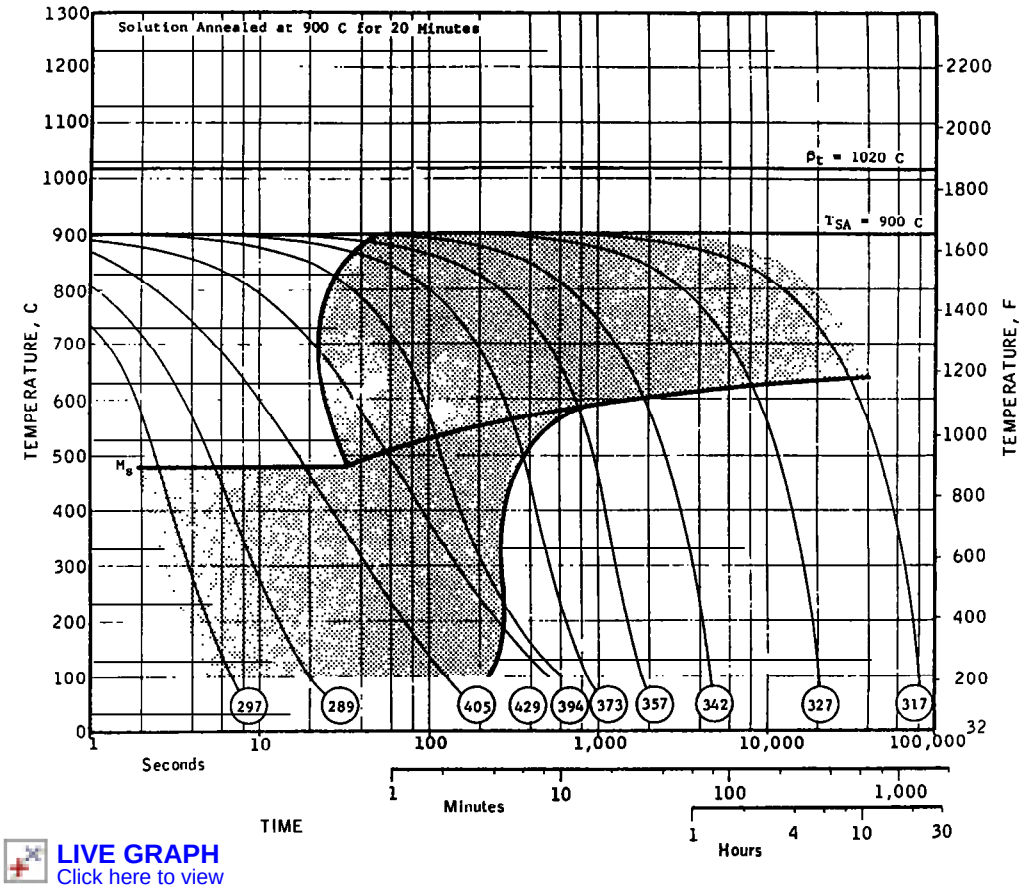
Composition: Ti - 6.1% Al - 2.1% Sn - 4.0% Zr - 6.3% Mo - 0.10% O_2
Treatment: Solution annealed at 900°C (1650°F) for 20 min



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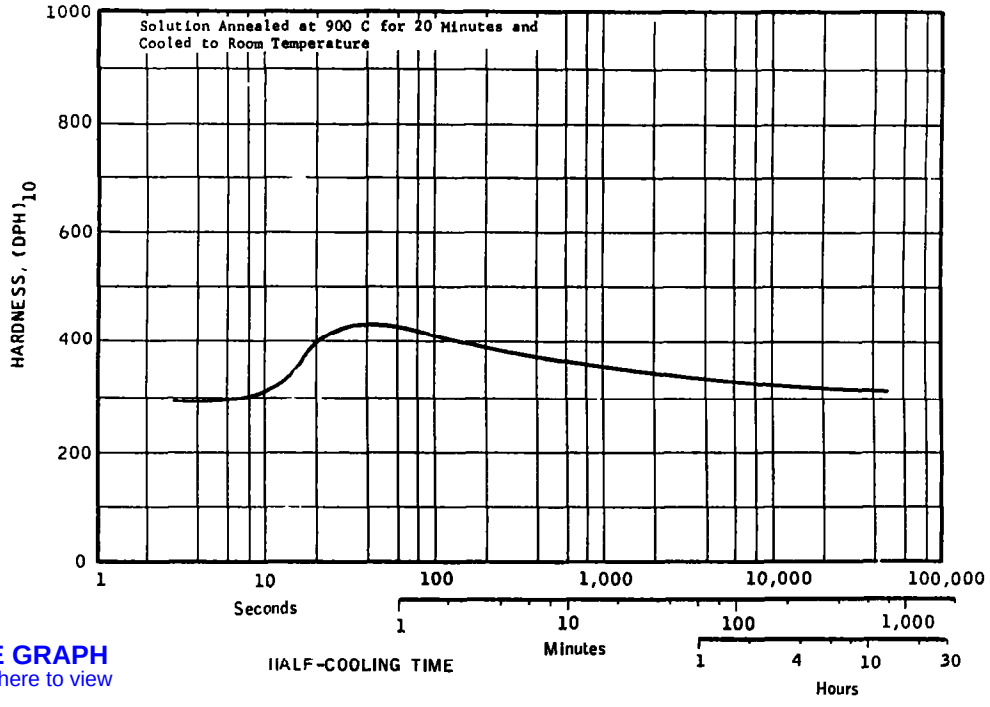
Treatment: Solution annealed at 900°C (1650°F) for 20 min, and continuously cooled at various rates



LIVE GRAPH
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Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

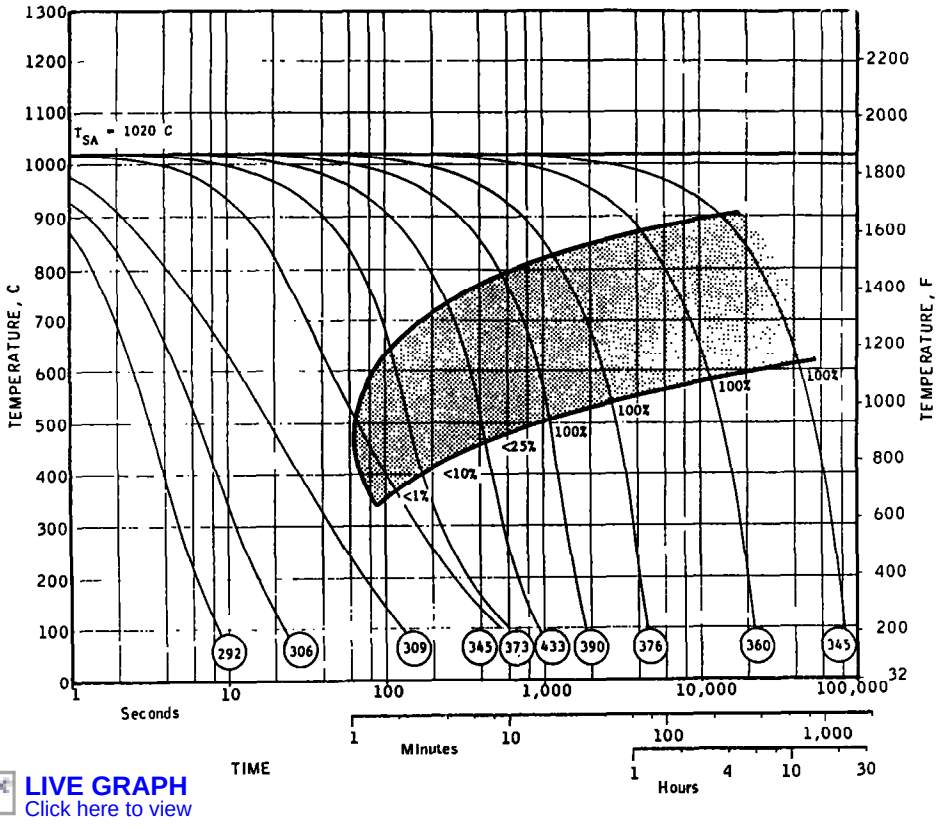
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Phase Transformational Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-6Mo Titanium Alloy," Rp-27-71-02, Climax Molybdenum, 2 March 1972

Ti-6248

Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O

Treatment: Solution annealed at 1020°C (1870°F) for 20 min



LIVE GRAPH
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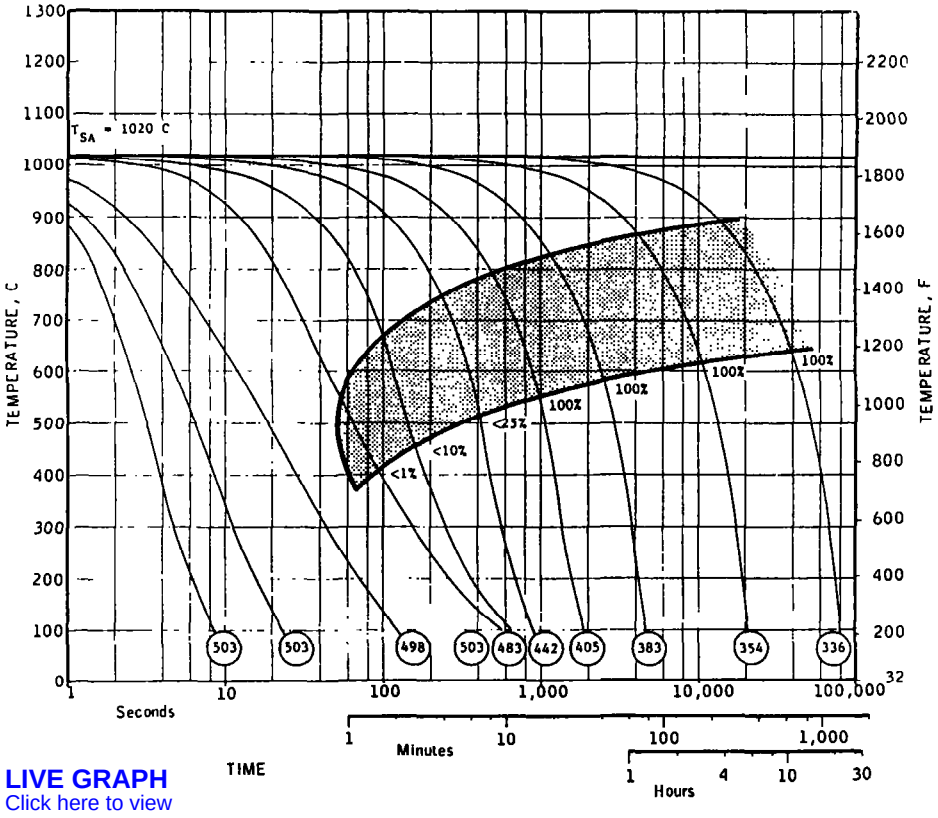
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-8Mo Titanium Alloy," Rp-27-72-07, Climax Molybdenum, 25 October 1972

Ti-6248

Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O
Treatment: Solution annealed at 1020°C (1870°F) for 20 min. hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
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Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-8Mo Titanium Alloy," Rp-27-72-07, Climax Molybdenum, 25 October 1972

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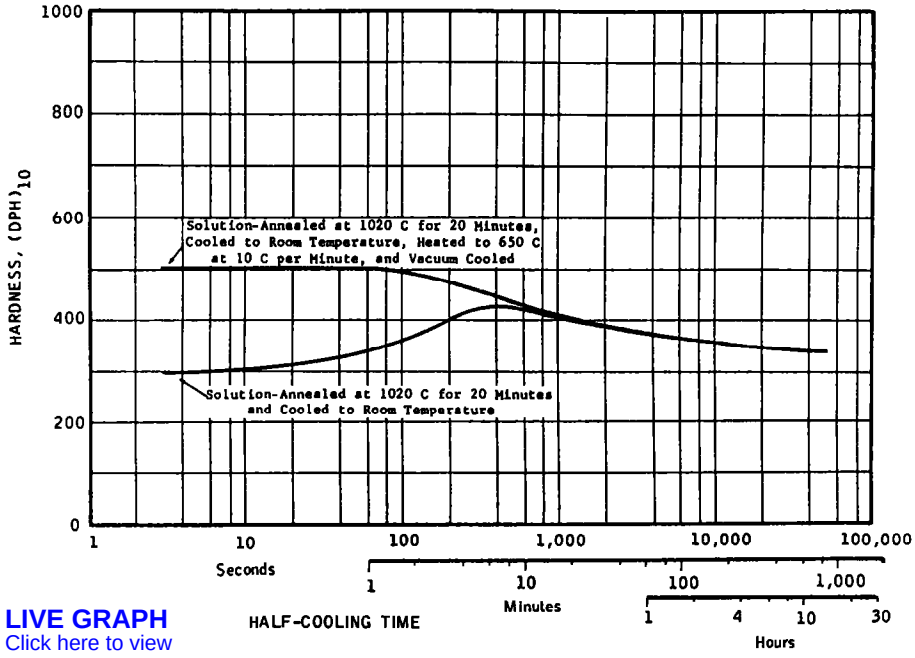
Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O
Treatment: Solution annealed at 1020°C (1870°F) for 20 min, cooled to room temperature at various rates, and optionally aged by heating up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
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Continuous-cooling-transformation and aging diagram
Hardness vs half cooling time *

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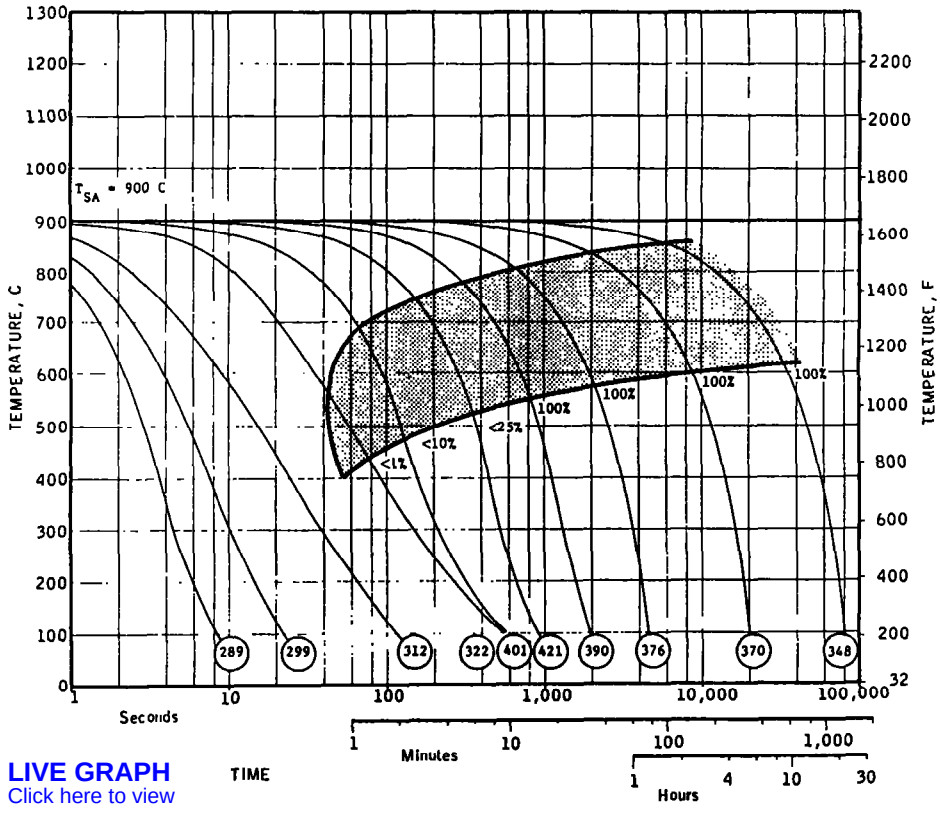
Ti-6248

Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O

Treatment: Solution annealed at 900°C (1650°F) for 20 min



LIVE GRAPH
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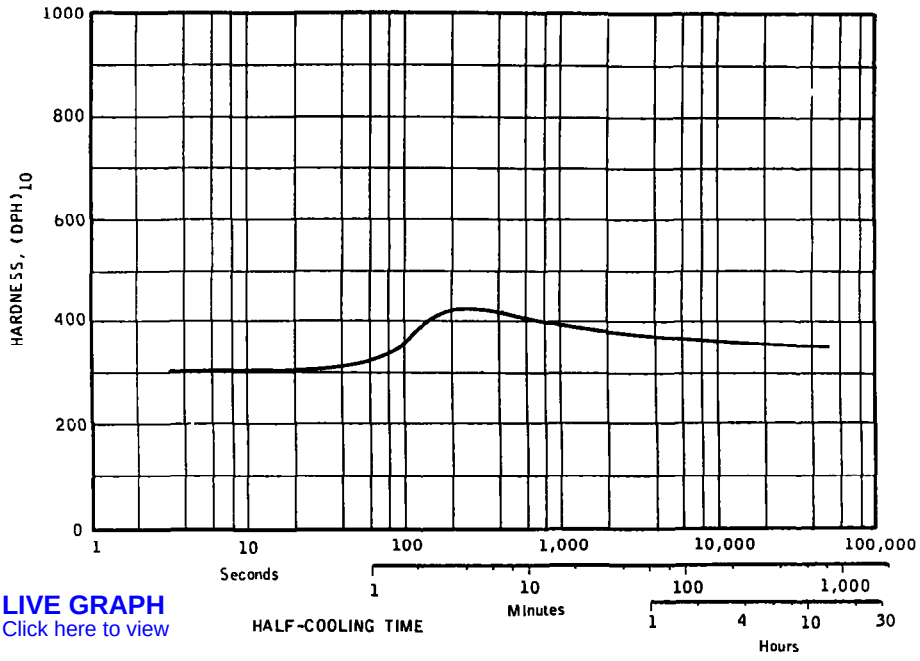
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-8Mo Titanium Alloy," Rp-27-72-07, Climax Molybdenum, 25 October 1972

Ti-6248

Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O
Treatment: Solution annealed at 900°C (1650°F) for 20 min, and continuously cooled at various rates



LIVE GRAPH
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Hardness vs half cooling time *

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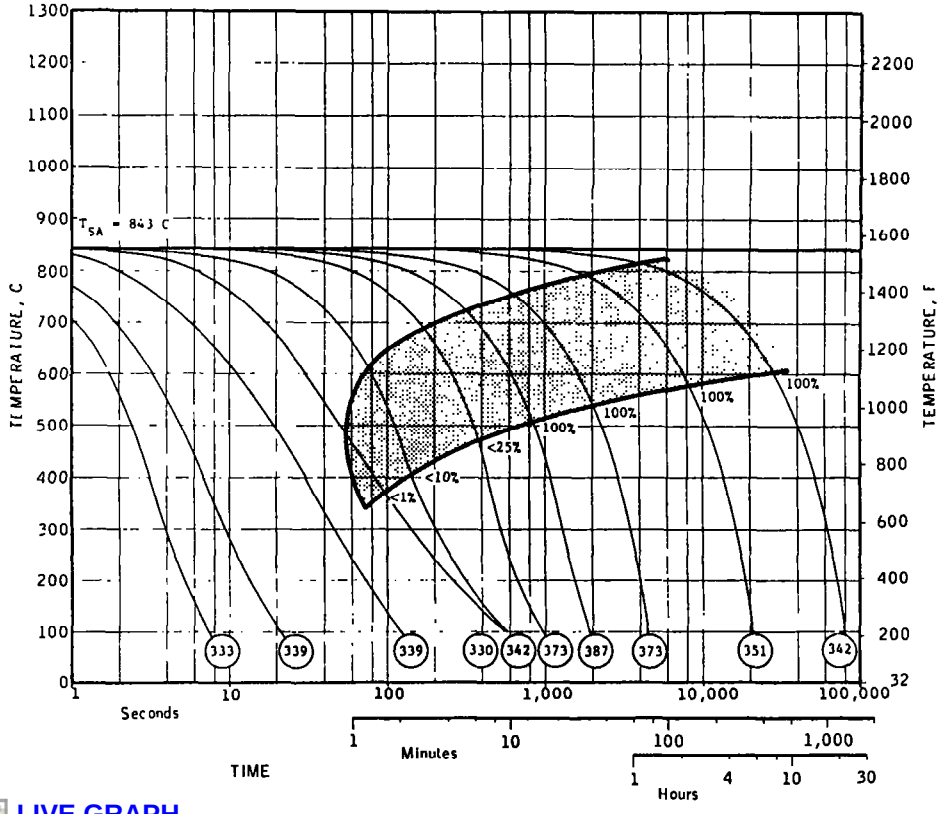
SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of The Ti-6Al-2Sn-4Zr-8Mo Titanium Alloy," Rp-27-72-07, Climax Molybdenum, 25 October 1972

Ti-6248

Composition: Ti - 5.9% Al - 1.93% Sn - 3.90% Zr - 7.96% Mo - 0.076% Fe - 0.004% H - 0.124% O

Treatment: Solution annealed at 843°C (1550°F) for 20 min



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Continuous-cooling-transformation diagram

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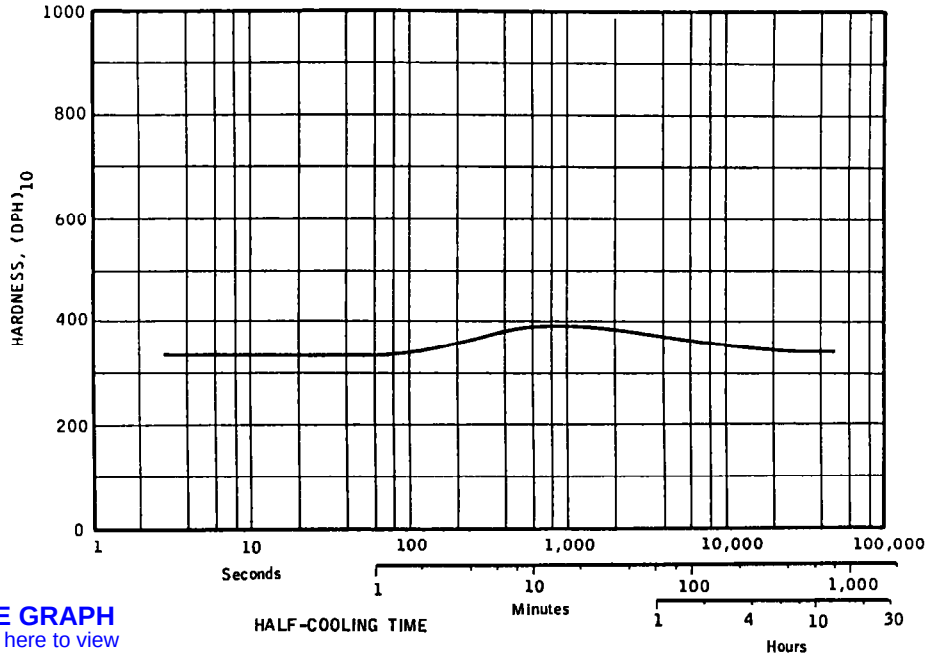
Treatment: Solution annealed at 843°C (1550°F) for 20 min, and continuously cooled at various rates



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Hardness vs half cooling time *

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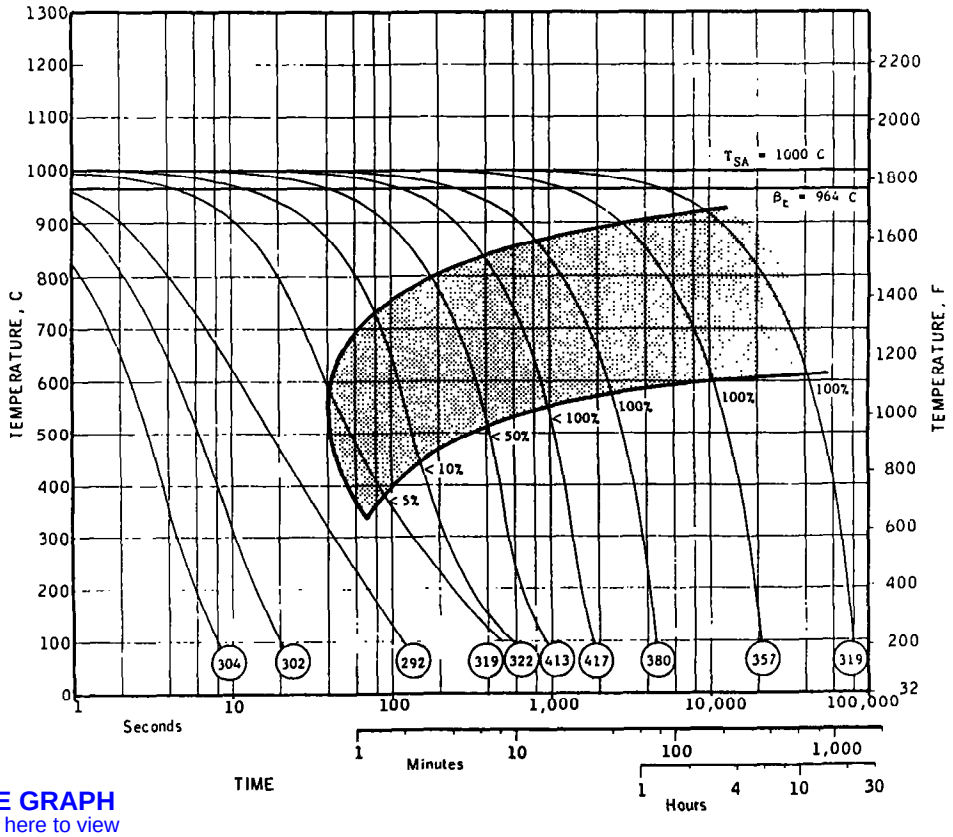
SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-6Al-2Sn-4Zr-8Mo Titanium Alloy," Rp-27-72-07, Climax Molybdenum, 25 October 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N

Treatment: Solution annealed at 1000°C (1830°F) for 20 min



LIVE GRAPH
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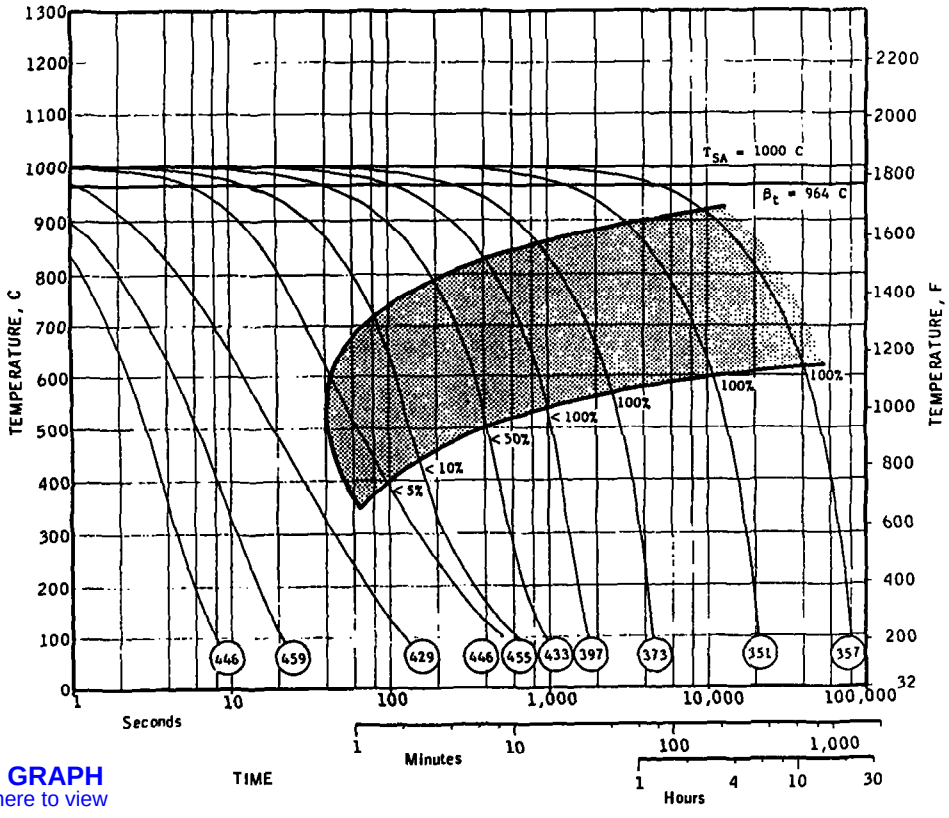
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N
Treatment: Solution annealed at 1000°C (1830°F) for 20 min, hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
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Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

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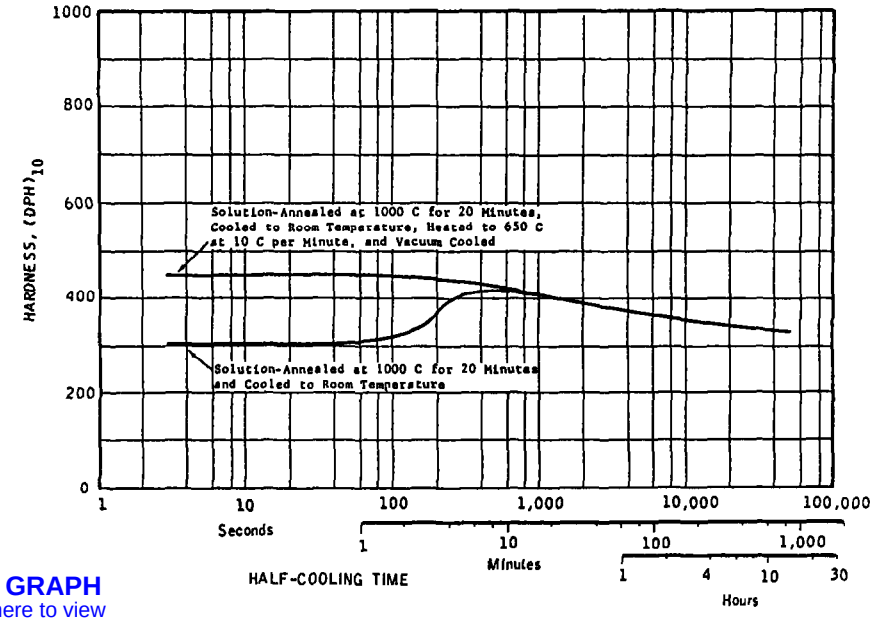
Treatment: Solution annealed at 1000°C (1830°F) for 20 min



LIVE GRAPH
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***Hardness vs half cooling time* ***

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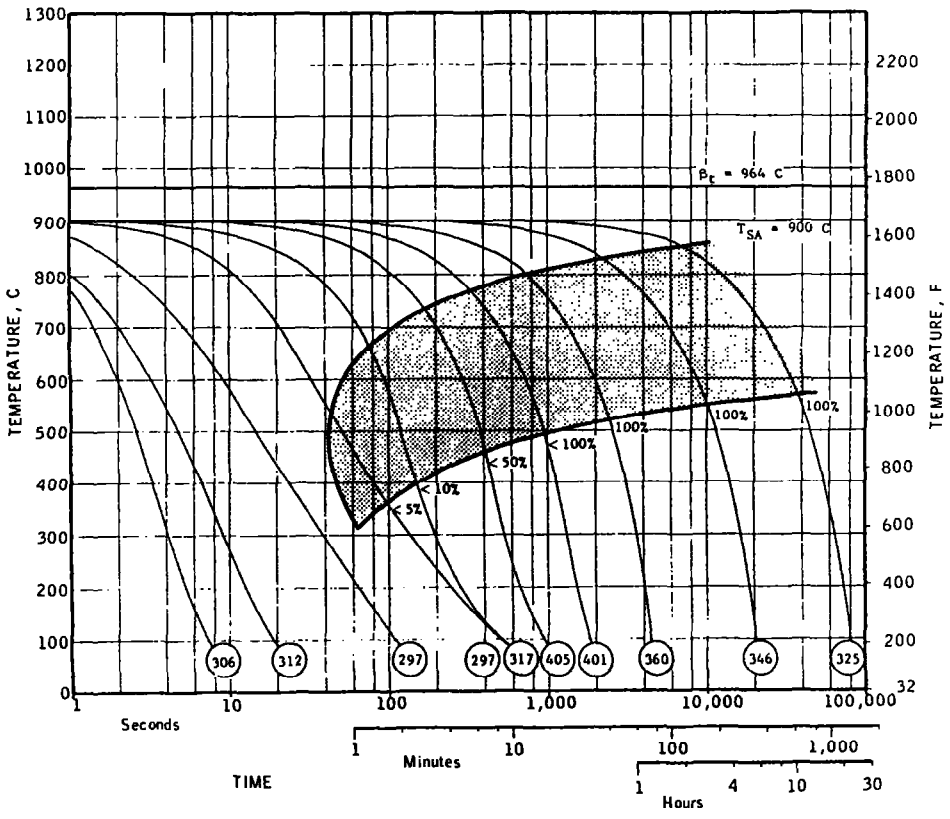
SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N

Treatment: Solution annealed at 900°C (1650°F) for 20 min



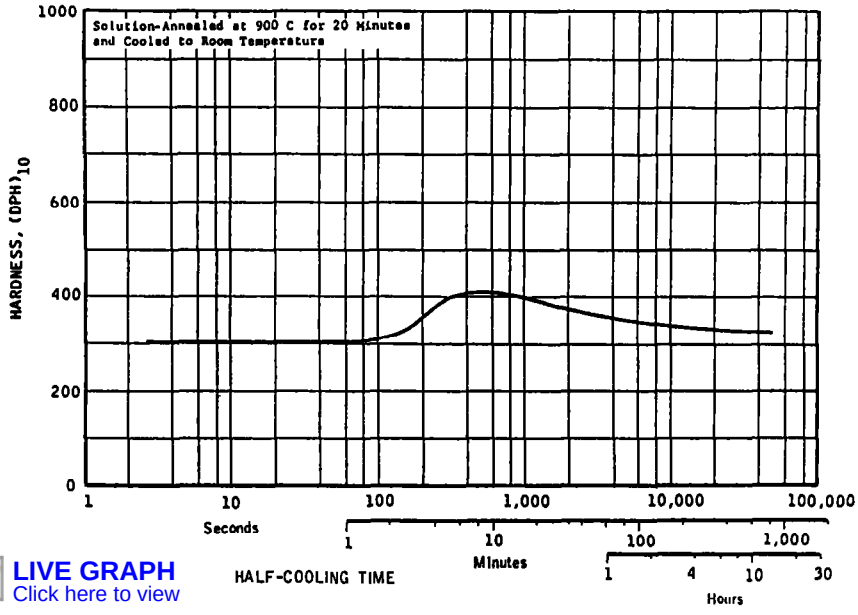
LIVE GRAPH
Click here to view

Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N
Treatment: Solution annealed at 900°C (1650°F) for 20 min, and cooled to room temperature



LIVE GRAPH
Click here to view

Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

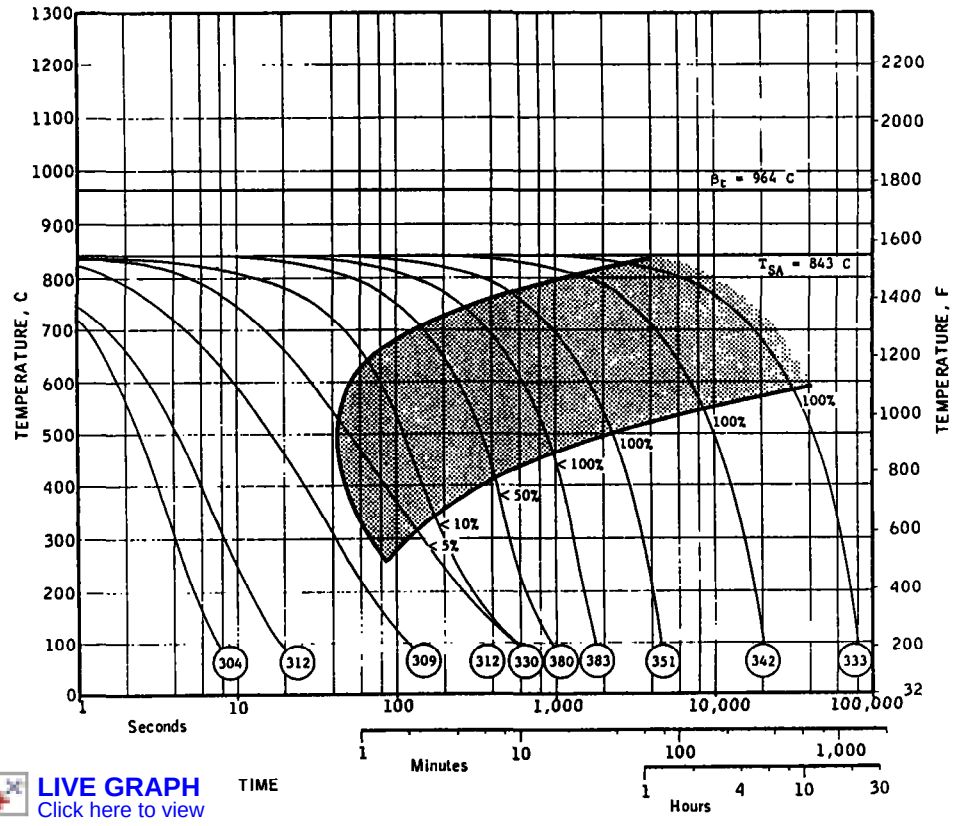
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N

Treatment: Solution annealed at 843°C (1550°F) for 20 min



LIVE GRAPH
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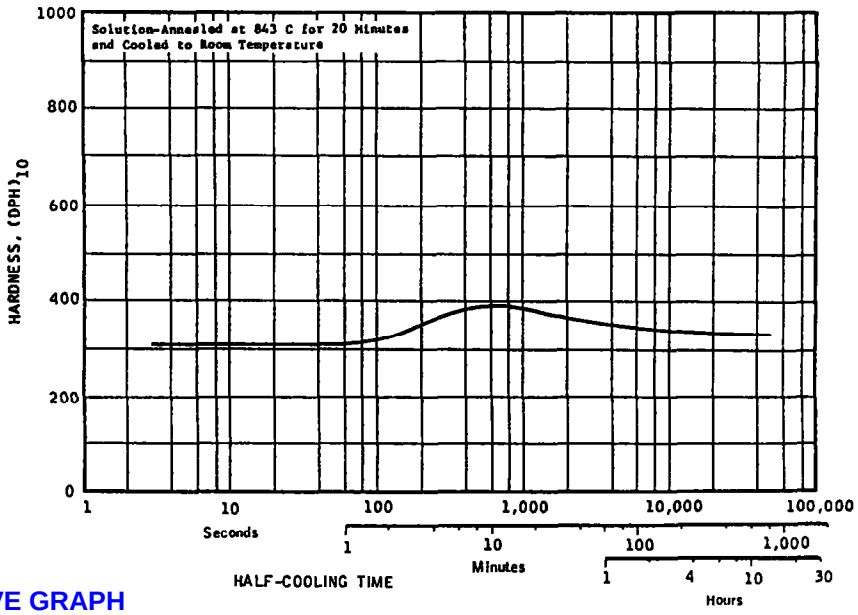
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17)

Composition: Ti - 4.52% Al - 2.41% Sn - 2.11% Zr - 3.78% Mo - 3.99% Cr - 0.063% O - 0.031% C - 0.102% Fe - 0.0010% N

Treatment: Solution annealed at 843°C (1550°F) for 20 min, and continuously cooled at various rates



LIVE GRAPH
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Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

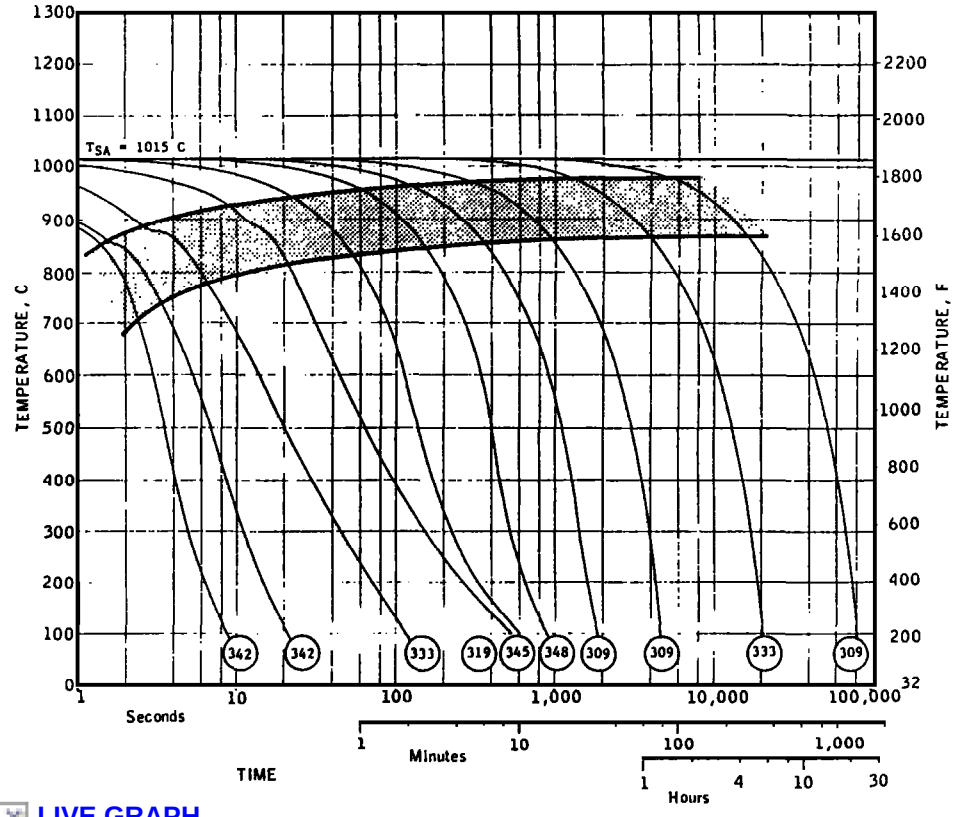
$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Titanium Alloy," Rp-27-72-04, Climax Molybdenum, 20 July 1972

Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si (Ti-11)

Composition: Ti - 5.86% Al - 2.05% Sn - 1.69% Zr - 1.01% Mo - 0.315% Bi - 0.102% Si - 0.067% Fe - 0.097% O - 0.006% N - 0.0180% H

Treatment: Solution annealed at 1015°C (1860°F) for 20 min



LIVE GRAPH
Click here to view

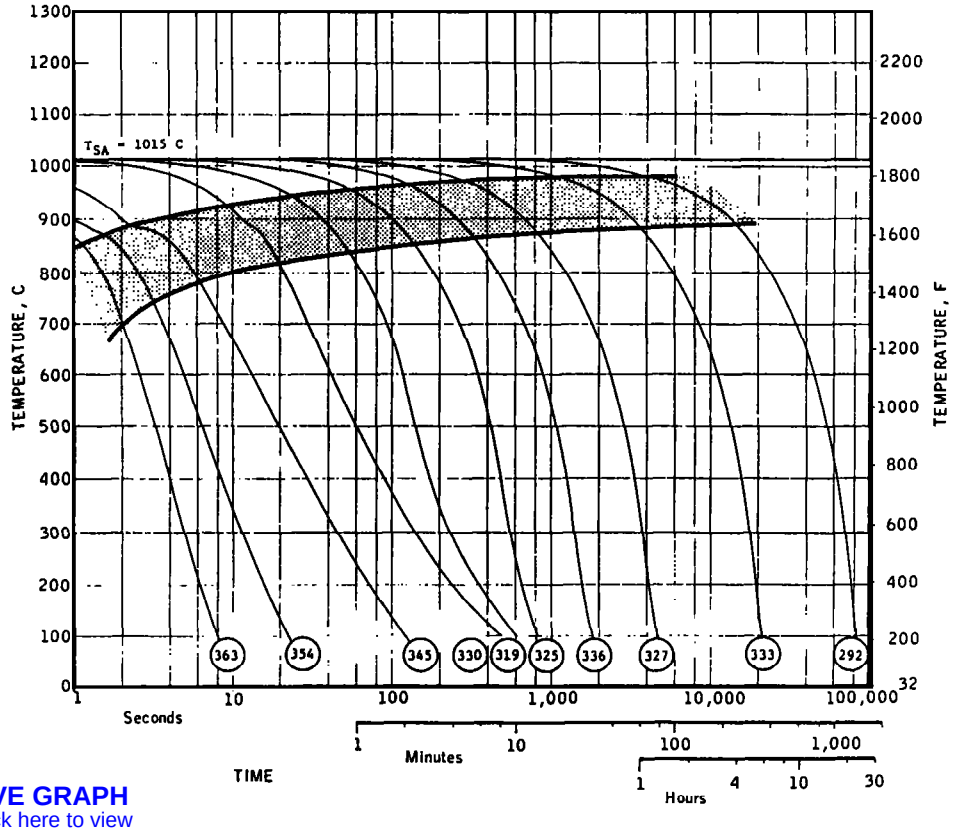
Continuous-cooling-transformation diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-11 (Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si) Titanium Alloy," Rp-27-72-06, Climax Molybdenum, 29 September 1972

Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si (Ti-11)

Composition: Ti - 5.86% Al - 2.05% Sn - 1.69% Zr - 1.01% Mo - 0.315% Bi - 0.102% Si - 0.067% Fe - 0.097% O - 0.006% N - 0.0180% H

Treatment: Solution annealed at 1015°C (1860°F) for 20 min, hardness values determined after additional aging by heating from room temperature up to 650°C (1200°F) at a rate of about 10°C/min, followed by vacuum cooling



LIVE GRAPH
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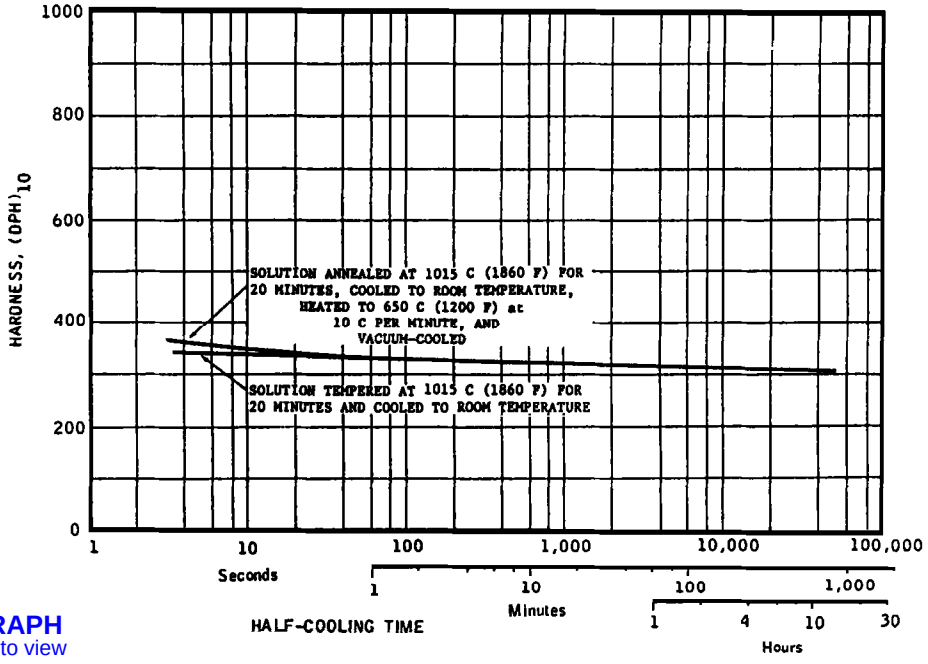
Continuous-cooling-transformation and aging diagram

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-11 (Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si) Titanium Alloy," Rp-27-72-06, Climax Molybdenum, 29 September 1972

Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si (Ti-11)

Composition: Ti - 5.86% Al - 2.05% Sn - 1.69% Zr - 1.01% Mo - 0.315% Bi - 0.102% Si - 0.067% Fe - 0.097% O - 0.006% N - 0.0180% H

Treatment: Solution annealed at 1015°C (1860°F) for 20 min, cooled to room temperature at various rates, and optionally aged by heating up to 650°C (1200°F) at a rate of about 10°/min, followed by vacuum cooling



LIVE GRAPH
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Hardness vs half cooling time *

*** NOTE: In relation to the applied operations of solution annealing and continuous cooling, half cooling time is determined as the time required to cool from the solution annealing temperature (T_{SA}) to the temperature that is midway between T_{SA} and room temperature, 25°C:**

$$T_{HC} = \frac{T_{SA} - 25}{2} + 25 = \frac{T_{SA} + 25}{2} \text{ (C)}$$

SOURCE: W.W. Cias, "Phase Transformation Kinetics, Microstructures, and Hardenability of the Ti-11 (Ti-6.25Al-2Sn-1.5Zr-1Mo-0.35Bi-0.1Si) Titanium Alloy," Rp-27-72-06, Climax Molybdenum, 29 September 1972

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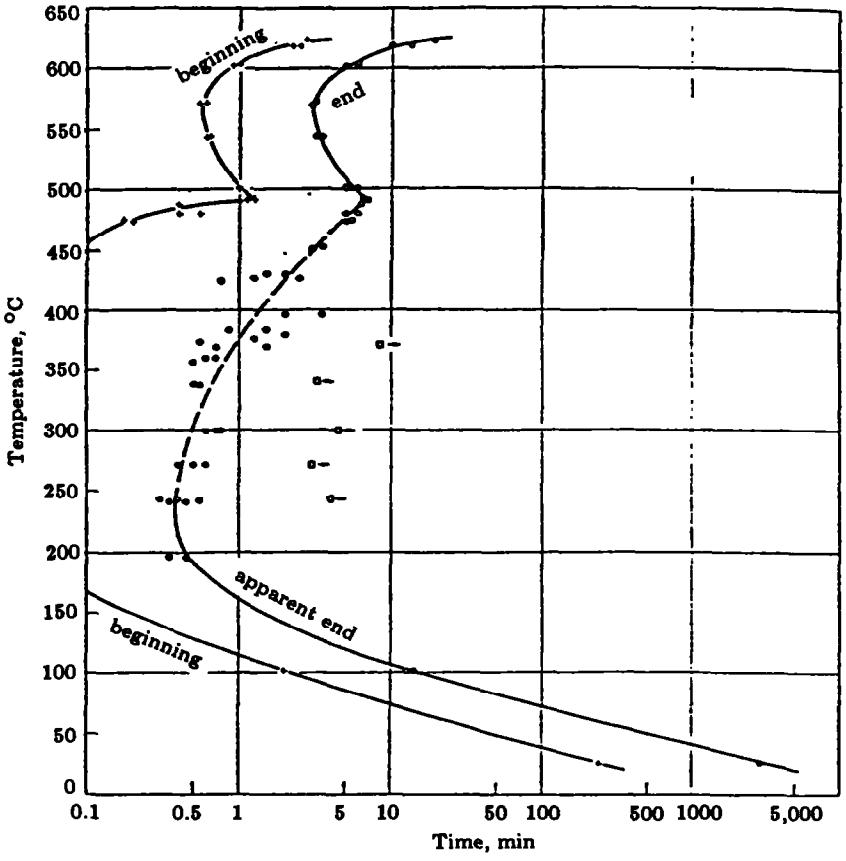
Uranium-Base Alloys

Uranium-Chromium Alloys

Composition: U - 0.3 at.% Cr

Treatment: Specimens were heated in a bath maintained at a beta-phase temperature of 700 to 725°C (1292 to 1337°F) for 5 min, then transferred quickly to a bath maintained at a desired lower temperature and held there until the specimen appeared to be fully transformed to alpha phase



LIVE GRAPH
Click here to view

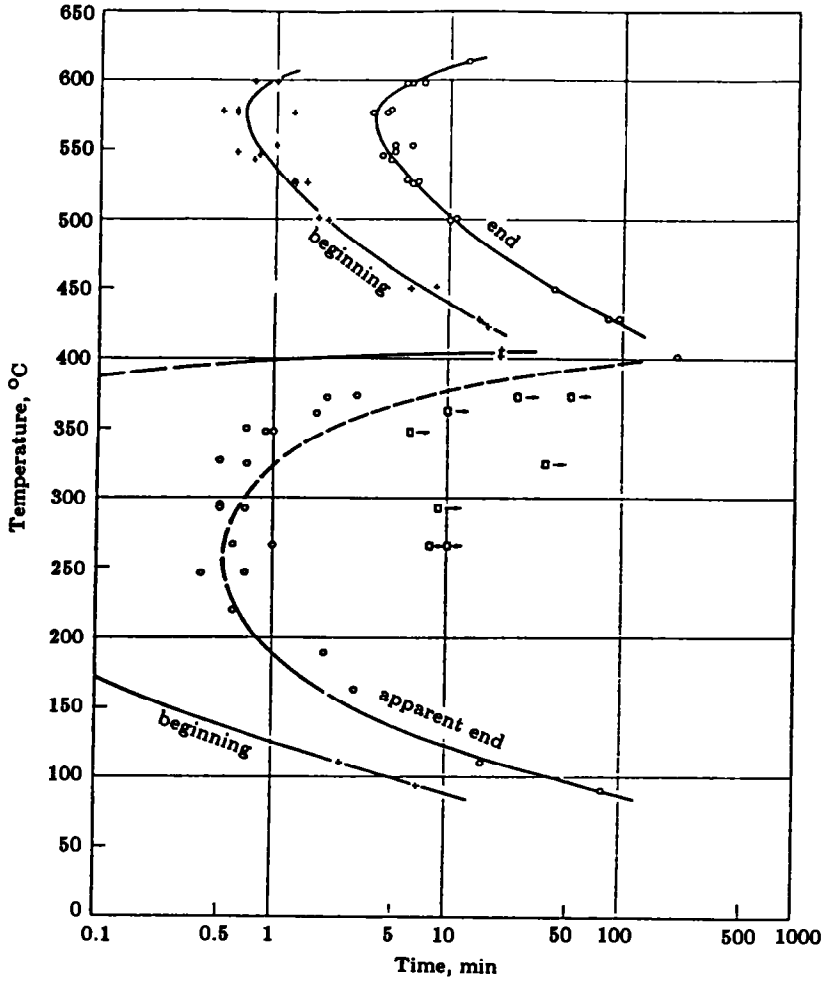
Time-temperature-transformation diagram

SOURCE: D.W. White, Jr., "Transformation Kinetics in Uranium-Chromium Alloys," Trans. AIME, Vol 203, November 1955, pp 1221-1228

Uranium-Chromium Alloys

Composition: U - 0.45 at.% Cr

Treatment: Specimens were heated in a bath maintained at a beta-phase temperature of 700 to 725°C (1292 to 1337°F) for 5 min, then transferred quickly to a bath maintained at a desired lower temperature and held there until the specimen appeared to be fully transformed to alpha phase



LIVE GRAPH
Click here to view

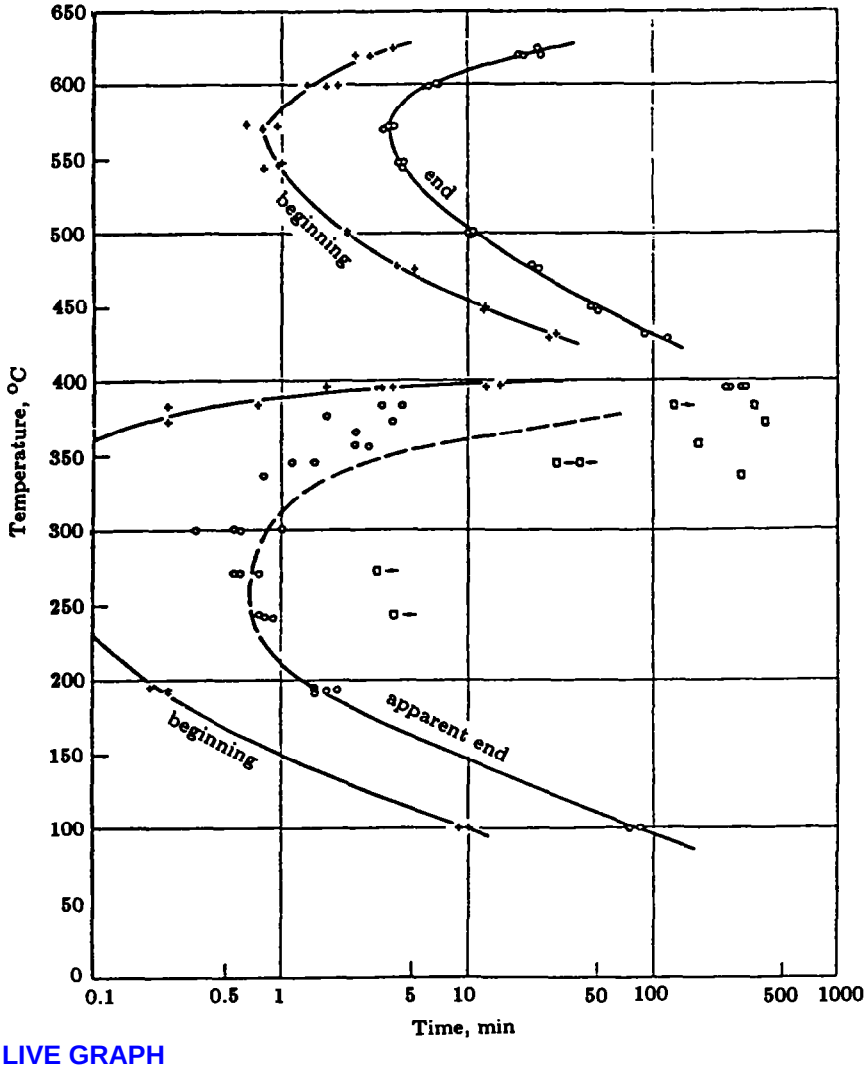
Time-temperature-transformation diagram

SOURCE: D.W. White, Jr., "Transformation Kinetics in Uranium-Chromium Alloys," Trans. AIME, Vol 203, November 1955, pp 1221-1228

Uranium-Chromium Alloys

Composition: U - 0.6 at.% Cr

Treatment: Specimens were heated in a bath maintained at a beta-phase temperature of 700 to 725°C (1292 to 1337°F) for 5 min, then transferred quickly to a bath maintained at a desired lower temperature and held there until the specimen appeared to be fully transformed to alpha phase



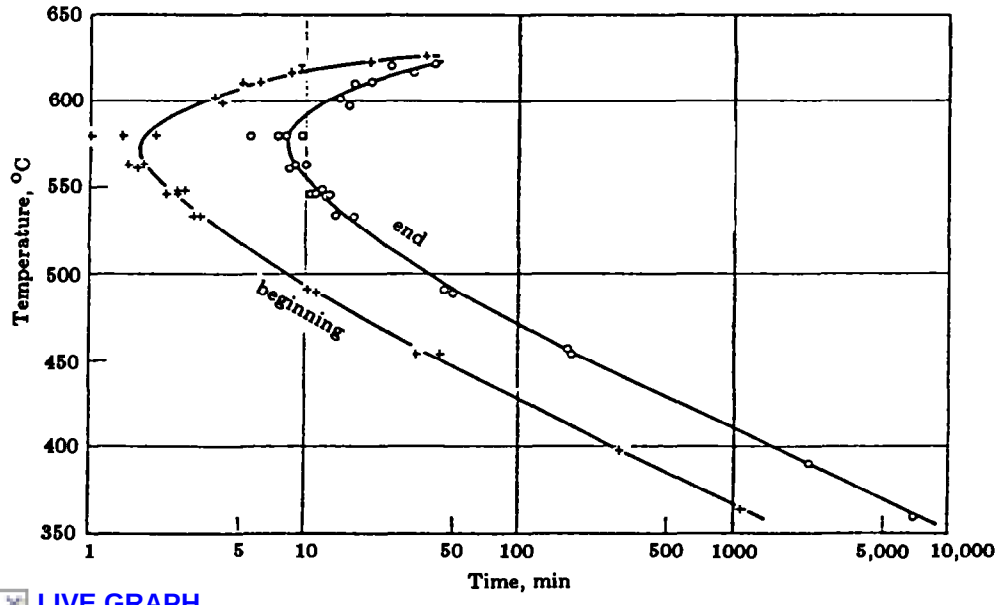
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D.W. White, Jr., "Transformation Kinetics in Uranium-Chromium Alloys," Trans. AIME, Vol 203, November 1955, pp 1221-1228

Uranium-Chromium Alloys

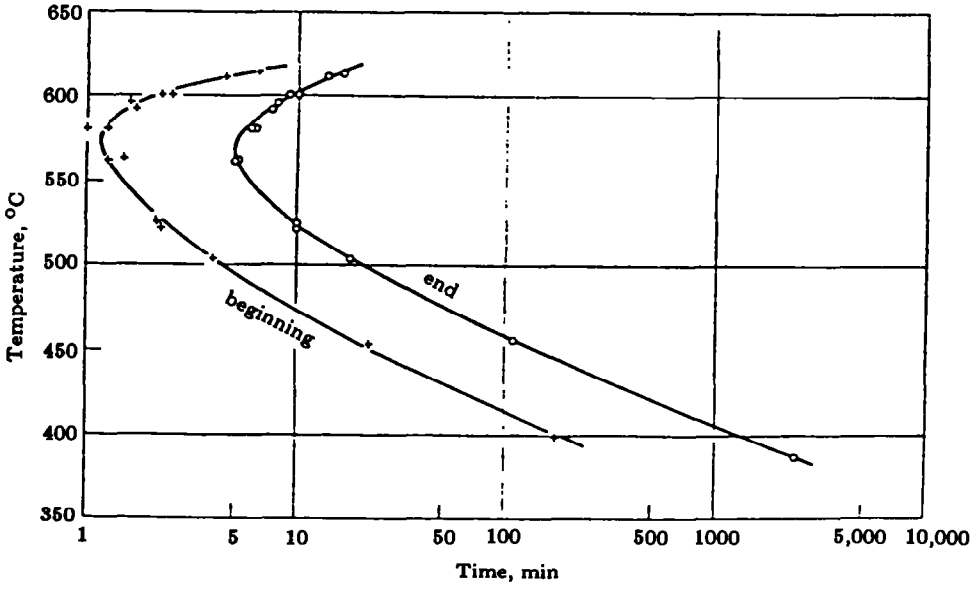
Composition: U - 1.8 at.% Cr
Treatment: Specimens were heated in a bath maintained at a beta-phase temperature of 700 to 725°C (1292 to 1337°F) for 5 min, then transferred quickly to a bath maintained at a desired lower temperature and held there until the specimen appeared to be fully transformed to alpha phase



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: U - 4.0 at.% Cr
Treatment: Specimens were heated in a bath maintained at a beta-phase temperature of 700 to 725°C (1292 to 1337°F) for 5 min, then transferred quickly to a bath maintained at a desired lower temperature and held there until the specimen appeared to be fully transformed to alpha phase



LIVE GRAPH
Click here to view

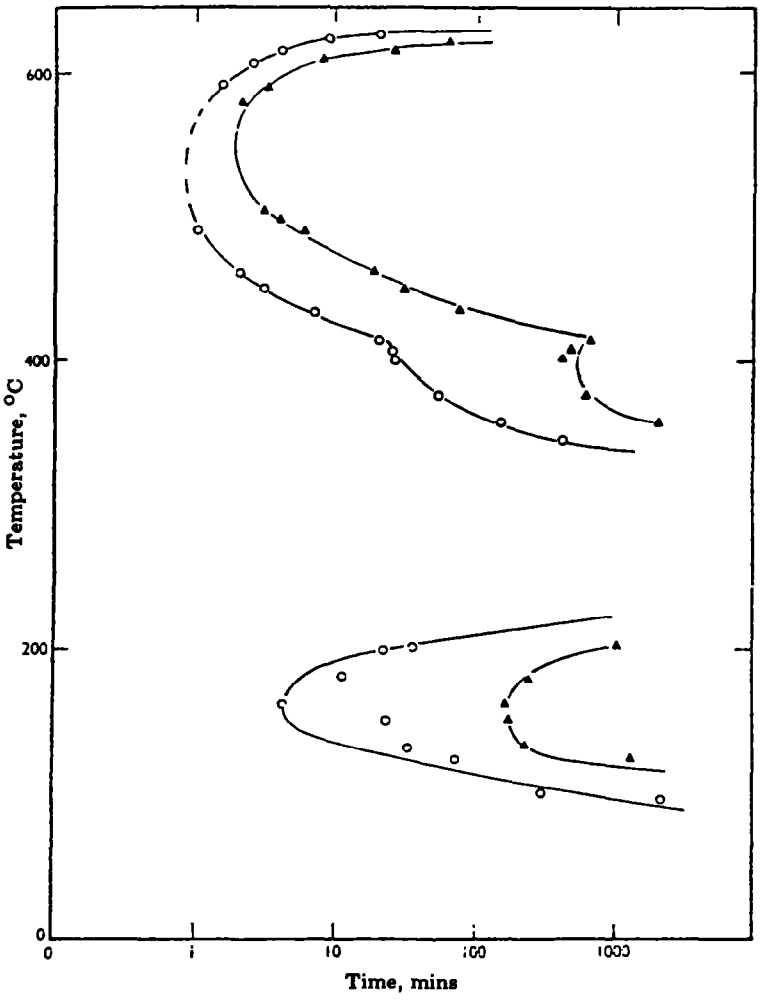
Time-temperature-transformation diagram

SOURCE: D.W. White, Jr., "Transformation Kinetics in Uranium-Chromium Alloys," Trans. AIME, Vol 203, November 1955, pp 1221-1228

Uranium-Chromium Alloys

Composition: U - 0.96% Cr

Treatment: Specimen homogenized at 800°C (1472°F) for 5 min. The transformation of the beta phase after gas-quenching to various alpha temperatures was followed by continuously monitoring the electrical resistivity during transformation, using a potential-drop method



Time-temperature-transformation diagram
After quenching from 700°C (1292°F)

LEGEND:

Broken line = the temperature range over which the resistivity change is too small to give meaningful results

Open circles = times for 5% transformation

Closed triangles = times for 95% transformation

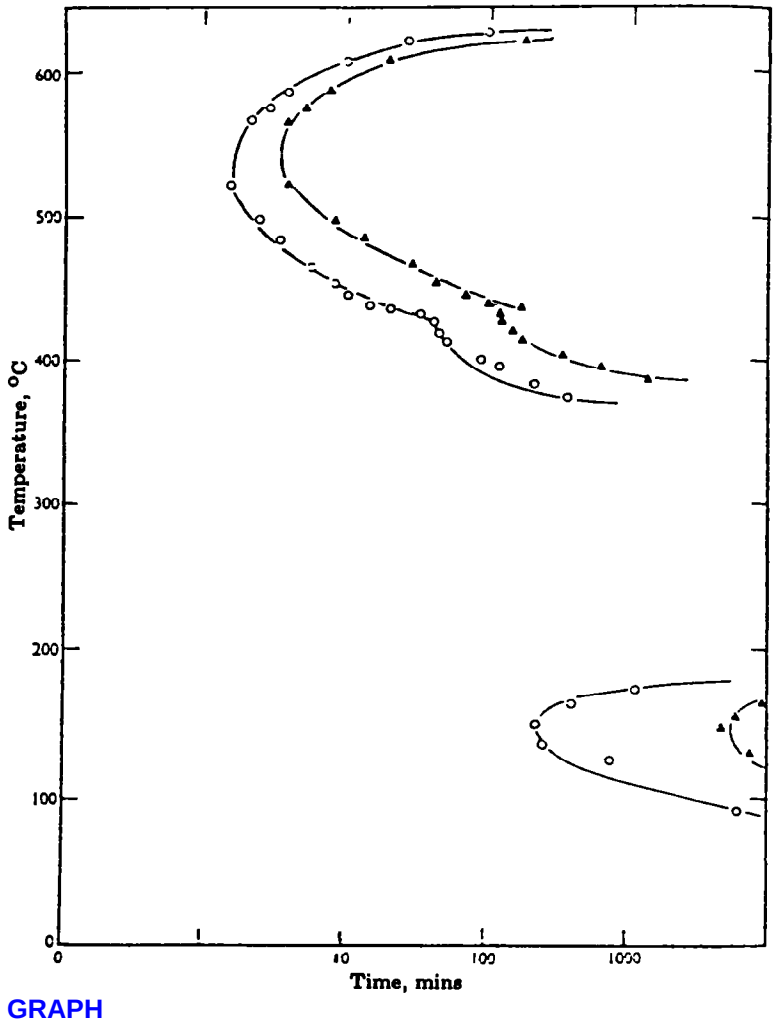
LIVE GRAPH
Click here to view

SOURCE: J. Burke, M.A. Evans, "Time/Temperature/Transformation Characteristics of Uranium-Chromium Alloys," Journal of the Institute of Metals, Vol 99, 1971, pp 315-318

Uranium-Chromium Alloys

Composition: U - 0.96% Cr

Treatment: Specimen homogenised at 800°C (1472°F) for 5 min. The transformation of the beta phase after gas-quenching to various alpha temperatures was followed by continuously monitoring the electrical resistivity during transformation, using a potential-drop method



LIVE GRAPH
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Time-temperature-transformation diagram
After quenching from 740°C (1364°F)

LEGEND:

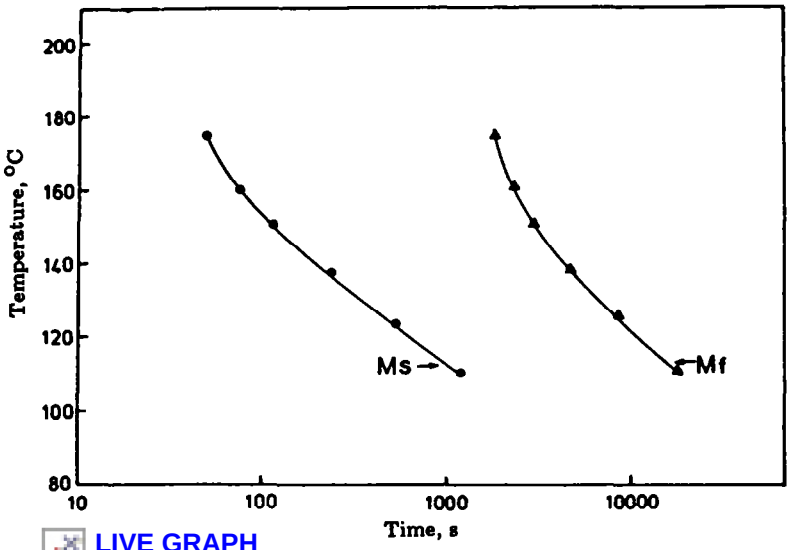
Open circles = times for 5% transformation

Closed triangles = times for 95% transformation

SOURCE: J. Burke, M.A. Evans, "Time/Temperature/Transformation Characteristics of Uranium-Chromium Alloys," Journal of the Institute of Metals, Vol 99, 1971, pp 315-318

Uranium-Gallium Alloys

Composition: U - 1.6 at.% Ga
Treatment: Samples were solution annealed at 720°C (1328°F) for 15 min, water quenched, then aged isothermally



LIVE GRAPH
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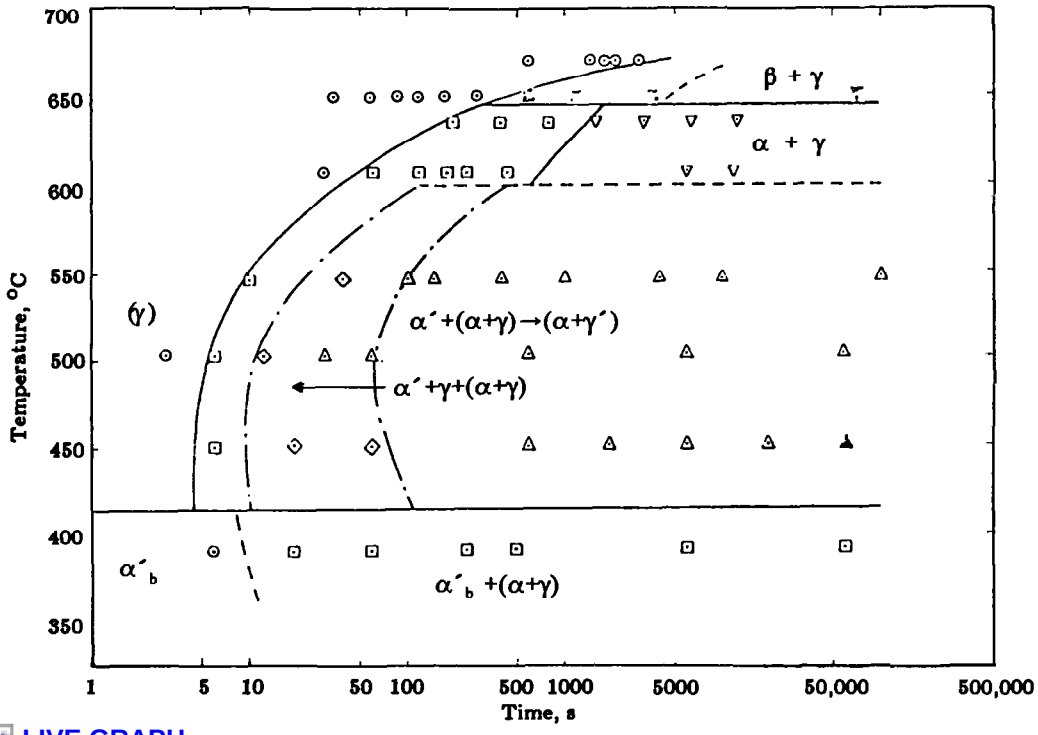
Time-temperature-aging

SOURCE: D. Dayan, H. Klimker, M. Talianker, M.P. Dariel, "The Kinetics of the Isothermal Martensitic Beta to Alpha Transformation in U(Ga) Alloys," Met. Trans. A, Vol 21A, August 1990, pp 2125-2129

Uranium-Molybdenum Alloys

Composition U - 6 at.% (2.5 wt.%) Mo
Treatment: Specimens were heated in a lead bath at a temperature of 700 to 760°C (1292 to1400°F) for 15 min, and isothermally transformed at 670 to 390°C (1238 to 734°F)



LIVE GRAPH
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Time-temperature-transformation diagram
Determined by metallography and hardness measurements

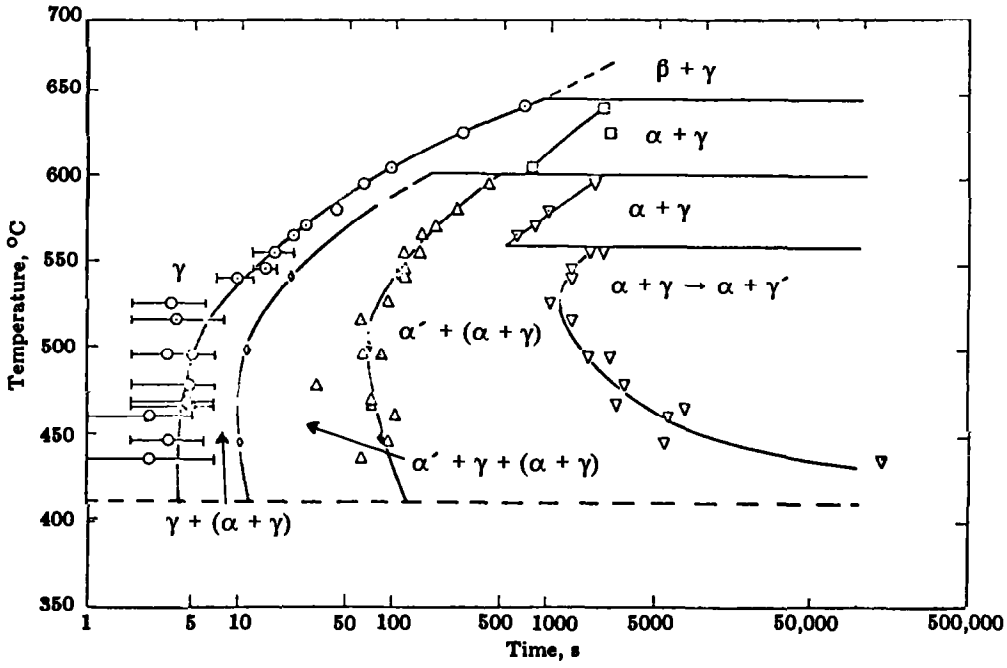
LEGEND:

- ⊙ BANDED, QUENCHED γ
- ▣ β + QUENCHED γ
- ⊡ (α + γ) + QUENCHED γ
- ▽ (α + γ)
- ◇ (α + γ) + QUENCHED γ + GRANULAR α′
- △ (α + γ) + GRANULAR α′
- ▼ (β + γ)
- ▲ (α + γ) NODULAR
- —·— START & FINISH OF STEEP HARDNESS RISE

SOURCE: B.W. Howlett, A.J. Eycott, I.K. Kang, D.R.F. West, "The Kinetics of the Isothermal Decomposition of a Gamma-Phase Uranium-6 Atomic % Molybdenum Alloy," Journal of Nuclear Materials, Vol 9, No. 2, 1963, pp 143-154

Uranium-Molybdenum Alloys

Composition U - 6 at.% (2.5% wt.) Mo
Treatment: Specimens were heated in a lead bath at a temperature of 700 to 760°C (1292 to1400°F) for 15 min, and isothermally transformed at 670 to 390°C (1238 to 734°F)



LIVE GRAPH
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Time-temperature-transformation diagram
Determined by dilatometry and hardness measurements

LEGEND:

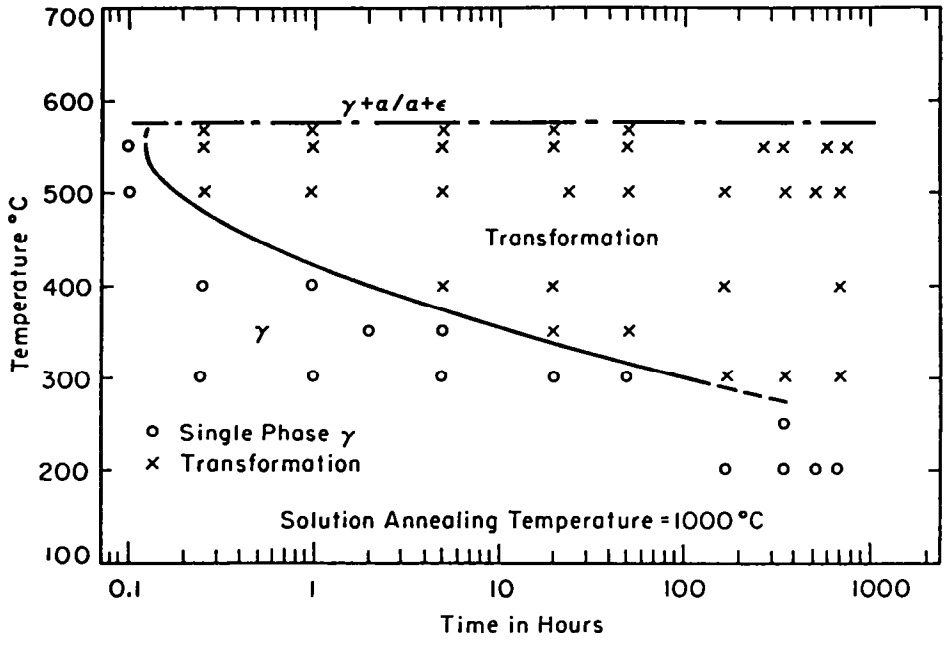
- ○ **Start of transformation**
- □ **End of transformation when only one stage present**
- △ **Start of second stage of transformation**
- ▽ **End of second stage of transformation**
- ◊ **Start of steep hardness rise**
- ♦ **End of steep hardness rise**

SOURCE: B.W. Howlett, A.J. Eycott, I.K. Kang, D.R.F. West, "The Kinetics of the Isothermal Decomposition of a Gamma-Phase Uranium-6 Atomic % Molybdenum Alloy," Journal of Nuclear Materials, Vol 9, No. 2, 1963, pp 143-154

Uranium-Molybdenum Alloys

Composition: U - 5.4% Mo

Treatment: Solution annealed at 1000°C (1830°F). The maximum transformation annealing time was generally 1000 h. However, several resistivity specimens were annealed for 2000 h at 400°C (750°F) and below. For most transformation annealing treatments, the encapsulated samples were quenched directly into lead (or lead-tin) baths, held for the desired time and water-quenched



LIVE GRAPH
Click here to view

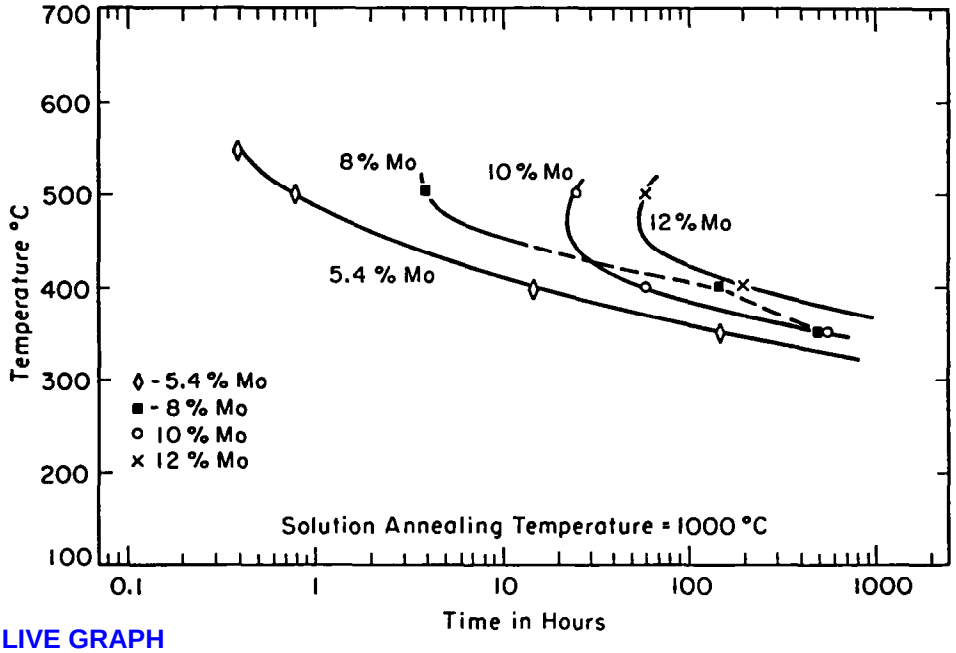
Time-temperature-transformation diagram

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Molybdenum Alloys," Trans. ASM, Vol 49, 1957, pp 598-621

Uranium-Molybdenum Alloys

Composition: U - 5.4 to 12% Mo

Treatment: Solution annealed at 1000°C (1830°F). The maximum transformation annealing time was generally 1000 h. However, several resistivity specimens were annealed for 2000 h at 400°C (750°F) and below. For most transformation annealing treatments, the encapsulated samples were quenched directly into lead (or lead-tin) baths, held for the desired time and water-quenched



LIVE GRAPH
Click here to view

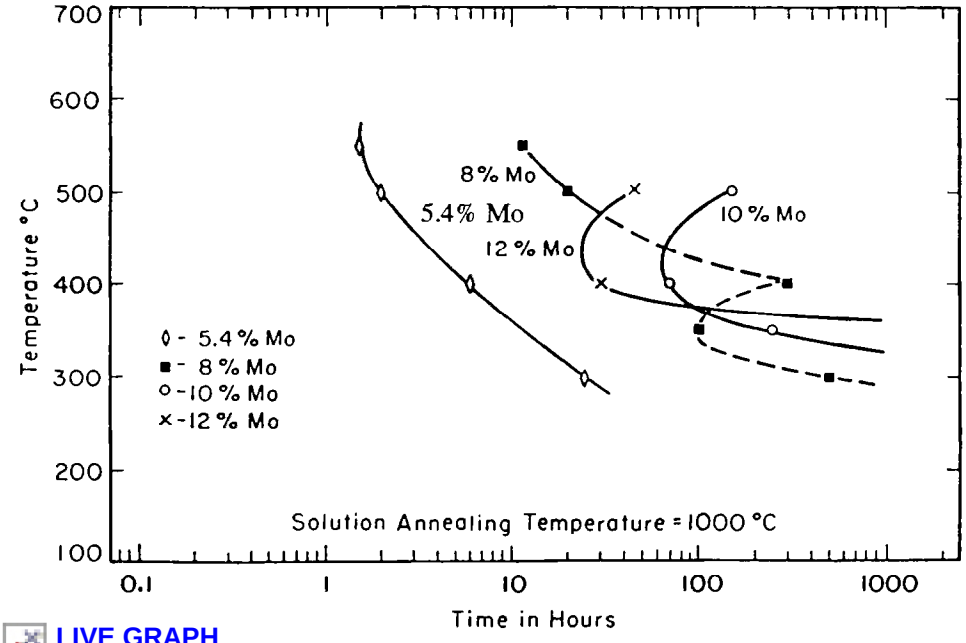
Time-temperature-transformation diagram
Beginning of transformation based on resistivity changes

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Molybdenum Alloys," Trans. ASM, Vol 49, 1957, pp 598-621

Uranium-Molybdenum Alloys

Composition: U - 5.4 to 12% Mo

Treatment: Solution annealed at 1000°C (1830°F). The maximum transformation annealing time was generally 1000 h. However, several resistivity specimens were annealed for 2000 h at 400°C (750°F) and below. For most transformation annealing treatments, the encapsulated samples were quenched directly into lead (or lead-tin) baths, held for the desired time and water-quenched



LIVE GRAPH
Click here to view

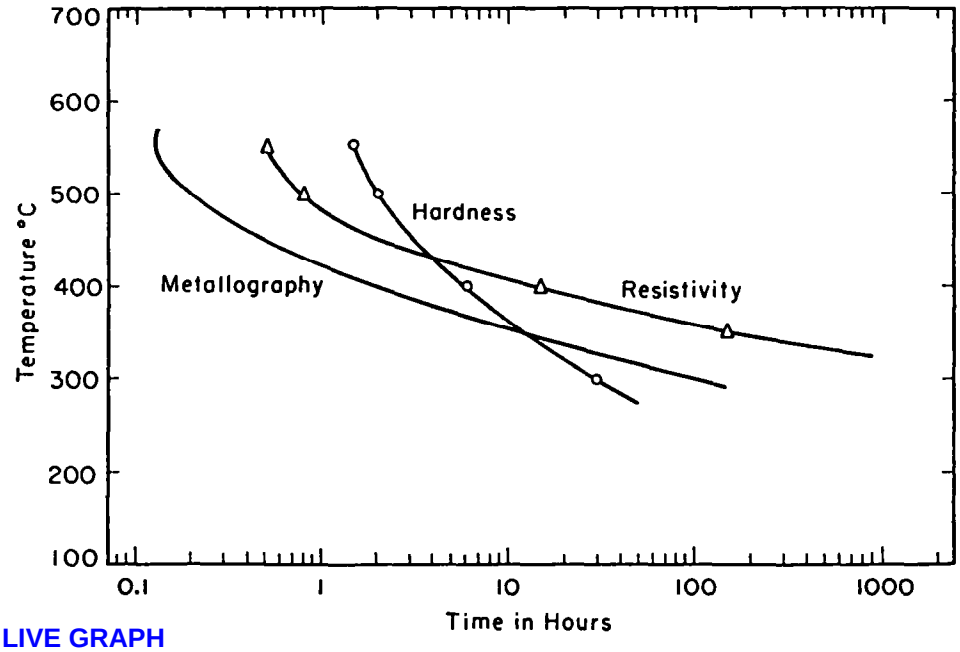
Time-temperature-transformation diagram
Start of transformation based on hardness changes

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Molybdenum Alloys," Trans. ASM, Vol 49, 1957, pp 598-621

Uranium-Molybdenum Alloys

Composition: U - 5.4% Mo

Treatment: Solution annealed at 1000°C (1830°F). The maximum transformation annealing time was generally 1000 h. However, several resistivity specimens were annealed for 2000 h at 400°C (750°F) and below. For most transformation annealing treatments, the encapsulated samples were quenched directly into lead (or lead-tin) baths, held for the desired time and water-quenched



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation as determined by various methods

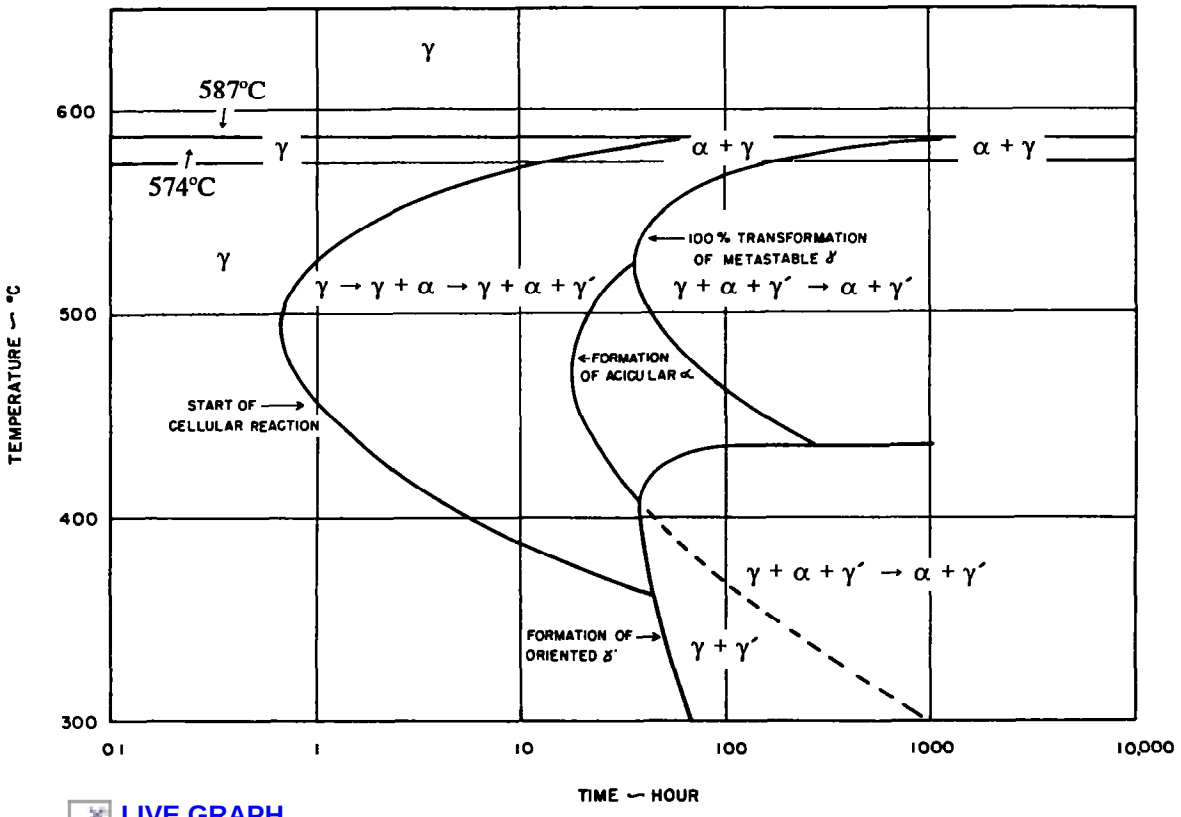
LIVE GRAPH
Click here to view

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Molybdenum Alloys," Trans. ASM, Vol 49, 1957, pp 598-621

Uranium-Molybdenum Alloys

Composition: U - 8% Mo

Treatment: The encapsulated specimens were solution heat treated at 980°C (1796°F) for 4 h and water quenched without breaking the capsules, then reheated to 900°C (1652°F) for 1 h prior to transferring them directly to the desired transformation temperature. Conventional salt baths were used with a temperature control of +/-3°. After holding the desired time, the capsules were quenched to room temperature by breaking them under water



LIVE GRAPH
Click here to view

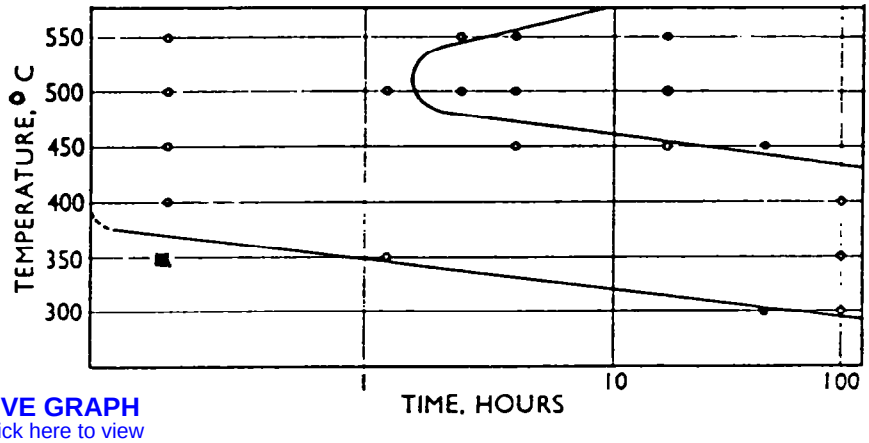
Time-temperature-transformation diagram
Quenched to temperature from 900°C (1652°F)

SOURCE: P.E. Repas, R.H. Goodenow, R.F. Hehemann, "Transformation Characteristics of U-Mo and U-Mo-Ti Alloys," Trans. ASM, Vol 57, 1964, pp 150-163

Uranium-Molybdenum Alloys

Composition: U - 8% Mo

Treatment: After homogenization, the silica tubes containing the specimens were heated at 950°C (1742°F) for 1 h in a resistance furnace and water-quenched, giving solid samples in the gamma phase



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Determined by X-ray powder photography

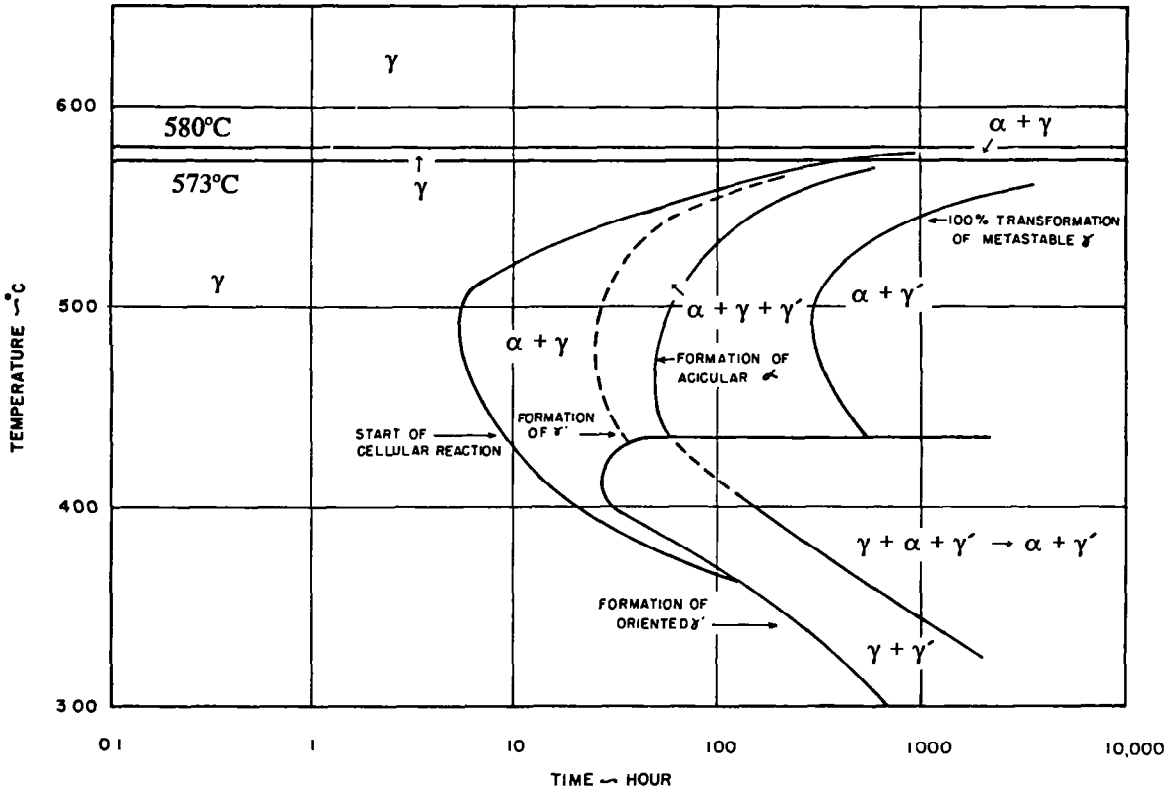
LEGEND:
■ γ ○ α + γ ● α + γ + γ′

SOURCE: Y. Goldstein, A. Bar-Or, "Decomposition of Gamma Phase in Uranium Alloys Containing 8, 10.8, and 14.3 wt.-% Molybdenum," Journal of the Institute of Metals, Vol 95, 1967, pp 17-21

Uranium-Molybdenum Alloys

Composition: U - 10% Mo

Treatment: The encapsulated specimens were solution heat treated at 980°C (1796°F) afor 4 h and water quenched without breaking the capsules, then reheated to 900°C (1652°F) for 1 h prior to transferring them directly to the desired transformation temperature. Conventional salt baths were used with a temperature control of +/-3°. After holding the desired time, the capsules were quenched to room temperature by breaking them under water



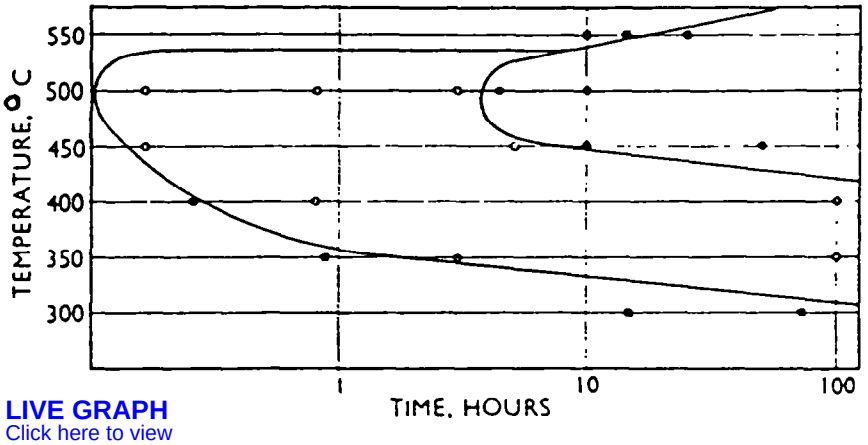
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Quenched to temperature from 900°C (1652°F)

SOURCE: P.E. Repas, R.H. Goodenow, R.F. Hehemann, "Transformation Characteristics of U-Mo and U-Mo-Ti Alloys," Trans. ASM, Vol 57, 1964, pp 150-163

Uranium-Molybdenum Alloys

Composition: U - 10.8% Mo
Treatment: After homogenization, the silica tubes containing the specimens were heated at 950°C (1742°F) for 1 h in a resistance furnace and water-quenched, giving solid samples in the gamma phase

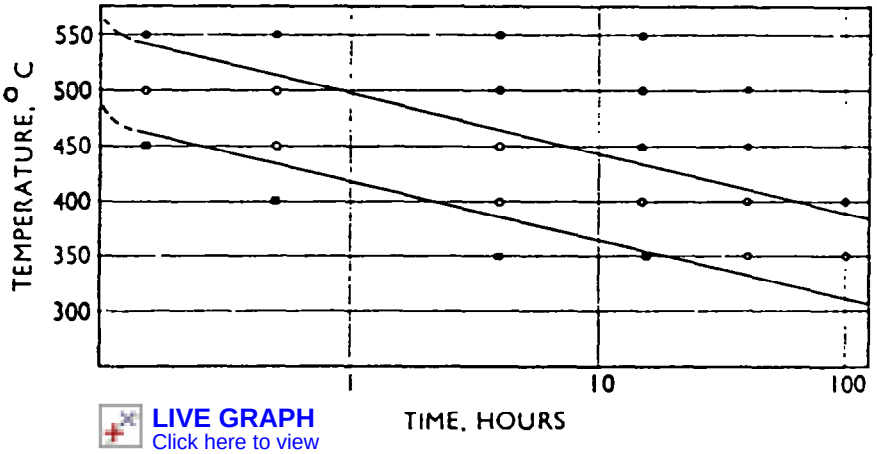


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Determined by X-ray powder photography

LEGEND:
■ γ ○ α + γ ● α + γ + γ′

Composition: U - 14.3% Mo
Treatment: After homogenization, the silica tubes containing the specimens were heated at 950°C (1742°F) for 1 h in a resistance furnace and water-quenched, giving solid samples in the gamma phase



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Determined by X-ray powder photography

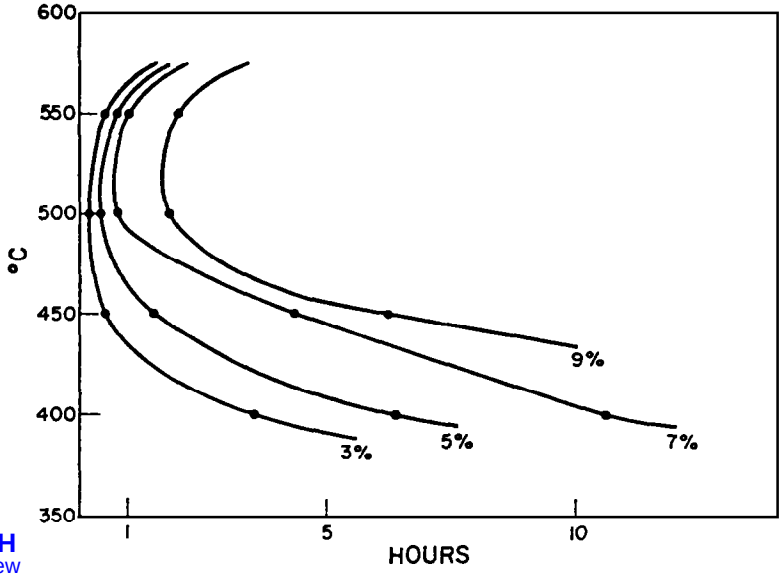
LEGEND:
■ γ ○ α + γ ● α + γ + γ′

SOURCE: Y. Goldstein, A. Bar-Or, "Decomposition of Gamma Phase in Uranium Alloys Containing 8, 10.8, and 14.3 wt.-% Molybdenum," Journal of the Institute of Metals, Vol 95, 1967, pp 17-21

Uranium-Molybdenum Alloys

Composition: U - 16.1% Mo

Treatment: Samples were wrapped in tantalum foil, sealed in evacuated (5 x 10^{-6} mm of Hg) quartz capsules, and annealed at 1110°C (2030°F) prior to being transferred directly to the transformation temperature



LIVE GRAPH
Click here to view

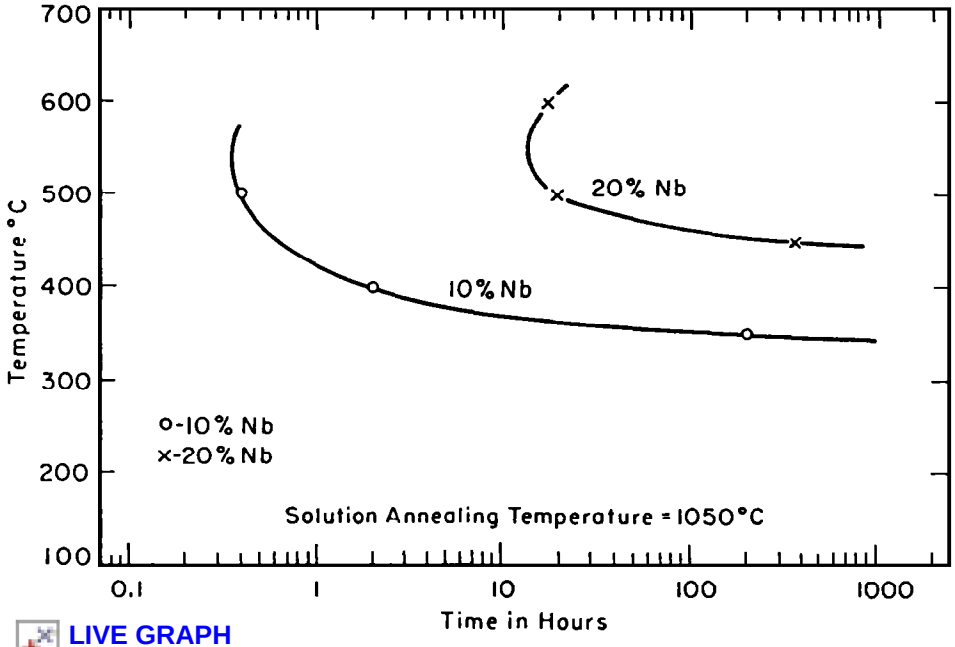
Time-temperature-transformation diagram

During the early stage of transformation, the fastest rate of alpha phase precipitation occurs at 500°C (932°F)

SOURCE: D. Kramer, C.G. Rhodes, "The Precipitation of Metastable Alpha Phase During the Gamma to Gamma Prime Transformation in Uranium-16 wt pct Molybdenum," Trans. AIME, Vol 224, October 1962, pp 1015-1020

Uranium-Niobium Alloys

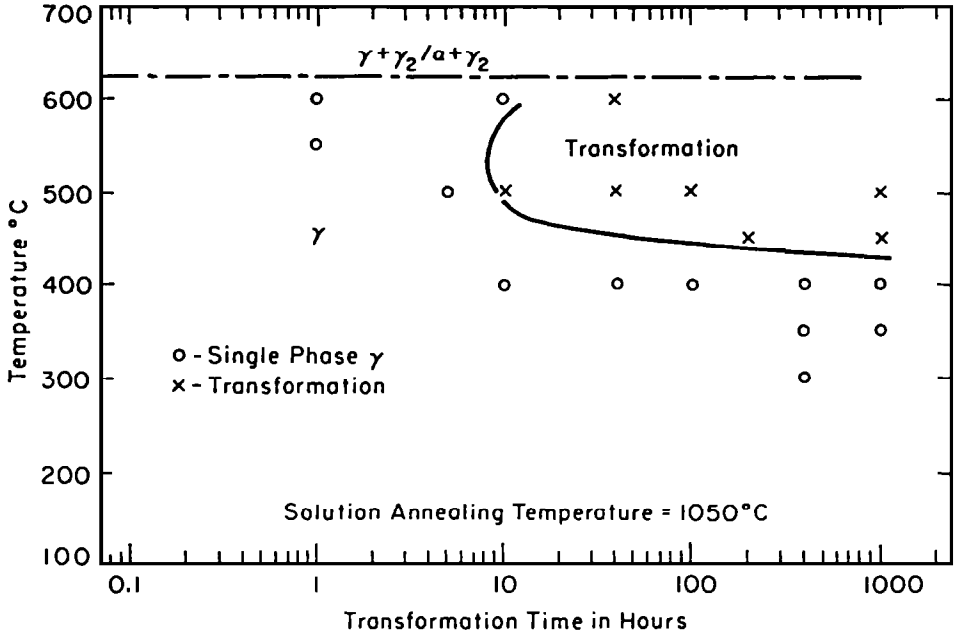
Composition: U - 10% Nb
Composition: U - 20% Nb
Treatment: Solution annealed at 1050°C (1920°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation (resistivity)

Composition: U - 20% Nb
Treatment: Solution annealed at 1050°C (1920°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



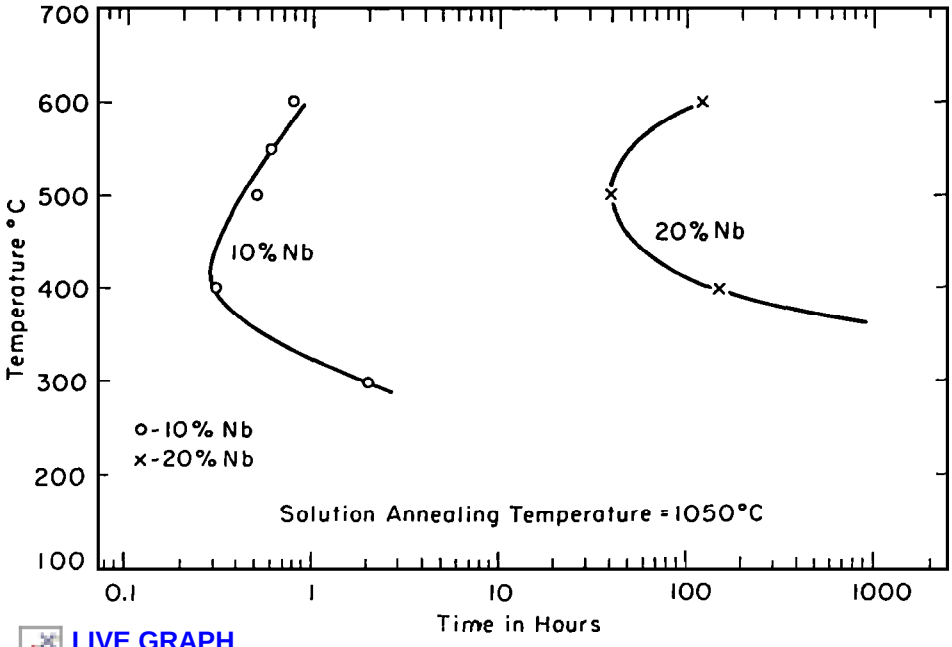
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation (metallography)

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. ASM, Vol 49, 1957, pp 576-597

Uranium-Niobium Alloys

Composition: U - 10% Nb
Composition: U - 20% Nb
Treatment: Solution annealed at 1050°C (1920°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



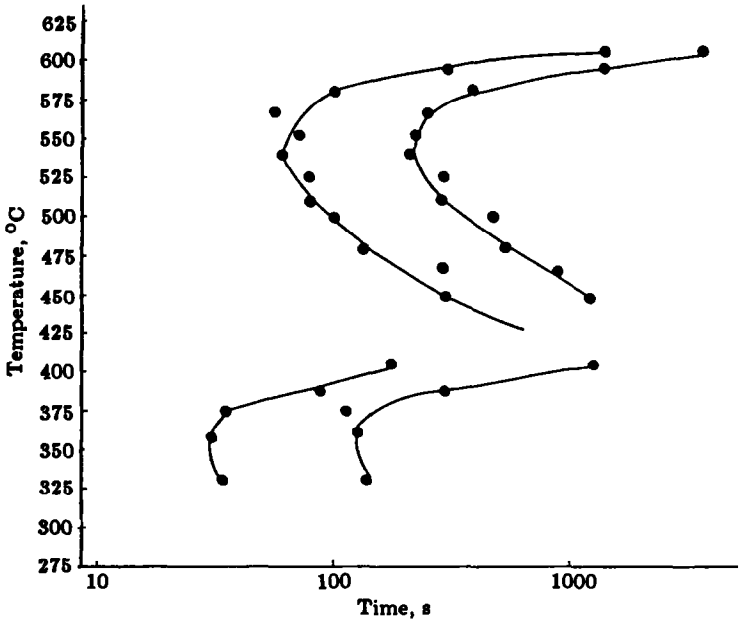
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation based on hardness

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. ASM, Vol 49, 1957, pp 576-597

Uranium-Chromium-Molybdenum Alloy

Composition: U - 0.25 at.% Cr - 0.5 at.% Mo
Treatment: Specimens were held at the soaking temperature of 720°C (1328°F) for 30 min, transferred rapidly to an intermediate-temperature lead bath, or a lower-temperature lead-tin eutectic bath; the two baths covered transformation ranges from 600 to 200°C (1112 to 392°F)

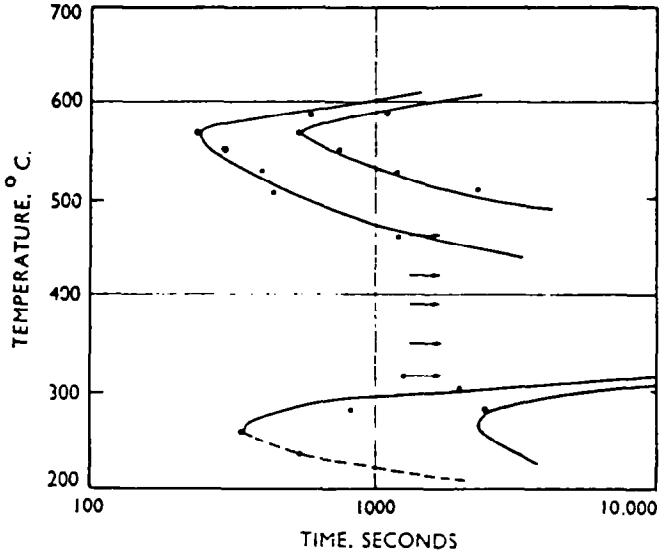


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

M.M. Haberlin, G.F. Slattery, "Transformation Kinetics of the Beta to Alpha Phase Change in a Uranium-Chromium-Molybdenum Alloy," proceedings of an International Symposium held in Manchester, 3-5 July 1968, The Mechanism of Phase Transformations in Crystalline Solids, Monograph and Report Series No. 33, The Institute of Metals, 1969, pp 254-259

Composition: U - 0.5% Cr - 0.5% Mo



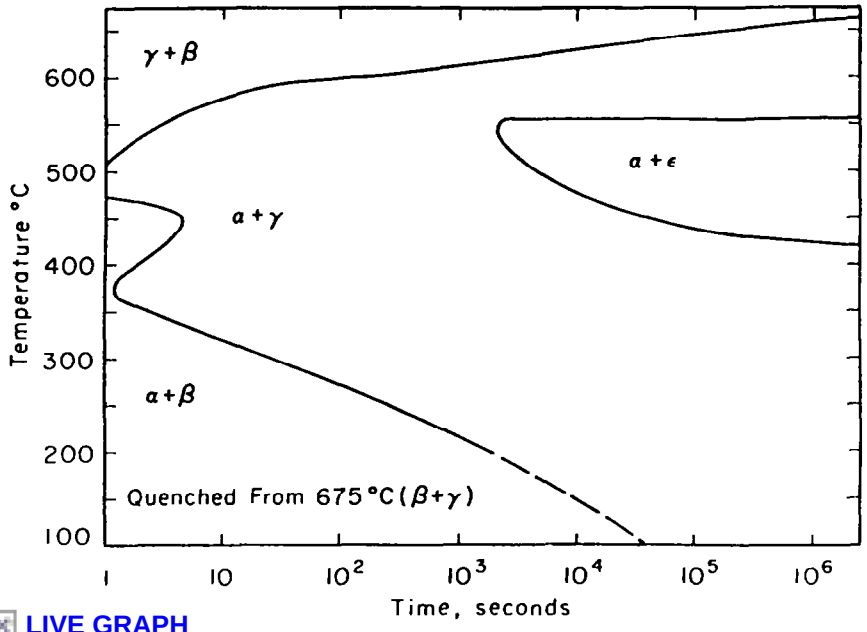
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: Jepson et al., proceedings of the 1958 Geneva Conference on Peaceful Uses of Atomic Energy, Paper 27, p 23, as published in an article by H.M. Finniston, "Metallurgical Developments Outlined at the 1958 Geneva Conference on Peaceful Uses of Atomic Energy," Journal of the Institute of Metals, Vol 87, 1958, pp 360-375

Uranium-Molybdenum-Niobium Alloys

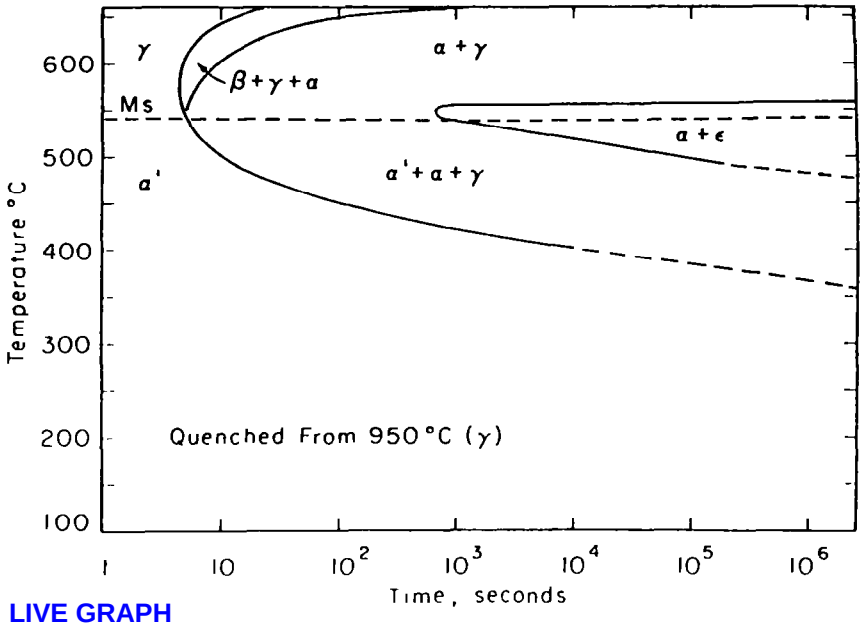
Composition: U - 0.5% Nb - 0.5% Mo
Treatment: Solution treated and quenched from 675°C (1245°F)



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: U - 0.5% Nb - 0.5% Mo
Treatment: Solution treated and quenched from 950°C (1740°F)



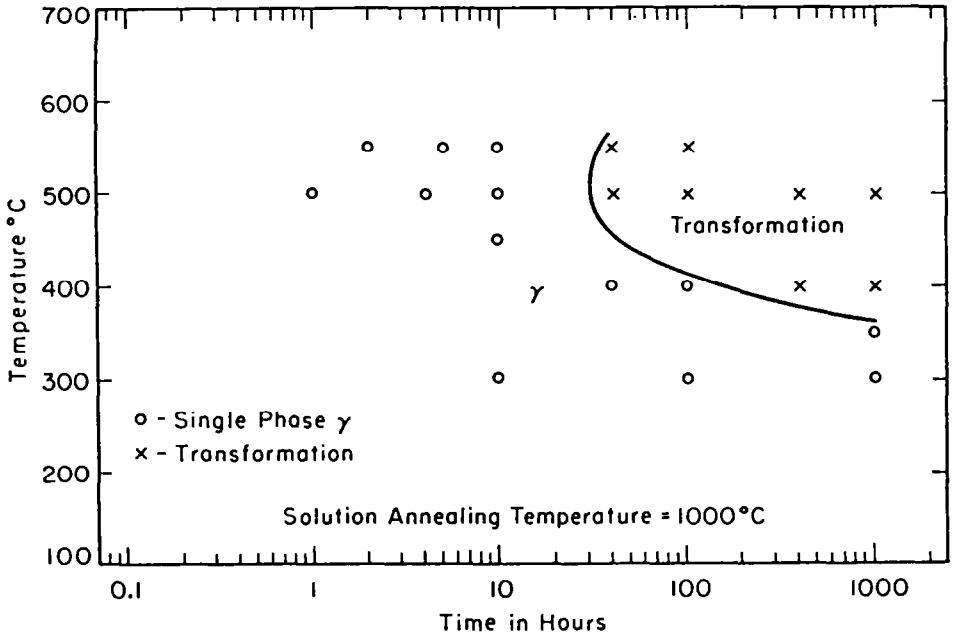
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: E.G. Zukas, "Transformation Kinetics and Mechanical Properties of Uranium-0.5 W/O Columbium-0.5 W/O Molybdenum Alloy," Trans. ASM, Vol 52, 1960, pp 797-811

Uranium-Molybdenum-Niobium Alloys

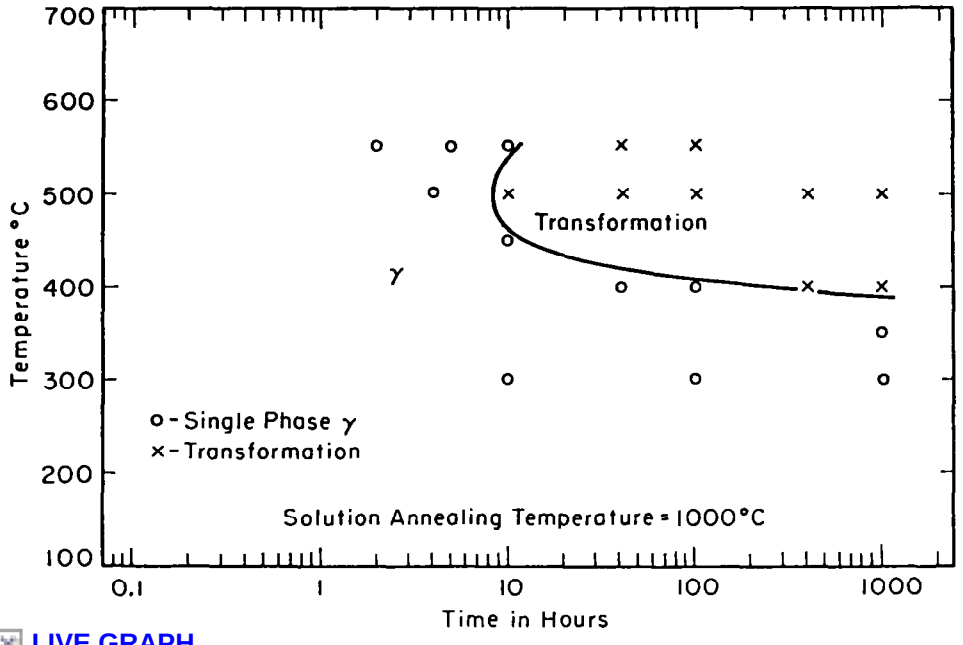
Composition: U - 8% Mo - 1.5% Nb
Treatment: Solution annealed at 1000°C (1830°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation (metallography)

Composition: U - 8% Mo - 3% Nb
Treatment: Solution annealed at 1000°C (1830°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



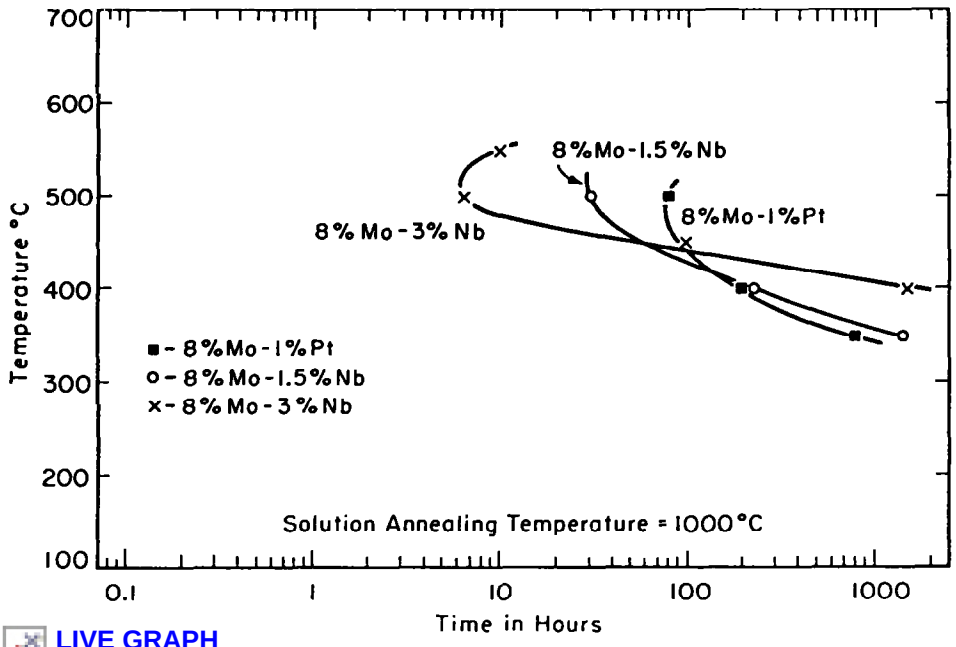
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation (metallography)

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. ASM, Vol 49, 1957, pp 576-597

Uranium-Molybdenum-Niobium *and* Uranium-Molybdenum-Platinum Alloys

Composition: U - 8% Mo - 1.5% Nb
Composition: U - 8% Mo - 3% Nb
Composition: U - 8% Mo - 1% Pt
Treatment: Solution annealed at 1000°C (1830°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



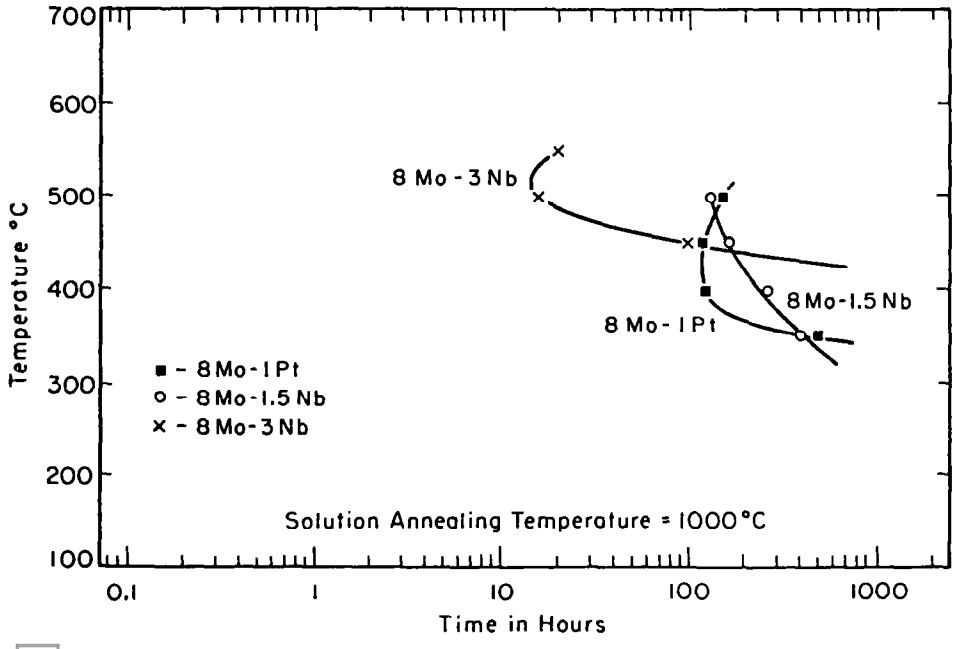
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Start of transformation (resistivity)

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. ASM, Vol 49, 1957, pp 576-597

Uranium-Molybdenum-Niobium *and* Uranium-Molybdenum-Platinum Alloys

Composition: U - 8% Mo - 1.5% Nb
Composition: U - 8% Mo - 3% Nb
Composition: U - 8% Mo - 1% Pt
Treatment: Solution annealed at 1000°C (1830°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



LIVE GRAPH
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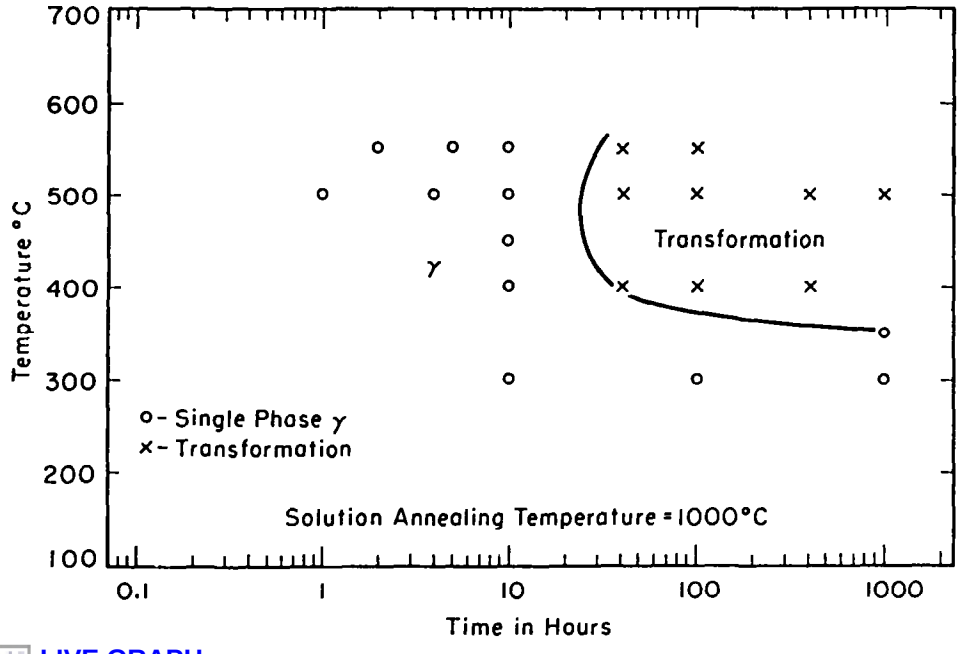
Time-temperature-transformation diagram
Start of transformation based on hardness

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. ASM, Vol 49, 1957, pp 576-597

Uranium-Molybdenum-Platinum Alloys

Composition: U - 8% Mo - 1% Pt
Treatment: Solution annealed at 1000°C (1830°F), quenched to and annealed at temperatures between 600 and 300°C (1110 and 570°F)



LIVE GRAPH
Click here to view

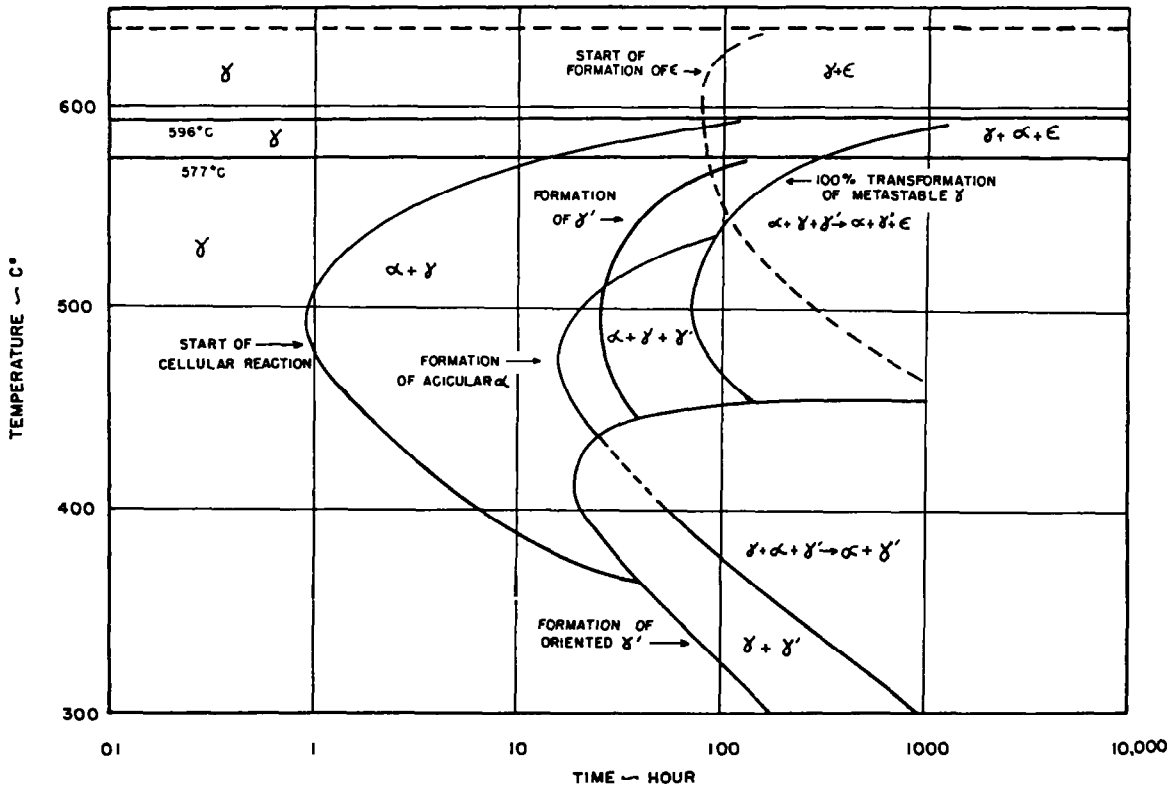
Time-temperature-transformation diagram
Start of transformation (metallography)

SOURCE: R.J. Van Thyne, D.J. McPherson, "Transformation Kinetics of Uranium-Niobium and Ternary Uranium-Molybdenum-Base Alloys," Trans. MM, Vol49, 1957, pp 676-697

Uranium-Molybdenum-Titanium Alloys

Composition: U - 8% Mo - 0.5% Ti

Treatment: The encapsulated specimens were solution heat treated at 980°C (1796°F) afor 4 h and water quenched without breaking the capsules, then reheated to 900°C (1652°F) for 1 h prior to transferring them directly to the desired transformation temperature. Conventional salt baths were used with a temperature control of +/-3°. After holding the desired time, the capsules were quenched to room temperature by breaking them under water



LIVE GRAPH
Click here to view

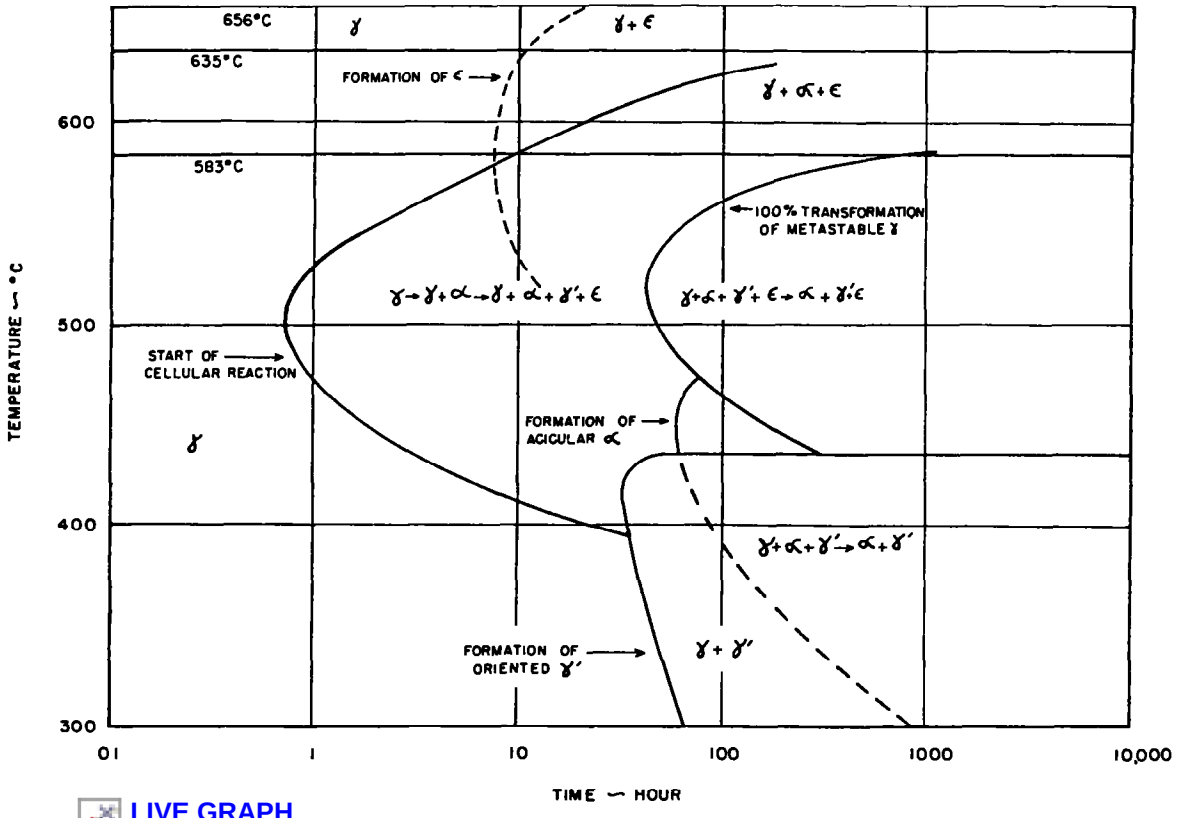
Time-temperature-transformation diagram
Quenched to temperature from 900°C (1652°F)

SOURCE: P.E. Repas, R.H. Goodenow, R.F. Hehemann, "Transformation Characteristics of U-Mo and U-Mo-Ti Alloys," Trans. ASM, Vol 57, 1964, pp 150-163

Uranium-Molybdenum-Titanium Alloys

Composition: U - 8% Mo - 1% Ti

Treatment: The encapsulated specimens were solution heat treated at 980°C (1796°F) afor 4 h and water quenched without breaking the capsules, then reheated to 900°C (1652°F) for 1 h prior to transferring them directly to the desired transformation temperature. Conventional salt baths were used with a temperature control of +/-3°. After holding the desired time, the capsules were quenched to room temperature by breaking them under water

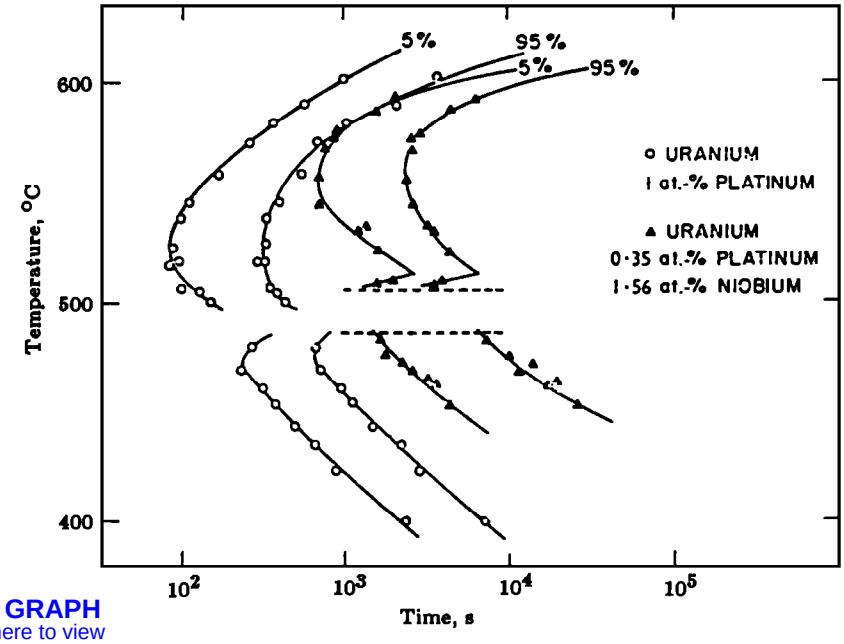


LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Quenched to temperature from 900°C (1652°F)

SOURCE: P.E. Repas, R.H. Goodenow, R.F. Hehemann, "Transformation Characteristics of U-Mo and U-Mo-Ti Alloys," Trans. ASM, Vol 57, 1964, pp 150-163

Uranium-Platinum Alloys *and*
Uranium-Niobium-Platinum Alloys
Composition: U - 1 at.% Pt
Composition: U - 1.56% at.% Nb - 0.35 at.% Pt
Treatment: Specimens annealed at 800°C (1472°F) for 5 min, and at 720°C (1328°F) for 5 min, and gas quenched



LIVE GRAPH
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Time-temperature-transformation diagram
Comparison of curves for the U-Nb-Pt vs U-Pt alloy

SOURCE: W.J. Kitchingman, K.M. Pickwick, "The Beta to Alpha Phase Change in a Uranium-Platinum-Niobium Alloy," Journal of the Institute of Metals, Vol 95, 1967, pp 61-63

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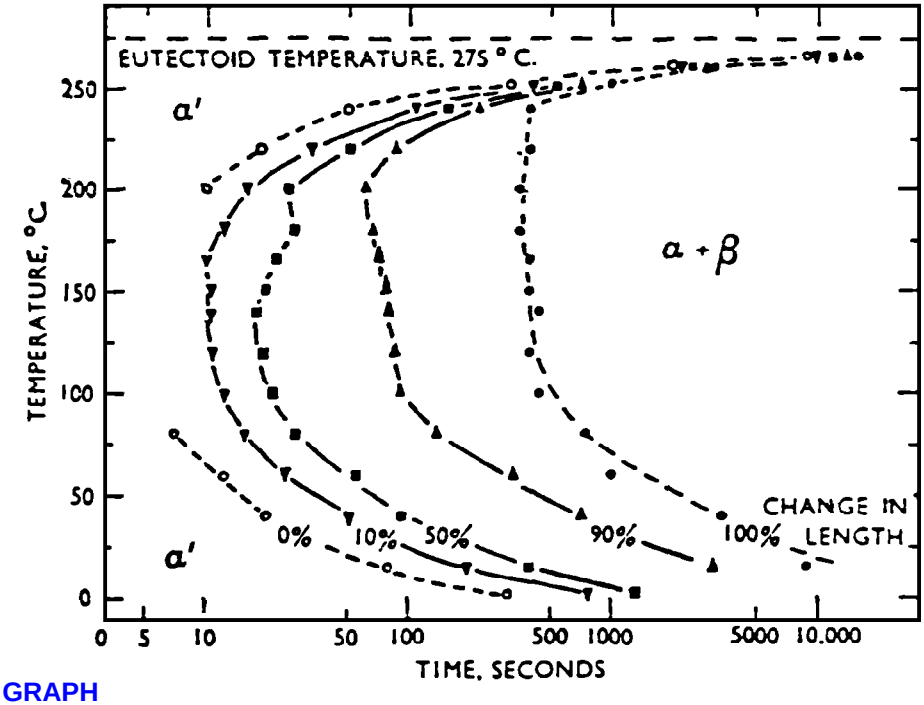
Zinc-Base Alloys

Zinc-Aluminum Alloys

Composition: Zn - 22.5% Al
Heat treatment: Dilatometer specimens heated to 375°C (707°F), held for 30 min and transferred to a constant temperature bath (0 to 270°C, 32 to 518°F). The reaction was followed by the change in length



LIVE GRAPH
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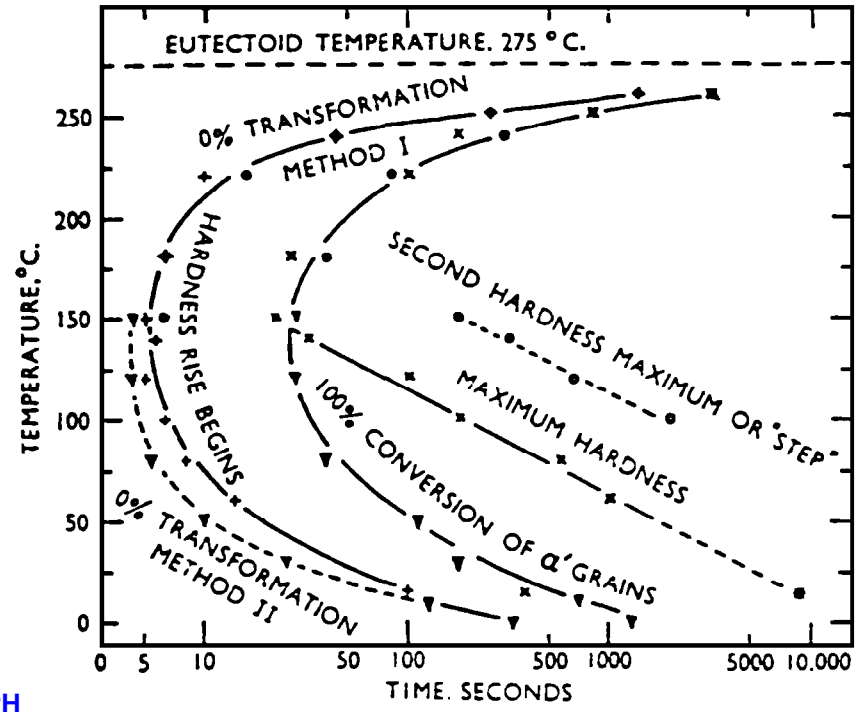
Time-temperature-transformation diagram
Based upon dilatometric data
Transformation start could not be precisely determined between 80 and 200°C (176 and 392°F)

SOURCE: R.D. Garwood, A.D. Hopkins, "The Kinetics of the Eutectoid Transformation in Zinc-Aluminium Alloys," Journal of the Institute of Metals, Vol 81, 1952, pp 407-415

Zinc-Aluminum Alloys

Composition: Zn - 22.5% Al

Heat treatment: Small specimens heated to 375°C (707°F), held for 30 min and transferred to a constant temperature bath (0 to 270°C, 32 to 518°F). Specimens were held for various times, quenched and evaluated by microscopy and hardness tests



LIVE GRAPH
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LEGEND:

- ● **Microstructure (Method I)**
- ▼ **" (" II)**
- \+ **Hardness change begins**
- × **Maximum hardness**
- o **Second hardness maximum or " step "**
- ✳ **Hardness change complete at room temperature**

Time-temperature-transformation diagram
Based on metallographic and hardness testing

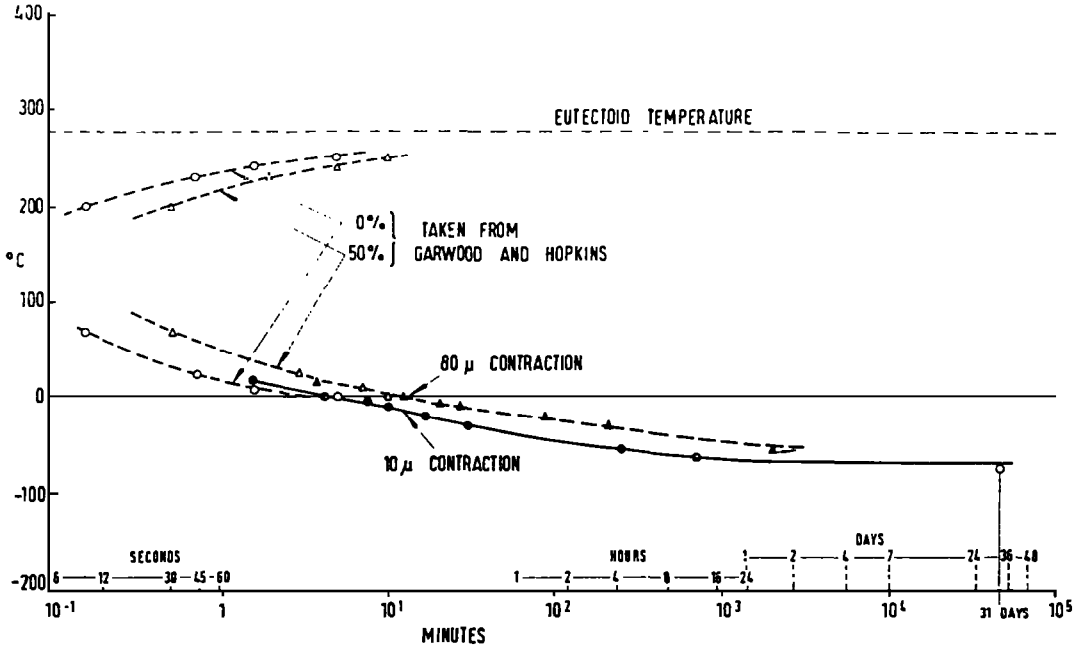
Method I
Specimens left in quench media for 24 h before sectioning, polishing, etching and examination. This ensured that any residual alpha prime was transformed without the microstructure being influenced by heat evolution

Method II
Transformation at lower temperatures was observed in specimens polished before heat treatment. After quenching, these specimens were lightly repolished and etched in <30 s, less time than required for alpha prime to decompose at room temperature

SOURCE: R.D. Garwood, A.D. Hopkins, "The Kinetics of the Eutectoid Transformation in Zinc-Aluminium Alloys," Journal of the Institute of Metals, Vol 81, 1952, pp 407-415

Zinc-Aluminum Alloys

Composition: Zn - 22% Al



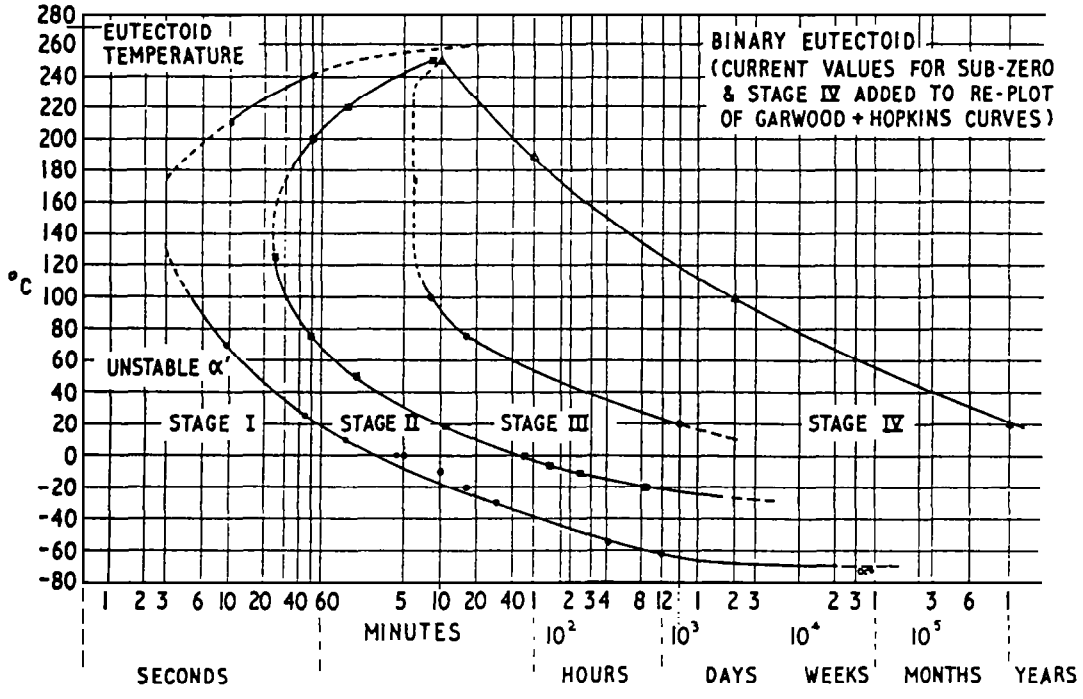
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: A.E.W. Smith, G.A. Hare, "Controlling the Zinc-Aluminium Eutectoid Reaction," Journal of the Institute of Metals, Vol 101, 1973, pp 320-328

Zinc-Aluminum Alloys

Composition: Zn - 22% Al



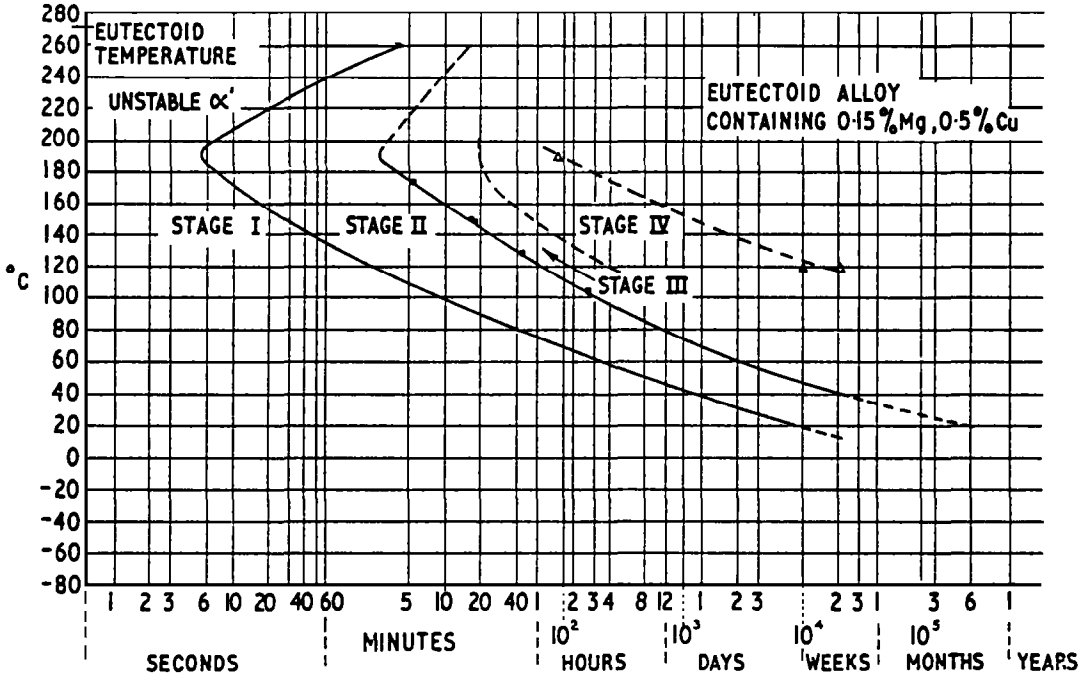
Time-temperature-transformation diagram

Four stages:
I: the quenched condition
II: breakdown of alpha prime to products of intermediate composition
III: adjustment of these productions to alpha and beta of equilibrium chemical composition
IV: adjustment of structure to virtual physical stability

SOURCE: A.E.W. Smith, G.A. Hare, "Controlling the Zinc-Aluminium Eutectoid Reaction," Journal of the Institute of Metals, Vol 101, 1973, pp 320-328

Zinc-Aluminum Alloys

Composition: Zn - 22% Al - 0.15% Mg - 0.5% Cu



Time-temperature-transformation diagram

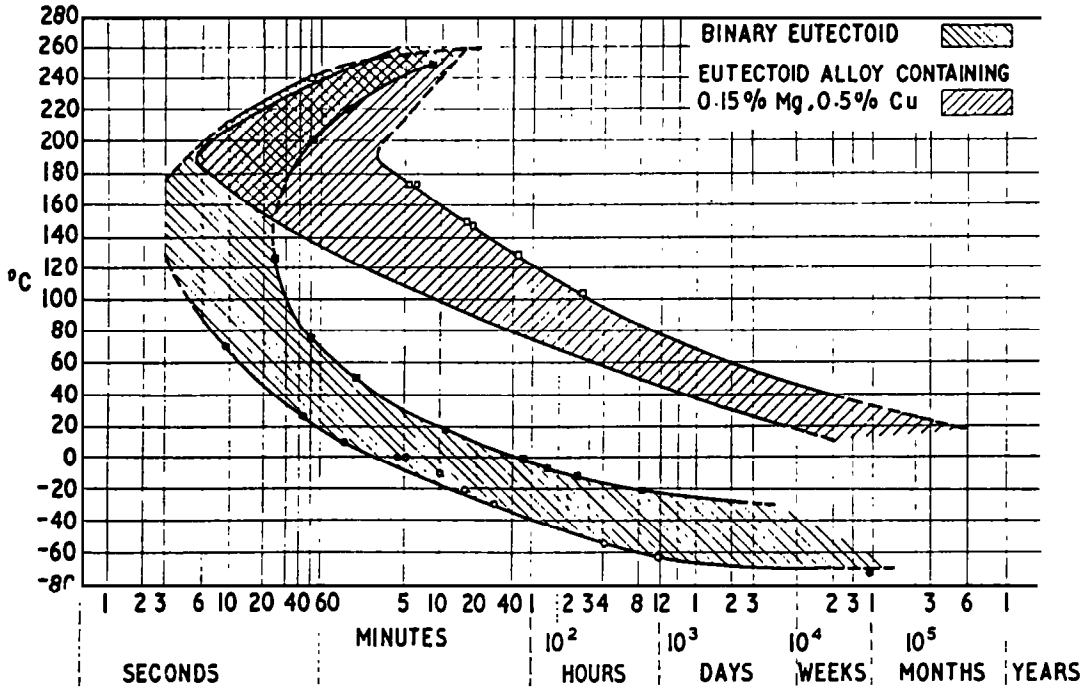
Four stages:

I: the quenched condition
II: breakdown of alpha prime to products of intermediate composition
III: adjustment of these productions to alpha and beta of equilibrium chemical composition
IV: adjustment of structure to virtual physical stability

SOURCE: A.E.W. Smith, G.A. Hare, "Controlling the Zinc-Aluminium Eutectoid Reaction," Journal of the Institute of Metals, Vol 101, 1973, p 320-328

Zinc-Aluminum Alloys

Composition: Zn - 22% Al
Composition: Zn - 22% Al - 0.15% Mg - 0.5% Cu



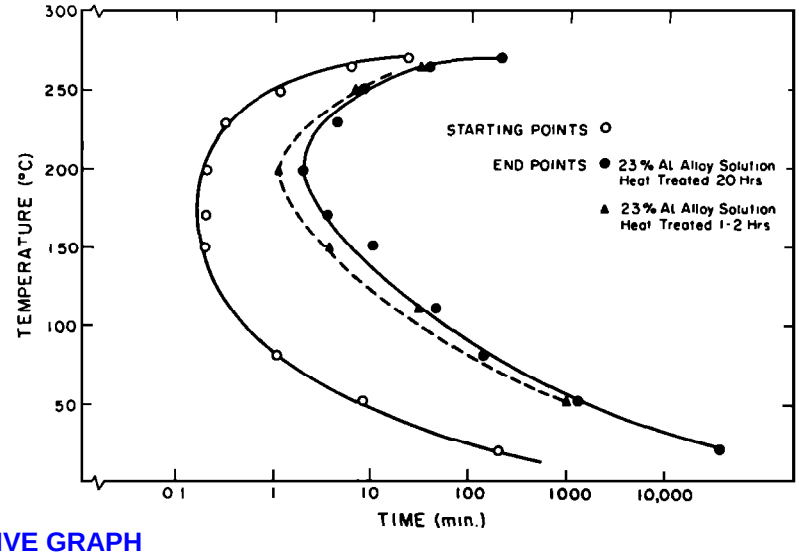
Time-temperature-transformation diagram
Comparison of stage II in binary and quaternary alloy

Stage II: breakdown of alpha prime to products of intermediate composition

SOURCE: A.E.W. Smith, G.A. Hare, "Controlling the Zinc-Aluminium Eutectoid Reaction," Journal of the Institute of Metals, Vol 101, 1973, p 320-328

Zinc-Aluminum Alloys

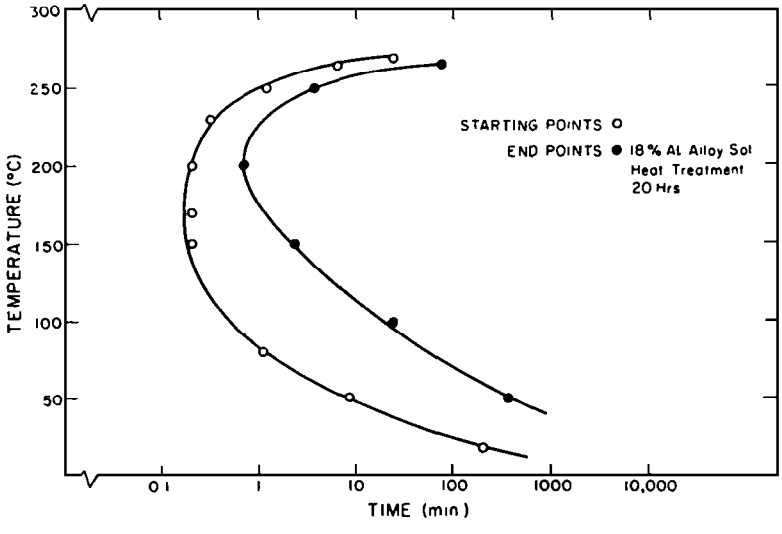
Composition: Zn - 23% Al - 0.92% Cu - 0.034% Mg - 0.026% Ca
Treatment: Solution treated at 350°C (662°F) for 17 to 20 h, quenched into a bath at various temperatures for various times, followed by a quench into water to room temperature



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Eutectoid transformation

Composition: Zn - 18% Al - 0.87% Cu - 0.037% Mg - 0.024% Ca
Treatment: Solution treated at 350°C (662°F) for 17 to 20 h, quenched into a bath at various temperatures for various times, followed by a quench into water to room temperature



Time-temperature-transformation diagram
Eutectoid transformation

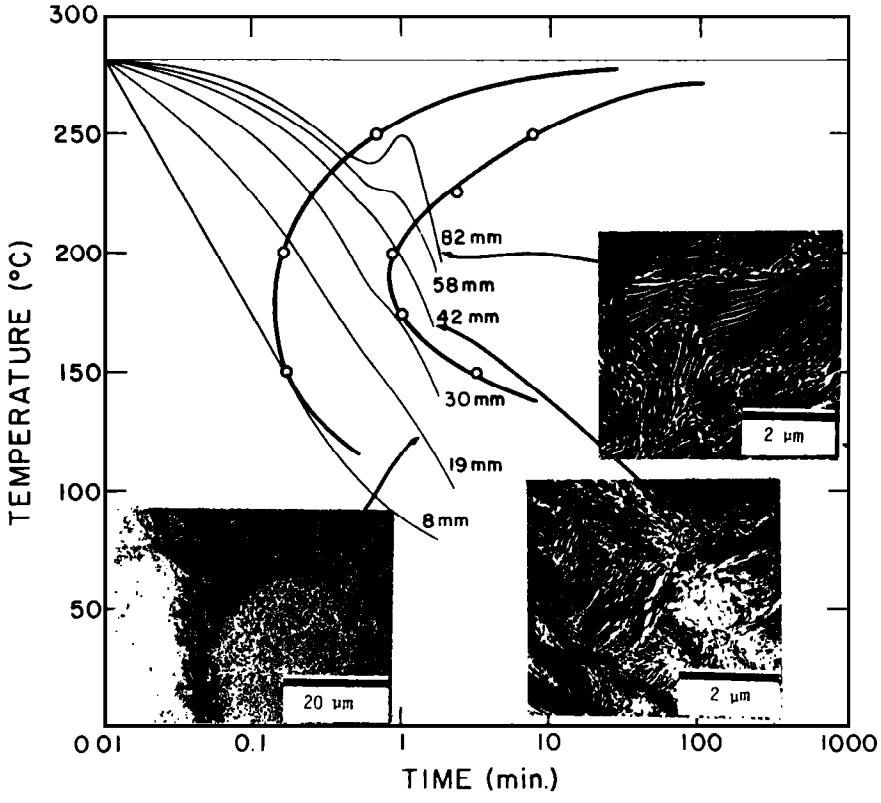
LIVE GRAPH
Click here to view

SOURCE: Fu-Wen Ling, David E. Laughlin, "The Kinetics of Transformation in Zn-Al Superplastic Alloys," Met. Trans. A, Vol 10A, July 1979, pp 921-928

Zinc-Aluminum Alloys

Composition: Zn - 23% Al - 0.92% Cu - 0.034% Mg - 0.026% Ca

Treatment: Solution treated at 350°C (662°F) for 17 to 20 h, quenched into a bath at various temperatures for various times, followed by a quench into water to room temperature



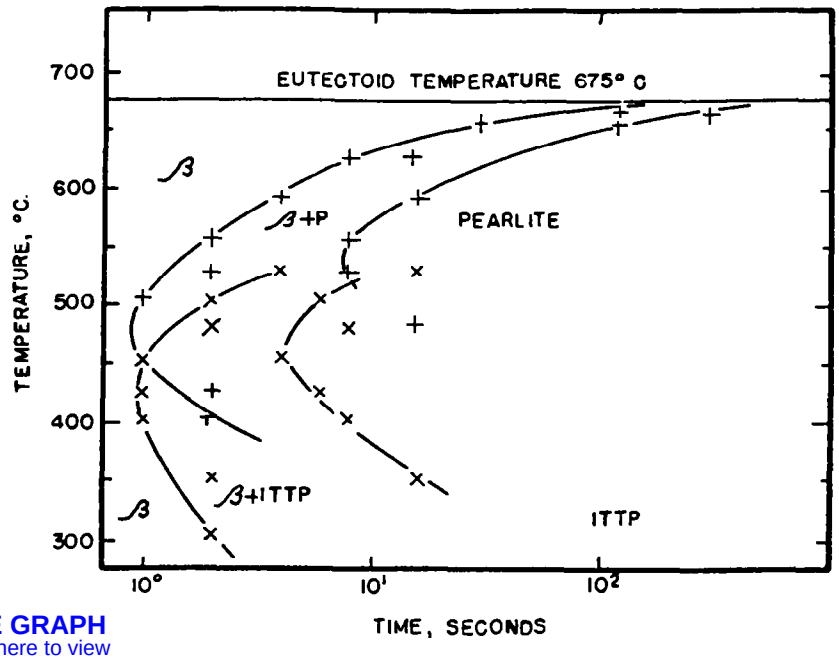
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
TTT curves, cooling curves, and microstructures

SOURCE: Fu-Wen Ling, David E. Laughlin, "The Kinetics of Transformation in Zn-Al Superplastic Alloys," Met. Trans. A, Vol 10A, July 1979, pp 921-928

Zinc-Nickel Alloy

Composition: Zn - 43.7% Ni
Treatment: Solution treated at 760°C (1400°F) to yield a homogeneous beta phase, then transferred to an isothermal salt bath



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

LEGEND:
Beta = parent phase
P = pearlite
ITTP = intermediate temperature transformation product

SOURCE: Chin Bea Kim, David J. Mack, "The Nickel-Zinc Eutectoid," Trans. AIME, Vol 224, April 1962, pp 323-327

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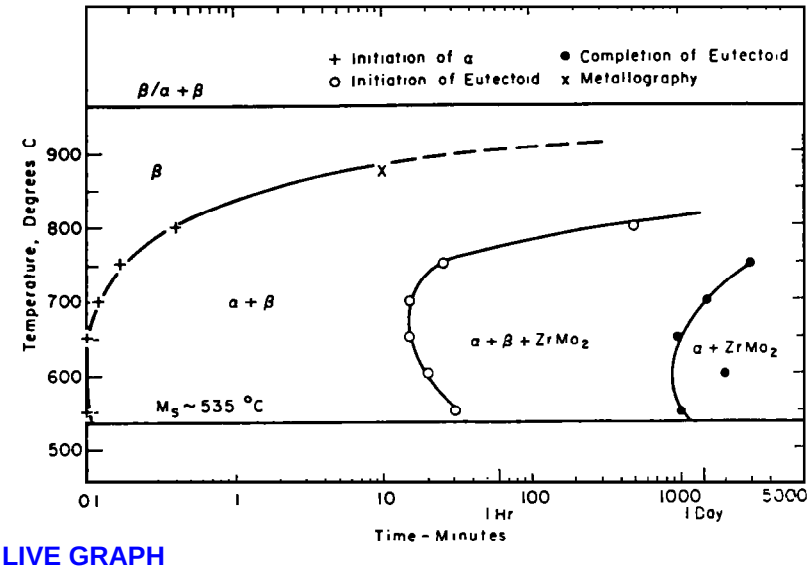
Zirconium-Base Alloys

Zirconium-Molybdenum Alloys

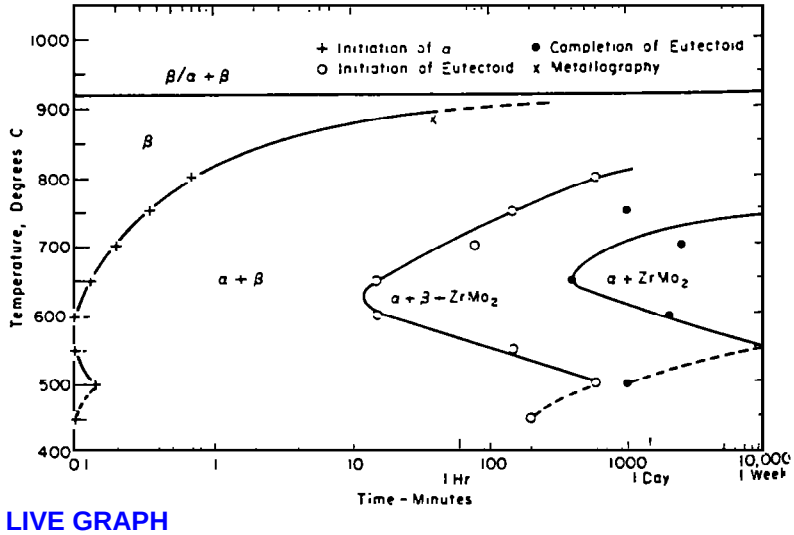
Composition: Zr - 1.3% Mo
Treatment: Forged alloy rods were held at 975 to 1000°C (1787 to 1832°F) for 15 to 30 min, isothermally quenched, held for a given length of time, then rapidly water quenched



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Zr - 3.3% Mo
Treatment: Forged alloy rods were held at 975 to 1000°C (1787 to 1832°F) for 15 to 30 min, isothermally quenched, held for a given length of time, then rapidly water quenched



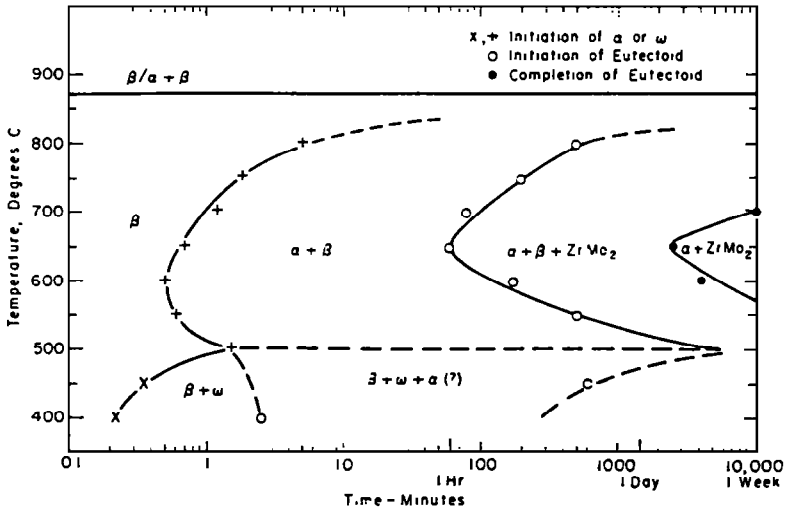
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: R.F. Domagala, D.W. Levinson, D.J. McPherson, "Transformation Kinetics and Mechanical Properties of Zr-Mo Alloys," Trans. AIME, Vol 209, October 1957, pp 1191-1196

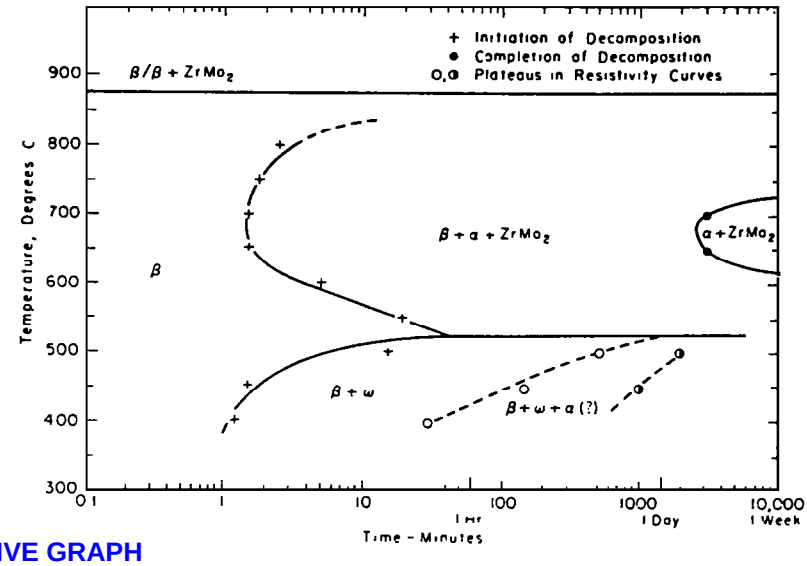
Zirconium-Molybdenum Alloys

Composition: Zr - 5.4% Mo
Treatment: Forged alloy rods were held at 975 to 1000°C (1787 to 1832°F) for 15 to 30 min, isothermally quenched, held for a given length of time, then rapidly water quenched



Time-temperature-transformation diagram

Composition: Zr - 7.5% Mo
Treatment: Forged alloy rods were held at 975 to 1000°C (1787 to 1832°F) for 15 to 30 min, isothermally quenched, held for a given length of time, then rapidly water quenched



LIVE GRAPH
Click here to view

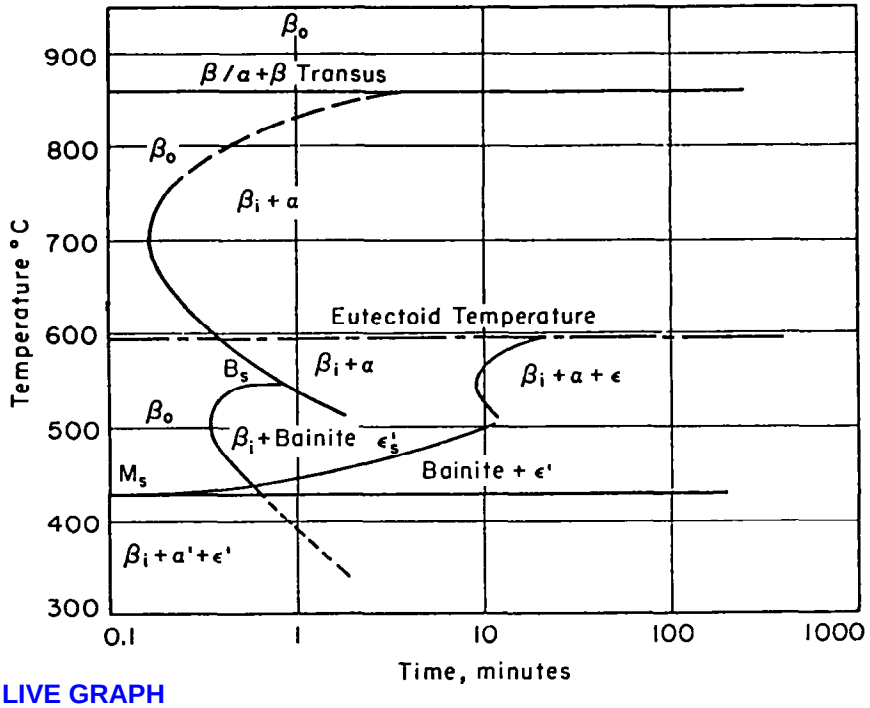
Time-temperature-transformation diagram

SOURCE: R.F. Domagala, D.W. Levinson, D.J. McPherson, "Transformation Kinetics and Mechanical Properties of Zr-Mo Alloys," Trans. AIME, Vol 209, October 1957, pp 1191-1196

Zirconium-Uranium Alloys

Composition: Zr - 8.85% U

Treatment: Forged and rolled specimens were individually sealed in 0.25 in diam Type 304 stainless steel tubing; ends of capsules were crimped shut, welded and attached to nichrome wire and suspended in a salt bath at 950°C (1740°F) for 1 h, then quenched into an intermediate salt bath maintained at the desired temperature, held for a given time, and water quenched to room temperature



LIVE GRAPH
Click here to view

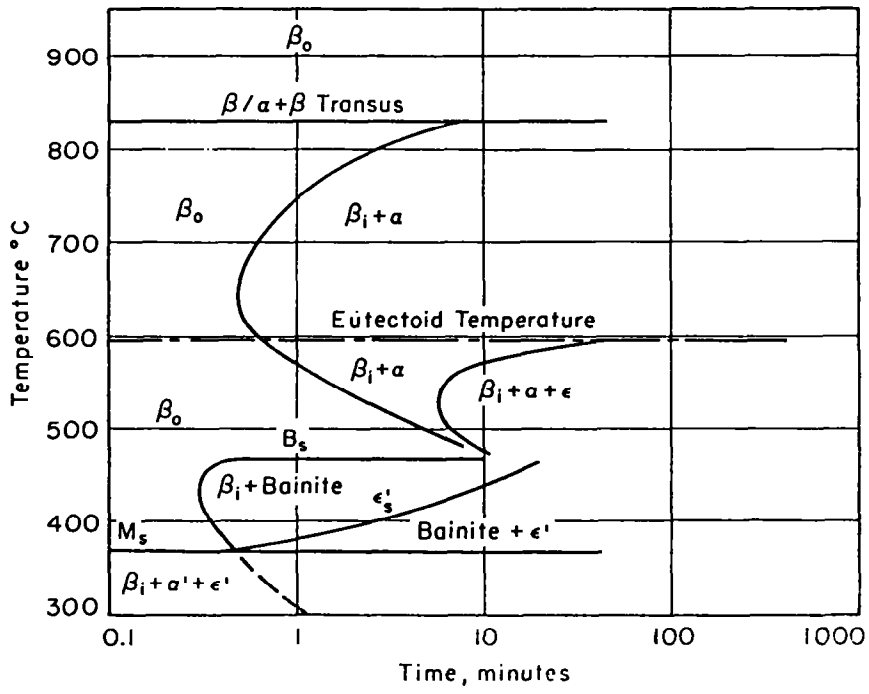
Time-temperature-transformation diagram

SOURCE: D.L. Douglass, L.L. Marsh, Jr., G.K. Manning, "Transformation Kinetics of Zirconium-Uranium Alloys," Trans. ASM, Vol 50, 1958, pp 305-322

Zirconium-Uranium Alloys

Composition: Zr - 11.1% U

Treatment: Forged and rolled specimens were individually sealed in 0.25 in diam Type 304 stainless steel tubing; ends of capsules were crimped shut, welded and attached to nichrome wire and suspended in a salt bath at 950°C (1740°F) for 1 h, then quenched into an intermediate salt bath maintained at the desired temperature, held for a given time, and water quenched to room temperature



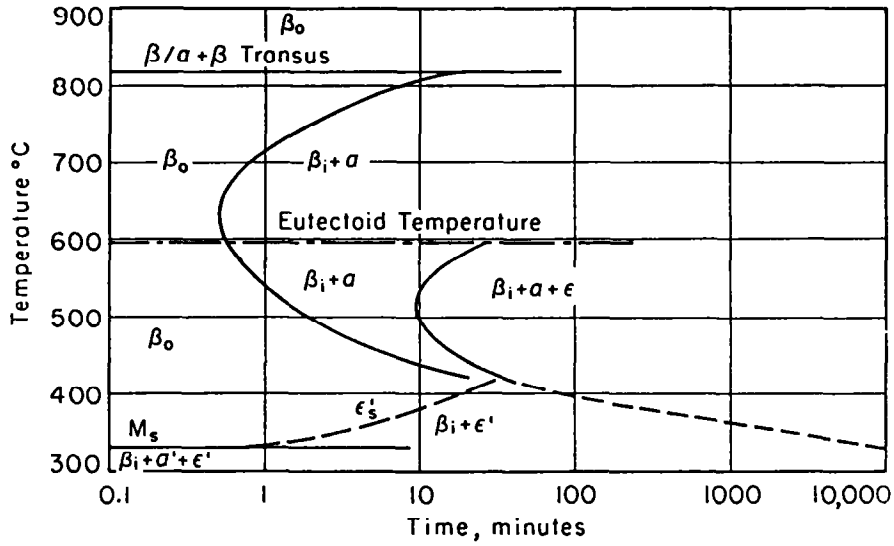
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: D.L. Douglass, L.L. Marsh, Jr., G.K. Manning, "Transformation Kinetics of Zirconium-Uranium Alloys," Trans. ASM, Vol 50, 1958, pp 305-322

Zirconium-Uranium Alloys

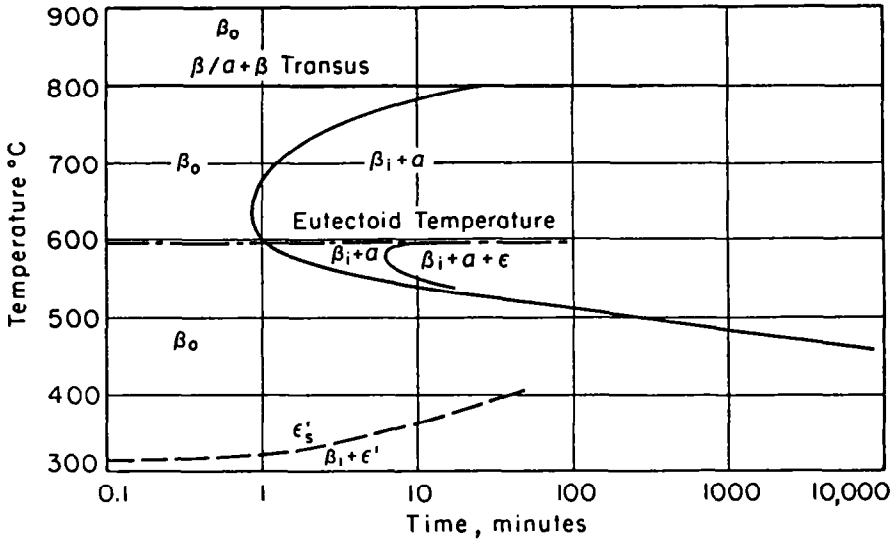
Composition: Zr - 14.3% U
Treatment: Forged and rolled specimens were individually sealed in 0.25 in diam Type 304 stainless steel tubing; ends of capsules were crimped shut, welded and attached to nichrome wire and suspended in a salt bath at 950°C (1740°F) for 1 h, then quenched into an intermediate salt bath maintained at the desired temperature, held for a given time, and water quenched to room temperature



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

Composition: Zr - 20.7% U
Treatment: Forged and rolled specimens were individually sealed in 0.25 in diam Type 304 stainless steel tubing; ends of capsules were crimped shut, welded and attached to nichrome wire and suspended in a salt bath at 950°C (1740°F) for 1 h, then quenched into an intermediate salt bath maintained at the desired temperature, held for a given time, and water quenched to room temperature



LIVE GRAPH
Click here to view

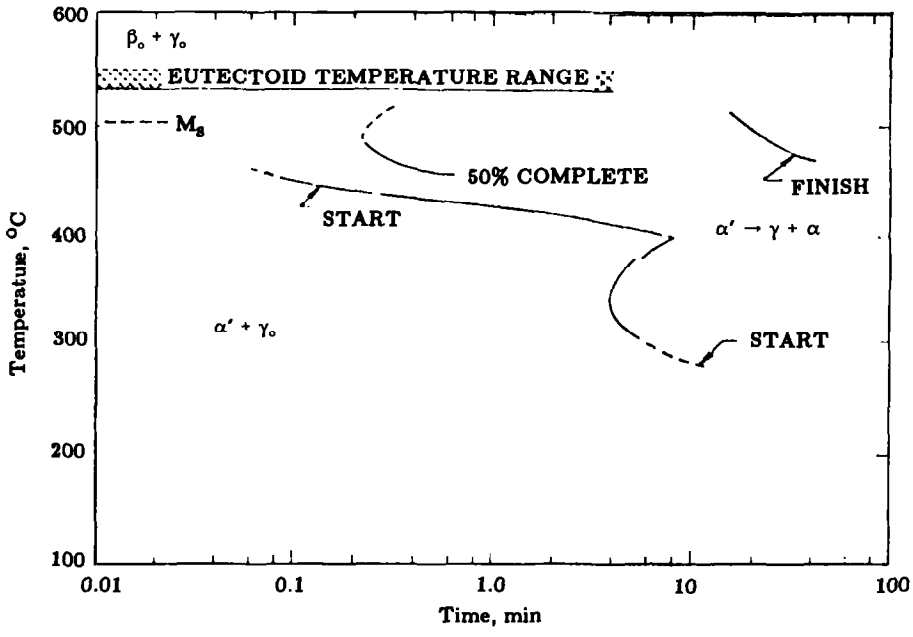
Time-temperature-transformation diagram

SOURCE: D.L. Douglass, L.L. Marsh, Jr., G.K. Manning, "Transformation Kinetics of Zirconium-Uranium Alloys," Trans. ASM, Vol 50, 1958, pp 305-322

Zirconium-Uranium-Hydrogen Alloy

Composition: Zr - 0.92% H - 0.0875% O - 0.0038% N - 0.0909% Fe - 0.0048% Si - 0.0052% Al - 0.0025% Mn

Treatment: ***Specimens in a quartz dilatometer were brought to*** **equilibrium above the transformation temperature by insertion into a lead bath at 600°C (1112°F), held for the required time, quenched to a lower constant temperature, held for a predetermined length of time, then quenched in water**



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: J.C. Bokros, "Transformation Kinetics of a Zirconium-Uranium-Hydrogen Alloy," Journal of Nuclear Materials, Vol 3, No. 3, 1961, pp 320-326

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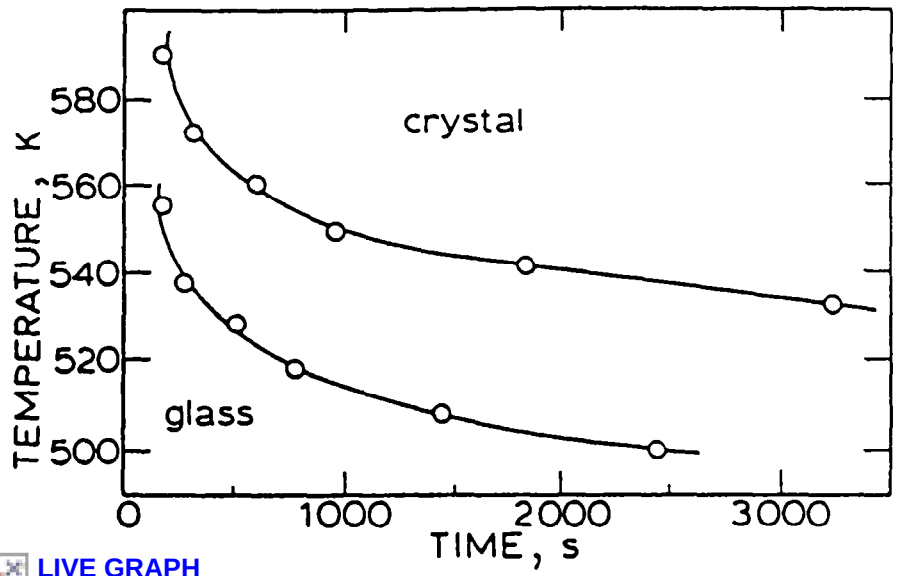
Amorphous Metals

Copper-Cadmium Alloy

Composition: $Cu_{60}Cd_{40}$



LIVE GRAPH
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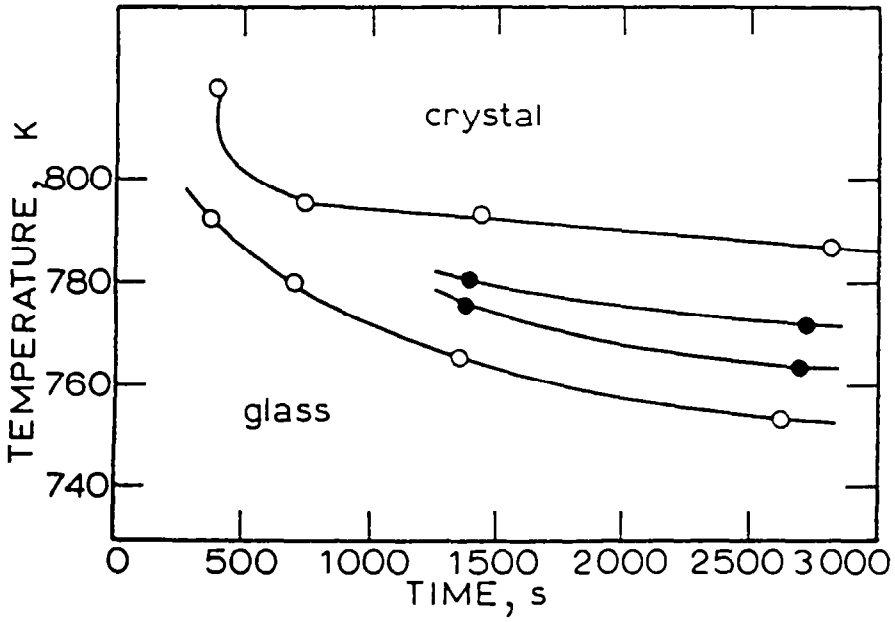
Time-temperature-transformation diagram

Copper-Zirconium Alloy

Composition: $Cu_{60}Zr_{40}$



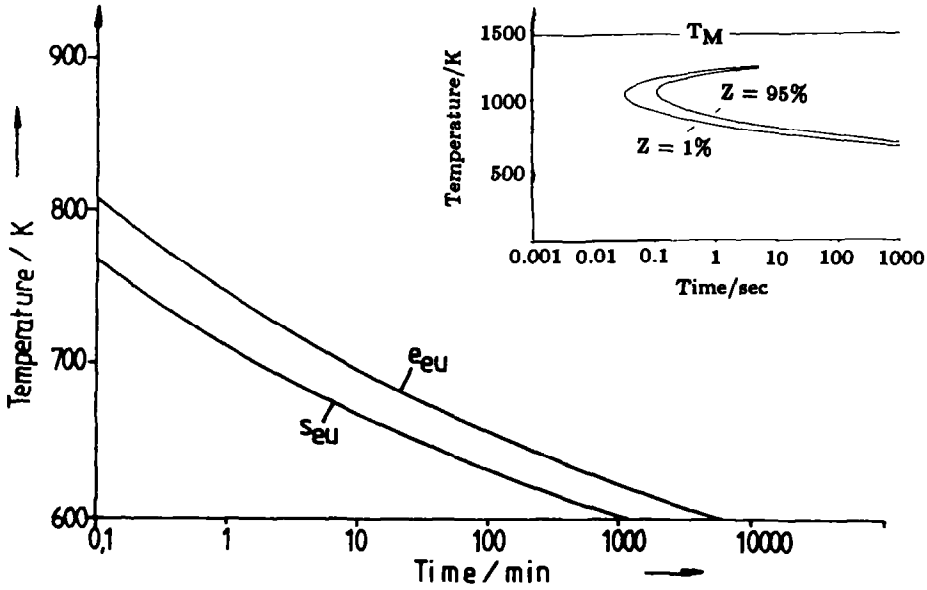
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram

SOURCE: J. Latuszkiewicz, M. Strzeszewska, A. Calka, P.G. Zielinski, H. Matyja, "Thermal Stability of Amorphous $Cu_{60}Me_{40}$ Alloys (Me = Cd, Zr)," Metals Technology, Vol 5, October 1978, pp 329-332

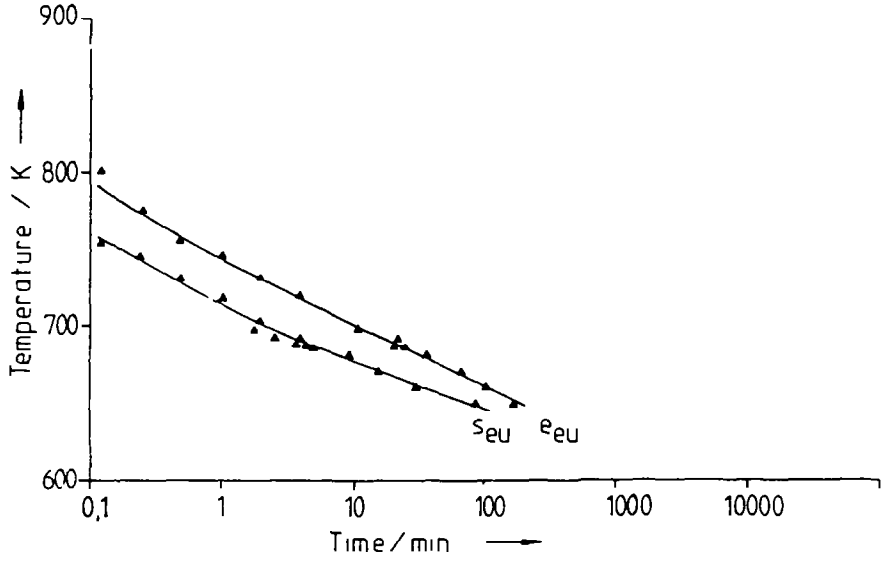
Iron-Boron Alloys

Composition: $Fe_{80}B_{20}$



Time-temperature-crystallization diagram
Calculated

Composition: $Fe_{80}B_{20}$

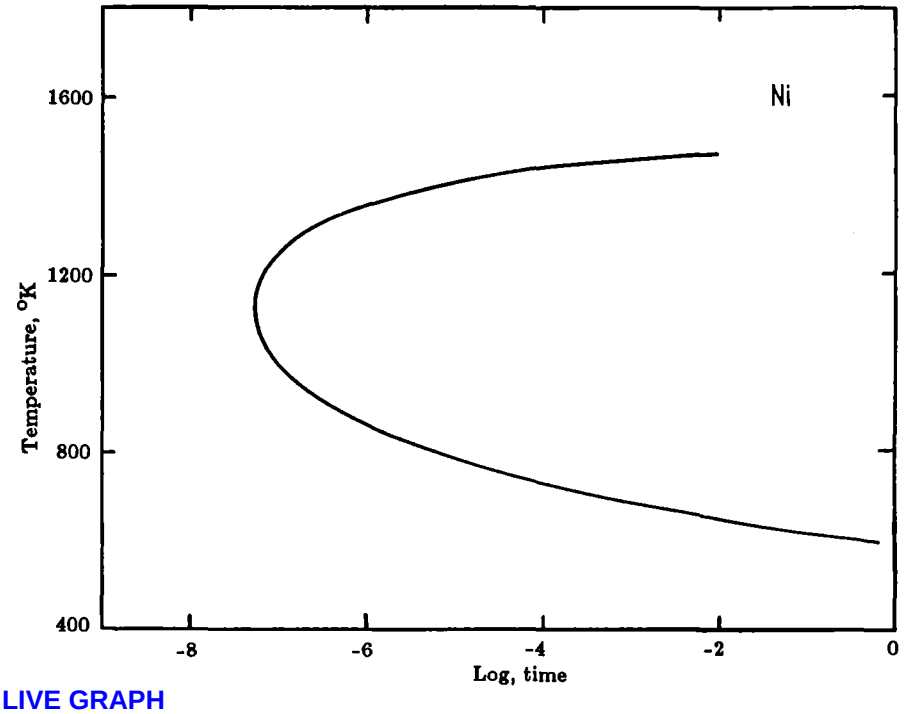


LIVE GRAPH
Click here to view

Time-temperature-crystallization diagram
Experimentally determined

SOURCE: H.W. Bergmann, H.U. Fritsch, "Calculation of the Crystallization Behaviour of Metallic Glasses," Rapidly Solidified Amorphous and Crystalline Alloys, B.H. Kear, B.C. Giessen, M. Cohen, Eds., Elsevier Science Publishing Co., 1982, pp 225-229

Nickel Alloy



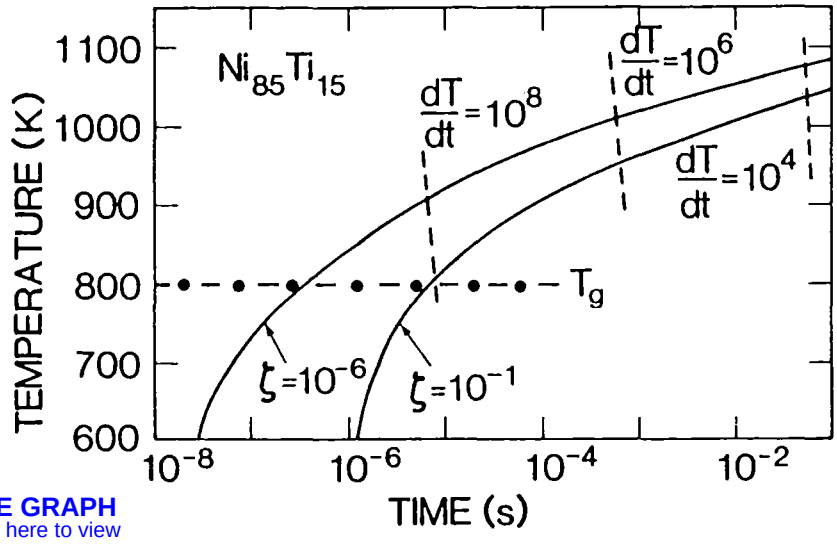
LIVE GRAPH
Click here to view

Time-temperature-crystallization diagram
Calculated curve for splat quenched nickel

SOURCE: H.A. Davies, J. Aucote, J.B. Hull, "The Kinetics of Formation and Stabilities of Metallic Glasses," Scripta Metallurgica, Vol 8, 1974, pp 1179-1190

Nickel-Titanium Alloy

Composition: $Ni_{85}Ti_{15}$



LIVE GRAPH
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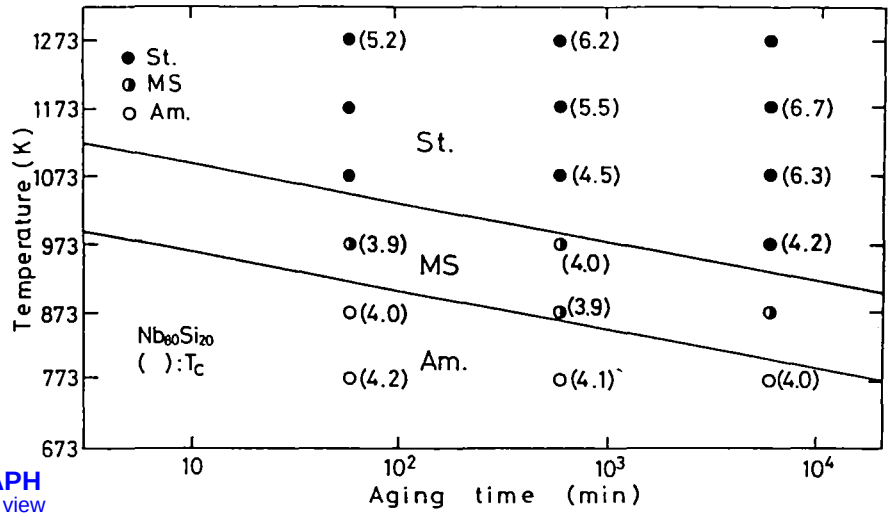
Continuous-cooling-transformation diagram for $Ni_{85}Ti_{15}$ alloy and volume fractions of the crystalline phase ζ of 10^{-6} and 10^{-1}

LEGEND:
Dashed lines = correspond to the temperature-time paths for the cooling rates labeled
Dash-dot line = corresponds to the extrapolated glass transition temperature (T_g)

SOURCE: P. Nash, R.B. Schwarz, "Calculation of the Glass Forming Range in Binary Metallic Systems Using Thermodynamic Models," Acta Metallurgica, Vol 36, No. 11, 1988, pp 3047-3053

Niobium-Silicon Alloy

Composition: $Nb_{80}Si_{20}$



LIVE GRAPH
Click here to view

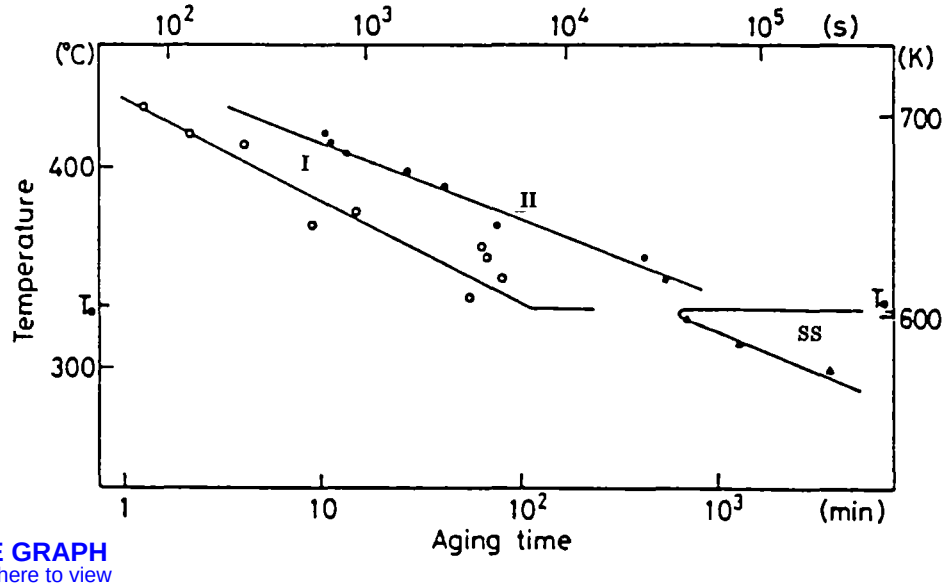
The superconducting transition temperature, T_c, of $Nb_{80}Si_{20}$ alloy annealed for various times and temperatures

LEGEND:
Am = amorphous
MS = metastable
St = stable
T_c = transition temperature

SOURCE: Akihisa Inoue, Tsuyoshi Masumoto, "Melt-Quenched Amorphous Superconducting Alloys," Structures and Properties of Amorphous Metals II, Tohoku University, 1979, pp 165-200

Palladium-Nickel-Silicon Alloys

Composition: $Pd_{70}Ni_{10}Si_{20}$



LIVE GRAPH
Click here to view

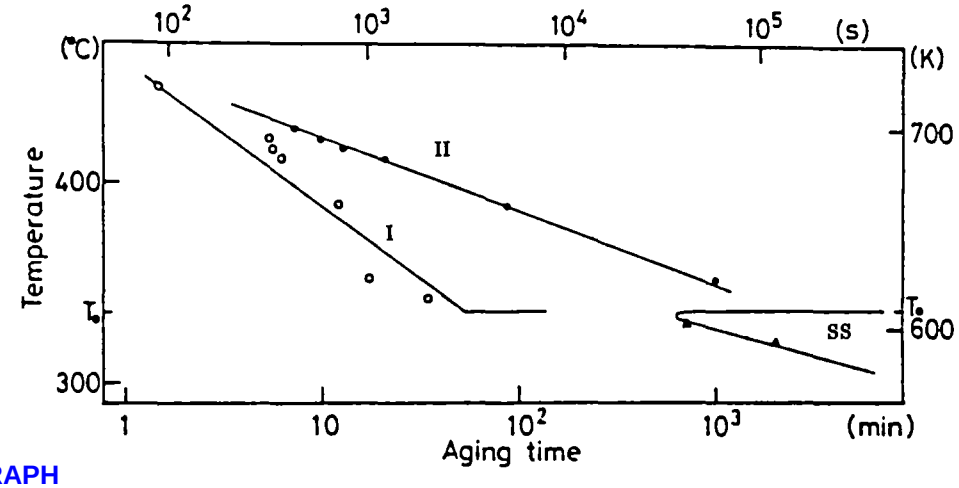
Time-temperature-transformation diagram showing the crystallization onset times at various annealing temperatures

LEGEND:
I = Pd_3Si
II = Pd-rich silicide
SS = supersaturated solid solution

SOURCE: Kazuo Utsumi, Kazutaka Kawamura, "Studies on Crystallization Processes of Amorphous Pd-Ni-Si Alloys," Trans. Japan Institute of Metals, Vol 21, No. 5, May 1980, pp 269-274

Palladium-Nickel-Silicon Alloys

Composition: $Pd_{60}Ni_{20}Si_{20}$



LIVE GRAPH
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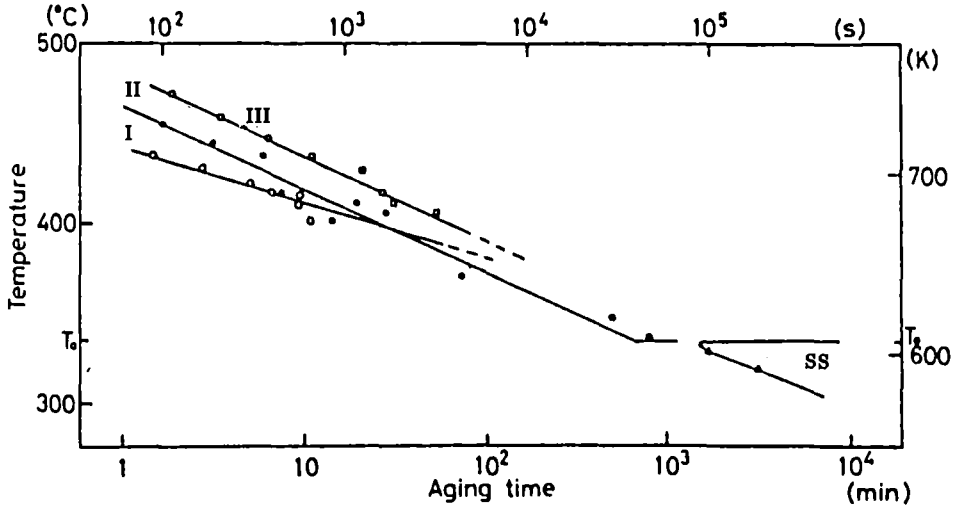
Time-temperature-transformation diagram
Showing the crystallization onset times at various annealing temperatures

LEGEND:
I = Pd_3Si
II = Pd-rich silicide
SS = supersaturated solid solution

Composition: $Pd_{55}Ni_{30}Si_{15}$



Time-temperature-transformation diagram
Showing the crystallization onset times at various annealing temperatures

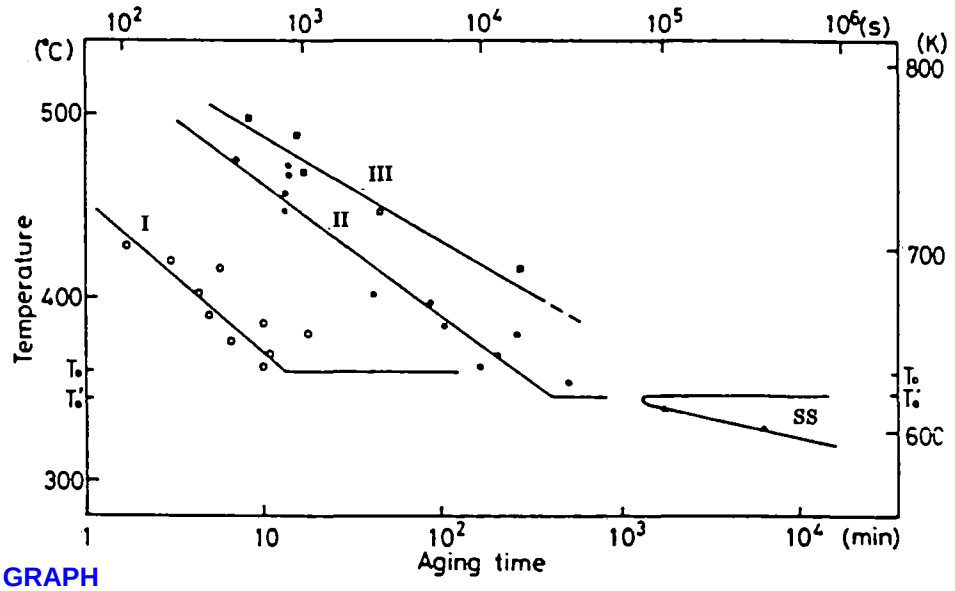
LEGEND:
I = Ni-based crystallite
II = Pd_3Si
III = Pd-rich silicide
SS = supersaturated solid solution

LIVE GRAPH
Click here to view

SOURCE: Kazuo Utsumi, Kazutaka Kawamura, "Studies on Crystallization Processes of Amorphous Pd-Ni-Si Alloys," Trans. Japan Institute of Metals, Vol 21, No. 5, May 1980, pp 269-274

Palladium-Nickel-Silicon Alloys

Composition: $Pd_{50}Ni_{30}Si_{20}$



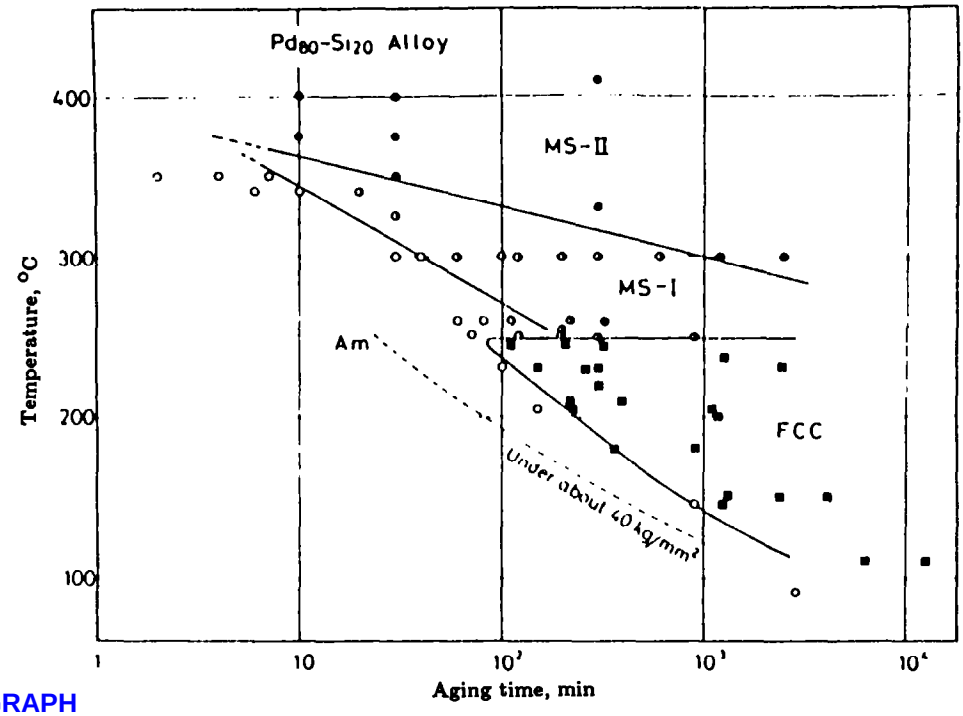
LIVE GRAPH
Click here to view

Time-temperature-transformation diagram
Showing the crystallization onset times at various annealing temperatures

LEGEND:
I = Ni-based crystallite
II = Pd_3Si
III = Pd-rich silicide
SS = supersaturated solid solution

SOURCE: Kazuo Utsumi, Kazutaka Kawamura, "Studies on Crystallization Processes of Amorphous Pd-Ni-Si Alloys," Trans. Japan Institute of Metals, Vol 21, No. 5, May 1980, pp 269-274

Palladium-Silicon Alloy
Composition: $Pd_{80}Si_{20}$



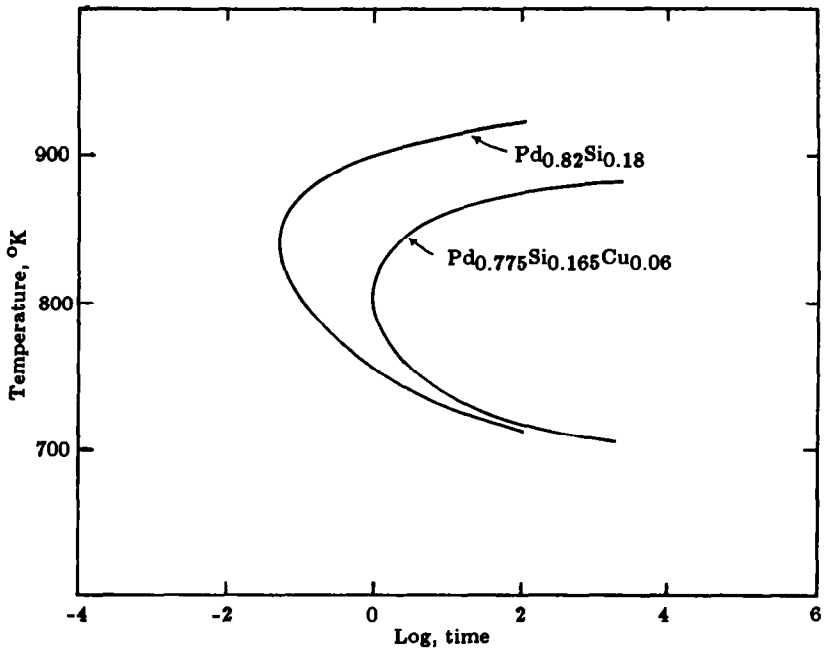
LIVE GRAPH
Click here to view

Time-temperature-aging diagram
Showing the transformation from the amorphous state to metastable (MS-I and MS-II) and crystalline (BCC) states

SOURCE: T. Masumoto, R. Maddin, "Structural Stability and Mechanical Properties of Amorphous Metals," Materials Science and Engineering, Vol 19, 1975, pp 1-24

Palladium-Silicon Alloy *and*
Palladium-Silicon-Copper Alloy

Composition: $Pd_{0.82}Si_{0.18}$
Composition: $Pd_{0.775}Si_{0.165}Cu_{0.06}$



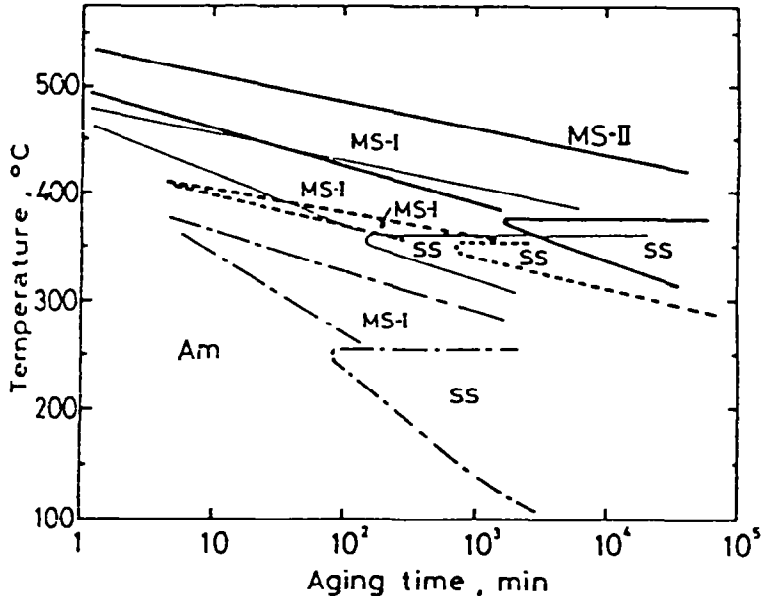
LIVE GRAPH
Click here to view

Time-temperature-crystallization diagram
Calculated curves

SOURCE: H.A. Davies, J. Aucote, J.B. Hull, "The Kinetics of Formation and Stabilities of Metallic Glasses," Scripta Metallurgica, Vol 8, 1974, pp 1179-1190

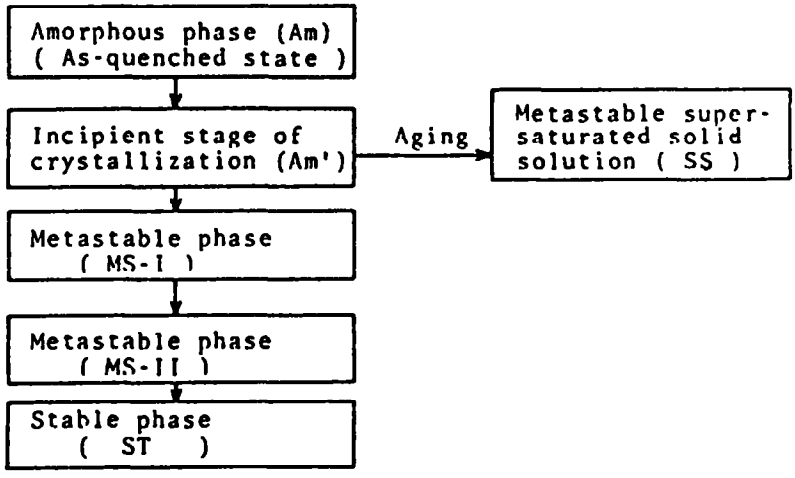
Palladium-Silicon Alloy
Iron-Phosphorus-Carbon Alloy
Cobalt-Silicon-Boron Alloy, *and*
Nickel-Silicon-Boron Alloy

Composition: $Pd_{80}Si_{20}$ — – —
Composition: $Fe_{80}P_{13}C_7$ – – – – –
Composition: $Co_{75}Si_{15}B_{10}$ ——
Composition: $Ni_{75}Si_8B_{17}$ ——



LIVE GRAPH
Click here to view

Time-temperature-transformation diagram For four amorphous alloys



Systematic transformation sequence of amorphous metal-metalloid systems

SOURCE: T. Masumoto, H. Kimura, A. Inoue, T. Waseda, "Structural Stability of Amorphous Metals," Materials Science and Engineering, Vol 23, 1976, pp 141-144

Amorphous Alloys

Phase	$Pd_{80}Si_{20}$	$Fe_{80}P_{13}C_7$	$Co_{75}Si_{15}B_{10}$	$Ni_{75}Si_8B_{17}$
SS	f.c.c. (a = 3.921 Å)	b.c.c. (a = 2.861 Å)	h.c.p. (a = 2.496 Å) (c = 4.041 Å)	f.c.c. (a = 3.508 Å)
MS-I	f.c.c. (a = 3.89 Å)	b.c.c. (a = 2.87 Å)	h.c.p. (a = 2.51 Å) (c = 4.07 Å)	f.c.c. (a = 3.52 Å)
MS-II	(Complex ordered phase?)			
ST	Pd,Pd_3Si	Fe,Fe_3C Fe_3P	Co,Co_3B Co_3Si	Ni,Ni_3B Ni_3Si
T_c	380 °C	410 °C	480 °C	482 °C
T_c'	250 °C	350 °C	375 °C	360 °C

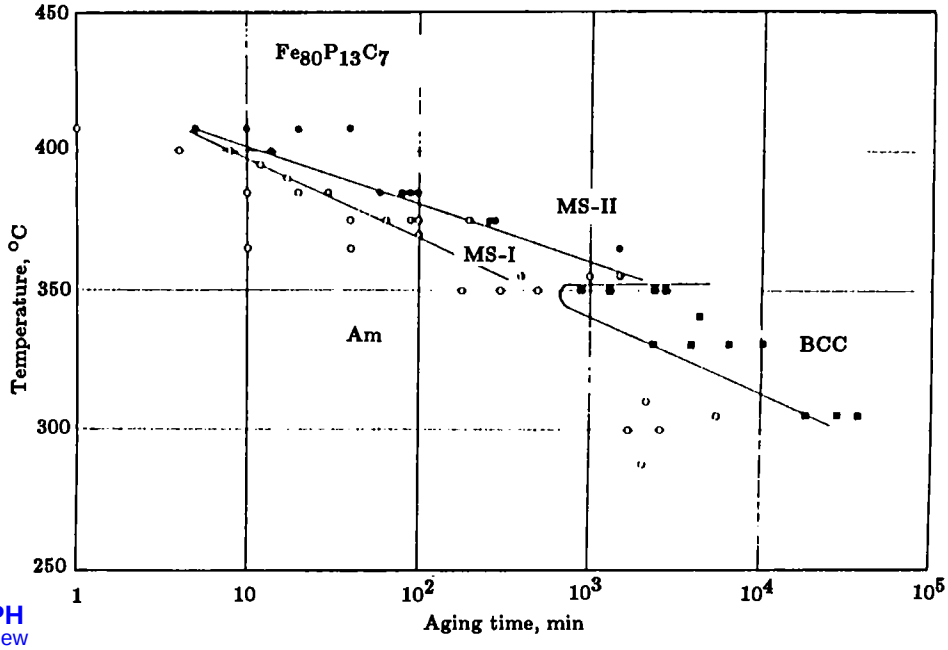
T_c: Crystallization temperature at which the exothermic peak begins to appear at a scanning rate of 5 deg C/min.

Characteristics of phases at each stage of various amorphous metals

SOURCE: T. Masumoto, H. Kimura, A. Inoue, T. Waseda, "Structural Stability of Amorphous Metals," Materials Science and Engineering, Vol 23, 1976, pp 141-144

Iron-Phosphorus-Carbon Alloy

Composition: $Fe_{80}P_{13}C_7$



LIVE GRAPH
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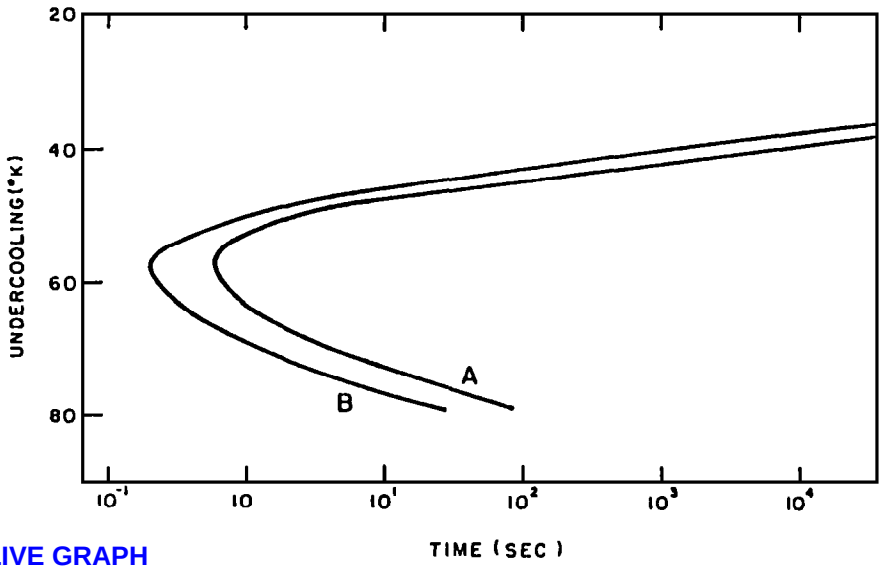
Time-temperature-aging diagram
Showing the transformation from the amorphous state to metastable (MS-I and MS-II) and crystalline (BCC) states

SOURCE: T. Masumoto, R. Maddin, "Structural Stability and Mechanical Properties of Amorphous Metals," Materials Science and Engineering, Vol 19, 1975, pp 1-24

Salol (Phenyl Salicylate)



LIVE GRAPH
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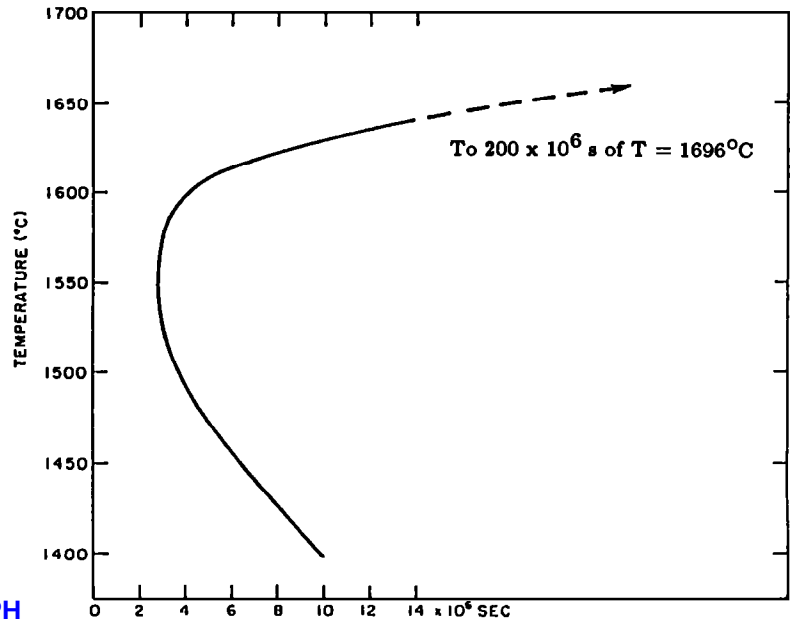
Time-temperature-transformation diagram
Curves correspond to volume fractions crystallized

A = 10^{-6}
B = 10^{-8}

SOURCE: D.R. Ulhmann, "A Kinetic Treatment of Glass Formation," Journal of Non-Crystalline Solids, Vol 7, 1972, pp 337-348

SiO_2, Silica



LIVE GRAPH
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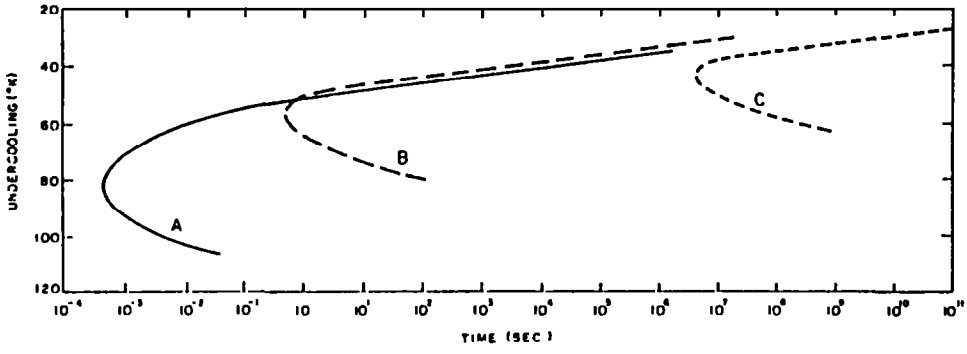
Time-temperature-transformation diagram
Calculated for materials having the same viscosity-temperature relation, entropy of fusion, and other properties as salol but with assumed melting points
Volume fractions crystallized of 10^{-6}

Salol-Like Material



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Time-temperature-transformation diagram
Corresponding to a volume fraction crystallized of 10^{-6}

(A) T_E = 83°C (182°F)
(B) T_E = 43°C (110°F)
(C) T_E = 4°C (38°F)

SOURCE: D.R. Ulhmann, "A Kinetic Treatment of Glass Formation," Journal of Non-Crystalline Solids, Vol 7, 1972, pp 337-348

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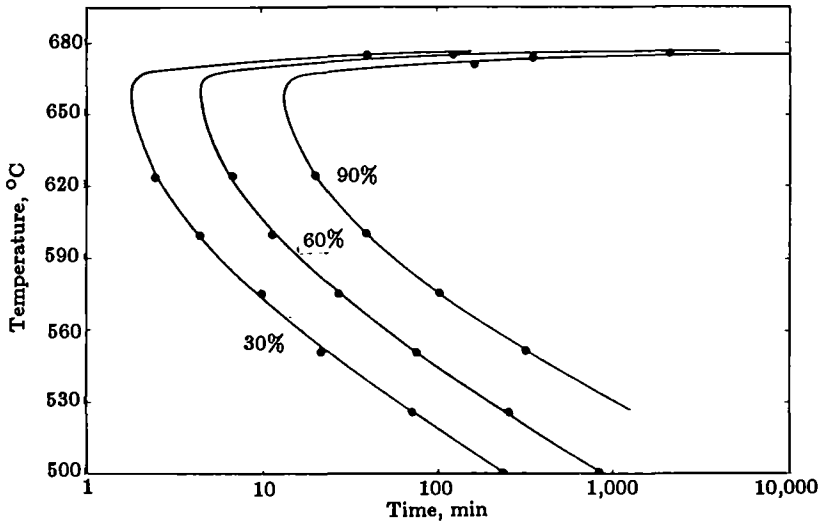
Intermetallic Compounds

Cobalt-Platinum Alloy

Composition: $CoPt_3$ (24.9 at.% Co)



LIVE GRAPH
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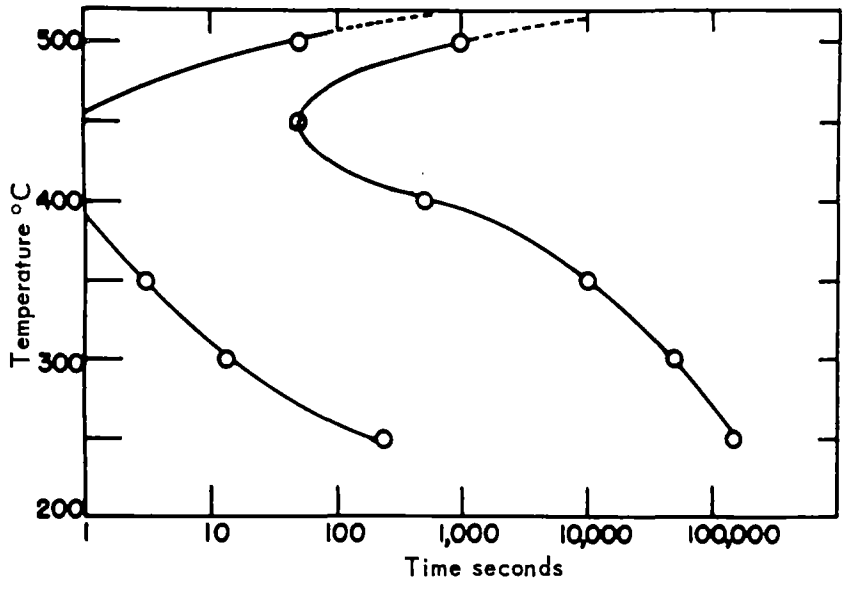
Time-temperature-ordering diagram

SOURCE: H. Berg, J.B. Cohen, "Long-Range Order and Ordering Kinetics in $CoPt_3$," Met. Trans., Vol 3, July 1972, pp 1797-1805

Iron-Aluminum Alloy

Composition: Fe_3Al



Time-temperature-transformation diagram
Curves of the start and completion of ordering

LIVE GRAPH
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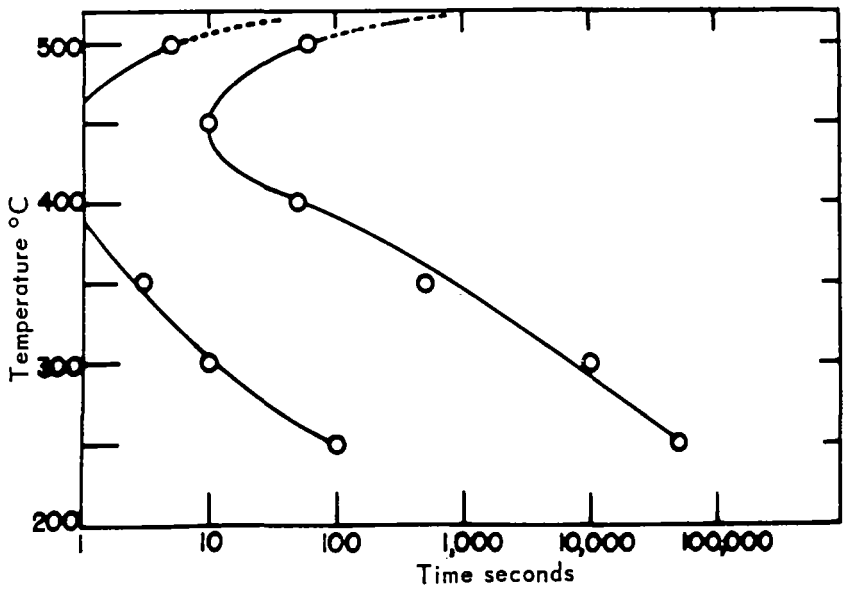
Treatment: wires previously disordered at 650°C (1202°F) for 20 h

SOURCE: H.J. McQueen, G.C. Kuczynski, "Order-Disorder Transformations in Iron-Aluminum Alloys," Trans. AIME, Vol 215, August 1959, pp 619-622

Iron-Aluminum Alloy

Composition: Fe_3Al



LIVE GRAPH
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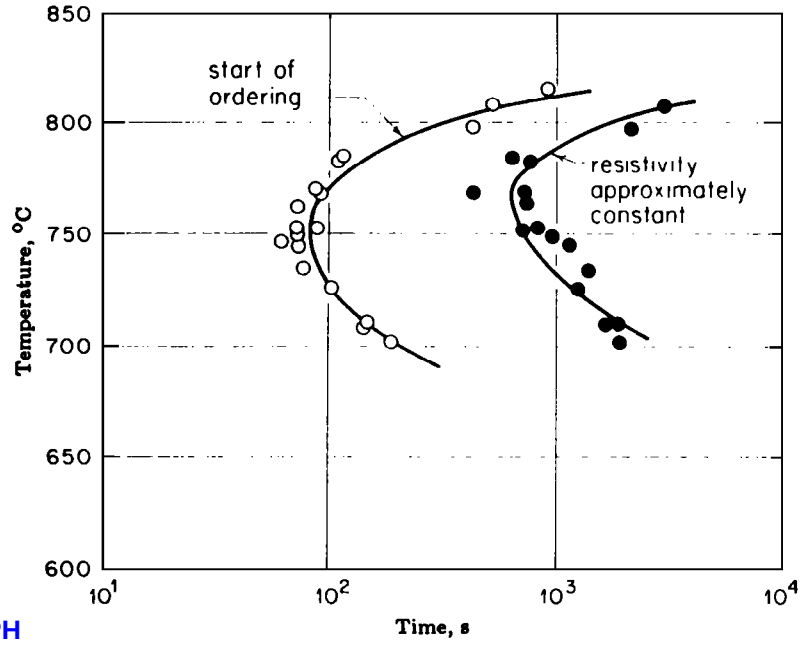
Time-temperature-transformation diagram
Curves of the start and completion of ordering

Treatment: wires previously disordered at 800°C (1472°F) for 20 h

SOURCE: H.J. McQueen, G.C. Kuczynski, "Order-Disorder Transformations in Iron-Aluminum Alloys," Trans. AIME, Vol 215, August 1959, pp 619-622

Nickel-Molybdenum Alloys

Composition: Ni - 20% Mo (Ni_4Mo)
Treatment: Samples held at 1000°C (1832°F) for about 10 min, then cooled rapidly to transformation temperature



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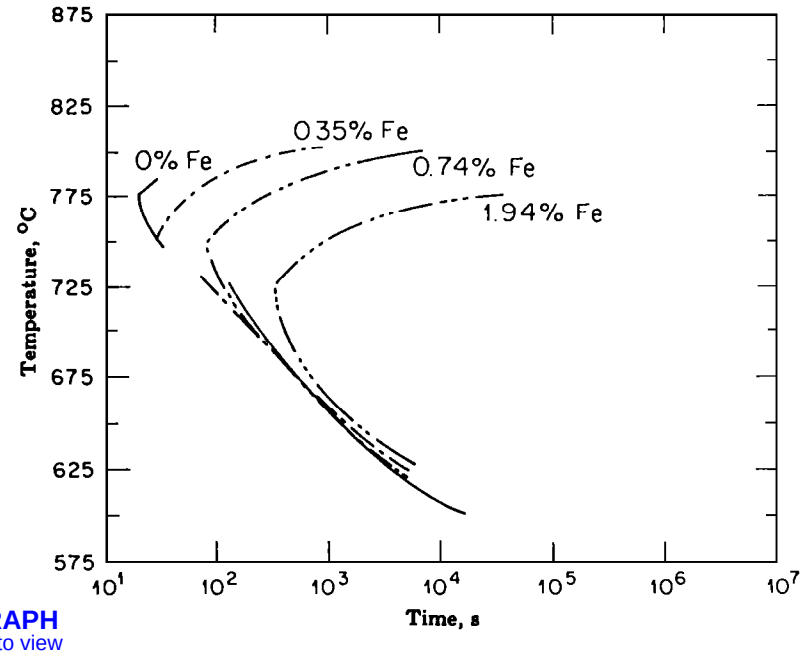
Isothermal-transformation diagram for ordering reaction
Data points show start of ordering and time at which resistivity remains constant for at least 1 h, although this is not equilibrium resistivity

SOURCE: C.R. Brooks, J.E. Spruiell, E.E. Stansbury, "Physical Metallurgy of Nickel-Molybdenum Alloys," International Metals Reviews, Vol 29, No. 3, 1984, pp 210-248

Nickel-Molybdenum Alloys

Composition: Ni_4Mo
Treatment: Results are based on electrical-resistivity measurements made on samples isothermally transformed after quenching from alpha to transformation temperature



LIVE GRAPH
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Time-temperature-transformation diagram
Showing effect of Fe additions on start of beta to alpha transformation

SOURCE: T.S. Lei, PhD dissertation, University of Tennessee, 1979 as published in International Metals Reviews, Vol 29, No. 3, 1984, p 241

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About the Editor

George F. Vander Voort is supervisor, Metal Physics Research, Carpenter Technology Corporation, Reading, Pennsylvania. Prior to joining Carpenter in 1983, he spent 16 years with Bethlehem Steel Corporation, first in the metallurgy division of their Bethlehem Plant, then with Homer Research Laboratories. He has had a long interest in heat treatment of ferrous and nonferrous alloys. Mr. Vander Voort received a BS degree in Metallurgical Engineering from Drexel University in 1967 and an MS in Metallurgy and Materials Science from Lehigh University in 1974.

A member of ASM for more than 25 years, and active in the Lehigh Valley Chapter as well as nationally, he is presently chairman of ASM's Technical Book Committee and a member of its Publication Council. He has taught many ASM MEI courses since 1977 and made eight of the ten video lectures for "Principles of Metallography."

Also active in other societies, he is presently chairman of ASTM Committee E-4 on Metallography and is a past president of the International Metallographic Society and is a fellow of both ASTM and ASM International.

Mr. Vander Voort is the holder of four US patents, and has over 60 publications to his credit including *Metallography: Principles and Practice*, McGraw-Hill, 1984.

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